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Evaluation of Silicon Carbide for Integrated Photonics

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Abstract

This thesis investigates the design and fabrication of strongly confined 4H-SiCOI (4H-Silicon Carbide on Insulator) waveguides for integrated photonic applications. The work combines numerical design, material characterization, and cleanroom process development to establish a reproducible framework for silicon carbide-based photonic structures.

A global design methodology is developed for silicon carbide core waveguides operating in the strong confinement regime. Systematic maps of waveguide cross-sections are generated, including modal confinement, effective and group indices, bending loss, angular loss, and free spectral range, enabling the identification of optimal geometries under technological constraints.

A pilot waveguide geometry of 300 nm height and 700 nm width is determined to follow with lithography and etching optimizations on bulk 4H-SiC. Spectroscopic ellipsometry is used to extract the optical constants of silicon carbide, and the resulting refractive index values are incorporated into the waveguide design pipeline. Maskless photolithography and reactive ion etching are calibrated to control proximity effects, tapering, and micron-sized pattern transfer leading the way towards realization of sub-micron designs on 4H-SiCOI platform.

The fabricated structures are characterized by scanning electron microscopy to assess dimensional accuracy and profile quality. This work establishes a coherent design-to-fabrication workflow for the 4H-SiCOI photonic platform.

This work was carried out at the PoliFAB cleanroom facilities, the micro- and nanotechnology center of Politecnico di Milano, as well as at the Photonic Devices Laboratory of Politecnico di Milano.

Keywords: Integrated Photonics; Waveguides; Silicon Carbide; 4H-SiCOI

Abstract in lingua italiana

Questa tesi indaga la progettazione e la fabbricazione di guide d'onda fortemente confinate su piattaforma 4H-SiCOI (4H-Silicon Carbide on Insulator) per applicazioni di fotonica integrata. Il lavoro combina progettazione numerica, caratterizzazione dei materiali e sviluppo di processi in cleanroom al fine di definire un framework riproducibile per strutture fotoniche basate su carburo di silicio.

Viene sviluppata una metodologia globale di progettazione per guide d'onda con nucleo in carburo di silicio operanti nel regime di forte confinamento ottico. Sono generate mappe sistematiche delle sezioni trasversali delle guide d'onda, comprendenti confinamento modale, indici effettivi e di gruppo, perdite per curvatura, perdite angolari e free spectral range, consentendo l'identificazione di geometrie ottimali in presenza di vincoli tecnologici.

Una geometria pilota di guida d'onda, con altezza di 300 nm e larghezza di 700 nm, viene individuata a seguito delle ottimizzazioni dei processi di litografia e incisione su campioni bulk di 4H-SiC. L'ellissometria spettroscopica è utilizzata per estrarre le costanti ottiche del carburo di silicio e i valori dell'indice di rifrazione ottenuti vengono integrati nel flusso di progettazione delle guide d'onda. La fotolitografia maskless e l'incisione mediante plasma reattivo (RIE) sono calibrate per controllare effetti di prossimità, tapering e trasferimento di pattern submicrometrici.

Le strutture fabbricate sono caratterizzate mediante microscopia elettronica a scansione (SEM) per valutare l'accuratezza dimensionale e la qualità dei profili. Questo lavoro definisce un flusso coerente dalla progettazione alla fabbricazione per la piattaforma fotonica 4H-SiCOI.

Il lavoro è stato svolto presso le cleanroom di PoliFAB, centro di micro- e nanotecnologie del Politecnico di Milano, e presso il laboratorio di Dispositivi Fotonici del Politecnico di Milano.

Parole chiave: Fotonica Integrata; Guide d'onda; Carburo di Silicio; 4H-SiCOI

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1 | Fundamentals of Silicon Carbide

This Chapter presents the fundamental properties of silicon carbide (SiC) that form the material basis of this thesis. It begins with a brief historical overview of SiC and its transition from an industrial abrasive material to a wide-bandgap semiconductor widely used in power electronics and emerging photonic platforms.

The crystallographic structure of SiC and its most relevant polytypes (3C, 4H, and 6H) are then introduced. Their stacking sequences and symmetry properties are discussed in order to explain the origin of anisotropy and birefringence in hexagonal polytypes. The main physical, electrical, and optical properties of SiC, including bandgap energy, refractive index dispersion, and temperature dependence, are summarized and compared with silicon where relevant.

The Chapter also reviews the development of SiC-based photonic integrated circuits and the emergence of the SiCOI platform, which enables strong optical confinement in thin-film geometries. Finally, the motivation and scope of this thesis are outlined, defining the objectives addressed in the following Chapters.

1.1. Brief History of Silicon Carbide

The development of semiconductor materials and devices has played a fundamental role in shaping modern technology, beginning with early solid-state devices and the subsequent establishment of silicon-based microelectronics enabled by planar integrated circuit technology [1–5]. Silicon-based large-scale integrated circuits have continued to evolve despite long-standing predictions of physical limitations [6, 7], while silicon has also been widely adopted for photovoltaic applications and sensor technologies. More recently, these developments have motivated the extension of silicon-based platforms beyond electronics toward integrated photonic systems.

In this context, photons have emerged as attractive information carriers for next-generation integrated systems due to their high bandwidth, low propagation loss, and low power consumption [8]. The ability to confine and guide light in nanophotonic structures enables photonic integrated circuits with small footprint and high integration density [8]. Silicon has become the core material platform for photonic integrated circuits owing to mature CMOS-compatible fabrication processes and the commercialization of silicon-on-insulator technology, which enables large-scale photonic integration with limited increase in cost [9, 10]. However, the indirect bandgap of silicon limits on-chip light sources, while its narrow bandgap and two-photon absorption introduce optical losses at telecom wavelengths, and the absence of the Pockels effect limits modulation speed and efficiency [10–12].

A variety of material platforms have therefore been investigated for as an alternative to Si photonics, including III–V semiconductors, lithium niobate (LiNbO_3), silicon nitride, indium phosphide, diamond, and silicon carbide [13–18]. III–V semiconductors such as GaAs have been extensively studied due to their direct bandgap and large second-order and Kerr nonlinearities [19]. Lithium niobate has attracted attention for photonic integration due to its wide transparency window, strong second- and third-order nonlinearities, ultra-low optical losses, and the availability of wafer-scale lithium-niobate-on-insulator substrates [14, 20–22]. However, its incompatibility with CMOS fabrication methods and reliance on hybrid integration approaches limit its suitability for low-cost and high-yield photonic integrated circuits [23].

Wide-bandgap semiconductors have also been explored in parallel with these developments, motivated by their established use in high-temperature and high-voltage electronic applications. Among these materials, silicon carbide has been broadly explored for electronic devices by exploiting well-developed device processing protocols and CMOS compatibility [24–28].

Silicon carbide is a group IV–IV compound semiconductor characterized by strong silicon–carbon bonding, resulting in high hardness, chemical inertness, and high thermal conductivity [29]. It exhibits a wide bandgap, high critical electric field strength, and high saturation drift velocity, while allowing both n-type and p-type doping over a wide concentration range and forming a native silicon dioxide layer advantageous for device fabrication [29]. These properties have positioned silicon carbide as a promising material for high-power and high-temperature electronic applications [30–32], and leads the way for its use in photonic applications.

The development of silicon carbide has historically been hindered by difficulties in crystal growth due to its strong chemical stability and the existence of multiple polytypes arising from different stacking sequences [33]. Early industrial production via the Acheson process enabled large-scale SiC powders and yielded small single-crystalline platelets, primarily of the 6H polytype, as by-products shown Fig 1.1 [34]. These platelets enabled early investigations of optical properties of silicon carbide, including electroluminescence [35]. The introduction of the sublimation-based Lely method enabled the growth of relatively pure 6H-SiC crystals and initiated systematic studies of optical and electronic properties during the 1960s [15, 36–38].



Figure 1.1: SiC fragments produced as secondary products during the Acheson process [39].

Subsequent advances in seeded sublimation techniques enabled reproducible growth of larger-diameter silicon carbide boules with reduced defect densities [40–42]. The commercial availability of single-crystalline silicon carbide wafers in the early 1990s represented a major milestone [39]. Progress in epitaxial growth further improved material quality, as early heteroepitaxial and liquid-phase approaches were limited by high defect densities [43–46]. The demonstration of step-controlled homoepitaxial growth on off-axis substrates enabled improved thickness uniformity, doping control, and reproducibility [47, 48]. These

developments established 4H-SiC as a technologically mature polytype for reproducible material growth and electronic device fabrication [15, 49], while optical properties of silicon carbide continued to be systematically investigated in the literature [50, 51].

1.2. Physical and Optical Properties of Silicon Carbide

Silicon carbide (SiC) is a compound semiconductor composed of equal amounts of silicon and carbon. The electronic ground-state configurations of the neutral constituent atoms are

$$\text{Si } (14e^-) : 1s^2 2s^2 2p^6 3s^2 3p^2, \quad (1.1)$$

$$\text{C } (6e^-) : 1s^2 2s^2 2p^2. \quad (1.2)$$

Both silicon and carbon are tetravalent and form covalent bonds through sp^3 hybridization. This results in a tetrahedral crystal lattice in which each silicon atom is bonded to four carbon atoms and each carbon atom is bonded to four silicon atoms. The Si–C bond energy is approximately 4.6 eV and is responsible for the material’s macroscopic properties [39].

Due to this atomic structure and bonding, silicon carbide exhibits characteristic structural, electrical, and optical properties. These properties are relevant for electronic and photonic applications and are discussed in the following sections.

1.2.1. Crystal Structure

Silicon carbide is the best-known crystalline material exhibiting polytypism [33, 52–55]. Polytypism in SiC results from different stacking sequences of atomic layers along the c -axis in a hexagonal close-packed lattice [39]. In this lattice, three possible stacking sites exist, labeled A, B, and C. Consecutive layers cannot occupy the same site; for example, a layer on site A must be followed by a layer on site B or C, and similar rules apply to the other sites. Although an almost infinite number of stacking sequences is theoretically possible, most materials stabilize in only one crystal structure, typically zincblende or wurtzite. In contrast, SiC crystallizes in more than 200 distinct polytypes [39].

SiC polytypes are described using Ramsdell’s notation, which specifies the number of Si–C bilayers in the unit cell and the crystal system: cubic (C), hexagonal (H), or rhombohedral (R) [39]. The cubic polytype, 3C-SiC, is referred to as β -SiC, while all other polytypes are classified as α -SiC [39]. The atomic structures of common polytypes, including 3C-

SiC, 4H-SiC, and 6H-SiC, are shown schematically in Fig. 1.2, where open and closed circles represent Si and C atoms, respectively. Using the A, B, and C site notation, 3C-SiC follows an ABC stacking sequence, while 4H-SiC and 6H-SiC follow ABCB (or ABAC) and ABCACB sequences [39]. Ball-stick representations of these structures are shown in Fig. 1.3. Because multiple notations are used to describe stacking sequences [33], Fig. 1.4 presents the primitive unit cells and fundamental translation vectors for cubic (3C) and hexagonal SiC. The 3C structure is equivalent to the zincblende lattice found in III–V semiconductors such as GaAs and InP [39]. The wurtzite structure, observed in materials such as GaN and ZnS, corresponds to the 2H notation [39]. The reason for the large number of SiC polytypes is not fully understood. In general, materials with strong covalent bonding favor the zincblende structure, while materials with higher ionicity favor the wurtzite structure [39]. The intermediate ionicity of SiC, approximately 11% according to Pauling’s definition, is considered a possible reason for the occurrence of SiC polytypism [56, 57].

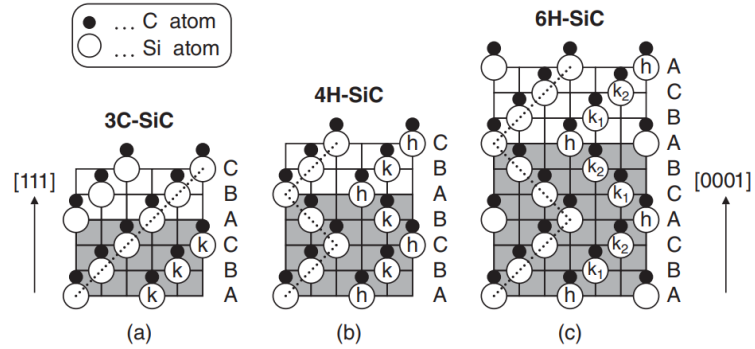


Figure 1.2: Schematic representations of commonly used SiC polytypes: (a) 3C-SiC, (b) 4H-SiC, and (c) 6H-SiC. Open circles correspond to Si atoms, while closed circles represent C atoms [39].

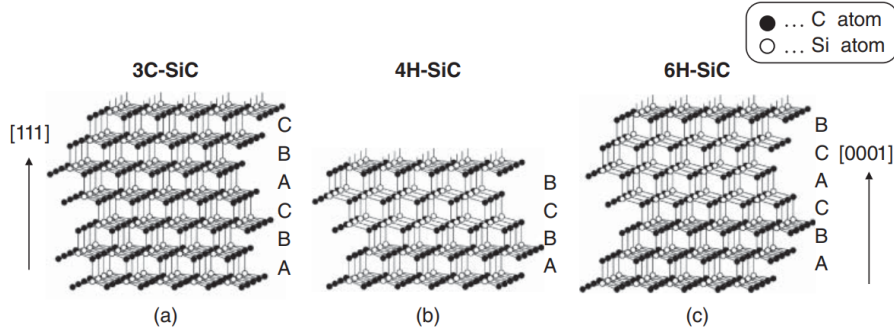


Figure 1.3: Ball-stick representations of the crystal structures of (a) 3C-SiC, (b) 4H-SiC, and (c) 6H-SiC [39].

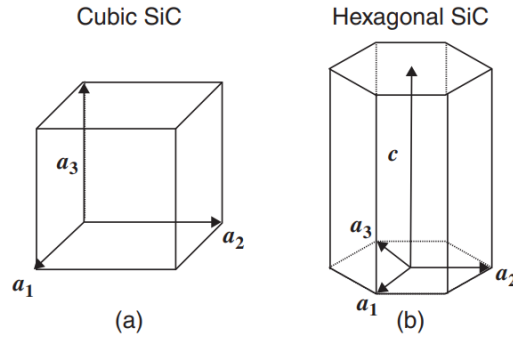


Figure 1.4: Primitive unit cells and the corresponding fundamental translation vectors of (a) cubic (3C) SiC and (b) hexagonal SiC [39].

All SiC polytypes contain similar Si–C bonds, and therefore their mechanical properties, including hardness, are similar [29]. In contrast, differences in the periodic crystal potential between polytypes lead to different electronic band structures, which cause significant changes in optical and electrical properties [39]. For device applications, growth of a single, well-defined SiC polytype is required, making polytype control an important part of SiC crystal growth [39].

The stability and nucleation of SiC polytypes depend strongly on temperature [58]. The cubic polytype, 3C-SiC, is unstable at high temperatures and transforms into hexagonal polytypes such as 6H-SiC when the temperature exceeds approximately 1900 to 2000 °C [59]. This limits the growth of large 3C-SiC bulk crystals at practical growth rates. The 2H-SiC polytype is also unstable at high temperature, and large 2H-SiC crystals have not been grown. As a result, 4H-SiC and 6H-SiC are the most widely used and

studied polytypes [60–66]. The 3C-SiC polytype is also of interest because it can be grown heteroepitaxially on silicon substrates [46, 67, 68].

Different stacking sequences of Si–C bilayers in SiC create multiple lattice sites with different local atomic environments [39]. Sites with hexagonal local coordination are referred to as hexagonal sites, while those with cubic coordination are referred to as cubic sites [39]. In Fig. 1.2, these sites are labeled as h (hexagonal) and k (cubic). The 4H-SiC polytype contains one hexagonal site and one cubic site, whereas 6H-SiC contains one hexagonal site and two inequivalent cubic sites [39]. The 3C-SiC polytype contains only cubic sites. Hexagonal and cubic sites differ in the arrangement of second-nearest neighbors, which leads to different local crystal fields [39]. As a result, the energy levels of dopants, impurities, and point defects, such as vacancies, depend on whether they occupy hexagonal or cubic sites. This phenomenon is known as the site effect [69–71].

Silicon carbide is a compound semiconductor with partial ionicity due to the higher electronegativity of carbon compared to silicon (C: 2.5, Si: 1.8), which introduces polarity in the crystal [39]. This polarity leads to direction-dependent bonding along the crystallographic axes. As a result, in hexagonal and rhombohedral SiC, the (0001) surface is defined as the Si face, while the opposite (000 $\bar{1}$) surface is defined as the C face [39]. In 3C-SiC, the corresponding Si and C faces are the (111) and ($\bar{1}\bar{1}\bar{1}$) planes [39]. In addition to these polar faces, hexagonal SiC also exhibits nonpolar surfaces such as the A face {11 $\bar{2}$ 0} and the M face {1 $\bar{1}$ 00} [39]. The surface energy, chemical reactivity, and electronic properties depend on the crystallographic face [39].

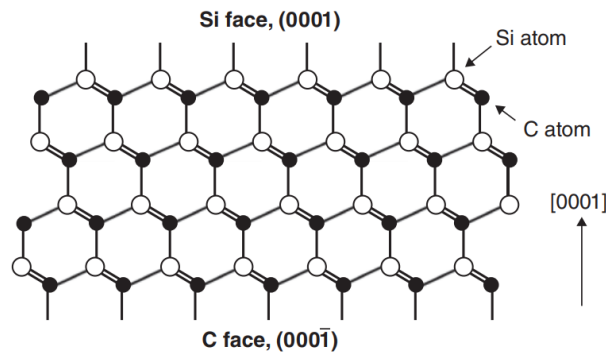


Figure 1.5: Schematic illustration of the bonding configurations in a hexagonal SiC polytype. The SiC 0001 surface is polar and can correspond to either the Si-face or the C-face [39].

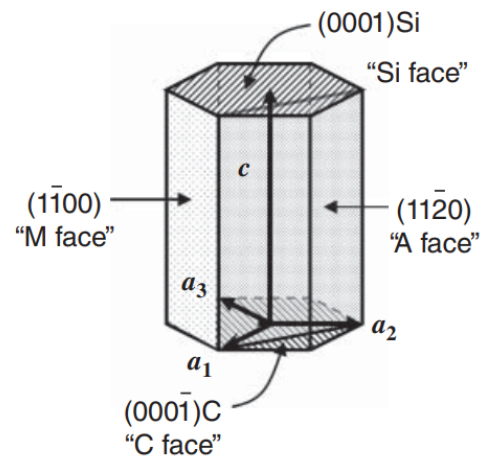


Figure 1.6: Definition of the principal crystallographic planes in a hexagonal SiC polytypes [39].

Physical and electrical properties of common SiC polytypes

	3C-SiC	4H-SiC	6H-SiC
Crystal structure	Zinc blende	Hexagonal	Hexagonal
Energy gap (eV)	2.36	3.23	3.0
Bulk modulus (dyn/cm²)	25×10^{11}	22×10^{11}	22×10^{11} (th.) 9.7×10^{11} (exp.)
Melting point (at 35 atm)	~ 3100 K	~ 3100 K	~ 3100 K
Specific heat (J g⁻¹ °C⁻¹)	0.69	0.69	0.69
Thermal conductivity (W cm⁻¹ °C⁻¹)	3.6	3.7	4.9
Thermal diffusivity (cm² s⁻¹)	1.6	1.7	2.2
Debye temperature (K)	1200	1300	1200
Density (g/cm³)	3.21	3.21	3.21
Dielectric constant (static)	9.72	9.66	9.66 (ϵ_e) 10.03 (ϵ_o)
Dielectric constant (high frequency)	6.52	6.52	6.52 (ϵ_e) 6.70 (ϵ_o)
Effective electron mass m_l/m_0	0.68	0.29	2.0
Effective electron mass m_t/m_0	0.25	0.42	0.42
Effective hole mass (m_0 units)	0.6	~ 1	~ 1
Lattice constant a (Å)	4.3596	3.0730	3.0806
Lattice constant c (Å)	4.3596	10.053	15.1173

Table 1.1: Properties of 3C-, 4H-, and 6H-SiC polytypes. *th.: theoretical value; exp.: experimental value; ϵ_e : extraordinary dielectric constant; ϵ_o : ordinary dielectric constant.

1.2.2. Physical and Electrical Properties

In this section, basic physical, electrical and optical parameters of the main SiC polytypes commonly used in practice are summarized, see Figs. 1.7, 1.8, and 1.9, and Table 1.1. The values are intended for comparison and general reference. Detailed data for these polytypes, as well as for other SiC polytypes, are available in the literature. Further information on related topics such as energy band structures and carrier concentrations, temperature dependences, effective masses and electron mobility etc. can be found in

Chapter 5 of [72].

The data summarized in Table 1.1 highlight the combination of wide bandgap, high mechanical stiffness, and favorable thermal properties that distinguish SiC from conventional semiconductors. In particular, the large energy gaps of 4H- and 6H-SiC (above 3 eV) and their high bulk moduli on the order of 10^{12} dyn/cm² reflect the strong covalent bonding in the crystal, approaching that of diamond in terms of mechanical hardness and thermal robustness. At the same time, the relatively high thermal conductivity and thermal diffusivity values enable efficient heat dissipation, which is critical for high-power and high-temperature device operation. The anisotropy observed in dielectric constants for hexagonal polytypes further illustrates the strong dependence of physical and electrical properties on crystal structure and orientation, motivating the widespread use of 4H- and 6H-SiC in electronic and photonic applications.

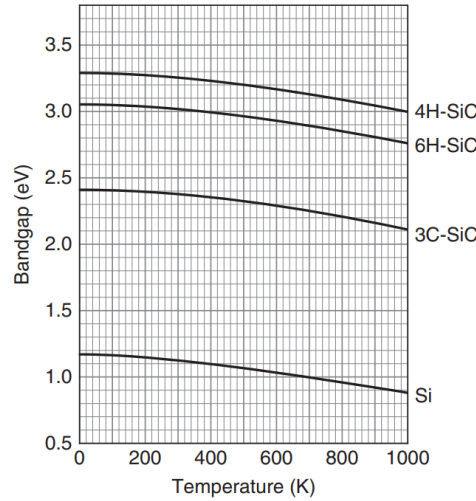


Figure 1.7: Temperature dependence of the bandgap energy for silicon and the main SiC polytypes [39].

1.2.3. Optical Properties

Based on Table 1.2, silicon and 4H-SiC exhibit distinct optical, nonlinear, and thermal properties at 1550 nm that influence their suitability for integrated photonic applications.

At this wavelength, silicon presents a higher refractive index ($n = 3.476$) compared to 4H-SiC ($n_e = 2.59$, $n_o = 2.55$), resulting in stronger index contrast and tighter optical confinement in high-index-contrast platforms. The extinction coefficient is negligible for both materials at telecom wavelengths. A fundamental difference arises from the bandgap values: silicon (1.12 eV) undergoes two-photon absorption at 1550 nm ($\beta = 0.79$ cm GW⁻¹),

whereas the wide bandgap of 4H-SiC (3.2 eV) suppresses TPA under the same conditions.

Regarding nonlinear response, silicon exhibits a larger third-order (Kerr) nonlinearity ($\chi^{(3)} \approx 5 \times 10^{-18} \text{ m}^2/\text{W}$) than 4H-SiC ($1 \times 10^{-18} \text{ m}^2/\text{W}$). However, 4H-SiC possesses a non-zero second-order nonlinear susceptibility ($\chi^{(2)}$), with reported tensor components in the range of several pm/V, while silicon does not exhibit an intrinsic second-order response due to its centrosymmetric crystal structure [73]. Furthermore, measurable electro-optic coefficients have been reported for 4H-SiC, whereas silicon lacks an intrinsic linear electro-optic effect.

From a thermal standpoint, 4H-SiC demonstrates higher thermal conductivity ($3.7 \text{ W cm}^{-1} \text{ K}^{-1}$) compared to silicon ($1.4 \text{ W cm}^{-1} \text{ K}^{-1}$), supporting improved heat dissipation. Its thermo-optic coefficient ($2.1 \times 10^{-5} \text{ K}^{-1}$) is significantly lower than that of silicon ($1.818 \times 10^{-4} \text{ K}^{-1}$), which contributes to enhanced thermal stability in temperature-sensitive photonic devices. In addition, 4H-SiC offers a broader transparency window extending from the ultraviolet to the mid-infrared region.

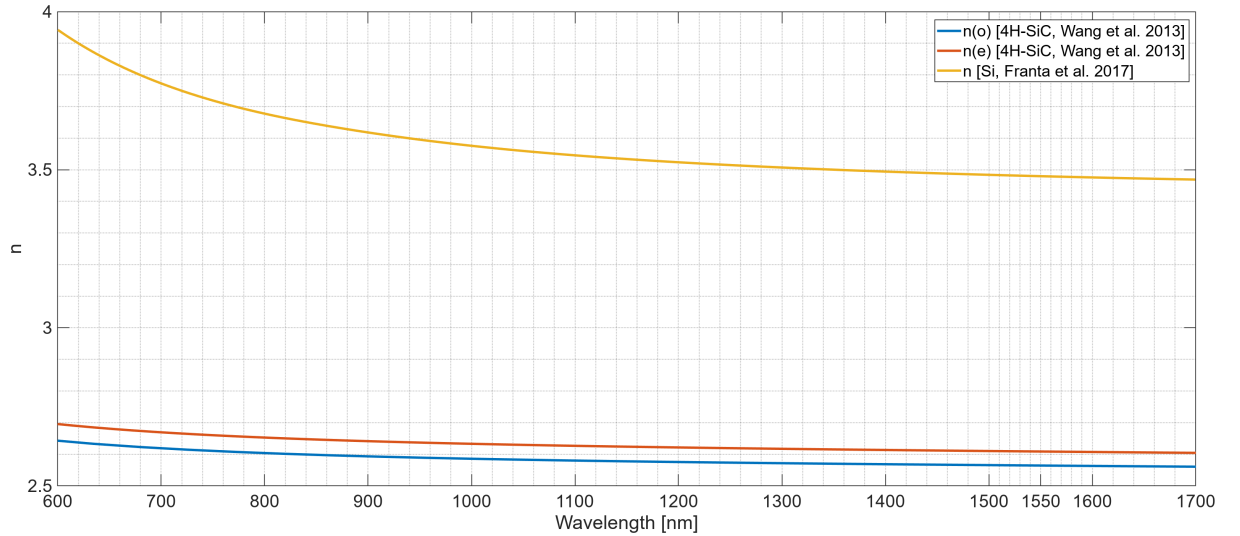


Figure 1.8: Wavelength-dependent refractive indices of 4H-SiC (ordinary and extraordinary polarizations) and Si in the 600–1700 nm range [74, 75].

In the vicinity of 1550 nm, the refractive index dispersion of 4H-SiC is moderate and maintains a distinct separation between $n(o)$ and $n(e)$, confirming its intrinsic birefringent behavior, whereas silicon shows a consistently higher refractive index across the investigated wavelength range.

Optical properties at 1550 nm (300 K)

Parameter	4H-SiC	Si
Refractive index n	2.59 (n_e)	3.476
[72, 76]	2.55 (n_o)	
Extinction coefficient k	≈ 0	$\approx 10^{-8}$
[77, 78]		
Bandgap (eV) [77, 79]	3.2	1.12
Transparency range (μm) [80, 81]	0.37-5.6	1.2-8
Second-order nonlinearity $\chi^{(2)}$ (pm/V) [81, 82]	At 1064 nm d_{31} : 6.5 d_{15} : 6.73 d_{33} : -11.7	—
Third-order (Kerr) nonlinearity $\chi^{(3)}$ ($\text{m}^2 \text{W}^{-1}$) [80, 81]	1×10^{-18}	5×10^{-18}
Thermo-optic coefficient dn/dT (K^{-1}) [76, 77]	2.1×10^{-5}	1.818×10^{-4}
Two-photon absorption coefficient β (cm GW^{-1}) [80, 83]	—	0.79
Thermal conductivity ($\text{W cm}^{-1} \text{K}^{-1}$) [72, 76]	3.7	1.4
Electro-optic coefficient (pm/V) [84]	r_{13} : 0.3–0.7 r_{33} : 0–0.03	—

Table 1.2: Comparison of key optical and thermal parameters at 1550 nm and 300 K.

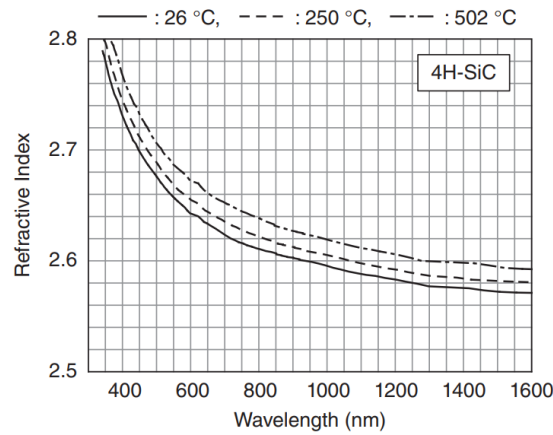


Figure 1.9: Temperature-dependent refractive index dispersion of 4H-SiC across UV to IR wavelengths [39].

1.3. Evolution of SiC and SiCOI Photonic Integrated Circuits

At present, the most widely investigated silicon carbide polytypes for photonic applications are 3C-SiC with a cubic zinc-blende structure, and the hexagonal polytypes 4H-SiC and 6H-SiC. The ability to reproducibly fabricate these polytypes has enabled the development of a variety of elementary nanophotonic devices that are essential for densely integrated and high-performance photonic integrated circuits [85]. Early photonic studies primarily focused on the 3C-SiC platform due to the relative simplicity of its hetero-epitaxial growth on silicon substrates [86–88]. More recently, significant progress has been reported in photonic cavities based on epitaxially grown 4H-SiC [89], as well as micro-ring resonators realized in 4H-SiC-on-insulator platforms fabricated through bonding, thinning, and polishing techniques [25, 27, 90].

Silicon carbide is a wide-bandgap semiconductor exhibiting a large number of polytypes, of which only 3C-, 4H-, and 6H-SiC can be stably grown and are commercially available for optoelectronic applications [85]. Early photonic research explored several material configurations, including bulk SiC [91], hetero-epitaxial 3C-SiC [92, 93], homo-epitaxial 4H-SiC thin films [94], amorphous SiC deposited on silicon substrates [95], and SiC-on-insulator platforms [96].

Among these, 3C-SiC initially emerged as a preferred platform for optoelectronic devices owing to its compatibility with hetero-epitaxial growth on large-area silicon wafers [97]. The availability of high-quality, low-cost silicon substrates enabled cost-effective fabrication of single-crystalline 3C-SiC thin films over large wafer areas [85]. From a photonic perspective, 3C-SiC-on-Si platforms offer CMOS compatibility and facilitate integration with electronic circuits, which is attractive for large-scale photonic systems [95, 98–101]. Optical confinement in such platforms is typically achieved by selectively undercutting the silicon substrate, allowing light confinement within the SiC layer through the refractive index contrast with air, as a similar structure for 4H-SiC is illustrated in Fig. 1.10 [102].

However, this undercut-based configuration requires complex fabrication processes, which restrict device versatility and integration with other materials [93, 99, 103]. Furthermore, the large lattice mismatch ($\sim 20\%$) and thermal expansion mismatch ($\sim 8\%$) between silicon and 3C-SiC introduce a high density of stacking faults and extended defects during CVD growth [104]. Additional defects are also generated at the Si/SiC interface due to silicon out-diffusion, leading to voids and pits in the substrate [85]. As a result of these limitations, both selective etching approaches and 3C-SiC-on-Si platforms have gradually

fallen out of favor in recent SiC photonics research [85].

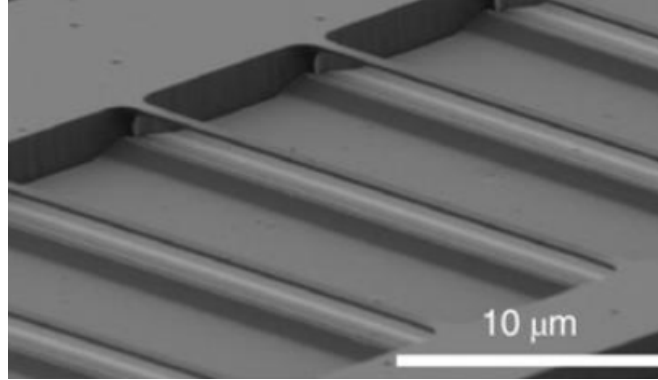


Figure 1.10: Scanning electron microscope (SEM) image of an array of fabricated photonic crystal nanobeams [102].

Compared with epi-3C-SiC-on-Si, 4H-SiC exhibits higher technological maturity and has attracted increasing interest in nonlinear and quantum photonics [27, 102, 105, 106]. Nevertheless, the absence of scalable hetero-epitaxial growth techniques represents a major obstacle to the widespread adoption of 4H-SiC photonic platforms [85]. To address this challenge, angled etching techniques have been developed as an alternative fabrication route for nanophotonic structures on bulk 4H-SiC, similar to approaches previously applied in diamond photonics [107].

Using this method, suspended nanophotonic waveguides and cavities have been demonstrated on bulk 4H-SiC [102]. The process relies on a two-step dry-etching sequence, where vertical structures are first defined by plasma etching, followed by angled etching using a Faraday cage or ion sheath control to form suspended nanobeam geometries [102]. These structures provide strong optical confinement through the refractive index contrast with air, as shown Fig. 1.10 [102]. While angled etching enables effective fabrication of nanobeams and crystal cavities [102, 108, 109], realizing system-level integrated photonic devices on bulk SiC platforms remains challenging [85].

Towards SiCOI

Based on the preceding discussion, it becomes evident that efficient, stable, and generic structures are required for the realization of scalable integrated photonic systems on silicon carbide platforms, beyond demonstrations of individual devices [85]. A widely proposed approach to address this requirement is the use of silicon carbide thin films on insulator substrates, commonly referred to as silicon-carbide-on-insulator (SiCOI) platforms [85].

Analogous to silicon-on-insulator technology, SiCOI provides a large refractive index contrast in the vertical direction, enabling efficient patterning of waveguides and resonators within the SiC device layer for optical confinement, which is essential for scalable photonic integration [85]. Over the past decade, extensive efforts have been devoted to the development of high-quality SiCOI platforms [27, 80, 88].

Although 3C-SiCOI platforms have demonstrated considerable potential for photonic integrated circuits, intrinsic material imperfections and stacking defects originating from lattice mismatch lead to increased absorption losses, imposing fundamental performance limits on nanophotonic devices [85]. In contrast, hexagonal 4H-SiCOI exhibits significantly lower intrinsic optical losses and offers a more versatile material platform for photonic technologies [85]. The interest in 4H-SiC is primarily driven by the availability of well-established techniques for wafer-scale crystal growth with controlled crystalline quality [110]. Wafer-scale growth and processing of 4H-SiC were originally developed in the 1990s for high-power electronic applications [85], and similar processing routes were later employed to demonstrate 4H-SiCOI substrates using ion-implantation methods analogous to those used for silicon-on-insulator platforms [85].

Ion-cut (smart-cut) 4H-SiCOI substrates are particularly advantageous because this approach preserves the crystalline integrity of the photonic device layer, thereby improving device quality [85]. In addition, ion cutting enables the fabrication of wafer-scale 4H-SiC thin films on SiO₂/Si substrates with well-controlled thickness uniformity and surface roughness, which is beneficial for future foundry-compatible photonic device fabrication [85]. Over the past decade, substantial efforts have focused on the fabrication of 4H-SiCOI substrates using ion-cutting techniques [111–115], including multiple demonstrations of wafer-scale 4H-SiCOI platforms [27, 80, 116, 117].

Thanks to the well-controlled H⁺ implantation depth and the subsequent thermally induced exfoliation process, the thickness of the transferred 4H-SiC layer can be precisely defined by the implantation energy and ion distribution profile [112, 115, 116, 118, 119]. After removing the surface amorphous layer, a high-quality single-crystalline 4H-SiC thin film on insulator with uniform thickness and preserved lattice integrity is obtained [85].

An alternative fabrication route for realizing 4H-SiC thin films on SiO₂/Si substrates is based on bonding, thinning, and polishing techniques. This approach has been employed in several reported studies over recent years, demonstrating its applicability for photonic device fabrication on 4H-SiC-on-insulator platforms [27, 90, 120, 121]. The process enables the transfer of high-quality 4H-SiC thin films while maintaining crystalline integrity and supporting scalability toward wafer-level production. Using this platform, nonlinear pho-

tonic devices have been demonstrated with performance approaching the intrinsic limits of high-purity 4H-SiCOI material. In particular, optical resonators fabricated using this method have achieved quality factors on the order of 5×10^6 , exceeding values reported in earlier SiC-based photonic implementations [25, 90, 120]. Nevertheless, for sustained operation and industrial-scale fabrication, further improvements in thickness uniformity are required to ensure compatibility with standardized photonic circuit manufacturing processes [85].

Optical micro-ring resonators constitute a core building block in integrated photonics[80, 93, 98]. In SiC platforms, micro-ring resonators are typically fabricated using electron-beam lithography followed by reactive-ion etching or inductively coupled plasma etching, which allow precise definition of sub-micrometer features and control of sidewall geometry [93, 98, 122]. The optical performance of SiC micro-rings is commonly quantified by the quality factor Q , which is determined by the combined contributions of sidewall-scattering loss, intrinsic material absorption, and radiation loss [80, 123].

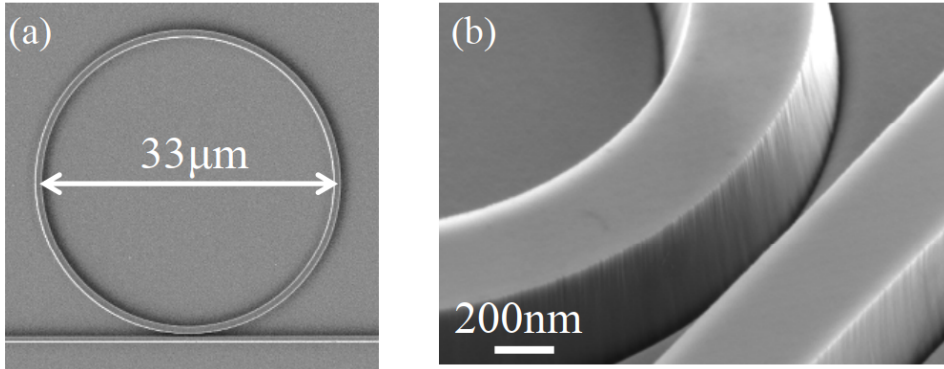


Figure 1.11: Scanning electron microscopy (SEM) images of a 4H-SiCOI microring resonator with a radius of 16.5 μm (a) and a close-up view of its coupling region (b) [124].

Early micro-ring resonators realized on epitaxial 3C-SiC platforms exhibited intrinsic Q factors on the order of 10^4 , corresponding to propagation losses exceeding several tens of dB cm^{-1} [125]. These losses were primarily attributed to crystalline defects arising from the large lattice and thermal-expansion mismatches between 3C-SiC and silicon substrates [88, 104]. Subsequent process optimizations, including high-temperature oxidation and annealing treatments, enabled partial mitigation of sidewall roughness and material absorption, reducing propagation losses to the single-digit dB cm^{-1} range in optimized 3C-SiC micro-ring devices [122]. Nevertheless, the achievable performance of 3C-SiC micro-rings remained fundamentally constrained by the intrinsic defect density of hetero-epitaxial 3C-SiC thin films [80].

A decisive improvement in micro-ring resonator performance was achieved with the transition to hexagonal 4H-SiC-on-insulator (4H-SiCOI) platforms [27, 80, 90, 120]. In contrast to 3C-SiC, 4H-SiC benefits from wafer-scale bulk crystal growth with well-controlled crystalline quality, which significantly reduces intrinsic absorption losses [110]. Micro-ring resonators fabricated on 4H-SiCOI substrates-using standard nanofabrication flows based on electron-beam lithography and dry etching, combined with ion cutting or bonding-and-thinning techniques for substrate preparation-have demonstrated quality factors exceeding 10^6 , with reported values reaching several million [25, 80, 126]. These results reflect the preservation of single-crystalline integrity in the photonic device layer, improved sidewall quality, and the strong vertical refractive-index contrast provided by the buried SiO_2 layer [27, 90, 120]. Furthermore, the availability of wafer-scale 4H-SiCOI substrates enables reproducible fabrication of low-loss micro-ring resonators suitable for large-scale integrated photonic circuits [116, 117]. A quantitative comparison of representative SiC photonic platforms and their reported micro-ring resonator performance is summarized in Table X. The table highlights the progression from early 3C-based implementations to 4H-SiCOI platforms, emphasizing the substantial improvement in achievable quality factors and overall device performance.

Reported performance of SiC photonic platforms

Platform	Fabrication Method	Quality Factor	Wavelength [nm]	Year	Ref.
a-SiCOI	PECVD	1.6×10^5	1568.2	2019	[127]
3C-SiC on Si	Hetero-epitaxial grown on Si	4.10×10^4	1532.7	2020	[122]
3C-SiCOI	Epitaxy, bonding, etching, thinning	1.74×10^4	1310	2021	[128]
4H-SiCOI	Bonding and thinning	5.61×10^6	1550	2021	[126]

Table 1.3: Comparison of reported micro-ring resonator quality factors for different SiC photonic platforms.

1.4. Motivation and Original Contributions

Silicon carbide (SiC) has emerged as a compelling alternative to silicon for integrated photonics due to its wide bandgap, high refractive index, broad transparency window extending from the ultra-violet (UV) to the infrared, high optical damage threshold,

and superior thermal conductivity. These properties make SiC particularly suitable for high-power, nonlinear, and thermally robust photonic applications where silicon exhibits intrinsic limitations such as two-photon absorption and limited electro-optic functionality. Among the technologically relevant SiC polytypes, 4H-SiC represents the most suitable choice for photonic integration. Unlike hetero-epitaxial 3C-SiC, which suffers from high defect densities due to lattice and thermal mismatches with silicon substrates, 4H-SiC benefits from mature wafer-scale bulk crystal growth with significantly lower intrinsic defect density and improved crystalline uniformity. The development of 4H-SiCOI platforms has enabled strong vertical refractive index contrast and low optical losses, with reported micro-ring resonators exhibiting quality factors exceeding 10^6 , clearly demonstrating the superior optical performance achievable with this polytype.

Despite these advances, existing studies on 4H-SiCOI predominantly focus on individual high-performance device demonstrations rather than on establishing systematic waveguide design methodologies. While the material platform has proven capable of supporting low-loss and high- Q resonant structures, comprehensive design frameworks defining single-mode operation regions, strong-confinement boundaries, effective and group index engineering, and bending-loss-aware geometry selection remain largely unexplored. As photonic integration moves toward submicron and strongly confined waveguide geometries, the absence of global and fabrication-aware design rules represents a critical limitation. The motivation of this thesis is therefore to establish a systematic design framework for strongly confined 4H-SiCOI waveguides, enabling reproducible geometry selection and scalable photonic circuit implementation on this technologically mature platform.

This work contains some original contributions that are listed below:

- **Chapter 2 – Global design rules for strongly confined 4H-SiCOI waveguides**

A systematic global mapping of 4H-SiCOI waveguide geometries operating in the strong confinement regime has been developed. Single-TE and single-TM operation regions, effective and group index trends, modal confinement, bending loss and free spectral range have been jointly evaluated through parametric cross-sectional sweeps. The resulting maps provide compact and transferable design tools for waveguide and resonator-oriented photonic structures.

- **Chapter 2 – Pilot waveguide geometry extraction based on global parameter maps**

Using the developed background, a pilot waveguide geometry with 700 nm width

and 300 nm height has been identified. The selected dimensions fall within the range of cross-sections reported in literature for high-performance 4H-SiCOI devices, demonstrating the consistency of the proposed approach with experimentally validated platforms while enabling independent geometry selection.

- **Chapter 2 – Evaluation of extremely small propagation and bending losses**

A numerical methodology for the estimation of very small propagation and bending losses in high-index-contrast 4H-SiCOI waveguides has been implemented. The analysis quantifies radiation sensitivity under submicron dimensional variations and directly connects waveguide geometry to resonator-level performance considerations.

- **Chapter 3 – Process optimization for 4H-SiCOI waveguide fabrication**

Since 4H-SiCOI fabrication processes are not yet fully standardized and the platform is still emerging, systematic optimization was carried out using direct-write photolithography, enabling rapid evaluation of different mask configurations. Mask dimensions, exposure doses, and lithography strategies were optimized for multiple scenarios. These studies provided the preliminary groundwork for electron-beam lithography for submicron geometries. Based on the lithography outcomes, optimized dry-etch recipes were developed. The obtained etch rate and photoresist selectivity values were found to be consistent with reference data reported in the literature, establishing critical technological steps toward 4H-SiCOI waveguide and photonic device realization.

2 | Global Design Rules for Silicon Carbide Waveguides

This Chapter introduces a systematic design study and a global parameter optimization framework for silicon carbide waveguides operating in the strong optical confinement regime on the SiCOI platform. The Chapter begins by addressing the fundamental properties of optical modes in waveguides and the numerical approaches employed for their accurate and reliable analysis. Following this, previous work on silicon carbide and other strongly confined waveguide platforms is reviewed in order to establish the technological and scientific context of the presented study.

The attention is then focused on global waveguide geometry design and optimization considerations, with particular emphasis on the accurate evaluation of extremely small propagation and bending losses. While the Chapter does not aim to provide a detailed resonator design, the analysis of waveguide bending behavior inherently represents a first step toward resonator-oriented structures. In this framework, special attention is devoted to single-TE-mode and single-TM-mode silicon carbide waveguides, for which systematic maps of waveguide cross-sections, modal confinement, effective and group indices, bending loss, and free spectral range are presented.

More generally, the design plots provided in this Chapter are intended to map critical performance parameters in a compact and broadly applicable manner. These maps are conceived as general design tools that can be employed to identify optimal waveguide geometries under different technological constraints and, where relevant, to support the initial stages of resonator-based device development.

2.1. Optical Modes in Waveguides and Numerical Approach

Among optical waveguide geometries, only a limited class admits analytical solutions. Dielectric slab waveguides provide a convenient and widely adopted starting point for the theoretical description of guided optical modes.

We consider a symmetric dielectric slab waveguide composed of a core layer of thickness d and refractive index n_2 (see Fig. 2.1a), embedded between two semi-infinite cladding regions with refractive index $n_1 < n_2$ (see Fig. 2.1b). The structure is invariant along the propagation direction z and uniform along y , while the refractive index varies only along the transverse coordinate x . Time-harmonic fields with angular frequency ω are assumed, with a longitudinal dependence given by $\exp(i\beta z)$, where β denotes the propagation constant.

Starting from the frequency-domain Maxwell equations in source-free, non-magnetic media, and assuming a piecewise uniform refractive index profile, the electromagnetic problem reduces within each region to a scalar wave equation. In this formulation, the transverse field distribution satisfies an eigenvalue problem, where the propagation constant β plays the role of the eigenvalue.

Due to the slab symmetry, the modal solutions decouple into transverse-electric (TE) and transverse-magnetic (TM) polarizations. For TE modes, the electric field is polarized along the y direction and can be written as

$$\mathbf{E}_m(x, z; \omega) = \hat{\mathbf{y}} E_0 \phi_m(x; \omega) e^{-i\beta_m(\omega)z}, \quad (2.1)$$

where the integer index $m = 0, 1, 2, \dots$ labels the guided modes. The transverse field profile $\phi(x)$ satisfies

$$\left[\frac{d^2}{dx^2} + k_0^2 n^2 - \beta^2 \right] \phi(x) = 0, \quad (2.2)$$

with $k_0 = \omega/c$. Guided solutions correspond to oscillatory fields in the core and exponentially decaying fields in the cladding regions. This behavior is ensured by defining

$$k^2 = k_0^2 n_2^2 - \beta^2, \quad \gamma^2 = \beta^2 - k_0^2 n_1^2, \quad (2.3)$$

such that k is real in the core and γ is real in the cladding.

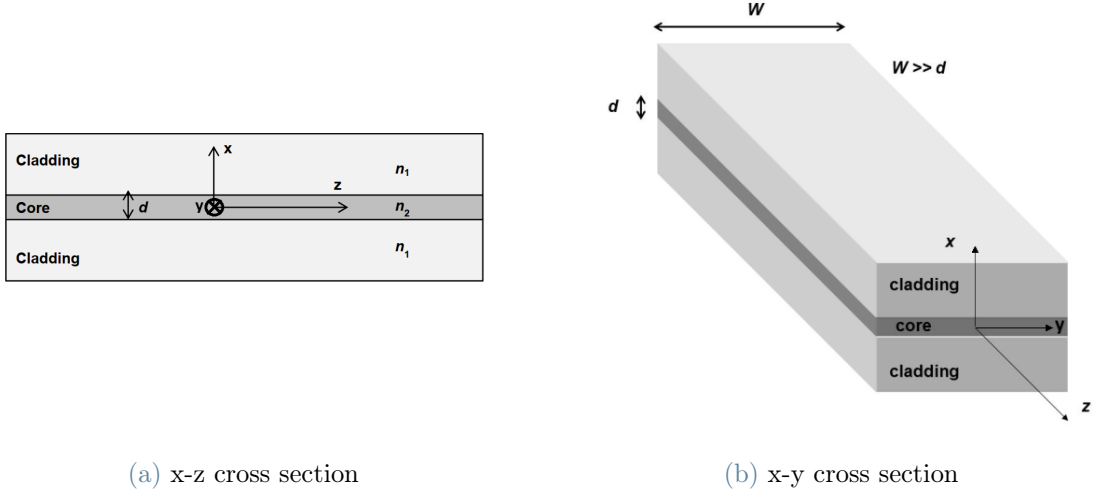


Figure 2.1: Symmetric dielectric slab waveguide geometry used for analytical modal derivation. The structure consists of a core layer of thickness d and refractive index n_2 , embedded between semi-infinite cladding regions of index n_1 . The waveguide is uniform along y , invariant along the propagation direction z , and the refractive index varies only along the transverse coordinate x .

For a symmetric slab centered at $x = 0$, the transverse field profile for TE modes is expressed as

$$\phi(x) = \begin{cases} C_1 e^{-\gamma(x-\frac{d}{2})}, & x \geq \frac{d}{2}, \\ C_2 \cos(kx), & |x| \leq \frac{d}{2} \quad (\text{even TE modes}), \\ C_2 \sin(kx), & |x| \leq \frac{d}{2} \quad (\text{odd TE modes}), \\ C_1 e^{\gamma(x+\frac{d}{2})}, & x \leq -\frac{d}{2}. \end{cases} \quad (2.4)$$

Here, C_1 and C_2 are amplitude coefficients determined by the boundary conditions at the core-cladding interfaces. Imposing continuity of the tangential field components at the core-cladding interfaces leads to the TE dispersion relations

$$\tan\left(\frac{kd}{2}\right) = \frac{\gamma}{k} \quad (\text{even TE modes}), \quad (2.5)$$

$$-\cot\left(\frac{kd}{2}\right) = \frac{\gamma}{k} \quad (\text{odd TE modes}). \quad (2.6)$$

Each solution corresponds to a discrete guided mode characterized by a propagation constant β and an effective refractive index $n_{\text{eff}} = \beta/k_0$.

For TM modes, an analogous formulation is obtained by expressing the magnetic field

along the y direction. The resulting dispersion relations differ from those of the TE modes only by the presence of refractive-index-squared weighting factors in the boundary conditions,

$$\tan\left(\frac{kd}{2}\right) = \frac{n_2^2}{n_1^2} \frac{\gamma}{k} \quad (\text{even TM modes}), \quad (2.7)$$

$$-\cot\left(\frac{kd}{2}\right) = \frac{n_2^2}{n_1^2} \frac{\gamma}{k} \quad (\text{odd TM modes}). \quad (2.8)$$

Apart from these factors, the general behavior of the TM modes is similar to that of the TE modes. A more detailed discussion of polarization-dependent modal properties can be found in standard references on optical waveguide theory, such as those by Snyder and Love [129].

In slab waveguides, optical confinement occurs in a single transverse direction, while propagation takes place along the longitudinal axis. Practical integrated optical waveguides, however, confine light in two transverse dimensions, leading to a fully two-dimensional guiding problem.

For such two-dimensional waveguides, exact analytical solutions are generally not available. The modal fields cannot be classified as purely transverse-electric or transverse-magnetic, since both electric and magnetic fields exhibit nonzero longitudinal components. As a result, numerical methods are required to determine the modal properties, including finite element and finite difference based approaches.

The finite-difference eigenmode method is formulated directly from the frequency-domain Maxwell equations under the assumption of a harmonic field dependence along the propagation direction [130, 131]. By expressing the electromagnetic fields with a longitudinal phase factor and discretizing the transverse plane using finite-difference schemes, the continuous waveguide problem is transformed into a matrix eigenvalue equation [130, 131]. In this formulation, the eigenvalue corresponds to the propagation constant of the mode, while the associated eigenvector represents the transverse field distribution.

In this section, a detailed waveguide analysis of the SiCOI platform is performed using Lumerical MODE and the Flexcompute Tidy3D Mode Solver. In both tools, optical modes are computed by solving a finite-difference eigenmode (FDE) problem derived from the frequency-domain Maxwell equations. These solvers are used to calculate modal field distributions and propagation constants for the considered waveguide geometries.

In the reported formulations, the eigenvalue problem is written explicitly in terms of the transverse field components, while the longitudinal components are eliminated using Maxwell's curl relations [130]. The discretization is performed on a Yee-type staggered

grid, which allows a consistent placement of electric and magnetic field components and facilitates accurate enforcement of material interface conditions [130]. As described in [131], such finite-difference formulations enable full-vectorial mode analysis of complex waveguide cross-sections. Depending on the boundary treatment, the resulting eigenvalue problem yields either real propagation constants for guided modes or complex propagation constants when absorbing boundary conditions such as perfectly matched layers are included, enabling the analysis of leaky modes and confinement losses [130]. The solvers used in this work, Lumerical MODE [131] and the Flexcompute Tidy3D Mode Solver [130], are based on these formulations. Further details on the numerical implementations can be found in the cited references and in the documentation provided by the respective solver platforms.

2.2. Design Methodology for Strongly Confined 4H-SiCOI Waveguides

This section reviews previous work on 4H-SiCOI and other strongly confined waveguide platforms to define the technological and design context. A global waveguide design back is then introduced, in which systematic width–height sweeps are used to construct design maps of confinement, effective index, group index, and loss behavior over a broad geometric space. In this context, the pipeline-based computational setup used to generate these maps is presented. Particular attention is given to minimizing numerical errors when evaluating extremely small propagation and bending losses.

The methodology adopted in this chapter follows the systematic design scheme introduced in Chapter 5 of *Theory and Design of High-Index-Contrast Microphotonic Circuits* [132], which presents an extensive study of silicon waveguide geometries. In the present work, it is adapted to the 4H-SiCOI platform.

2.2.1. Previous work on 4H-SiCOI and other strongly Confined Waveguides

High-index-contrast photonic devices (e.g., ring resonators, polarization beam splitters) based on 4H-SiCOI waveguides have typically employed rectangular cross-sections defined by the available device-layer thickness after bonding, ion implantation, thinning, or CMP processes. Reported waveguide heights are in the range of 350–500 nm, while widths span from about 560 nm up to 1.44 μm . Silicon dioxide is often used as a top cladding layer, deposited by thermal oxidation or PECVD, providing vertical refractive-index contrast

and physical protection.

Reported 4H-SiCOI device geometries

Device	Width (nm)	Height (nm)	Top cladding	Reference
MRR	560	350	SiO ₂ (PECVD)	[133]
MRR	680	500	–	[124]
MRR	1200	400	SiO ₂ (PECVD)	[134]
PBS	600	400	–	[135]
PBS	1440	400	–	[136]

Table 2.1: Reported geometries of 4H-SiCOI integrated devices. MRR: Microring Resonator; PBS: Polarization Beam Splitter.

Various device-oriented investigations have been reported for 4H-SiCOI photonic platforms, focusing on structures such as microring resonators, directional couplers, and nanowire waveguides [73, 137]. In these works, dimensional sweep analyses and performance studies have been carried out in relation to the intrinsic photonic properties of 4H-SiC, targeting specific device functionalities and applications [73, 137]. While high-performance devices have thus been demonstrated using selected cross-sections, a comprehensive and systematic mapping of the 4H-SiCOI waveguide design space remains limited and is addressed in the present work. The representative geometries collected from the literature are summarized in Table 2.1.

2.2.2. Global waveguide geometry design and optimization considerations

At the initial stage of the project, no fabricated samples or wafers were available. In order to enable rapid regeneration of the design maps once material parameters become accessible through later characterization, the entire simulation workflow was structured as a computational pipeline.

The simulated structure consisted of a 4H-SiC core embedded in SiO₂. Following fabrication considerations reported in the literature [39], the waveguide sidewalls were modeled with an 85° angle rather than perfectly vertical interfaces. Although this sidewall angle was achieved using silica as a mask, which is a common masking material for SiC, the developed simulation pipeline allows quick regeneration of the results presented in the following sections for any sidewall angle attainable at PoliFAB.

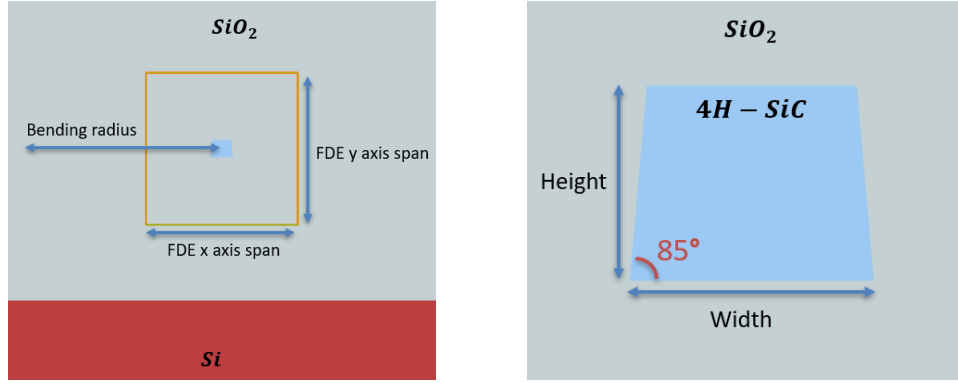


Figure 2.2: Solver cross section of the buried-strip 4H-SiCOI waveguide and various considered simulation parameters on Lumerical MODE

Within this setup, systematic parametric sweeps were performed using the Lumerical MODE FDE solver, with metallic boundary conditions applied at the simulation domain boundaries. Based on waveguide dimensions reported in the literature, the sweep limits were defined between 100 nm and 1250 nm for the height, and between 200 nm and 1250 nm for the width. Within these bounds, both geometric parameters were sampled at 30 discrete points each, corresponding to uniform discretization across the specified ranges.

The number of sampling points was selected as a compromise between adequate resolution of the geometric parameter space and computational cost, taking into account the total simulation time and available computational resources. The selected sweep limits allowed the investigation of literature-reported geometries, the exploration of intermediate configurations, and the evaluation of potentially smaller waveguide dimensions that could be practically realized. In addition, the selected height and width ranges enable a systematic analysis of TM-mode designs within the same parameter space.

Prior to the full parameter sweep, convergence tests were carried out on the effective refractive index, requiring stability up to the third decimal place. Based on this criterion, the transverse simulation window and FDE mesh resolution were defined. The window was centered on the geometric midpoint of the trapezoidal cross-section to ensure symmetric field profiles and consistent modal extraction, see Fig. 2.2. These settings were kept fixed throughout all simulations to guarantee numerical stability and comparability across the design maps.

In all simulations, the operating wavelength was set to 1550 nm. The five modes with the highest effective refractive indices supported by the given waveguide cross-section were considered.

This configuration was selected to ensure that, at each sweep point, at least the fundamental and the first higher-order TE and TM modes could be identified whenever supported by the geometry. Examination of the simulation results confirmed that this condition was satisfied throughout the investigated parameter space.

The consideration of multiple modes is necessary for the construction of the design maps presented in the following sections, where the emergence of higher-order TE and TM modes as a function of waveguide dimensions must be clearly identified. This enables the determination of single-mode and multi-mode operating regions within the explored geometric space.

For each of the five computed modes, the extracted parameters included the electric and magnetic field distributions over the simulated cross-section, the effective refractive index, the group index, the effective mode area, the TE polarization fraction, and the propagation loss.

In order to facilitate the systematic examination of the modal results obtained from the sweep simulations, a dedicated application was developed using MATLAB App Designer. This tool enables efficient visualization and comparison of the computed data across the sampled waveguide geometries. In addition, it allows interpolation of the results to evaluate modal properties at waveguide dimensions not explicitly included in the discrete sweep points.

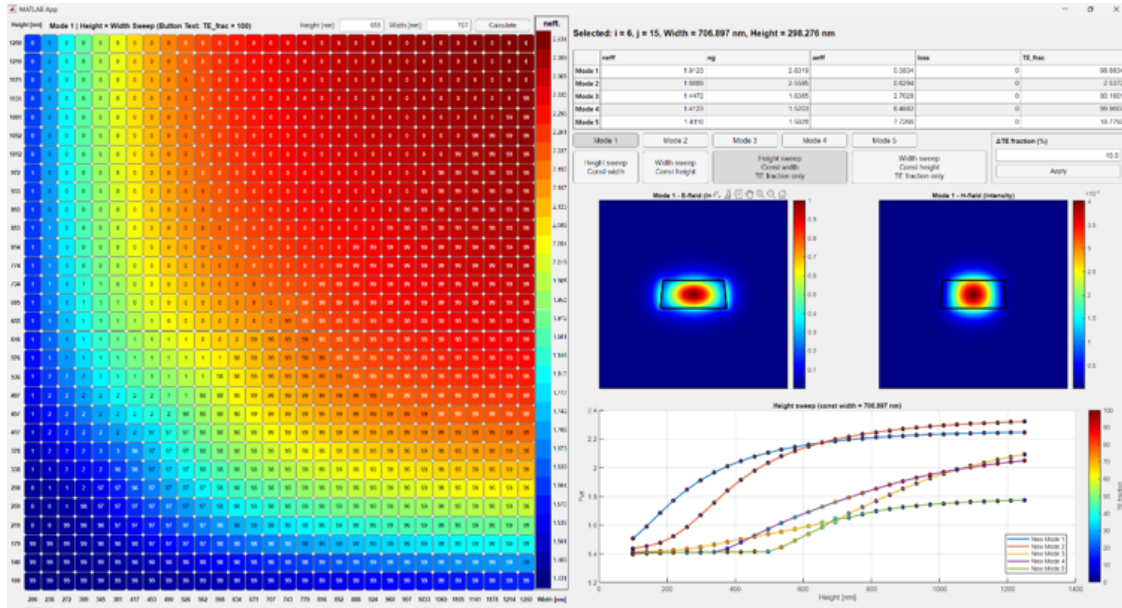


Figure 2.3: Developed MATLAB interface for waveguide sweep analysis visualization

The visualization interface (see Fig. 2.3) of the application consists of two main sections.

On the left-hand side, a button matrix provides direct access to the discrete width–height combinations corresponding to the simulated sweep points. Each button is color-coded according to the effective index of the mode with the highest effective refractive index at that geometry, enabling rapid visual identification of trends across the parameter space. In addition to the predefined sweep points, a dedicated input section allows arbitrary width and height values to be entered, upon which the interpolated modal quantities are computed.

On the right-hand side, a results panel displays the principal modal quantities in tabular form for the selected or user-defined geometry. Below this table, dedicated controls allow visualization of the electric and magnetic field intensity distributions of the computed modes. Furthermore, separate controls enable plotting of effective index variations along width or height sweeps, with the option to activate or deactivate the mode-tracking algorithm, thereby allowing direct comparison between raw solver indexing and continuity-corrected modal curves. The mode tracking procedure yields continuous modal evolution curves across the selected geometric sweep. At each sweep step, modes are associated with their counterparts from the previous step by enforcing a consistent ordering in effective index and preserving polarization continuity, thereby preventing artificial mode crossings or mislabeling. It details are given in Algorithm 2.1. For geometries that do not coincide with the sampled grid, the input width and height values are located between two adjacent width samples and two adjacent height samples, forming four surrounding boundary points in the parameter space. The modal quantities are then estimated using an inverse-distance weighting approach, where each boundary point contributes proportionally to the inverse of its distance from the target geometry. This weighted averaging procedure is applied independently to each mode and to each extracted parameter, ensuring continuity of the modal behavior across the geometric space.

However, special care must be taken near regions of the geometry space where physically distinct modes may numerically swap in the computed results, as discussed in the following sections. In such intersection regions, interpolation may lead to incorrect estimations. This issue can be mitigated by performing mode tracking around the selected point, examining discrete neighboring waveguide geometries and monitoring the evolution of the modes with respect to variations in height and width.

Through this interface, variations of the effective refractive index with respect to changing width or height parameters can be directly monitored, and consistent mode tracking across the parameter space can be performed within the generated design maps.

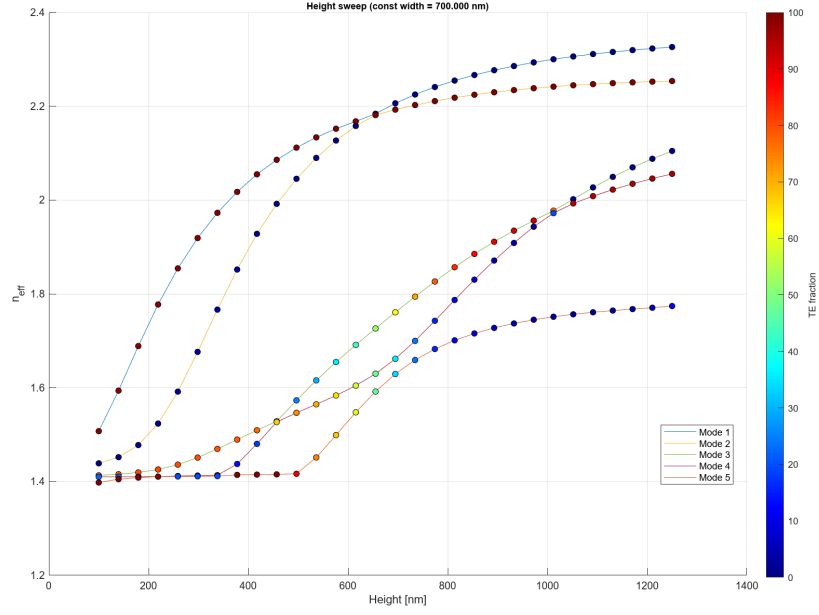
Lumerical MODE FDE solver labels the computed modes at each individual geometry

by ordering them in descending effective refractive index. In this default ordering, no distinction is made between TE- and TM-dominant character. However, when the waveguide height or width is varied, the TE-fraction of these numerically indexed modes may change significantly along the sweep. As a consequence, two modes that are consecutively numbered according to their effective index can exchange their polarization dominance at certain geometries. First 2 modes around 640 nm in height on Fig. 2.5, and 330nm in width on Fig. 2.5b. In particular, during individual parameter sweeps it can be observed that the two modes with the highest effective refractive index approach each other in value over specific geometric regions. In these regions, the TE-fraction does not evolve continuously along a single numerically labeled curve, indicating a change in modal dominance between the two solutions. This behavior implies that the raw solver indexing does not guarantee physical continuity of a given mode across the parameter space. This issue is addressed using Algorithm 2.1. It ensures that the effective index extracted from the raw eigenmode data is correctly associated with the corresponding physical mode, particularly in the presence of mode cross-over points. The identification is based on the TE and TM polarization fractions of each calculated mode. By evaluating these polarization components, the procedure determines whether a given n_{eff} value corresponds to a TE-like or TM-like mode, thereby preventing mislabeling after modal crossings. The tolerance value used in the TE-fraction discrimination within the algorithm can be directly specified in the application interface and adjusted interactively. By modifying this threshold, different mode-tracking behaviors can be tested and the continuity of modal branches across the parameter sweep can be controlled. This flexibility allows consistent tracking of modal curves under varying separation conditions between TE- and TM-dominant solutions.

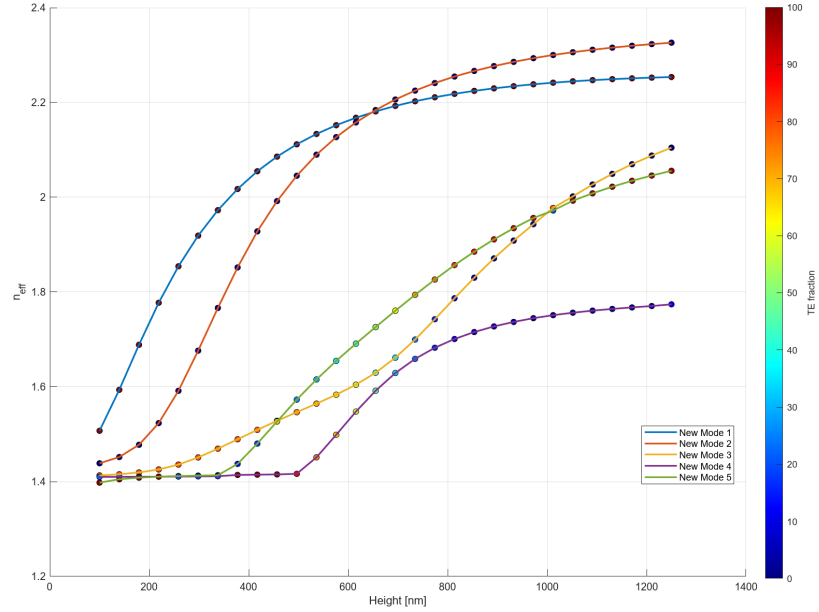
The MATLAB App Designer interface described so far corresponds to the simulation results visualization window developed for the design analysis workflow. This window is dedicated to examining discrete sweep data, interpolated modal quantities, and mode-tracking behavior across the geometric parameter space.

In addition to this visualization module, an optimization window, described in Section 2.3, is available, where the parameters used for generating and displaying the design maps can be controlled and examined. Details of this window are provided in the corresponding parts of Section 2.3.

Furthermore, a dedicated measurements window is included for the characterization of the refractive indices of 4H-SiCOI along the ordinary and extraordinary crystallographic axes. This module enables comparison between ellipsometric measurements and literature-reported values, allowing validation and calibration of the material parameters used in the design analysis.

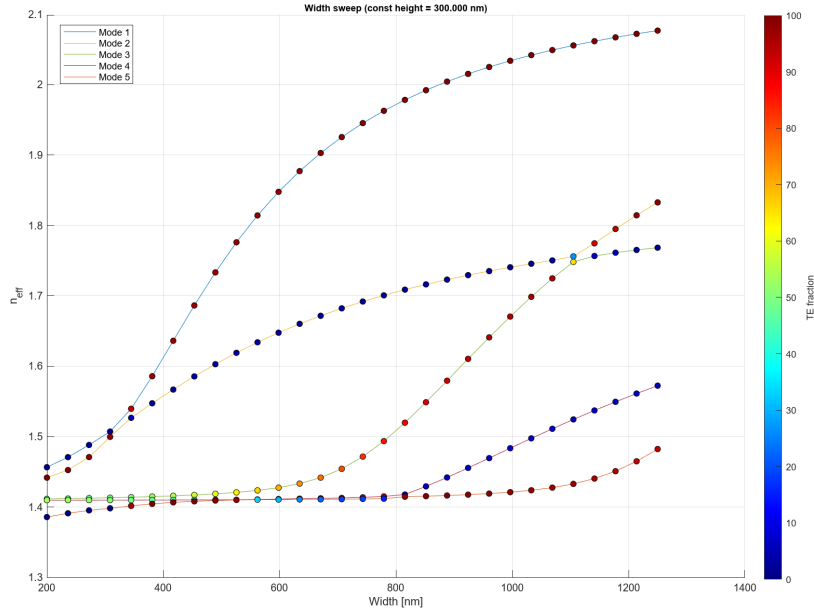


(a) Without mode tracking.

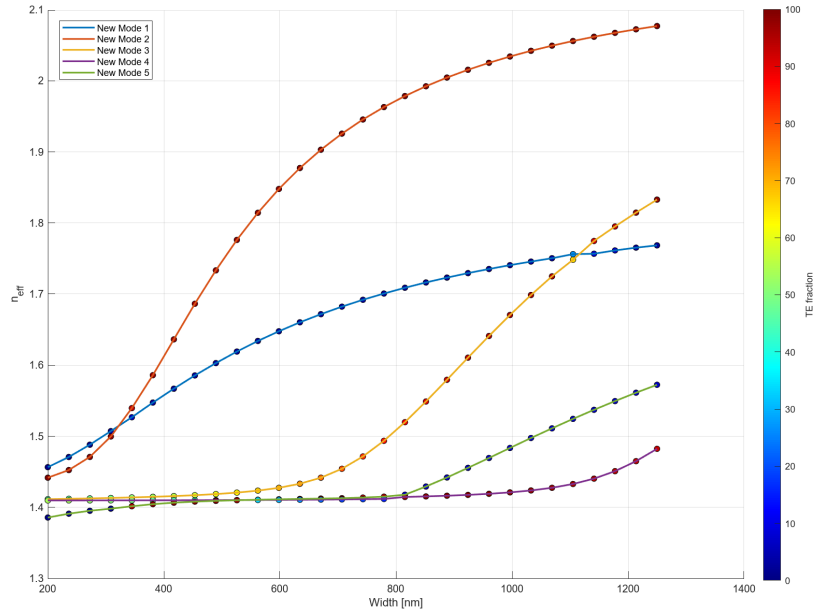


(b) With mode tracking.

Figure 2.4: Comparison for the effect of mode tracking for height sweep at 700 nm width. Continuity of the modes can be seen through TE fractions indicated with the point colorings on their corresponding lines.



(a) Without mode tracking.



(b) With mode tracking.

Figure 2.5: Comparison for the effect of mode tracking for width sweep at 300 nm height. Continuity of the modes can be seen through TE fractions indicated with the point colorings on their corresponding lines.

Algorithm 2.1 Mode Tracking Based on n_{eff} Monotonicity and TE-Fraction Continuity

- 1: **Load** raw modal data (n_{eff} and TE-fraction) for all sweep points.
 - 2: **Initialize** tracked modes at the first sweep point by sorting raw modes in descending n_{eff} .
 - 3: **for** each subsequent sweep point **do**
 - 4: **Form candidate modes** by selecting raw modes with n_{eff} greater than the previous tracked value (monotonic condition).
 - 5: **Evaluate TE-fraction spread** at the current sweep point.
 - 6: **if** TE-fraction values are well separated **then**
 - 7: **Match modes** by minimizing the difference in TE-fraction with respect to the previous sweep point.
 - 8: **else**
 - 9: **Match modes** by minimizing variations in the slope of n_{eff} along the sweep.
 - 10: **end if**
 - 11: **Perform one-to-one assignment** between tracked and raw modes to avoid duplicate usage.
 - 12: **Update** tracked modal curves with the selected assignments.
 - 13: **end for**
 - 14: **Return** the tracked mode evolution across the full sweep.
-

2.2.3. Minimizing errors for extremely small propagation/bending losses

In order to realize fundamental integrated photonic devices on the 4H-SiCOI platform, a well-defined waveguide design is required. In practical device implementations such as ring resonators, the selected waveguide geometry is subjected to bending. Therefore, beyond straight-waveguide analysis, the bending behavior of the proposed geometries must also be evaluated.

For the waveguides to be described in Section 2.3.1, bending simulations must be performed for the waveguide dimensions proposed in the dimension map, as well as for the possible dimensions selected by considering additional conditions in addition to these proposed dimensions. The resulting outcomes, such as mode confinement and angular loss, must then be evaluated.

For several different width and height values selected from the design space, bending radius sweep simulations have been carried out and the resulting angular propagation losses have been analyzed. As can be seen in the Fig. 2.6, at certain bending radius

values, the calculated loss values become negative for different waveguide dimensions. These negative loss values are observed only for waveguide dimensions and bending radii where very small angular propagation losses are expected.

Height: 300 nm, Width: 700 nm, Bend Rad: 8 μm

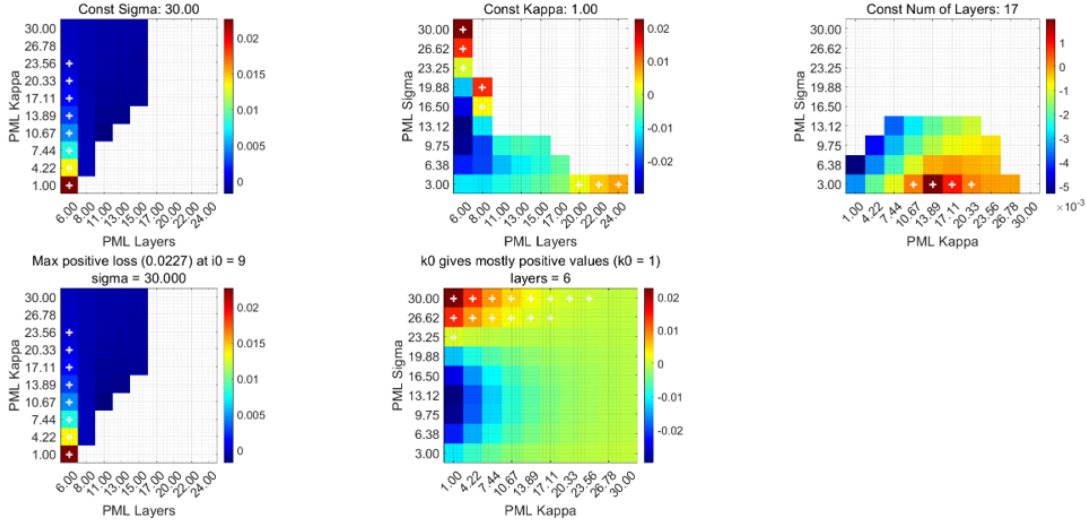


Figure 2.6: Parametric sweep of PML settings to ensure positive bending loss values for a 300×700 nm waveguide with an 8 μm bending radius.

An examination of the documentation by solvers for such simulations indicates that the occurrence of these values can be attributed to numerical instability arising from spurious reflections associated with the boundary conditions, in particular the perfectly matched layers (PML) [138, 139]. In these scenarios, errors within the calculations exceed the physically expected low loss values, which leads to negative propagation and hence angular losses. Since this work focuses on passive photonic device simulations, such non-physical behavior must not occur. At the same time, this issue would also lead to incorrect results in the maps to be generated under Section 2.3.

In the Lumerical MODE FDE solver, perfectly matched layer (PML) boundary conditions are selected when performing bent waveguide simulations. This choice is made to ensure that the fields radiating outward from the waveguide are fully absorbed in such curved waveguide configurations.

When defining these boundary conditions, the Lumerical 2020 R2 MODE environment allows certain PML parameters to be adjusted. These parameters include kappa, sigma, the number of layers, and the polynomial grading.

The layers parameter represents the number of discretized cell layers assigned to the PML

region within the computational domain in order to properly implement the absorbing boundary condition.

Sigma defines the attenuation strength inside the PML region and directly controls how rapidly outward-propagating fields are damped as they enter the absorbing layer [130, 140, 141]. Within the implementation, sigma is introduced as a normalized unitless parameter and is spatially graded across the PML thickness using polynomial functions [130, 140, 141]. This grading ensures a gradual increase of attenuation from the inner interface toward the outer boundary, thereby reducing artificial reflections at the PML entrance [130, 140, 141].

From the discrete formulation perspective, sigma contributes to the effective loss term added to Maxwell's equations within the PML region, ensuring attenuation of the fields as they propagate through the absorbing layer [130, 140, 141]. The stability of the numerical update scheme requires the constitutive parameters to remain positive and real; when sigma satisfies this condition, the resulting discrete operators remain stable [130, 140, 141]. Therefore, sigma primarily governs the absorption magnitude while simultaneously influencing numerical robustness through its role in the loss mechanism.

Kappa is a dimensionless scaling parameter associated with the stretched-coordinate transformation that defines the PML formulation. Unlike sigma, which directly determines the magnitude of attenuation, kappa modifies the effective coordinate stretching inside the PML. This affects how propagating and evanescent waves experience absorption across different frequency ranges [130, 140, 141].

Through its presence in the stretched-coordinate tensor, kappa shapes the reflection characteristics and broadband absorption behavior of the PML [130, 140, 141]. Proper selection of kappa is therefore essential to minimize reflection error and maintain absorption efficiency over the frequency range of interest [130, 140, 141]. Similar to sigma, κ must be chosen as a positive real parameter to satisfy the stability conditions of the discrete formulation [130, 140, 141]. Consequently, while sigma determines how strongly fields are attenuated, kappa governs how that attenuation is distributed and optimized within the PML structure.

For a given waveguide geometry and bending radius scenario, proximity of the waveguide inside the simulation region to the PML boundary (using center of the mesh and size of FDE) and these parameters were swept in a brute-force manner in order to eliminate the negative loss values and enforce physically attainable positive results (see Fig. 2.6). Although certain various parameter intervals and combinations were able to yield positive loss values for a specific geometry and radius, applying the same parameter set to a

different waveguide dimension or bending radius did not consistently resolve the issue. In most cases, while the magnitude of the negative loss values changed, the results remained negative.

The brute-force parameter sweeps performed using Lumerical MODE (FDE) required a large number of independent simulations, each associated with significant computational cost. Given the size of the simulation domains and the need to repeat the analysis over multiple geometries and bending radii, solver runtime became a decisive factor. The comparative study reported in [142] shows that Tidy3D completes three-dimensional simulations faster than Lumerical FDTD when the latter is executed on a local CPU workstation. For the ring resonator case, the reported runtimes indicate that Tidy3D requires substantially less wall-clock time than Lumerical FDTD on a local machine, while Lumerical FDTD executed on cloud GPU resources achieves significantly reduced runtime compared to its local CPU execution [142]. The study further notes that direct wall-clock comparisons reflect the best-effort use of each platform rather than identical compute resources [142], indicating that the observed runtime differences are linked to computational architecture of solvers.

In this context, the reported runtime performance of Tidy3D in repeated simulations, together with the demonstrated agreement between the two solvers at converged spatial resolutions for both the waveguide crossing and the ring resonator, supports the selection of Tidy3D for the monochromatic bent waveguide simulations conducted in this work [142].

The minimization of the evanescent field components extending from the bent waveguide into the PML cell layers can be achieved by increasing the separation between the waveguide and the PML boundary. As recommended in the Tidy3D example script documentation [139] and previously implemented during the brute-force parameter sweeps, this is realized by enlarging the FDE computational domain, thereby moving the PML boundary farther in the outward radial direction with respect to the center of curvature.

In the preliminary test simulations, it was observed that, in addition to uniformly enlarging the simulation region, shifting the computational domain and specifically increasing the distance of the PML boundary located opposite to the center of curvature could also eliminate the negative angular loss values. However, considering the reduced simulation time and the simplicity of implementation, the numerical instability was minimized by directly enlarging the simulation region rather than applying asymmetric domain shifts or selective boundary displacement.

Using Tidy3D scripting, an algorithm was developed to evaluate the bending radius sweep

simulations for the waveguide dimensions obtained from the cross-section design maps to be presented in Chapter 2.3. At each point of the bending radius sweep, numerical instability was addressed by scanning different FDE computational domain sizes. Through this procedure, negative angular propagation loss values were shifted to positive values and brought to physically acceptable levels.

Considering the number of waveguide dimension points, the number of bending radius samples evaluated for each dimension, and the different FDE domain sizes tested for every configuration, the overall computational cost increases substantially. In order to reduce this cost, additional parameter optimizations were introduced in the algorithm based on the evaluation of mode confinement and the requirement of positive angular loss values. The main objective of this process was to enlarge the FDE region only when necessary and to maintain numerical consistency with solver parameters across different bending radii and waveguide dimensions.

Algorithm 2.2 Adaptive Radius Sweep for Bending-Loss Extraction

- 1: Define the bending-radius sweep and initialize result storage matrices for TE and TM quantities.
 - 2: Select a target waveguide geometry from the precomputed dimension list and define the corresponding output file.
 - 3: **for** each bending radius in the sweep **do**
 - 4: Initialize the transverse simulation window size using the last successful value from the previous radius.
 - 5: Reset mode indices, loss values, and snapshot containers for TE and TM modes.
 - 6: **while** geometry constraints and maximum trial limit allow further attempts **do**
 - 7: Increase the transverse simulation window size incrementally.
 - 8: Instantiate and run the bent-waveguide mode solver for the current radius and window size.
 - 9: Identify the lowest-order guided TE and TM modes using the guidedness test and polarization classification.
 - 10: Extract the corresponding bending loss and modal parameters.
 - 11: **if** a valid mode (finite and non-negative loss) is found for the first time **then**
 - 12: Store a snapshot of its modal properties.
 - 13: **end if**
 - 14: **if** both TE and TM are valid **then**
 - 15: Terminate the size sweep for the current radius.
 - 16: **else if** one mode is valid while the other is not found **then**
 - 17: Accept the valid solution and terminate the sweep.
 - 18: **else if** one mode is valid while the other exhibits negative loss **then**
 - 19: Continue increasing the window size.
 - 20: **end if**
 - 21: **if** the maximum allowed window size is reached **then**
 - 22: Terminate the sweep for the current radius.
 - 23: **end if**
 - 24: **end while**
 - 25: Store the first valid snapshot (or the last valid solution if no snapshot exists) in the result arrays.
 - 26: Update the starting window size for the next radius based on the successfully used value.
 - 27: **end for**
 - 28: Assemble all stored modal data into a structured format and export it in MATLAB-compatible form.
-

2.3. Fundamental Constraints in 4H-SiCOI Waveguide Geometries

The analysis carried out in this chapter is structured around two principal stages. The first stage defines the admissible set of 4H-SiCOI waveguide cross-sections to be examined. The second stage assesses these geometries according to application-driven performance metrics, such as their capability to sustain tight curvature and to enable resonators exhibiting both large free spectral range (FSR) and high quality factor. In defining the candidate geometries, the conventional width-to-height ratio of approximately 2:1, widely adopted in TE-oriented waveguide designs, is used as a guiding reference.

The overall study proceeds in two stages. First, the complete set of admissible rectangular 4H-SiCOI core waveguides with silica cladding is established over a range of aspect ratios. Second, these geometries are evaluated according to application-driven criteria, including their suitability for small bending radii and their ability to support resonators with large free spectral range (FSR) and high quality factor. In particular, strong confinement, arising from the high refractive index contrast between the SiC core and the silica cladding, is treated as a central design objective. Strong confinement enables reduced radiation loss in curved sections, thereby allowing shorter cavity round-trip lengths and consequently larger FSR values. Since the free spectral range scales inversely with the group index and the round-trip cavity length, reducing the resonator size directly increases the achievable FSR. For microring resonators, this translates into the requirement of sufficiently small radii while maintaining negligible bending-induced radiation loss.

All optimization results reported, correspond to waveguides intended to operate with a single selected polarization and a single guided mode. Polarization parallel to the chip plane is denoted as TE, while polarization normal to the chip plane is denoted as TM. Although dielectric waveguides with high index contrast inherently support hybrid electromagnetic modes rather than strictly transverse electric or transverse magnetic fields, the dominant modal behavior in the structures examined here can be clearly categorized as TE-like or TM-like. For clarity and consistency, these dominant modal families are referred to simply as TE and TM throughout the chapter. The structures analyzed consist of rectangular 4H-SiCOI cores surrounded by a uniform silica cladding, though the qualitative conclusions are applicable to other high-index-contrast systems with comparable symmetry [132].

The modal indexing scheme follows the convention established in Chapter 5 of M. Popović's work [132] in order to maintain continuity with silicon-based platforms. In geometries

possessing symmetry about a horizontal reflection axis, TE modes are identified as those exhibiting perfect magnetic conductor (PMC) symmetry with respect to that axis, characterized by symmetric transverse electric and antisymmetric transverse magnetic field components. Conversely, TM modes correspond to perfect electric conductor (PEC) horizontal symmetry, with symmetric transverse magnetic and antisymmetric transverse electric components [132]. While this classification does not strictly coincide with classical textbook definitions of TE and TM, it provides a consistent and physically meaningful methodology for distinguishing the fundamental and higher-order modes of each polarization family [132]. Considered labeling remains particularly appropriate for wide and relatively shallow geometries, which are of primary interest in this study. Correspondance of the mode nomenclature with physical TE and TM modes will be thoroughly explained in the next section.

The geometrical design domain considered in this work consists of rectangular 4H-SiCOI waveguides with silica cladding, symmetric about both horizontal and vertical planes, and characterized by varying width-to-height aspect ratios. Two categories of operation are defined. The first category targets waveguides operating in the fundamental TE mode. For each aspect ratio, the configuration with the largest cross-sectional area that preserves single-TE-mode operation is selected; these are denoted as maximally confined single-TE-mode (MC-STE) designs. The second category targets waveguides operating in the fundamental TM mode, where the second TM mode must be suppressed. These geometries are referred to as single-TM-mode (STM) designs, and when the largest admissible configuration is selected for a given aspect ratio, they are denoted as maximally confined single-TM-mode (MC-STM).

The waveguide material was modeled as lossless and anisotropic at the operating wavelength of 1550 nm, since 4H-SiCOI is effectively transparent in this spectral region. The refractive index values used in the simulations were obtained from optical constant models derived from ellipsometry measurements of bulk 4H-SiCOI wafer, which are described in detail in Chapter 3. These material models were consistently implemented in both Lumerical MODE and the Tidy3D Mode Solver.

Modal classification was performed based on the TE fraction parameter. Modes exhibiting a TE fraction greater than 50% were categorized as TE modes, whereas modes with a TE fraction below this threshold were classified as TM modes.

Due to the computational cost associated with Lumerical MODE simulations, the modal quantities, including effective index, group index, and loss, were initially computed over a discrete 30×30 grid of width and height values. To obtain higher-resolution design

maps, these results were subsequently interpolated onto a 500×500 grid across the same geometrical domain. Since the modal properties are expected to vary continuously with cross-sectional dimensions as observed through monitoring the results, two-dimensional interpolation was performed in MATLAB to generate smooth and numerically consistent maps.

Unlike Lumerical MODE, in bent waveguide simulations performed with the Tidy3D mode solver, the computed eigenmodes may not always be confined within the waveguide core. In certain geometrical configurations and bending radii, some of the calculated modes correspond to radiation-like or weakly confined solutions rather than physically guided modes.

For this reason, the number of computed modes was increased from the default value of five to twenty-five in order to ensure that physically relevant solutions were captured for each waveguide dimension and bending radius.

A confinement verification procedure was then applied to the computed eigenmodes by evaluating the spatial distribution of the electric field intensity. Only modes whose field energy was predominantly concentrated within the core region were retained, while spatially extended solutions were discarded. Among the TE-like and TM-like modes satisfying this confinement requirement, the mode with the highest effective refractive index was identified as the fundamental mode of each polarization. The angular loss values associated with these fundamental modes were subsequently used in the construction of the maps and graphical results presented in the following sections.

2.3.1. Map of Single-Mode SiC Waveguide Cross-sections

In [132], for mode labeling, it is stated that for wide and thin waveguides ($AR > 1$ where $AR = \text{Width}/\text{Height}$), the cutoff in the MC-STE configuration is determined by the second-order TE mode (TE_{21}), while in the MC-STM configuration it is determined by the second-order TM mode (TM_{21}). For tall and narrow geometries ($AR < 1$), the corresponding cutoff modes are the 90° -rotated counterparts of those in the $AR > 1$ regime, see Fig. 2.7.

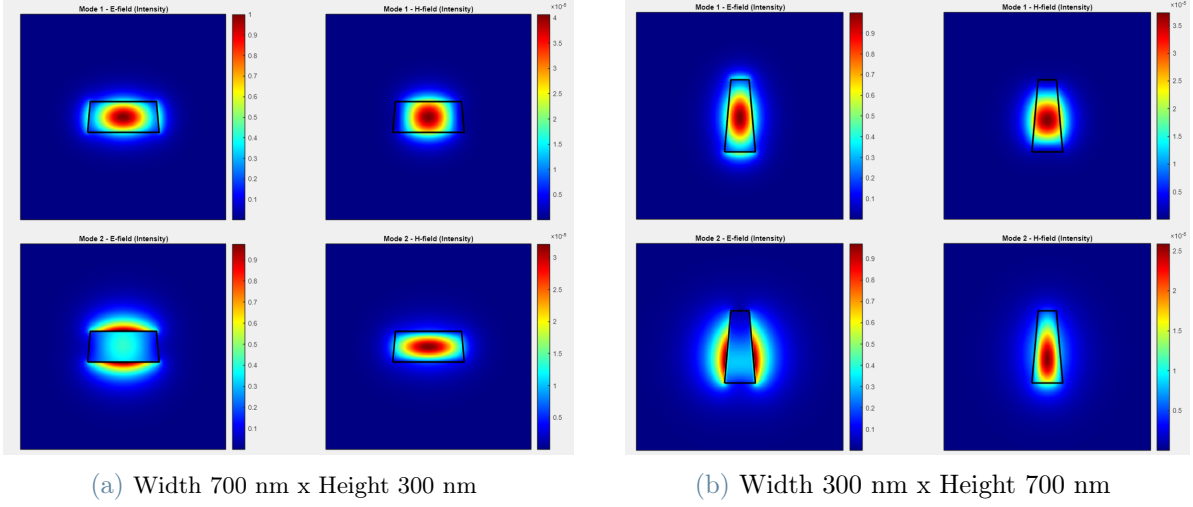


Figure 2.7: 90°-rotated electric and

It is also emphasized that this nomenclature is not strictly rigorous, since a mode labeled, for example, as TE_{21} may exhibit predominantly vertical (TM-like) polarization. Further, the physically observed fundamental and first higher-order modes are decisions has been done with TE fraction data as stated. For waveguide geometries with an aspect ratio above unity ($AR > 1$), in the adopted labeling scheme, the physical modes are referred to as TE_{11} and TE_{21} , respectively. When the aspect ratio is reconsidered by interchanging height and width (taking $AR = 1$ as the symmetry centre of the geometrical space) the mode corresponding to TE_{11} becomes fundamental TM, and the mode corresponding to TE_{21} becomes first higher-order TM in the $AR < 1$ regime, see Fig. 2.8a.

Similarly, for $AR < 1$ waveguides, the TM modes are labeled as TM_{11} for fundamental TE and TM_{21} for the higher-order TE within the adopted notation. Finalizing the equivalence of physical TE and TM modes and naming exchange, for waveguide dimensions with $AR > 1$, the physical mode corresponding to TM_{11} is identified as fundamental TM, while the counterpart of TM_{21} corresponds to higher-order TM. This labeling scheme is solely used to have a continuous and consistent identification of single mode cut-off curves, MC-STE and MC-STM designs, in the waveguide geometry space. So for the following figures and explanations, adopted labeling of fundamental TE and TM is TE_{11} and TM_{11} , and first higher-order TE and TM is TE_{21} and TM_{21} , respectively.

In the cutoff analysis performed in this work, the equivalence behavior of TE and TM around AR of 1 was observed when tracking the physically identified fundamental and first higher-order TE and TM modes across the design space with TE fraction data. The single-mode cutoff boundaries were found to interchange as the aspect ratio approached

to 1. The transition did not occur exactly at $AR = 1$ as case for Si [132], but around $AR \approx 1.08$. This can be attributed to differences in simulation assumptions (e.g., neglect of sidewall angle in [132]), to finite sampling resolution near $AR = 1$ and mainly due to the birefringence of 4H-SiC.

As shown in Table 1.2, 4H-SiC possesses anisotropy. Used fabrication methods result with its c-axis (extra-ordinary) in its crystallographic cell, being aligned with the surface normal of wafer. Hence, considering device fabrication steps (lithography etc.), resulting waveguide would have higher material refractive index on its vertical axis, and slightly lower one on the horizontal plane (ordinary axis). This shifts the point where TE and TM modes swap their performance metrics to higher AR values. The weaker confinement on horizontal plane (TM modes) causes requires higher AR values in order to be able to match with the modes lie on horizontal plane (TE modes).

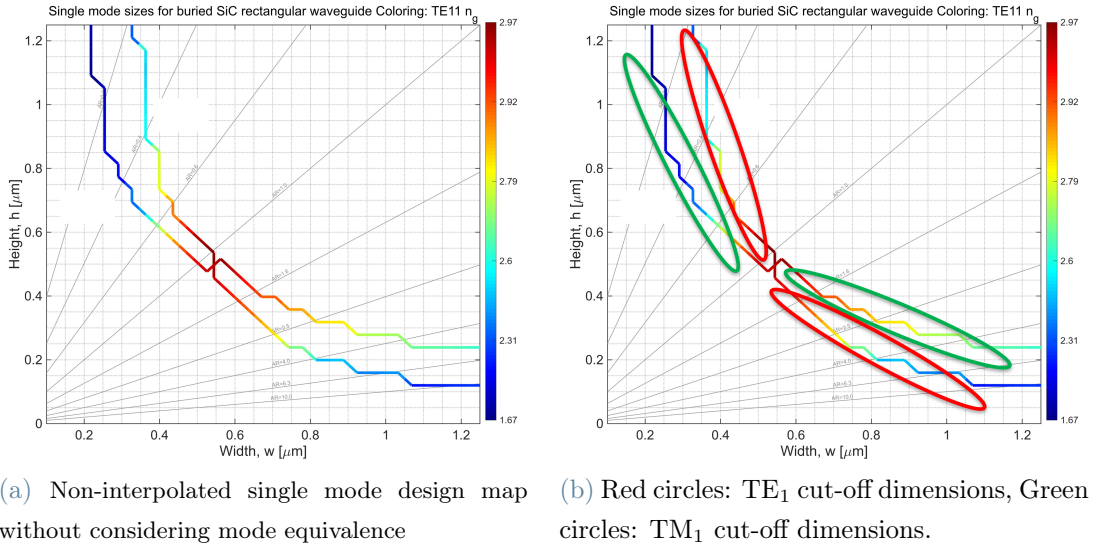


Figure 2.8: Non-interpolated Single Mode Design Map for Rectangular 4H-SiCOI Waveguides. Before adopting the mode-labeling convention presented in [132], the simulation results obtained from Lumerical MODE were analyzed directly using the TE-fraction values. The cutoff points were identified in the modal space as the waveguide dimensions at which the first higher-order mode becomes guided for the first time. In the corresponding maps, the regions marked in red indicate the cutoff contour of the TE_1 mode, while the regions marked in green represent the cutoff contour of the TM_1 mode. In order to transition to the naming convention used in the [132] and enable a direct comparison with the corresponding silicon-based map, the mode labels has been redefined at the aspect-ratio value corresponding to the intersection of these curves.

Nevertheless, when the TE/TM interchange is interpreted consistently with the adopted labeling convention, the apparent shift in AR becomes negligible for the contours. The

resulting cutoff curves can therefore be directly compared with the maximally confined MC-STE and MC-STM dimension maps obtained for silicon in [132].

Inspection of the same map in [132] reveals that the MC-STE and MC-STM boundaries exhibit a polynomial-like behavior across the aspect ratio range. In this work, the contours shown in the corresponding figures were obtained from a limited set of discrete sampling points and subsequently approximated using polynomial fitting. The height and width coordinates defining these fitted contours were constrained to the previously interpolated geometrical grid used for the modal result matrices.

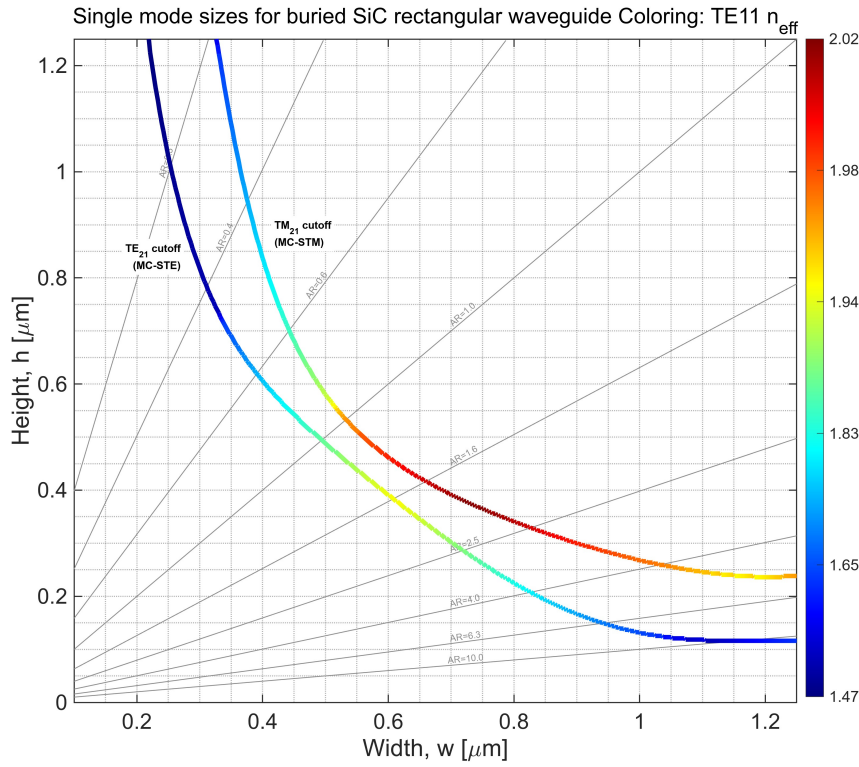


Figure 2.9: Map of Maximally Confined Single-Mode 4H-SiCOI Waveguide Cross-sections

Figure 2.9 presents the contours defining the MC-STE and MC-STM waveguide cross-sections for 4H-SiCOI over a broad aspect-ratio range (approximately $AR = 1/10$ to $AR = 10$). Each contour represents the geometrical boundary below which the corresponding polarization remains single-mode.

The contour trends further indicate that TE-oriented waveguides must become progressively thinner, reaching thicknesses on the order of 100 nm at large aspect ratios, in order to maintain single-mode behavior. In contrast, wide TM-oriented waveguides can remain single-mode even at thickness values exceeding 200 nm.

To remain consistent with [132], the mode nomenclature used in the following sections

follows the labeling convention described above. For example, when considering the TE_{11} effective-index contour shown in the figure, the effective-index values corresponding to the fundamental TE mode were used for the associated waveguide dimensions, as the TE mode with highest effective refractive index among the calculated TE modes at those waveguide dimensions has been used. Additional coloring of the contours on Fig. 2.9 based on different modes and their corresponding modal quantities can be found in Appendix A.

2.3.2. Non-degenerate higher-order modes in square-like 4H-SiCOI waveguides

At an aspect ratio of $AR = 1.08$ (Fig. 2.10), the TE and TM designs correspond to square-like cross-sections. In this configuration, the fundamental modes of the two design families are degenerate, namely TE_{11} for the MC-STE configuration and TM_{11} for the MC-STM configuration as this lies on the symmetrical axis in terms of AR. However, the corresponding higher-order modes, TE_{21} in the TE design and TM_{21} in the TM design, do not exhibit degeneracy.

As discussed in [132], this non-degeneracy ensures continuity of a single higher-order mode at cutoff along each waveguide-dimension contour.

A detailed numerical analysis of the effective indices of the TE_{21} and TM_{21} modes for square cross-sections reveals that these modes become nearly degenerate at index values significantly above cutoff, although their dependence on waveguide dimension exhibits distinct slopes. Consequently, their respective cutoff conditions occur at different core sizes despite their close proximity in effective index.

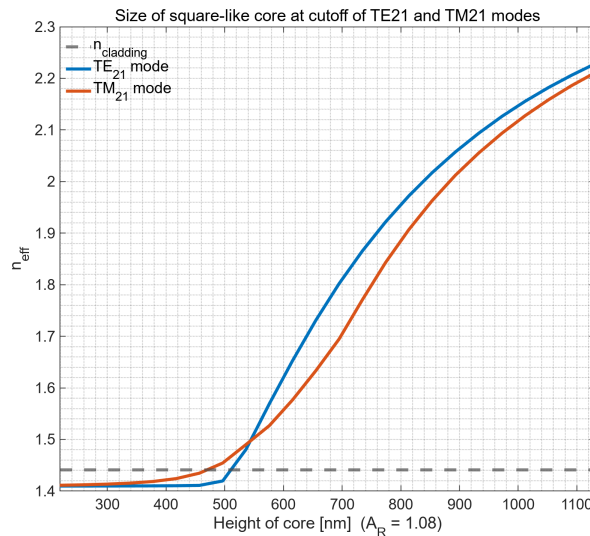


Figure 2.10: Size of Square-Like Core at the Cutoff of TE_{21} and TM_{21} Modes

This observation points to the theoretical feasibility of adiabatic transformation between higher-order modes. If the cross-section is varied gradually from $AR < 1.08$ to $AR > 1.08$, while maintaining symmetry with respect to the waveguide center, a higher-order mode characteristic of one geometrical regime can evolve continuously into its 90° -rotated counterpart in the opposite regime. Notably, along the MC-STM contour, a guided TE_{21} mode may persist while the corresponding TM_{21} mode is already cut off, creating a parameter window in which such modal evolution can occur. Because symmetry forbids coupling between these specific modes, avoided crossings are suppressed and a smooth transformation becomes possible. Although, the small effective-index separation between the two higher-order modes implies that satisfying the adiabatic criterion would require a comparatively long device length.

2.3.3. Mode effective and group indices at single mode waveguide designs

The variation of effective and group indices with aspect ratio AR provides direct insight into confinement strength and resonator-level performance.

Fig. 2.11 and Fig. 2.12 presents the effective index and group index of the modes belonging to the MC-STE and MC-STM designs as functions of aspect ratio. In all plots, both TE and TM fundamental modes are displayed for each design family. Nevertheless, the primary focus in the present discussion is placed on the TE_{11} mode of the MC-STE configuration and the TM_{11} mode of the MC-STM configuration.

The effective index, when evaluated relative to the refractive indices of the core and cladding materials, serves as a quantitative measure of modal confinement. Larger values of n_{eff} indicate stronger optical confinement within the high-index core, which also implies reduced bending loss for a given curvature radius. The group index n_{group} , in contrast, directly influences device-level parameters such as the free spectral range (FSR) and the cavity quality factor Q . For fixed distributed loss per unit length and unchanged geometrical parameters, an increase in n_{group} leads to a reduction in FSR and an increase in cavity Q .

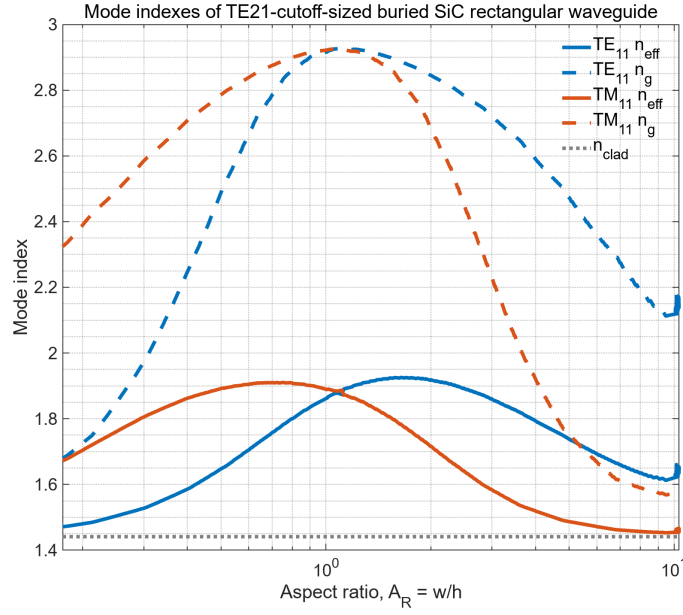


Figure 2.11: Mode Indexes of the TE_{21} Cutoff-Sized Buried SiC Rectangular Waveguide

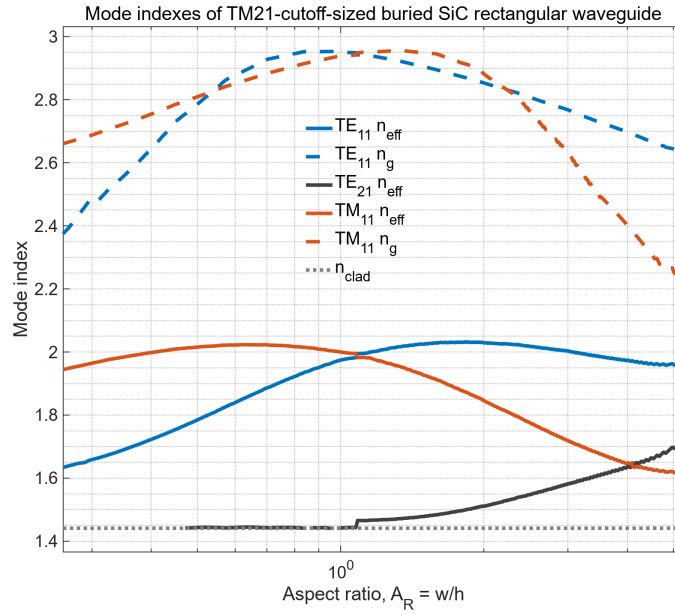


Figure 2.12: Mode Indexes of the TM_{21} Cutoff-Sized Buried SiC Rectangular Waveguide

Several observations can be drawn from Fig. 2.11, the maximum confinement for the TE_{11} mode within the MC-STE configuration is obtained near $AR \approx 1.62$, corresponding to a waveguide cross-section of approximately 595×367 nm. For the TM_{11} mode, the strongest confinement occurs near $AR \approx 1/1.62 \approx 0.61$, corresponding to a cross-section of approximately 372×604 nm. Similar cross-sectional dimensions have been reported in the literature for 4H-SiCOI waveguides, see Table 2.1. When $AR < 0.2$, the effective index

of the TE_{11} mode approaches the cladding index, indicating weak confinement. Therefore, this region of the design space ($AR < 0.2$) may be excluded for MC-STE configurations.

All index curves exhibit an approximate symmetry around $AR \approx 1.08$, reflecting the fact that a 90° rotation of the waveguide cross-section preserves the effective-index performance of the corresponding mode. Consequently, interchanging the width and height yields comparable modal characteristics between TE and TM configurations.

Because this symmetry is also observed in the group-index behavior, a similar correspondence is expected for quantities derived from n_{group} , such as the free spectral range (FSR) and angular loss. Therefore, the fundamental TE and TM modes can be considered mutually corresponding configurations around $AR \approx 1.08$, both geometrically and in terms of their performance metrics.

Fig. 2.12 presents the modal effective and group indices for the MC-STM designs. At the cutoff condition, the TM_{21} mode is suppressed, while two TE modes, TE_{11} and TE_{21} , remain guided. The maximum effective index—and therefore the strongest confinement—for the TM_{11} mode in the MC-STM configuration occurs at approximately $AR \approx 0.66$, corresponding to a tall and narrow waveguide cross-section with dimensions of roughly 440×660 nm (width $\times$ height).

An important observation is that the TE_{21} mode becomes degenerate with the TM_{11} mode near $AR = 4$, meaning that they share the same effective index. Although TE and TM modes are ideally orthogonal in a perfectly symmetric waveguide—and remain nearly orthogonal in practical cases—degeneracy significantly increases their susceptibility to coupling. Even minor perturbations, when extended over a sufficient propagation length, can induce strong interaction between the modes. For instance, unevenly slanted sidewalls introduced during fabrication, or asymmetries in coupling regions, may facilitate TE–TM coupling. Such coupling can lead to crosstalk, which may be further amplified in resonant structures. For this reason, operation near $AR = 4$ is preferably avoided in MC-STM designs; instead, aspect ratios sufficiently larger or smaller than this value are recommended.

Considering the variation of the effective indices of the fundamental TE and TM modes with aspect ratio, a representative TE-oriented waveguide geometry was selected for the integration of optical integrated circuits on the 4H-SiCOI platform with dimensions of 700 nm width and 300 nm height.

The cross-section corresponding to the maximum TE confinement condition was intentionally not selected. Although that geometry provides the highest effective index for the

fundamental TE mode, it was observed that the fundamental TM mode at those same dimensions also exhibits a relatively high effective index and remains guided. Therefore, in order to maintain strong confinement for the TE mode while simultaneously reducing the confinement of the TM mode, a compromise geometry was adopted.

Under the maximum TE confinement condition, the effective refractive indices are approximately $n_{\text{eff,TE}} = 1.93$ and $n_{\text{eff,TM}} = 1.80$. For the selected $700 \text{ nm} \times 300 \text{ nm}$ cross-section, which remains close to conventional 2:1 TE waveguide design practices, the effective index of the fundamental TE mode is approximately 1.90, while the effective index of the fundamental TM mode decreases to approximately 1.66.

It should also be noted that the cross-sectional maps were constructed using interpolation and curve-fitting procedures, which introduce a finite numerical tolerance in the extracted effective index values. Consequently, the purpose of this study was not to determine a strictly optimal waveguide dimension, but rather to identify a set of practically usable geometries. From this set, a pilot dimension was selected to enable the initiation of lithography and etching processes in the subsequent fabrication stages, without being tied to a specific target application.

2.3.4. Bending loss and FSR at single mode waveguide designs

To investigate confinement under lateral bending, a few assumptions are made. A planar geometry is assumed. A rectangular, 4H SiCOI-core, silica-cladded waveguide with 85 degree walls is considered, nominally with no other material layers inside Tidy3D Mode solver mesh. Number of PML layers of the boundary has been kept as 12 (default), uniform resolution has been set to 15 points per wavelength of operation (1550 nm), as it has been noted as a good trade of accuracy and computational cost [139]. Varying FDE size with bending radius explained in algorithm 2.2 has been utilized. For these simulations, limited number of points from non-interpolated MC-STE and MC-STM contours and bend radiuses have been considered. Later, obtained results has been parabolically fitted as characteristics of these plots has been demonstrated as such in [132].

For the waveguide designs located on the MC-STE and MC-STM contours in the waveguide dimension space, the use of the fundamental TE and TM modes in ring resonators was considered. The minimum bending radius values required to achieve the target quality factor of 250,000—reported for silicon in the reference—were mapped with respect to the corresponding aspect-ratio values along these contours. The quality factor (Q) is related to bending loss as [132],

$$Q \approx \frac{40\pi^2 R n_g}{\lambda_0 \ln 10 L_{\text{dB90}}} = \frac{0.2 \pi n_g}{\lambda_0 \ln 10 L_{\text{dB/cm}}} \quad (2.9)$$

where L_{dB90} the bending loss in dB/90°, R is the bend radius.

Figure 2.13 shows that fundamental modes in both designs can support small bend radii with low bend loss that results in high quality factor for the wavelength of operation at 1550 nm. A significant difference among fundamental modes is where TM mode can utilize lower bending radii for the same quality factor for both of the design contours. This is because the vertically polarized field is generally well confined in a tall waveguide even at very small aspect ratios. Also, birefringence of 4H-SiC grants higher confinement for vertically aligned TM modes with higher refractive index for its extraordinary axis makes it furtherly well suited to maintain low radiation loss in bending in the plane resulting in higher Qs. However, these taller and narrower waveguide designs have high sensitivity to lithographic dimensional errors affecting the aspect ratio, as well as to sidewall roughness originating from higher side-wall area. Therefore, these are not ideal for high-fidelity filter applications.

Utilizing the group indexes computed for those waveguide dimensions and minimum bending radii in,

$$\text{FSR} = \frac{c_0}{n_g L} = \frac{c_0}{2\pi n_g R} \quad (2.10)$$

One can have an idea about the corresponding maximum FSRs for the quality factor of choice ($Q = 250,000$) in Fig. 2.14. It shows that high- Q rings can be made with large FSRs (around 1 THz or more) with proposed MC-STE and MC-STM designs. It should be emphasized that, within the developed framework, application-specific parameters such as target quality factors, minimum bending radii, and the corresponding FSR values can be readily calculated and fitted to the desired design requirements.

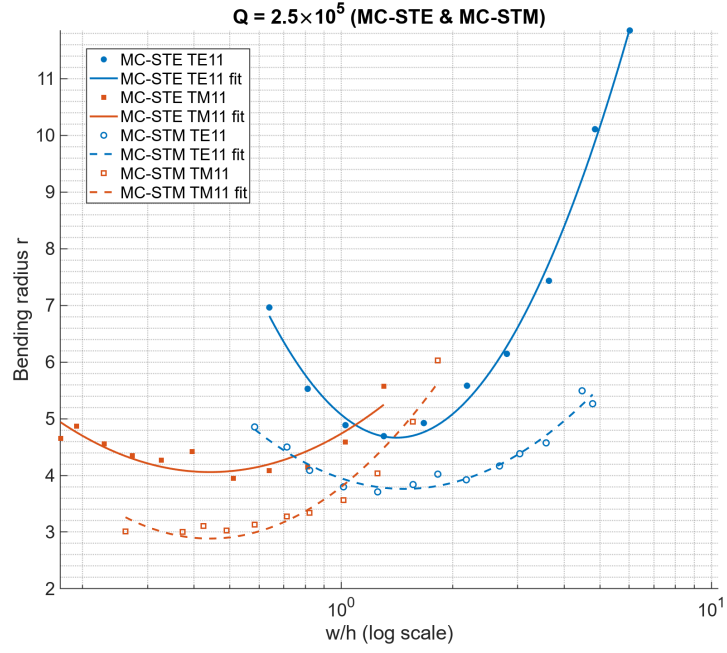
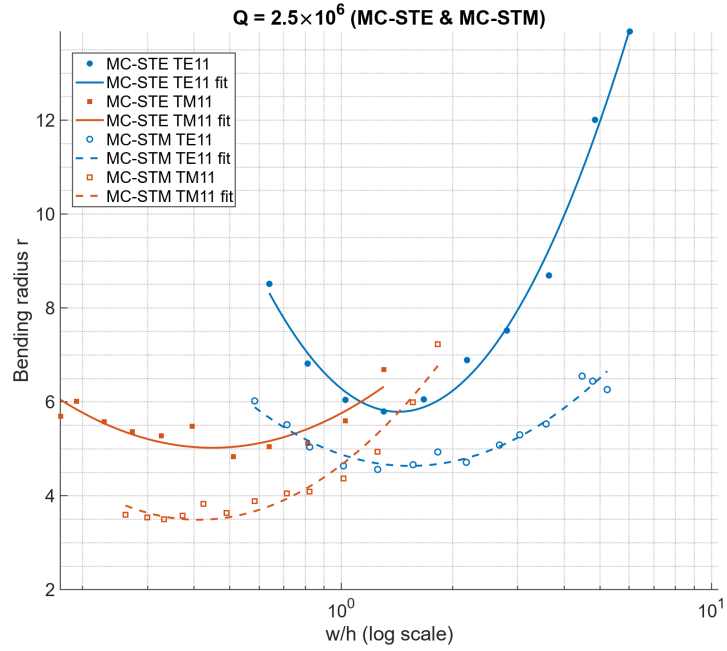
(a) $Q = 2.5 \times 10^5$ (b) $Q = 2.5 \times 10^6$

Figure 2.13: Minimum bending radius to achieve $Q = 2.5 \times 10^5$ and $Q = 2.5 \times 10^6$ for MC-STE & MC-STM designs. The figure presents the minimum waveguide bending radius required to ensure a bending loss sufficiently low to sustain a radiation-limited quality factor Q exceeding 2.5×10^5 . It should be emphasized that even if the target Q value changes by an order of magnitude, the overall trend and shape of the plot shown in Fig. 2.13b remain largely unaffected.

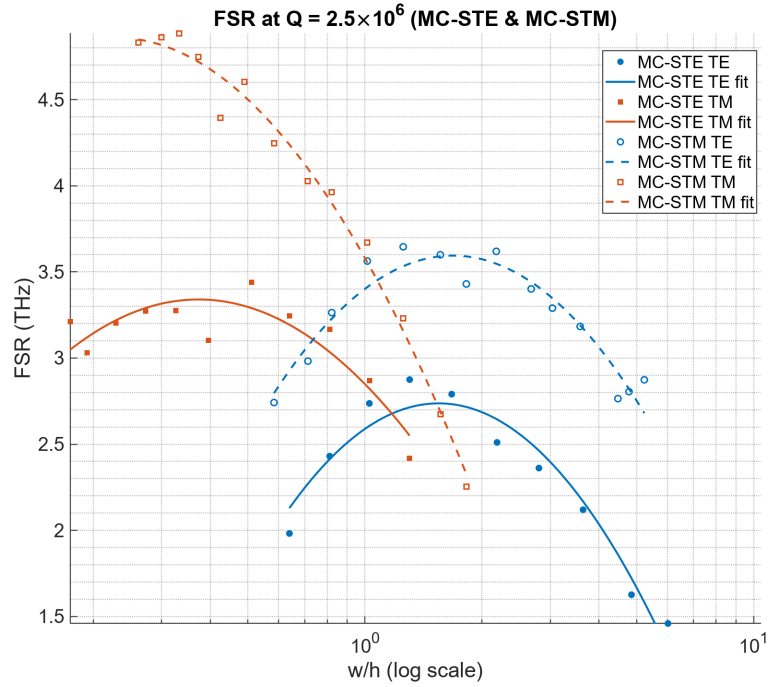
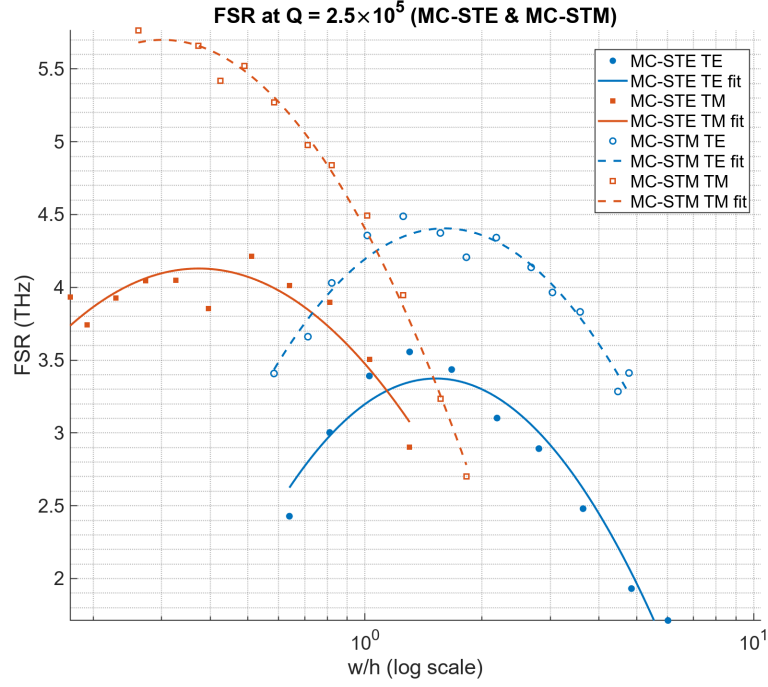
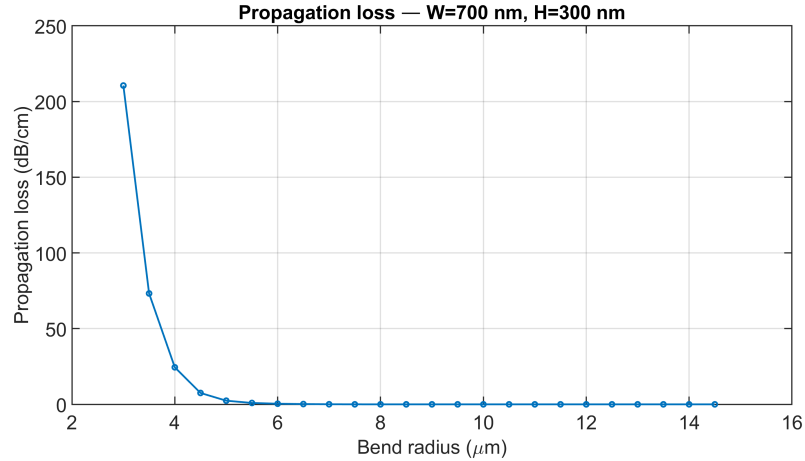


Figure 2.14: Maximum FSR values for $Q = 2.5 \times 10^5$ and $Q = 2.5 \times 10^6$ for MC-STE & MC-STM designs. It should again be emphasized that even if the target Q value changes by an order of magnitude, the overall trend and shape of the plot shown in Fig. 2.14b remain largely unaffected. Effect of the higher confinement for the fundamental TM mode is also repeated in these figures.

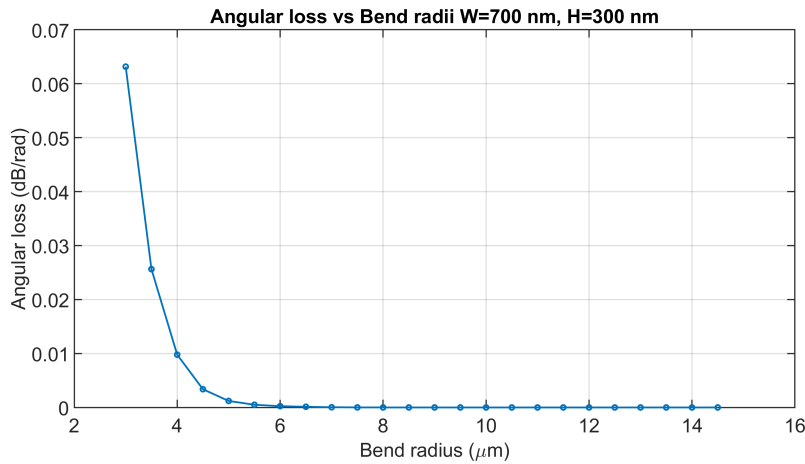
2.3.5. Bent waveguide analysis for the proposed design

The waveguide geometry selected as the pilot design, with a width of 700 nm and a height of 300 nm, was analyzed using Algorithm 2.2 in order to evaluate the performance achievable in possible ring resonator implementations. From the bending simulations and the fitted curvature trends presented in the previous section (Fig. 2.13b and Fig. 2.14b), it was observed that at the corresponding aspect ratio ($700/300 \approx 2.33$) of this geometry, only the fundamental TE mode is guided, while the TM mode is not supported.

Accordingly, the propagation and angular losses obtained for the fundamental TE mode are shown in the corresponding figure. By employing Equations 2.9 and 2.10, the achievable quality factors and the corresponding FSR values as functions of the bending radius can be calculated.



(a) Propagation loss vs Bend radii



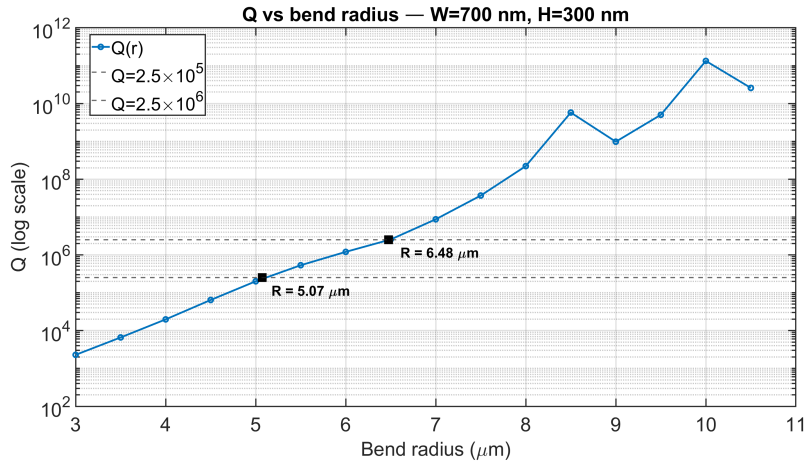
(b) Angular loss vs Bend radii

Figure 2.15: Angular and propagation losses for pilot waveguide bendings (Minimum bending radius is $6\mu\text{m}$)

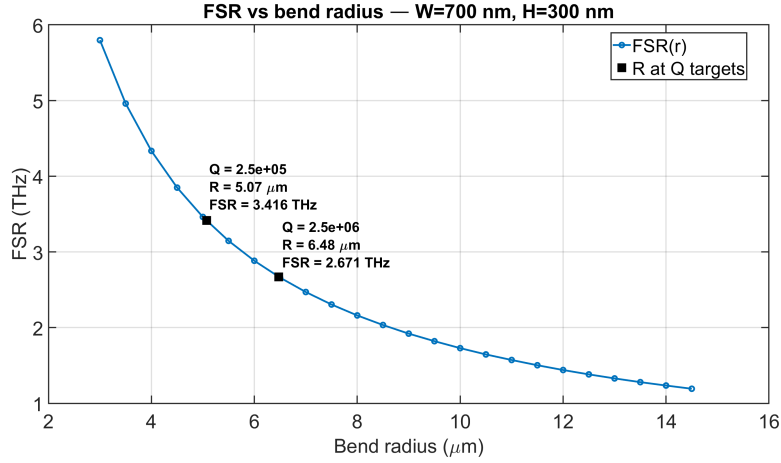
For an operating wavelength of $\lambda_0 = 1550$ nm and considering the previously discussed target quality factors of 2.5×10^5 and 2.5×10^6 , the results were obtained as follows:

$$Q = 2.5 \times 10^5 \Rightarrow R = 5.0736 \mu\text{m}, \quad \text{FSR} = 3.4156 \text{ THz} \quad (2.11)$$

$$Q = 2.5 \times 10^6 \Rightarrow R = 6.4764 \mu\text{m}, \quad \text{FSR} = 2.6713 \text{ THz} \quad (2.12)$$



(a) Q vs Bend radii



(b) FSR vs Bend radii

Figure 2.16: Quality factor and FSR for pilot waveguide bendings

Fig. 2.17 below further illustrates the variation of the simulation domain size, adjusted by Algorithm 2.2, as a function of the bending radius. When examining the propagation loss values, it should be noted that since the material was modeled as lossless, the computed losses must tend toward zero. Consequently, numerical inaccuracies may lead to slightly

negative loss values. To mitigate this issue and improve numerical stability and accuracy, as expected, the simulation domain size has increased with increasing bending radius.

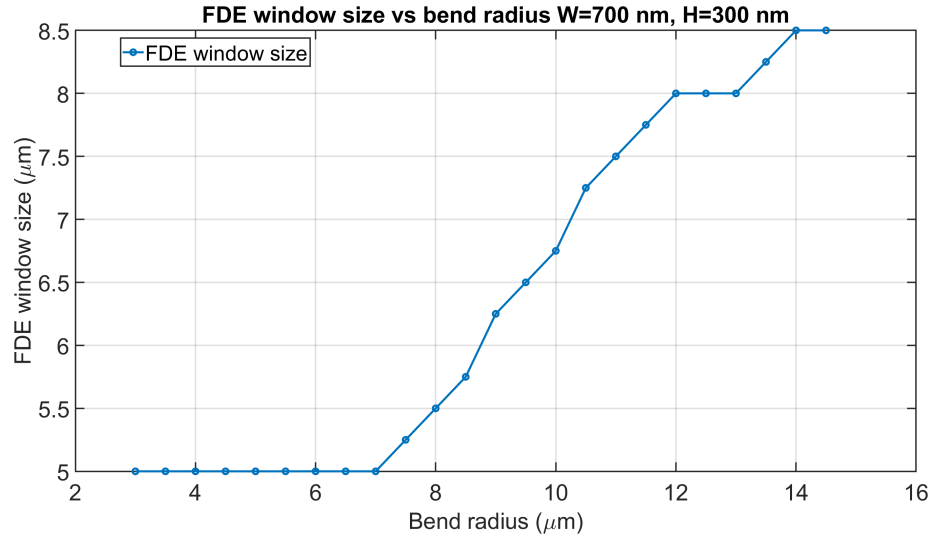


Figure 2.17: FDE window sizes used for pilot waveguide bendings

3 | Fabricational Steps of 4H-SiCOI Waveguides

This Chapter describes the fabrication route followed for the realization of 4H-SiCOI waveguides on the silicon carbide-on-insulator platform, with the objective of implementing the selected $700\text{ nm} \times 300\text{ nm}$ pilot waveguide geometry through a reproducible cleanroom process. Prior to targeting this final geometry, preliminary fabrication steps were carried out to optimize mask design, lithography parameters, and etching conditions for 4H-SiC, establishing reliable process windows and dimensional control.

The Chapter follows the fabrication flow. It begins with sample selection and preparation, followed by spectroscopic ellipsometry for material characterization. The measurement setup, dispersion modeling, and extracted optical constants of bulk and thin-film silicon carbide are presented. The refractive index constant derived from ellipsometric models used in the waveguide designs of Chapter 2 and were compared with reported literature values for 4H-SiC.

The lithography section describes the theoretical background, resist selection, spin-coating conditions, exposure parameters, and development processes used to define submicron waveguide structures. Special attention is given to resolution limits, proximity effects, and dimensional control required for approaching the resolution capability of the available equipment.

The etching section focuses on the transfer of the lithographically defined patterns into the 4H-SiC layer. Different SiC etching approaches are reviewed, and the selected method for this work is detailed in terms of process conditions, etch rate, selectivity, and profile control. Experimental observations and process adjustments carried out during optimization are presented in alignment with the fabrication objectives.

Scanning electron microscopy (SEM) and digital microscopy was employed for the inspection and characterization of the structures obtained after lithography and etching processes. It was used to evaluate the fidelity of the photoresist masks, critical dimensions, sidewall profiles, and the quality of pattern transfer into the 4H-SiC.

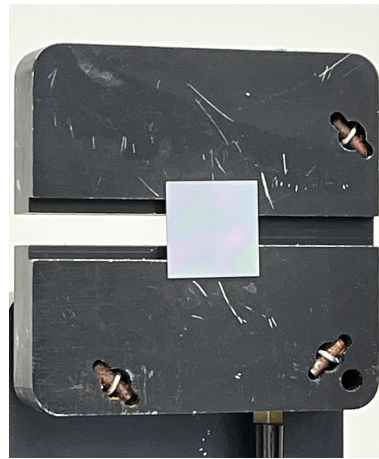
3.1. Sample Selection

As discussed in Chapter 1, although silicon carbide is widely established in electronic applications, its integration into optical device fabrication is comparatively recent and still evolving. Consequently, adapting the available cleanroom infrastructure at PoliFAB to 4H-SiC processing requires careful assessment of equipment compatibility, parameter optimization, resist selection, and etching recipes. Many of these process variables cannot be directly transferred from silicon-based fabrication flows and therefore must be defined through a combination of literature guidance and empirical process trials.

Considering the high cost and limited availability of SiCOI wafers, initial lithography and etching optimization studies were performed on bulk 4H-SiC substrates. This approach enabled systematic evaluation of mask performance, resist behavior, and etch characteristics under controlled conditions while minimizing material risk. Accordingly, the processes described in this chapter were developed and validated on bulk 4H-SiC prior to implementation on SiCOI structures. Different 4H-SiC and 4H-SiCOI suppliers, together with the wafer and sample specifications they provide, were surveyed and comparatively evaluated prior to material procurement, see Fig. 3.2. The comparison criteria included wafer diameter, estimated delivery time, doping of the silicon carbide layer, production grade, polishing quality, and, where available, pricing information. These parameters were considered in order to ensure compatibility with the intended fabrication flow and characterization requirements.



(a) 4-inch HPSI 4H-SiC wafer.



(b) 20 mm $\times$ 20 mm HPSI 4H-SiCOI sample.

Figure 3.1: 4H-SiC bulk wafer and 4H-SiCOI sample on VASE stage.

Based on these criteria, a 4-inch bulk high purity semi-insulating (HPSI) 4H-SiC wafer supplied by Nanovision was selected and purchased for process development and fabrication trials, see Fig. 3.1a. In addition, for use in later stages of the project, two 20 mm × 20 mm HPSI 4H-SiCOI samples supplied by OMedaSemi were acquired, see Fig. 3.1b.

Company	Country	SiC Wafer	SiCOI Wafer	Wafer/Die Sizes	Type	SiC Thickness (Wafer/Die)	Grade
PAM-XIAMEN	China	Yes	Yes	2"	Semi-Insulating (SiC)	250 ± 25 µm	AB Production Grade*
				3"	Semi-Insulating (SiC)	330 ± 25 µm	C/D Research Grade D Dummy Grade*
				4"	HPSI (SiC, V-Doped)	330 ± 25 µm	AB Production Grade*
				4"	HPSI (SiC, V-Doped)	430 ± 25 µm	C/D Research Grade D Dummy Grade*
				6"	HPSI (SiC, V-Doped)	500 ± 25 µm	AB Production Grade*
OMedaSemi	China	Yes	Yes	4"	HPSI (SiC)	500.0 µm ± 15.0 µm	C/D Research Grade D Dummy Grade*
				6"	HPSI (SiC)	500.0 µm ± 25.0 µm	A. Production Grade*
				6"	HPSI (SiCOI)	500nm ± 100.0 nm HPSI SiC 1-20 nm AlO ₂ 3000 nm SiO ₂ ± 5% nm 675 nm ± 25nm Si	B. Research Grade*
				6"	HPSI (SiCOI)	700nm ± 100.0 nm HPSI SiC 1-20 nm AlO ₂ 3000 nm SiO ₂ ± 5% nm 675 nm ± 25nm Si	C. Dummy Grade*
				6"	HPSI (SiCOI)	1000nm ± 100.0 nm HPSI SiC 1-20 nm AlO ₂ 3000 nm SiO ₂ ± 5% nm 675 nm ± 25nm Si	Overall Roughness <0.3nm
				6"	HPSI (SiCOI)	1000nm ± 100.0 nm HPSI SiC 3000 nm SiO ₂ ± 5% nm 675 nm ± 25nm Si	
				8"	HPSI (SiC)	500.0 µm ± 25.0 µm	
				4"	HPSI (SiC)	500.0 µm ± 25.0 µm	Research Grade*
				6"	HPSI (SiC)	500.0 µm ± 25.0 µm	Dummy Grade*
				6"	HPSI (SiC)	500.0 µm ± 25.0 µm	Research-grade*
Wolfspeed	USA	Yes	No	4"	HPSI (SiC)	500.0 µm ± 25.0 µm	Production-grade*
MTI Corporation	USA	Yes	No	4"	Semi-Insulating (SiC)	350 ± 25 µm	Research Grade
				4"	Semi-Insulating (SiC)	500 µm ± 25 µm (Semi-Insulating (SiC) type).	Production Grade
MSE Supplies	USA	Yes	Customization available	4"	HPSI (SiC)	500 µm ± 25 µm	Research Grade
				6"	Semi-Insulating (SiC)	500 µm ± 25 µm (Semi-Insulating (SiC) type).	Dummy Grade
				6"	HPSI (SiC)	500 µm ± 25 µm	Production Grade
				8"	HPSI (SiC)	500 µm ± 25 µm	Research Grade
				10 mm x 10 mm (+/- 1mm)	Semi-Insulating (SiC)	500 µm ± 25 µm (Si type)	Dummy Grade
				10 mm x 10 mm (+/- 1mm)	Semi-Insulating (SiC)	1000 µm ± 50 µm (Si type)	Production Grade

Figure 3.2: SiC Supplier Research

3.1.1. Sample Preparation

Prior to initiating cleanroom processing, several preparation steps were required for the purchased wafers and samples. In order to enable lithography and etching optimization trials, the 4-inch 4H-SiC wafer was diced into $15 \times 15 \text{ mm}^2$ pieces, following predefined cutting lines as shown in Fig. 3.3. This approach allowed efficient material usage while providing multiple test samples for process development.

The 4H-SiCOI samples were delivered with a thin protective layer, presumed to be a photoresist, applied to minimize mechanical damage during dicing and subsequent handling processes. Prior to ellipsometry measurements, this coating had to be completely removed. To eliminate the organic coating, the samples were cleaned using an ultrasonic bath in acetone, followed by a rinse in isopropyl alcohol (IPA). The acetone step enabled effective dissolution of organic contaminants, while the subsequent IPA rinse removed

residual acetone from the surface and reduced the risk of solvent-related staining. This cleaning sequence was repeated until no visible contamination remained.

Following solvent cleaning, a PVA TePla 300 AL, Fig. 3.4, system was used to perform oxygen (O_2) plasma treatment at 500 W for 5 minutes (Recipe 5). This step removed remaining microscopic contaminants and prepared the surfaces for reliable optical characterization and subsequent fabrication processes.

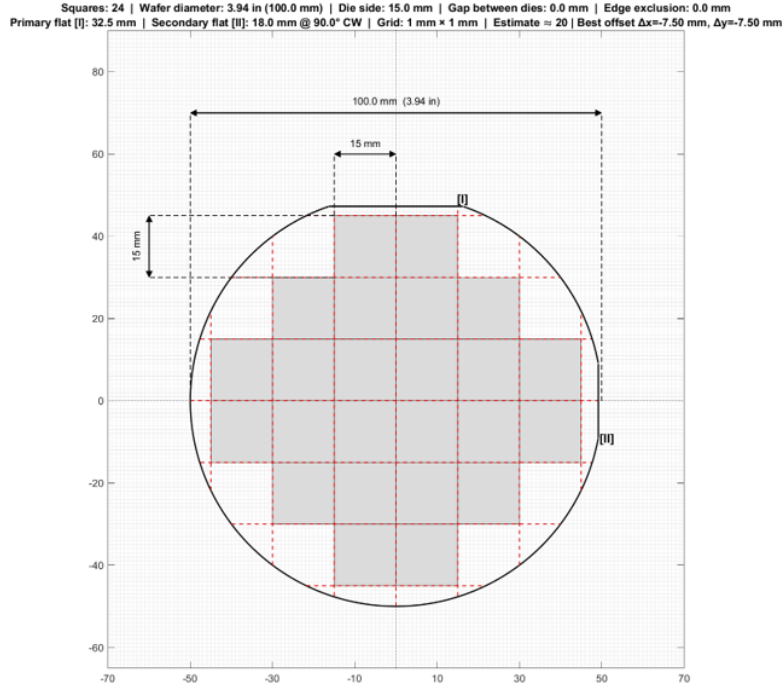


Figure 3.3: Laser dicing layout of the 4-inch 4H-SiC wafer (15 mm × 15 mm dies).



Figure 3.4: PVA TePla 300 AL Plasma Asher

3.2. Spectroscopic Ellipsometry

3.2.1. Overview

Ellipsometry is a highly sensitive optical characterization technique that analyzes the change in the polarization state of light upon reflection from a sample surface. It is widely used for thin-film characterization, including the extraction of optical constants, layer thickness determination, and surface feature evaluation. In this work, its applicability was demonstrated not only for thin films but also for bulk and wafer-scale 4H-SiC samples.

Variable Angle Spectroscopic Ellipsometry (VASE) combines spectroscopic measurements with multiple angles of incidence, enabling the acquisition of polarization data over a broad spectral range and at different geometrical configurations [143]. The use of multiple incidence angles reduces parameter correlation during model fitting and improves the reliability of thickness and optical constant extraction [144]. Compared to fixed-angle or single-wavelength ellipsometry, spectroscopic measurements allow direct access to the wavelength-dependent dispersion behavior of the material, which can be described using physically consistent parametric models such as Cauchy, Lorentz, or semiconductor oscillator models [144].

The strength of ellipsometry lies in its ability to retrieve precise optical properties through physically consistent modeling of the measured polarization response. This becomes particularly important for anisotropic materials such as 4H-SiC, which exhibit direction-dependent refractive indices. Ellipsometric modeling enables the extraction of the ordinary and extraordinary refractive indices, providing accurate directional optical constants. These parameters constitute a critical input for the TE-mode waveguide design presented in Chapter 2 and directly influence the determination of the proposed waveguide dimensions.

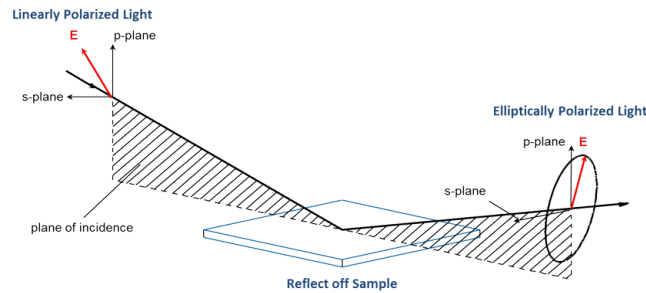


Figure 3.5: Geometry of an ellipsometry setup illustrating the polarization directions parallel (p) and perpendicular (s) to the plane of incidence [144].

Ellipsometry is based on the analysis of the polarization change of light upon reflection from a material surface [145]. In a typical configuration, linearly polarized light is incident on a sample at an oblique angle [145]. The plane defined by the incident beam and the surface normal is referred to as the plane of incidence [145]. The electric field of the incoming light can be decomposed into two orthogonal components: the p-component, which lies parallel to the plane of incidence, and the s-component, which is perpendicular to it, see Fig. 3.5 [145].

Upon receiving reflection, the p- and s-components generally undergo different amplitude variations and phase shifts. As a result, even if the incident light is linearly polarized, the reflected light becomes elliptically polarized [145]. This polarization transformation carries information about the optical response of the sample [145].

The measurable quantities in ellipsometry are expressed in terms of two parameters, Δ and Ψ . The parameter Δ represents the phase difference between the reflected p- and s-components, while Ψ is related to the ratio of their amplitudes [145]. These parameters are defined through the complex reflection coefficients of p- and s-polarized light [145]. The fundamental ellipsometric relation can be written as

$$\rho = \frac{\tilde{R}_p}{\tilde{R}_s} = \tan \Psi e^{i\Delta},$$

where $\tilde{R}_p$ and $\tilde{R}_s$ are the complex reflection coefficients for p- and s-polarized light, respectively. The phase parameter Δ can vary between -180° and $+180^\circ$, while Ψ ranges from 0° to 90° [145].

An important aspect of this formulation is that ellipsometry relies on the ratio of reflection coefficients rather than absolute intensity measurements [145]. Since the formalism is inherently normalized, the method is less sensitive to fluctuations in source intensity or detector response while keeping high sensitivity through the inclusion of phase difference. This relative measurement formalism contributes to the robustness, repeatability, and overall reliability of the extracted optical constants and model parameters [145].

Any totally polarized beam can be described using the Jones formalism by specifying the components of its electric field along the p - and s -directions [145]. These components are complex quantities and can be expressed as a two-component vector:

$$\tilde{\mathbf{E}} = \begin{bmatrix} \tilde{E}_p \\ \tilde{E}_s \end{bmatrix} = \begin{bmatrix} E_p e^{i\Phi_p} \\ E_s e^{i\Phi_s} \end{bmatrix} \quad (3.1)$$

Here, E_p and E_s denote the amplitudes of the p - and s -components of the electric field, while Φ_p and Φ_s represent their respective phase angles. If $\Phi_p = \Phi_s$, the light is linearly polarized. If $\Phi_p = \Phi_s \pm \frac{\pi}{2}$ and $E_p = E_s$, the light is circularly polarized. In all other cases, the polarization state is elliptical [145].

The interaction of light with a material surface—through reflection, transmission, refraction, or absorption—modifies this polarization state [145]. Such interaction can be described by a 2×2 transfer matrix, known as the Jones matrix, which relates the incident and reflected electric field vectors [145]:

$$\begin{bmatrix} \tilde{E}_p \\ \tilde{E}_s \end{bmatrix}_{\text{ref}} = \begin{bmatrix} \tilde{E}_{pp} & \tilde{E}_{sp} \\ \tilde{E}_{ps} & \tilde{E}_{ss} \end{bmatrix} \begin{bmatrix} \tilde{E}_p \\ \tilde{E}_s \end{bmatrix}_{\text{inc}} \quad (3.2)$$

The diagonal elements describe the change in amplitude and phase of the p - and s -components, while the off-diagonal elements represent coupling between polarization components [145].

For isotropic materials, the Jones matrix is diagonal, indicating that p -polarized light remains p -polarized upon reflection and similarly for s -polarized light. In anisotropic materials, however, off-diagonal elements may appear, corresponding to polarization conversion. Such behavior can originate from intrinsic crystal anisotropy or from structural features at the surface or interface [145].

In spectroscopic ellipsometry, Ψ and Δ are measured over a range of wavelengths and often at multiple angles of incidence. Since optical experiments do not directly measure physical parameters such as layer thickness or optical constants, their determination requires solving an inverse problem in which material properties are inferred from the measured polarization response [144].

A physically consistent dispersion model is constructed to describe the optical behavior of the sample, incorporating known experimental conditions (e.g., wavelength and angle of incidence) and unknown parameters such as layer thicknesses and optical constants [144]. These parameters are obtained through multivariate regression analysis, where the Levenberg–Marquardt algorithm minimizes the deviation between measured and calculated spectra [144].

After convergence, the best-fit solution must be evaluated to ensure physical consistency, parameter uniqueness, and low correlation. If necessary, the model is refined and the fitting repeated. Once validated, refractive index, extinction coefficient, and layer thickness are extracted within the assumptions of the selected model [144]. Through this

model-based analysis of polarization changes (see Fig. 3.6), ellipsometry enables precise determination of both isotropic and anisotropic optical constants.

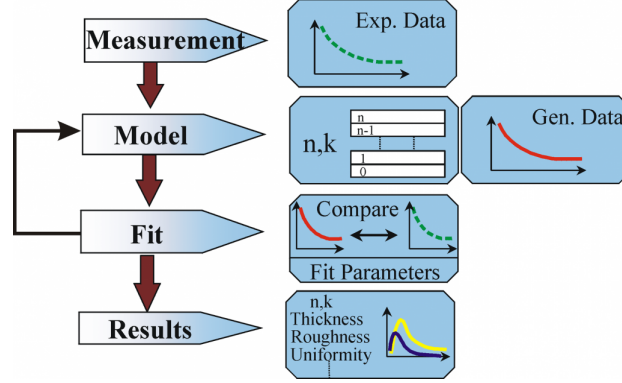


Figure 3.6: Fundamental workflow in ellipsometric analysis for retrieving material parameters from measured data [144].

3.2.2. Setup

The spectroscopic ellipsometry measurements in this work were performed using a VASE® (Variable Angle Spectroscopic Ellipsometer) [143]. The system is configured as a Rotating Analyzer Ellipsometer (RAE) combined with a patented AutoRetarder® module and automated wavelength selection through a custom-built monochromator. This configuration enables high-precision polarization measurements over a broad spectral and angular range.

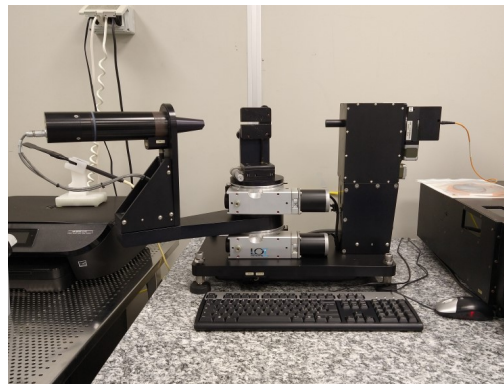


Figure 3.7: Spectroscopic Ellipsometer – J.A. Woollam VASE

The instrument operates over a standard spectral range of 240–2500 nm, with a deep-ultraviolet (DUV) extension down to 193 nm, and an upper limit extending to 4000 nm depending on system configuration. Wavelength selection is achieved using a custom-designed double-chamber scanning monochromator located before the sample [143]. This

placement ensures superior stray-light rejection and restricts the incident beam to a narrow spectral bandwidth at each measurement step [143]. The monochromator utilizes multiple diffraction gratings to maintain high reflectivity and spectral efficiency across the full operating range [143]. Positioning the monochromator prior to the sample also minimizes broadband exposure, reducing potential photo-induced effects in light-sensitive materials [143].

Angle of incidence is fully automated and adjustable within a range of 15° to 90° , with an angular accuracy of 0.01° [144]. Precise angle definition is essential, as ellipsometric parameter extraction directly depends on the incidence geometry. A key component of the system is the AutoRetarder[®], which dynamically adjusts the polarization state of the incident beam to optimize measurement sensitivity [144].

In a conventional rotating analyzer ellipsometer, accuracy depends on the polarization state at the detector: sensitivity is highest near circular polarization ($\Delta \approx 90^\circ$) and decreases near linear states ($\Delta \approx 0^\circ$ or 180°) [144]. Although the physical phase difference Δ spans 0° – 360° , the rotating analyzer configuration maps this range into 0° – 180° , preventing determination of the handedness of the polarization ellipse. This phase ambiguity limits reliable Δ extraction, particularly for anisotropic samples [144].

The AutoRetarder introduces a computer-controlled variable retardation before the sample, allowing the incident polarization to be tuned such that the reflected beam remains close to circular polarization. This improves sensitivity and enables accurate determination of Δ over the full 0° – 360° range.

Using the VASE system described above, spectroscopic ellipsometry measurements were performed on both bulk 4H-SiC wafer and SiCOI thin-film sample. The spectral range considered in this work was 300–1700 nm. Measurements were acquired with a spectral step size of 5 nm.

As indicated in the instrument specifications, thicker layers exhibit rapid oscillatory behavior in the measured ellipsometric parameters (Ψ and Δ) due to interference effects. In such cases, the angular-dependent response varies with high frequency across the measured spectral band. In order to accurately capture these rapid oscillations in wavelength and ensure reliable dispersion modeling, a finer spectral step size adopted for the bulk samples.

Visual inspection of the SiCOI samples revealed observable color variations across the surface, indicating possible local thickness non-uniformities introduced during fabrication. To account for these variations and evaluate the consistency of the extracted refractive

index values, measurements were performed at two distinct regions of the same sample indicated by #1 and #2 in results. Identical ellipsometric settings were used for both measurement locations to enable direct comparison of the obtained optical constants.

For both bulk and thin-film samples, measurements were performed at multiple angles of incidence ranging from 55° to 75° in 10° increments. All measurements were carried out using the full AutoRetarder capability in order to maximize sensitivity, improve data robustness, and ensure reliable extraction of the refractive index dispersion.

3.2.3. Dispersion Models for Silicon Carbide

Following the acquisition of spectroscopic ellipsometry data from bulk and thin-film samples, an appropriate initial optical layer model was required in order to extract the refractive index dispersion and initiate the regression procedure. The construction of a physically meaningful starting model is essential for stable convergence of the fitting algorithms and to avoid non-physical solutions.

Bulk 4H-SiC

For the bulk 4H-SiC sample (Fig. 3.8) the optical response was modeled using a single uniaxial anisotropic layer. This configuration was selected because the extraordinary optical axis of 4H-SiC is aligned along the surface normal of the wafer, and the ellipsometer configuration employed in this work assumes this anisotropy orientation. The initial model parameters were defined using supplier-provided thickness information together with dispersion models for 4H-SiC reported in the literature [146]. Although the literature models, Eq. 3.4, do not fully cover the entire measured spectral range (300–1700 nm), they provided a physically consistent starting point for regression.

$$n_o(\lambda) = 2.5610 + 3.4 \times 10^4 \lambda^{-2}, (\lambda, \text{ in } n) \quad (3.3)$$

$$n_e(\lambda) = 2.6041 + 3.75 \times 10^4 \lambda^{-2}, (\lambda, \text{ in } n) \quad (3.4)$$

During the model fitting of the bulk 4H-SiC wafer measurements, the thickness of the single layer was kept fixed. Since the measured wafer consists solely of 4H-SiC, which is known to be transparent within the spectral measurement range, the extinction coefficient (k) was assumed to be zero.

The refractive index along the ordinary axis was modeled using a Cauchy dispersion relation (Eq. 3.5 and Eq. 3.6) in WVASE [144], following the expression reported in the

[146]. The extinction-related coefficients of the model were set to zero.

Uniaxial 4H-SiC layer (500 μm)

Figure 3.8: Initial layer model of the bulk 4H-SiC wafer used in the ellipsometric model.

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}, (\lambda \text{ in } \mu\text{m}) \quad (3.5)$$

$$k(\lambda) = \alpha \exp \left[\beta (1.24 \mu\text{m}) \left(\frac{1}{\lambda} - \frac{1}{\gamma} \right) \right], (\lambda, \gamma \text{ in } \mu\text{m}) \quad (3.6)$$

The six parameters in Cauchy dispersion model are A , B , C . For this case, we have only used A and B to obtain a similar expression to Eq. 3.4. The extinction coefficient amplitude α , the exponent factor β , and the band-edge parameter γ has not been included to the fit and α has been set to 0.

The refractive index corresponding to the extraordinary axis was described using a polynomial function ($n = A \left(1 + B (\text{eV})^2 + C (\text{eV})^4 + D (\text{eV})^6 + \frac{E}{(\text{eV})^2} \right)$, $k = 0$.) defined additively with respect to the ordinary-axis model, thereby accounting for birefringence through a differential contribution. Again only terms considered for the fit is A and B . Generated refractive index dispersion from the fitted model can be seen in Fig. 3.9.

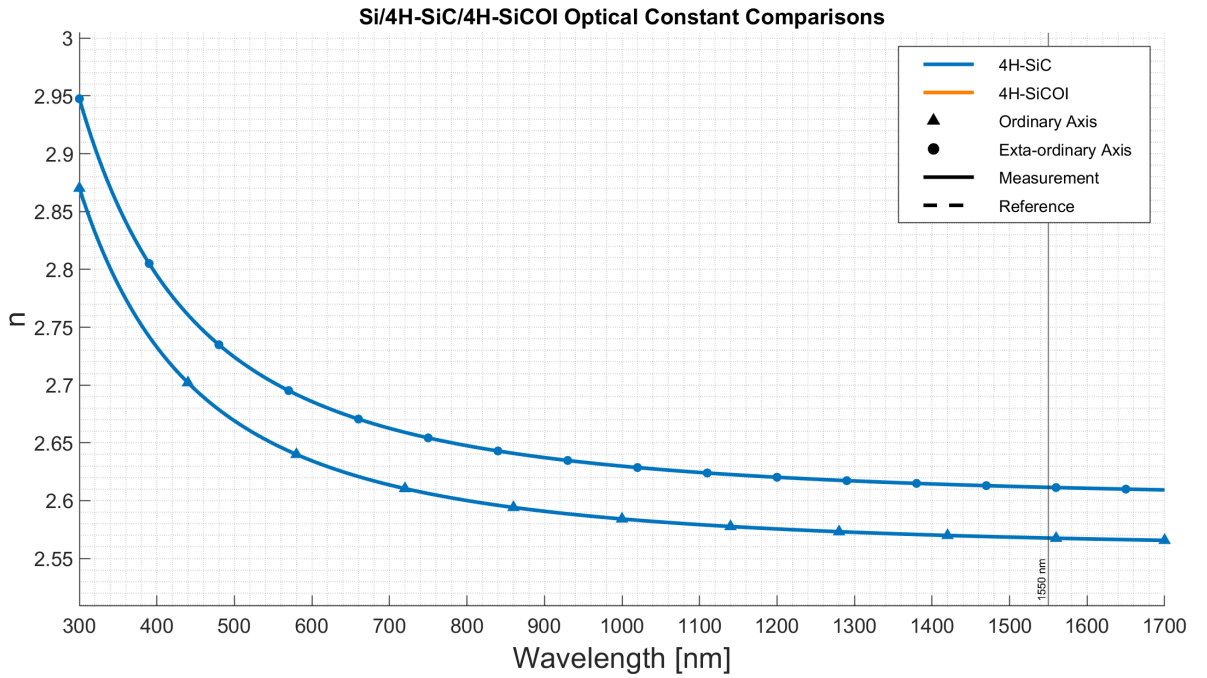


Figure 3.9: n: Bulk 4H-SiC Refractive Index Measurement

Thin-film 4H-SiCOI

Surface roughness (0–5 nm)
Uniaxial 4H-SiC film layer (500 nm)
SiO ₂ layer (3 μ m)
Si substrate (675 μ m)

Figure 3.10: Initial layer stack of the 4H-SiCOI sample used in the ellipsometric model.

The layer model prepared for fitting the 4H-SiCOI samples is shown in Fig. 3.10. In this initial model, the optical constants of silicon, SiO₂, and 4H-SiC (including both ordinary and extraordinary axes) were taken from the WVASE built-in material library. The layer thicknesses were selected according to the sample datasheet.

During the fitting procedure, no fitting was performed on the silicon substrate. The thickness of the SiO₂ layer was included as a fitting parameter, while for the 4H-SiC layer only the ordinary axis optical constants and thickness were fitted. WVASE does not allow simultaneous fitting of both ordinary and extraordinary components. For the following subsection this should be taken into account when considering 2 different 4H-SiCOI measurements, as they will be sharing the same $n(e)$ and $k(e)$.

For the 4H-SiC layer, a general Gaussian oscillator model was employed, see Table 3.1. Multiple Gaussian oscillators representing different energy band distributions were included, and their coefficients were fitted according to their relative significance. Different combinations and ordering of oscillators were tested in order to minimize the mean square error (MSE) through the window given in Fig. 3.11.

It was observed that introducing a surface roughness layer and including its thickness as a fitting parameter reduced the MSE. In addition, a parameter accounting for non-ideal experimental conditions and setup-related imperfections was incorporated into the fitting process as a percentage contribution.

General Oscillator (Genosc) Model	
Dielectric Function	$\varepsilon(E) = \varepsilon_1 + i\varepsilon_2 = \text{Offset} + \frac{A_1}{E_1^2 - E^2} + \frac{A_2}{E_2^2 - E^2 - iB_2E} + \text{Gaussian}(E, A_3, E_3, B_3)$ The dielectric function is modeled as a linear superposition of real and complex oscillators, each defined as a function of photon energy E (in eV).
Gaussian Oscillator Formulation	
Definition	$\varepsilon_{n,\text{Gaussian}} = \varepsilon_{n1} + i\varepsilon_{n2}$ $\varepsilon_{n2} = A' \left[\exp\left(-\left(\frac{E - E_n}{\sigma}\right)^2\right) - \exp\left(-\left(\frac{E + E_n}{\sigma}\right)^2\right) \right]$ $\varepsilon_{n1} = \frac{2}{\pi} P \int_0^\infty \frac{\xi \varepsilon_{n2}(\xi)}{\xi^2 - E^2} d\xi$ $\sigma = \frac{B_n}{2\sqrt{\ln(2)}} \quad (B_n = \text{FWHM})$
Fit Parameters	A_n (amplitude), E_n (center energy, eV), B_n (broadening, eV)

Table 3.1: General oscillator (Genosc) dielectric function model and Gaussian oscillator component used in ellipsometric analysis [144].

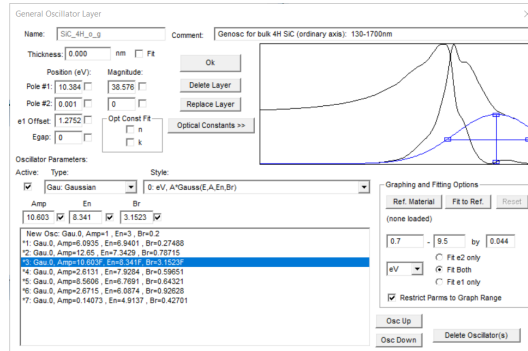


Figure 3.11: General Oscillator window on WVASE

The “All 3 non-idealities” option allows the fitting model to simultaneously include Thickness Non-Uniformity (%), Light Bandwidth, and Angular Spread as fitting parameters. Any two of these parameters may be fixed to zero if necessary. In practice, the specific type of non-ideality present in the measured data cannot always be uniquely determined from the fit alone. Therefore, prior knowledge of the sample structure and the measurement geometry is often required to select the most appropriate non-ideality model.

Due to the observable color variations on the surface of the 4H-SiCOI samples, a thickness non-uniformity was expected and therefore included as a fitting parameter. The inclusion

of all three non-idealities was motivated by the fact that the employed measurement setup deviates from ideal conditions. After incorporation into the fitting procedure, the thickness non-uniformity parameter converged to approximately 1.27%. Considering the total layer thickness and specifically the thickness of the 4H-SiC layer, this percentage indicates that the sample exhibits measurable thickness inhomogeneity across these samples. Generated refractive index dispersion from the fitted model can be seen in Fig. 3.12.

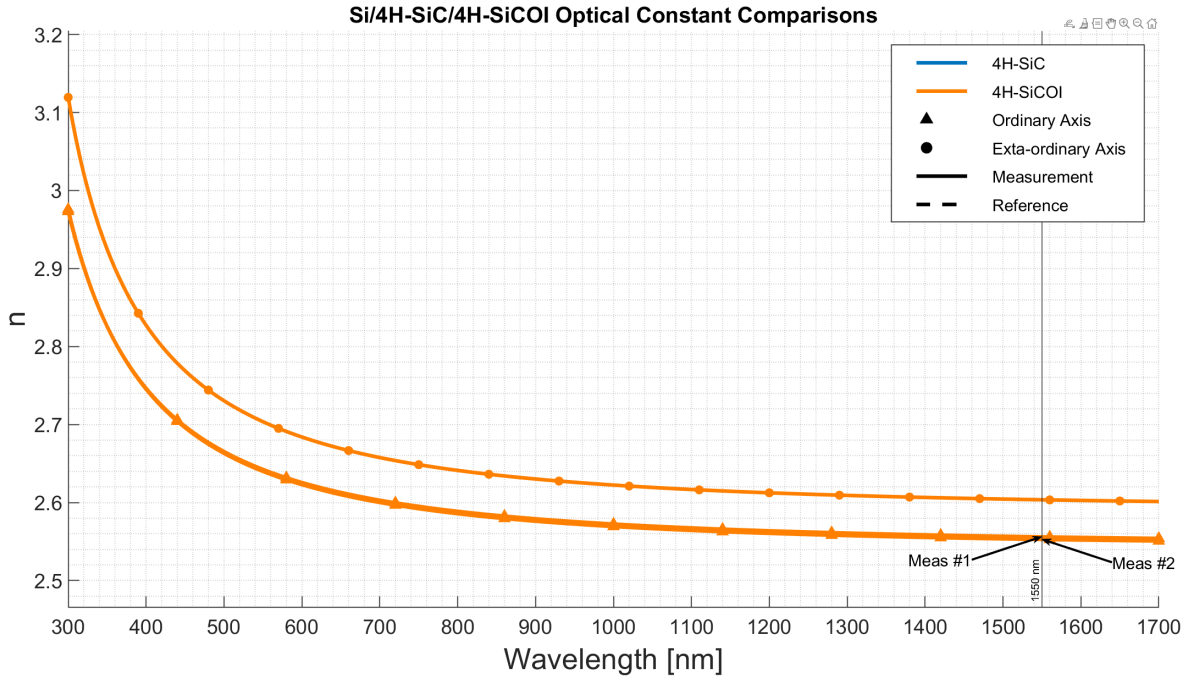


Figure 3.12: Thin-film 4H-SiCOI Refractive Index Measurements

The regression procedure resulted in mean squared error (MSE) values ranging between 15 - 30 for the fitted models. When compared empirically with other fitting performed under similar measurement conditions, and seeing layer thicknesses being aligned with the data noted in their datasheets, these MSE values indicate an acceptable level of agreement between the modeled and measured data.

Furthermore, the fitted layer thicknesses obtained after regression were found to be within the tolerance limits specified in the supplier data sheets. This consistency between fitted parameters and nominal specifications provides additional confidence in the physical validity of the constructed optical models.

Based on these results, the extracted ordinary and extraordinary refractive index dispersions were considered reliable and were subsequently used in the waveguide simulations presented in Chapter 2.

3.2.4. Optical properties of Bulk and Thin Film Silicon Carbide Samples

On Fig. 3.13 and Fig. 3.14, solid lines represent measured values, while dashed lines correspond to literature [74]. Triangles denote ordinary indexes and circles denote extraordinary indexes.

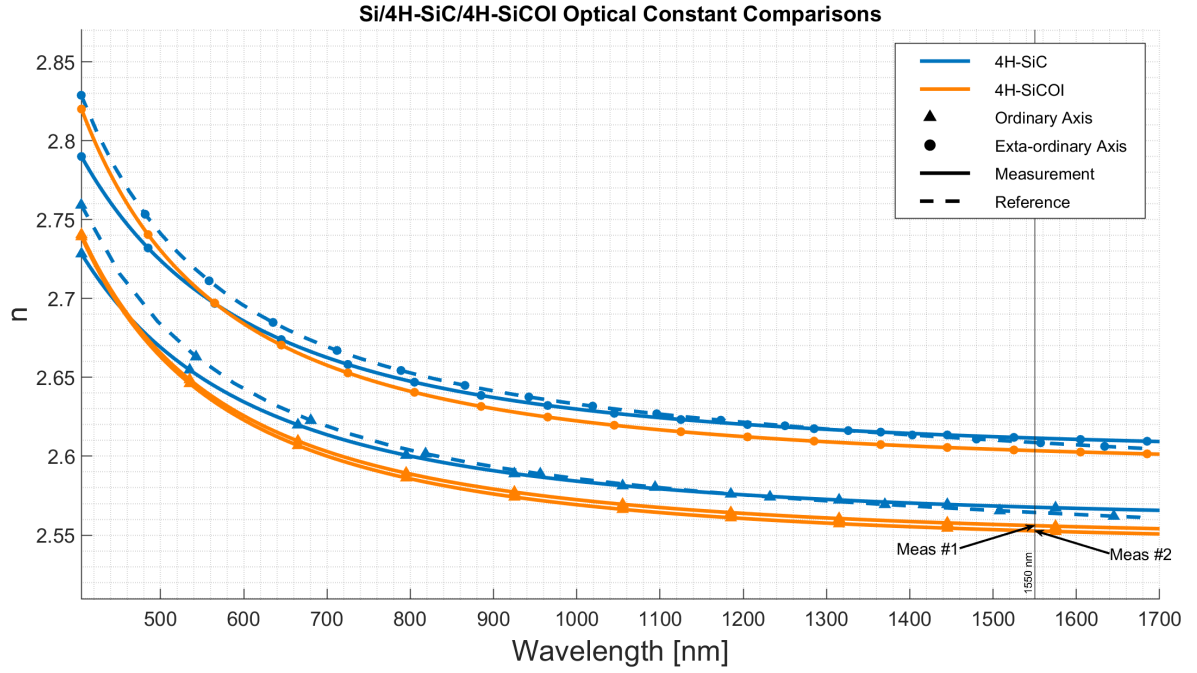


Figure 3.13: Refractive index dispersion of 4H-SiC and 4H-SiCOI samples obtained from spectroscopic ellipsometry measurements and compared with reference data.

As shown in Fig. 3.13, both bulk and SiCOI thin-film samples exhibit normal dispersion behavior across the investigated spectral range. At 1550 nm, which is the operating wavelength considered throughout this work, the measured refractive index values are in good agreement with reference data [74] for both the ordinary and extraordinary components.

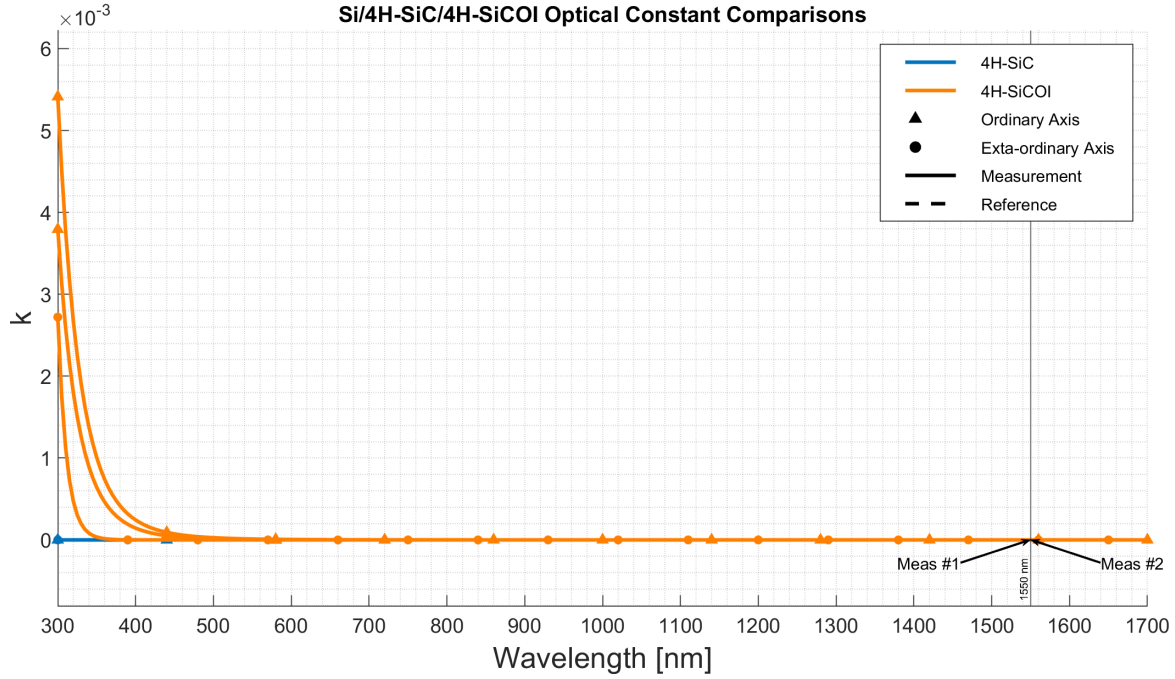


Figure 3.14: Extinction coefficients of 4H-SiC and 4H-SiCOI samples obtained from spectroscopic ellipsometry measurements and compared with reference data.

Measurements	$n(o)$	$n(e)$	$k(o)$	$k(e)$
4H-SiC	2.567	2.611	0	0
4H-SiCOI #1	2.555	2.603	1.88×10^{-8}	1.43×10^{-19}
4H-SiCOI #2	2.552	2.603	6.91×10^{-9}	1.43×10^{-19}
4H-SiC [74]	2.564	2.608	—	—

Table 3.2: Optical constants at $\lambda = 1550$ nm.

The thin-film sample shows a slightly reduced refractive index compared to the bulk material, which can be attributed to thin-film effects and possible microstructural differences. However, the deviation at 1550 nm remains limited, confirming the reliability of the ellipsometric modeling and the suitability of the extracted optical constants for subsequent waveguide design and simulation studies.

Aligning with our previous assumptions, our samples are basically transparent at 1550 nm and over the bandwidth of measurement, see Fig. 3.14 and Table 3.2

3.3. Scanning Electron Microscopy

3.3.1. Setup

Scanning electron microscopy (SEM) was employed as the primary structural characterization technique to evaluate the lithography and etching outcomes. The acquired high-resolution images were used to assess the photoresist mask profile after lithography, to analyze the transferred SiC etch profile, and to estimate etch selectivity and sidewall roughness of the patterned waveguide structures.

All high-resolution micrographs were obtained using a LEO 1525 field-emission scanning electron microscope (FE-SEM), shown in Fig. 4.5. The field emission gun enables the formation of a finely focused electron probe with high current density, providing enhanced spatial resolution and improved surface sensitivity. The instrument is equipped with a standard secondary electron (SE) detector for topographic imaging and an in-lens detector for enhanced surface-detail contrast.

The microscope was operated within an accelerating voltage range of 0.5 kV-20 kV. In this work, imaging was performed at 5 kV for samples coated with gold or Electra 92. To reduce charging effects on semi-insulating 4H-SiC samples, where low conductivity causes electron accumulation at the surface and image distortion, an accelerating voltage of 2 kV was used with signal collection via the secondary electron detector. The working distance between the SiC sample and the electron column was maintained at approximately 7 mm. To maximize the accuracy of dimensional measurements extracted from SEM images, image sharpness was carefully optimized for each inspected region.

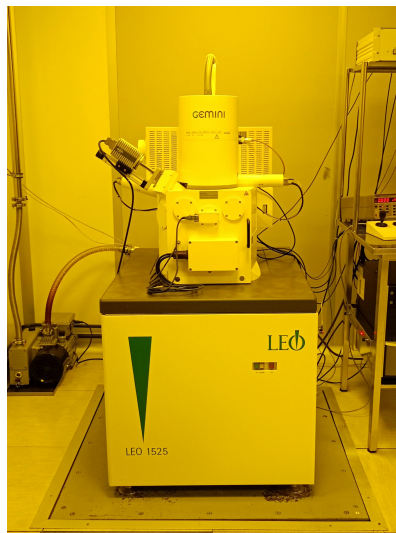


Figure 3.15: Scanning Electron Microscope - LEO 1525

3.3.2. Coating for SEM Imaging

To mitigate electron charging effects during SEM imaging, certain sample surfaces were coated with a thin conductive layer. Conventionally, this was achieved by depositing a few nanometers of gold using an Anatech Hummer 6.2 DC sputtering system. The conductive coating improves charge dissipation and enhances image stability, particularly for insulating or semi-insulating samples as the samples at hand.

However, following reoccurring lithography trials, repeated reuse of the same samples became necessary. The presence of a gold coating significantly complicates subsequent processing steps, as complete removal of the metallic layer and restoration of the original surface condition is challenging and may introduce surface contamination or damage.

For this reason, an alternative conductive coating based on Electra 92 conductive polymer was employed. The polymer was applied using the same spin-coating protocol as used for electron-beam lithography resist deposition, consisting of 2 steps, First one is going up to 4000 rpm and then staying at 4000 rpm for 60 seconds. After deposition, a soft-bake process was carried out at 90 °C for 2 minutes, resulting in an approximately 40 nm thick conductive layer on top of features.

Unlike gold metallization, the Electra 92 coating can be easily removed by rinsing the sample in water for 30 seconds to 1 minute, restoring the surface for subsequent fabrication, characterization steps or new trials.

3.4. Lithography

3.4.1. Overview

Lithography encompasses the techniques used to transfer a predefined pattern from a design layout onto a substrate surface . It represents a fundamental step in nanofabrication, particularly in semiconductor technologies and integrated photonics. Depending on the radiation source and exposure mechanism, lithography can be classified into optical lithography, electron-beam lithography, and imprint-based approaches, each offering different trade-offs in terms of resolution, throughput, cost, and process flexibility [147].

In optical lithography, photons modify a photosensitive polymer layer (photoresist) deposited on the substrate [148]. The resist thickness typically ranges from a few hundred nanometers to several tens of micrometers [148]. After exposure, the resist solubility changes according to its chemistry: in positive resists, exposed regions dissolve during development, whereas in negative resists, the exposed areas remain due to cross-linking

[148]. The achievable resolution is fundamentally limited by diffraction, meaning that the minimum feature size scales with the exposure wavelength and process parameters [148]. Consequently, deep submicron patterning becomes increasingly challenging with conventional ultraviolet sources, although optical lithography remains attractive due to its robustness and compatibility with large-area processing [148].

Optical lithography can be implemented either through mask-based exposure or maskless direct writing [148]. In mask-based systems, a photomask containing the desired geometry is aligned with the resist-coated substrate and the pattern is transferred in a single exposure step. In contrast, maskless techniques generate patterns by scanning a focused beam across the resist surface, eliminating the need for physical masks [148].

Direct-write photolithography employs a focused light beam to define structures directly on the photoresist [149]. As a maskless method, it significantly reduces fabrication time and cost associated with mask production, which is particularly advantageous during research and process development stages requiring multiple design iterations. The technique supports both single-layer and multilayer fabrication and provides considerable flexibility for rapid prototyping. For emerging platforms such as silicon carbide, where fabrication processes are still under optimization, this flexibility enables fast evaluation of waveguide geometries and etching conditions [149]. Although the resolution remains diffraction-limited, it is generally sufficient for micron-scale and certain submicron photonic structures, offering a balanced compromise between precision and processing speed [149].

Electron-beam lithography (EBL) utilizes a focused electron beam to locally modify an electron-sensitive resist such as Polymethylmethacrylate (PMMA) [148]. Electron-resist interactions induce bond scission or cross-linking, thereby changing the solubility of the exposed regions. Owing to the extremely short wavelength of electrons, EBL enables nanometer-scale patterning [148]. In practice, the achievable resolution is limited by electron scattering within the resist and substrate, known as the proximity effect [148]. Despite being a relatively slow and costly serial process, EBL remains one of the most precise nanofabrication techniques available [148].

The ability of electron-beam lithography to define deep submicron features makes it particularly suitable for tightly confined optical waveguides and high-index-contrast photonic devices. In silicon carbide photonics, EBL can therefore be considered for advanced structures requiring higher geometrical accuracy than that achievable with optical direct writing. While direct-write lithography serves as an efficient tool for rapid development and process optimization, electron-beam lithography represents a complementary approach

for future stages where finer dimensional control becomes necessary.

3.4.2. Setup

For the lithographic step, a maskless aligner exposure system based on the Heidelberg MLA100 Maskless Aligner was employed.

The MLA100 enables direct laser writing into photoresist without requiring a physical photomask. The unit at hand achieves minimum feature sizes of approximately $1\ \mu\text{m}$ with writing speeds up to $50\ \text{mm}^2/\text{min}$. Arbitrary geometries can be directly transferred from the design file to the exposure tool, making it particularly advantageous during device optimization stages.



Figure 3.16: Heidelberg MLA100 Maskless Aligner

3.4.3. Lithography Process

In this work, both the lithography processes and the etching steps described in the following section were carried out on bulk 4H silicon carbide samples. The exposure system operates with a 365 nm LED(i-line) [150]. At this wavelength, 4H-SiC exhibits a high refractive index and a low extinction coefficient, indicating limited optical absorption within the material. As a consequence, a significant portion of the incident optical energy is transmitted rather than absorbed at the surface, which reduces the effective energy density available for resist activation. Therefore, trials with exposure doses higher than those typically used in conventional lithographic processes on silicon substrates were required.

Due to these material-specific optical properties, a calibration procedure involving dose, focus, and mask dimension optimization was performed. The objective was to determine the appropriate exposure window ensuring accurate pattern transfer while maintaining

dimensional fidelity and sidewall integrity.

For this purpose, a dedicated calibration mask was designed. The mask contained 6 mm long line structures with nominal widths of 1, 2, 5, and 10 μm , each separated by gaps of identical dimensions. Every configuration was repeated five times, and all combinations were implemented to enable statistical evaluation of critical dimension control and pattern uniformity.

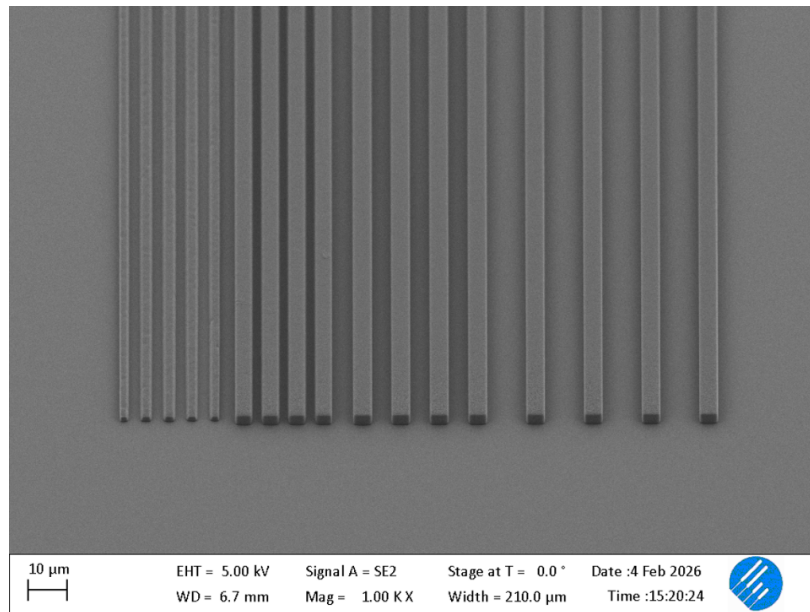


Figure 3.17: SEM image 5 μm width mask lines trial with sweeping spacings

Based on the literature review [39], reactive ion etching (RIE) was selected as the pattern transfer technique, as will be detailed in the following chapter. For this purpose, AZ[®] 15nXT negative photoresist, known for its high resistance to plasma-based etching processes, was employed as the masking material for the silicon carbide samples [151].

As a usual consequence of photomasks, a negative resist in particular for our case, the relationship between exposure dose and resulting feature dimensions was not strictly linear. It was observed empirically that the linewidths increased with increasing exposure dose in a non-linear manner, while the corresponding gap dimensions decreased inversely with dose. Consequently, dose optimization required experimental calibration rather than direct proportional scaling. To partially compensate for dimensional deviations, a defocus value of -1 was introduced in the MLA exposure settings for all of the trials.

The combinations of line widths and inter-line spacings targeted within the mask were grouped into three separate dose levels, taking advantage of the MLA-100 system's capability to apply different exposure doses sequentially within the same mask layout. The

grouping strategy was determined based on the spacing between the lines, as the proximity effect strongly depends on the distance between adjacent features.

Accordingly, lines with inter-line spacings of 5 and 10 μm were grouped together, lines with 2 μm spacing formed a second group, and lines with 1 μm spacing constituted a third group. To investigate the most pronounced proximity effect conditions, the dose corresponding to the resolution limit of 1 μm feature size was further examined under different spacing configurations. In some experiments, only patterns with 1 μm spacing were considered, and different line widths were exposed to different dose values in order to analyze the proximity effect in greater detail.

Each lithography trial was carried out according to the following procedure. To ensure that the substrates were free of organic contaminants and surface residues, an initial cleaning step was performed using a plasma asher (Recipe 5). This cleaning step was followed by surface activation and adhesion promotion through hexamethyldisilazane (HMDS) treatment on a hotplate at 120 °C for 1 min, see Fig. 3.18a.

After this step, to prevent any reduction in the adhesion-promoting effect of HMDS, the process proceeded immediately to the spin-coating stage without delay, see Fig. 3.18c. The AZ[®] 15nXT negative photoresist was spin-coated onto the sample using the SM150 according to a multi-step program optimized for this resist. The process began with an acceleration step to 500 rpm, followed by a 5 s spin step at 500 rpm to ensure uniform resist spreading. Subsequently, a second acceleration ramp was applied to reach 6000 rpm within 9 s. The final thinning step consisted of a 20 s spin at 6000 rpm, resulting in the desired uniform film thickness across the substrate. This was followed by a soft-bake step on the hotplate (Fig. 3.18b) at 110 °C for 2 min to remove residual solvents and stabilize the resist layer.

Subsequently, exposure was carried out using the MLA100 maskless aligner with the designed mask layout and selected dose/defocus parameters, completing the pattern transfer onto the sample. A carefully timely-mannered post-bake was then performed at 120 °C for 1 min (sharp) to finalize the cross-linking reaction of the negative resist.

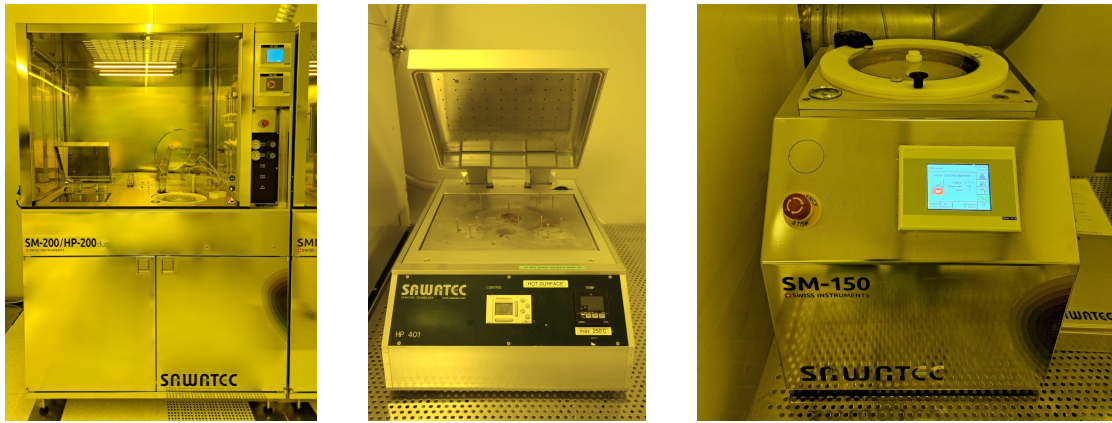
The sample was developed in AZ[®] 726 MIF for approximately 100 s. During development, the sample could be gently agitated in the developer solution, particularly in regions where the transferred pattern was less apparent, to enhance development effectiveness. Finally, the process was completed with a deionized water rinse followed by nitrogen drying.

In cases where the fabricated patterns did not yield the desired results, the photoresist layer had to be removed to allow for subsequent lithography trials. For this purpose,

TechniStrip® NI555 was used as a stripping solution. The samples were immersed in the stripper and placed on a hotplate at 70°C for 10 minutes to facilitate resist dissolution.

While still immersed in the stripping solution, the samples were subsequently treated in an ultrasonic cleaner for 2-3 minutes at a frequency of 59 kHz and 70% power to enhance the removal of residual resist.

After this step, the samples were rinsed thoroughly with deionized water, dried, and subjected to an additional plasma ashing process to eliminate any remaining organic residues. If visible traces of photoresist persisted by bare eye or microscopy, the stripping and cleaning sequence was repeated until complete removal was achieved.



(a) Spin Module with Hot Plate – Sawatec SM-200/HP-200duo (b) Hot Plate – Sawatec HP-401 (c) Spin Coater – Sawatec SM-150

Figure 3.18: PoliFAB equipment used the lithography process.

3.4.4. Experimental Conclusions

As a result of the lithography trials, the exposure parameters required to achieve the nominal 1 μm resolution in terms of linewidth and spacing, specified for the MLA100 on bulk 4H-SiC were determined to be a dose value of 110 mJ/cm² and a defocus setting of -1. Under these conditions, a mask linewidth of 750 nm resulted in an effective patterned linewidth of approximately 1 μm on the substrate. In order to maintain a final gap of 1 μm between adjacent lines, the mask spacing was increased to 1.25 μm , see Fig. 3.19.

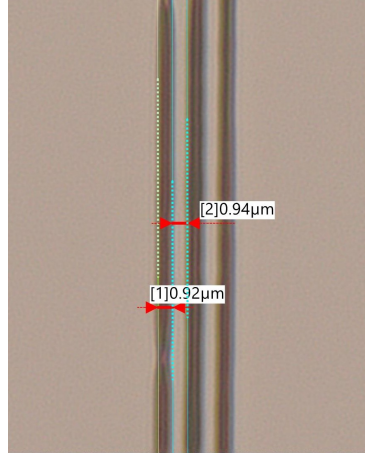


Figure 3.19: Digital microscope image of trial mask lines with $1\mu\text{m}$ linewidth and $1\mu\text{m}$ spacing

It is important to emphasize that, for the configuration consisting of five parallel lines with $1\mu\text{m}$ linewidth and $1\mu\text{m}$ spacing, only the three central lines were successfully resolved, while the two outermost lines were not fully obtained. This behavior should be considered in future processes employing optical lithography. A similar phenomenon was observed for the $2\mu\text{m}$ linewidth and $1\mu\text{m}$ spacing configuration of the mask, where the outermost lines appeared narrower compared to the central ones, see Fig. 3.20. For the remaining linewidth and spacing combinations (i.e. 5 and $10\mu\text{m}$), stable and dimensionally consistent pattern transfer was achieved.

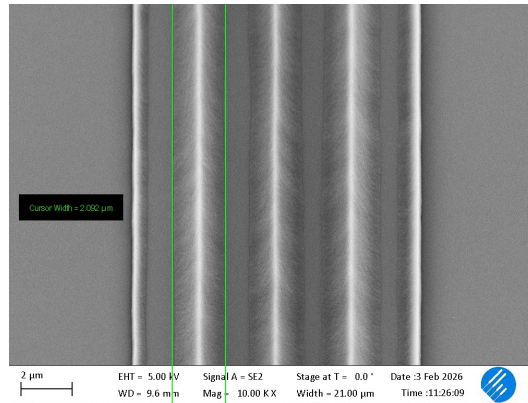


Figure 3.20: SEM image of trial mask lines with $2\mu\text{m}$ linewidth and $1\mu\text{m}$ spacing

This behavior can be attributed to the proximity effect: during exposure, the central lines are subjected to additional scattered energy contributions from neighboring features, resulting in a higher effective dose compared to the outermost lines. Consequently, polymerization becomes more pronounced in the central region, leading to comparatively

prominent features, while the outer lines remain narrower due to reduced cumulative exposure. As another example in Fig. 3.21, outer lines pose mostly vertical sidewalls. However, on its opposite side, proximity effect enlarges the mask towards others. Inversely, if an outer line of certain sparsely spaced line is close to tighter line group, outer lines would be more evident.

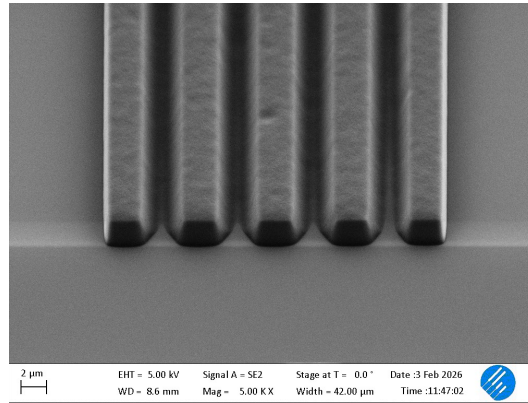
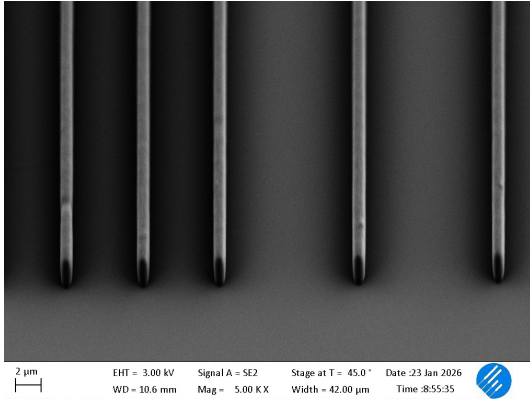


Figure 3.21: SEM image of trial mask lines with $2\mu\text{m}$ linewidth and $2\mu\text{m}$ spacing

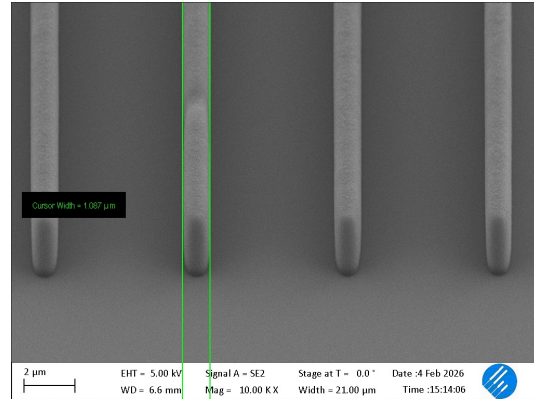
It should be noted that the considered dose values and mask dimensions do not represent the final parameters required to reach the resolution limit. During the design stage, both the proximity effect and the spacing between adjacent lines must be carefully taken into account. By reducing the mask feature size and increasing the exposure dose, further optimization may be achieved. However, even if the nominal dose is increased, the total energy delivered to a reduced feature area may effectively decrease, leading to a lower-than-expected degree of polymerization. Therefore, empirical studies tailored to the targeted feature dimensions are essential. For instance, applying a dose of $155\text{ mJ}/\text{cm}^2$ to a design with $1\mu\text{m}$ linewidth and $1\mu\text{m}$ spacing resulted in a developed mask width of approximately $1.1\mu\text{m}$. Similarly, a dose of $68\text{ mJ}/\text{cm}^2$ applied to a mask with $1.1\mu\text{m}$ linewidth yielded a final patterned structure corresponding to the targeted $1\mu\text{m}$ linewidth and spacing. These indicate that multiple parameter sets can converge to the nominal resolution limit possibly with different taper profiles, depending on the interplay between effective exposure, feature size, and proximity effects.

During the experiments, it was observed that for configurations involving narrow lines and small gap dimensions, low exposure doses resulted in reduced mask heights compared to larger feature structures. This behavior is attributed to insufficient polymerization of the negative photoresist at lower dose levels, leading to incomplete cross-linking and consequently thinner resist profiles after development. For these cases, proximity effects would be the dominant mask profile influence.

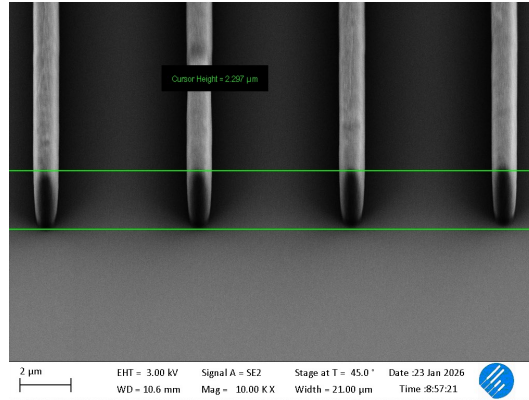
On the contrary, When higher doses are utilized, even the $1\ \mu\text{m}$ lines can achieve nearly uniform profiles if the spacing is sparse. This has been seen as true for spacings over $2\ \mu\text{m}$. However, with slight adjustments, we may smaller spacings with a similiar mask profile. The case in Fig. 3.22 is $1\ \mu\text{m}$ linewidth and $5\ \mu\text{m}$ spacing. There, we have almost polymerized all of the resist that has been put on it (height is around $3.3\ \mu\text{m}$) and obtained almost perfect uniform mask profile.



(a) SEM image of trial mask lines with $1\ \mu\text{m}$ linewidth and $5\text{-}10\ \mu\text{m}$ spacings



(b) SEM image of trial mask lines with $1\ \mu\text{m}$ linewidth and $5\ \mu\text{m}$ spacing



(c) SEM image of trial mask lines with $1\ \mu\text{m}$ linewidth and $5\ \mu\text{m}$ spacing

Figure 3.22: SEM image of uniform profile mask lines with $1\ \mu\text{m}$ linewidth.

An interesting trade-off is observed at an exposure dose of $180\ \text{mJ}/\text{cm}^2$, where the line width can be reduced to $738\ \text{nm}$ (see Fig. 3.23) for $5\ \mu\text{m}$ gap spacings; however, considering the $1\ \mu\text{m}$ resolution limit of the MLA100 and the influence of subsequent fabrication steps, the repeatability of this result remains uncertain, and achieving similar performance at smaller gap values is expected to be unlikely, although further empirical optimization studies may be pursued in future work utilizing photolithography.

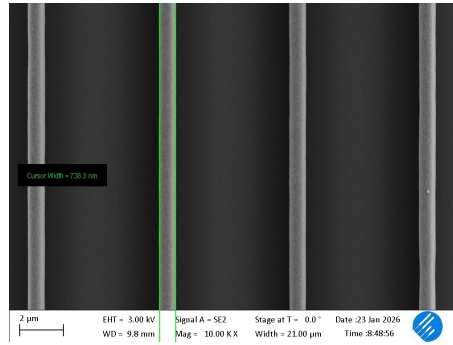


Figure 3.23: SEM image of trial mask lines with $0.73\mu\text{m}$ linewidth and $5\mu\text{m}$ spacing

The primary reason for insufficient polymerization is the total energy delivered to the specific location where the mask feature is defined. In this context, not only the nominal dose value but also the linewidth of the tested mask plays a critical role. For instance, in the previously mentioned $155\text{ mJ}/\text{cm}^2$ scenario, the mask width had a specific value; if the linewidth is reduced, a higher nominal dose is required to reach the same effective exposure. The total effective polymerization ultimately determines the resulting mask height and profile. This is one of the challenges behind achieving resolution limit with uniform profile.

One consequence of mask width variation is that for larger features, such as $5\mu\text{m}$ and $10\mu\text{m}$ linewidths, the expected resist thickness of approximately $3.5\mu\text{m}$ (depending on the photoresist condition and processing history) was largely preserved, as they may be formed by higher doses. In such cases, provided that the proximity effect is not relatively dominant, a uniform- mask profile can be obtained when linewidths are adjusted accordingly with the dose.

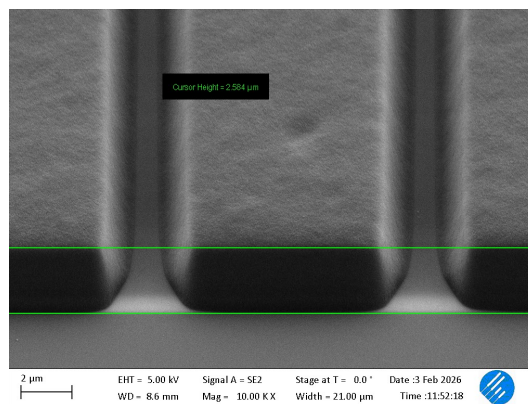


Figure 3.24: SEM image of trial mask lines with $10\mu\text{m}$ linewidth and $1\mu\text{m}$ spacing

When the proximity effect is also taken into account, achieving a uniform mask with

maximum height in low-linewidth and small-spacing configurations becomes considerably challenging and requires dimension-specific empirical optimization. However, in this work, the targeted waveguide height is 300 nm. As will be discussed in the following section, although the selectivity between the photoresist and 4H-silicon carbide is relatively low, it is extremely hard to etch chemically inert SiC, and the mask profile may be tapered, the required etch depth is sufficiently small such that acceptable mask heights can still be achieved.

Dose (mJ/cm ²)	Ideal Gap (μm)	Ideal Width (μm)	Mask Gap (μm)	Mask Width (μm)	ΔW (μm)
90	1	1	0.8	1.2	-0.2
	1	2	0.9	2.1	-0.1
	1	5	1.5	4.5	0.5
	1	10	1.7	9.3	0.7
150	2	1	1.9	1.1	-0.1
	2	2	2.2	1.8	0.2
	2	5	2.3	4.7	0.3
	2	10	2.4	9.6	0.4
205	5	1	4.7	1.3	-0.3
	5	2	5.0	2.0	0.0
	5	5	5.0	5.0	0.0
	5	10	5.0	10.0	0.0
205	10	1	9.7	1.3	-0.3
	10	2	10.0	2.0	0.0
	10	5	10.0	5.0	0.0
	10	10	10.0	10.0	0.0

Table 3.3: Mask configuration for the etched 4H-SiC sample. The last column shows $\Delta W = W_{\text{ideal}} - W_{\text{mask}}$.

The interpretations derived from the SEM images presented so far can also be extended to the mask design considerations summarized in Table 3.3. The table groups the mask layers according to the targeted line-gap combinations and reports the implemented mask linewidths, the nominal (target) linewidths, and the dimensional bias required to reproduce the intended structures. In this way, it provides a systematic comparison between the designed geometries and the adjustments introduced to compensate for fabrication-related effects.

In particular, at low exposure doses and small gap values, thicker lines were intentionally designed narrower than their nominal targets in order to compensate for proximity effects. Since thick features correspond to larger exposed areas, polymerization becomes more pronounced, and this effect is further reinforced by additional exposure contributions from neighboring thick lines. Conversely, for closely spaced thin lines, the exposed area is significantly smaller; therefore, linewidths larger than the nominal target were assigned in the mask to ensure sufficient polymerization, even at the initial stage of exposure. As will be evident from the etching results presented in the following section, the magnitude of the proximity effect becomes clearly observable under these conditions. If this exposure dose is selected in future trials, mask linewidths closer to — or potentially even smaller than — the nominal values may be preferable for thin features. More generally, when considering increasing gap values together with increasing dose, it can be inferred that the relative influence of the proximity effect decreases, even though the absolute exposure dose increases.

3.5. Etching

3.5.1. Overview

Silicon carbide (SiC) is chemically highly inert, which makes conventional wet etching processes difficult to implement effectively [39]. At room temperature, single-crystal SiC is largely resistant to both acidic and alkaline solutions. Although high-temperature gas-phase etching and certain wet or electrochemical approaches can provide advantages such as surface smoothing or material selectivity, they generally require extreme process conditions and often lead to surface defects, limited dimensional control, or poor uniformity [39].

For the fabrication of mesa and trench structures with well-defined geometries, a technique offering better anisotropy and pattern fidelity is required [39]. Reactive ion etching (RIE) has therefore become the preferred approach for SiC microstructuring, as it enables controlled material removal compatible with high-resolution device fabrication. In the following section, the fundamentals and implementation of RIE for SiC processing are presented [39].

3.5.2. Reactive Ion Etching

Reactive ion etching (RIE) of SiC can be performed using commercially available plasma systems originally developed for Si and other semiconductor materials, without the need

for extreme temperatures or highly specialized equipment [39]. Although the etch rates are generally lower than those obtained for Si, RIE provides sufficient controllability for device fabrication [39]. The process combines chemical reactions driven by plasma-generated reactive species with physical sputtering induced by ion bombardment at the substrate surface. The relative contribution of these mechanisms determines the overall etch behavior and profile characteristics.

Different plasma configurations have been investigated for SiC, including capacitively coupled, inductively coupled, and high-density plasma systems [39]. In practice, the etching performance is strongly influenced by parameters such as plasma density, process pressure, and substrate bias power [152]. In particular, increasing the bias enhances the etch rate due to stronger ion bombardment, but may also introduce surface damage [152]. Among these approaches, high-density plasma systems offer improved process control, as plasma generation and ion energy can be adjusted independently, making them especially attractive for achieving anisotropic and controllable etching of SiC structures [39].

In addition to etch rate and selectivity, control of the etched profile is a critical aspect of SiC processing [153]. Depending on the plasma and masking conditions, structures such as high-aspect-ratio trenches with nearly vertical sidewalls can be achieved [153], demonstrating the capability of RIE to produce well-defined and anisotropic features.

At the same time, variations in mask material and etch selectivity can intentionally or unintentionally modify the final geometry, leading to rounded bottoms or beveled mesa profiles [153]. Such profile control can be advantageous for specific device applications, particularly where edge termination or junction management is required [153]. These examples highlight the flexibility of RIE in tailoring both vertical and non-vertical structures according to design requirements.

3.5.3. Setup

The SPTS Omega[®] SynapsE process module employs a high-density plasma source specifically designed for the etching of strongly bonded materials. The system features a heated process chamber combined with magnetic confinement, enabling plasma densities significantly higher than those achieved in conventional ICP systems. As a result, enhanced etch rates can be obtained, particularly for materials with high bond strength.

The Omega SynapsE module is commonly utilized for the fabrication of deep features in dielectric materials such as silicon oxide, quartz, and glass. In addition, materials characterized by low volatility and high chemical stability, including SiC and AlScN, can be effectively processed using this system, making it well suited for advanced microfabrication

applications.



Figure 3.25: SPTS Omega SYNAPSE

3.5.4. Experimental Results

The mask dimensions summarized in Table 3.3 were used as the starting point for the optimization of the 4H-SiC etching recipe.

Reactive ion etching (RIE) was performed using the SPTS Omega SYNAPSE 200 LPX module under fluorine-based plasma conditions. The process chemistry consisted of SF_6 (100 sccm) as the primary etching gas and O_2 (10 sccm) as an additive gas. In SiC dry etching, the dominant mechanism is governed by the volatility of the reaction by-products and the energy of the ionized species; therefore, the selection of gas composition, chamber pressure, and substrate bias power plays a critical role. The addition of O_2 promotes the removal of carbon-containing species and enhances the overall etch rate under fluorine-based chemistry [39].

The chamber pressure was maintained at 10 mTorr. An inductively coupled plasma (ICP) power of 1500 W was applied to generate a high-density plasma, while a capacitively coupled plasma (CCP) bias power of 200 W was used. The platen temperature was set to -10°C .

When the proposed etching recipe was applied for a duration of two minutes, the cross-sectional profiles shown below were obtained. These cross-sections were prepared by cleaving the samples after the completion of the lithography and etching steps.

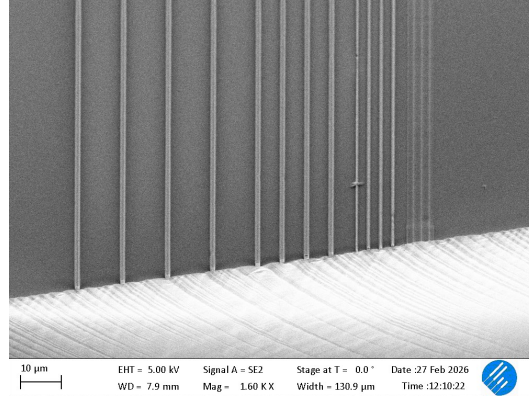


Figure 3.26: SEM image of cleaved bulk 4H-SiC sample

3.5.5. Experimental Results

In order to observe possible photoresist modifications after etching and to provide a more accurate evaluation of the etch selectivity, SEM imaging was first performed without applying any conductive coating. To mitigate charging effects during this initial characterization, the accelerating voltage was set to 2 kV. Subsequently, as described in the lithography and SEM sections, the photoresist was stripped and a clean, etched bulk 4H-SiC sample was obtained. Afterwards, Electra 92 was spin-coated to form a conductive layer. This conductive coating enabled the use of relatively higher accelerating voltages during SEM imaging, allowing improved signal stability and higher-resolution cross-sectional images to be acquired.

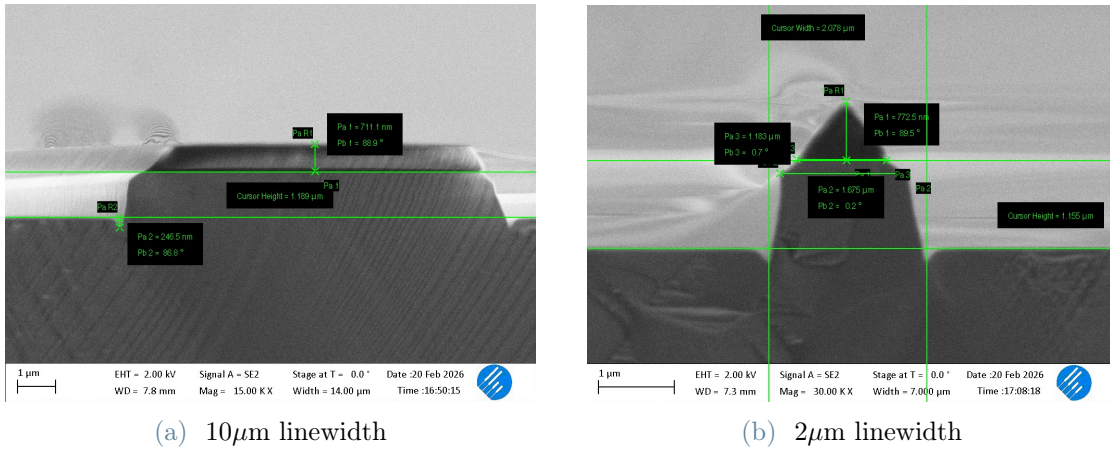


Figure 3.27: SEM image of cross-section of an etched line with 2 and 10µm linewidth with remaining photoresist

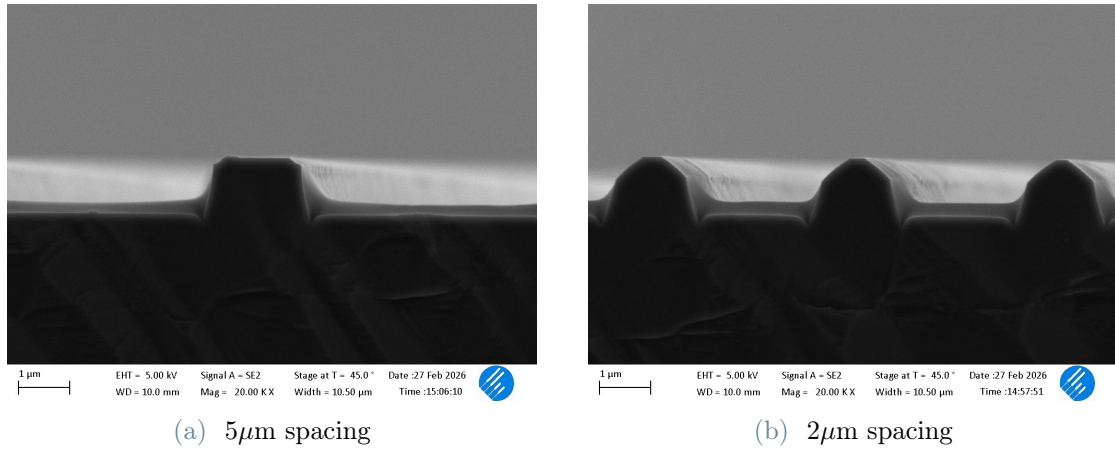


Figure 3.28: SEM image of cross-section of an etched line with 2 μm linewidth and 2 and 5 μm spacings (Covered with Electra 92)

As observed in Figures 3.27 and 3.28, the dimensional values obtained for the mask-defined linewidth and gap combinations should be regarded as approximate. Due to measurement limitations and possible local non-uniformities along the cross-section, slight variations are expected. Therefore, representative values were determined based on multiple observations and comparative evaluation of the SEM images.

Accordingly, the photoresist thickness on top of the waveguide was estimated to be 725 ± 50 nm. From the cross-sectional images of the waveguides where the photoresist was not completely etched through, as well as from the inspection of structures where the photoresist remained on top, the resulting waveguide height was determined to be 1150 ± 25 nm. Considering that the applied etching duration for this recipe was 2 minutes, these values provide a basis for estimating the effective etch depth and evaluating the etching performance under the proposed process conditions.

The sidewall angle was measured as $82^\circ \pm 3^\circ$, while sidewall roughness could not be quantified. SEM imaging required a conductive Electra 92 coating, reaching up to 40 nm on line tops and 200 nm in narrow gaps (see Fig. 3.29), which also covered the sidewalls and prevented reliable roughness extraction. Additional SEM images have been taken without them using a different SEM unit. However, even if the ridges are visible (see Fig. 3.30) those images are still low fidelity where no accurate assessment can be made. A proper evaluation would require extreme low voltage, high-resolution SEM without coating; alternatively, a thinner conductive layer (e.g., gold) may be used in future studies when more etched samples become available. Dips observed at the bottom corners of the waveguide sidewalls (see Fig. 3.28) can be minimized through further etch-recipe optimization.

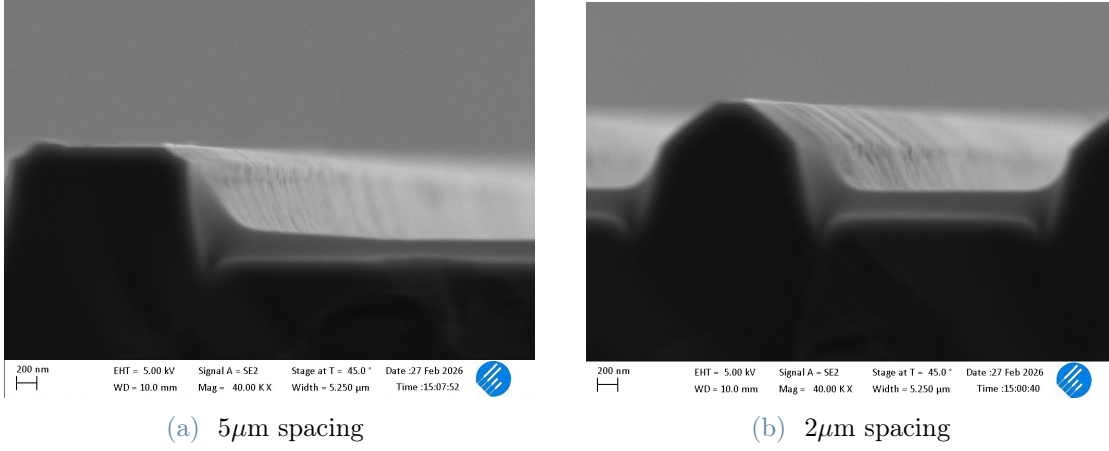


Figure 3.29: SEM image of sidewall covered with Electra 92 for an etched line with 2μm linewidth and 2 and 5μm spacings (Covered with Electra 92)

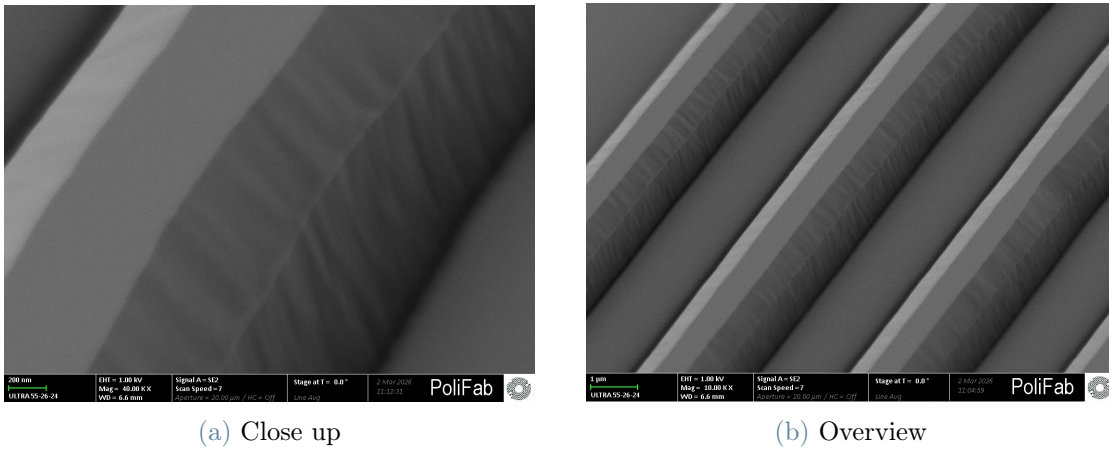


Figure 3.30: SEM image of etched line sidewall

However, in these low-dose conditions, noticeable tapering of the photoresist profile was observed. Consequently, during the etching process, once a portion of the resist is consumed, the tapered sidewalls may lead to premature exposure of the regions intended to remain as the waveguide core. This would initiate unintended etching of the protected SiC areas, potentially compromising dimensional accuracy and structural integrity of the fabricated waveguides. During the lithography process, profilometry and SEM measurements indicated that, for the mask configurations corresponding to nominal linewidth and gap values of 10 μm and 5 μm (i.e., the maximum mask height conditions encountered), the resulting photoresist thickness was determined to be 3600 ± 100 nm.

Accordingly, the etch selectivity between SiC and the photoresist can be calculated as:

$$t = 2 \text{ min}$$

Initial photoresist thickness:

$$h_{\text{initial}} = (3600 \pm 100) \text{ nm}$$

Remaining photoresist thickness after etch:

$$h_{\text{remaining}} = (725 \pm 50) \text{ nm}$$

$$\Delta h_{\text{PR}} = h_{\text{initial}} - h_{\text{remaining}} = (3600 - 725) \text{ nm} = 2875 \text{ nm}$$

Uncertainty propagation for subtraction:

$$\delta(\Delta h_{\text{PR}}) = \sqrt{(100)^2 + (50)^2} = \sqrt{10000 + 2500} = \sqrt{12500} = 112 \text{ nm}$$

$$\Delta h_{\text{PR}} = (2875 \pm 112) \text{ nm}$$

$$\Delta h_{\text{SiC}} = (1150 \pm 25) \text{ nm}$$

$$R_{\text{SiC}} = \frac{\Delta h_{\text{SiC}}}{t} = \frac{1150}{2} = 575 \text{ nm/min}$$

$$\delta R_{\text{SiC}} = \frac{25}{2} = 12.5 \text{ nm/min}$$

$$R_{\text{PR}} = \frac{\Delta h_{\text{PR}}}{t} = \frac{2875}{2} = 1437.5 \text{ nm/min}$$

$$\delta R_{\text{PR}} = \frac{112}{2} = 56 \text{ nm/min}$$

$$S_{\text{SiC:PR}} = \frac{R_{\text{SiC}}}{R_{\text{PR}}} = \frac{575}{1437.5} = 0.400$$

$$\left(\frac{\delta S}{S}\right)^2 = \left(\frac{12.5}{575}\right)^2 + \left(\frac{56}{1437.5}\right)^2$$

$$\frac{\delta S}{S} = \sqrt{(0.0217)^2 + (0.0390)^2} = 0.0446$$

$$\delta S = 0.400 \times 0.0446 = 0.018$$

$$\boxed{S_{\text{SiC:PR}} = 0.40 \pm 0.02}$$

For the proposed waveguide dimensions defined as 300 nm in height and 700 nm in width, the minimum required photoresist thickness was determined to be 0.75 μm based on the calculated etch selectivity ($S_{\text{SiC:PR}} \approx 0.40$). In the lithography trials conducted so far, even the masks exposed at the lowest dose levels resulted in photoresist thicknesses exceeding 1 μm . Therefore, from a purely etch-selectivity perspective, the available resist thickness provides a sufficient process margin for the realization of the targeted waveguide height. Consequently, further optimization efforts can be primarily focused on profile control, dimensional fidelity, and proximity-effect compensation rather than on mask thickness limitations.

4 | Conclusions and future developments

In future studies, the issues related to proximity effects and tapered mask profiles can be addressed through empirical optimization of mask design and exposure dose, allowing the definition of a finalized photolithography and RIE process flow. Once these parameters are established, fabrication trials of the pilot waveguide dimensions can be pursued, potentially employing electron-beam lithography to achieve improved dimensional control.

After successful realization of the proposed structures, the process can be transferred to a 4H-SiCOI platform, enabling the fabrication of fully integrated photonic devices. The realization of the proposed waveguide geometry on 4H-SiCOI wafers would constitute a critical step toward device-level implementation, where the refractive index values extracted from ellipsometric analysis and the optimized etching parameters can be directly utilized within a controlled device fabrication workflow.

Subsequently, the experimentally fabricated waveguides can be optically characterized and directly compared with the previously performed numerical simulations. Such a comparison would provide a systematic verification of the mode confinement, effective index values, propagation losses, and bending performance predicted by the design maps and numerical analyses developed in this work. In this way, the fabrication on the 4H-SiCOI platform would not only demonstrate technological feasibility but also serve as an experimental validation of the waveguide dimension based map design methodology.

At more advanced stages, once lithographic and etching imperfections are minimized, waveguide designs operating in the TM mode—known to be more sensitive to dimensional variations—can be explored. In addition to TM-oriented structures, photonic devices based on the established proposed waveguide dimensions may be fabricated, and the performance of components such as ring resonators can be experimentally evaluated and directly benchmarked against numerical simulations, thereby completing the loop between material characterization, process optimization, device fabrication, and theoretical modeling.

Bibliography

- [1] J. Bardeen and W.H. Brattain. The transistor, a semi-conductor triode. *Phys. Rev.*, 74:230, 1948.
- [2] W. Shockley. The theory of p-n junctions in semiconductors and p-n junction transistors. *Bell Syst. Tech. J.*, 28:435, 1949.
- [3] D. Kahng and M.M. Atalla. Ire-aieee solid-state device research conference silicon-silicon dioxide field induced surface devices. In *IRE-AIEEE Solid-State Device Research Conference*, 1960.
- [4] J. Kilby. Miniaturized electronic circuits, 1959.
- [5] R. Noyce. Semiconductor device-and-lead structure, 1959.
- [6] Y. Taur and T.H. Ning. *Fundamentals of Modern VLSI Devices*. Cambridge University Press, 2 edition, 2009.
- [7] International technology roadmap for semiconductors, 2014. URL <http://www.itrs.net/reports.html>.
- [8] Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson. Micrometre-scale silicon electro-optic modulator. *Nature*, 435:325–327, 2005. doi: 10.1038/nature03569.
- [9] Richard A. Soref. The past, present, and future of silicon photonics. *IEEE Journal of Selected Topics in Quantum Electronics*, 12(6):1678–1687, 2006. doi: 10.1109/JSTQE.2006.883151.
- [10] D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Viot, J. M. Fédéli, J. M. Hartmann, J. H. Schmid, D. X. Xu, F. Boeuf, P. O’Brien, G. Z. Mashanovich, and M. Nedeljkovic. Roadmap on silicon photonics. *J. Opt.*, 18:073003, 2016. doi: 10.1088/2040-8978/18/7/073003.
- [11] G. T. Reed and C. E. J. Png. Silicon optical modulators. *Mater. Today*, 8:40–50, 2005. doi: 10.1016/S1369-7021(04)00678-9.

- [12] A. D. Bristow, N. Rotenberg, and H. M. van Driel. Two-photon absorption and kerr coefficients of silicon for 850–2200 nm. *Appl. Phys. Lett.*, 90:191104, 2007. doi: 10.1063/1.2737359.
- [13] Jianwei Wang, Alberto Santamato, Pisu Jiang, Damien Bonneau, Erman Engin, Joshua W. Silverstone, Matthias Lerner, Johannes Beetz, Martin Kamp, Sven Hofling, Michael G. Tanner, Chandra M. Natarajan, Robert H. Hadfield, Sander N. Dorenbos, Val Zwiller, Jeremy L. O’Brien, and Mark G. Thompson. Gallium arsenide (gaas) quantum photonic waveguide circuits. *Optics Communications*, 327: 49–55, 2014. doi: 10.1016/j.optcom.2014.02.040.
- [14] A. Boes, B. Corcoran, L. Chang, J. Bowers, and A. Mitchell. Status and potential of lithium niobate on insulator (lnoi) for photonic integrated circuits. *Laser & Photonics Reviews*, 12:1700256, 2018. doi: 10.1002/lpor.201700256.
- [15] W.J. Choyke. Optical properties of polytypes of sic: Interband absorption, and luminescence of nitrogen-exciton complexes. *Mater. Res. Bull.*, 4:141, 1969.
- [16] M. Cazzanelli, F. Bianco, E. Borga, G. Pucker, M. Ghulinyan, E. Degoli, E. Luppi, V. Vénier, S. Ossicini, and D. Modotto. Second-harmonic generation in silicon waveguides strained by silicon nitride. *Nat. Mater.*, 11:148–154, 2012. doi: 10.1038/nmat3200.
- [17] X. Leijtens. Jeppix: the platform for indium phosphide-based photonics. *IET Optoelectron.*, 5:202, 2011. doi: 10.1049/iet-opt.2010.0070.
- [18] I. Aharonovich, A. D. Greentree, and S. Prawer. Diamond photonics. *Nat. Photonics*, 5:397–405, 2011. doi: 10.1038/nphoton.2011.54.
- [19] L. Chang, A. Boes, X. Guo, D. T. Spencer, M. J. Kennedy, J. D. Peters, N. Volet, J. Chiles, A. Kowligy, N. Nader, D. D. Hickstein, E. J. Stanton, S. A. Diddams, S. B. Papp, and J. E. Bowers. Heterogeneously integrated gaas waveguides on insulator for efficient frequency conversion. *Laser & Photonics Reviews*, 12:1800149, 2018. doi: 10.1002/lpor.201800149.
- [20] C. Wang, M. Zhang, X. Chen, M. Bertrand, A. Shams-Ansari, S. Chandrasekhar, P. J. Winzer, and M. Lončar. Integrated lithium niobate electro-optic modulators operating at cmos-compatible voltages. *Nature*, 562:101–104, 2018. doi: 10.1038/s41586-018-0551-y.
- [21] M. Kösters, B. Sturman, P. Werheit, and K. Buse. Optical cleaning of congruent

- lithium niobate crystals. *Nature Photon*, 3:510–513, 2009. doi: 10.1038/nphoton.2009.142.
- [22] Mian Zhang, Cheng Wang, Rebecca Cheng, Amirhassan Shams-Ansari, and Marko Lončar. Monolithic ultra-high-q lithium niobate microring resonator. *Optica*, 4: 1536–1537, 2017. doi: 10.1364/OPTICA.4.001536.
- [23] A. W. Elshaari, W. Pernice, K. Srinivasan, O. Benson, and V. Zwiller. Hybrid integrated quantum photonic circuits. *Nat. Photonics*, 14:285–298, 2020. doi: 10.1038/s41566-020-0639-4.
- [24] B. J. M. Hausmann, I. Bulu, V. Venkataraman, P. Deotare, and M. Lončar. Diamond nonlinear photonics. *Nat. Photonics*, 8:369–374, 2014. doi: 10.1038/nphoton.2014.72.
- [25] C. Wang, Z. Fang, A. Yi, B. Yang, Z. Wang, L. Zhou, C. Shen, Y. Zhu, Y. Zhou, R. Bao, Z. Li, Y. Chen, K. Huang, J. Zhang, Y. Cheng, and X. Ou. High-q microresonators on 4h-silicon-carbide-on-insulator platform for nonlinear photonics. *Light Sci Appl*, 10:139, 2021. doi: 10.1038/s41377-021-00584-9.
- [26] S.J. Whiteley, G. Wolfowicz, C.P. Anderson, A. Bourassa, A.L. Yeats, E. Janitz, C. Muller, P.V. Klimov, E.S. Bielejec, J.J. Whalen, and D.D. Awschalom. Spin–phonon interactions in silicon carbide addressed by gaussian acoustics. *Nat. Phys.*, 15:490–495, 2019. doi: 10.1038/s41567-019-0420-0.
- [27] D.M. Lukin, C. Dory, M.A. Guidry, K.Y. Yang, R. Trivedi, M.K. Bhaskar, D.D. Sukachev, A. Sipahigil, M. Radulaski, S. Sun, and J. Vučković. 4h-silicon-carbide-on-insulator for integrated quantum and nonlinear photonics. *Nat. Photonics*, 14: 330–334, 2020. doi: 10.1038/s41566-019-0556-6.
- [28] K. Bray, B. Regan, A. Trycz, R. Previdi, G. Seniutinas, K. Ganesan, M. Kianinia, S. Kim, and I. Aharonovich. Single crystal diamond membranes and photonic resonators containing germanium vacancy color centers. *ACS Photonics*, 5:4817–4822, 2018. doi: 10.1021/acsp Photonics.8b00930.
- [29] G.L. Harris. *Properties of Silicon Carbide*. INSPEC, 1995.
- [30] R.F. Davis, G. Kelner, M. Shur, J.W. Palmour, and J.A. Edmond. Thin film deposition and microelectronic and optoelectronic device fabrication and characterization in monocrystalline alpha and beta silicon carbide. *Proc. IEEE*, 79:677, 1991. doi: 10.1109/5.90132.

- [31] P.A. Ivanov and V.E. Chelnokov. Recent developments in sic single-crystal electronics. *Semicond. Sci. Technol.*, 7:863, 1992. doi: 10.1088/0268-1242/7/7/001.
- [32] H. Morkoç, S. Strite, G.B. Gao, M.E. Lin, B. Sverdlov, and M. Burns. Large-band-gap sic, iii-v nitride, and ii-vi znse-based semiconductor device technologies. *J. Appl. Phys.*, 76:1363, 1994. doi: 10.1063/1.358463.
- [33] A.R. Verma and P. Krishna, editors. *Polymorphism and Polytypism in Crystals*. John Wiley & Sons, Inc., New York, 1966. doi: 10.1063/1.3034193.
- [34] E.G. Acheson. Production of artificial crystalline carbonaceous materials, carborundum, 1892. English Patent No. 17911.
- [35] H.J. Round. A note on carborundum. *Electr. World*, 19:309, 1907.
- [36] J.A. Lely. Darstellung von einkristallen von siliziumcarbid und beherrschung von art und menge der eingebauten verunreinigungen. *Ber. Dtsch. Keram. Ges.*, 32:229, 1955.
- [37] J.R. O'Connor and J. Smiltens, editors. *Silicon Carbide – A High Temperature Semiconductor*. Pergamon Press, 1960.
- [38] R.C. Marshall, J.W. Jr. Faust, and C.E. Ryan. *Silicon Carbide 1973*. University of South Carolina Press, 1974.
- [39] Tsunenobu Kimoto and James A. Cooper. *Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices, and Applications*. Wiley-IEEE Press, Singapore, 2014. doi: 10.1002/9781118313527.
- [40] Y.M. Tairov and V.F. Tsvetkov. Investigation of growth processes of ingots of silicon carbide single crystals. *J. Cryst. Growth*, 43:209, 1978.
- [41] Y.M. Tairov and V.F. Tsvetkov. General principles of growing large-size single crystals of various silicon carbide polytypes. *J. Cryst. Growth*, 52:146, 1981.
- [42] R.F. Davis, Jr. Carter, C.H., and C.E. Hunter. Sublimation of silicon carbide to produce large, device quality single crystals of silicon carbide, 1995. US Patent No. Re 34,861.
- [43] G. Ziegler, P. Lanig, D. Theis, and C. Weurich. Single crystal growth of sic substrate material for blue light emitting diodes. *IEEE Trans. Electron. Devices*, 30:277–281, 1983. doi: 10.1109/T-ED.1983.21117.

- [44] M. Ikeda, T. Hayakawa, and S. Yamagiwa. Fabrication of 6h-sic light-emitting diodes by a rotation dipping technique: Electroluminescence mechanisms. *J. Appl. Phys.*, 50:8215–8225, 1979. doi: 10.1063/1.325920.
- [45] H. Matsunami, S. Nishino, and H. Ono. Iva-8 heteroepitaxial growth of cubic silicon carbide on foreign substrates. *IEEE Trans. Electron. Devices*, 28:1235–1236, 1981. doi: 10.1109/T-ED.1981.20556.
- [46] S. Nishino, A. Powell, and H.A. Will. Production of large-area single-crystal wafers of cubic sic for semiconductor devices. *Appl. Phys. Lett.*, 42:460, 1983.
- [47] N. Kuroda, K. Shibahara, and W.S. Yoo. Step controlled vpe growth of sic single crystals at low temperatures. In *Extended Abstracts, 19th Conference on Solid State Devices and Materials*, page 227, Tokyo, Japan, 1987.
- [48] H.S. Kong, H.J. Kim, and J.A. Edmond. Growth, doping, device development and characterization of cvd beta-sic epilayers on si(100) and alpha-sic(0001). *Mater. Res. Soc. Symp. Proc.*, 97:233, 1987.
- [49] A. Itoh, H. Akita, T. Kimoto, and H. Matsunami. Step-controlled epitaxy of 4h-sic and its physical properties. In *Silicon Carbide and Related Materials 1993*, page 59. IOP, 1994.
- [50] D.J. Larkin, P.G. Neudeck, J.A. Powell, and L.G. Matus. Site-competition epitaxy for superior silicon carbide electronics. *Appl. Phys. Lett.*, 65:1659, 1994.
- [51] O. Kordina, C. Hallin, and R.C. Glass. A novel hot-wall cvd reactor for sic epitaxy. In *Silicon Carbide and Related Materials 1993*, page 41. IOP, 1994.
- [52] C.S. Schneer. Polymorphism in one dimension. *Acta Crystallogr.*, 8:279, 1955.
- [53] C. Cheng, R.J. Needs, and V. Heine. Inter-layer interactions and the origin of sic polytypes. *J. Phys. C*, 21:1049, 1988.
- [54] P.J.H. Denteneer and W. van Haeringen. Ground-state properties of polytypes of silicon carbide. *Phys. Rev. B*, 33:2831, 1986.
- [55] G.R. Fisher and P. Barnes. Towards a unified view of polytypism in silicon carbide. *Philos. Mag. B*, 61:217, 1990.
- [56] V. Heine, C. Cheng, and R.J. Needs. The preference of silicon carbide for growth in the metastable cubic form. *J. Am. Ceram. Soc.*, 74:2630, 1991.
- [57] W.S. Yoo and H. Matsunami. Growth simulation of sic polytypes and application

- to dpb-free 3c-sic on alpha-sic substrates. In *Amorphous and Crystalline Silicon Carbide IV*, page 66. Springer-Verlag, 1992.
- [58] W.F. Knippenberg. Growth phenomena in silicon carbide. *Philips Res. Rep.*, 18:161, 1963.
 - [59] W.S. Yoo and H. Matsunami. Solid-state phase transformation in cubic silicon carbide. *Jpn. J. Appl. Phys.*, 30:545, 1991.
 - [60] A. Itoh, H. Akita, T. Kimoto, and H. Matsunami. High-quality 4h-sic homoepitaxial layers grown by step-controlled epitaxy. *Appl. Phys. Lett.*, 65:1400, 1994.
 - [61] T. Kimoto, A. Itoh, and H. Akita. Step-controlled epitaxial growth of α -sic and application to high-voltage schottky rectifiers. In *Compound Semiconductors – 1994*, page 437. IOP, 1995.
 - [62] R. Raghunathan, D. Alok, and B.J. Baliga. High voltage 4h-sic schottky barrier diodes. *IEEE Electron Device Lett.*, 16:226, 1995.
 - [63] A. Itoh, T. Kimoto, and H. Matsunami. High-performance of high-voltage 4h-sic schottky barrier diodes. *IEEE Electron Device Lett.*, 16:280, 1995.
 - [64] O. Kordina, J.P. Bergman, C. Hallin, and E. Janzen. The minority carrier lifetime of n-type 4h- and 6h-sic epitaxial layers. *Appl. Phys. Lett.*, 69:679, 1996.
 - [65] J. Tan, J.A. Jr. Cooper, and M.R. Melloch. High-voltage accumulation-layer umosfets in 4h-sic. *IEEE Electron Device Lett.*, 19:467, 1998.
 - [66] J.A. Jr. Cooper, M.R. Melloch, and R. Singh. Status and prospects for sic power mosfets. *IEEE Trans. Electron Devices*, 49:658, 2002.
 - [67] S. Nishino, H. Suhara, H. Ono, and H. Matsunami. Epitaxial growth and electric characteristics of cubic sic on silicon. *J. Appl. Phys.*, 61:4889, 1987.
 - [68] M. Yamanaka, H. Daimon, and E. Sakuma. Temperature dependence of electrical properties of n-and p-type 3c-sic. *J. Appl. Phys.*, 61:599, 1987.
 - [69] W. J. Choyke and L. Patrick. Exciton recombination radiation and phonon spectrum of 6H SiC. *Phys. Rev.*, 127:1868, 1962.
 - [70] M. Ikeda, H. Matsunami, and T. Tanaka. Site effect on the impurity levels in 4H, 6H, and 15R SiC. *Phys. Rev. B*, 22:2842, 1980.
 - [71] W. Suttrop, G. Pensl, W. J. Choyke, et al. Hall effect and infrared absorption

- measurements on nitrogen donors in 6H-silicon carbide. *J. Appl. Phys.*, 72:3708, 1992.
- [72] M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur. *Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, SiC, SiGe*. Wiley, 2001. ISBN 978-0470350249.
- [73] Yi Zheng. *Nonlinear Integrated 4H-SiC-on-Insulator Platform*. PhD thesis, Technical University of Denmark, 2020.
- [74] S. Wang, M. Zhan, G. Wang, H. Xuan, W. Zhang, C. Liu, C. Xu, Y. Liu, Z. Wei, and X. Chen. 4h-sic: A new nonlinear material for midinfrared lasers. *Laser & Photonics Reviews*, 7:831–838, 2013.
- [75] D. Franta, D. Nečas, L. Zajíčková, I. Ohlídal, and J. Stuchlík. Advanced modeling for optical characterization of amorphous hydrogenated silicon films. *Thin Solid Films*, 541:12–16, 2013. doi: 10.1016/j.tsf.2013.04.129.
- [76] H. H. Li. Refractive index of silicon and germanium and its wavelength and temperature derivatives. *J. Phys. Chem. Ref. Data*, 9(3):561–658, 1980. doi: 10.1063/1.555624.
- [77] Giuliana Faggio, Giacomo Messina, Andrea Gnisci, Angela Malara, and Sandro Rao. Thermo-optic effect of 4h-silicon carbide at fiber-optic communication wavelengths. In *Photonics & Electromagnetics Research Symposium (PIERS — SPRING)*, pages 658–662, Rome, Italy, June 2019. doi: 10.1109/PIERS-Spring46901.2019.9017327.
- [78] Jessica Steinlechner, Christoph Krüger, Nico Lastzka, Sebastian Steinlechner, Alexander Khalaidovski, and Roman Schnabel. Optical absorption measurements on crystalline silicon test masses at 1550 nm. *Classical and Quantum Gravity*, 30(9):095007, 2013. doi: 10.1088/0264-9381/30/9/095007.
- [79] R. A. Soref and B. R. Bennett. Electrooptical effects in silicon. *IEEE Journal of Quantum Electronics*, QE-23(1):123–129, Jan 1987. doi: 10.1109/JQE.1987.1073206.
- [80] Yi Zheng, Minhao Pu, Ailun Yi, Bingdong Chang, Tiangui You, Kai Huang, Ayman N. Kamel, Martin R. Henriksen, Asbjørn A. Jørgensen, Xin Ou, and Haiyan Ou. High-quality factor, high-confinement microring resonators in 4h-silicon carbide-on-insulator. *Opt. Express*, 27(9):13053–13060, 2019. doi: 10.1364/OE.27.013053.
- [81] Mark A. Foster, Alexander C. Turner, Michal Lipson, and Alexander L. Gaeta.

- Broad-band optical parametric gain on a silicon photonic chip. *Nature*, 441(7096): 960–963, 2006. doi: 10.1038/nature04837.
- [82] Hiroaki Sato, Makoto Abe, Ichiro Shoji, Jun Suda, and Takashi Kondo. Accurate measurements of second-order nonlinear optical coefficients of 6h and 4h silicon carbide. *Journal of the Optical Society of America B*, 26(10):1892–1896, 2009. doi: 10.1364/JOSAB.26.001892.
- [83] M. Dinu, F. Quochi, and H. Garcia. Third-order nonlinearities in silicon at telecom wavelengths. *Applied Physics Letters*, 82(18):2954–2956, 2003. doi: 10.1063/1.1571665.
- [84] Ruixuan Wang, Jingwei Li, Lutong Cai, and Qing Li. Investigation of the electro-optic effect in high-q 4h-sic microresonators. *Opt. Lett.*, 48:1482–1485, 2023. doi: 10.1364/OL.482844.
- [85] Ailun Yi, Chengli Wang, Liping Zhou, Yifan Zhu, Min Zhou, Shibin Zhang, Tianguai You, Jiayang Zhang, and Xin Ou. Silicon carbide for integrated photonics. *Light Sci. Appl.*, 9(3):031302, 2022. doi: 10.1063/5.0079649.
- [86] Yue Yang, Sydney Taylor, Hassan Alshehri, and Liping Wang. Wavelength-selective and diffuse infrared thermal emission mediated by magnetic polaritons from silicon carbide metasurfaces. *Appl. Phys. Lett.*, 111:051904, 2017. doi: 10.1063/1.4996865.
- [87] X. Wu, T. Fan, T.G. Allen, S. Abdollahramezani, A.A. Eftekhari, M. Bosi, J.W. Perry, and A. Adibi. Nonvolatile tunable integrated mid-infrared gst-sic metasurfaces. In *2018 IEEE Photonics Conference (IPC)*, pages 1–2, 2018. doi: 10.1109/IPCon.2018.8527263.
- [88] Tianren Fan, Hesam Moradinejad, Xi Wu, Ali A. Eftekhari, and Ali Adibi. High-q integrated photonic microresonators on 3c-sic-on-insulator (sicoi) platform. *Opt. Express*, 26:25814–25826, 2018.
- [89] Alexander L Crook, Christopher P Anderson, Kevin C Miao, Alexandre Bourassa, Hope Lee, Sam L Bayliss, David O Bracher, Xingyu Zhang, Hiroshi Abe, Takeshi Ohshima, et al. Purcell enhancement of a single silicon carbide color center with coherent spin control. *Nano letters*, 20(5):3427–3434, 2020.
- [90] Bong-Shik Song, Takashi Asano, Seungwoo Jeon, Heungjoon Kim, Changxuan Chen, Dongyeon Daniel Kang, and Susumu Noda. Ultrahigh-q photonic crystal nanocavities based on 4h silicon carbide. *Optica*, 6:991–995, 2019.
- [91] S. Castelletto, B. Johnson, V. Ivády, N. Stavrias, T. Umeda, A. Gali, and

- T. Ohshima. A silicon carbide room-temperature single-photon source. *Nature Mater*, 13:151–156, 2014. doi: 10.1038/nmat3806.
- [92] Greg Calusine, Alberto Politi, and David D. Awschalom. Silicon carbide photonic crystal cavities with integrated color centers. *Appl. Phys. Lett.*, 105(1):011123, 2014. doi: 10.1063/1.4890083.
- [93] Xiyuan Lu, Jonathan Y. Lee, Philip X.-L. Feng, and Qiang Lin. High q silicon carbide microdisk resonator. *Appl. Phys. Lett.*, 104(18):181103, 2014. doi: 10.1063/1.4875707.
- [94] Andrew P. Magyar, David Bracher, Jonathan C. Lee, Igor Aharonovich, and Evelyn L. Hu. High quality sic microdisk resonators fabricated from monolithic epilayer wafers. *Appl. Phys. Lett.*, 104(5):051109, 2014. doi: 10.1063/1.4863932.
- [95] Jonathan Y. Lee, Xiyuan Lu, and Qiang Lin. High-q silicon carbide photonic-crystal cavities. *Appl. Phys. Lett.*, 106(4):041106, 2015. doi: 10.1063/1.4906923.
- [96] Bong-Shik Song, Shota Yamada, Takashi Asano, and Susumu Noda. Demonstration of two-dimensional photonic crystals based on silicon carbide. *Opt. Express*, 19:11084–11089, 2011. doi: 10.1364/OE.19.011084.
- [97] W. G. Spitzer, D. A. Kleinman, and C. J. Frosch. Infrared properties of cubic silicon carbide films. *Phys. Rev.*, 113:133–136, Jan 1959. doi: 10.1103/PhysRev.113.133. URL <https://link.aps.org/doi/10.1103/PhysRev.113.133>.
- [98] Xiyuan Lu, Jonathan Y. Lee, Philip X.-L. Feng, and Qiang Lin. Silicon carbide microdisk resonator. *Opt. Lett.*, 38:1304–1306, 2013.
- [99] Marina Radulaski, Thomas M. Babinec, Sonia Buckley, Armand Rundquist, J. Provine, Kassem Alassaad, Gabriel Ferro, and Jelena Vučković. Photonic crystal cavities in cubic (3c) polytype silicon carbide films. *Opt. Express*, 21:32623–32629, 2013. doi: 10.1364/OE.21.032623.
- [100] Xiyuan Lu, Jonathan Y. Lee, Steven Rogers, and Qiang Lin. Optical kerr nonlinearity in a high-q silicon carbide microresonator. *Opt. Express*, 22:30826–30832, 2014. doi: 10.1364/OE.22.030826.
- [101] Francesco Martini and Alberto Politi. Four wave mixing in 3c sic ring resonators. *Appl. Phys. Lett.*, 112(25):251110, 2018. doi: 10.1063/1.5034456.
- [102] C. Babin, R. Stohr, N. Morioka, T. Linkewitz, T. Steidl, R. Wornle, D. Liu, E. Hesselmeier, V. Vorobyov, A. Denisenko, M. Hentschel, C. Gobert, P. Berwian, G.V.

- Astakhov, W. Knolle, S. Majety, P. Saha, M. Radulaski, N.T. Son, J. Ul-Hassan, F. Kaiser, and J. Wrachtrup. Fabrication and nanophotonic waveguide integration of silicon carbide colour centres with preserved spin-optical coherence. *Nat. Mater.*, 21:67, 2022. doi: 10.1038/s41563-021-01148-3.
- [103] Alexander Lohrmann, Timothy James Karle, Vikas Kanayalal Sewani, Arne Laucht, Matteo Bosi, Marco Negri, Stefania Castelletto, Steven Prawer, Jeffrey Colin McCallum, and Brett Cameron Johnson. Integration of single-photon emitters into 3c-sic microdisk resonators. *ACS Photonics*, 4(3):462–468, 2017. doi: 10.1021/acsp Photonics.6b00913.
- [104] M. Bosi, G. Attolini, M. Negri, C. Ferrari, E. Buffagni, C. Frigeri, M. Calicchio, B. Pécz, F. Riesz, I. Cora, Z. Osvath, L. Jiang, and G. Borionetti. Defect structure and strain reduction of 3c-sic/si layers obtained with the use of buffer layer and methyltrichlorosilane addition. *CrystEngComm*, 18:2770–2779, 2016. doi: 10.1039/C6CE00280C.
- [105] F.F. Yan, A.L. Yi, J.F. Wang, Q. Li, P. Yu, J.X. Zhang, A. Gali, Y. Wang, J.S. Xu, X. Ou, C.F. Li, and G.C. Guo. Room-temperature coherent control of implanted defect spins in silicon carbide. *npj Quant. Inform.*, 6:38, 2020. doi: 10.1038/s41534-020-0270-8.
- [106] J.F. Wang, F.F. Yan, Q. Li, Z.H. Liu, H. Liu, G.P. Guo, L.P. Guo, X. Zhou, J.M. Cui, J. Wang, Z.Q. Zhou, X.Y. Xu, J.S. Xu, C.F. Li, and G.C. Guo. Coherent control of nitrogen-vacancy center spins in silicon carbide at room temperature. *Phys. Rev. Lett.*, 124:223601, 2020. doi: 10.1103/PhysRevLett.124.223601.
- [107] Michael J. Burek, Nathalie P. de Leon, Brendan J. Shields, Birgit J. M. Hausmann, Yiwen Chu, Qimin Quan, Alexander S. Zibrov, Hongkun Park, Mikhail D. Lukin, and Marko Lončar. Free-standing mechanical and photonic nanostructures in single-crystal diamond. *Nano Letters*, 12(12):6084–6089, 2012. doi: 10.1021/nl302541e.
- [108] B.S. Song, S. Jeon, H. Kim, D.D. Kang, T. Asano, and S. Noda. *Appl. Phys. Lett.*, 113:231106, 2018.
- [109] S. Majety, V.A. Norman, L. Li, M. Bell, P. Saha, and M. Radulaski. *J. Phys. Photonics*, 3:034008, 2021.
- [110] Masahiko Ito, Liutauras Storasta, and Hidekazu Tsuchida. Development of 4h-sic epitaxial growth technique achieving high growth rate and large-area uniformity. *Appl. Phys. Express*, 1:015001, 2008. doi: 10.1143/APEX.1.015001.

- [111] Peng Cong and Darrin J. Young. Single crystal 6h-sic mems fabrication based on smart-cut technique. *J. Micromech. Microeng.*, 15:2243, 2005. doi: 10.1088/0960-1317/15/12/005.
- [112] V. P. Amarasinghe, L. Wielunski, A. Barcz, L. C. Feldman, and G. K. Celler. Properties of h+ implanted 4h-sic as related to exfoliation of thin crystalline films. *ECS J. Solid State Sci. Technol.*, 3:P37, 2014. doi: 10.1149/2.001404jss.
- [113] L. Di Cioccio, F. Letertre, Y. Le Tiec, A.M. Papon, C. Jaussaud, and M. Bruel. Silicon carbide on insulator formation by the smart-cut® process. *Materials Science and Engineering: B*, 46:349–356, 1997. doi: 10.1016/S0921-5107(96)02004-1.
- [114] M. Ionescu, A. Deslandes, R. Holmes, M.C. Guenette, I. Karatchevtseva, and G.R. Lumpkin. Effect of annealing upon retention of he and h in irradiated sic. *Mater. Sci. Forum*, 879:810, 2017. doi: 10.4028/www.scientific.net/MSF.879.810.
- [115] B.S. Li, Z.G. Wang, and J.F. Jin. Implantation temperature and thermal annealing behavior in h2+-implanted 6h-sic. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 316:239–244, 2013. doi: 10.1016/j.nimb.2013.09.016.
- [116] Ailun Yi, Yi Zheng, Hao Huang, Jiajie Lin, Youquan Yan, Tiangui You, Kai Huang, Shibin Zhang, Chen Shen, Min Zhou, Wei Huang, Jiaxiang Zhang, Shengqiang Zhou, Haiyan Ou, and Xin Ou. Wafer-scale 4h-silicon carbide-on-insulator (4h-sicoi) platform for nonlinear integrated optical devices. *Optical Materials*, 107:109990, 2020. doi: 10.1016/j.optmat.2020.109990.
- [117] Jaime Cardenas, Mengjie Yu, Yoshitomo Okawachi, Carl B. Poitras, Ryan K. W. Lau, Avik Dutt, Alexander L. Gaeta, and Michal Lipson. Optical nonlinearities in high-confinement silicon carbide waveguides. *Opt. Lett.*, 40:4138–4141, 2015. doi: 10.1364/OL.40.004138.
- [118] T. Höchbauer, A. Misra, M. Nastasi, and J. W. Mayer. Physical mechanisms behind the ion-cut in hydrogen implanted silicon. *J. Appl. Phys.*, 92(5):2335–2342, 2002. doi: 10.1063/1.1494844.
- [119] L. Zhang and B.S. Li. Study of surface exfoliation on 6h-sic induced by h2+ implantation. *Physica B: Condensed Matter*, 508:104–111, 2017. doi: 10.1016/j.physb.2016.12.027.
- [120] M. A. Guidry, K. Y. Yang, D. M. Lukin, A. Markosyan, J. Yang, M. M. Fejer, and

- J. Vučković. Optical parametric oscillation in silicon carbide nanophotonics. *Optica*, 7(9):1139–1142, 2020. doi: 10.1364/OPTICA.394138.
- [121] S. D. Ko, B. Hamelin, J. Yang, and F. Ayazi. In *2018 IEEE Micro Electro Mechanical Systems (MEMS)*, pages 996–999, 2018.
- [122] Keith Powell, Amirhassan Shams-Ansari, Smit Desai, Mitchell Austin, Jiangdong Deng, Neil Sinclair, Marko Lončar, and Xiaoke Yi. High-q suspended optical resonators in 3c silicon carbide obtained by thermal annealing. *Opt. Express*, 28:4938–4949, 2020. doi: 10.1364/OE.381601.
- [123] T. Fan, X. Wu, A.A. Eftekhar, M. Bosi, H. Moradinejad, E.V. Woods, and A. Adibi. *Opt. Lett.*, 45:153, 2020.
- [124] Yi Zheng, Ailun Yi, Minhao Pu, Bingdong Chang, Tiangui You, Kai Huang, Xin Ou, and Haiyan Ou. High-confinement, high-q microring resonators on silicon carbide-on-insulator (sicoi). In *2018 Asia Communications and Photonics Conference (ACP)*, pages 1–3, Hangzhou, China, 2018. doi: 10.1109/ACP.2018.8595751.
- [125] Jaime Cardenas, Mian Zhang, Christopher T. Phare, Shreyas Y. Shah, Carl B. Poitras, Biswajeet Guha, and Michal Lipson. High q sic microresonators. *Opt. Express*, 21:16882–16887, 2013. doi: 10.1364/OE.21.016882.
- [126] M. A. Guidry, D. M. Lukin, K. Y. Yang, R. Trivedi, and J. Vučković. Quantum optics of soliton microcombs. *Nature Photonics*, 16(1):52–58, 2022. doi: 10.1038/s41566-021-00901-z.
- [127] P. Xing, D. Ma, K. J. A. Ooi, J. W. Choi, A. M. Agarwal, and D. Tan. Silicon carbide nonlinear integrated photonics. *ACS Photonics*, 6:1162–, 2019. doi: 10.1021/acsp Photonics.9b00123.
- [128] X. Wu, T. Fan, A. A. Eftekhar, A. H. Hosseinnia, and A. Adibi. Low-loss 4h-sic waveguides for integrated photonics. *Opt. Lett.*, 46:4316–, 2021. doi: 10.1364/OL.434321.
- [129] A. W. Snyder and J. D. Love. *Optical Waveguide Theory*. Chapman and Hall, London, 1983.
- [130] Chin-Ping Yu and Hung-Chun Chang. Yee-mesh-based finite difference eigenmode solver with pml absorbing boundary conditions for optical waveguides and photonic crystal fibers. *Optics Express*, 12(25):6165–6177, 2004. doi: 10.1364/OPEX.12.006165.

- [131] Zhaoming Zhu and Thomas G. Brown. Full-vectorial finite-difference analysis of microstructured optical fibers. *Optics Express*, 10(17):853–864, 2002. doi: 10.1364/OE.10.000853.
- [132] Miloš Popović. *Theory and Design of High-Index-Contrast Microphotonic Circuits*. Phd thesis, Massachusetts Institute of Technology, February 2008.
- [133] Dmitry M. Lukin, Connor Dory, Michael A. Guidry, Kai Y. Yang, Rahul Trivedi, Matt Radulaski, and Jelena Vučković. 4h-silicon-carbide-on-insulator for integrated quantum and nonlinear photonics. *Nature Photonics*, 14:330–334, 2020. doi: 10.1038/s41566-019-0556-6.
- [134] Xiaodong Shi, Yaoqin Lu, Didier Chaussende, Karsten Rottwitt, and Haiyan Ou. Wet-oxidation-assisted chemical mechanical polishing and high-temperature thermal annealing for low-loss 4h-sic integrated photonic devices. *Materials*, 16(6): 2324, 2023. doi: 10.3390/ma16062324.
- [135] Xiaodong Shi, Jun Zhang, Weichen Fan, Yao Lu, Nan Peng, Karsten Rottwitt, and Haiyan Ou. Compact low-birefringence polarization beam splitter using vertical-dual-slot waveguides in silicon carbide integrated platforms. *Photonics Research*, 10(1):A8–A13, 2022. doi: 10.1364/PRJ.443543.
- [136] Xiaodong Shi, Yaoqin Lu, and Haiyan Ou. High-performance silicon carbide polarization beam splitting based on the asymmetric directional coupler for mode conversion. *Optics Letters*, 2023.
- [137] Yi Zheng, Ailun Yi, Chaochao Ye, Kresten Yvind, Han Zhang, Xin Ou, and Minhao Pu. Efficient second-harmonic generation in silicon carbide nanowaveguides. *ACS Photonics*, 12(9):4879–4885, 2025. doi: 10.1021/acsp Photonics.5c01636.
- [138] Ansys Innovation Space Forum. Negative waveguide loss, 2026. URL <https://innovationspace.ansys.com/forum/forums/topic/negative-waveguide-loss-2/>. Accessed: 2026-02-26.
- [139] Flexcompute Inc. Tidy3d learning center: Example library, 2026. URL <https://www.flexcompute.com/tidy3d/learning-center/example-library/>. Accessed: 2026-02-26.
- [140] Jean-Pierre Berenger. *Perfectly Matched Layer (PML) for Computational Electromagnetics*. Morgan & Claypool Publishers, 2007.
- [141] S. D. Gedney and B. Zhao. An auxiliary differential equation formulation for the

- complex-frequency shifted pml. *IEEE Transactions on Antennas and Propagation*, 58(3), 2010. doi: 10.1109/TAP.2009.2037765.
- [142] Zuyang Liu and Joyce K. S. Poon. Comparison of numerical fdtd and tidy3d for three-dimensional fdtd simulations of passive silicon photonic components. *Optica Continuum*, 4:2427–2451, 2025. doi: 10.1364/OPTCON.572107.
- [143] J.A. Woollam Co., Inc. VASE Ellipsometer Brochure. Technical report, J.A. Woollam Co., Inc., n.d.. URL <https://www.jawoollam.com/download/pdfs/vase-brochure.pdf>. Accessed: 2026-03-02.
- [144] J.A. Woollam Co., Inc. *Guide to Using WVASE: Spectroscopic Ellipsometry Data Acquisition and Analysis Software*. J.A. Woollam Co., Inc., Lincoln, NE, USA, n.d.. URL <https://www.jawoollam.com>. Accessed: 2026-03-02.
- [145] Rasheed MA Azzam, Nicholas Mitchell Bashara, and Stanley S Ballard. *Ellipsometry and polarized light*, 1978.
- [146] P. T. B. Shaffer. Refractive index, dispersion, and birefringence of silicon carbide polytypes. *Applied Optics*, 10:1034–1036, 1971. doi: 10.1364/AO.10.001034.
- [147] Harry J. Levinson. *Principles of Lithography, Fourth Edition*. SPIE Press, Bellingham, WA, 2019. ISBN 9781510627604. doi: 10.1117/3.2525393.
- [148] Stefan Landis, editor. *Lithography*. John Wiley & Sons, Inc., 2013. ISBN 9781848212022. doi: 10.1002/9781118557662.
- [149] Costas Papadopoulos. Direct-write lithography approaches. In *Nanofabrication*, SpringerBriefs in Materials. Springer, Cham, 2016. doi: 10.1007/978-3-319-31742-7_3.
- [150] Heidelberg Instruments Mikrotechnik GmbH. μ MLA: The Tabletop Maskless Aligner — Datasheet. Technical report, Heidelberg Instruments, 2024. URL <https://heidelberg-instruments.com/wp-content/uploads/2024/04/Heidelberg-Instruments-μMLA-Datasheet.pdf>. Accessed: 2026-03-01.
- [151] MicroChemicals GmbH. AZ 15nXT Series — Technical Data Sheet. Technical report, MicroChemicals GmbH, 2023. URL https://www.microchemicals.com/dokumente/datenblaetter/tds/merck/en/tds_az_15nxt_series.pdf. Accessed: 2026-03-01.
- [152] Koutarou Kawahara, Michael Krieger, Jun Suda, and Tsunenobu Kimoto. Deep

- levels induced by reactive ion etching in n- and p-type 4h-sic. *Journal of Applied Physics*, 108(2):023706, 2010. doi: 10.1063/1.3460636.
- [153] Toru Hiyoshi, Tsutomu Hori, Jun Suda, and Tsunenobu Kimoto. Simulation and experimental study on the junction termination structure for high-voltage 4h-sic pin diodes. *IEEE Transactions on Electron Devices*, 55(8):1841–1846, 2008. doi: 10.1109/TED.2008.926643.

A | Waveguide Modal Quantities

The modal quantities used in this study are defined within the Lumerical MODE eigenmode solver as follows. The effective refractive index is obtained from the phase velocity relation and is defined as $n_{\text{eff}} = c/v = \beta/k_0$, where β denotes the modal propagation constant and k_0 is the free-space wavevector. In contrast to the bulk refractive index, the effective index incorporates geometric confinement and modal field distribution effects. For guided modes, its value is bounded between the refractive index of the waveguide core and that of the surrounding materials.

The modal propagation loss is derived from the imaginary part of the complex effective refractive index. For a mode propagating in the z -direction in a medium characterized by a complex refractive index $n + i\kappa$, the electric field amplitude decays exponentially along the propagation direction. The corresponding loss in dB/m is expressed as $\text{loss} = -20 \log_{10} (e^{-2\pi\kappa/\lambda_0})$, where κ represents the imaginary component of the refractive index and λ_0 is the free-space wavelength.

The TE polarization fraction is evaluated from the relative contribution of the transverse electric field components. For propagation along the z -direction, it is defined as

$$\frac{\int |E_x|^2 dx dy}{\int (|E_x|^2 + |E_y|^2) dx dy},$$

where values close to one indicate predominantly TE-polarized modes, while values approaching zero correspond to TM-like modes. This definition allows identification of quasi-TE and quasi-TM modes within the computed eigenmode set.

Finally, the effective mode area is calculated using the intensity-based definition

$$A_{\text{eff}} = \frac{(\int |E|^2 dA)^2}{\int |E|^4 dA},$$

which provides a quantitative measure of modal confinement without assuming a predefined field distribution. This definition is particularly relevant for evaluating nonlinear interaction strength in strongly confined waveguides.

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