

Review

Silicon Carbide Microring Resonators for Integrated Nonlinear and Quantum Photonics Based on Optical Nonlinearities

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Abstract: Silicon carbide (SiC) electronics has seen a rapid development in industry over the last two decades due to its capabilities in handling high powers and high temperatures while offering a high saturated carrier mobility for power electronics applications. With the increased capacity in producing large-size, single-crystalline SiC wafers, it has recently been attracting attention from academia and industry to exploit SiC for integrated photonics owing to its large bandgap energy, wide transparent window, and moderate second-order optical nonlinearity, which is absent in other centrosymmetric silicon-based material platforms. SiC with various polytypes exhibiting second- and third-order optical nonlinearities are promising for implementing nonlinear and quantum light sources in photonic integrated circuits. By optimizing the fabrication processes of the silicon carbide-on-insulator platforms, researchers have exploited the resulting high-quality-factor microring resonators for various nonlinear frequency conversions and spontaneous parametric down-conversion in photonic integrated circuits. In this paper, we review the fundamentals and applications of SiC-based microring resonators, including the material and optical properties, the device design for nonlinear and quantum light sources, the device fabrication processes, and nascent applications in integrated nonlinear and quantum photonics.

Keywords: silicon carbide-on-insulator; integrated nonlinear and quantum photonics; second harmonic generation; four-wave mixing; spontaneous parametric down-conversion



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1. Introduction

Silicon-based photonic platforms, commonly using silicon (Si) and silicon nitride (SiN), have become mature over the past two decades leveraging the well-established infrastructures for complementary metal-oxide-semiconductor (CMOS) fabrication processes. As Si and SiN are centrosymmetric materials, they possess only third-order optical nonlinearity ($\chi^{(3)}$), which is orders of magnitude weaker than the second-order optical nonlinearity ($\chi^{(2)}$) present in non-centrosymmetric materials. Based on $\chi^{(3)}$ nonlinearities, the four-wave mixing (FWM) process for frequency conversions and the spontaneous four-wave mixing (SFWM) process for parametric oscillations or photon pair generations are typically inefficient. Researchers have explored various methods to obtain $\chi^{(2)}$ nonlinearities through breaking the centrosymmetry in Si [1,2] and SiN [3–6]. However, Si has a relatively narrow bandgap energy of ~ 1.12 eV, which limits applications in the near-infrared wavelengths (>1.1 μm) due to linear absorption, while the loss is limited by two-photon absorption (TPA) in the optical communications C-band and O-band. A commonly adopted 450 nm wide Si waveguide with a typical propagation loss of ~ 1 dB/cm [7] is, however, not ideal for large-scale photonic integrated circuits (PICs), aiming for nascent optical neuromorphic computing and quantum applications. The SiN platform, which exhibits a low propagation loss and a moderate optical Kerr nonlinearity, is suitable for forming large-scale integrated linear and Kerr nonlinear PICs, such as for generating chip-based microcombs [8] and

solitons [9]. However, being an amorphous insulator, SiN does not intrinsically exhibit a second-order optical nonlinearity or other active functionalities including electro-optic effects. To enhance the active functionalities of SiN beyond optical Kerr nonlinearities, one needs to employ hybrid or heterogeneous integration with other material platforms [10–12].

To address the emerging needs of PICs for technological applications using chip-based efficient nonlinear frequency conversions and quantum light sources, along with low-loss passive optical components, researchers have recently conducted extensive investigations on various $\chi^{(2)}$ optical nonlinear platforms, including lithium niobate (LN) [13–15]; III-V compound semiconductors (e.g., aluminum nitride (AlN) [16–19], gallium nitride (GaN) [20,21], gallium arsenide (GaAs) [22,23], and aluminum gallium arsenide (AlGaAs) [24–27]); and SiC [28–30]. Among these material platforms, SiC is the only Si-based $\chi^{(2)}$ nonlinear material platform for operational wavelengths at the visible and near-infrared wavelengths. It is compatible with the CMOS process and can be manufactured in a large wafer size and single-crystalline. Therefore, SiC has been recognized as a promising integrated photonic platform.

1.1. Material and Optical Properties

SiC is a photonic material platform featuring moderate $\chi^{(2)}$ and $\chi^{(3)}$ optical nonlinearities, together with relatively low-loss waveguides. SiC is known as a so-called “third-generation” semiconductor (along with GaN) featuring a wide bandgap energy. The transparency window of SiC extends into the visible wavelengths. SiC eliminates the TPA in the telecommunications C-band and O-band to attain potentially low-loss waveguides.

The commonly investigated polytypes of SiC are in cubic (3C-SiC) and hexagonal (4H-SiC and 6H-SiC) crystal structures. Figure 1 shows schematics of the crystal structures of 3C-SiC, 4H-SiC, and 6H-SiC [31]. All polytypes of SiC possess non-centrosymmetric crystal structures. They exhibit $\chi^{(2)}$ optical nonlinearities and the Pockels effect that enable potentially efficient nonlinear frequency conversions, spontaneous parametric down-conversion (SPDC), and linear electro-optic modulation for integrated nonlinear and quantum photonics applications.

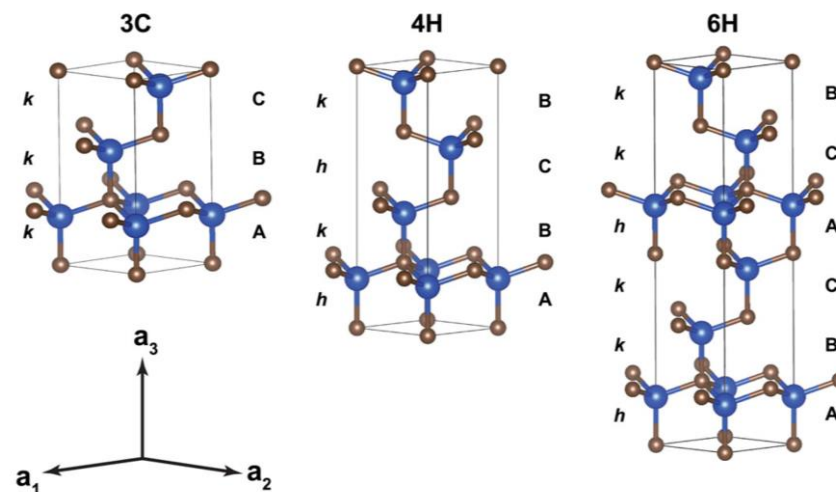


Figure 1. Schematics of the crystal structures of 3C-SiC, 4H-SiC, and 6H-SiC. Hexagonal lattice vectors a_1 and a_2 are at an angle of 120° . Blue and brown balls depict silicon and carbon atoms, respectively. The stacking sequence is indicated by symbols A, B, and C. For the hexagonal polytypes, primitive unit cells are shown. A hexagonal representation is used to illustrate 3C to facilitate the comparison with the hexagonal polytypes. Indices h and k indicate a Si-C bilayer sandwiched between those in the same adjacent stacking (i.e., a hexagonal bilayer) and a Si-C bilayer sandwiched between those in different stacking (i.e., a cubic bilayer), respectively [31].

Table 1 summarizes the material and optical properties of SiC and of various $\chi^{(2)}$ nonlinear material platforms. 4H- and 6H-SiC have the same point-group symmetry of

6 mm. They exhibit similar second-order nonlinear susceptibilities for type-0 and type-I phase matching. For type-0 phase matching, the polarizations of the three mixing light waves are the same. For type-I phase matching, the high-frequency wave and the two low-frequency waves have orthogonal polarizations. 3C-SiC has a cubic crystal structure with a point-group symmetry of $\bar{4}3m$ while having a smaller bandgap energy ($E_g = 2.36$ eV) compared to that of 4H-SiC ($E_g = 3.26$ eV) and of 6H-SiC ($E_g = 3.03$ eV) [32].

Table 1. Summary of the material and optical properties of various $\chi^{(2)}$ nonlinear platforms.

Material	Si	SiN	6H-SiC	4H-SiC	3C-SiC	LN	AlN [33]	Al _x Ga _{1-x} As ^a [27]
Point-group symmetry	m3m	N/A	6 mm	6 mm	$\bar{4}3m$	3 m	6 mm	$\bar{4}3m$
Transparency window (μm)	1.1~9 [34]	0.28~6.70 [35]	0.41~4 [36]	0.37~5.60 [37]	0.53~10 [38]	0.39~3.80 [39]	0.2~5	(0.57 for x = 1~0.90 for x = 0)~17
Refractive index	3.50 @ 1550 nm [40]	2.00 @ 1550 nm [41]	2.56(o)/2.60(e) @ 1550 nm 2.61(o)/2.65(e) @ 775 nm [37]		2.56 @ 1550 nm [42] 2.61 @ 775 nm [43]	2.21(o)/2.14(e) @ 1550 nm 2.26(o)/2.18(e) @ 775 nm [44]	2.12(o)/2.16(e) @ 1550 nm 2.14(o)/2.18(e) @ 775 nm [45]	3.18 @ 1550 nm 3.39 @ 775 nm (x = 0.41) [46]
Second-order nonlinear susceptibility ^b (pm/V)	N/A	N/A	$d_{33} = -12.5$ $d_{31} = 6.7$ $d_{15} = 6.5$ @ 1064 nm [47]	$d_{33} = -11.7$ $d_{31} = 6.5$ $d_{15} = 6.7$ @ 1064 nm [47]	$d_{36} = d_{14} = d_{25} = 17$ [48] d = 16.2 ^c [49]	$d_{31} = 4.5$ $d_{33} = 27$ @ 1064 nm [50]	$d_{33} = 2.35$ [51]	$d_{14} \in [39, 170]$ @ 1064 nm
Electro-optic effect (pm/V)	Carrier plasma dispersion	N/A	$r_{33} = 3.85$ $r_{31} = -2.30$ $r_{15} = -2.14$ @ 1064 nm [52] / Carrier plasma dispersion	$r_{33} = 0.02$ $r_{13} = 0.64$ @ 1550 nm [53] / Carrier plasma dispersion	$r = 1.5$ @ 1550 nm [49] / Carrier plasma dispersion	$r_{33} = 30.8$ $r_{13} = 8.6$ $r_{22} = 3.4$ [54]	$r_{33} = -0.59$ $r_{13} = 0.67$ @ 633 nm	$r_{14} = -(1.54 \pm 0.08)$ @ 1.52 μm [55]
Nonlinear refractive index, n ₂ (m ² /W)	6×10^{-18} @ 1550 nm [56]	3.1×10^{-19} (LPCVD) @ 1550 nm [57]	3.69×10^{-19} @ 780 nm [58]	$n_{2,\text{TM}} = (13.1 \pm 7.0) \times 10^{-19}$ $n_{2,\text{TE}} = (7 \pm 3) \times 10^{-19}$ @ 1550 nm [59]	$(5.31 \pm 0.04) \times 10^{-19}$ @ 1550 nm [60]	$\sim 10^{-19}$ @ 1064 nm [61]	2.3×10^{-19} @ 1550 nm	$\sim 1.5 \times 10^{-17}$ @ 1550 nm [62]
Phase matching method for χ ⁽²⁾	N/A	N/A	Birefringent phase matching, MPM	Birefringent phase matching, MPM	$\bar{4}$ -QPM, MPM	Birefringent phase matching, MPM, periodic poling-based quasi-PM	Birefringent phase matching, MPM	$\bar{4}$ -QPM, MPM
Thermo-optic coefficient (K ⁻¹)	1.86×10^{-4} @ 1550 nm [63]	2.45×10^{-5} @ 1550 nm [64]	6×10^{-5} @ 1550 nm [65]	4.94×10^{-5} @ 1550 nm [66]	2.92×10^{-5} [67]	o-wave: 6.9×10^{-5} e-wave: 22.4×10^{-5} @ 632 nm [68]	4.26×10^{-5} @ 1000 nm	2.67×10^{-4} @ 1000 nm [69]
Photorefractive effect	N/A	N/A	N/A	No [70]	No [71]	Yes [72]	Yes [73]	Yes [72]
Wafer form	Commercial 8" SOI wafers [74]	Deposition on 8" oxidized Si wafers [75]	6" wafers [76]	8" wafers [77]	Grown on 4" Si wafers [78]	Commercial 8" LNOI wafers [79]	Deposition on oxidized Si wafers [33]/6" AlN-on-Sapphire [80]	Grown on 6" III-V wafers [81]

^a Optical properties vary for $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with various chemical compositions. ^b In this table, the adopted relationship between d and $\chi^{(2)}$ is $d = \chi^{(2)}/2$. ^c Calculated value from the measured r reported in Ref. [49].

3C-SiC has non-zero nonlinear susceptibility tensor elements $d_{36} = d_{14} = d_{25}$ with a theoretical value of 17 pm/V [48], enabling type-II phase matching that imposes the two low-frequency waves having orthogonal polarizations. The SiC platforms offer a moderate nonlinear refractive index n_2 for Kerr phase shifts larger than that in SiN. Considering the potential needs of electro-optic modulation for reconfigurable photonic components, such as optical filters [82–85], in nonlinear and quantum photonic circuits, we can exploit the polytypes of SiC that exhibit both the Pockels effect and the carrier plasma dispersion effect. The drawbacks, however, are that, for the former, the electro-optic coefficient is small (see Table 1) for attaining a low-power modulation, while, for the latter, the carrier mobility is low [32] for attaining a high-speed modulation.

LN and AlN are two other wide-bandgap nonlinear photonic materials of broad interests. LN is the most adopted nonlinear/electro-optic photonic material owing to

its wide transparency window, large $\chi^{(2)}$, and large electro-optic coefficient (see Table 1). However, LN exhibits the undesirable photorefractive effect [15,72,86], which induces optical damage. The thin-film LN-on-insulator (LNOI) exhibits a lower power threshold and at a shorter wavelength [86] for optical damage than the bulk LN [87]. A Yale group [87] reported a significant photorefractive effect upon a low optical power of only ~ -20 dBm in a thin-film LN microring resonator with a silica top-cladding, which would compromise quantum photonic applications using the thin-film LN. Possible mitigations include the use of air-cladded devices, which would, however, compromise the use of integrated metal heaters for thermo-optic-controlled integrated nonlinear and quantum photonic circuits on this platform. The AlN platform also exhibits a photorefractive effect [73]. Its applications, however, could be limited by the small d_{33} .

$\text{Al}_x\text{Ga}_{1-x}\text{As}$ also attracts extensive interests due to its large $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities [27,62], together with a direct bandgap for $x < 0.45$, promising potentially fully integrated nonlinear and quantum photonic circuits with an on-chip electrically injected pump-laser source. However, $\text{Al}_x\text{Ga}_{1-x}\text{As}$ has a relatively narrow bandgap. Considering a pump wavelength of ~ 780 nm below the bandgap energy, we note that the presence of surface and bulk defect states could still result in a considerable propagation loss of tens of dB/cm [26].

1.2. Fabrication Technologies: State-of-the-Art and Opportunities

To develop PICs on the various SiC platforms, photonic structures with high optical confinement is necessary. One method is to exploit selective etching to form suspended optical structures, such as suspended waveguides or microcavities [60,67,88,89]. However, suspended structures over a large area are generally not desirable for large-scale PICs. Another method is using femtosecond laser direct-writing to pattern waveguides in bulk SiC crystal films, such as 6H-SiC [90,91] and 4H-SiC [92] films (by optically raising the refractive index of the SiC to form the waveguide core). The advantages of this method include high precision, capability for two-/three-dimensional (2D/3D) lithography, and compatibility with various materials, such as silica and silicon. However, the lithography efficiency of the laser direct-writing is low [93], which is not suitable for fabricating large-scale PICs.

The silicon carbide-on-insulator (SiCOI) is another platform to form highly confined SiC waveguides. Due to the commercially available 8" SiC wafers using physical vapor transport growth for 4H-SiC/6H-SiC [77] or using epitaxy technology for 3C-SiC on silicon substrates [78], wafer bonding and thinning techniques are necessary for attaining the SiCOI platforms. We briefly review three commonly adopted methods below.

1.2.1. The Ion-Cutting Technique for 4H-SiCOI and 6H-SiCOI

The ion-cutting process uses a high-dose hydrogen ion implantation and direct wafer bonding, which has been developed in the fabrication of silicon-on-insulator (SOI) wafers [94]. In 1997, Di Cioccio et al. first applied this method to form 4H-SiCOI and 6H-SiCOI [95] wafers for high-temperature microelectronics. Figure 2 schematically illustrates the fabrication process flow of the ion-cutting process for realizing SiCOI wafers [96]. The typical receiver wafer is an oxidized silicon wafer used as an under-cladding layer on a Si substrate. The SiC wafer is implanted with hydrogen ions at a typical dose of $10^{16} \text{ cm}^{-2} \sim 10^{17} \text{ cm}^{-2}$. The implantation energy is determined by the desired thickness of the SiC film. The two wafers are subsequently bonded using hydrophilic bonding, which requires hydrophilic, smooth, and clean surfaces for both wafers. Afterwards, a heat treatment with a temperature below 1100°C enables the bulk SiC to split from the bonded wafer. The bonding force needs to be strengthened by another thermal treatment (above 1100°C). Finally, chemical mechanical polishing (CMP) is performed to smoothen the wafer surface [96]. This technique achieves an efficient utilization of the SiC wafer, as one can reuse the remaining SiC wafer. This method enables an excellent uniformity of the SiC film thickness with a deviation of $\pm 0.2\%$ for a $1.1 \mu\text{m}$ thick transferred 4H-SiC layer [97].

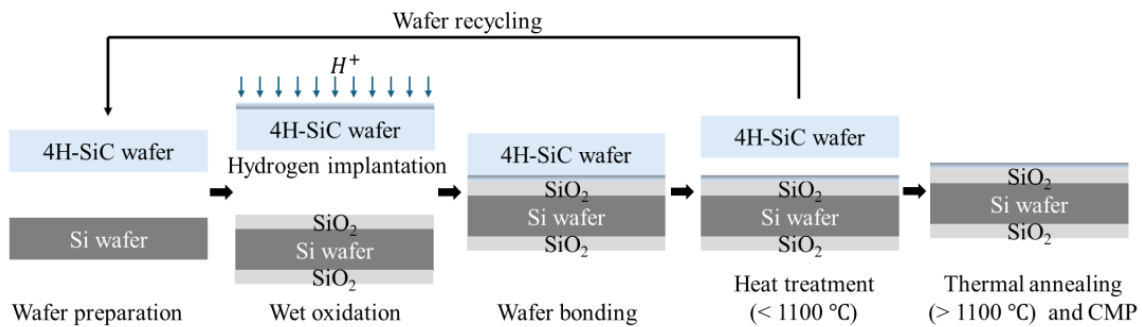


Figure 2. Schematics of the ion-cutting technique for the wafer bonding to attain the SiCOI platform.

In 2011, Bong-Shik Song et al. applied such an ion-cut 6H-SiCOI platform to realize photonic nanocavities [98] and demonstrated a second harmonic generation (SHG) [28] in a 6H-SiC photonic nanocavity. 6H-SiC, however, is not commonly used in electronics due to its low carrier mobility [99] compared to that of 4H-SiC. The latter has become the widely adopted and developed electronic material. As 4H-SiC and 6H-SiC show similar optical properties, researchers in photonics have been devoting more efforts to developing the 4H-SiCOI platform for PICs in recent years.

In 2018, researchers have demonstrated photonic crystal cavities for quantum technologies using the 4H-SiCOI platform fabricated by the ion-cutting technique [100]. In 2019, a DTU group demonstrated integrated nonlinear photonic sources in this platform. A drawback, however, is that the hydrogen ion implantation causes defects in the SiC layer, which increases the intrinsic loss of the SiC. To reduce the optical propagation loss, a high-temperature annealing is needed to recover the defects due to the ion implantation [66,101,102].

1.2.2. The Wafer Bonding and Thinning Methods

A technique to obtain a low-loss 4H-SiCOI platform is by means of wafer bonding and thinning processes that have been developed rapidly in recent years [30,103–106]. Figure 3 shows the schematic process flow of this technique. The surface of a 4" high-purity 4H-SiC wafer and a thermally oxidized Si wafer are both plasma-activated and directly bonded at room temperature. Thermal annealing is adopted to enhance the bonding strength. To obtain the desired thickness of a bonded SiC film, mechanical grinding is first applied to reduce the thickness of the SiC layer to sub-10 μm . After dicing the wafer, CMP and inductively coupled-plasma (ICP) reactive-ion etching (RIE) are applied to further reduce the thickness of the SiC layer to the target thickness [70]. One can readily adopt this versatile technique for bonding 4H-SiC with other under-cladding layers, such as AlN deposited on silicon substrates with slight modifications that are compatible with the fabrication process. Recently, Li et al. demonstrated the 4H-SiC-on-AlN with AlN replacing the typical silicon dioxide (SiO₂) under-cladding layer to overcome the poor thermal conductivity [107].

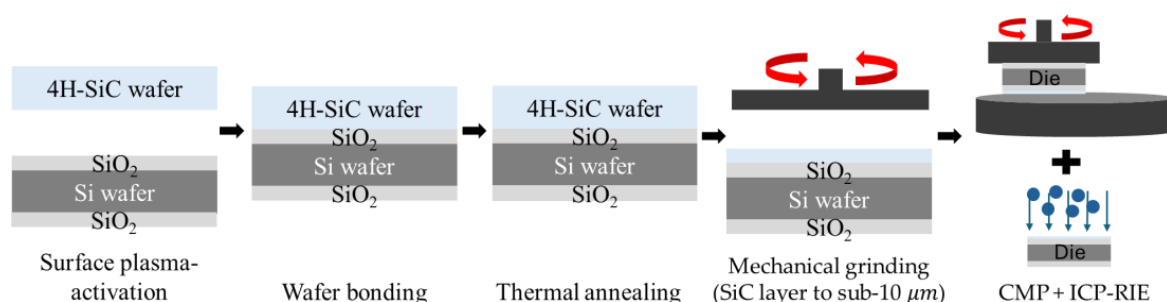


Figure 3. Schematics of the wafer bonding and thinning techniques for the fabrication of the 4H-SiCOI platform.

The commercially available 3C-SiC wafers are grown by epitaxy on Si substrates (NOVAsiC SA) [29,71,89,108–110]. Our group [71,110] recently developed the anodic bonding process for fabricating 3C-SiC on glass substrates. 3C-SiC-on-Si dies with a size of $1 \times 1 \text{ cm}^2$ are bonded on a 4-inch thermo-resist borosilicate glass substrate (Borofloat 33) with a 500 nm thick SiO_2 deposited on the top of the 3C-SiC using plasma-enhanced chemical vapor deposition. A wafer bonder (Karl Suss SB6) applies a high temperature and a voltage to move the oxygen ions across the interface from the glass side (cathode) to the 3C-SiC side (anode) (Figure 4a), generating a transient current during the formation of the bonding (Figure 4b). As shown in Figure 4c–e, we attained an almost 100% bonding yield (except near the edges) under the bonding conditions of 380 °C, 1000 V, and 540 N. Subsequently, the Si substrate is removed by using a 25% tetramethylazanium hydroxide solution heated to 80 °C, followed by using a mixed acid solution (nitric/hydrofluoric acid/acetic acid). We adopted a fluorine-based deep RIE process to etch the 3C-SiC layer into the target thickness. Our bonding process can be readily transferred to wafer-to-borosilicate glass wafer bonding. However, the borosilicate glass wafer is incompatible with the CMOS processes.

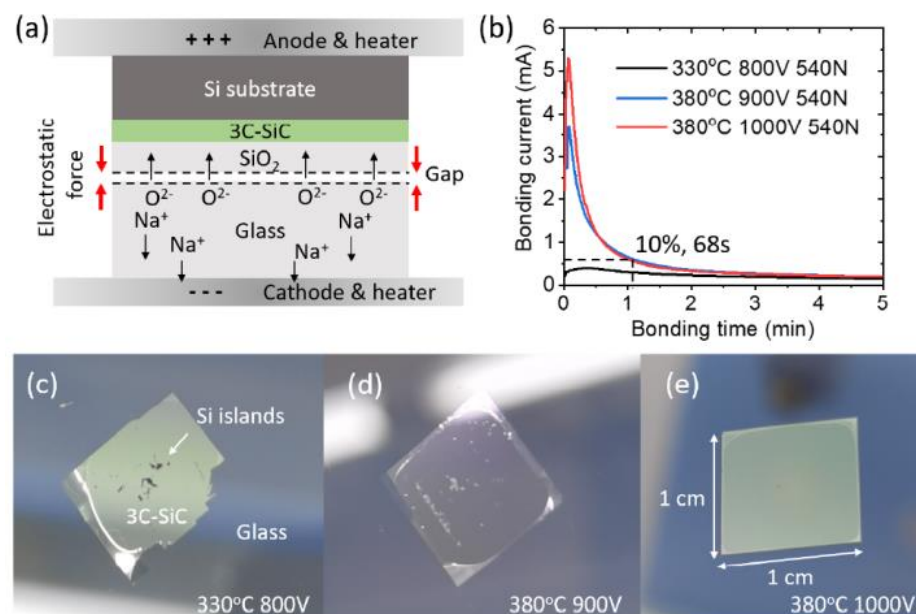


Figure 4. (a) Schematics of the anodic bonding process for fabricating a 3C-SiC film on a glass substrate. (b) Measured total bonding current flowing through four $1 \times 1 \text{ cm}^2$ 3C-SiC dies during the bonding process under different conditions. (c–e) Successfully transferred 3C-SiC films on glass substrates after removing the Si substrate under different process conditions. The remaining Si islands could be readily removed by wet etching using a mixed acid solution [71,110].

To bond SiC on a silicon substrate, one can adopt the hydrophilic bonding method. Figure 5 shows the schematic process flow for fabricating the 3C-SiCOI platform. A 3C-SiC-on-Si wafer is bonded on a wet-oxidized Si wafer by first depositing a 30 nm thick SiO_2 film on the 3C-SiC using atomic layer deposition (ALD). This interface layer introduces a high-quality surface with dangling -OH bonds enabling a high hydrophilic bonding strength. The bonding process is conducted at $\sim 300^\circ\text{C}$ to avoid the formation of cracks due to the different thermal expansion coefficients of the two materials. Finally, one can remove the Si substrate by using the Bosch dry-etching process and potassium hydroxide (KOH) wet etching [108].

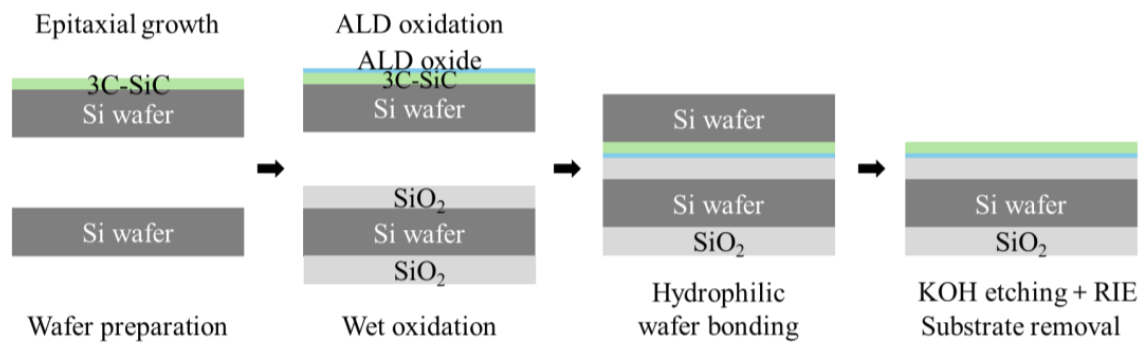


Figure 5. Schematics of the fabrication process flow of the 3C-SiCOI platform.

1.3. SiC Microring Resonators

On-chip microresonators have been commonly adopted to attain efficient nonlinear frequency conversions and photon pair generation over a compact footprint. Compared to whispering gallery (WG) microdisk cavities, microring resonators offer the flexibility in tailoring the waveguide dispersion to satisfy the phase matching condition for nonlinear frequency conversions and photon pair generation. The SiCOI platforms are suitable for fabricating microring resonators integrated with large-scale PICs. Recent advancements in the fabrication processes of the SiC platforms have significantly improved the waveguide propagation losses and thereby the intrinsic quality (Q_I) factor of the microring resonators.

In 2013, Cardenas et al. first demonstrated microring resonators with a Q_I factor of 14,100 on a suspended 3C-SiC platform through a silicon undercutting process [88]. In 2017, Martini et al. improved the Q factor to 24,000 on the same platform by removing the underlying substrate using two additional steps of electron-beam lithography [89]. In 2020, Powell et al. further enhanced the Q factor on this platform to 41,000 through thermal annealing in an O_2 atmosphere at 1100 °C for 2 h to minimize the optical propagation losses of the SiC waveguide to 7 dB/cm [111].

On the 3C-SiCOI platforms, Fan et al. in 2018 demonstrated microring resonators with a Q_I factor of 142,000, which significantly exceeded that of the suspended microring resonator on the 3C-SiC platform, by employing a combination of molecular bonding and RIE using an alumina hard mask [108]. In 2023, our group demonstrated on a 3C-SiCOI platform waveguide-coupled microring resonators with a loaded Q (Q_L) factor of 140,000 [71]. We could enhance the Q factor through reducing the scattering losses due to the remaining lattice defects in the epitaxial 3C-SiC film by using a thinner film that is more distant from the epitaxial interface. This is because the defect density in a 3C-SiC film introduced by the lattice mismatch during the epitaxy is gradually reduced in the film growth direction [110,112].

The 4H-SiCOI platform has shown remarkable advancements in achieving ultra-high- Q microring resonators. In 2019, Zheng et al. first reported a Q_I factor of 73,000 by using an ion-cutting process [113]. Lukin et al. demonstrated a Q factor of 78,000 in the same year based on a similar method [30]. In 2020, Guidry et al. demonstrated the Q_I factor exceeding 10^6 by using electron-beam lithography and a low-power SF_6 -based dry etching [105]. Later, multiple groups from Stanford University, Carnegie Mellon University, and from the Shanghai Institute of Microsystem and Information Technology independently demonstrated microring resonators with high Q factors exceeding 10^6 . In 2021, Guidry et al. realized 4H-SiCOI microring resonators with the highest Q factor of 5.6×10^6 reported to date for soliton microcombs [114]. The many demonstrations of high- Q microring resonators pave the way towards the SiCOI-based large-scale PICs and help accelerate the recent developments of efficient chip-based nonlinear and quantum light sources on the various SiCOI platforms.

2. Device Design for Efficient Nonlinear Frequency Conversions in Nonlinear Microring Resonators

2.1. Phase Matching Condition for 4H-SiC and 3C-SiC

The high-Q microring resonators enable a long interaction length between the nonlinear mixing optical fields and the medium over a compact footprint. The phase matching condition is required for efficient nonlinear frequency conversions. Here, we outline the key design considerations for nonlinear frequency conversions using both the $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities of the 4H-SiC and 3C-SiC platforms.

2.1.1. Dispersion Engineering for Degenerate-Pump FWM

FWM has been widely investigated in various $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear integrated photonic platforms. Specifically, chip-based FWM-generated Kerr combs have been widely investigated for applications towards precision metrology [115] and wavelength-division multiplexed parallel data processing and optical communications [116]. The SiCOI platforms possessing moderate $\chi^{(3)}$ nonlinearities are suitable for generating FWM. To attain an efficient FWM process, a large parametric gain is desired. The parametric gain for pump-degenerate FWM [117] is expressed as

$$g = \left[(2\gamma P_p)^2 - \left(\frac{\kappa}{2} \right)^2 \right]^{1/2}, \quad (1)$$

where γ is the effective nonlinearity, P_p is the pump power, and κ is the net phase mismatch. The effective nonlinearity $\gamma = \frac{n_2 \omega_p}{A_{eff} c}$, where n_2 is the nonlinear refractive index, ω_p is the angular frequency of the pump, A_{eff} is the effective mode area, and c is the speed of light in a vacuum. The net phase mismatch $\kappa = \Delta\beta + 2\gamma P_p$ comprises the waveguide wavevector mismatch between the signal (β_s), the idler (β_i), and the degenerate pump (β_p) components, given as $\Delta\beta = \beta_s + \beta_i - 2\beta_p$, and the cross-phase modulation $2\gamma P_p$.

From the Taylor expansion of $\beta(\omega)$ around ω_p , one obtains the second-order approximation $\Delta\beta \approx \beta_2 (\Delta\omega)^2$, where β_2 is the group velocity dispersion (GVD) at ω_p and $\Delta\omega$ is the angular frequency difference between the degenerate pump and the signal/idler (ω_s/ω_i), given as $\Delta\omega = \omega_p - \omega_i = \omega_s - \omega_p$, assuming $\omega_s > \omega_p > \omega_i$.

In the case that $\kappa = 0$, $\Delta\beta = -2\gamma P_p$, corresponding to an anomalous dispersion ($\beta_2 < 0$) at the pump frequency, the parametric gain g following Equation (1) reaches its maximum value of $2\gamma P_p$. Hence, dispersion engineering is essential to obtain an anomalous dispersion balancing the pump power-induced cross-phase modulation over a desirable bandwidth. A commonly adopted method for dispersion engineering is to modify the mode-field distribution by designing the waveguide geometry [116,118].

Here, we numerically simulate the waveguide dispersion of a 4H-SiCOI strip waveguide and a 3C-SiCOI ridge waveguide using the Lumerical finite element method (FEM) solver. Figure 6a shows the FEM-simulated mode-field amplitude distributions of the fundamental transverse-electric (TE₀₀) and transverse-magnetic (TM₀₀) modes in a 4H-SiCOI strip waveguide with a width W of 1 μm and a thickness T of 800 nm. Figure 6b shows the numerically simulated GVD of the TE₀₀ and TM₀₀ modes of the 4H-SiCOI waveguides with various T from 600 nm to 900 nm in a step of 100 nm and of the bulk material (based on the anisotropic Sellmeier equation [37]). The simulations show that the adopted 4H-SiCOI waveguide designs can attain an anomalous dispersion for both TE₀₀ and TM₀₀ modes from 1480 nm to 1620 nm.

Our numerical simulations for a 3C-SiCOI waveguide adopted a trapezoidal geometry following our fabricated waveguide cross-sections with a sidewall angle of 86°, a width of 1 μm , and varied film thicknesses, along with a slab thickness of 100 nm (to ensure bonding with the glass substrate underneath). Figure 6c shows the FEM-simulated mode-field amplitude distributions of the TE₀₀ and TM₀₀ modes. Figure 6d shows the numerically simulated GVD of the TE₀₀ and TM₀₀ modes of the 3C-SiCOI waveguides with various T from 600 nm to 900 nm in a step of 100 nm and of the bulk thin film (based on ellipsometry

measurements). Our simulations suggest that 3C-SiCOI can attain an anomalous dispersion for both TE_{00} and TM_{00} modes from 1480 nm to 1620 nm, though with a larger dependence on the waveguide film thickness, particularly in longer wavelengths compared to those of the 4H-SiCOI waveguides, as shown in Figure 6b.

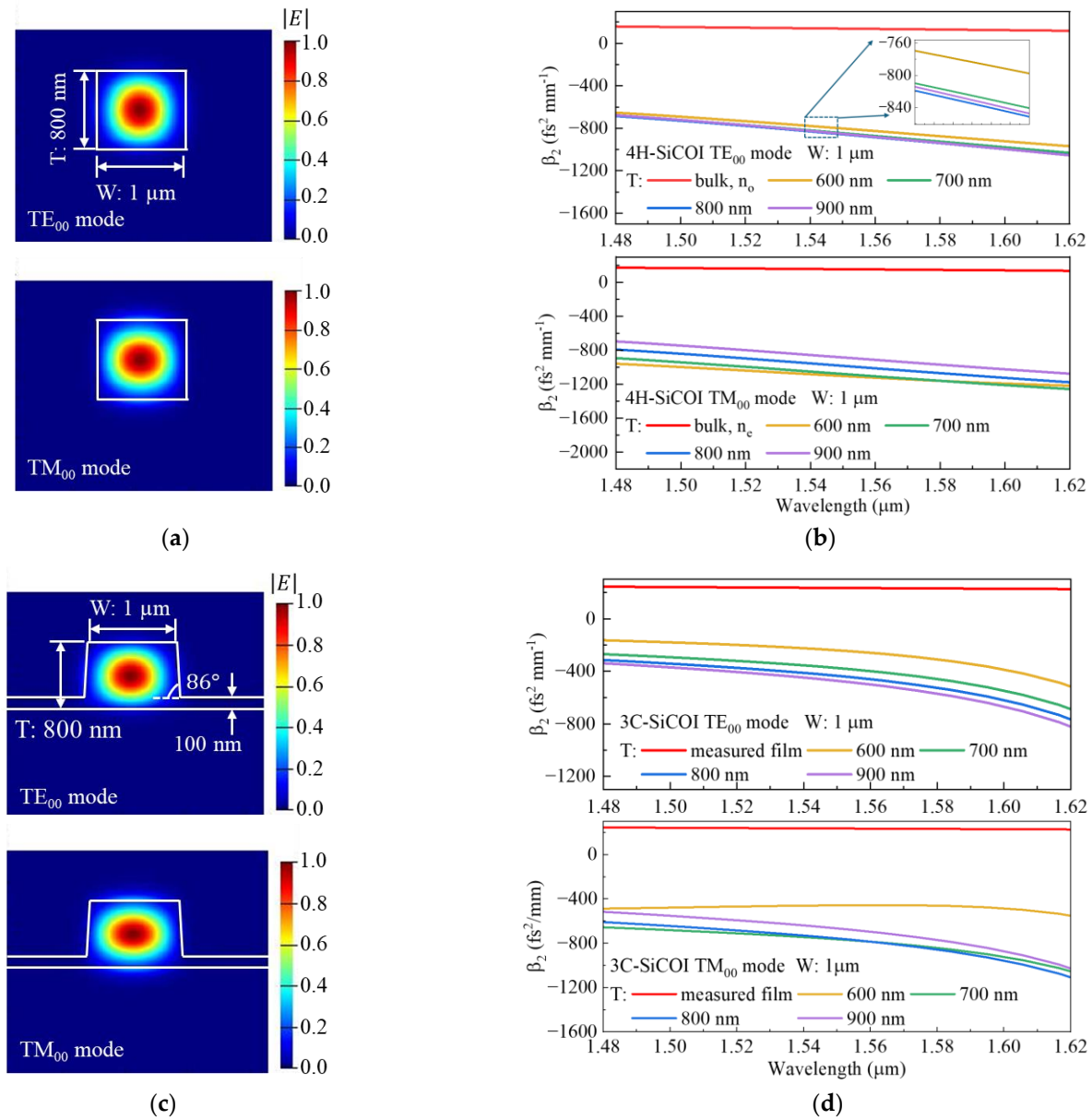


Figure 6. (a) Simulated 4H-SiCOI waveguide geometry and the mode-field amplitude distributions of the TE_{00} mode (top) and TM_{00} mode (bottom) in a $1 \mu\text{m}$ wide, 800 nm thick strip waveguide. (b) Simulated GVD of the bulk 4H-SiC calculated by adopting anisotropic Sellmeier equations [37] and of the TE_{00} mode (top) and TM_{00} mode (bottom) in the $1 \mu\text{m}$ width 4H-SiCOI waveguides with various waveguide thicknesses. (c) Simulated 3C-SiCOI waveguide geometry and the mode-field amplitude distributions of the TE_{00} mode (top) and TM_{00} mode (bottom) in a $1 \mu\text{m}$ wide, 700 nm thick ridge waveguide with a 100 nm thick slab. (d) Simulated GVD of the bulk 3C-SiC and of the TE_{00} (top) and TM_{00} (bottom) modes in $1 \mu\text{m}$ wide 3C-SiCOI waveguides with various waveguide thicknesses T .

2.1.2. Modal Phase Matching Condition for Silicon Carbide Platforms

For $\chi^{(2)}$ nonlinear frequency conversions, the phase matching condition is required over frequencies spanning typically an octave [117]. Using SHG as an example, we express the phase mismatch as

$$\Delta\beta = 2\beta_F - \beta_{SH}, \quad (2)$$

where β_F and β_{SH} are the waveguide wavevectors of the fundamental frequency and of the second harmonic frequency, respectively. The relationship between the SHG field amplitude A_{SH} and $\Delta\beta$ is expressed to first-order approximation without considering propagation losses of A_{SH} as

$$\frac{dA_{SH}}{dl} \propto \epsilon_0 \chi_{eff}^{(2)} A_F^2 \exp(i\Delta\beta \cdot l), \quad (3)$$

where A_F is the field amplitude of the fundamental frequency, l is the propagation length of the nonlinear mixing optical fields, ϵ_0 is the electric permittivity in a vacuum, and $\chi_{eff}^{(2)}$ is the effective second-order nonlinear susceptibility of the material considering the field and nonlinear polarization components. In the case that $\chi_{eff}^{(2)}$ is constant along the propagation direction, assuming A_F remains constant and $\Delta\beta = 0$, A_{SH} increases linearly with l . For the SHG, considering Equation (2) and the energy conservation, $2\omega_F = \omega_{SH}$, $\Delta\beta = 0$ imposes equal effective refractive indices at the fundamental and second harmonic frequencies, given as $n_F = n_{SH}$ [29].

It is, however, difficult to satisfy the phase matching condition with the same fundamental waveguide modes for both the fundamental and second harmonic frequencies. Polarization-dependent modal phase matching (MPM) is one of the commonly adopted methods for designing efficient $\chi^{(2)}$ nonlinear frequency conversions in integrated waveguides [119–121]. We adopted a higher-order waveguide mode of the second harmonic frequency to obtain a reduced effective refractive index while accounting for the material normal dispersion for satisfying the phase matching condition. To ensure a proper overlap between the two different orders of the waveguide mode, the third-order mode and the fundamental mode with the same even symmetry about the waveguide axis are commonly adopted for second harmonic and fundamental frequencies, respectively [29,119–121].

4H- and 6H-SiC own the non-zero second-order nonlinear susceptibility tensor elements d_{33} and d_{31} . To exploit the larger tensor element d_{33} , we only need the pump light polarization component to be along the [001] axis for type-0 phase matching. There is no fundamental difference in requirements between the SHG in straight waveguides and in microring resonators in the 4H-SiCOI and 6H-SiCOI platforms exploiting the tensor element d_{33} . As 4H- and 6H-SiC exhibit a positive birefringence, one can combine the MPM condition and the birefringence to compensate for the normal material dispersion. To utilize the d_{31} tensor element in the (001)-cut 4H-SiC, a Stanford group [30] numerically simulated the MPM condition for 4H-SiCOI waveguides, assuming the TE_{00} mode at the fundamental wavelength at 1555 nm and the TM_{20} mode at the SHG wavelength at 777.5 nm in a 350 nm thick waveguide with a microring radius of 27.5 μm . Their FEM-simulated results using the anisotropic Sellmeier equation [37] suggest that the 4H-SiCOI waveguide with a width of 560 nm can satisfy the MPM condition.

Recently, our group numerically demonstrated the MPM condition in a 3C-SiCOI waveguide. We adopted the same waveguide geometry for FWM analysis, as shown in Figure 6c. Figure 7a shows the FEM-simulated mode-field amplitude distributions of the TE_{00} mode at 1560 nm and the TM_{20} mode at 780 nm [29]. Figure 7b shows the simulation results for the MPM condition between the TE_{00} mode at 1560 nm and the TM_{20} mode at 780 nm in a 3C-SiCOI waveguide with T of 400 nm, 600 nm, and 800 nm. Our simulation results suggest the MPM condition with a waveguide width of ~ 1000 nm and a thickness of 800 nm or a correspondingly narrower waveguide with a thinner 3C-SiC.

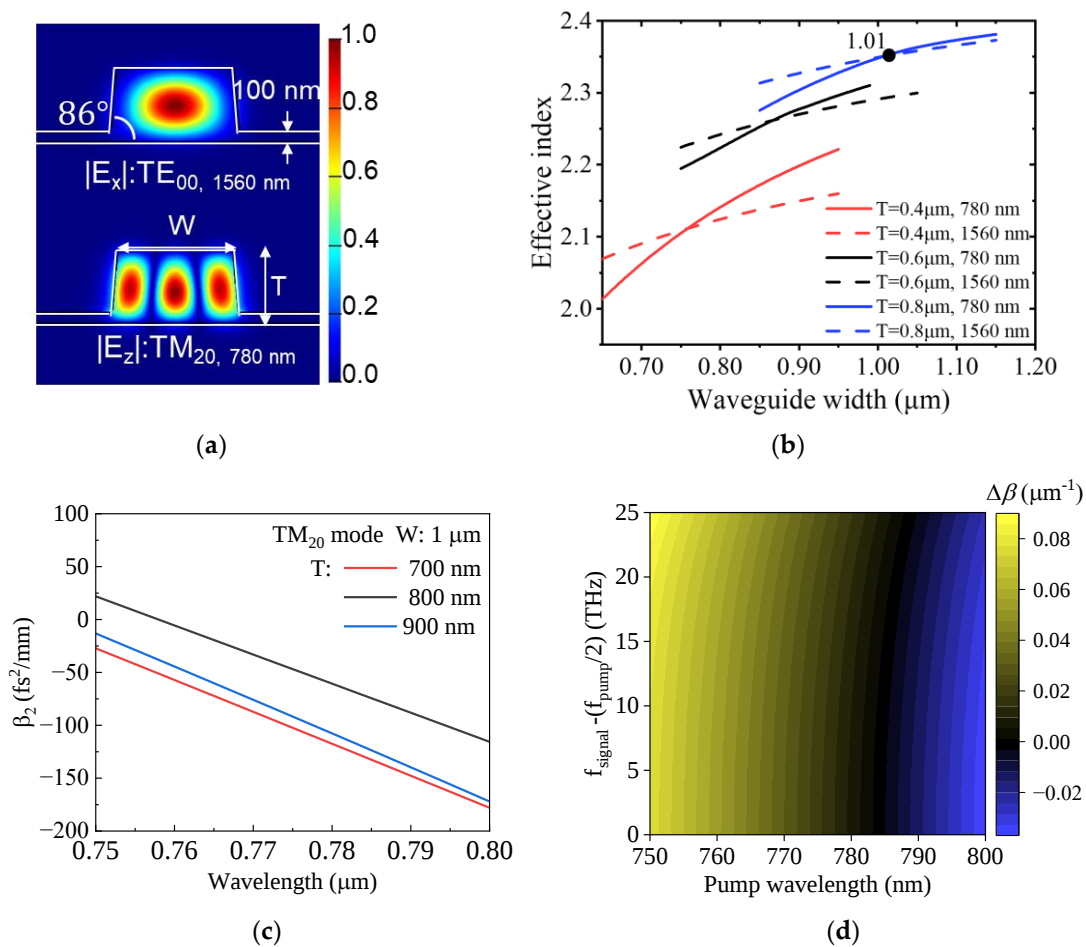


Figure 7. Numerical simulations of the MPM condition between the TE_{00} mode at 1560 nm and the TM_{20} mode at 780 nm in a 3C-SiCOI waveguide with a width of $1 \mu m$, a slab thickness of $100 nm$, and a sidewall slope of 86° . (a) Mode-field amplitude distributions of the TE_{00} (top) and TM_{20} (bottom) modes. (b) Calculated effective indices for the TE_{00} (dashed lines) and TM_{20} (solid lines) modes with the waveguide width at $T = 0.4 \mu m$ (red), $0.6 \mu m$ (black), and $0.8 \mu m$ (blue). The MPM condition for $T = 0.8 \mu m$ is denoted with a black dot. (c) Numerically simulated GVD for the TM_{20} mode in a $1 \mu m$ wide waveguide with the waveguide width at $T = 0.7 \mu m$ (red), $0.8 \mu m$ (black), and $0.9 \mu m$ (blue). (d) Calculated map of the phase mismatch $\Delta\beta$ for DFG with the non-degeneracy within 25 THz spanning the pump wavelength from 750 nm to 800 nm, assuming $T = 0.8 \mu m$.

The GVD of the TE_{00} mode at 1560 nm and of the TM_{20} mode at 780 nm in the desired waveguide for the MPM condition are shown in the plot (top) in Figure 6d and in Figure 7c (for a thickness from 700 nm to 900 nm in a step of 100 nm), respectively. The simulation results suggest that fabrication-induced deviations of the target waveguide thickness in the order of 100 nm can result in a significant deviation of the GVD for both the TE_{00} mode at 1560 nm and the TM_{20} mode at 780 nm wavelengths. This could compromise the bandwidth for attaining the MPM condition.

Figure 7d shows the numerically calculated $\Delta\beta$ assuming non-degenerate difference frequency generation (DFG) for a waveguide with $T = 0.8 \mu m$ and $W = 1.01 \mu m$. For a pump wavelength ranging from 750 nm to 800 nm, and the non-degeneracy defined as the detuning of the signal frequency from the half-pump frequency ($f_{signal} - (f_{pump}/2)$) up to 25 THz, the calculated $|\Delta\beta|$ is below $0.1 \mu m^{-1}$.

2.2. Microring Resonator Design and Analysis for Second-Order Nonlinear Frequency Conversions in the 3C-SiCOI Platform

3C-SiC exhibits a $\bar{4}3m$ point-group symmetry. The $\bar{4}$ symmetry means that the crystal arrangement is inverted, which is equivalent to flipping the sign of $\chi^{(2)}$, with a rotation of every 90° about the $[001]$ axis [22–24,29,122,123]. As the commercially available 3C-SiC wafer is typically (001) cut, the inversion of the $\chi^{(2)}$ matters for nonlinear frequency conversions in a microring resonator. Like Equation (3), the second harmonic field amplitude varies with the propagation length l along the microring circumference without considering propagation losses of A_{SH} as

$$\frac{dA_{SH}}{dl(\theta)} \propto \varepsilon_0 \chi_{eff}^{(2)}(\theta) A_F^2 \exp[i\Delta\beta \cdot l(\theta)], \quad (4)$$

where θ is the azimuthal angle with respect to the crystal x-axis, and $\chi_{eff}^{(2)}(\theta)$ is the effective nonlinear susceptibility as a function of θ . We note that $l(\theta)$ is a function of θ . Given the tensor element $\chi_{zxy}^{(2)}$, we express $\chi_{eff}^{(2)}(\theta)$ for the type-I phase matching condition in a 3C-SiC waveguide as

$$\chi_{eff}^{(2)}(\theta) = \chi_{zxy}^{(2)} \cdot \cos\theta \cdot \sin\theta = \frac{1}{2} \chi_{zxy}^{(2)} \cdot \sin 2\theta. \quad (5)$$

Equation (5) indicates that $\chi_{eff}^{(2)}(\theta)$ oscillates sinusoidally and is maximized at $\pm\chi_{zxy}^{(2)}/2$, with the fundamental field linearly polarized at $\theta = 45^\circ/135^\circ$, as shown in Figure 8.

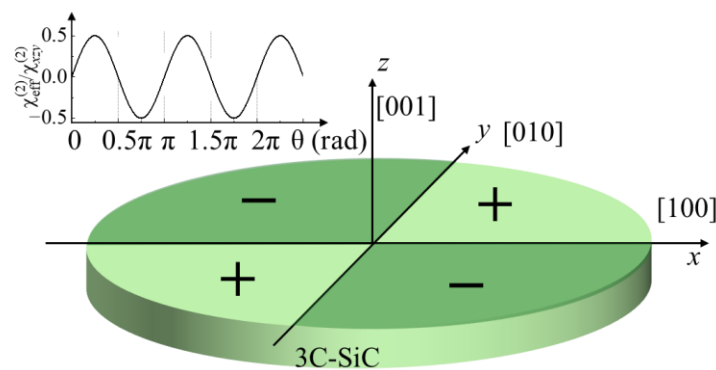


Figure 8. Schematic illustration of the sinusoidal modulation of $\chi_{eff}^{(2)}(\theta)/\chi_{zxy}^{(2)}$ every 90° in a (001)-cut 3C-SiC wafer. Inset: the sinusoidal modulation of $\chi_{eff}^{(2)}(\theta)/\chi_{zxy}^{(2)}$.

2.2.1. The $\bar{4}$ -Quasi-Phase Matching Condition

Given the sinusoidal modulation of $\chi_{eff}^{(2)}(\theta)$ in 3C-SiC, one can adopt the natural inversion of the susceptibility for satisfying a quasi-phase matching (QPM) condition. The so-called $\bar{4}$ -QPM is a method proposed for efficient SHG in GaAs WG microdisks with $\bar{4}3m$ point-group symmetry [22–24,122,123]. The concept of $\bar{4}$ -QPM is to periodically modulate the $\chi_{eff}^{(2)}$ as the linearly polarized fundamental field component rotates about the crystal z-axis while the field travels in roundtrips in a WG microdisk or in a microring resonator. The resulting grating effect enables an additional phase shift to quasi-phase match the fundamental fields with the nonlinear polarization. The quasi-phase-matched roundtrip length is approximately given as $4\pi/|\Delta\beta|$ [119,122,123], corresponding to two periodic modulations of $\chi_{eff}^{(2)}(\theta)$.

2.2.2. Elliptical Microring Resonators

Recently, our group [29,110] proposed an alternative elliptical microring design that is applicable to a nonlinear medium with $\bar{4}3m$ point-group symmetry (e.g., 3C-SiC) while

tailoring the microring waveguide geometry for approximately satisfying the phase matching condition $|\Delta\beta| \approx 0$. The elliptical microring design breaks the rotational symmetry of a circular microring, while orientating the microring major axis along the direction of $45^\circ/135^\circ$ with respect to the crystal x-axis, as shown in Figure 9, lengthens the interaction length, where $\chi_{eff}^{(2)}(\theta) \approx \pm\chi_{zxy}^{(2)}/2$ is closest to the maximum.

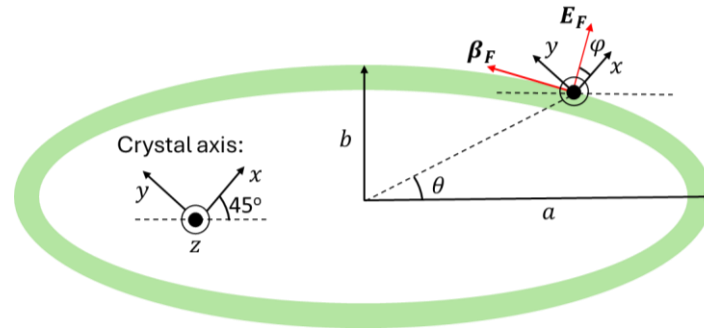


Figure 9. Schematics of an elliptical microring resonator in the polar coordinate. The coordinate origin is at the center of the elliptical microring.

To theoretically analyze the SHG in an elliptical microring resonator in a nonlinear medium with $\bar{4}3m$ point-group symmetry, we adopted an effective nonlinear susceptibility following Equation (5) $\chi_{eff}^{(2)}(\varphi) = \chi_{zxy}^{(2)} \cdot \cos\varphi \cdot \sin\varphi$, where φ is now the azimuthal angle between the fundamental optical field polarization and the crystal x-axis. We denote the polar angular coordinate on the elliptical microring as θ measured from the semi-major axis, with the origin centered at the elliptical microring, as shown in Figure 9. The φ and θ are related as

$$\varphi = \frac{\pi}{4} - \arctan\left(\frac{b}{a} \cot\theta\right), \quad (6)$$

where a and b are the semi-major and semi-minor axes of the elliptical ring. We define the elliptical microring aspect ratio as a/b . We define the SHG normalized intensity to analyze the frequency conversion efficiency in elliptical microring resonators with a roundtrip length L . One can attain the maximum SHG intensity utilizing the maximum $\chi_{eff}^{(2)}(\theta) = \pm\chi_{zxy}^{(2)}/2$ upon a perfect phase matching condition in a waveguide oriented along the direction of $45^\circ/135^\circ$ with respect to the crystal x-axis. We normalized the SHG intensity in a microring resonator to the maximum SHG intensity accumulated along a propagation length L . The SHG normalized intensity over resonator roundtrips with a nondepleted pump and without considering the cavity losses of A_{SH} is obtained from Equations (4) and (5) as

$$I_{nor} = \left| \frac{\int \left[\cos\varphi \sin\varphi \chi_{zxy}^{(2)} e^{i\Delta\beta \cdot l(\theta)} \right] \sqrt{a^2 \cos^2\theta + b^2 \sin^2\theta} d\theta}{\left(\chi_{zxy}^{(2)}/2 \right) L} \right|^2, \quad (7)$$

where $dl(\theta) = \sqrt{a^2 \cos^2\theta + b^2 \sin^2\theta} d\theta$ and $l(\theta) = \int \sqrt{a^2 \cos^2\theta + b^2 \sin^2\theta} d\theta$.

Assuming a perfect phase matching condition $\Delta\beta = 0$ in the elliptical microring, we analyze the elliptical microring aspect ratio dependence of the I_{nor} over the number of cavity roundtrips by using Equation (7), as shown in Figure 10a. We fix L while varying a/b . The inset in Figure 10a shows the calculated I_{nor} for light propagating in one roundtrip. The result reveals a sharp rise in I_{nor} with an aspect ratio from 1 to ~ 20 . The I_{nor} rolls off after the aspect ratio of ~ 20 and asymptotically approaches its theoretical limit of 0.25. However, a large aspect ratio given a fixed L imposes larger waveguide bending losses at the two poles of the elliptical microring and compromises the cavity Q factor. With multiple cavity roundtrips, the calculated I_{nor} shows a similar trend.

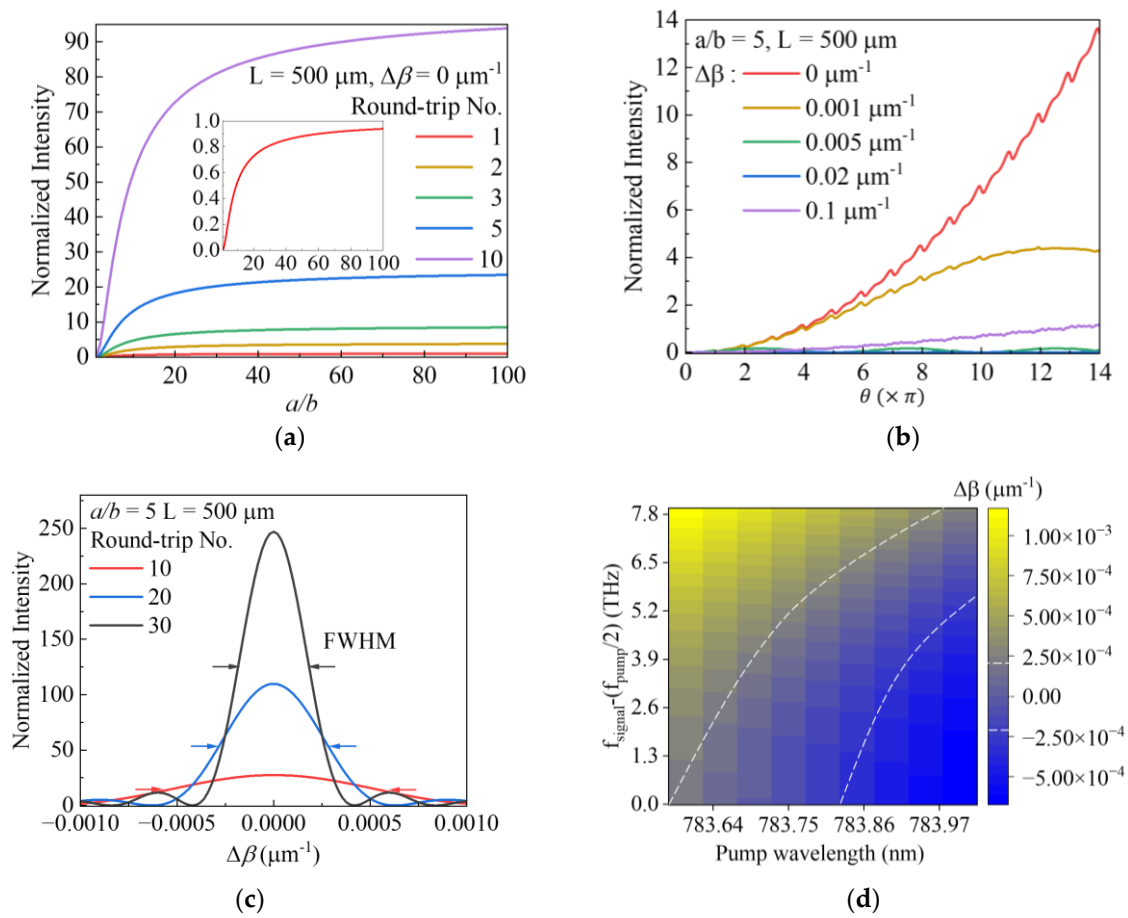


Figure 10. Calculated normalized intensity of SHG adopting the 4-QPM and the elliptical microring methods. (a) Accumulated normalized intensity after 1, 2, 3, 5, and 10 roundtrips in an elliptical microring resonator with a fixed circumference of $500 \mu\text{m}$ and various aspect ratios from 1 (a circular microring) to 100. Inset: The zoom-in view of the normalized intensity after one cavity roundtrip. (b) Accumulated normalized intensity in an elliptical microring resonator ($a/b = 5$, $L = 500 \mu\text{m}$) with various phase mismatches $\Delta\beta$ of $0 \mu\text{m}^{-1}$, $0.001 \mu\text{m}^{-1}$, $0.005 \mu\text{m}^{-1}$, $0.02 \mu\text{m}^{-1}$, and $0.1 \mu\text{m}^{-1}$. (c) The $\Delta\beta$ dependence of the accumulated normalized intensity with various cavity roundtrips of 10 (red), 20 (blue), and 30 (black) for an elliptical microring resonator ($a/b = 5$, $L = 500 \mu\text{m}$). (d) Zoom-in view of the calculated $\Delta\beta$ map for DFG spanning the pump wavelength from $\sim 783.5 \text{ nm}$ to $\sim 784 \text{ nm}$, assuming $T = 0.8 \mu\text{m}$ and $W = 1 \mu\text{m}$.

Figure 10b illustrates, as an example, the calculated I_{nor} for seven cavity roundtrips with various $\Delta\beta$. We fix $L = 500 \mu\text{m}$ and $a/b = 5$ while varying the $\Delta\beta = 0, 0.001, 0.005, 0.02$, and $0.1 \mu\text{m}^{-1}$. The net stepwise growth of I_{nor} in every half an elliptical microring roundtrip length, assuming $\Delta\beta = 0$, resembles the calculated stepwise growth of I_{nor} in every coherence length, assuming $\Delta\beta \neq 0$, exploiting 4-QPM in a circular microring. The calculated results show that the accumulated normalized intensity starts to decrease with $\Delta\beta > 0$. With $\Delta\beta = 0.005 \mu\text{m}^{-1}$, the accumulated I_{nor} is $\ll 0.25$, indicating that the elliptical microring design imposes a near-perfect phase matching condition. We note that, however, with $\Delta\beta = 0.1 \mu\text{m}^{-1}$, the accumulated I_{nor} suggests a monotonic increase up to ~ 0.25 after seven cavity roundtrips.

We further calculate the $\Delta\beta$ bandwidth (defined as the full-width half-maximum) for an elliptical microring with an a/b of 5 and a roundtrip length of $500 \mu\text{m}$. Figure 10c shows the calculated $\Delta\beta$ dependence of I_{nor} for various numbers of cavity roundtrips. For a $500 \mu\text{m}$ long microring with a Q factor of 10^4 , the cavity light propagates for around 10 cavity roundtrips. The results show that the $\Delta\beta$ bandwidth narrows to $\sim 0.0004 \mu\text{m}^{-1}$ with $Q \sim 10^4$.

Figure 10d shows the calculated $\Delta\beta$ for a MPM 3C-SiCOI, highlighting the potential pump wavelengths and the non-degenerate DFG for a $\Delta\beta$ bandwidth of $\sim 0.0004 \mu\text{m}^{-1}$.

3. Integrated Nonlinear and Quantum Light Sources

3.1. Third-Order Optical Nonlinearity

The nonlinear light sources using the third-order nonlinearities in SiC are promising for broadband applications in high-data rate optical processing and communications. In 2018, Martini et al. demonstrated FWM at the 1550 nm wavelength in a suspended 3C-SiC waveguide-coupled microring resonator. The measured microring resonator exhibits a Q-factor of 7400. The conversion efficiency is -72 dB at a low pump power of ~ 3 mW [60]. The limitation of the efficient frequency comb generation on the 3C-SiCOI platform is due to its low-Q factors. To increase the Q factor, one can adopt a thicker epitaxially grown 3C-SiC film with a reduced defect density in the top layer. Given the same device design, the waveguide fabricated in a 3C-SiC film that is more distant from the epitaxial interface can lead to reduced lattice defect-induced scattering losses.

Using 4H-SiC microring resonators, researchers have demonstrated myriad third-order nonlinear frequency conversions, including FWM [59,115], optical parametric oscillation (OPO) [105], Raman lasing [106,124], and soliton [114,125]. In 2019, a DTU group [115] demonstrated FWM with a conversion efficiency of -21.7 dB using a TE-polarized pump at a power of 79 mW in a waveguide-coupled microring resonator with a Q-factor of 26,000. They showed the potential of attaining a broadband FWM conversion over 130 nm, as shown in Figure 11.

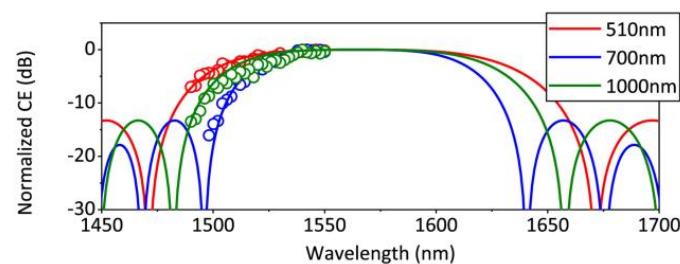


Figure 11. Normalized measured conversion efficiencies (open circles) for FWM in 4H-SiCOI waveguides pumping by a continuous-wave laser at 1565 nm compared to the simulated results (solid lines) [115].

A Stanford group [105] demonstrated OPO in a SiC waveguide-coupled microring resonator. Figure 12a,b show the device structure and the inverse-designed vertical coupler used as input and output couplers. They dispersion engineered the waveguide geometry to attain the OPO in the TE_{10} mode. Figure 12c shows the measured OPO spectra generated upon various injection powers. With a Q_L factor of 1.8×10^5 for the TE_{10} mode, they obtained two sideband peaks upon a pump power of 65 mW and obtained subcombs upon a pump power of 75 mW. At 85 mW, the subcombs fill out, indicating the generation of a chaotic frequency comb.

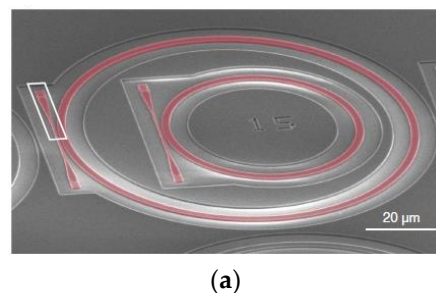


Figure 12. Cont.

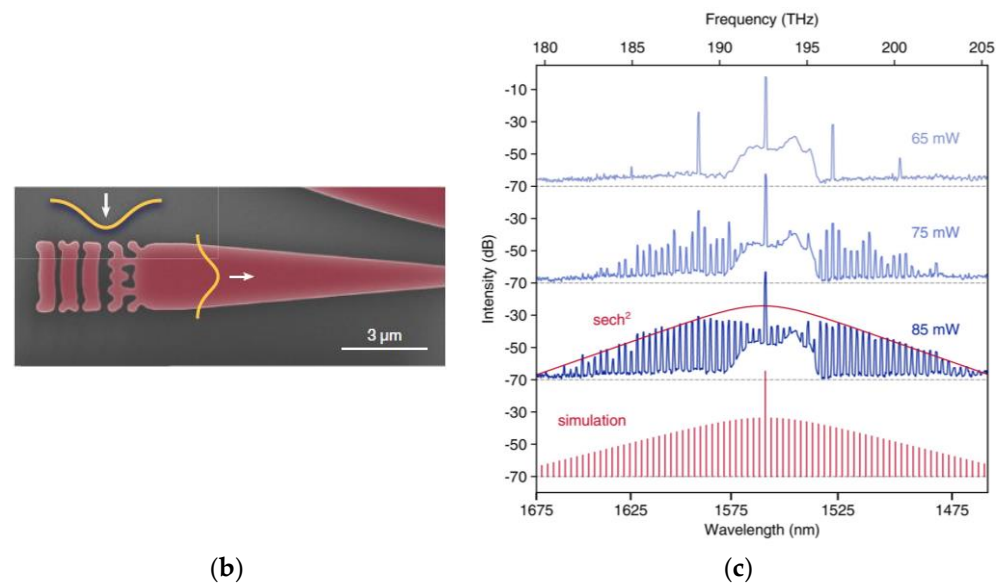


Figure 12. (a) Scanning electron micrograph (SEM) of two SiC microring resonators (false-colored) with diameters of 55 μm and 100 μm before SiO_2 encapsulation. (b) SEM of the inverse-designed vertical coupler used as input and output couplers, as highlighted (white box) in (a). (c) Measured OPO spectra (blue) at different injected powers, featuring three distinct stages in the microcomb formation. A sech^2 fit (red envelope) is overlaid onto the chaotic frequency comb for comparison to the characteristic soliton spectral shape. Simulation (red) of the soliton [105].

In 2022, Cai et al. [106] demonstrated an octave-spanning SiC microcomb. Figure 13 shows their measured microcomb spectra spanning a wavelength range from 1150 nm to 2400 nm upon an on-chip pump power near 120 mW. This is the broadest comb generated in SiC platforms to date. By optimizing the waveguide width of the microring resonator, they showed that the mean power of the comb lines near the pump wavelength can be nearly -20 dBm. Recently, a CMU group [124] explored Raman lasing-generated cascaded Raman combs and Raman–Kerr comb generation in SiC. The measured power threshold is 2.5 mW to obtain the first-order Stokes lasing. The required pump power is near 120 mW to attain a comb spanning 700 nm for the Stokes-induced Kerr microcomb. The low Raman threshold shows the potential application of the 4H-SiC platform towards Raman lasers.

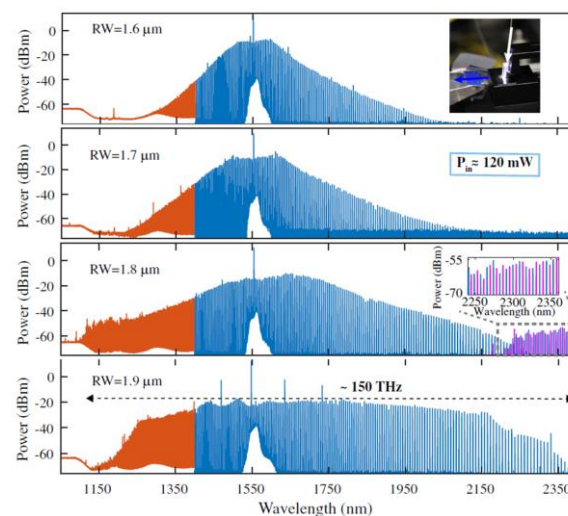


Figure 13. The first demonstrated octave-spanning frequency comb in the SiCOI platform for the TE_{00} modes of 36- μm radius SiC microrings with varied ring widths and an estimated on-chip power

of 120 mW. The orange and light blue colors indicate the data collected from two different optical spectrum analyzers given the wide wavelength range. The inset in the top figure shows the experimental setup for broadband comb measurements. The input is a continuous-wave laser near the wavelength of 1550 nm coupled from a fiber V groove array to the waveguide through a grating coupler while the broadband output is routed to the polished waveguide facet and collected using a lensed fiber (butt coupling). For the ring width (RW) = 1.8 μm , a secondary mode family appears beyond a wavelength of 2200 nm (see the inset in the third figure from top), which is likely caused by accidental phase matching for the frequency mixing process between the TE_{00} mode and a higher-order waveguide mode at these wavelengths. The spectral bandwidths corresponding to the ring widths of 1.8 μm and 1.9 μm are estimated to exceed 150 THz [106].

Researchers have exploited the $\chi^{(3)}$ nonlinearities in the SiCOI platforms to demonstrate chip-based photon pair sources based on SFWM. A CMU group recently reported an entangled photon pair source using SFWM in a 4H-SiCOI microring resonator, as shown in Figure 14a [126]. The wavelengths of the pump, the signal, and of the idler are at the telecommunications C-band, with a Q factor of 8×10^5 . Figure 14b,c show the measured photon pair generation rate (PGR) of 9 kHz and the measured coincidence-to-accidental ratio (CAR) of 620 with 0.17 mW on-chip pump power. The low PGR is attributed to the $\chi^{(3)}$ nonlinear susceptibility being orders of magnitude smaller than the $\chi^{(2)}$ nonlinear susceptibility.

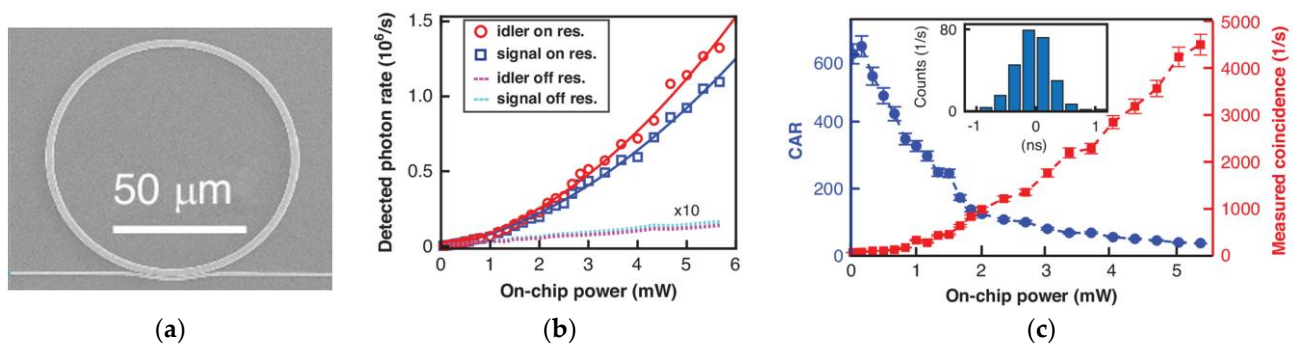


Figure 14. (a) SEM of the 4H-SiCOI microring resonator for photon pair generation. (b) Detected photon rate of the signal and idler as a function of on-chip pump power for both resonant (markers) and non-resonant pumping (dashed lines with the off-resonance number multiplied by a factor of 10 for better visibility). The on-resonance results are fitted by a quadratic curve in solid lines. (c) Measured coincidence-to-accidental ratio (CAR, left y-axis) and the detected coincidence count (right y-axis) as a function of on-chip pump powers with 0.24 ns for the timing window. The inset shows a plot of coincidence histogram for 0.17 mW pump power corresponding to the measured CAR of 620. The temporal full-width at half-maxima (FWHM) width is approximately 0.68 ns [126].

3.2. Second-Order Optical Nonlinear Processes

Second-order nonlinear optical effects in the SiCOI platforms have attracted recent attention. To date, there are only some works demonstrating SHG or DFG in SiC microring resonators. In 2020, a Stanford group [30] reported an efficient SHG exploiting type-I phase matching (using the tensor element d_{31}) and the MPM condition in a 4H-SiC microring resonator with a Q of 8×10^4 . They measured a SHG frequency conversion efficiency of $360\% \text{ W}^{-1}$. Another work [70] demonstrated SHG in a high-Q WG microdisk with a mean Q factor of 6.75×10^6 . As the microdisk is not properly phase-matched with the waveguide, the measured frequency conversion efficiency is only $3.91\% \text{ W}^{-1}$ with a pump power of 10 mW.

Recently, our group [29] demonstrated SHG on a 3C-SiCOI platform. We adopted the polarization-dependent MPM between the TE_{00} mode at 1560 nm and the TM_{20} mode at 780 nm. We adopted an elliptical microring resonator based on the analysis discussed in Section 2 to demonstrate the SHG and DFG. Figure 7a,b and Figure 15a show the numerical

simulations of the polarization-dependent MPM. We adopted the semi-major and semi-minor axes of 30 μm and 15 μm (an aspect ratio of 2). The microring is coupled with two waveguides designed separately for the TE_{00} mode at ~ 1560 nm and for the TM_{20} mode at ~ 780 nm wavelengths. Figure 15b shows the SEM of the measured device.

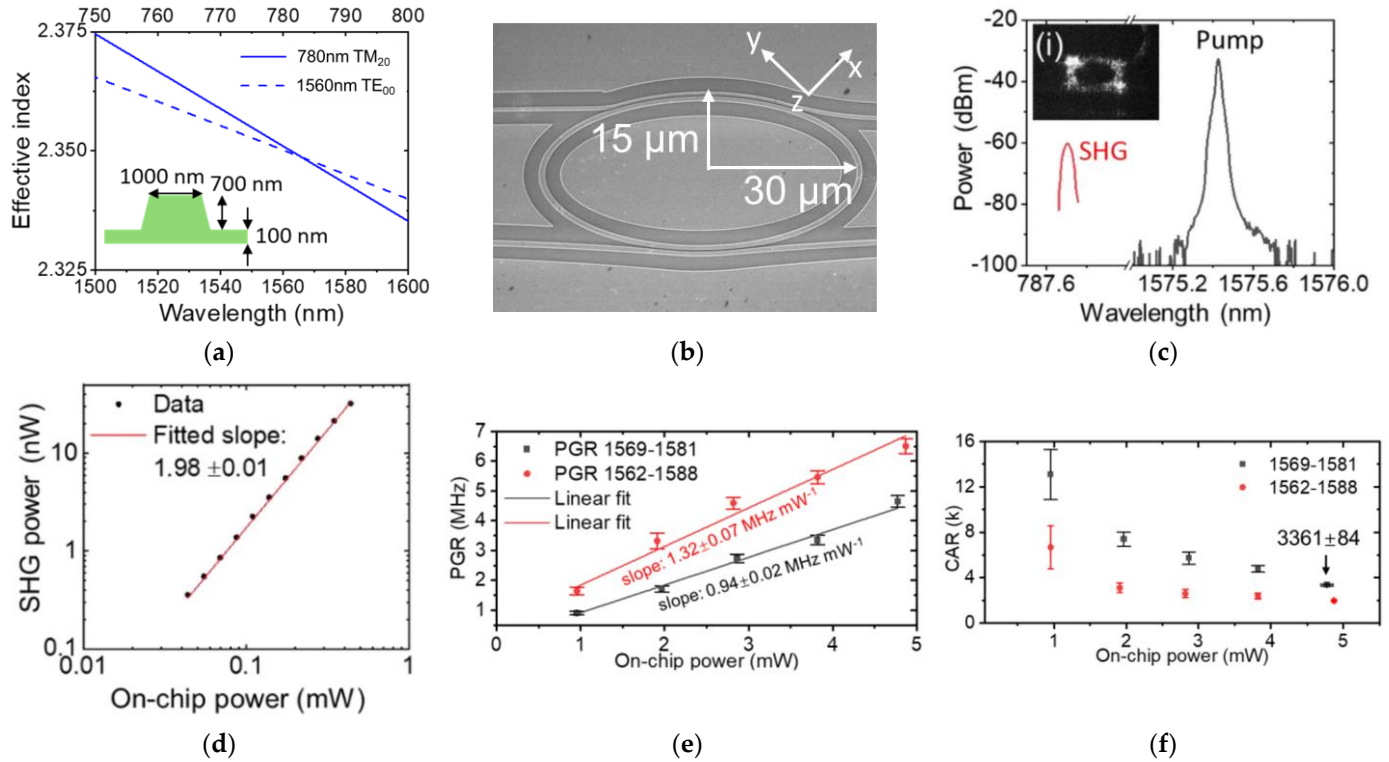


Figure 15. (a) Calculated dispersion of the TM_{20} mode at 780 nm (solid line) and of the TE_{00} mode at 1560 nm (dashed line). (b) SEM of the measured 3C-SiCOI elliptical microring resonator. (c) Measured pump (black) and SHG (red) spectra. Inset: Top-view scattering of the SHG light. (d) Measured and fitted pump-to-SHG power dependence in a log-log scale. Measured power dependence of (e) the estimated PGRs and (f) the estimated CARs [29].

We demonstrated a SHG at 787.7 nm with a fundamental frequency at 1575.5 nm, as shown in Figure 15c. The fundamental and SHG wavelengths align with the microring cavity resonances, showing a Q_L factor of 1.4×10^4 at 787.7 nm and a Q_L factor of 2.5×10^4 at 1575.5 nm. The inset (i) shows the top-view optical microscope image of the injected microring captured by a charge-coupled device camera. Figure 15d shows the measured power dependence of the SHG. The linear fit on the log-log plot confirms a slope of nearly 2. The extracted conversion efficiency is $17.4 \pm 0.2\% \text{ W}^{-1}$. We can enhance the conversion efficiency by using an elliptical microring cavity with a higher Q factor.

We demonstrated the SPDC photon pair source with the same device, as shown in Figure 15e [29]. Figure 15f shows our measured PGR of 4.8 MHz and a CAR of 3361 ± 84 with an on-chip pump power of ~ 5 mW. The PGR is limited by low Q factors of our 3C-SiCOI microring resonators.

4. Summary and Outlooks

This paper reviewed the state-of-the-art of the SiC-based integrated photonics. We highlighted the material and optical properties of three commonly adopted polytypes of SiC (6H-SiC, 4H-SiC, and 3C-SiC) and the fabrication processes to form highly confined waveguide structures. Larger-size, single-crystalline SiC wafers will be beneficial for realizing large-scale PICs on SiCOI platforms.

Table 2 summarizes the waveguide geometry, the Q factors, and the propagation losses of the microring resonators for nonlinear and quantum photonics on various material platforms. While the 4H-SiCOI platform has already demonstrated ultra-high-Q microring resonators [53,114], which is comparable with other photonic platforms [9,127–130], the microring resonators on the 3C-SiCOI platform have been, until now, limited by the scattering losses due to the remaining lattice defects in the epitaxial 3C-SiC film [29,49]. A reduced waveguide propagation loss will enable ultra-high-Q microring resonators and low-loss PICs. The phase matching condition and the microring design are especially critical for 3C-SiC due to its $\bar{4}3m$ point-group symmetry.

Table 2. Summary of the state-of-the-art microring resonator performance for nonlinear and quantum photonics on various material platforms.

Platform		3C-SiC		4H-SiC		Si	SiN	LN	AlN	Al _x Ga _{1-x} As
Microring geometry		Circular [49]	Elliptical [29]	Circular [114]	Racetrack [53]	Racetrack [127]	Circular [9]	Circular [128]	Circular [129]	Circular [130]
Device parameters	Ring width (μm)	0.8	1	1.85	2.5	0.5	1.58	1.3	3.5	1
	Thickness (nm)	530	800	500~600	850	220	810	600	1000	400
	Radius (μm)	N/A	30/15 (semi-major/minor)	100	100 (bended waveguides)	20 (bended waveguides)	N/A	80	100	143
Q factors (×10 ⁶)		Q_I : 0.089 Q_L : 0.034 @ ~1580 nm	Q_I : 0.03 Q_L : 0.024 @ 1575.4 nm	Q_I : 5.61 Q_L : 3.19 @ 1553.3 nm	Q_I : 5.3 Q_L : 4.3 @ ~1550 nm	Q_I : 3.2 Q_L : 1.1 @ 1549.8 nm	Q_I : 15 Q_L : 6.6 @ 1621.8 nm	Q_I : 1.1 Q_L : 0.66 @ ~1550 nm	Q_I : 3 @ ~1533 nm	Q_I : 3.52 Q_L : 1.76 @ ~1565 nm
Propagation loss (dB/cm)		~5.2	~11	~0.09	~0.09	0.21	~0.005	~0.08	~0.03	0.17

Recent demonstrations of nonlinear and quantum light sources using SiC-based microring resonators indicate their potential for enabling chip-based nonlinear and quantum photonic applications, along with potentially high-speed optical signal processing and data transmission systems.

Besides serving as a time–energy entangled photon pair source, the SiC platforms show potential to generate polarization-entangled photon pair sources using its nonlinear susceptibilities to attain the type-II phase matching condition [47,48]. On-chip components, such as polarization rotators [131] and waveguide-coupled dual microring resonators [132], can help ease the strict phase matching design requirements for realizing polarization entanglements. A SiC-based high-flux polarization entangled photon pair source could be useful for quantum key distributions [133].

To further develop SiC-based nonlinear and quantum PICs, it is essential to further explore passive and active components based on microresonators and waveguide interferometers. The heterogeneous integration of direct-bandgap semiconductor III-V materials, such as InP, AlGaAs, and GaN, on the SiC platforms will enable the demonstration of fully integrated photonic circuits with on-chip electrically injected pump lasers, which will pave the way for applications of SiC on various portable devices.

The wide transparency window of SiC enables the operational wavelengths spanning the visible to the mid-infrared regimes. The potential of generating nonlinear and quantum light sources in the visible wavelengths renders the SiC platforms an alternative platform for developing chip-based biosensors, integrated atomic/molecular photonics, and atomic clocks, along with precision metrology and spectroscopy [134–136].

Besides the nonlinear optic-based quantum light sources, SiC is a host for color centers that enable single-photon sources (SPSs) at room temperature spanning from the visible wavelengths to the optical communications bands [137–141]. This is another good reason the SiC platforms are considered as a promising integrated quantum photonics platform. The high-Q microring resonators on the SiC platforms can be readily coupled with the color

centers to enable Purcell enhancement for the SPSs [142]. High-quality, deterministic SPSs are essential for quantum communications and sensing.

Recently, the 4H-SiCOI-based high-performance on-chip polarization-(in)dependent beam splitters, Mach–Zehnder interferometers [143–145], and the 3C-SiCOI-based on-chip pump-rejection long-pass filters [146] have been demonstrated for quantum photonic applications. These devices, together with the chip-based entangled photon pair sources, show potentials of the SiCOI platforms towards efficient and reliable components in integrated quantum photonic circuits.

Another potential application direction of SiC photonics is in the aerospace industry due to SiC's unique material properties, including the high temperature stability, the high thermal conductivity, the chemical inertness, and the radiation resistance [147,148]. With more investigations and continuous enhancements on integrated SiC-based photonic devices, potential applications of SiC-based PICs in a harsh environment will be full of vitality.

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References

1. Cazzanelli, M.; Schilling, J. Second Order Optical Nonlinearity in Silicon by Symmetry Breaking. *Appl. Phys. Rev.* **2016**, *3*, 011104. [\[CrossRef\]](#)
2. Timurdogan, E.; Poulton, C.V.; Byrd, M.J.; Watts, M.R. Electric Field-Induced Second-Order Nonlinear Optical Effects in Silicon Waveguides. *Nat. Photonics* **2017**, *11*, 200–206. [\[CrossRef\]](#)
3. Zhang, Y.; Nauriyal, J.; Song, M.; Baez, M.G.; He, X.; Macdonald, T.; Cardenas, J. Engineered Second-Order Nonlinearity in Silicon Nitride. *Opt. Mater. Express* **2023**, *13*, 237–246. [\[CrossRef\]](#)
4. Porcel, M.A.G.; Mak, J.; Taballione, C.; Schermerhorn, V.K.; Epping, J.P.; van der Slot, P.J.M.; Boller, K.-J. Photo-Induced Second-Order Nonlinearity in Stoichiometric Silicon Nitride Waveguides. *Opt. Express* **2017**, *25*, 33143–33159. [\[CrossRef\]](#)
5. Lu, X.; Moille, G.; Rao, A.; Westly, D.A.; Srinivasan, K. Efficient Photoinduced Second-Harmonic Generation in Silicon Nitride Photonics. *Nat. Photonics* **2021**, *15*, 131–136. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Nitiss, E.; Hu, J.; Stroganov, A.; Brès, C.-S. Optically Reconfigurable Quasi-Phase-Matching in Silicon Nitride Microresonators. *Nat. Photonics* **2022**, *16*, 134–141. [\[CrossRef\]](#)
7. Ding, M.; Zhang, M.; Hong, S.; Zhao, Y.; Zhang, L.; Wang, Y.; Chen, H.; Yu, Z.; Gao, S.; Dai, D. High-Efficiency Four-Wave Mixing in Low-Loss Silicon Photonic Spiral Waveguides beyond the Singlemode Regime. *Opt. Express* **2022**, *30*, 16362–16373. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Hu, J.; Nitiss, E.; He, J.; Liu, J.; Yakar, O.; Weng, W.; Kippenberg, T.J.; Brès, C.S. Photo-induced cascaded harmonic and comb generation in silicon nitride microresonators. *Sci. Adv.* **2022**, *8*, eadd8252. [\[CrossRef\]](#)
9. Liu, J.; Raja, A.S.; Karpov, M.; Ghadiani, B.; Pfeiffer, M.H.P.; Du, B.; Engelsen, N.J.; Guo, H.; Zervas, M.; Kippenberg, T.J. Ultralow-power chip-based soliton microcombs for photonic integration. *Optica* **2018**, *5*, 1347–1353.
10. Xiang, C.; Jin, W.; Bowers, J.E. Silicon nitride passive and active photonic integrated circuits: Trends and prospects. *Photonics Res.* **2022**, *10*, A82–A96. [\[CrossRef\]](#)
11. Churaev, M.; Wang, R.N.; Riedhauser, A.; Snigirev, V.; Blésin, T.; Möhl, C.; Anderson, M.H.; Siddharth, A.; Popoff, Y.; Drechsler, U.; et al. A heterogeneously integrated lithium niobate-on-silicon nitride photonic platform. *Nat. Commun.* **2023**, *14*, 3499. [\[CrossRef\]](#)
12. de Beeck, C.O.; Haq, B.; Elsinger, L.; Gocalinska, A.; Pelucchi, E.; Corbett, B.; Roelkens, G.; Kuyken, B. Heterogeneous III-V on silicon nitride amplifiers and lasers via microtransfer printing. *Optica* **2020**, *7*, 386–393. [\[CrossRef\]](#)
13. Park, T.; Stokowski, H.S.; Ansari, V.; McKenna, T.P.; Hwang, A.Y.; Fejer, M.M.; Safavi-Naeini, A.H. High-Efficiency Second Harmonic Generation of Blue Light on Thin-Film Lithium Niobate. *Opt. Lett.* **2022**, *47*, 2706–2709. [\[CrossRef\]](#) [\[PubMed\]](#)

14. Xin, C.J.; Mishra, J.; Chen, C.; Zhu, D.; Shams-Ansari, A.; Langrock, C.; Sinclair, N.; Wong, F.N.C.; Fejer, M.M.; Lončar, M. Spectrally Separable Photon-Pair Generation in Dispersion Engineered Thin-Film Lithium Niobate. *Opt. Lett.* **2022**, *47*, 2830–2833. [[CrossRef](#)] [[PubMed](#)]
15. Lu, J.; Surya, J.B.; Liu, X.; Bruch, A.W.; Gong, Z.; Xu, Y.; Tang, H.X. Periodically Poled Thin-Film Lithium Niobate Microring Resonators with a Second-Harmonic Generation Efficiency of 250,000%/W. *Optica* **2019**, *6*, 1455–1460. [[CrossRef](#)]
16. Bruch, A.W.; Liu, X.; Guo, X.; Surya, J.B.; Gong, Z.; Zhang, L.; Wang, J.; Yan, J.; Tang, H.X. 17 000%/W Second-Harmonic Conversion Efficiency in Single-Crystalline Aluminum Nitride Microresonators. *Appl. Phys. Lett.* **2018**, *113*, 131102. [[CrossRef](#)]
17. Alden, D.; Troha, T.; Kirste, R.; Mita, S.; Guo, Q.; Hoffmann, A.; Zgonik, M.; Collazo, R.; Sitar, Z. Quasi-Phase-Matched Second Harmonic Generation of UV Light Using AlN Waveguides. *Appl. Phys. Lett.* **2019**, *114*, 103504. [[CrossRef](#)]
18. Guo, X.; Zou, C.-L.; Tang, H.X. Second-Harmonic Generation in Aluminum Nitride Microrings with 2500%/W Conversion Efficiency. *Optica* **2016**, *3*, 1126–1131. [[CrossRef](#)]
19. Guo, X.; Zou, C.; Schuck, C.; Jung, H.; Cheng, R.; Tang, H.X. Parametric Down-Conversion Photon-Pair Source on a Nanophotonic Chip. *Light Sci. Appl.* **2017**, *6*, e16249. [[CrossRef](#)]
20. Chowdhury, A.; Ng, H.M.; Bhardwaj, M.; Weimann, N.G. Second-Harmonic Generation in Periodically Poled GaN. *Appl. Phys. Lett.* **2003**, *83*, 1077–1079. [[CrossRef](#)]
21. Xiong, C.; Pernice, W.; Ryu, K.K.; Schuck, C.; Fong, K.Y.; Palacios, T.; Tang, H.X. Integrated GaN Photonic Circuits on Silicon (100) for Second Harmonic Generation. *Opt. Express* **2011**, *19*, 10462–10470. [[CrossRef](#)]
22. Kuo, P.S.; Solomon, G.S. On-and off-Resonance Second-Harmonic Generation in GaAs Microdisks. *Opt. Express* **2011**, *19*, 16898–16918. [[CrossRef](#)] [[PubMed](#)]
23. Kuo, P.S.; Bravo-Abad, J.; Solomon, G.S. Second-Harmonic Generation Using-Quasi-Phasematching in a GaAs Whispering-Gallery-Mode Microcavity. *Nat. Commun.* **2014**, *5*, 3109. [[CrossRef](#)] [[PubMed](#)]
24. Yang, Z.; Chak, P.; Bristow, A.D.; van Driel, H.M.; Iyer, R.; Aitchison, J.S.; Smirl, A.L.; Sipe, J.E. Enhanced Second-Harmonic Generation in AlGaAs Microring Resonators. *Opt. Lett.* **2007**, *32*, 826–828. [[CrossRef](#)] [[PubMed](#)]
25. May, S.; Kues, M.; Clerici, M.; Sorel, M. Second-Harmonic Generation in AlGaAs-on-Insulator Waveguides. *Opt. Lett.* **2019**, *44*, 1339–1342. [[CrossRef](#)] [[PubMed](#)]
26. Placke, M.; Schlegel, J.; Mann, F.; Della Casa, P.; Thies, A.; Weyers, M.; Tränkle, G.; Ramelow, S. Telecom-Band Spontaneous Parametric Down-Conversion in AlGaAs-on-Insulator Waveguides. *Laser Photonics Rev.* **2024**, 2301293. [[CrossRef](#)]
27. Mobini, E.; Espinosa, D.H.G.; Vyas, K.; Dolgaleva, K. AlGaAs Nonlinear Integrated Photonics. *Micromachines* **2022**, *13*, 991. [[CrossRef](#)] [[PubMed](#)]
28. Yamada, S.; Song, B.-S.; Jeon, S.; Upham, J.; Tanaka, Y.; Asano, T.; Noda, S. Second-Harmonic Generation in a Silicon-Carbide-Based Photonic Crystal Nanocavity. *Opt. Lett.* **2014**, *39*, 1768–1771. [[CrossRef](#)] [[PubMed](#)]
29. Li, J.; Zhang, Q.; Wang, J.; Poon, A.W. An Integrated 3C-Silicon Carbide-on-Insulator Photonic Platform for Nonlinear and Quantum Light Sources. *Commun. Phys.* **2024**, *7*, 125. [[CrossRef](#)]
30. Lukin, D.M.; Dory, C.; Guidry, M.A.; Yang, K.Y.; Mishra, S.D.; Trivedi, R.; Radulaski, M.; Sun, S.; Vercruysse, D.; Ahn, G.H. 4H-Silicon-Carbide-on-Insulator for Integrated Quantum and Nonlinear Photonics. *Nat. Photonics* **2020**, *14*, 330–334. [[CrossRef](#)]
31. Kuroiwa, Y.; Matsushita, Y.; Oba, F. Unraveling Crystal Symmetry and Strain Effects on Electronic Band Structures of SiC Polytypes. *AIP Adv.* **2020**, *10*, 105014. [[CrossRef](#)]
32. Elasser, A.; Chow, T.P. Silicon Carbide Benefits and Advantages for Power Electronics Circuits and Systems. *Proc. IEEE* **2002**, *90*, 969–986. [[CrossRef](#)]
33. Li, N.; Ho, C.P.; Zhu, S.; Fu, Y.H.; Zhu, Y.; Lee, L.Y.T. Aluminium Nitride Integrated Photonics: A Review. *Nanophotonics* **2021**, *10*, 2347–2387. [[CrossRef](#)]
34. Gardes, F.; Shooa, A.; De Paoli, G.; Skandalos, I.; Ilie, S.; Rutirawut, T.; Talataisong, W.; Faneca, J.; Vitali, V.; Hou, Y. A Review of Capabilities and Scope for Hybrid Integration Offered by Silicon-Nitride-Based Photonic Integrated Circuits. *Sensors* **2022**, *22*, 4227. [[CrossRef](#)] [[PubMed](#)]
35. Beliaev, L.Y.; Shkondin, E.; Lavrinenko, A.V.; Takayama, O. Optical, Structural and Composition Properties of Silicon Nitride Films Deposited by Reactive Radio-Frequency Sputtering, Low Pressure and Plasma-Enhanced Chemical Vapor Deposition. *Thin Solid Films* **2022**, *763*, 139568. [[CrossRef](#)]
36. Bakin, A.S.; Dorozhkin, S.I.; Zubrilov, A.S. 6H-and 4H-Silicon Carbide for Device Applications. In Proceedings of the 1998 Fourth International High Temperature Electronics Conference. HITEC (Cat. No. 98EX145), Albuquerque, NM, USA, 14–18 June 1998; pp. 253–256.
37. Wang, S.; Zhan, M.; Wang, G.; Xuan, H.; Zhang, W.; Liu, C.; Xu, C.; Liu, Y.; Wei, Z.; Chen, X. 4H-SiC: A New Nonlinear Material for Midinfrared Lasers. *Laser Photonics Rev.* **2013**, *7*, 831–838. [[CrossRef](#)]
38. Wu, X.; Fan, T.; Eftekhari, A.A.; Adibi, A. High-Q Microresonators Integrated with Microheaters on a 3C-SiC-on-Insulator Platform. *Opt. Lett.* **2019**, *44*, 4941–4944. [[CrossRef](#)]
39. Leidinger, M.; Fieberg, S.; Waasem, N.; Kühnemann, F.; Buse, K.; Breunig, I. Comparative Study on Three Highly Sensitive Absorption Measurement Techniques Characterizing Lithium Niobate over Its Entire Transparent Spectral Range. *Opt. Express* **2015**, *23*, 21690–21705. [[CrossRef](#)]
40. Li, H.H. Refractive Index of Silicon and Germanium and Its Wavelength and Temperature Derivatives. *J. Phys. Chem. Ref. Data* **1980**, *9*, 561–658. [[CrossRef](#)]

41. Luke, K.; Okawachi, Y.; Lamont, M.R.E.; Gaeta, A.L.; Lipson, M. Broadband Mid-Infrared Frequency Comb Generation in a Si₃N₄ Microresonator. *Opt. Lett.* **2015**, *40*, 4823–4826. [[CrossRef](#)]
42. Wang, Y.; Lin, Q.; Feng, P.X.-L. Single-Crystal 3C-SiC-on-Insulator Platform for Integrated Quantum Photonics. *Opt. Express* **2021**, *29*, 1011–1022. [[CrossRef](#)]
43. Singh, S.; Potopowicz, J.R.; Van Uitert, L.G.; Wemple, S.H. Nonlinear Optical Properties of Hexagonal Silicon Carbide. *Appl. Phys. Lett.* **1971**, *19*, 53–56. [[CrossRef](#)]
44. Zelmon, D.E.; Small, D.L.; Jundt, D. Infrared Corrected Sellmeier Coefficients for Congruently Grown Lithium Niobate and 5 Mol.% Magnesium Oxide-Doped Lithium Niobate. *JOSA B* **1997**, *14*, 3319–3322. [[CrossRef](#)]
45. Pastrňák, J.; Roskovcová, L. Refraction Index Measurements on AlN Single Crystals. *Physica Status Solidi (B)* **1966**, *14*, K5–K8. [[CrossRef](#)]
46. Papatryfonos, K.; Angelova, T.; Brimont, A.; Reid, B.; Guldin, S.; Smith, P.R.; Tang, M.; Li, K.; Seeds, A.J.; Liu, H. Refractive Indices of MBE-Grown Al_xGa_(1-x)As Ternary Alloys in the Transparent Wavelength Region. *AIP Adv.* **2021**, *11*, 025327. [[CrossRef](#)]
47. Sato, H.; Abe, M.; Shoji, I.; Suda, J.; Kondo, T. Accurate Measurements of Second-Order Nonlinear Optical Coefficients of 6H and 4H Silicon Carbide. *JOSA B* **2009**, *26*, 1892–1896. [[CrossRef](#)]
48. Wu, I.J.; Guo, G.Y. Second-Harmonic Generation and Linear Electro-Optical Coefficients of SiC Polytypes and Nanotubes. *Phys. Rev. B* **2008**, *78*, 035447. [[CrossRef](#)]
49. Powell, K.; Li, L.; Shams-Ansari, A.; Wang, J.; Meng, D.; Sinclair, N.; Deng, J.; Lončar, M.; Yi, X. Integrated Silicon Carbide Electro-Optic Modulator. *Nat. Commun.* **2022**, *13*, 1851. [[CrossRef](#)] [[PubMed](#)]
50. Miller, R.C.; Nordland, W.A.; Bridenbaugh, P.M. Dependence of Second-harmonic-generation Coefficients of LiNbO₃ on Melt Composition. *J. Appl. Phys.* **1971**, *42*, 4145–4147. [[CrossRef](#)]
51. Pernice, W.H.P.; Xiong, C.; Schuck, C.; Tang, H.X. Second Harmonic Generation in Phase Matched Aluminum Nitride Waveguides and Micro-Ring Resonators. *Appl. Phys. Lett.* **2012**, *100*, 223501. [[CrossRef](#)]
52. Zhao, Z.; Chen, Z.; Shi, W. An Investigation of Terahertz Response in Monocrystalline 6H-SiC for Electro-Optic Sampling. *Jpn. J. Appl. Phys.* **2014**, *53*, 022601. [[CrossRef](#)]
53. Wang, R.; Li, J.; Cai, L.; Li, Q. Investigation of the Electro-Optic Effect in High-Q 4H-SiC Microresonators. *Opt. Lett.* **2023**, *48*, 1482–1485. [[CrossRef](#)] [[PubMed](#)]
54. Turner, E.H. High-frequency Electro-optic Coefficients of Lithium Niobate. *Appl. Phys. Lett.* **1966**, *8*, 303–304. [[CrossRef](#)]
55. Berseth, C.; Wuethrich, C.; Reinhart, F.K. The Electro-optic Coefficients of GaAs: Measurements at 1.32 and 1.52 μm and Study of Their Dispersion between 0.9 and 10 μm. *J. Appl. Phys.* **1992**, *71*, 2821–2825. [[CrossRef](#)]
56. Xia, J.; Serna, S.; Zhang, W.; Vivien, L.; Cassan, É. Hybrid Silicon Slotted Photonic Crystal Waveguides: How Does Third Order Nonlinear Performance Scale with Slow Light? *Photonics Res.* **2016**, *4*, 257–261. [[CrossRef](#)]
57. Krückel, C.J.; Fülöp, A.; Ye, Z.; Andrekson, P.A. Optical Bandgap Engineering in Nonlinear Silicon Nitride Waveguides. *Opt. Express* **2017**, *25*, 15370–15380. [[CrossRef](#)] [[PubMed](#)]
58. Guo, X.; Peng, Z.; Ding, P.; Li, L.; Chen, X.; Wei, H.; Tong, Z.; Guo, L. Nonlinear Optical Properties of 6H-SiC and 4H-SiC in an Extensive Spectral Range. *Opt. Mater. Express* **2021**, *11*, 1080–1092. [[CrossRef](#)]
59. Shi, X.; Fan, W.; Lu, Y.; Hansen, A.K.; Chi, M.; Yi, A.; Ou, X.; Rottwitt, K.; Ou, H. Polarization and Spatial Mode Dependent Four-Wave Mixing in a 4H-Silicon Carbide Microring Resonator. *APL Photonics* **2021**, *6*, 076106. [[CrossRef](#)]
60. Martini, F.; Politi, A. Four Wave Mixing in 3C SiC Ring Resonators. *Appl. Phys. Lett.* **2018**, *112*, 251110. [[CrossRef](#)]
61. DeSalvo, R.; Said, A.A.; Hagan, D.J.; Van Stryland, E.W.; Sheik-Bahae, M. Infrared to Ultraviolet Measurements of Two-Photon Absorption and n₂ in Wide Bandgap Solids. *IEEE J. Quantum Electron.* **1996**, *32*, 1324–1333. [[CrossRef](#)]
62. Shoji, I.; Kondo, T.; Kitamoto, A.; Shirane, M.; Ito, R. Absolute Scale of Second-Order Nonlinear-Optical Coefficients. *JOSA B* **1997**, *14*, 2268–2294. [[CrossRef](#)]
63. Dwivedi, S.; Ruocco, A.; Vanslebrouck, M.; Spuesens, T.; Bienstman, P.; Dumon, P.; Van Vaerenbergh, T.; Bogaerts, W. Experimental Extraction of Effective Refractive Index and Thermo-Optic Coefficients of Silicon-on-Insulator Waveguides Using Interferometers. *J. Light. Technol.* **2015**, *33*, 4471–4477. [[CrossRef](#)]
64. Arbabi, A.; Goddard, L.L. Measurements of the Refractive Indices and Thermo-Optic Coefficients of Si₃N₄ and SiO_x Using Microring Resonances. *Opt. Lett.* **2013**, *38*, 3878–3881. [[CrossRef](#)] [[PubMed](#)]
65. Riza, N.A.; Arain, M.; Perez, F. 6-H Single-Crystal Silicon Carbide Thermo-Optic Coefficient Measurements for Ultrahigh Temperatures up to 1273 K in the Telecommunications Infrared Band. *J. Appl. Phys.* **2005**, *98*, 103512. [[CrossRef](#)]
66. Shi, X.; Fan, W.; Hansen, A.K.; Chi, M.; Yi, A.; Ou, X.; Rottwitt, K.; Ou, H. Thermal Behaviors and Optical Parametric Oscillation in 4H-Silicon Carbide Integrated Platforms. *Adv. Photonics Res.* **2021**, *2*, 2100068. [[CrossRef](#)]
67. Lu, X.; Lee, J.Y.; Feng, P.X.-L.; Lin, Q. Silicon Carbide Microdisk Resonator. *Opt. Lett.* **2013**, *38*, 1304–1306. [[CrossRef](#)] [[PubMed](#)]
68. Moretti, L.; Iodice, M.; Della Corte, F.G.; Rendina, I. Temperature Dependence of the Thermo-Optic Coefficient of Lithium Niobate, from 300 to 515 K in the Visible and Infrared Regions. *J. Appl. Phys.* **2005**, *98*, 036101. [[CrossRef](#)]
69. Della Corte, F.G.; Cocorullo, G.; Iodice, M.; Rendina, I. Temperature Dependence of the Thermo-Optic Coefficient of InP, GaAs, and SiC from Room Temperature to 600 K at the Wavelength of 1.5 μm. *Appl. Phys. Lett.* **2000**, *77*, 1614–1616. [[CrossRef](#)]
70. Wang, C.; Fang, Z.; Yi, A.; Yang, B.; Wang, Z.; Zhou, L.; Shen, C.; Zhu, Y.; Zhou, Y.; Bao, R. High-Q Microresonators on 4H-Silicon-Carbide-on-Insulator Platform for Nonlinear Photonics. *Light Sci. Appl.* **2021**, *10*, 139. [[CrossRef](#)] [[PubMed](#)]

71. Li, J.; Poon, A.W. A 3C-SiC-on-Insulator-Based Integrated Photonic Platform Using an Anodic Bonding Process with Glass Substrates. *Micromachines* **2023**, *14*, 399. [\[CrossRef\]](#)
72. Glass, A.M.; Strait, J. The Photorefractive Effect in Semiconductors. In *Photorefractive Materials and Their Applications I: Fundamental Phenomena*; Springer: Berlin/Heidelberg, Germany, 2005; pp. 237–262.
73. Nagai, T.; Fujimura, R.; Shimura, T.; Kuroda, K. Photorefractive Effect in Undoped Aluminum Nitride. *Opt. Lett.* **2010**, *35*, 2136–2138. [\[CrossRef\]](#)
74. Available online: <https://www.inseto.co.uk/wafers/soi-wafers/> (accessed on 28 June 2024).
75. Available online: <https://www.ligentec.com/technology/> (accessed on 28 June 2024).
76. Available online: https://www.innotronix.com.cn/?page_id=2745 (accessed on 28 June 2024).
77. Available online: <https://www.powerwaywafer.com/sic-wafer/sic-wafer-substrate.html> (accessed on 28 June 2024).
78. Available online: <https://www.msosupplies.com/products/mse-pro-4-inch-undoped-3c-sic-epitaxial-wafer-on-silicon-epi-thickness-300nm?variant=39639133585466> (accessed on 28 June 2024).
79. Available online: <https://www.shalomeo.com/wafers-and-substrates/300-900nm-linbo3-lnoi/product-226.html> (accessed on 28 June 2024).
80. Lu, T.-J.; Fanto, M.; Choi, H.; Thomas, P.; Steidle, J.; Mouradian, S.; Kong, W.; Zhu, D.; Moon, H.; Berggren, K. Aluminum Nitride Integrated Photonics Platform for the Ultraviolet to Visible Spectrum. *Opt. Express* **2018**, *26*, 11147–11160. [\[CrossRef\]](#) [\[PubMed\]](#)
81. Available online: <https://www.powerwaywafer.com/gaas-wafers/gaas-wafer.html> (accessed on 28 June 2024).
82. Toma, A.; Brunetti, G.; Saha, N.; Ciminelli, C. Fully reconfigurable photonic filter for flexible payloads. *Appl. Sci.* **2024**, *14*, 488. [\[CrossRef\]](#)
83. Li, A.; Bogaerts, W. An actively controlled silicon ring resonator with a fully tunable Fano resonance. *APL Photonics* **2017**, *2*, 096101. [\[CrossRef\]](#)
84. Errando-Herranz, C.; Niklaus, F.; Stemme, G.; Gylfason, K.B. Low-power microelectromechanically tunable silicon photonic ring resonator add-drop filter. *Opt. Lett.* **2015**, *40*, 3556–3559. [\[CrossRef\]](#)
85. Saha, N.; Brunetti, G.; di Toma, A.; Armenise, M.N.; Ciminelli, C. Silicon Photonic Filters: A Pathway from Basics to Applications. *Adv. Photonics Res.* **2024**, 2300343. [\[CrossRef\]](#)
86. Jiang, H.; Luo, R.; Liang, H.; Chen, X.; Chen, Y.; Lin, Q. Fast Response of Photorefraction in Lithium Niobate Microresonators. *Opt. Lett.* **2017**, *42*, 3267–3270. [\[CrossRef\]](#) [\[PubMed\]](#)
87. Xu, Y.; Shen, M.; Lu, J.; Surya, J.B.; Sayem, A.A.; Tang, H.X. Mitigating Photorefractive Effect in Thin-Film Lithium Niobate Microring Resonators. *Opt. Express* **2021**, *29*, 5497–5504. [\[CrossRef\]](#)
88. Cardenas, J.; Zhang, M.; Phare, C.T.; Shah, S.Y.; Poitras, C.B.; Guha, B.; Lipson, M. High Q SiC Microresonators. *Opt. Express* **2013**, *21*, 16882–16887. [\[CrossRef\]](#)
89. Martini, F.; Politi, A. Linear Integrated Optics in 3C Silicon Carbide. *Opt. Express* **2017**, *25*, 10735–10742. [\[CrossRef\]](#)
90. Castelletto, S.; Almutairi, A.F.M.; Kumagai, K.; Katkus, T.; Hayasaki, Y.; Johnson, B.C.; Juodkazis, S. Photoluminescence in Hexagonal Silicon Carbide by Direct Femtosecond Laser Writing. *Opt. Lett.* **2018**, *43*, 6077–6080. [\[CrossRef\]](#)
91. Zhang, B.; He, S.; Yang, Q.; Liu, H.; Wang, L.; Chen, F. Femtosecond Laser Modification of 6H-SiC Crystals for Waveguide Devices. *Appl. Phys. Lett.* **2020**, *116*, 111903. [\[CrossRef\]](#)
92. Zhang, B.; Liu, H.; Wang, L.; Chen, F. Fabrication and Polarization Modulation of Waveguides in 4H-SiC Crystals by Femtosecond Laser Direct Writing. *Appl. Phys. A* **2022**, *128*, 651. [\[CrossRef\]](#)
93. Chen, J.; Liu, Z.; Song, L.; Sun, C.; Wang, G.; Cheng, Y. Ultra-High-Speed High-Resolution Laser Lithography for Lithium Niobate Integrated Photonics. In Proceedings of the Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XXIII, San Francisco, CA, USA, 28 January–3 February 2023; Volume 12411, p. 1241109.
94. Bruel, M.; Aspar, B.; Charlet, B.; Maleville, C.; Poumeyrol, T.; Soubie, A.; Auberton-Herve, A.J.; Lamure, J.M.; Barge, T.; Metral, F.; et al. “Smart Cut”: A Promising New SOI Material Technology. In Proceedings of the 1995 IEEE International SOI Conference Proceedings, Tucson, AZ, USA, 3–5 October 1995; pp. 178–179.
95. Di Cioccio, L.; Letertre, F.; Le Tiec, Y.; Papon, A.M.; Jaussaud, C.; Bruel, M. Silicon Carbide on Insulator Formation by the Smart-Cut® Process. *Mater. Sci. Eng. B* **1997**, *46*, 349–356. [\[CrossRef\]](#)
96. Joly, J.-P.; Aspar, B.; Bruel, M.; Di Cioccio, L.; Letertre, F.; Hugonnard-Bruyère, E. New SiC on Insulator Wafers Based on the Smart-Cut® Approach and Their Potential Applications. In *Progress in SOI Structures and Devices Operating at Extreme Conditions*; Balestra, F., Nazarov, A., Lysenko, V.S., Eds.; Springer: Dordrecht, The Netherlands, 2002; pp. 31–38. ISBN 978-94-010-0339-1.
97. Yi, A.; Zheng, Y.; Huang, H.; Lin, J.; Yan, Y.; You, T.; Huang, K.; Zhang, S.; Shen, C.; Zhou, M.; et al. Wafer-Scale 4H-Silicon Carbide-on-Insulator (4H-SiCOI) Platform for Nonlinear Integrated Optical Devices. *Opt. Mater.* **2020**, *107*, 109990. [\[CrossRef\]](#)
98. Song, B.-S.; Yamada, S.; Asano, T.; Noda, S. Demonstration of Two-Dimensional Photonic Crystals Based on Silicon Carbide. *Opt. Express* **2011**, *19*, 11084–11089. [\[CrossRef\]](#) [\[PubMed\]](#)
99. Langpoklakpam, C.; Liu, A.-C.; Chu, K.-H.; Hsu, L.-H.; Lee, W.-C.; Chen, S.-C.; Sun, C.-W.; Shih, M.-H.; Lee, K.-Y.; Kuo, H.-C. Review of Silicon Carbide Processing for Power MOSFET. *Crystals* **2022**, *12*, 245. [\[CrossRef\]](#)
100. Myers-Ward, R.L.; Hobart, K.D.; Daniels, K.M.; Giles, A.J.; Tadjer, M.J.; Luna, L.E.; Kub, F.J.; Pavunny, S.P.; Carter, S.G.; Banks, H.B.; et al. Processing of Cavities in SiC Material for Quantum Technologies. *Mater. Sci. Forum* **2018**, *924*, 905–908. [\[CrossRef\]](#)
101. Shi, X.; Lu, Y.; Chaussende, D.; Rottwitt, K.; Ou, H. Wet-Oxidation-Assisted Chemical Mechanical Polishing and High-Temperature Thermal Annealing for Low-Loss 4H-SiC Integrated Photonic Devices. *Materials* **2023**, *16*, 2324. [\[CrossRef\]](#)

102. Zhou, L.; Yi, A.; Su, Y.; Yang, B.; Zhu, Y.; Cai, J.; Wang, C.; Wu, Z.; Song, S.; Zhang, J.; et al. High-Q Adiabatic Micro-Resonators on a Wafer-Scale Ion-Sliced 4H-Silicon Carbide-on-Insulator Platform. *Opt. Lett.* **2023**, *48*, 6279–6282. [[CrossRef](#)]
103. Ko, S.-D.; Hamelin, B.; Yang, J.; Ayazi, F. High-Q Monocrystalline Silicon Carbide Disk Resonators Fabricated Using Drie of Thick SiC-on-Insulator Substrates. In Proceedings of the 2018 IEEE Micro Electro Mechanical Systems (MEMS), Belfast, UK, 21–25 January 2018; pp. 996–999.
104. Song, B.-S.; Asano, T.; Jeon, S.; Kim, H.; Chen, C.; Kang, D.D.; Noda, S. Ultrahigh-Q Photonic Crystal Nanocavities Based on 4H Silicon Carbide. *Optica* **2019**, *6*, 991–995. [[CrossRef](#)]
105. Guidry, M.A.; Yang, K.Y.; Lukin, D.M.; Markosyan, A.; Yang, J.; Fejer, M.M.; Vučković, J. Optical Parametric Oscillation in Silicon Carbide Nanophotonics. *Optica* **2020**, *7*, 1139–1142. [[CrossRef](#)]
106. Cai, L.; Li, J.; Wang, R.; Li, Q. Octave-Spanning Microcomb Generation in 4H-Silicon-Carbide-on-Insulator Photonics Platform. *Photonics Res.* **2022**, *10*, 870–876. [[CrossRef](#)]
107. Wang, R.; Li, J.; Cai, L.; Li, Q. Demonstration of 4H-Silicon Carbide on an Aluminum Nitride Integrated Photonic Platform. *Opt. Lett.* **2024**, *49*, 2934–2937. [[CrossRef](#)] [[PubMed](#)]
108. Fan, T.; Moradinejad, H.; Wu, X.; Eftekhar, A.A.; Adibi, A. High-Q Integrated Photonic Microresonators on 3C-SiC-on-Insulator (SiCOI) Platform. *Opt. Express* **2018**, *26*, 25814–25826. [[CrossRef](#)] [[PubMed](#)]
109. Fan, T.; Wu, X.; Eftekhar, A.A.; Bosi, M.; Moradinejad, H.; Woods, E.V.; Adibi, A. High-Quality Integrated Microdisk Resonators in the Visible-to-near-Infrared Wavelength Range on a 3C-Silicon Carbide-on-Insulator Platform. *Opt. Lett.* **2020**, *45*, 153–156. [[CrossRef](#)]
110. Li, J. *Nonlinear and Quantum Light Sources Based on an Integrated 3C-Silicon Carbide-on-Insulator Photonic Platform*; The Hong Kong University of Science and Technology: Clear Water Bay, Hong Kong, 2023.
111. Powell, K.; Shams-Ansari, A.; Desai, S.; Austin, M.; Deng, J.; Sinclair, N.; Lončar, M.; Yi, X. High-Q Suspended Optical Resonators in 3C Silicon Carbide Obtained by Thermal Annealing. *Opt. Express* **2020**, *28*, 4938–4949. [[CrossRef](#)] [[PubMed](#)]
112. Ishida, Y.; Takahashi, T.; Okumura, H.; Arai, K.; Yoshida, S. Effect of Reduced Pressure on 3C-SiC Heteroepitaxial Growth on Si by CVD. *Chem. Vap. Depos.* **2006**, *12*, 495–501. [[CrossRef](#)]
113. Zheng, Y.; Pu, M.; Yi, A.; Chang, B.; You, T.; Huang, K.; Kamel, A.N.; Henriksen, M.R.; Jørgensen, A.A.; Ou, X. High-Quality Factor, High-Confinement Microring Resonators in 4H-Silicon Carbide-on-Insulator. *Opt. Express* **2019**, *27*, 13053–13060. [[CrossRef](#)] [[PubMed](#)]
114. Guidry, M.A.; Lukin, D.M.; Yang, K.Y.; Trivedi, R.; Vučković, J. Quantum Optics of Soliton Microcombs. *Nat. Photonics* **2022**, *16*, 52–58. [[CrossRef](#)]
115. Zheng, Y.; Pu, M.; Yi, A.; Ou, X.; Ou, H. 4H-SiC Microring Resonators for Nonlinear Integrated Photonics. *Opt. Lett.* **2019**, *44*, 5784–5787. [[CrossRef](#)]
116. Fortier, T.; Baumann, E. 20 Years of Developments in Optical Frequency Comb Technology and Applications. *Commun. Phys.* **2019**, *2*, 153. [[CrossRef](#)]
117. Boyd, R.W. *Nonlinear Optics*, 3rd ed.; Boyd, R.W., Ed.; Academic: Burlington, NJ, USA, 2008.
118. Yang, J.; Guidry, M.A.; Lukin, D.M.; Yang, K.; Vučković, J. Inverse-Designed Silicon Carbide Quantum and Nonlinear Photonics. *Light Sci. Appl.* **2023**, *12*, 201. [[CrossRef](#)] [[PubMed](#)]
119. Moutzouris, K.; Rao, S.V.; Ebrahimzadeh, M.; De Rossi, A.; Calligaro, M.; Ortiz, V.; Berger, V. Second-Harmonic Generation through Optimized Modal Phase Matching in Semiconductor Waveguides. *Appl. Phys. Lett.* **2003**, *83*, 620. [[CrossRef](#)]
120. Luo, R.; He, Y.; Liang, H.; Li, M.; Ling, J.; Lin, Q. Optical Parametric Generation in a Lithium Niobate Microring with Modal Phase Matching. *Phys. Rev. Appl.* **2019**, *11*, 034026. [[CrossRef](#)]
121. Troha, T.; Rigler, M.; Alden, D.; Bryan, I.; Guo, W.; Kirste, R.; Mita, S.; Gerhold, M.D.; Collazo, R.; Sitar, Z. UV Second Harmonic Generation in AlN Waveguides with Modal Phase Matching. *Opt. Mater. Express* **2016**, *6*, 2014–2023. [[CrossRef](#)]
122. Dumeige, Y.; Feron, P. Whispering-Gallery-Mode Analysis of Phase-Matched Doubly Resonant Second-Harmonic Generation. *Phys. Rev. A* **2006**, *74*, 063804. [[CrossRef](#)]
123. Kuo, P.S.; Fang, W.; Solomon, G.S. 4-Quasi-Phase-Matched Interactions in GaAs Microdisk Cavities. *Opt. Lett.* **2009**, *34*, 3580–3582. [[CrossRef](#)] [[PubMed](#)]
124. Li, J.; Wang, R.; Afridi, A.A.; Lu, Y.; Shi, X.; Sun, W.; Ou, H.; Li, Q. Efficient Raman Lasing and Raman–Kerr Interaction in an Integrated Silicon Carbide Platform. *ACS Photonics* **2024**, *11*, 795–800. [[CrossRef](#)] [[PubMed](#)]
125. Wang, C.; Li, J.; Yi, A.; Fang, Z.; Zhou, L.; Wang, Z.; Niu, R.; Chen, Y.; Zhang, J.; Cheng, Y. Soliton Formation and Spectral Translation into Visible on CMOS-Compatible 4H-Silicon-Carbide-on-Insulator Platform. *Light Sci. Appl.* **2022**, *11*, 341. [[CrossRef](#)]
126. Rahmouni, A.; Wang, R.; Li, J.; Tang, X.; Gerrits, T.; Slattery, O.; Li, Q.; Ma, L. Entangled Photon Pair Generation in an Integrated SiC Platform. *Light Sci. Appl.* **2024**, *13*, 110. [[CrossRef](#)]
127. Zeng, D.; Liu, Q.; Mei, C.; Li, H.; Huang, Q.; Zhang, X. Demonstration of Ultra-High-Q Silicon Microring Resonators for Nonlinear Integrated Photonics. *Micromachines* **2022**, *13*, 1155. [[CrossRef](#)] [[PubMed](#)]
128. Wang, C.; Zhang, M.; Yu, M.; Zhu, R.; Hu, H.; Loncar, M. Monolithic lithium niobate photonic circuits for Kerr frequency comb generation and modulation. *Nat. Commun.* **2019**, *10*, 978. [[CrossRef](#)] [[PubMed](#)]
129. Liu, X.; Gong, Z.; Bruch, A.W.; Surya, J.B.; Lu, J.; Tang, H.X. Aluminum nitride nanophotonics for beyond-octave soliton microcomb generation and self-referencing. *Nat. Commun.* **2021**, *12*, 5428. [[CrossRef](#)] [[PubMed](#)]

130. Xie, W.; Chang, L.; Shu, H.; Norman, J.C.; Peters, J.D.; Wang, X.; Bowers, J.E. Ultrahigh-Q AlGaAs-on-insulator microresonators for integrated nonlinear photonics. *Opt. Express* **2020**, *28*, 32894–32906. [[CrossRef](#)]
131. Matsuda, N.; Le Jeannic, H.; Fukuda, H.; Tsuchizawa, T.; Munro, W.J.; Shimizu, K.; Yamada, K.; Tokura, Y.; Takesue, H. A Monolithically Integrated Polarization Entangled Photon Pair Source on a Silicon Chip. *Sci. Rep.* **2012**, *2*, 817. [[CrossRef](#)] [[PubMed](#)]
132. Zhang, Q.; Wu, K.; Poon, A.W. Polarization Entanglement Generation in Silicon Nitride Waveguide-Coupled Dual Microring Resonators. *Opt. Express* **2024**, *32*, 22804–22816. [[CrossRef](#)]
133. Carral, G.M.; Liñares, J.; Mateo, E.F.; Prieto-Blanco, X. Bell-State-Exchange-Parity-Based Protocol for Efficient Autocompensation of Quantum Key Distribution Encoded in Polarization or Spatial Modes. *Appl. Sci.* **2023**, *13*, 12907. [[CrossRef](#)]
134. Chauhan, N.; Wang, J.; Bose, D.; Liu, K.; Compton, R.L.; Fertig, C.; Hoyt, C.W.; Blumenthal, D.J. Ultra-Low Loss Visible Light Waveguides for Integrated Atomic, Molecular, and Quantum Photonics. *Opt. Express* **2022**, *30*, 6960–6969. [[CrossRef](#)] [[PubMed](#)]
135. Hoffman, L.; Subramanian, A.; Helin, P.; Du Bois, B.; Baets, R.; Van Dorpe, P.; Gielen, G.; Puers, R.; Braeken, D. Low Loss CMOS-Compatible PECVD Silicon Nitride Waveguides and Grating Couplers for Blue Light Optogenetic Applications. *IEEE Photonics J.* **2016**, *8*, 2701211. [[CrossRef](#)]
136. Ojambati, O.S.; Chikkaraddy, R.; Deacon, W.D.; Horton, M.; Kos, D.; Turek, V.A.; Keyser, U.F.; Baumberg, J.J. Quantum Electrodynamics at Room Temperature Coupling a Single Vibrating Molecule with a Plasmonic Nanocavity. *Nat. Commun.* **2019**, *10*, 1049. [[CrossRef](#)]
137. Castelletto, S. Silicon Carbide Single-Photon Sources: Challenges and Prospects. *Mater. Quantum Technol.* **2021**, *1*, 023001. [[CrossRef](#)]
138. Castelletto, S.; Boretti, A. Silicon Carbide Color Centers for Quantum Applications. *J. Phys. Photonics* **2020**, *2*, 022001. [[CrossRef](#)]
139. Fuchs, F.; Stender, B.; Trupke, M.; Simin, D.; Pflaum, J.; Dyakonov, V.; Astakhov, G. V Engineering Near-Infrared Single-Photon Emitters with Optically Active Spins in Ultrapure Silicon Carbide. *Nat. Commun.* **2015**, *6*, 7578. [[CrossRef](#)] [[PubMed](#)]
140. Castelletto, S.; Johnson, B.C.; Ivády, V.; Stavrias, N.; Umeda, T.; Gali, A.; Ohshima, T. A Silicon Carbide Room-Temperature Single-Photon Source. *Nat. Mater.* **2014**, *13*, 151–156. [[CrossRef](#)]
141. Wang, J.-F.; Liu, Z.-H.; Yan, F.-F.; Li, Q.; Yang, X.-G.; Guo, L.; Zhou, X.; Huang, W.; Xu, J.-S.; Li, C.-F. Experimental Optical Properties of Single Nitrogen Vacancy Centers in Silicon Carbide at Room Temperature. *ACS Photonics* **2020**, *7*, 1611–1616. [[CrossRef](#)]
142. Crook, A.L.; Anderson, C.P.; Miao, K.C.; Bourassa, A.; Lee, H.; Bayliss, S.L.; Bracher, D.O.; Zhang, X.; Abe, H.; Ohshima, T. Purcell Enhancement of a Single Silicon Carbide Color Center with Coherent Spin Control. *Nano Lett.* **2020**, *20*, 3427–3434. [[CrossRef](#)]
143. Shi, X.; Zhang, J.; Fan, W.; Lu, Y.; Peng, N.; Rottwitt, K.; Ou, H. Compact Low-Birefringence Polarization Beam Splitter Using Vertical-Dual-Slot Waveguides in Silicon Carbide Integrated Platforms. *Photonics Res.* **2022**, *10*, A8–A13. [[CrossRef](#)]
144. Shi, X.; Lu, Y.; Ou, H. High-Performance Silicon Carbide Polarization Beam Splitting Based on an Asymmetric Directional Couplers for Mode Conversion. *Opt. Lett.* **2023**, *48*, 616–619. [[CrossRef](#)]
145. Shi, X.; Lu, Y.; Peng, N.; Rottwitt, K.; Ou, H. High-Performance Polarization-Independent Beam Splitters and MZI in Silicon Carbide Integrated Platforms for Single-Photon Manipulation. *J. Light. Technol.* **2022**, *40*, 7626–7633. [[CrossRef](#)]
146. Li, J.; Poon, A.W. On-Chip Passive Pump-Rejection Long-Pass Filters for Integrated SiC-Based Nonlinear and Quantum Photonic Chips. *Opt. Lett.* **2024**, *49*, 411–414. [[CrossRef](#)]
147. Šimko, F.; Lenčič, Z.; Kim, Y.-W.; Nosko, M.; Kontrik, M.; Korenko, M. High Temperature Corrosion Resistance of Electrically Conductive Nitrogen Doped Silicon Carbide Ceramics in Molten Fluorides. *J. Eur. Ceram. Soc.* **2023**, *43*, 3931–3940. [[CrossRef](#)]
148. Soltys, L.M.; Mirnyuk, I.F.; Mykytyn, I.M.; Hnylytsia, I.D.; Turovska, L.V. Synthesis and Properties of Silicon Carbide. *Phys. Chem. Solid State* **2023**, *24*, 5–16. [[CrossRef](#)]

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