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Review of Recent Progress on Silicon Nitride-Based Photonic Integrated Circuits

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ABSTRACT Silicon photonic devices used in the photonics industry over the past three decades have helped in realizing large-scale photonic integrated circuits. Silicon nitride (Si_3N_4) is another CMOS-compatible platform that provides several advantages such as low loss, high optical power tolerance, and broad spectral operation band from visible to infrared wavelengths. Recently, the combination of Si_3N_4 waveguide technology with silicon photonics and III-V materials has opened up new areas in on-chip applications. Researchers in the field are primarily focusing on its applications such as on-chip gas sensing, nonlinear optical signal processing, and label-free biosensors based on photonic integrated circuits. In this review paper, we discuss Si_3N_4 material-based platforms for a variety of applications with devices ranging from passive to active and hybrid photonic devices.

INDEX TERMS Grating coupler, microring resonator, photonic integrated circuits, silicon nitride.

I. INTRODUCTION

Recently, high-performance communication systems have been in a huge demand that can only be dealt with by large-scale photonic solutions and super-channel transmissions. These new technologies such as super-channel transmission, large-scale photonic integration, high-level quadrature amplitude modulation (QAM), and faster-than-Nyquist (FTN) are being introduced, which helps in the increase of channel data rate to beyond 1 Tb/s. Easy fabrication of the very complex photonic integrated circuits (PICs) for optical communication provided by silicon chip-based integrated optics technology and other variants like InP and Si_3N_4 has been attracting considerable interest from the researchers in recent years. The complexity of optical components and stability issues are eliminated by these types of integrated optical technology platform. The compact footprint, low power consumption, and cost-effectiveness of the system have been enhanced by PIC. Further, the high density, high data rates, and flexible solutions in telecommunications and other fields like gas sensing have also got enabled with the use of PIC. This silicon chip-based integrated optics technology has witnessed rapid changes and growth since the 1980s. The compatibility of Si photonics with CMOS technology makes it low cost with a high volume of production. However, all the needs and requirements of photonic devices cannot be addressed by focusing only on Si alone as it has its shortcomings as a photonics material [1]. For example, Si has the drawback of low bandgap (corresponding to the wavelength of $\approx 1\mu$m), which ultimately limits the operational wavelengths to the infrared. Furthermore, due to the high optical intensity required for the nonlinear frequency conversion, nonlinear losses can arise from the material, due to free carrier absorption caused by two-photon absorption (TPA), when pumped in the near-infrared (below the wavelength of 2.2μm) [2], [3].

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To address these shortcomings of Si, silicon nitride (Si_3N_4) material came into being in the last decade, where Si_3N_4 replaces the Si core of silicon-on-insulator (SOI) devices [4], [5]. The combination of Si_3N_4 with SOI and III-V photonics has opened up the new platforms for the on-chip applications. In this direction, Si_3N_4 proves to be a better passive CMOS-compatible material compared with Si owing to its various advantages, such as a moderate refractive index (RI) of ~1.98, lower sidewall roughness,scattering loss with very high tolerance to dimension variations, and free from TPA. The use of Si_3N_4 in place of Si without leaving the CMOS fabrication facility helps us to deal with the limitations of the SOI platform.

Si_3N_4 is used for different applications, ranging from passive to active devices and nonlinear optics [6]–[9]. In this direction, different optical components of Si_3N_4 and Si_3N_4 on SOI platforms have been demonstrated recently, such as antennas, arrayed waveguide gratings, grating couplers, and polarization rotator and beam-splitters [10]–[15]. The multilayered stack integration of Si_3N_4 with different materials for the different applications is still a challenging task [16]–[21]. Thus, different types of modulators [22]–[29], resonators [30]–[35], and photodetectors [36]–[39] based on Si_3N_4 have been introduced in the field from time to time. The nonlinear functionality and gas sensing with on-chip broadband light sources have also been realized using silicon nitride from near-IR to mid-IR wavelengths [39]–[43]. Despite these advantages of Si_3N_4, the fabrication and integration of large-scale photonic devices based on thick low-pressure chemical vapor deposition (LPCVD) methods are challenging tasks. The adjustment of inductively coupled plasma (ICP) reactor and the etch selectivity between Si_3N_4 and photoresist in the multilayered etching of Si_3N_4 based devices is still a challenging task that needs to be addressed for hybrid photonic devices. The high-stressed deposition affects the uniformity of the process and becomes paramount for good circuit performances. The dielectric nature of Si_3N_4 lacks in the realization of high-speed modulation and many other approaches that rely on the conductivity of doped Si waveguide cannot be used with Si_3N_4 alone. The integration of detectors with only Si_3N_4 for 1.3/1.5 μm wavelengths is a challenging task [44].

One way to incorporate active devices with Si_3N_4 is devising the hybrid Si_3N_4/SOI platform where the Si layer mainly serves as an active layer for modulators because it is helpful in cost-efficient small form factor coherent modulators influencing scalable silicon photonic architectures, and giving higher levels of integration than InP or $LiNbO_3$ for high baud rate datacenter interconnect demands. Another way to incorporate active functionalities with Si_3N_4 is to integrate 2D materials such as transition metal dichalcogenides (TMDCs) and graphene for active photonic devices such as high-speed modulators, optical switching [24]–[29], and photodetectors [36]–[38]. Figure 1 depicts the schematic for the three basic integrated photonics technology platforms used for passive and active optical components. Figure 1(a) shows the simple SOI platform as it is used as a most basic form of technology for passive optical components, such as splitter, filters, and de-multiplexers. The Si_3N_4 platform is shown in Fig. 1(b), which has a larger transparency window with low loss and good layer stack flexibility due to the much broader wavelength transparency range between 500 nm and 3.7 μm of Si_3N_4. Besides this, two-photon absorption is also absent over awide wavelength range. The hybrid platform with Si_3N_4 on SOI is shown in Fig. 1(c), which has the flexibility for the combination of SOI with Si_3N_4 on a single chip.

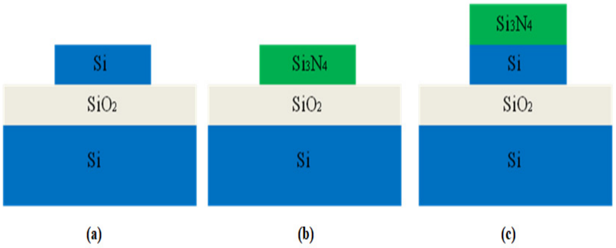


FIGURE 1. Schematics of integrated photonic platforms. (a)SOI platform. (b)Silicon nitride platform. (c)Hybrid Si_3N_4/Si platform.

Each integration platform requires the trade-off between propagation losses and bend radius. The strong confinement of light in the Si waveguide core leads to compact PICs with small bending radius and low loss. Si_3N_4 photonics, a third integration platform works on a spectral range from visible to beyond the infrared with low optical attenuation, which is not accessible with other platforms. The waveguide provided by Indium phosphide (InP) gives efficient signal modulation and optical gain at telecommunication wavelengths. However, InP has been seen as a trade-off between larger bend radii and higher waveguide loss (2 to 0.4 dB/cm) compared with SOI waveguides [45].

Further, the InP to silica waveguide coupling loss limits the performance of the device. To deal with the issue of on-chip losses and to offer the low loss with compactness in the range of 0.3 dB/m to 1.0 dB/cm over the wavelength range from 400 nm to 2350 nm, the optical waveguide with a core layer of Si_3N_4 has been used widely in comparison to the InP waveguides which have low transmission window. Besides this, there are III-V (AlGaAs) and InGaP material on insulator platforms which are used for the demonstration of nonlinear platforms with ultra-high device nonlinearity at telecom wavelengths for on-chip pumped comb generation [46], [47]. Figure 2 shows the propagation loss in the waveguide for the minimum bending radius for Si_3N_4, SOI, and InP waveguides [48]–[50].

The Si_3N_4 platforms alone and with III-V materials have broadly been used for the polarization rotation and modulators [51]–[55], resonators and photodetectors [56]–[65], grating couplers [14], [66]–[69], sensing applications [70]–[73], high-performance lasers on-chip, delay lines, optical filters, and optical frequency comb generation [74], [75] polarization beam splitters and couplers [76]–[79]. The foundries all over

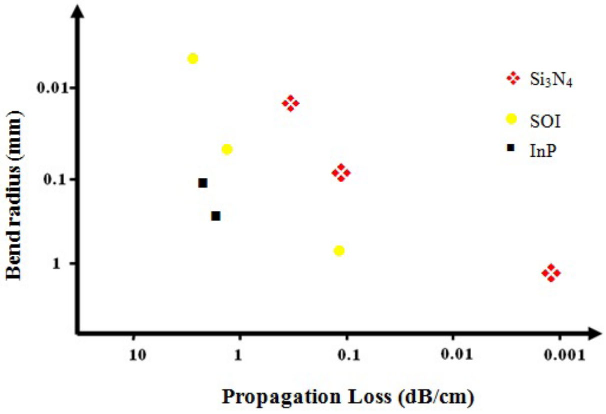


FIGURE 2. Si_3N_4, SOI, and InP waveguide bending radius with propagation loss.

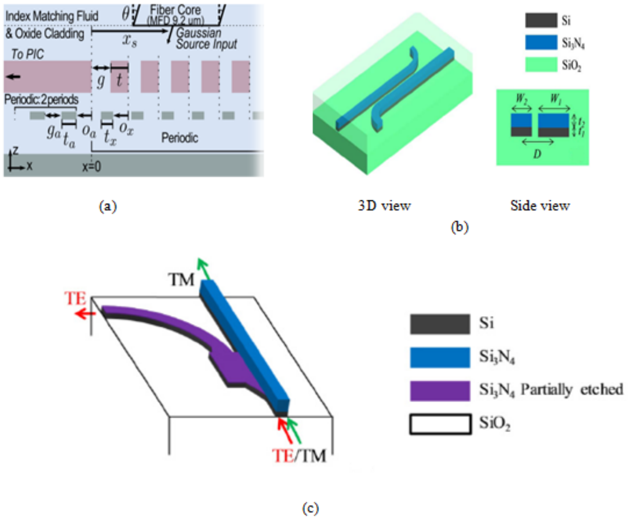
the world, such as CEA-Leti, AIM photonics, ST microelectronics, and others have announced Si photonics as a platform that integrates Si_3N_4 waveguide layer onto Si waveguides for various applications [80]–[88]. As the world is moving towards the high signal bandwidth and data rate, Si_3N_4 waveguide technology with SOI and III-V platform has recently opened up the new quarters for on-chip applications.

This review paper has been addressing the importance of Si_3N_4 waveguide technology as an integration platform for silicon photonics. This review paper shows the current research survey done by the researchers worldwide on Si_3N_4 for a variety of devices ranging from passive to active and sensing applications. The paper is detailed as follows: Section II has discussed the application of Si_3N_4 for passive devices such as splitters, demultiplexers, grating couplers, resonators, and polarization management devices. In Section III, the applications of Si_3N_4 for active devices have been discussed. The hybrid integration of Si_3N_4 for various photonic integrated circuits has been demonstrated in Section IV. The paper ends up with section V, giving a prospect of these technologies for future applications.

II. Si_3N_4 FOR PASSIVE PHOTONIC INTEGRATED CIRCUITS

Si_3N_4 has drawn the attention of researchers in the field for a variety of passive photonic devices from visible to near-infrared wavelengths. Si_3N_4 has offered itself as an improved CMOS-compatible material than Si in many ways. When the high temperature deposition is used for Si_3N_4, an absorption peak appears at 1520 nm due to residual N-H bonds and film stresses. However, the benefits of Si_3N_4 over Si have led to the demonstration of Si waveguides integrated into Si_3N_4 platforms and Si_3N_4 waveguides integrated on Si photonic platforms to merge the passive optical routing layers of Si_3N_4 with active functionality in Si. In the given section, we have discussed the various types of passive devices based on the Si_3N_4 platform.

Grating-based passive devices based on the Si_3N_4 platform have been demonstrated by different research groups all over the world. The experimental illustration of an apodized grating coupler on the Si_3N_4 platform is shown in [23]. They experimentally achieved a peak coupling efficiency of -1.5 dB and 3 dB bandwidth of 60 nm in the C band. A peak fiber-to-chip coupling efficiency of -2.2 dB with 1 dB bandwidth of around 73 nm in the O band is achieved in [77] using a bi-layer grating coupler on the Si_3N_4-on-SOI platform, as shown in Fig. 3(a). The issue of beam divergence and field of view in the grating coupler has been taken care of in [78]. They demonstrated a Si_3N_4-on-SOI grating coupler which simultaneously achieves the maximum field of view with the minimal beam divergence by maintaining the robustness to fabrication variations. This fabrication process helps in the demonstration of beam divergence of 0.089° for a millimeter long waveguide. This type of platform has been used for potential applications in phased arrays such as light detection and ranging, wireless communications, and particle trapping. A dual-band grating coupler on the 700 nm thick Si_3N_4 platform for O and C band coupling for the single-state polarization i.e. (TE) was proposed in [17]. The TE_{00} mode is for C band coupling and TE_{01} mode for O band coupling. A bottom reflector based high efficiency apodized grating coupler with Si_3N_4 photonic integrated circuits is presented in [83]. Their single etch CMOS compatible design gives the measured peak coupling efficiency of -1.75 dB and a 3 dB wavelength bandwidth of 76.34 nm with a 20-layerreflector. A highly efficient Si_3N_4 based grating coupler with the bottom distributed Bragg reflectors was experimentally demonstrated in [84]. The reported peak coupling efficiency on the 500 nm thick $Si_3N_4$is -2.29 dB obtained at 1573 nm with 1 dB bandwidth of 49 nm. Similarly, the peak coupling efficiency of -2.58 dB at 1576 nm with 1 dB bandwidth of 52 nm is obtained on the 400 nm thick Si_3N_4. A low loss LPCVD based Si_3N_4 platform with a coupling loss of -6.5 dB at 1541 nm and 1 dB bandwidth of 55 nm was proposed in [85].



(a)

3D view

Side view

(b)

(c)

FIGURE 3. Si_3N_4 **based passive devices. (a) The side view of the geometry for 1D uniform bi-layer grating coupler. (b) 3D view of the polarization rotator and side view of the coupling region. (c) 3D view of proposed polarization beam splitter [79]. Fig. 3(a) is reprinted with permission from Ref. [77], Copyright ©2018 Optical Society of America (OSA). Fig. 3(b) is reprinted with permission from Ref. [54], Copyright ©2016 OSA. Fig. 3(c) is reprinted with permission from Ref. [79] Copyright ©2017 OSA.**

TABLE 1. Comparison of passive devices based on different platforms.

Devices	Platform	Property
Grating Coupler	Si_3N_4 waveguide [21]	Peak coupling efficiency: -1.5 dB (1550 nm);3 dB bandwidth: 60 nm.
	Si_3N_4-on- Si photonic platform [22]	Peak coupling efficiency: -2.1dB (1490 nm); 1dB bandwidth: 69 nm.
	Si_3N_4 waveguide [23]	Peak coupling efficiency: -1.5 dB(1550 nm); 1 dB bandwidth: 53 nm.
	Si_3N_4-on- Si photonic platform [77]	Peak coupling efficiency: -2.2 dB; 1 dB bandwidth: 73 nm in the O band.
Polarization rotation/splitter devices(PR)	Si_3N_4-Si waveguide [14]	Polarization crosstalk: < -19 dB; Insertion loss: <1.5 dB;Polarization dependent loss: <1.0 dB; Bandwidth of 80 nm (1500 nm- 1580 nm); TM0-TE1 mode conversion.
	Si_3N_4-Si dual core waveguide [56]	The TE-to-TM & TM-to-TE rotation for mode peak conversion efficiencies: 97%; The polarization extinction ratio for TE-to-TM rotation > 20 dB over 50 nm bandwidth in C- band.
	Si_3N_4-Si dual core waveguide[79]	Insertion loss <1 dB for both TM &TE polarizations;TE Polarization extinction ratio: 25 dB; TM Polarization extinction ratio: 17 dB.
Micro-resonators	Si_3N_4 platform [32]	Q-factors: 3.7 × 106; Broadband temporal DKS based frequency comb generation with 3 dB bandwidth of 6.6 THz.
	Si_3N_4 platform [74]	Quality factor: 17 million;Free spectrum range: 24.7 GHz; Frequency comb onset power: 2.36 mW;Single FSR combs generated at a low pump power: 24 mW.
	Si_3N_4-$LiNbO_3$ [75]	Quality factor:1.85×10^5, Ring propagation loss, 0.32 dB/cm; Spectral linewidth: 13 pm; Resonance extinction ratio: 27 dB.

On the other hand, the Si_3N_4-on-SOI platform has been demonstrated for various types of polarization rotation (PR) devices. The demonstration of the fabrication and characterization of a PR based on the Si_3N_4-on-SOI platform is mainly helpful in transverse electric (TE) mode to transverse magnetic (TM) mode conversion and vice versa [48], as shown in Fig. 3(b). The measured conversion efficiency is obtained as 97% for the reported device. The PR splitter and the polarization controller were proposed by [14] on the Si_3N_4-on-SOI platform. This adiabatic design has features of the broader spectral band and larger fabrication tolerance than previously reported work on Si_3N_4-on-SOI PR [68]. The compact polarization beam splitter on the Si_3N_4-on-SOI platform is proposed in [79]. Their concept of low index region in which thin Si and Si_3N_4 layer work as a core after the TE and TM polarization controlled by varying the waveguide dimensions is shown in Fig. 3(c). The low-index input waveguide of the device is connected to the asymmetric MMI section and split into two different polarization sections. The polarization extinction ratios for TM to TE at bar port and TE to TM at the cross port are 17 dB and 25 dB, respectively. A vertical symmetric waveguide formed with Si_3N_4 and Si layer for the adiabatic transformation of fundamental TM mode to first order TE mode was proposed in [69], which is based on the angled multimode interferometer structure and used for the fluorescence sensing application in the visible light.

The experimentally demonstrated broadband and low-loss 2×2 polarization beam splitter based on the Si_3N_4 platform has minimum insertion losses of 0.13 dB and 0.34 dB for TE and TM polarization, with extinction ratios over 20 dB from 1530 to 1610 nm in [86]. Moreover, micro-resonators based on the Si_3N_4 platform have also been studied widely, especially for portable and low-cost biochemical sensing applications and nonlinear applications [74], [75]. The nonlinear application based on the micro-resonators on the Si_3N_4 platform is listed in Table 1. The low detection limit and high quality (Q) factor for high sensitivity detection are given by [14] and [69]. In this regard, the Mach-Zehnder interferometer (MZI) based interferometer structure [72] has been adopted as integrated interferometric biochemical sensors. Based on this design, a coupled resonator-based optical waveguide (CROW) for biochemical sensors in the visible wavelength on the Si_3N_4 platform was demonstrated

TABLE 2. Comparison of active devices based on different platforms.

Devices	Platform	Property
Modulator and Switching	Si_3N_4 platform with graphene [24]	Bandwidth of 30 GHz; Modulation efficiency of 15 dB /10 V.
	Si and Si_3N_4 waveguide platform [25]	Modulation rate of 25-GBit/s; Extinction ratio of 5 dB on Si waveguide; Extinction ratio of 23 dB on Si_3N_4waveguide.
	Si_3N_4 platform with graphene [26]	The modulation bandwidth of 30.6GHz; Extinction ratio of 0.1658dB/µm;
	Si_3N_4 platform with zirconatetitanate (PZT) [27]	The bandwidth of 33 GHz; low propagation loss of 1 dB/ cm; Half-wave voltage length of 3.2 Vcm.
	Si_3N_4/SiO2/Si layers [53]	Half-wave voltage-length of 1.02 Vmm; Operating speed of 50 MHz
Photodetector	Graphene with Si_3N_4 waveguide [36-37]	The responsivity of 126mA/W. Dynamic response of 1kHz; Waveguide absorption loss of 0.025 dB/µm.
	Graphene-on- Si_3N_4 waveguide [56]	Bandwidth of 30 GHz; Intrinsic responsively of 15 mA/W at 1550 nm.
	III-V photodetectors-on- Si_3N_4 platform [93]	Bandwidth of 80 GHz.

by [73]. The CROW sensors have the capacity for the future smartphone-based point of care applications. Besides the advantages of Si_3N_4 to be compatible with the integrated circuits, the fabrication allows the multiple resonators to be coupled together to achieve narrowband selectivity and compact footprint. Further, the Si_3N_4 microring resonator with a high Q factor and large free spectral range has been demonstrated [33]. The reported microring resonator has a free spectral range of 2.72 GHz with an 80 dB ultra high extinction ratio tunable over a free spectral range of 100% and with an insertion loss less than 1.3 dB. A backend monolithic integration of Si_3N_4 microring filter with the bulk (CMOS) integrated circuit has been accomplished in [80]. Further, the Si_3N_4 photonic layer is integrated on the top surface of the CMOS IC die which is manufactured in the commercial CMOS foundry. Recently, Si_3N_4 microring filters for resonant wavelength stabilization with monolithic integration of CMOS temperature control circuit is demonstrated in [81]. They proposed Si_3N_4 microring filters which are almost immune to environment temperature changes due to the automatic temperature control.

III. Si_3N_4 FOR ACTIVE PHOTONIC INTEGRATED CIRCUITS

In this section, the growth and development of flexible multilayered Si_3N_4-on-Si platforms have been discussed. In the 1.3-1.6 μm wavelength range, Si is transparent, and SiO_2 has a lower refractive index than Si, enabling it for submicron waveguides.

As silicon photonics devices are very sensitive to geometry variations during the CMOS fabrication, researchers in the field have integrated Si_3N_4 material to extend its capability for the Si photonics platform and found Si_3N_4 as particularly attractive for passive photonics devices owing to many advantages over the SOI platform. But for active photonic devices fabricated at high temperatures, Si_3N_4 would cause undesirable doping diffusion which rules out its capability for integration of optoelectronics devices alone. To overcome this limitation, researchers have produced stress-free Si_3N_4 and obtained an integrated platform by combing Si_3N_4/Si with graphene and other integrated multilayered waveguides for active photonic devices such as high-speed modulation, switching [24]–[29], and photodetection [36]–[38]. In the given section, the recent progress in the field of active photonic devices based on the Si_3N_4 materials has been discussed. The main advantages of the optical modulators are its speed, device voltage, modulation depth, compactness, optical loss, temperature sensitivity, wavelength range, and polarization dependence. Thus, different types of modulators with Si_3N_4 material are summarized here. The phase modulator and vertical coupling taper on the Si_3N_4-on-Si platform proposed in [55] give half voltage length product of 1.02 V · mm with a chirp factor of 18.42. The phase modulators proposed on SOI and Si_3N_4 platforms have trade-offs between speed and efficiency. The graphene has evolved as a new material which in combination with Si_3N_4 gives enormously speedy and broadband electro-optic devices because of its merit of high carrier mobility and broadband absorption.

To overcome the trade-off between speed and efficiency by exploiting the critical coupling effects, a high-speed graphene on Si_3N_4-on-Si modulator was demonstrated [25]. In this work, they have targeted the on-off switching of guided-mode at telecombands of 1310 nm and 1550 nm wavelengths. The parametric optimization of the device is done for waveguide dimensions (height and width), device length, contact spacing, and material platform (Si and Si_3N_4). Recently, [27] demonstrated the efficient and high-speed modulator on the Si_3N_4 platform, which gives 33 GHz modulation bandwidth in both the O and C band with the bias-free operation. This work used a novel approach for the co-integration of thin-film piezoelectric lead zirconatetitanate (PZT) on the Si_3N_4 waveguides as shown in the microscopic image and scanning electron microscope (SEM) image of Figure 4(a) and (b), respectively. On the other hand, the prerequisites for photodetectors (PDs) are the lowest possible power consumption and compatibility with Si technology while maintaining high performance in terms of efficiency, bandwidth, and

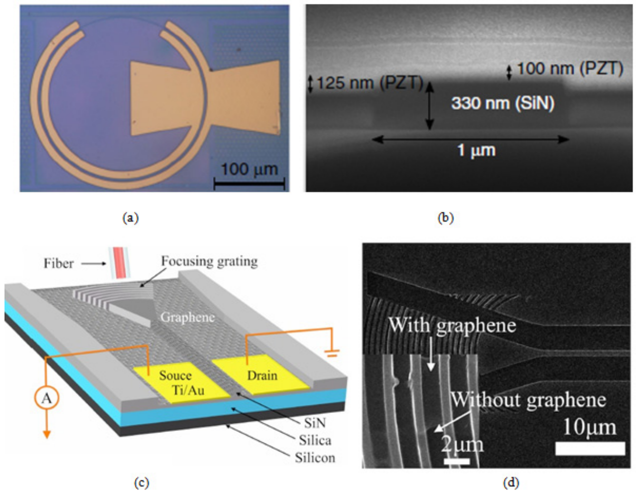


FIGURE 4. **Si_3N_4 based active devices. (a) Microscopic image of the microring modulator. (b) SEM image of a PZT-covered silicon nitride waveguide [29]. (c) Schematic of the PD with graphene on the Si_3N_4 waveguide. (d) SEM image of areas with graphene and without graphene [33]. Fig. 4(a) and (b) are reprinted with permission from Ref. [27], Copyright ©2018 Springer Nature. Fig. 4(c) and (d) is reprinted with permission from Ref. [36], Copyright ©2015 American Institute of Physics.**

optical loss. Most PDs are introduced on III-V materials with CMOS incompatibility at a high cost and harmful to the environment.In [36] a graphene-based photodetector integrated on the Si_3N_4 ridge waveguide was demonstrated, as shown in Figure 4(c) and (d), which has a responsivity of 126 mA/W at 1550 nm wavelengths.

IV. HYBRID INTEGRATION OF SI_3N_4 FOR VARIOUS PHOTONIC INTEGRATED CIRCUITS

The mixed integration of III-V material on silicon is helpful in the realization of LED and laser devices. This might be the first example of hybrid material integration in silicon photonics devices. As of now, this hybrid integration is expanded to the other materials than silicon such as Si_3N_4, III–V, glass, or even hybrid versions of these different materials. The hybrid photonic devices have unique advantages for the realization of different photonic structures by combining desirable properties of different materials on a single chip. This hybrid integration gives the benefit of Si and Si_3N_4 on the single chip for different applications, which cannot alone be realized with the Si or Si_3N_4 platform in the mid-IR or visible spectral range. In this section, the hybrid platforms used for different applications are presented.

The hybrid integration heterogeneous platform for the laser structure is presented in [94]. A high gain optical amplifier on the Si_3N_4 platform using a double photonic layer approach and a broadband gain operation over 70 nm covering wavelength in the S, C, and L bands is proposed in [95]. Further, the Si_3N_4 waveguide devices have been demonstrated for nonlinear applications such as frequency comb [34], supercontinuum generation [43], nonlinear signal processing, and quantum photonics [96], [97]. A mode-selective, tapered coupling scheme is used to generate coherent mode-locked frequency combs. The concentric race track-shaped resonator proposed by them [34] on the 300 nm thick Si_3N_4 can help lift the limitation such as material choice, film thickness, and spectral ranges where combs can be generated. The on-chip frequency comb integrated source can be achieved with this type of demonstration. In [96] researchers have demonstrated a silicon-rich nitride waveguide which is low stressed and high-confinement with flat and anomalous dispersion for optical signal processing over the entire C and L optical wavelength transmission bands. In [97] they have shown the significant needs of Si_3N_4 waveguides for photonic quantum information processing, with the demonstration of a programmable 8×8 unitary network universal quantum photonic processor based on Si_3N_4 waveguides. A nonlinear photonic integrated circuit in [99] shows the bonding of lithium niobate thin film into a Si_3N_4 waveguide layer on the Si platform. The variation of the width of the Si_3N_4 ridge waveguide leads to the adiabatic transition of the mode. They achieved dispersion engineering with the parametric optimization of the waveguide at 620 nm wavelengths.

A passive hybrid photonic device proposed in [98] consists of Si_3N_4 waveguides for optical input and output, an electro-optic hybrid waveguide region with Si_3N_4 and $LiNbO_3$ acting as an active device, and the mode conversion structure which is between the Si_3N_4 and hybrid waveguide section, as shown in Figure 5(a). The integration of multi-layered Si_3N_4 on the Si platform for monolithic integration is presented in [29]. This platform consists of two Si_3N_4 waveguide layers integrated with the Si waveguide at the top. Besides, hybrid photonic devices on Si_3N_4 platforms have also been demonstrated for on-chip polarization handling and high-speed data communications. A highly efficient horizontally asymmetric TM-pass polarizer on amorphous-silicon (a-Si) and Si_3N_4 was proposed in [16]. The intended purpose of this device is to pass the TM-like mode and suppress the TE-like mode at the output. The coupling of the TM-like mode is achieved through a horizontal asymmetrical structure to keep the possible phase matching errors to a minimum. In contrast to earlier mentioned polarization-splitters which employ vertical asymmetry and the air-only directional coupler, this configuration has a horizontal asymmetry using silicon nitride as the polarizer section in one place. The major significance of this design is the minimization of the insertion loss when the light is coupled via horizontal waveguide layers, as shown in Figure 5(b). Another hybrid platform was proposed in [20] on the double-layer Si and Si_3N_4-on-Si formed by the optimized bonding process. The 40 μm radius of the micro-resonator gives a 4×10^5 Q factor. This hybrid device has the unique feature of high power handling with a high-speed configuration, as shown in Figure 5(c). Hybrid photonic devices on the Si_3N_4 platform have also been demonstrated for different sensing applications. The key advantages of Si_3N_4 are its chemical and thermal stability, mechanical properties, and a large transparency window from mid-infrared to the visible wavelengths. By taking these

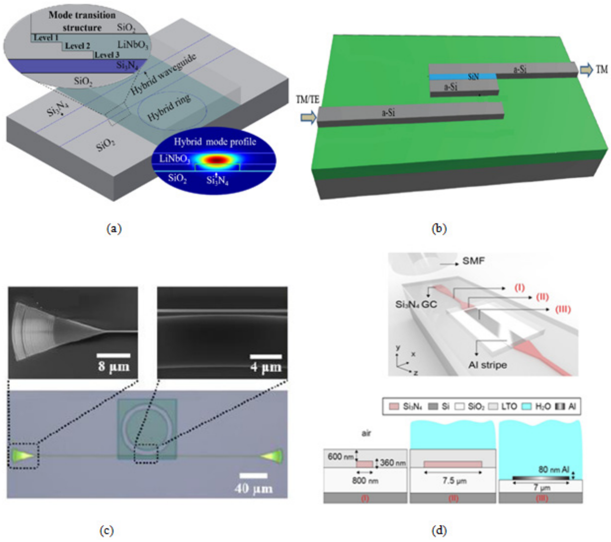


FIGURE 5. **Hybrid Si_3N_4 photonic integrated circuits. (a) HPD for mode transition structure [98]. (b) Schematic of TM pass hybrid polarizer [16] (c) The SEM images and microscopic image of the resonator coupled to bus waveguide with the double layer of Si with grating coupler [20]. (d) The 3D view and cross-section view of the proposed co-integrated device. The Al stripes have been interfaced with Si_3N_4 waveguides and their cladding material on the top is liquid, tapered photonics and plasmonics are covered fully with water [102]. Fig. 5(a) is reprinted with permission from Ref. [98], Copyright ©2018 OSA. Fig. 5(b) is reprinted with permission from Ref. [16], Copyright ©2018 SPIE. Fig. 5(c) is reprinted with permission from Ref. [20], Copyright ©2018 Optical Society of America. Fig. 5(d) is reprinted with permission from Ref. [102], Copyright ©2018 Springer Nature.**

advantages of Si_3N_4, [101] proposed a Si_3N_4-based hybrid platform for high-sensitivity sensor devices and instruments at visible wavelengths. The Si_3N_4 waveguide is combined with the plasmonic photonic platform which has a high data traffic of 25 Gb/s.

The first of its kind of aluminum plasmonic strip integration with a low loss Si_3N_4 photonics platform has been proposed in [102] and is shown in Figure 5(d). This co-integrated platform is helpful for the biosensing and on-chip interconnect applications. The lower fabrication loss of the Si_3N_4 waveguide due to its low index compared with Si is helpful for the realization of these kinds of devices.

V. SUMMARY AND FUTURE PROSPECTS

This article covered various research studies related to passive and active devices on Si_3N_4 platforms. The ability of Si_3N_4 as a CMOS-compatible material for passive applications helps in the realization of the multilayered platform for optical filters and wavelength multiplexers. The combination of Si_3N_4 with and without SOI, and III–V devices, together opens up a whole new generation of on-chip applications. A broad range of applications has been addressed from the low loss and optical transparency of Si_3N_4 which includes the microwave synthesizers, optical inertial rotation sensors, quantum communications, biophotonics, and nano-particle analysis. Different companies all over the world get the commercialization of various devices based on these platforms. These devices produce future photonic devices which give high-speed tuning and modulation with very low energy consumption and more promising applications such as quantum computation and neuromorphic technology. The broad wavelength range benefits the silicon nitride platform for building blocks of different devices such as narrow-linewidth tunable lasers, tunable analog RF, ultra-high Q resonators, ultra-narrow band tunable filters, and optical signal processors. The future challenges in the field are the realization of on-chip nanophotonic to perform the complex task on the single-chip such as quantum computing, energy conversion, biomedical sensing, and cryptography.

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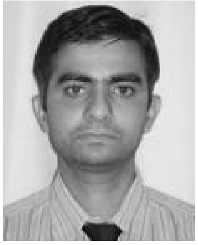

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