Silicon Nitride Integrated Photonics: Enabling Versatile PICs for Diverse Applications

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ABSTRACT

The scope of photonic integrated circuits (PICs) has expanded to applications where the material properties of silicon present limitations. Silicon nitride (SiN) has emerged as a key technology for the development of PICs, offering a complementary solution to silicon-based platforms due to its versatile optical properties. These properties have established SiN as an optimal material for a broad spectrum of applications, ranging from the NIR to the visible wavelengths. In this talk, we highlight our journey to demonstrate low-loss and low-temperature (<350 °C) silicon nitride layers with refractive indices ranging between 1.5 and 2.7, showcasing their potential to enable enhanced linear and nonlinear functionalities in both near-infrared and visible wavelength regimes paving the way for innovative applications in various technological fields.

Keywords: Silicon Nitride, Integrated Photonics

1. INTRODUCTION

SiN is a dielectric material that can be processed with standard CMOS fabrication techniques, making it highly compatible with silicon photonics. As a result, the silicon nitride (SiN) platform has become a key technology in the field of integrated photonics due to its unique combination of properties that address various of the limitations of traditional silicon-based platforms. Although it has a refractive index lower than that of silicon, it provides a moderate optical confinement that allows the realization of compact devices that have the advantage of being more tolerant to both surface roughness and dimensional variations. As a result, SiN can provide robust devices with low propagation losses. Furthermore, it exhibits a low thermo-optic coefficient (10^{-5}) and negligible two-photon absorption in the near infrared (NIR), which make SiN a suitable candidate for devices that require high-temperature stability and for non-linear applications. One of the key advantages of the SiN platform is its wide transparency window, covering visible to mid-infrared wavelengths. This broad operational range, combined with the versatility of the platform, makes SiN an exceptionally flexible and efficient choice for developing photonic integrated circuits across various applications, particularly those requiring broadband operation, such as quantum technologies, sensing, and spectroscopy.

2. SILICON NITRIDE FOR THE NEAR-INFRARED

SiN films are generally deposited using gas-phase chemical reactions that produce hydrogenated amorphous films, which contain Si-H and N-H bonds that cause absorption losses in the near-infrared, particularly around 1550 nm. High-temperature processes such as low-pressure chemical vapor deposition (LPCVD) are often used to break the hydrogen bonds to achieve ultra-low losses well below 1.0 dB/cm. However, high-processing temperatures limit the use of SiN in multilayer structures, which are required to improve the integration density and functionality of photonic devices, since they can cause thermal stress and compatibility issues with other materials in the stack.

We have investigated a plasma-enhanced chemical vapor deposition (PECVD) process to grow SiN layers with low propagation losses at processing temperatures suitable for multilayer integration. We explored a modified

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recipe that uses N_2 as a precursor gas instead of NH_3 to reduce the hydrogen available during the PECVD process. This method enables the fabrication of low-loss SiN layers at a maximum processing temperature of 350°C, achieving propagation losses below 1 dB/cm in the O-band (1310 nm) and 1.5 dB/cm in the C-band (1550 nm).[1] Additionally, while SiN typically exhibits a refractive index of 2.0 at 1550 nm, this method allows tuning the N/Si ratio of the deposited films to adjust their optical properties to meet the requirements of various linear and non-linear applications,[2,3] as elaborated in the following sections.

2.1 N-rich Silicon Nitride

The nitrogen content in the deposited films can be adjusted by modifying the deposition parameters to create nitrogen-rich (N-rich) SiN layers with a refractive index close to 1.9. These layers, with their lower refractive index compared to stoichiometric SiN, enable the implementation of passive devices with better tolerance to phase errors and fabrication variations while still benefiting from the increased temperature stability offered by the material. These improved properties are especially advantageous for wavelength division multiplexing (WDM) applications, since devices built on the traditional silicon-on-insulator (SOI) platform often face challenges due to its high refractive index contrast, non-linear absorption, lower temperature stability, and large birefringence.

Using the N-rich SiN platform, we have reported the design, fabrication and characterization of compact (de)multiplexers, based on angle multimode interferometers (AMMI), for coarse wavelength division multiplexing (CWDM) in the O-band (1260 nm to 1320 nm). These devices show spectral performances with insertion losses as low as 1.5 dB and crosstalk below 20 dB, while exhibiting high tolerance to dimensional errors (<120 pm/nm) and low sensitivity to temperature variations (<20 pm/°C).[2,4,5] Additionally, the low mechanical stress of N-rich SiN enables the realization of devices with polarization-independent operation, since it is possible to fabricate micrometer thick structures with high optical confinement and reduced birefringence. Following this approach, we have demonstrated (de) multiplexers based on 1 µm-thick SiN with insertion losses <1 dB, cross-talk <21 dB, and a difference of <3 nm between the central wavelengths of orthogonal polarizations. Finally, we have fully incorporated the 1 µm-thick SiN (de)multiplexers into SOI circuits using a novel butt-coupling integration scheme which does not impact the overall device response, except for an additional 1 dB loss introduced by the interfaces between the two materials.[6] This concept can also be extended to integrate active devices with thick material stacks that are challenging to integrate with typical thin SOI geometries.

2.2 Si-rich Silicon Nitride

When the silicon content of the deposited films is increased, it is possible to obtain silicon-rich (Si-rich) SiN layers with refractive indices as high as 3.1. This variation of the refractive index is also reflected in the nonlinear properties of the deposited films. As the silicon concentration increases, a greater nonlinear Kerr coefficient can be realized, though this often comes at the expense of higher propagation losses. If the deposition conditions are carefully selected, it is possible to create layers with a relatively high nonlinear coefficient, compared to that of stoichiometric SiN, and low losses. The enhanced properties of these layers make them attractive for all-optical processing applications, such as wavelength conversion.

Using the Si-Rich SiN platform, we have demonstrated that broadband four-wave mixing (FWM) can be achieved by exploiting interband nonlinearities between pump and signal waves located in different communication bands.[7] We have extended this concept to demonstrate the wavelength conversion of a 16 Quadrature Amplitude Modulation (QAM) signal operating at 40 Gb/s, with a power penalty of less than 1 dB and a conversion bandwidth greater than 40 nm.[2] These results have pave the way for the realization of on-chip wavelength conversion, multiplexing, and de-multiplexing.[8]

3. SIN FOR BROADBAND VISIBLE PHOTONICS

Integrated photonic platforms capable of broadband operation have become increasingly important due to their ability to handle a wide range of wavelengths, supporting various applications beyond traditional telecommunications. SiN stands out among these platforms for its technology maturity, low propagation losses, and broad spectral transparency. However, creating devices that function efficiently within the visible spectrum presents challenges. This is due to the increased sensitivity to scattering losses at shorter wavelengths, and the necessity for smaller dimensions to ensure single-mode operation. To address these challenges, we have designed a single-mode waveguide geometry that supports red (633 nm), green (520 nm), and blue (480 nm) wavelengths simultaneously, marking the first steps towards a SiN photonic integrated platform for broadband operation.[9]

4. CONCLUSIONS

SiN is a versatile and efficient platform for integrated photonics. Advances in deposition techniques have enabled the creation of low-loss SiN layers at lower processing temperatures, facilitating multilayer integration. Additionally, they have provided the ability to tailor the nitrogen and silicon content in the SiN films for the production of N-rich and Si-rich layers with specific optical properties that are suitable for wavelength division multiplexing and all-optical processing applications. These advances along the demonstration of broadband waveguide geometries highlight the potential of the platform to revolutionize integrated photonics across a wide range of applications.

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