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ABSTRACT
We demonstrate four-wave mixing (FWM) interactions in a-Si:H waveguides in a multilayer integrated silicon photonic chip. The a-Si:H waveguides are accessed through interlayer couplers from waveguides composed of SiNx. The interlayer couplers achieve a coupling of 0.51 dB loss per transition at the target wavelength of 1550 nm. We observe greater idler power extraction and conversion efficiency from the FWM interaction in the interlayer-coupled multilayer waveguides than in single-material waveguides.

I. INTRODUCTION
Integrated photonics has enabled fantastic growth in the field of optics. By fabricating devices in a single and monolithic platform, photonic systems gain tremendous mechanical stability, precision, and improved performance over those composed of discrete components. Many photonic systems of the complexity commonly seen in modern integrated photonics would be impractical to build out of discrete components. In addition, integrated photonic devices can benefit from economy of scale, reducing cost per device.

As a result of the planar nature of the fabrication process, conventional integrated photonics exist in a single two-dimensional plane. Although these devices have achieved extraordinary success, their planar structure poses limitations. The first comes from the topological limitations of a two-dimensional circuit layout, namely, that photonic interconnects cannot cross without the inclusion of relatively complicated enabling structures, which take up valuable chip area. Additionally, the footprint of the chip grows rapidly as more components are added to a two-dimensional circuit. The use of a three-dimensional circuit layout has the potential to address many of the inherent drawbacks of two-dimensional devices.

Another shortcoming of two-dimensional circuits is the limitation to a single material platform. A two-dimensional device is often fabricated from material either grown or deposited in layers on a wafer, which makes it impractical to have more than one material in a single layer. Furthermore, every material platform has its own advantages and disadvantages. Correspondingly, no single material platform is optimal for every application. In smaller single device chips, this may not be such a problem, but as circuits grow more and more complex and multiple devices or even entire optical systems are integrated onto single chips, a single material platform will pose significant design limitations.

Specifically, to illustrate the trade-offs faced by the designers of integrated nonlinear photonic devices, consider Table I, which lists the propagation loss and effective nonlinearity of a variety of materials commonly used in integrated photonics. Low propagation loss is desirable to make a device more power efficient, and high effective nonlinearity is required to efficiently harness nonlinear optical phenomena, such as in ultrafast switches and wavelength converters. Notably, silicon nitride (SiNx) can have extremely low propagation loss but has a low effective nonlinearity. Conversely, Table I shows that amorphous silicon (a-Si:H) has the largest effective nonlinearity but high propagation loss.

To address these trade-offs, an effective solution is the use of heterogeneous multilayer integration, where devices fabricated from different materials can be tightly integrated. Previous heterogeneous multilayer devices using silicon and silicon nitride layers have been demonstrated for linear photonic circuits. In one demonstration, the two layers were wafer bonded together to form a heterogeneous...
chip.\(^2\) In another, silicon nitride was deposited using low temperature plasma-enhanced chemical vapor deposition (PECVD) directly on top of a silicon layer.\(^2\) Here, for nonlinear integrated photonics, we propose a similar heterogeneous platform in which nonlinear optical processes and low loss propagation are performed in different material waveguides on the same chip. To this end, a-Si:H devices have excellent nonlinear performance but have significant propagation loss and are not ideal for linear applications such as routing, filtering, etc. Conversely, SiNx devices exhibit extremely low propagation loss but have poor nonlinear performance. Here, we demonstrate a heterogeneous device using these two silicon-based material platforms for nonlinear photonics that can exploit the best material properties on a single integrated chip.

A simplified cross section of our design is shown in Fig. 1. Because the integrated photonic fabrication is dominated by planar processes, the most practical way to realize this type of heterogeneous device is to stack layers of material on top of each other. Consequently, devices must include structures to transfer the light between the two material planes. This is achieved using an interlayer coupler. There are two widespread approaches for achieving efficient interlayer coupling. The first is the use of grating couplers to diffract light out of the plane in one layer and back into the plane in another.\(^21\)\(^{-23}\) Grating couplers are common in integrated photonic devices and are traditionally used for input and output coupling through the chip surface to, for example, an optical fiber. The same principles that allow light to couple from a grating to a fiber or vice versa allow them to transmit and receive light between material layers. However, grating couplers have several drawbacks. First, by their diffractive nature, they are highly wavelength sensitive, which imposes severe bandwidth limitations on their coupling performance. The direction of light diffraction for a grating is wavelength dependent and therefore results in bandwidth limitations for interlayer coupling. If the wavelength is offset from that value, the light will not couple optimally. Second, grating couplers can have multiple diffracted orders. While a grating may be designed to diffract light optimally in one direction, it can also diffract to lesser degrees in other directions. In a single layer device, this would merely result in loss from stray light coupling to the substrate or out of the chip entirely. However, in a three-dimensional device, this stray light might also couple into waveguides in other layers, causing cross talk or other undesirable interactions.

The second major approach to interlayer coupling is the use of evanescent couplers.\(^21\)\(^{-23}\)\(^,\)\(^26\)\(^{-28}\) Evanescent coupling occurs when two waveguides are positioned in close proximity such that the evanescent field of the propagating light in one waveguide interacts with the other waveguide, causing light to couple from one waveguide to another. Thus, by positioning two waveguides in different layers collinearly, in close proximity, and propagating for some distance, light can evanescently couple from one layer to another. Additionally, by adjusting the waveguide geometry, the evanescent field can be made larger or smaller as necessary so that the evanescent field is large in the coupling region and small in other areas to mitigate cross talk. Evanescent couplers are generally simpler in design than grating couplers, have wider operational bandwidth due to less inherent wavelength sensitivity, and provide larger design tolerances. They generally require larger areas on a chip and are less suited to coupling between layers with large vertical offsets. However, their simple design and potential for large coupling efficiency over broad bandwidths make them ideal for applications in nonlinear optics where extremely broad bandwidth interactions are required for applications such as ultrafast switching and signal processing.

**TABLE I.** Propagation loss and effective nonlinearity for a selection of materials.

| References | Material              | $\alpha$ (dB/cm) | $\gamma$ (1/Wm) |
|------------|-----------------------|------------------|-----------------|
| 2          | SiON:D (hydex)        | 0.06             | 0.23            |
| 2–7        | Si$_3$N$_4$           | 0.0032           | 1.2             |
| 8,9        | As$_2$S$_3$           | 0.05             | 5               |
| 10,37      | USRN:Si$_3$N$_3$      | 0.4              | 500             |
| 11–13      | c-Si                  | 0.027            | 350–500         |
| 14–16      | AlGaAs                | 0.9              | 630             |
| 17–20      | a-Si:H                | 0.8              | 770–3000        |

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**FIG. 1.** Possible heterogeneous material platform, with SiNx waveguides in one layer and a-Si:H waveguides in another.

**II. DESIGN**

Our heterogeneous multilayer nonlinear photonic circuit is composed of two layers of waveguide material: SiNx and a-Si:H. This combination allows for optimal access to both low propagation loss (SiNx) and large effective nonlinearity (a-Si:H). The SiNx waveguide was designed to be single-mode (with TE-like polarization) to avoid coupling to higher order modes. However, as the geometry decreases, the evanescent field increases and causes increases in bending loss, substrate leakage, and cross talk/cross loss to the a-Si:H layer at undesired locations. Based on finite difference method (FDM) simulations of the waveguide and surrounding materials, we chose SiNx waveguides with dimensions of 1-μm width by 240-nm height, shown in Fig. 2(a). These dimensions represent a feasible
thickness for low-pressure chemical vapor deposition (LPCVD) and a width that ensures that this waveguide is single-mode (for TE-like polarization) at the operational C-band wavelengths.

The a-Si:H waveguides were designed to achieve high nonlinear four-wave mixing (FWM) performance. This involved engineering the dispersion to place a zero-group velocity dispersion (zGVD) point near our operational wavelength of 1550-nm. FDM simulations to calculate GVD were performed for a range of dimensions (Fig. 3), and a device with a width of 360-nm and a height of 240-nm was chosen to provide the desired dispersion profile.

Finally, we designed the evanescent couplers for routing light between the SiNx and a-Si:H waveguides. The couplers consisted of two overlapping adiabatically tapered waveguides. In one layer, the width of the waveguide tapers from its propagation width to a much smaller width, causing its mode to delocalize and foster efficient interlayer coupling. In the other layer, the width of the waveguide tapers up from a very small width to its normal propagation width, causing the delocalized mode from the other layer to gradually couple to this layer over the taper length. In addition to increasing coupling efficiency through mode delocalization, the tapering of the widths changes the effective indices of the guided modes of the two waveguides over the coupling length. For our case, the effective indices of the untapered a-Si:H and SiNx waveguides are significantly different, and therefore, in order to enhance the mode-matching over the coupler region, we design the a-Si:H waveguide to have a two-stage adiabatic taper. This is shown in Fig. 4(b), and the waveguide effective indices for the SiNx and a-Si:H waveguides over the coupler region are shown in Fig. 4(c). The use of a two-stage taper of the a-Si:H waveguide provides enhanced effective index matching over the majority of the interlayer coupler length.

Eigenmode Expansion (EME) and Finite-Difference Time-Domain (FDTD) simulations are performed while varying a wide range of dimensions, including coupling interaction length, final taper width, and vertical displacement (interlayer gap), shown in Fig. 5. EME simulations [Fig. 5(a)] confirm the expected trend that an increased interlayer gap requires longer interaction lengths (coupler lengths) for maximum transmission. An FDTD simulation of a crossing [Fig. 5(b)] indicates that increasing interlayer gap will also provide a reduction in cross loss since increasing the gap between the waveguides allows the evanescent field to remain unperturbed by the presence of a waveguide crossing. As a result, there is a trade-off between interlayer coupler footprint (length) and reduction of unwanted cross talk (or cross loss) in other areas of the chip. We have designed our interlayer coupler gap (700-nm) to provide 97\% transmission during waveguide crossings and our coupler length (300-μm) to ensure efficient coupling through the interlayer coupler. Notably, the chosen size of the interlayer gap or vertical offset (700-nm) allows for negligible cross talk and small cross losses without any modification of the waveguides in the crossing region. As shown as the single data point in Fig. 5(a), additional and more robust FDTD simulations were performed to ensure the accuracy of the chosen interlayer coupler design.

III. FABRICATION AND TESTING

We began device fabrication with a 100-mm silicon wafer with a 3-μm thick layer of thermal oxide on its surface. We first deposited 240-nm of low-pressure chemical vapor deposition (LPCVD) SiNx. The SiNx layer was deposited at a rate of 4-nm/min and a temperature of 775 °C, with 1000-MPa tensile stress and 250 mTorr chamber.
pressure. No high-temperature annealing step was performed for the SiNx layer after deposition. Next, platinum alignment marks were patterned using electron beam lift-off lithography. We then wrote waveguides in the SiNx layer by e-beam lithography and reactive ion etching and clad them with plasma-enhanced chemical vapor deposition (PECVD) silicon dioxide (SiO₂). The SiO₂ surface was planarized with chemical mechanical polishing. 240-nm of a-Si:H was then deposited by PECVD. The a-Si:H layer was deposited at a
temperature of 350 °C, a RF power of 75-W, 200-SCCM of silane gas flow, and 800-SCCM of argon gas flow. The lower a-Si:H deposition temperature allows us to deposit it directly on top of the SiNx waveguides without damaging or altering their properties. Waveguides are again written by e-beam lithography and reactive ion etching. Finally, this top layer of waveguides is clad with PECVD SiO$_2$ and individual chips are diced out of the wafer.

The first experimental measurements of these devices were CW power measurements used to determine loss performance in the waveguides and couplers. Optical coupling was achieved through inverse adiabatic tapers for both the a-Si:H waveguides and the SiNx waveguides. Multiple SiNx waveguides of varying length were tested, and losses associated with input/output coupling and propagation were extracted. As expected, the dominant loss mechanism was the input/output coupling, which was found to be around 3-dB in both cases. We extracted the losses associated with the interlayer coupler transitions and a-Si:H propagation using interlayer devices with a total length of 7.5-mm that have the input/output in the SiNx layer, 2 interlayer couplers, and 3 different a-Si:H propagation lengths (1-mm, 2.5-mm, 3.5-mm). For each a-Si:H propagation length, we tested 7 different waveguides and fit the transmission data as a function of the a-Si:H propagation length to extract the propagation losses of the a-Si:H waveguides to be 29 dB/cm. We note that our a-Si:H propagation losses are higher than the state-of-the-art value in Table I. However, reported a-Si:H propagation values with comparable effective nonlinearity to this sample are around 3–5 dB/cm.\textsuperscript{18,19}

Finally, using the extracted input/output coupling and propagation losses associated with the SiNx waveguides (excluding the interlayer coupling region), and the propagation losses associated with the a-Si:H waveguides (excluding the interlayer coupling region), we were able to estimate the average insertion loss of an interlayer coupler. Bandwidth measurements were performed using a CW laser source and wavelength sweeping to extract the bandwidth of the coupler over the C-band and L-band wavelengths. These results are shown in Fig. 6. Our measurements show the interlayer coupler to have a bandwidth greater than 100-nm. As shown in Table II, the total insertion loss per interlayer coupler is 0.51 dB/transition at the target wavelength of 1550-nm. Although this value is larger than some of the state-of-the-art values reported for heterogeneous evanescent interlayer couplers, the increased losses are likely due to our larger interlayer gap design which removes the need for complex enabling structures to have minimal crossing loss.\textsuperscript{22} Instead in our design, no modifications to the waveguide cross section are needed in a crossing region to achieve sub 1 dB cross losses. Discrepancies between our simulated and experimental performance (98% vs 89%, respectively) are most likely due to variations in the thickness between the waveguide layers, as well as propagation losses of the a-Si:H waveguides in the region of the coupler with higher confinement in the a-Si:H layer. For example, factoring out the a-Si:H propagation losses in 1/4 of the length of a coupler reduces the calculated coupler loss to 0.24 dB compared to the 0.51 dB experimentally measured insertion loss. Therefore, a lower loss a-Si:H waveguide such as those demonstrated in Ref. 20 would significantly improve the overall performance of the interlayer coupler platform.

Crossing loss was measured using waveguides of the same propagation length with and without perpendicular waveguide

| Device characteristic | Measured result |
|-----------------------|-----------------|
| SiNx propagation loss | 0.58 dB/cm       |
| a-Si:H propagation loss | 29 dB/cm       |
| Cross loss (SiNx crossing a-Si:H) | <0.01 dB |
| Cross loss (a-Si:H crossing SiNx) | 0.48 dB |
| Coupler loss per transition | 0.51 dB |

FIG. 7. (a) Overview of achieving FWM in the a-Si:H layer of our interlayer device. (b) Setup for our FWM experiment. Originally published in Ref. 29.
crossings in the opposite layer. Based on the difference in transmission between these waveguides, we extracted the crossing loss to be 0.48 dB/crossing for TE-like polarized light guided in a SiNx waveguide with an a-Si:H waveguide crossing over it and <0.01 dB/crossing for TE-like polarized light guided in an a-Si:H waveguide with a SiNx waveguide crossing under it. The higher crossing loss for the former configuration is expected as the mode is less confined in the SiNx waveguides as compared to the a-Si:H waveguide and therefore has a larger evanescent field that can be perturbed. These results are summarized in Table II.

We next investigated nonlinear phenomena in the a-Si:H layer, in the form of pump-degenerate four-wave mixing (FWM). This process is a four-photon interaction, in which two pump photons annihilate and form two new photons, a signal and an idler, where the sum of the pump photon energies is equal to the sum of the signal and idler photon energies. Because the propagation length in a-Si:H needed to generate a strong FWM response is relatively short, we only required our device to couple from SiNx into a-Si:H for a short distance (~2.5-mm) and then couple back to SiNx, so as to achieve comparable FWM efficiencies to a traditional length a-Si:H waveguide. In addition, our SiNx waveguides have superior input coupling performance as compared to a-Si:H, further increasing the optical power delivered to the a-Si:H waveguides.

To investigate FWM, we begin with a 100-MHz repetition rate mode-locked laser (MLL). We then separate wavelengths of 1538-nm and 1549-nm with a wavelength division multiplexer (WDM) to form the pump (1549-nm) and signal (1538-nm) pulses. The pump was amplified using an erbium-doped fiber amplifier (EDFA) and tuned with a polarization controller. An optical delay line ensured the same optical path length in each line. Finally, the pump and signal were recombined with another WDM and coupled into the interlayer device via lensed fiber. The output of the device went to

![Graphs showing FWM efficiency vs FWM pump power, FWM efficiency vs signal wavelength, and other related data.](image-url)
an optical spectrum analyzer (OSA) to measure the resulting spectrum of the FWM interaction. This experimental setup is shown in Fig. 7. We measure the FWM efficiency in three different waveguide devices including (1) a multilayer device consisting of 5-mm of SiNx waveguide (total) and 2.5-mm of a-Si:H waveguide, (2) a traditional SiNx waveguide of 7.5-mm length, and (3) a traditional a-Si:H waveguide of 4-mm length (the minimum length to traverse our chip). This was done for comparison of the three different devices and to ensure that in the multilayer devices, the nonlinear optical interaction was indeed occurring in the highly nonlinear a-Si:H device. A plot of incident pump power and FWM conversion efficiency (output idler power divided by output signal power) is displayed in Fig. 8(a). This figure shows several orders of magnitude difference between the FWM efficiency of the SiNx waveguide and the a-Si:H interlayer/a-Si:H waveguide as expected since the SiNx waveguide exhibits significantly lower Kerr nonlinearity, as shown in Table I. This confirms that the FWM interaction is primarily occurring in the 2.5-mm a-Si:H waveguide of the interlayer device. The nonlinear interaction is assumed to be minimal over the interlayer coupler length as simulations indicate that the light is only tightly confined in the a-Si:H layer over the first 50-μm, which would not greatly affect the effective length of the nonlinear interaction. Additionally, the efficiency vs incident pump power for the interlayer device follows a similar trend to that of the pure a-Si:H waveguide; however, the interlayer device displays superior FWM conversion efficiency for a given incident pump power due to the better input and interlayer coupling in the interlayer devices as compared to the input coupling of the traditional a-Si:H waveguide. Therefore, it can be deduced that for the interlayer devices, the nonlinear optical process is occurring in the a-Si:H layer as desired and that the effective nonlinear length is ~2.5-mm or less. We note that the majority of the FWM efficiency improvement of the interlayer devices comes from the increased coupling efficiency, and therefore, even with state-of-the-art a-Si:H propagation losses, significant improvement would still be present. The FWM conversion efficiency for both the multilayer device and traditional a-Si:H waveguide is shown to saturate in Figs. 8(b) and 8(c), when the conversion efficiency as a function of incident pump power on the log-log scale deviates from a linear slope of 2 at higher incident pump powers. We suspect that this is due to a form of noninstantaneous absorption that has previously been observed in a-Si:H waveguides. The received idler power as a function of incident pump power for the pure a-Si:H waveguide and the interlayer a-Si:H/SiNx waveguide is shown in Fig. 8(c). We find that our interlayer devices always have larger received idler power out from the chip compared to traditional a-Si:H waveguides due to both lower propagation losses in the SiNx layer and better fiber-to-waveguide coupling efficiency from the SiNx waveguide. Increased input coupling efficiency to the SiNx waveguide occurs due to the increased mode matching and refractive index matching between SiNx waveguides and single-mode fiber (SMF) as compared to a-Si:H waveguides and SMF. Other groups have shown that a similar approach of using polymer waveguides can be used to increase coupling efficiency from SMF to silicon waveguides. This again validates that an interlayer-based device can have superior performance than that of a single-material device, given the same incident pump power. Finally, we performed a FWM bandwidth measurement of interlayer devices, as shown in Fig. 8(e), by sweeping the signal wavelength. The FWM conversion efficiency is nearly constant over a 120-nm bandwidth, indicating small dispersion and validating our dispersion engineering of the zGVD point. Using these results and modeling the interaction using the split-step Fourier Method and Nonlinear Schrödinger equation, we estimate the nonlinear parameter (γ) of the a-Si:H waveguides to be 1000 1/Wm.

IV. CONCLUSION

In this work, we demonstrate the first example of FWM through interlayer coupling between waveguides of SiNx and a-Si:H. Our interlayer coupler enables a heterogeneous material platform capable of utilizing both low propagation loss SiNx devices and high nonlinearity a-Si:H devices. This approach can be extended to add more materials and more device possibilities, which could eventually allow building entirely nonlinear optical systems on a single chip such as ultrahigh-speed optical processing circuits, wavelength-agnostic parametric optical sources, and quantum optical networks.

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