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# Heterogeneous Photonic Integration by Direct Wafer Bonding

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Direct wafer bonding is a powerful technique for combining semiconductor materials that cannot normally be monolithically integrated. It allows combination of heterogeneous materials with different properties onto a single substrate, enabling the production large scale and multi-functional photonic circuits.

## Introduction

The silicon (Si) photonics platform has emerged as a promising integration platform for use in many applications, particularly datacenter communications, which is expected to produce demand for large numbers of low cost photonic integrated circuits (PICs). Si-based PICs are almost universally based on Si-on-insulator (SOI) wafers, which are enabled by wafer bonding technology. Si is useful as a waveguide material due to its high index contrast, low intrinsic absorption, and mature manufacturing technology. However, it does not strongly absorb or emit light in wavelength ranges of interest for data transmission. Heterogeneous integration of InP-based materials with Si using wafer bonding technology is able to overcome this limitation and has allowed the realization of a wide range of photonic devices on Si, including lasers, photodetectors, and modulators with high performance (1).

## Vertical Integration

Wafer bonding may also be used to produce complex vertically-integrated circuits. A crystalline Si layer transferred to an ultra-low loss silicon nitride (SiN) waveguide allows for integration of highly confined Si photonic waveguide components such as couplers, compact wavelength multiplexers, and micro-ring modulators with high performance and low insertion loss passive components in SiN.

After bonding of the Si layer to the SiN waveguide substrate, the wafer is functionally an SOI wafer, with the SiN waveguide embedded in the buried oxide. Any device that can be realized on an SOI wafer can be integrated with the SiN waveguide, including InP-based heterogeneously integrated devices. Multiple die bonding of InP chips can add lasers, amplifiers, modulators, and photodetectors to the circuit. Lateral tapers of the waveguides allows coupling between the layers with below 0.5 dB loss.

This technology was used to combine a SiN arrayed waveguide grating (AWG) wavelength multiplexer with high-speed 50 Gb/s heterogeneous Si/InP photodetectors to form a 400 Gb/s wavelength division multiplexing (WDM) receiver (2). A cross section of the photodetector is shown in Figure 1.

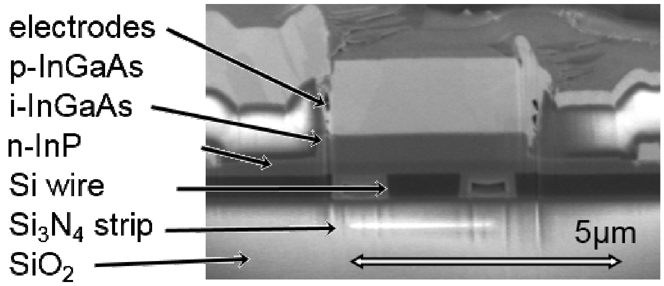



Figure 1: Cross section of a heterogeneous $Si_3N_4$/Si/InP device

## Magnetic Materials

One of the primary advantages of wafer bonding technology is the ability to integrate two materials together with large lattice mismatch. Using the heterogeneous integration approach, we are able to complement the superior wave-guiding qualities of Si and SiN with other desirable optical properties such as efficient optical non-linearities and optical nonreciprocity. The reciprocal nature of Si and other dielectric materials makes it very difficult to realize nonreciprocal devices such as optical isolators and circulators. Optical isolators are a one-way street for photons, and widely used to prevent spurious backreflections from entering a laser cavity, which can degrade or even destroy the laser. Optical circulators are a roundabout for photons in which light is routed in an ordered path, and each input is mapped to exactly one output. Both types of devices require a nonreciprocal medium, which can be achieved by bonding a magneto-optic material such as cerium substituted yttrium iron garnet (Ce:YIG) onto Si.

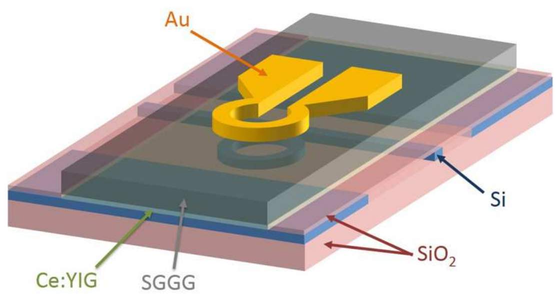



Figure 2: Schematic of the heterogeneous isolator

Our design for an optical isolator uses an all-pass Si microring with the bonded Ce:YIG die on top. The schematic of the device is shown in Figure 2. The bond is performed by contacting the die and the Si together following an oxygen plasma activation, and then strengthened with a 200°C anneal under physical pressure. After this bond, we perform substrate removal using a mechanical polishing technique. Since the Ce:YIG must be magnetized in order for the nonreciprocity to appear, we deposit a metallic microstrip on the backside of the Ce:YIG die. When a current is applied through the microstrip, a resonance wavelength split appears between the clockwise and counterclockwise mode in the ring. Thus, it is possible for the backwards light to be on resonance and eventually dissipated, while the forwards light is off resonance and passed. Here, we see a 0.16-nm resonance wavelength split as well as 32 dB of optical isolation (3), which is shown in Figure 3.

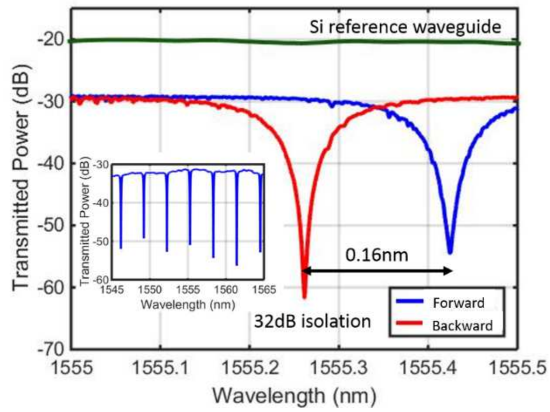
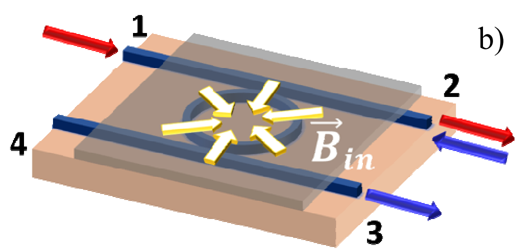



Figure 3: Spectral transmission of the forward and backward propagating light

This design can be expanded to optical circulators by using an add-drop configuration instead of the all-pass microring, as shown below in Figure 4. Here, light flowing from Port 1 to Port 2 is passed through, but light entering from Port 2 is instead dropped to Port 3. Following this analysis, the forwards propagating path in this device is 1→2→3→4→1. This is also shown by the highlighted entries in the table. By reversing the sign of the current and magnetic field, it is possible to reconfigure the circulator and change the flow to 4→3→2→1→4. This reconfigurability is a novel aspect that is made possible by photonic integration, and may lead to new applications in optical switching and interconnects (4).

a)




b)

Output Port

| Input Port | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | - | -9.7 | - | -17.2 |
| 2 | -20.7 | - | -12.4 | - |
| 3 | - | -21.0 | - | -11.0 |
| 4 | -10.5 | - | -22.0 | - |

Transmittance [dB]

Figure 4: a) Schematic of the circulator, and b) scattering matrix values for the device

## Non-linear Optical Materials

Lithium niobate (LN) is a material of paramount importance for non-linear optics, thanks to its large non-linear coefficient, broad transparent window (0.4-5.0 μm) and ferroelectric properties (5). Wavelength converters based on LN have been widely used in different area, e.g. telecommunication (6), quantum optics (7) and self-referencing of optical frequency combs (8). Recently, LN has attracted a lot of attention for use in photonic integrated circuits (PICs), in particular on Si platform, because of the lack second-order optical non-linearity in Si. At the same time, a compact scale of integrated waveguides results in high photon density that effectively enhances non-linear interaction.

The integration of LN in PICs is generally hindered by two major difficulties. One is the waveguide technology. The most commonly used LN waveguides are based on diffusion (9). They only provide a low index contrast and the optical mode is relatively large. Etching LN is another way to form waveguide but it suffers from high loss. More importantly, none of these techniques is compatible with photonic integration. Recently, the LN-on-insulator (LNOI) technology has been successfully demonstrated by ion injection and heterogeneous bonding (9). This allows the implementation of LN thin films with sub-micron thickness on various material platforms. Here based on this technology, we demonstrate a heterogeneous SiN-LN waveguide, with the cross section shown in Figure 5(a). Due to the high index contrast of the structure (~0.6) and the sub-micron thickness of the LN film, the waveguide modes are confined into an area that is more than one order of magnitude smaller than previously reported (10). This directly relates to more than an extra order of magnitude improvement for the conversion efficiency of non-linear effects. Loss of 0.3 dB/cm is demonstrated, which is a record-low value for LN waveguides.

Another important technology for LN is the domain engineering. By periodically inverse the domain to satisfy the quasi-phase matching conditions, the efficiency of non-linear effects can be improved (11). However, the previous bulk poling methods for LN are not suitable for PICs. Here we demonstrate a surface poling method for thin film, which can successfully achieve the domain engineering directly on chip. As shown in Figure 5 (b), a thin-film periodically-poled LN waveguide is fabricated by combining this and the heterogeneous waveguide (12). A second-harmonic generation conversion efficiency 4 times higher than previous bulk PPLN wavelength converters. Processing of this approach is much simpler and compatible with different platforms, as long as LN film is heterogeneous integrated.

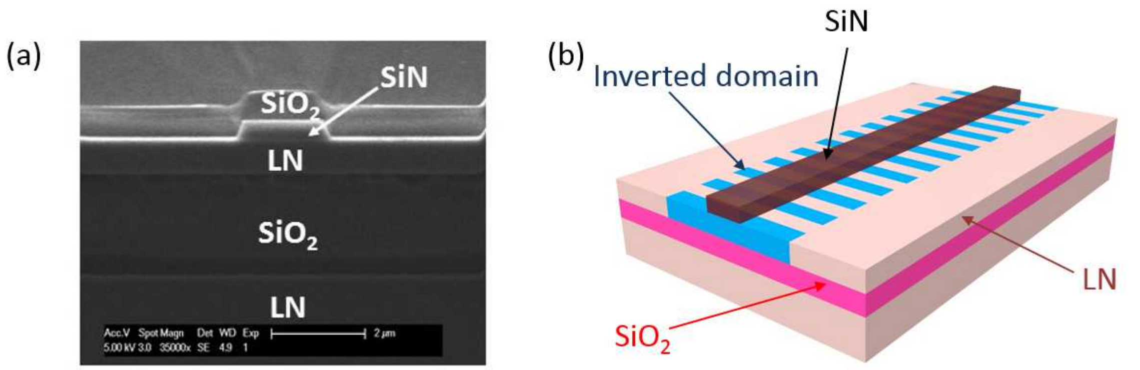



Figure 5: (a) Cross-section SEM of fabricated $Si_3N_4$-LNOI waveguide, (b) schematic of thin film PPLN wavelength converter.

## Conclusion

Wafer bonding technology allows the realization of complex and highly integrated photonic devices. The ability to combine multiple materials such as multiple-die bonding for integration of lasers, modulators, and detectors enables PICs with a wide variety of functions. Vertical integration through bonding of high-quality thin films, such as lithium niobate, crystalline Si, and thermal $SiO_2$ can be used to construct integrated waveguides with useful properties and high performance. This technology has played an important role in the emergence of the field of Si photonics.

## Acknowledments

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