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Mixing Materials for Integrated Photonic Innovation

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At a Glance

Photonics, an ever-growing field since the invention of lasers in the 1960s, has been applied in wide-ranging applications such as optical communications, sensing, imaging and more. Photonic integrated circuits (PIC) are the next step to take this technology and shrink it onto a semiconductor chip, leading to more compact, cheaper, and lower power consumption solutions. However, integrated photonics faces the challenge of lacking a single material platform that encompasses all the desired properties, unlike its more mature electronic integrated circuit counterpart which uses silicon with a standardised fabrication process known as complementary metal oxide semiconductor (CMOS). To overcome this limitation, researchers are exploring hybrid and heterogeneous integration techniques. By combining the strengths of different photonic platforms, such as III-V materials for light emission, silicon for strong light guidance, silicon-nitride for visible light guiding, and lithium niobate for its modulating capabilities, integrated photonic technologies can harness the collective advantages and unlock new possibilities.

Keywords: Integrated photonics, Semiconductor fabrication, Heterogeneous integration

> *"Light brings us the news from the universe."*
>
> *— Sir William Bragg*

PICs and Integrated Components

PICs convert glass fibre optic cables, which bring the internet to your home, into small refractive index-guided waveguides. PICs are the equivalent of integrated circuits in electronics, which take the red and black cables (that you may see attached to your car battery) and miniaturise them into metal tracks on silicon (like in your phone). The obvious advantage is that the system no longer requires bulky and messy fibres, as they are now miniaturised on a chip. PICs are made on wafers in a cleanroom foundry environment, with processes very similar to computer chip manufacturing. Once these PICs have been fabricated, they are then packaged and ready for use. One example application is in communications systems that use optical interconnects. Data transmission using electronic interconnects is slower and less efficient at high speeds when compared to optical. Instead, a PIC can be the instrument of transmission. These PICs can then send the information to a neighbouring server, or couple out to a fibre for longer-range transmission. The information, which may manifest as a funny video to send to your friend, is encoded in the light through changes in phase and intensity until it is received and decoded by a receiver.

PICs are comprised of many devices. Active devices have some external power source, this includes lasers (source of light), amplifiers (amplify signal), modulators (changes phase and intensity of light) and detectors (which detect light). Passive devices do not require power unless thermally tuned, such as splitters (splits light into two or more directions), filters (accepts or rejects certain wavelengths of light) and couplers (brings light in/out of the chip from/to an external source i.e. grating that diffracts light into a circuit). Lastly, these devices are connected through waveguides, which bring light to and from all the different devices. Waveguides are based on mode theory, for which electromagnetic radiation of a certain wavelength will have a set of 2D Electric-field profiles that will guide the light through that medium. An example video that describes the modes in a grape is available here.[1] The accumulation of all these devices, which can be arranged in countless configurations, is the formation of a PIC. This PIC could resemble Figure 1 below, with a fundamental mode of a silicon-on-insulator (SOI) waveguide next to it:

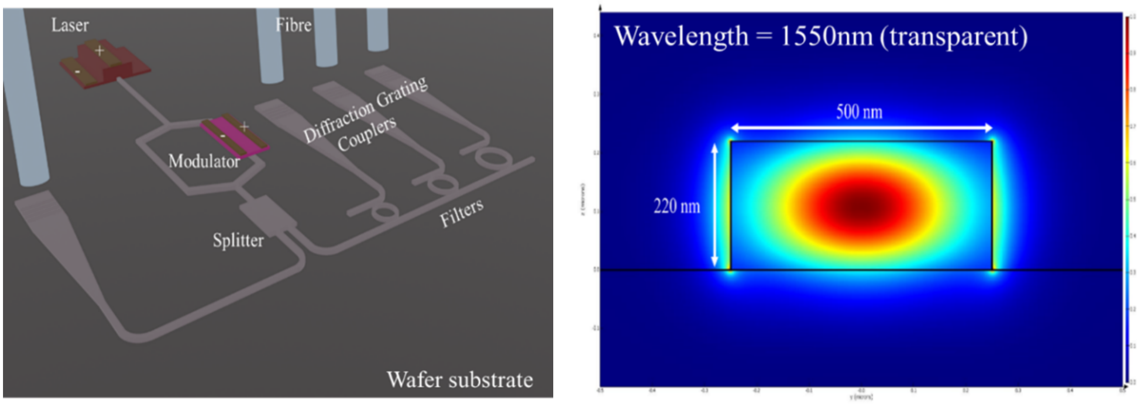


Figure 1: Example schematic of a PIC (left) and a simulation of light intensity in an SOI waveguide (right) using the Lumerical simulation suite (High-Performance Photonic Simulation Software - Lumerical)

Materials and their Advantages

Each photonic integrated circuit platform is researched and developed for a particular advantage associated with that material. However, other limitations always undermine the platform in favour of another, such as light guiding or modulating capabilities. Some material examples are III-V materials, III-Nitrides, Silicon/ Silicon nitride (otherwise known as silicon photonics or SiPh) and Lithium Niobate on insulator (LNOI) although there are others. These materials each have their unique characteristics and properties, and some features of each are described below.

III-V/Nitride Materials

III-V materials are compound semiconductors that are the workhorses for optical communication and PIC's currently. They are made of materials from groups 3 and 5 on the periodic table. The main semiconductors are Indium Phosphide (InP) and Gallium Arsenide (GaAs). These materials, along with their alloys, are of interest due to their direct bandgap, thus the chance of exciting an electron to a higher state is more likely than with an indirect bandgap. These excited electrons can then be stimulated to emit as a photon by other passing photons. This allows efficient amplification of light when oscillated in a cavity, which is how a laser works. Since a laser is the basis for many photonics applications, it is clear why these materials are so important in PIC technology. III-V materials can also provide a strong modulation effect and efficient absorption for detectors. While this does sound comprehensive, III-V materials tend to be higher loss for waveguiding and are also more expensive wafers than other alternatives.

III-nitrides contain a group 3 material and nitrogen (group V). These materials can cover the visible, and more recently, ultra-violet (UV) spectrum of light. The most known is Gallium Nitride (GaN).

Silicon Photonics

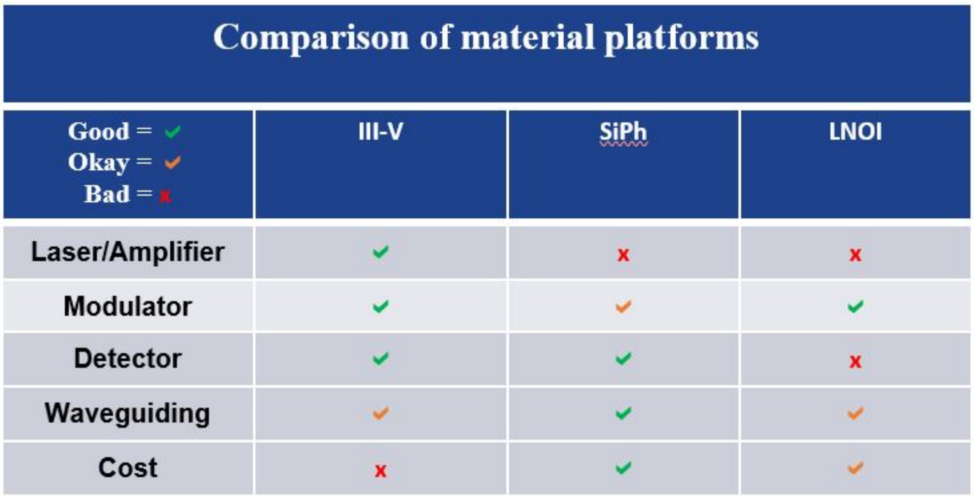
Interest in Silicon photonics has increased as SiPh makes use of the already immense CMOS infrastructure. This infrastructure reduces cost, leaning on economies of scale. The advantages don't end there. Si has a high refractive index which allows for submicron scale waveguides and sharp bends in a PIC, allowing for compact passive device designs. A Si waveguide cross-section is typically 500x220 nm2, for comparison, a human hair is about 50,000nm in diameter. While silicon is only transparent in the infrared (IR), Silicon Nitride overcomes that issue by being transparent in almost the whole visible spectrum. This is why SiPh is such an attractive platform for light propagation, and it is now the main platform for optical communications. SiPh has a monolithic detector using strained Germanium (Ge) or a SiGe alloy. It also has a modulator that relies on a carrier effect, while it is an option, modulators from other platforms do outperform it. Si lacks any efficient gain element as it is an indirect bandgap semiconductor, meaning electrons must jump to a higher state but must also vibrate the crystal accordingly for momentum conservation. This means practically that SiPh is a good option for guiding light but lacks a source to provide it.

LNOI

LNOI is a waveguiding platform, and it is interesting primarily for its modulating effect. It uses the Pockels effect, where with an applied field, the index of the material changes thereby changing the phase of the light. III-V materials have a modulating effect comparable to LN, but nonetheless, Pockels effect is broadband, linear, and tidy to implement. LNOI suffers in almost all other categories though with midrange guiding and no other active devices currently. In essence, LNOI is a platform of interest due to its impressive modulating capabilities but is otherwise limited.

Material Cohesion

It is clear from the above summary that each material has limitations when compared to the others. One solution could be to use SiPh for waveguiding and to be the underlying platform, while heterogeneously integrating the other materials. In the case of III-V, it makes more efficient use of the expensive material by not using it for longer passive components, from the perspective of SiPh it then solves the issue of having no gain element. The same kind of argument can also be made for LN modulators. The challenge is to identify an integration method that is scalable, efficient, and economical. This table acts as a summary of the different material platforms discussed.



Comparison of material platforms

Good = ✓ Okay = ✔ Bad = ✗	III-V	SiPh	LNOI
Laser/Amplifier	✓	✗	✗
Modulator	✓	✔	✓
Detector	✓	✓	✗
Waveguiding	✔	✓	✔
Cost	✗	✓	✔

Table 1: Comparison of different material platforms and their components

Integration Methods

The challenge to realise the mixing of these materials stems from their integration, which is not so simple. The integration process cannot be so consuming that it loses the value in assembly, at the very least, but further, it becomes making the integration as seamless and scalable as possible. This section explains the most likely candidates to address these challenges.

Bonding

Bonding is a research method of combining materials together for heterogeneous integration. One predominant example is flip-chip bonding, which flips the top device side of two wafers together, similar to a semiconductor sandwich. This is then heated and sometimes plasma assistance is used to bond the two materials together. The substrate of the top material is then removed to leave the heterogeneous devices on the target substrate. While this process is the most mature, it is slow and the throughput can be low, impacting how viable it is to scale up.

Transfer Printing

Micro transfer printing (uTP) is a form of “pick and place” technology that works by using a polymer stamp that attaches to a suspended coupon on a source platform. This coupon, suspended by polymer tethers is then transferred by the stamp to the target PIC. This can be an automated and scalable process whereby arrays of coupons (holding devices) can be printed to a target. This is used to transfer III-V to silicon or glass as it makes efficient use of the more expensive source substrate and there is even a capacity to reuse the III-V substrate. While an attractive option, it does require further processing and the coupons must be designed to accommodate the coupon structure to be transferred. There is a variance in the suitability of devices for printing, with bigger and square-shaped coupons being harder to engineer.

Heteroepitaxial Growth

Another possibility other than heterogeneous integration is the idea of growing each different material on top of one other, also known as heteroepitaxial growth. This is a difficult problem due to the large crystal mismatches that exist between the materials if the size of the atoms between the two materials differs a lot. If mismatches are present and the growth is not well engineered, it will produce dislocations in the material, essentially ruining the electronic characteristics. One example of clever engineering is by forming grooves in Si and using a Ge buffer layer to allow GaAs to grow without the common defect issues. This possibility is another appealing option as it means that one source wafer can in fact include all the needed materials. This option appeals by applying heterogeneous integration before any fabrication processing steps.

Example of Heterogeneous Integration in PICs

Heterogeneous integration is a primary topic in photonic research journals and papers. This technology solution races to keep up with the increasing demand for bandwidth, data transmission speeds, gas sensing and autonomous driving to name a few . This section explores some examples of heterogeneous integration research.

III-V Laser on SOI

One example of heterogeneous integration is seen in this study whereby a laser is integrated to different SiPh platforms by uTP.[2] Indeed, the laser can couple its light into the PIC and act as an integrated light source for the silicon platforms. This can be seen in Figure 2[2] (right), where light power vs applied laser current (LI) is measured from the PIC to a fibre and recorded using a power meter. The laser is edge coupled to inject light into the side facet of the waveguide and the other side facet of the waveguide is outputting to the fibre. This printing had placement accuracy to the order of a micron with a high yield (¿95%). This example of integrating a laser onto SOI is a harbinger of the use of heterogeneous integration in integrated photonics and opens up much more usability for PICs in the future.

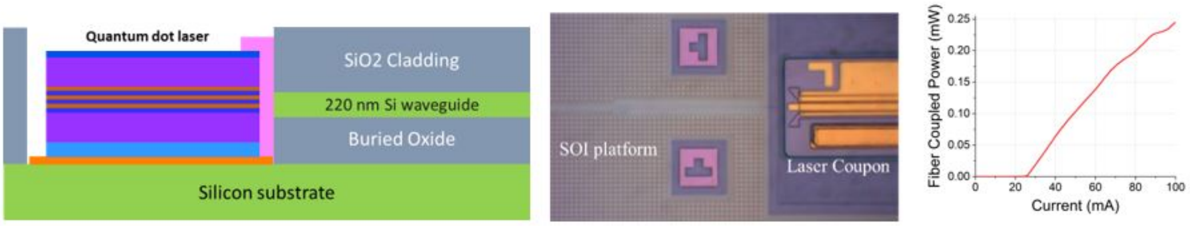


Figure 2: GaAs laser schematic on SOI (left), image (middle) and LI out of PIC (right)[2]

III-V Photodetector on SiPh

Another example in this study sees the addition of another type of device, a photodetector (PD), also integrated using uTP to SOI.[3] This works reciprocally to the laser, by light coupling-out of the waveguide to the detector which absorbs the light and detects it by turning light into current. This light is also edge coupled in the example shown but has also been measured through vertical diffraction coupling. This allows for on-chip high-speed detection of light, which is much more compact when compared to coupling the light out of the chip to an external detector, the PD is 600nm thick and 50µm2, as seen in Figure 3.[3]

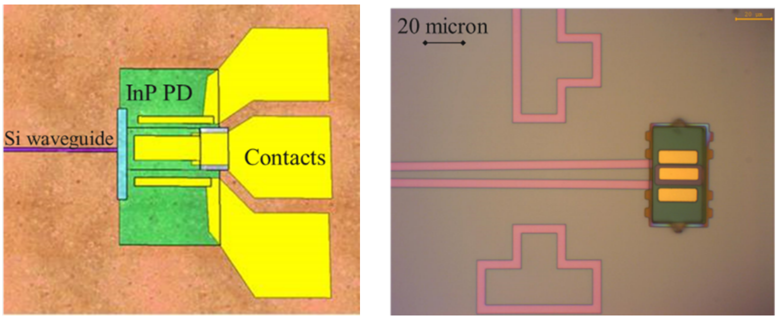


Figure 3: InP photodetector on SOI schematic (left) and image (right)[3]

The number of configurations of a PIC is multiplied with each addition of a new component, which expands the applicability of the technology overall. As these processes mature and develop, it will allow dense integration of these devices.

Conclusions

Heterogeneous integration is a promising solution to the limitations that currently undermine PIC's. The research now lies in optimising integration methods and the implementation of devices, as moving devices from one substrate to another is not trivial and requires further design and engineering requirements. uTP is an attractive option, along with other candidates. Important progress has been made on this topic with much more prospects and engineering innovations yet to come. This research progresses the state of the art for communications, sensing and more. This progress is driven by market demand created by the end users of these products (e.g., you, as you read this information hosted by a data centre).

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Declaration of Interests

Nothing to declare. I acknowledge the support of SFI in funding this work.

Author Bio

Owen is a 2nd year PhD researcher at the Tyndall National Institute. Working within the III-V group in IPIC, he specialises in the heterogeneous integration of III-V high-speed modulators to silicon photonic integrated circuits. This work includes the design, simulation and fabrication of III-V transfer printable modulators and the target SOI circuit, all in the Tyndall National Institute facilities and services. His interests begin in material science and fundamental physics, continuing to the applications that can be found with these insights.

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