Smaller and warmer: Merging photonics with electronics to build a quantum simulator

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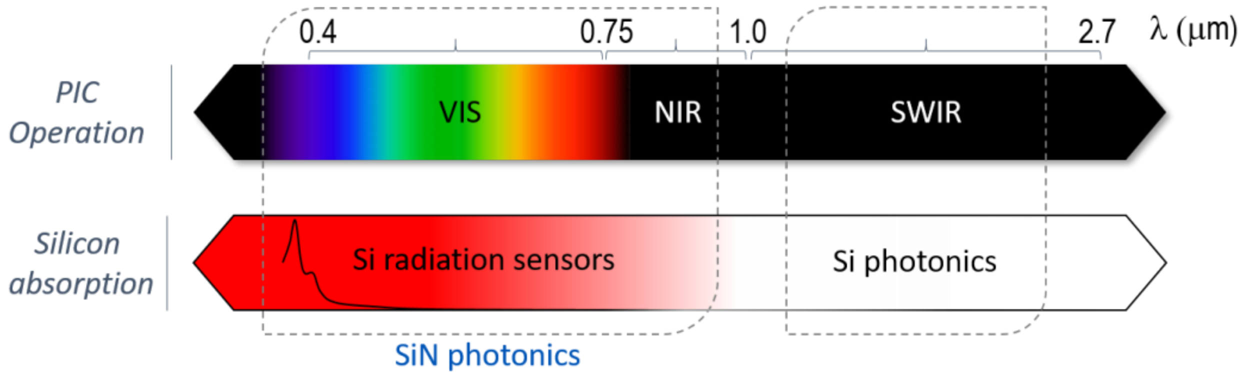

Figure 1: EPIQUS's approach for transparent SiN PICs and integration with Si photodetectors.

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The promise

The ability to process information using light signals has laid the cornerstone in the new Information Age, making optical fibre technologies indispensable over the past fifty years. As a result of exceptional advancements in micro- and nano-fabrication technologies, the capability to densely pack light guiding components on the chip-scale has announced the era of integrated photonic circuit (PIC) technologies.

These enable fast, parallel signal processing in a single waveguiding channel without interference, making the PIC platforms a preferred choice over their electronic counterparts (EIC) in several applications. Alongside, the Second Quantum Revolution revealed the remarkable potential of PIC technologies to revolutionise the future chip-scale devices, which can process quantum information using quantum bits encoded in photons – the single particles of light.

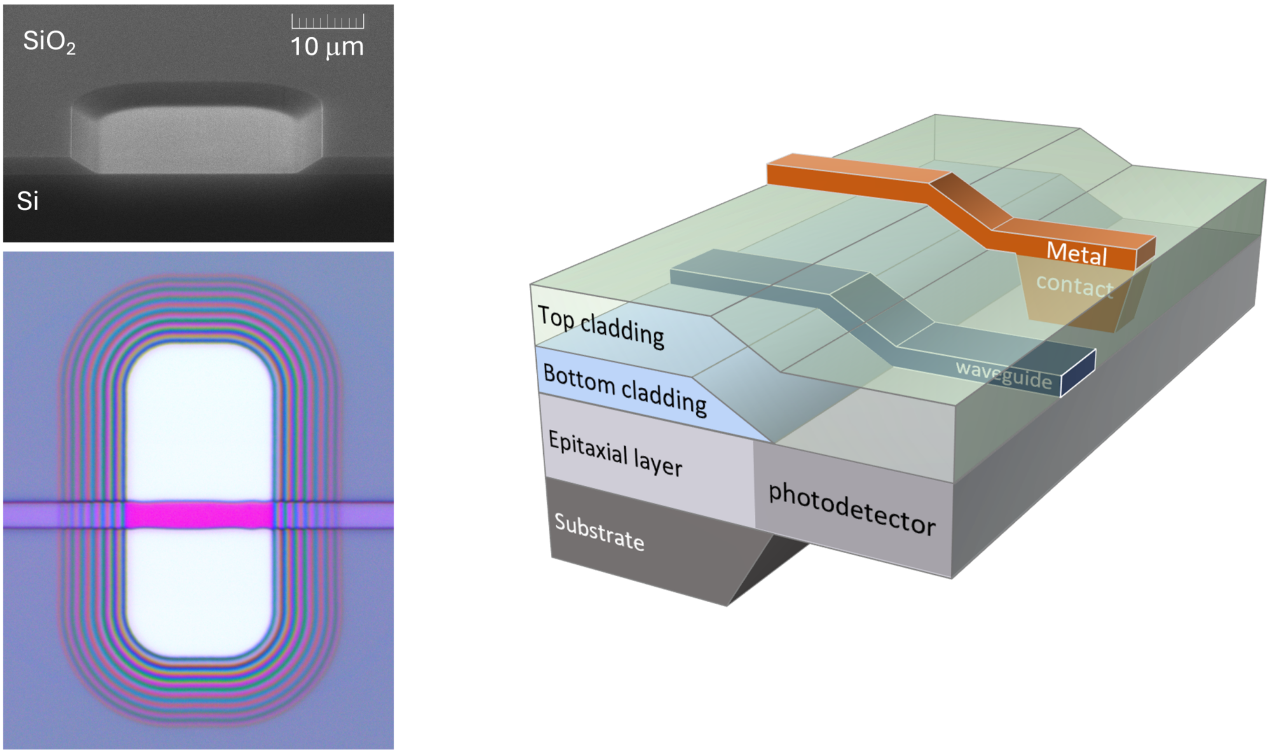

Figure 2 (left): A top-view optical image of a PIC-to-SPAD coupling and an SEM image showing the creation of smooth wedge boundaries around the SPAD position. (right) A schematic view of the EPIQUS device in the vicinity of the PIC-SPAD coupling and the substrate removal under the SPAD.

The challenge

Quantum simulators (QS) are a class of devices that can predict the real-world scenarios of processes, including the synthesis of new smart materials and efficient drugs or resolving problems from high-energy physics. All of these processes evolve obeying the rules of quantum mechanics.

Intending to develop a prototype QS device, the researchers of the EU-funded project EPIQUS merged together integrated photonics and advanced microelectronics technologies, realising a miniaturised QS on a single Silicon chip. Such a device, operable at room temperature, has the potential to provide many advantages, including supporting rapid and widespread innovation.

The strategy

Owing to its linear and nonlinear optical properties, crystalline Silicon is routinely used to realise low-loss PICs. On the other hand, Silicon – the prime material for microelectronics – is an excellent candidate for high-efficiency photodetectors. However, at a given operation wavelength, Silicon will either guide light signals efficiently or absorb it to generate an electrical signal. In fact, excellent PICs can be built to operate at telecom wavelengths (around 1.55 microns), while photon detectors can be realised for absorbing the UV and Visible light (Figure 1).

The strategy in EPIQUS was to build the quantum photonic circuit substituting Silicon with another material for light guiding – Silicon Nitride (SiN) – which is transparent to UV-VIS photons. This approach, consequently, enabled the use of Silicon substrates for the detection of single photons. When made of Silicon, these detectors, known as Single Photon Avalanche Diodes (SPADs), operate at room temperature, providing many advantages over other detecting technologies that require operation at cryogenic temperatures.

PIC-SPAD coupling

EPIQUS's approach was to merge the photonic and electronic functionalities in the same Silicon chip using a monolithic fabrication process. This would pave the way for future scalability and room-temperature operation for a mass-manufacturable technology. The researchers developed a smart fabrication process, where initially the SPADs and, potentially, part of the control electronics are fabricated within the Silicon substrate. In a second stage, the PIC is fabricated on top of the electronic layer.

A major challenge of this approach is the requirement to isolate optically the PIC from the substrate within the photon manipulation stage and to bring them into contact only at the point where the detectors are located. To do so, it is necessary to shape the thick isolating film between the PIC and the substrate into a smooth linear descent from the PIC towards the substrate.

Normally, superior quality smooth interfaces can be shaped using chemical dissolution of a glass material in an acidic bath. Unfortunately, the isotropic nature of chemical etching leads to semicircular profiles. This, in turn, causes very high optical losses due to the abrupt change of the geometrical profile, preventing optical signals from reaching the SPADs.

The researchers in EPIQUS developed a smart process where the film dissolution advances in the wafer plane at a faster rate than that of the isotropic chemical reaction. This phenomenon is in close analogy with that of the sonic boom propagation, released by a supersonic jet in the form of a perfect sound wave cone. In the case of chemical etching, the cone transforms into a triangular smooth shape (Figure 2, left). Using this technology, light signals can be transferred from the PIC waveguides to the photodetectors with very low optical losses.

Boosting SPAD efficiency

Once the photons are transferred from the PIC waveguide to the SPAD, they get absorbed within the Silicon material and generate a large electrical current burst. This sets a detection event of a quantum bit, often coined as a detector click. Still, only the photons which were absorbed within the first few micrometres of the millimetre-thick substrate generate clicks. This means that part of the useful optical signal is lost, leading to low detection efficiency.

Researchers adopted a smart approach to reduce the substrate down to a few micrometres under the SPAD devices (Figure 2, right). This way, the photons, which have not been absorbed at the first passage, bounce back and forth within the SPAD material until they get absorbed. Theoretical studies suggest an increase in detection efficiency from the current 20% to 90%, a huge step forward towards possible scaling of the technology.

What's next?

The European Commission is currently investing heavily to grow and advance the industry of PIC technologies in Europe through programmes such as the Photonics21, Quantum Flagship and the Pilot Lines of Chips Joint Undertaking.

While the EPIQUS project ended last October, the activities are progressing further. The success of EPIQUS allowed us to attract new funds, which will permit researchers to push further both the optimisation of the technology and to conduct a series of quantum simulation experiments on the demonstrator system.

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