Enhanced silicon light-emission for optical data communication

A new technological innovation by the University of Pretoria aims to develop low-cost, efficient and fast-switching silicon light-emitting devices in photonic integrated circuits.

The exponential growth of global data volumes and associated data centres is outpacing the industry's ability to efficiently produce more powerful data processing integrated circuits in accordance with Moore's Law. The modern trend of deploying more parallel computers with higher capacity data storage solves the problem of lagging microprocessor speeds, but the resultant significant proliferation of separate data computing equipment in turn leads to a growing need for faster and more efficient communication between computers and data storage.

Science meets art

According to Laurie Olivier, convenor of the international advisory board, the beauty of the injection-enhanced silicon in avalanche (INSiAVA) innovation is what happens when science meets art. This is clearly illustrated in the work of Prof Monuko du Plessis, who has instinctively conceived solutions that had been considered impossible when he initiated his research close to two decades ago.

The quest is to overcome the "interconnect dilemma" and to achieve enhanced interconnection performance by replacing electrical conductors with photonic interconnects. An initial patent that was filed more than a decade ago provided the fundamental basis for the subsequent research, development and associated investment.

INSiAVA's novel technologies

Complementary metal-oxide-semiconductor (CMOS), with its presence in almost every modern electronic device, is the most widespread semiconductor technology. This is largely due to its tight integration ability and considerable manufacturing ease when compared to other mainstream semiconductor materials. The result is a technology that is highly optimised for mass production. It has also become by far the least expensive semiconductor platform. Unfortunately, CMOS is based on silicon, an indirect band-gap material, which leads to poor performance

→ Prof Monuko du Plessis is the key inventor of INSiAVA technology and the principal research engineer leading the ongoing development work to refine INSiAVA technology to be suitable for widespread use in industry.

when generating light from the material. This creates difficulty when integrating optical circuitry, especially light emitters. It would, therefore, be very practical if one could combine the extensive reach of CMOS technology with the extreme functionality of optics.

INSiAVA's CMOS-compatible silicon-based light-emission technology has the potential to induce the new technological breakthrough that is needed over the next five years to solve the interconnect dilemma of electronic data transmission. This technology has the following key characteristics:

- It uses photonic devices to perform fast signal transmission among integrated circuits.
- The use of all-silicon light sources allows easy integration with associated circuitry.
- Full integration in standard CMOS and BiCMOS manufacturing technologies implies that integrated circuit development and manufacturing costs can be kept low.
- The technology allows switching frequencies in excess of 10 GHz.

INSiAVA's optical source features novel device physics and architecture.The basic device comprises a reverse-biased pn-junction at or very close to avalanche breakdown. Various techniques enhance the emission of light by injecting carriers into the avalanche region. This can, for example, be achieved by closely placing forward-biased injection junctions. Through impact ionisation, the injected carriers multiply in the avalanche field, which provide more carriers for radiative recombination. The resulting radiative recombination of hot and cold carriers improves the electro-optical conversion efficiency and the switching speed, which then enhance the signal transmission capability.

In addition, INSiAVA employs several novel geometric-optical device structure innovations to not only enhance the extraction of the generated light, but also to direct the emerging light beams into a useful direction.

INSiAVA has the following competitive advantages:

- Full compatibility with the CMOS integrated circuit manufacturing technology.
- Wide-band light emission spectrum ranging from 450 nm to 850 nm, peaking around 650 nm.
- Proven switching speed in excess of 10 GHz.
- An external quantum efficiency target of 1% (technology applications become feasible above 0.1%).

The optical solution

In order to increase bandwidth and data transmission speeds and solve the interconnect problem, the industry is increasingly considering optical signalling to replace the current industry standard slow electric connections.

Employing photons travelling at the speed of light, instead of electrons, increases the possible transmission speed of interconnect.

Opto-electronic interconnects are expected to significantly increase overall computing power in applications where large amounts of data are exchanged at ultra-high data rates. Most connections between data centres already employ optical communication. The next step is to expand the use of optical interconnects to include rack-to-rack back plane, board-to-board and ultimately chip-to-chip interconnects on motherboards. Current optical links require expensive discrete optical modulators to modulate light from large-chip external continuous-wave lasers with data.

INSiAVA sees an opportunity to eliminate the need for separate lasers and modulators by integrating optical light emitters and receivers into integrated circuits. This would allow direct fibre-optic data transmission between microchips. To realise inter-chip optical signalling, a fast-switching and efficient optical source that integrates easily into the existing state-of-art silicon CMOS-integrated circuit manufacturing technology is desirable. The innovative INSiAVA light source aims to fulfil these requirements.

Application of the technology

According to Prof Roelf van den Heever, CEO of INSiAVA (Pty) Ltd, an important aspect of the commercialisation of this technology, which is one of the outcomes of Phase IV of research and development, is the identification of products with "killer application" potential.

The technical team of Prof Monuko du Plessis at CEFIM has identified a number of technology demonstrators to illustrate the feasibility of the patented INSiAVA silicon light source technology in various application fields.

Optical communication

The potential of combining a complete optical transceiver on a single chip presents a very attractive opportunity. This may, for example, enable optical links between computers, while doing so at reasonable cost. This is what INSiAVA aims for with its drive to develop an optical data communication link.

The research team has demonstrated practical optical links, based completely on silicon, with transmission rates reaching multiple Mb/s, manufactured in the same type of process used for making computer CPUs. The main limitation is the efficiency of the electrical to optical conversion. The research emphasis is placed on improving the efficiency of the integrated light source in an attempt to create an all-silicon optical link with data rates exceeding hundreds of Mb/s or even into the Gb/s regime, all based on CMOS-compatible technologies. With such potential, it might even be plausible to expect optical ports on mass-produced devices such as cellular phones and portable electronic devices.

Lab-on-chip sensor

In the medical field, the chemical analysis of various samples is usually a slow process by dedicated specialists with expensive equipment in large laboratories. Small, inexpensive and disposable diagnostic devices are desirable as they can be operated by inexperienced persons and can yield fast and reliable results.

A lab-on-chip (LOC) system is therefore a miniature implementation of one or several processes that would traditionally be performed on a larger scale in a laboratory.

LOC devices are advantageous as they can be mass produced in mature, standard technologies. The resultant unit cost would be low enough to render disposable devices. Due to the small scale of such systems, only very small sample and reagent quantities are required for operation and results can usually be attained faster.

INSiAVA's CMOS-compatible light sources can integrate with the electronic circuitry that forms part of an LOC system, eliminating the need for external light sources in LOC implementations where samples need to be illuminated. INSiAVA is combining its novel sources and expertise with the microfluidic capability and expertise of the Materials Science and Manufacturing Group at the Council for Scientific and Industrial Research (CSIR) to develop an optical LOC. A very promising possibility is the development of an inexpensive, rapid diagnostic point-of-care system for the detection of certain infectious diseases that currently take months to diagnose. All chemical processing of a sample will occur on-chip and even the diagnosis will be performed and displayed by the system, eliminating the need for skilled personnel and complex analysis equipment.

Near-to-eye displays

Near-to-eye displays find increasing implementation in a wide range of industrial, medical and military applications where products like microscopes, binocular rangefinders, electronic viewfinders, telescopes and head-mounted displays enhance situational awareness, surveillance, thermal imaging, training, simulation, surgery, optometric diagnosis and reconnaissance through the display of superimposed information, augmented reality or substitutional imaging. In contrast to conventional displays, near-to-eye displays enable longer viewing times with less stress on the eye. They also offer mobility, privacy and three-dimensional imaging. Compared to competing liquid crystal (LCD) and organic light-emitting diode (OLED) micro-displays, INSiAVA's CMOS near-to-eye display technology offers several advantages.

CMOS micro-displays can be located on the same integrated circuit with associated digital electronics, deliver higher resolution displays with pixel dimensions down to five by five micrometers and have a wider operating temperature range than LCDs and OLEDs, which usually perform poorly or not at all below freezing point. Furthermore, CMOS micro-displays exhibit a longer lifetime than OLEDs, which degrade over time and typically lose half their brightness after about 50 000 operating hours.

In contrast to LCD's maximum switching frequency of about 240 Hz, the much higher intrinsic switching speed of silicon light sources makes CMOS displays blur-free. In contrast to commercial OLEDs and LCDs that are usually only available in fixed sizes and custom-made displays, and are prohibitively expensive, CMOS displays offer lower non-recurring engineering (NRE) and production costs to implement customised display sizes, shapes, pixel dimensions and resolutions. INSiAVA's integrated CMOS reflector technology allows a customisable viewing angle up to 180º.

Technical team

Prof Monuko du Plessis is the key inventor of the INSiAVA technology and the principal research engineer leading the ongoing development work to refine INSiAVA technology to be suitable for widespread industrial and commercial use. Other research engineering team members are Jannes Venter and Alfons Bogalecki, who are responsible for the design, processing and characterisation of INSiAVA microchips, Hannetjie Nell, who is responsible for the lab-on-chip research and development, and Marius Goosen, who is responsible for the development of digital and analogue optical communication links. Dr Pieter Rademeyer, co-founder and former director of CEFIM, has been appointed to perform market research, and to direct the development of technology demonstrators of INSiAVA's intellectual property.