Moore's law for photonics

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The twentieth century is sometimes referred to as the century of electronics. The twenty-first century could well be the century of photonics. In other words the century of light but then light used in technical applications such as screens, solar cells, LED lighting, optical communication, 3D printers, medical diagnostics, metrology and sensors. The market for photonic technology is currently about one fifth of the global market for electronics but it is growing faster and Europe has a strong position in this market. Electronics and photonics can be found almost everywhere but electronics is currently further developed and relatively cheaper, especially due to the emergence of microelectronic and nanoelectronic integration technology. In photonics, integration technology is still in its infancy but it is developing rapidly.

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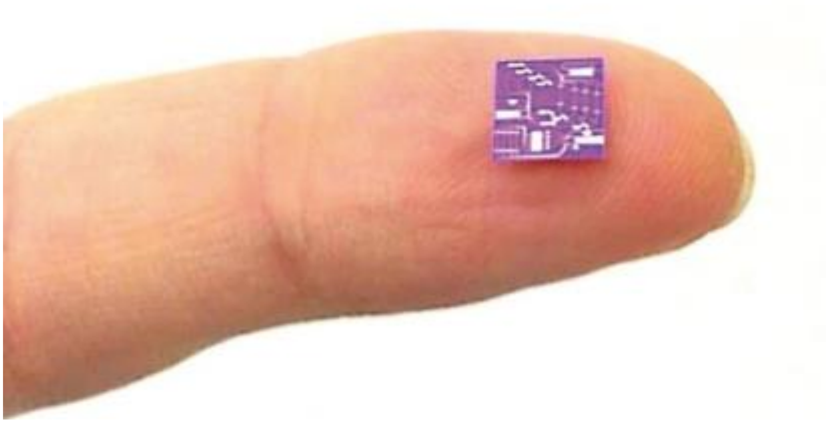

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Photonic integration

Integrated optical chips are the optical counterparts of microelectronic integrated circuits. Electronic equipment used to consist of a box or a cabinet full of electronic components such as vacuum tubes, resistors, capacitors and coils. After the invention of the transistor, electronics became more compact and circuits that were not too big could be integrated on a single print plate. However the real breakthrough came in the 1960s and 1970s when a growing volume of electronics could be integrated in a piece of silicon with dimensions of just a few millimetres. In photonics we are now in the same situation as the initial years of microelectronics. Most optical systems still consist of separate components such as lasers, modulators, detectors and filters, which are connected to each other with lenses or glass fibres or plastic fibres. However the technology to integrate tens to hundreds of optical components on a small piece of semiconductor material, an optical chip, has made considerable progress in the past twenty years.

In such an optical chip the components are connected with each other by miniscule optical channels – optical waveguides. Optical chips can be made from several different materials and the most important are indium phosphide (InP) and silicon. At present a lot of research is being done into optical chips in silicon, the basic material for electronic chips, in which you can also make a large number of optical components: waveguides, modulators, detectors, switches and numerous passive components, such as couplers and wavelength filters. Only lasers and optical amplifiers, the most important components in many optical chips, cannot be made yet in silicon, as it does not have the right material properties for this. However that is possible in indium phosphide, a semiconductor material that is quite similar to silicon but has superior optical and electrical properties.

Just as for electronic chips, optical chips can be used for a very wide range of applications. Figure 1 shows several examples of optical chips that have been made in InP. Figure 1a shows how small the chips are: typically several millimetres to a maximum of 1 cm. The chip on the finger is 6 x 6 mm in size. The chips shown have been designed for use in data communication (1b), gas detection (1c), two-photon microscopy (1d) and spectrometry (1e). Further information about these chips can be found in the figure caption.

Figure 1
a-e) Microscope images of a number of optical chips for various applications.

Moore's Law

The complexity of optical chips – the number of components that can be integrated on a single chip – has strongly increased since 1990, boosted by the emergence of the technology to transmit dozens of signals with different wavelengths (and with that terabits of information) through a single glass fibre. This technology forms the backbone of the modern Internet. The American company Infinera recently presented the most complex chip produced so far which has about 1700 components [1], whereas at the Eindhoven research school COBRA chips with a complexity up to 500 components have been developed. The development of the number of components per chip is illustrated in Figure 2 (the red dots in the graph correspond with chips made within COBRA) [2]. The development of complexity is clearly exponential, comparable with Moore's Law in microelectronics [3]. Although the dotted line suggests a continuous development a number of technological breakthroughs are needed to continue this development to integration densities of more than one million components per chip. In the remainder of the article we discuss recent developments in the complexity range of one to one thousand components and future developments to a higher degree of integration based on recent research at COBRA.

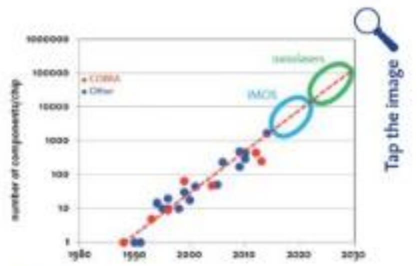

Figure 2

Graph of the number of optical components per chip against time. The linear relationship on a logarithmic scale shows exponential growth of the number of components over time, which is comparable to Moore's Law in microelectronics.

Generic integration technology

The development of the manufacturing technology for complex optical chips, as illustrated in Figure 1, is incredibly expensive. The costs of a well-equipped chip factory add up to several hundred million euros and then you only have the equipment and the building. Also the development of the integration processes that involve a large number of lithography, deposition and etching steps costs many millions of euros. There are few markets large enough to justify such huge investments. In microelectronics this problem has been solved by the development of standardised technology in which a number of building blocks, such as transistors, resistors and capacitors, can be integrated in large numbers – billions of transistors per chip – in a single standardised manufacturing process. As a result of this the high investment costs can be earned back across a combined market that is much larger than the markets for the individual applications.

To drastically reduce the high costs for the use of optical chips a similar development is underway in photonics. If you have a technology with which components for manipulating the amplitude, phase and polarisation of light can be integrated as basic building blocks, then you can realise chips with different functionalities in a single integration process. Such a technology is called a generic integration technology. The analogy with microelectronics is illustrated in Figure 3 (top left) for which components that manipulate the amplitude, phase and polarisation of light correspond with transistors, resistors and capacitors. In 2000, the Eindhoven research school COBRA started with the development of such a standardised technology in which optical amplifiers, phase shifters and polarisation converters are used as basic building blocks. The schematic cross-section in Figure 3 (top right) shows how the different building blocks are realised in the same of layer stack and the white spots indicate where the light beam is located in the different building blocks. The layers are grown from the gas phase on a crystalline InP substrate in a crystal growth reactor. The light propagates through a layer with a thickness of 0.5 µm. At the bottom of the figure electron microscope photos of the different building blocks are shown.

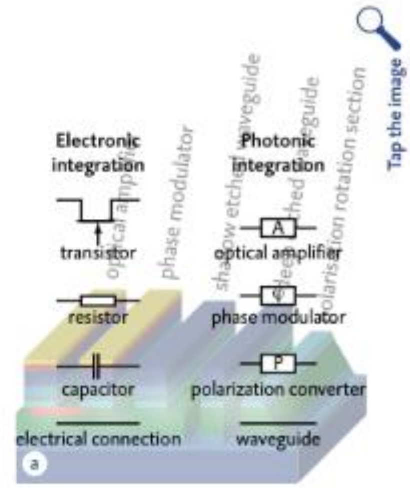

Figure 3
a) The basic components for electronic and photonic integration. b) This illustration shows a schematic cross-section of the basic components in a generic integration process. c) This figure shows electron microscope images of the basic components in the COBRA process.

Technology platform

In 2007 several technology platforms to provide access to generic photonic integration processes were set up within a network that contained more than sixty European research groups who collaborate in the field of optical integration. The ePIXfab technology platform, developed by the Institute for microelectronics (Imec), gives access to a manufacturing process for the integration of passive optical circuits in silicon and more recently modulators and detectors as well. The JePPIX technology platform, which is coordinated by COBRA, gives access to three industrial InP manufacturing processes in which in addition to passive components, active components, such as lasers, optical amplifiers and modulators can be made. One of these processes is being offered by a Dutch company, SMART Photonics. In 2009 an additional platform was added to this for dielectric waveguides with very low losses based on a combination of silicon oxide and silicon nitride (the TriPleX process of the Dutch company LioniX).

In the JePPIX consortium a number of industrial and academic partners are working together, including four chip manufacturers, three software companies and a number of universities. In 2010 and 2011, the JePPIX consortium started two large European research projects with the aim of converting the foundry model (see box The foundry model) from a university environment (COBRA) to an industrial environment to further improve the performances and functionality of the InP platform technology. Since 2014 JePPIX offers access to a number of foundry processes in which the designs of various users can be combined in a single wafer, a so-called Multi-Project Wafer (MPW). This allows the costs of a wafer to be shared by several users, which leads to considerable cost savings in the R&D phase. In this way the development of advanced optical chips comes within the reach of small high-tech companies and universities. This is an essential step for future increased integration of optical components, cost reduction and access to the market. With the JePPIX foundry service Europe has a considerable head start over the rest of world.

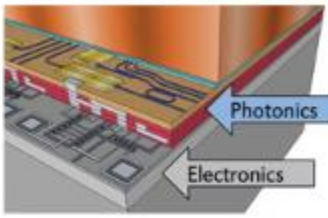

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Figure 4
Schematic representation of photronic chip: the chip in which the photonic circuit is manufactured above the electronic circuit.

Integration of photonics and electronics

Now that the costly development of advanced optical chips have been drastically reduced, the costs of packaging are playing an increasingly important role. In many cases they are considerably higher than the actual costs of the chip. Packaging is an umbrella term for the production of optical and electrical connections with the chip, optical, electrical and thermal insulation of the chips, and the robust packaging of the optical and electronic chips in a single casing. Integration of the optical and electronic functionality in a single chip is a dream of many chip users that could drastically reduce the cost of packaging. The integration of complete photonic and electronic circuits in a single chip still lies beyond the horizon for many researchers, but COBRA has taken the first steps in this direction. Figure 4 is a schematic representation of what such a combined photonic-electronic ('photronic') chip could look like. The optical waveguide layer is realised in a thin InP membrane that with the help of wafer bonding (a process with which two wafers are stuck to each other using adhesive or Van der Waals forces) is placed above a silicon wafer where the electronics have already been realised. We call this technology IMOS (InP Membrane On Silicon). An associated advantage of realising the optical circuits in a thin membrane is that the components are not only thinner but also smaller. As a result of this more components can be integrated on the chip.

Nanolasers

Optical communication was first introduced on long distance connections but the increase in the bit rate makes it increasingly interesting from an economic viewpoint to replace copper with glass at increasingly shorter distances, for example for data transport between equipment racks in data centres and also on print cards between chips. Ultimately, the connectors between processors in a single chip will be optical as well. For these connections low costs and low energy use are vitally important and both are possible by means of optical integration of the transmitters and receivers. Consequently there is a lot of interest in small and rapid lasers that can transport large quantities of data using little energy. Figure 5 shows a nanolaser that is being worked on within COBRA. It is a small pillar with a diameter of about 400 nm. In the middle it has an active area in which stimulated emission occurs if current is injected into the pillar. The pillar is covered with a silver coating (see inset) that forms the optical cavity for the laser. A part of the laser light is coupled beneath to the nanowaveguide (photonic wire) on which the laser is located and that can guide the light further to other locations on the chip. In the future we will be able to integrate thousands of such lasers in a single chip. A futuristic view is that they can be used for optical data transport between large numbers of electronic processors on a single integrated photronic chip. But we still have a long way to go before we reach that point.

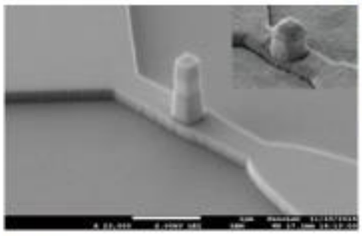

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Figure 5

A nanolaser on top of a nanowaveguide, with which the light from the laser can be guided to a different place on the chip to be detected there.

References

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