Moore with less silicon

How the silicon substrate slowly comes alive

There has been much attention for the tremendous developments integrated circuit technology has went through. The focus is always on the size and speed of the devices. In past years, however, the substrate itself also underwent remarkable developments. This has resulted in silicon-on-glass technology and flexible circuits. The future holds even more, with stretchable circuits and even LivingChips on the horizon. The following article presents an overview.

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In 1965 Gordon Moore made a remarkable prediction. He predicted that every two years or so, the number of transistors on a chip would double. Forty years later his prediction still holds. A remarkable feat, especially since the maximum number of transistors on a chip was only 50 when Moore formulated his law, while it is exceeding 2 billion for the latest designs! [1] To make all this happen, extremely advanced and expensive production tools have been developed. Probably best known are the wafer steppers, the photolithographic tools that are used to define features as small as 45 nm.

Less known is that, besides the production tools, also the development of silicon substrates has gone through a tremendous development. Whereas in the early days circuits were processed on 1 inch wafers, today silicon wafers with a diameter of 300 mm are standard, while 450 mm is ready in research. Compared to wafer steppers, the development of these silicon substrates receives only little publicity. Nevertheless, they belong to the most perfect and purest objects made by man. A blank silicon wafer is essentially a single crystal with a purity and perfection far better than that of diamond, at a price of less than 100 euro.

From a silicon technologist perspective, silicon is nearly an ideal material to work with. It is strong, cheap, easily forms a stable isolating oxide, it is a good thermal conductor and can be etched in various ways. From an electrical perspective, it has a good mobility for carriers, a band gap that is high enough to prevent leakage of transistors at normal temperatures and a resistance that can be accurately controlled over seven orders of magnitude, just by incorporating tiny amounts of impurities in its crystal.

What is often not realised is that in most integrated circuits everything of interest is usually confined to the top one or two micron of silicon. Comparing the thickness of a silicon wafer to the height of a table, this layer has the thickness of a sheet of paper! The remainder of the silicon substrate just serves to keep the whole thing together during fabrication. Fortunately, in most cases the material properties of the silicon substrate are such that they don’t interfere with the functioning of the circuit. Silicon, for instance, is a good thermal conductor, which is helpful to remove the heat from the circuit layer to the package for high speed processors. However, for a lab on chip, where for instance a small compartment has to be heated for a certain reaction, the leakage of heat through the thermally conductive substrate can be a real problem. Also for RF circuits the conductive silicon substrate underneath the circuits introduces losses and an undesired coupling of different circuit parts.

**Substrate Transfer**

Substrate Transfer combines the ease and advantages of standard silicon processing, with a complete freedom of substrate choice. Basically, fully processed silicon wafers are glued, top down, to a new substrate with properties more suitable for the application. Next the original silicon substrate is removed by a combination of grinding and wet-etching down to an etch stop layer directly underneath the circuit. In this way the thin layer containing the circuits is transferred to the new substrate. For many applications the circuits are transferred to glass substrates. Glass is a good thermal and electrical isolator, and its transparency allows for ultraviolet curing of the adhesive. The strength
of the technology is that it is a so called “post-processing” technology which does not interfere with the normal IC processing.

The technology was developed at Philips Research and later transferred to NXP Hamburg, where it was subsequently industrialised. In Delft, Lis Nanver from ECTM-DIMES immediately recognised the advantages of Substrate Transfer for RF circuits. Together with the staff from DIMES, she explored the fascinating possibility of double sided device processing that Substrate Transfer offers. Recently, Leo de Vreede and Lis Nanver demonstrated varactor diodes on glass with a world-record performance, again showing the advantages of a substrate free of parasitics. [2]

Flexible circuits
During the development work at NXP in Hamburg, an accidental discovery was made. In order to improve bondability of the circuits, in an experiment a 10 µm thick layer of polyimide (Kapton) was applied to the wafer before it was glued to the glass substrate. However, a fortunate mistake was made! The wrong procedure was used to ensure an optimal adhesion between the polyimide and the adhesive. During the subsequent wet etch that was used to remove the silicon substrate, the circuit layer attached to the 10 µm thick film of polyimide spontaneously delaminated. To everybody’s surprise the transistors and circuits on the foil still functioned perfectly.

At Philips Research the procedure was modified to control the moment of delamination. The reliability of these flexible circuits is obviously a concern. Extensive experiments have shown that as long as the circuit layer is held under a slight compressive stress, these circuits can be bent in either direction to a radius of less than 1 mm without breaking of the circuit layer. A 10 µm thick RFID chip for chip-in-paper applications was designed and fabricated (Fig. 3). This chip, which constitutes the world’s thinnest IC, remains fully functional, even while bended to very small radii.

The flexibility of these ICs makes them ideally suitable for biomedical applications. Due to their flexibility, these chips
can better follow the intricate shapes of the human body. In a recently granted STW project for instance, a flexible flow-and-pressure sensor chip will be developed at DIMES for application in 300 µm thick guide wires that are being used to diagnose the severity of a stenosis in balloon angioplasty procedures.

**Stretchable circuits**

The next step after flexible is obviously stretchable. The most appealing applications of these flexible circuits can again be found in the medical domain. Stretchable chips will be able to comply with the twisting and stretching of skin, muscles and other tissues. Additionally, whereas flexible ICs can be bent to follow cylindrical surfaces, stretchable circuits can be bent over spherical surfaces, which is important in for instance retinal implants.

Several approaches are being pursued to fabricate stretchable integrated circuits. One school of researchers considers the use of elastic substrates. Lacour et al. have found that very thin gold conductors on elastic PDMS membranes can survive an elongation of up to 100%. At ECTM -DIMES, Theodorous Zoumpoulidis and Marian Bartek follow a different approach to make stretchable ICs. Rather than using an elastic substrate, they partition the silicon into rigid islands that are connected by conductive springs (Fig. 4). The springs not only provide stretchability to the circuit, but also form the electrical interconnect between the rigid silicon islands containing the active elements.

**LivingChips**

From silicon processing to stem cell research seems an enormous step. However, recent progress in stem cell research has demonstrated that it is about to master the three basic steps in IC-fabrication: reproducible production by differentiation of stem cells into specialised cells, deposition of these cells on suitable substrates, and cultivation of the cells into designed patterns [3]. On the other hand silicon technology is, as we have seen, adapting more and more biological features such as flexibility, stretchability and biocompatibility. These developments have brought both disciplines on an intersection course.

At the present pace of research, it is very well conceivable that within a few years, the incorporation of living cells in micro-systems for diagnostic and therapeutic use becomes a practical reality. Similar to the growth or deposition and patterning of dielectrics and metals in today’s Micro-systems, in the future the flowcharts used for the fabrication of bio-MEMS may well specify the deposition of structured layers of [human] cells.

These cells may be used for sensing or actuation. Already researchers from the Tokyo University of Agriculture and Technology in Japan have demonstrated how the periodic contraction of heart muscle cells can be used to generate useful amounts of electricity. Additionally, muscle cells may be used to actuate the movement of e.g. catheter tips or implants.

Concluding, progress in micro-electronics encompasses more than just cramming more and more components on a silicon chip. Also in the field of substrate engineering significant progress is being made, extending the scope of silicon technology to new fields of application. For information on positions for PhD’s, graduation projects and internships feel free to send an e-mail to Ronald Dekker via r.dekker@tudelft.nl.