# The end of the road for silicon?

**Max Schulz**

**Computer chips continue to shrink. But the discovery that a layer of silicon dioxide must be at least four to five atoms thick to function as an insulator suggests that silicon-based microchips will reach the physical limits of miniaturization early next century.**

Silicon-based microelectronic devices have revolutionized our world in the past three decades. Integrated circuits, built up from many silicon devices (such as transistors and diodes) on a single chip, control everything from cars to telephones, not to mention the Internet. The thirst for cheaper electronic memory, and faster and more powerful processors, is still not satisfied. Each year we see more powerful chips with smaller device features, making them smarter and cheaper. The miniaturization of the devices found in integrated circuits is predicted by the semiconductor industry roadmap to reach atomic dimensions in 2012. According to Muller *et al.* (page 758 of this issue[1]), the narrowest feature of silicon devices — the gate oxide — will then reach its fundamental physical limit. In a transistor, the gate oxide insulates the voltage electrode from the current-carrying electrodes (Fig. 1). At a thickness of less than four layers of silicon atoms, current will penetrate through the gate oxide causing the chip to fail.

In 1925, Lilienfeld patented[2] the first field-effect device (one where current flow is modified by applying an electric field) based on silicon, but he probably never got it to work. It wasn't until 1960 that Kahng and Atalla[3] demonstrated the first metal-oxide semiconductor field-effect transistor (MOSFET), a remarkably simple device (Fig. 1), in which the semiconductor silicon plays a crucial role. This planar electronic device revolutionized electronics because a large number of MOSFETs and their interconnections could be built up on the surface of a single silicon chip.

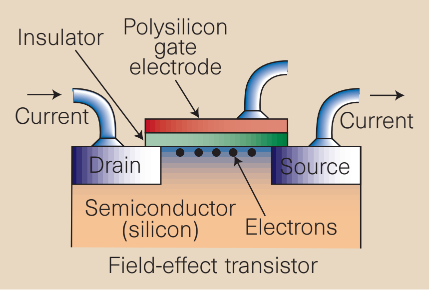


Figure 1 **A field effect transistor (FET), such as that used in computer memory chips. The FET consists of source and drain channel contacts, and a polysilicon gate electrode separated from the semiconductor silicon by the insulator $SiO_2$. When the voltage on the gate is positive, electrons accumulate on the semiconductor surface making the channel between source and drain conducting and so turning the transistor from the 'off' into the 'on' state.**

Only ten years later, the first integrated circuits — a 1 kilobit memory chip and a 750 kHz microprocessor unit — appeared on the market as the first 'large-scale integrated' devices with 100 to 5,000 components squeezed onto a single chip. Since then, continuous evolution has increased the number of device components on a chip by a factor of 64,000 to a fully integrated 64 megabit memory chip, in which there are more than one hundred million electronic components. The scaling down of device sizes not only increases the number of transistors per chip, but also increases the speed of the circuits, up to 600 MHz in today's personal computers.

The progress up to now is well described by 'Moore's law'[4]. Gordon Moore predicted in 1965 that for each new generation of memory chip and microprocessor unit on the market, the device size would reduce by 33%, the chip size would increase by 50%, and the number of components on a chip would quadruple every three years. So far this trend has shown no sign of stopping.

Several properties of silicon have made these developments in microelectronics possible. Silicon can be grown in single crystals more than 1 m long and 30 cm across, weighing approximately 200 kg. The purity of the crystal and the number of electrically active defects are well under control. The number of atomic crystal defects in sub-micrometre-sized MOSFETs is now limited to individual centres that act as traps for electrons. Such traps may be identified, individually characterized, and counted, so that single-electron transistors are possible[5].

The special feature of silicon, which makes it the semiconductor of choice for MOSFETS, is its native oxide. Silicon dioxide ($SiO_2$) is an almost perfect insulator with a resistivity in excess of $10^{16}$ Ωcm. The insulating films of $SiO_2$ grown on silicon are smooth and coherent with no holes in a thickness range down to single atomic layers[6–8]. The interface with silicon is abrupt and there are very few electrically active defects at the interface[5]. In the laboratory it is now possible to produce MOSFETs and integrated circuits[9] with gate oxides less than ten atoms across. Such thin films are required to maintain the current response of the transistor to lower voltages at the gate electrode. Manufacturers need to lower the

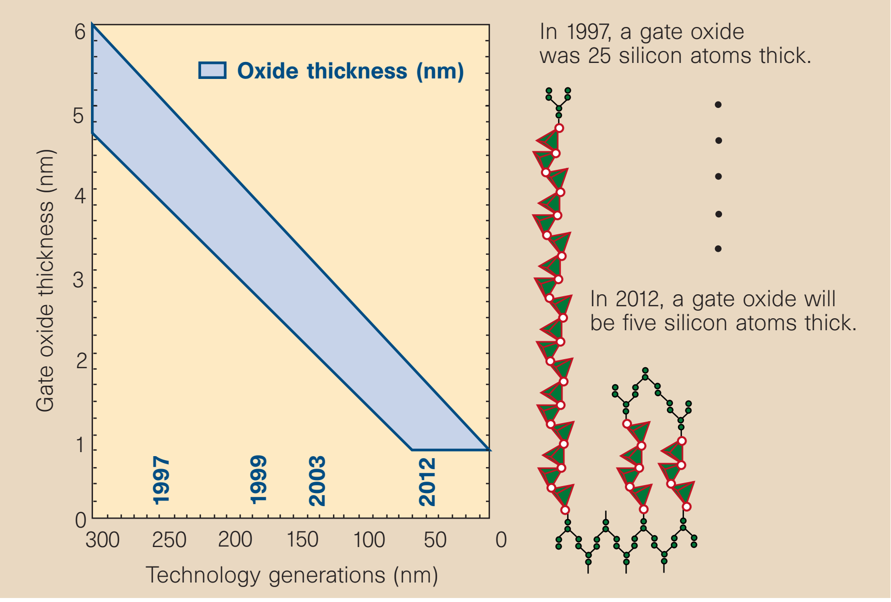


Figure 2 **Semiconductor industry roadmap. Predictions of the gate oxide ($SiO_2$) thickness for future technology generations, which are defined by the critical device size. The gate oxide is so thin that it can be drawn on an atomic scale (see right of plot). Full circles indicate the silicon atoms in the silicon substrate and the polysilicon gate electrode. White circles indicate the silicon atoms in the oxide structure. In 2012 a gate oxide will be only 1.3 nm thick, or five silicon layers thick. Two of the silicon atoms are bound to the crystalline silicon at the interface, so the 'bulk' oxide only consists of three atomic layers, which is now demonstrated by Muller *et al.*[1] to be just enough to provide a working insulating layer.**

power supply to individual components, if they are going to cram more devices onto a chip. The performance of the gate oxide is crucial to the device, so ultrathin gate oxides are being studied intensively, as witnessed last week at a conference on insulating films on semiconductors in Kloster Banz, Germany[10].

The Semiconductor Industry Association in the United States extrapolates Moore's law into the future to create a roadmap that predicts future developments in microelectronics based on silicon devices[11]. The roadmap sets yearly targets for the performance of integrated circuits and defines the advances in semiconductor technology required to reach those goals. Figure 2 shows the 1997 prediction for the next few generations of chips. In this plot the generations are defined by a critical device size, which is projected to decrease from 200 nm to 50 nm over the next 12 years. The gate oxide must be reduced in turn, from 25 silicon atoms today to 5 atoms in 2012 to achieve the roadmap goal. Clearly, there must be a limit to this scaling down because the gate-oxide thickness will eventually reach zero. The end of the line for the $SiO_2$ gate insulator is now expected early next century.

The work of Muller *et al.*[1] from Lucent Technologies is an experimental proof of the fundamental physical limit to the size of a working gate oxide. Using an electron microscope in combination with spectroscopic analysis of the electron energy levels in the Si–$SiO_2$ interface, they show that electronic wavefunctions penetrate through the ultrathin oxide film from both interfaces. This means that the electrical insulation of the gate oxide breaks down for an oxide thickness less than 0.7 nm, or four atomic layers of silicon in the oxide. Such an oxide is actually only two atomic layers thick, because the two silicon atoms at the boundaries of the oxide are not completely oxidized (Fig. 2). In practice the gate oxide has to be slightly thicker than the theoretical limit, say five layers of silicon atoms, because the interface is rough on an atomic level.

In the past, many technological limitations to Moore's law have been predicted. All these have been overcome by new developments, leading to silicon materials of unprecedented quality. Device processing is carried out in clean rooms with less than one dust particle per cubic metre. The components of an integrated circuit are usually fabricated by lithography — etching a pattern onto the silicon using blue light. As device size continues to shrink, lithographic techniques have moved to shorter wavelengths of light, with chips today being manufactured using ultraviolet light sources (193 nm). Future devices will require structures smaller than the wavelength of the light used, but there may be a way round this problem by using phase-contrast methods. So far there has seemed to be no obstacle to stop the continuous development of microelectronic chips.

The new limit to oxide thickness is fundamental, however, and cannot simply be overcome by technological improvements. The end of $SiO_2$ as a gate insulator will be reached in the year 2012, according to the roadmap for silicon technology. The science community and the semiconductor industry will have to come up with new ideas to avoid a bottleneck in growth. One possible solution is to use an insulating film with a dielectric constant higher than that for $SiO_2$. A high dielectric constant allows the use of a thicker insulating layer for the gate electrode. Unfortunately, all the materials studied so far are not as good as $SiO_2$. It is going to be difficult to replace $SiO_2$ or to modify its composition to increase the dielectric constant. But, so far, all the problems in the development of semiconductor technology have been solved. I am almost certain that this barrier will also be overcome, but this time using a different solution than further thinning of the oxide. Perhaps new device structures more complex than the MOSFET will one day be needed[12].

For the next 12 years, microelectronic circuits based on silicon technology will remain the basis for further 'electronization' of our world. The everyday demand for electronic equipment can be met in the short term. Silicon technology is still the most reliable and cost-efficient way to fabricate large microelectronic circuits. It is almost unthinkable that we are nearing the end of the silicon era, but in the meantime silicon chips will be further enhanced. Eventually science and industry will have to find new ways to build faster and larger computers. □

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**Hox clusters**

# Size doesn't matter

**Mark Q. Martindale and Matthew J. Kourakis**

Molecular biology has had a huge effect on our ability to understand the evolution of biological diversity. As we learn more about how embryos develop at the molecular level, we hope to be able to reconstruct the transitions in developmental programmes that lead to new forms. We need to know, for example, which organisms are most closely related to which others; what features these organisms have inherited from a common ancestor; at which critical junctures new innovations appeared; and, finally, how the genetic machinery could allow such transitions. But before we can determine the direction of evolutionary change, we need to sort out the natural evolutionary relationships of living animals. This is the subject of a report by de Rosa *et al.*[1] on page 772 of this issue.

Our understanding of the relationships between metazoan (multicellular) animals comes mainly from detailed examinations of how different animals are put together — the kinds of tissues and organs they possess, and the extent to which their embryonic development is shared. Animals that have a common anatomical organization, or 'body plan', are grouped into 'phyla'. Crustaceans and insects, for example, are invertebrates grouped in the same phylum (Arthropoda). This is in part because all have individual body segments covered in a hard exoskeleton. Phyla are often then grouped into larger categories, or taxonomic units, such as the 'Articulata' (invertebrate animals with sequential body segments). But these taxonomic units are intellectual constructs, which may or may not reflect features of common ancestry. Even defining concepts such as 'body plan' are difficult to agree on. Instead, an accurate representation of evolution must identify true clades of animals (groups derived from a common evolutionary ancestor).

Molecular biology promises to be a key tool in unravelling such relationships. Using this technique, de Rosa and colleagues[1] have sought to confirm a radical reorganization in metazoan evolutionary relationships. Two years ago, Aguinaldo *et al.*[2] compared the sequences of a common structural RNA from many different animals with a uniform pattern of molecular evolution (that is, species with unusually fast rates of evolution were eliminated). These authors confirmed the idea that bilaterally symmetrical animals (the Bilateria) can be divided into two groups, deuterostomes and protostomes, which were originally defined by the embryological origin of the mouth (Fig. 1). The