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**Moore's Law Forever?**

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ed immune cells in which the Syk/SLP-76 signaling pathway is activated be responsible for the separation of the blood and lymphatic networks? If so, then the absence of these signaling molecules in SLP-76– or Syk-deficient animals might result in fusion of the peripheral lymphatic vessels with blood vessels resulting in the vascular malformations observed in the knockout mice.

Although Abtahian *et al.* argue to the contrary, another possibility is that the bone marrow–derived cells they used to rescue the lethally irradiated wild-type mice included lymphatic endothelial progenitor cells (*6*). These circulating cells differentiate into endothelial cells expressing lymphatic markers in vitro (see the figure, step 5). They may be important for lymphatic development as well as for postnatal lymphangiogenesis under physiological or pathological conditions. Could signaling through the SLP-76/Syk pathway trigger the early differentiation of a multipotent bone marrow stem cell into a more differentiated lymphatic endothelial progenitor cell? Because SLP-76 or Syk could not be detected in the endothelial cells of the lethally irradiated wild-type mice, the expression of these molecules may be down-regulated before lymphatic endothelial progenitor cells become incorporated into the developing lymphatic vessels.

The careful functional studies of Abtahian *et al*. have broad implications. First, the identification of SLP-76 and Syk during the separation of the blood and lymphatic systems implicates these molecules in AVMs. The new findings may help to elucidate other proteins involved in various congenital AVM syndromes, thus speeding development of improved treatment strategies. Second, the Abtahian *et al*. work focuses attention on early events in the development of lymphatic vessels and the part played by cells derived from bone marrow. It is becoming clear that multiple molecules are necessary to ensure proper differentiation and patterning of lymphatic endothelial cells into a functional lymphatic system. By expanding the roster of molecules, many more targets for therapeutic intervention will emerge beyond VEGFR-3 and its ligands, yielding more possibilities for new treatments for lymphedema. Third, the new work may offer fresh insights into the dysregulation of both the vascular and lymphatic systems during tumor formation, specifically through the SLP-76/Syk pathway. Syk expression is lower in breast tumors than in normal mammary tissue and correlates with an increase in metastases and a poor prognosis (*7, 8*). Could reduced Syk expression lead to abnormalities in the developing tumor vasculature, hence boosting metastasis? Could mutations in SLP-76, Syk, or other pathway components also explain the finding that blood-filled vessels associated with some tumors bear lymphatic markers (*9*)? Blood vessels and lymphatic vessels present metastatic tumor cells with two major routes for dispersal. Thus, strategies to selectively eradicate these vessels may provide a potent weapon against cancer. Increased understanding of the signaling pathways driving lymphatic vessel development should boost the impact of therapeutics on diseases associated with the lymphatic system.


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APPLIED PHYSICS

# Moore's Law Forever?

**Mark Lundstrom**

When Gordon Moore predicted in 1965 that the number of transistors per integrated circuit chip would continue to double in each technology generation, there were just 30 transistors on a chip. Today, transistor counts—a measure of the capability of an electronic system—exceed a few hundred million for logic chips and even more for memory chips. How long can Moore's law continue?

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The semiconductor industry follows Moore's law by shrinking transistor dimensions. But transistors cannot be scaled down infinitely. A few years ago, as critical dimensions approached 100 nm, a number of formidable challenges arose (*1*). It seemed that progress would slow, but during the past few years, device scaling has accelerated, as evidenced by several talks at the recent International Electron Devices Meeting (IEDM) (*2*).

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Today's electronic devices are based on the metal oxide semiconductor field-effect transistor (MOSFET), which consists of source and drain electrodes, through which current can flow, and a gate electrode, which controls the current through the other two (see the figure). MOSFETs operate on a simple principle: When the gate voltage is low, an energy barrier prevents electrons from flowing from source to drain, whereas a high gate voltage lowers the energy barrier, allowing current to flow (see the figure). The gate electrode is separated from the silicon channel by a thin insulating layer to prevent the flow of gate current.

To comply with Moore's law, the transistor designer must shrink the distance between source and drain by a factor of $\sqrt{2}$ in each technology generation. This reduces the area by a factor of 2, thereby doubling the number of transistors per chip. Remarkable advances in subwavelength lithography allow current-generation technologies with gate lengths of 65 nm to be manufactured. Economic considerations have not yet slowed progress, and state-of-the-art technology still operates far below fundamental limits imposed by thermodynamics and quantum mechanics (*3*). The serious transistor design issues arise from materials limitations and transistor physics.

For digital applications, a transistor switch must, first, deliver a large on-current that rapidly charges and discharges the capacitance of the wires connecting it to other transistors in the circuit. The switching power is proportional to the operating frequency and to the square of the power supply voltage. Transistor scaling increases the number of gates on a chip and their operating frequency. To limit power dissipation and prevent the chip from overheating, the power supply voltage must therefore decrease in each technology generation, while maintaining the on-current.

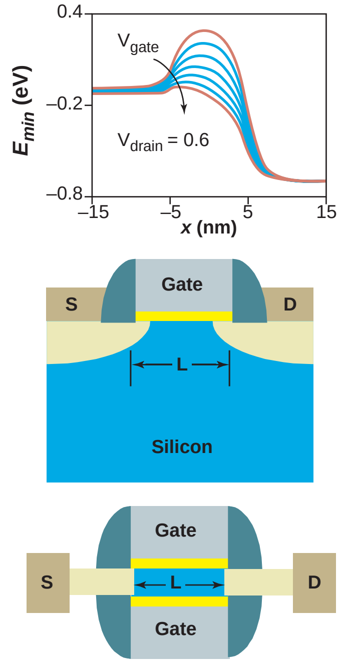
Second, a transistor switch should conduct very little current when off. However, as the distance between the source and drain shrinks, it becomes increasingly difficult to turn a MOSFET off. Because off-currents increase exponentially with device scaling, the off-state power consumption is now substantial.

Third, transistors should switch on abruptly as the gate voltage increases. However, because the current is controlled by thermal emission over an energy barrier, it takes a change in gate voltage of at least 60 mV to change the current by a factor of 10 at room temperature. As power supply voltages decrease, the voltage range between on and off states also decreases, and the 60-mV limit makes it difficult to obtain both high on-currents and low off-currents.

The challenge, then, is to engineer an appropriate energy barrier between source

and drain so that the device can be turned off, while at the same time designing a gate structure that can effectively modulate the barrier and turn the transistor on. As channel lengths decrease, drain-induced electrostatic effects lower the barrier, thereby increasing the off-current and reducing gate control.

Drain-induced barrier lowering can be controlled by increasing the density of dopants in the silicon channel between source and drain. However, the thickness of the $SiO_2$ gate insulator must be reduced to maintain gate control of the barrier. High channel doping and thin gate oxides lead to quantum mechanical tunneling, which increases leakage currents. Furthermore, the number of dopant atoms in the channel decreases with each technology generation, so that statistical fluctuations in their precise number lead to variations in device characteristics.




**The MOSFET principle. (Top)** Minimum electron energy ($E_{min}$) versus position from source to drain ($x$) under high drain voltage. An increasing gate voltage lowers the energy barrier between source and drain. **(Middle)** Planar MOSFET with source (S), drain (D), gate, and doped silicon substrate. **(Bottom)** Double-gate MOSFET, with a gate above and below the undoped silicon film; channel length (L).

Several new transistor structures aim to improve the electrostatic control by the gate and mitigate the deleterious effects of dopants in the channel. For example, sophisticated two-dimensional channel doping profiles have been used to push the traditional, bulk-silicon MOSFET to channel lengths below 15 nm (*4*).

Other structures promise even better device scaling. In the silicon-on-insulator MOSFET, the off-state barrier height is set by the gate-to-semiconductor work function difference rather than by channel doping. With extremely thin silicon films, channel lengths of 6 nm have been achieved (*5*). Gate control of the barrier is improved by placing a gate above and below the channel (see the figure). Several variations of this theme exist (*6*). In the FinFET, the silicon channel is a vertical "fin," and the gates are placed on both sides of the fin (*7*). A FinFET with a 10-nm channel length has been reported (*8*). The gate-all-around MOSFET promises even better gate control (*9*).

Another route to smaller, faster transistors is the use of new materials. Silicon has been the material of choice for electronic devices because of its high-quality native oxide, but $SiO_2$ films have been scaled to near their limit. Materials with higher dielectric constants would permit the use of thicker layers, which would decrease leakage currents (*10*). The use of channel materials with higher mobility could provide high on-currents at the low voltages needed to manage power.

Strained materials have been shown to improve carrier transport substantially (*11, 12*), and manufacturing processes to introduce stress are being readied for production (*13, 14*). Germanium, the semiconductor originally used for transistors, is being reexamined because of the high mobilities that it provides (*15, 16*). For ultrahigh-speed applications (albeit with lower transistor counts than for silicon logic chips), high electron mobility transistors (HEMTs) that use compound semiconductors rather than silicon have achieved speeds of 100 gigabits per second (*17*).

Recent developments in molecular electronics are also promising. Carbon nanotube FETs (*18, 19*) are particularly interesting because they might provide much better on/off-current ratios and device speed (*20*). Furthermore, because they are similar to MOSFETs, the sophisticated electronic design tools now in use might be extendable to carbon nanotube FETs. Alternatively, small molecules might be gated to realize single-molecule transistors (*21*). However, it seems unlikely that electrostatically gated molecular transistors could operate at channel lengths much smaller than those of silicon transistors (*22*).

Instead of using molecules to make transistors smaller, it may be preferable to complement silicon transistors with new types of molecular devices for applications such as high-density memory (*23*). But doing so will not be easy. Small devices tend to be dominated by effects at the contacts and can have high defect densities. They are likely to show wide variations in performance and often deliver low on-currents. Small electronic devices can operate at high frequencies, but high-speed operation of high-density circuits leads to unacceptably high power dissipation. Success will require both small devices and new information-processing schemes—perhaps inspired by biology—to make use of them.

Until now, chip performance has been driven by transistor scaling, but with the acceleration of Moore's law, transistors will reach their limiting size within a decade or so. A recent study concludes, however, that another 30 years of progress in silicon nanoelectronics is still possible (*3*). One approach, exploiting the third dimension by producing layers of devices on a chip, has recently been demonstrated (*24*). But as the number of devices per chip increases, the power dissipation per chip becomes a critical issue (*3, 6*). In the absence of expensive cooling systems, the power per chip is limited to about 200 W. Without innovative solutions, power dissipation constraints, not device physics or economics, will limit the number of transistors per chip.

Moore's law is about lowering cost per function, and molecular electronics might continue the trend without transistors by self-assembling new types of electronics on a Complementary MOS (CMOS) platform. The future of electronics may lie in such heterogeneous systems that complement digital CMOS with new devices and information-processing schemes. For the past 30 years, we have known what to do: make transistors smaller. Progress continues at a breathtaking pace, but transistor scaling is approaching its limit. When that limit is reached, things must change, but that does not mean that Moore's law has to end.

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