Special issue:

The science of VLSI

The emergence of silicon-based very-large-scale integration is one of the major technological events of our time. This development was fueled in large measure by previously obtained scientific knowledge, but the devices of modern microelectronics in turn have made possible dramatic advances in all fields of science. Physics (and the physical sciences generally) has played an important part in this story. As this special issue of PHYSICS TODAY shows, very important contributions are still being made; more are needed to support continued progress in VLSI.

The major theme in today's worldwide VLSI development is keeping the silicon juggernaut rolling; the minor theme is finding a viable supplement or alternative to the silicon-based technology. In both cases progress is often severely limited by lack of basic understanding of materials, processes and their interactions under the extreme conditions present during the fabrication and use of VLSI structures. These conditions include drastic concentration gradients, dominance of interfacial phenomena, large electric fields, material compositions that must remain far from thermodynamic equilibrium during subsequent hot processing, and extreme sensitivity to defects. Furthermore, the standards of reliability are now such that, once fabricated, individual devices and interconnections must be so durable that not one in, say, ten million will fail in ten thousand hours of use. Here again, lack of fundamental understanding is often a severe handicap to further progress.

Despite these gaps in scientific understanding, silicon VLSI has progressed faster and further than anyone could have foreseen only 15 years ago. Moreover, the pace of development and of competition in silicon technology is greater than ever. And although pushing forward is not getting any easier, it is not unreasonable to expect at least 10 to 15 years of continued progress.

On the other hand, it is possible that practical, if not fundamental, limits will gradually slow the remarkable exponential growth that has characterized the past decades. Such areas as lithographic tooling, complexity of interconnections and heat dissipation may emerge as potential limits. Therefore considerable research is being done on other kinds of devices, primarily in the III–V semiconductor family. The hope is that some or all of the possible limitations of silicon VLSI will be circumvented (at least for a time) by the improved characteristics of the new devices and their VLSI embodiments. This is a very great challenge for a new technology that, to be economically significant, will have to be clearly superior to some future state of silicon-VLSI development where the standard of performance is much higher than it is today. Moreover, modest superiority at the device level will seldom be sufficient, because VLSI performance at the chip level is strongly affected by wiring capacitance and the availability of sufficient interconnectivity, factors not related to transistor device physics.

It is against this background that we hope with this special issue to illustrate the opportunities for contributions by the physical sciences to the future of VLSI technology. The articles were chosen to illustrate areas of research in physical science that are of known or potential importance to VLSI technology.

One of the most direct means by which science contributes to technology is through the invention of new techniques. For example, the dramatic progress in surface science over the past two decades has given rise to a number of surface spectroscopic techniques that are immensely important in the analysis and diagnosis of the extremely complex structures and processes of modern microelectronics. Laser science, too, has contributed techniques of great usefulness. The article by Gottlieb Oehrlein (page 26) illustrates the power of a combination of new and established diagnostic techniques in elucidating problems that arise in VLSI structure fabrication. As an example, he treats the problem of analyzing the damage done during a typical reactive-ion-etching step. Incidentally, the whole field of reactive-ion etching is one to which the combined tools and understanding of plasma physics, laser spectroscopy, and surface physics and chemistry can make great contributions.

In addition to providing novel diagnostic techniques, research in surface physics, chemistry and materials science has, over the past few years, produced methods of materials preparation that may be very useful in microelectronics. These include molecular-beam epitaxy and metal–organic vapor-phase epitaxy. The article by John Bean (page 36) describes important new directions in the preparation of silicon and silicon-alloy structures

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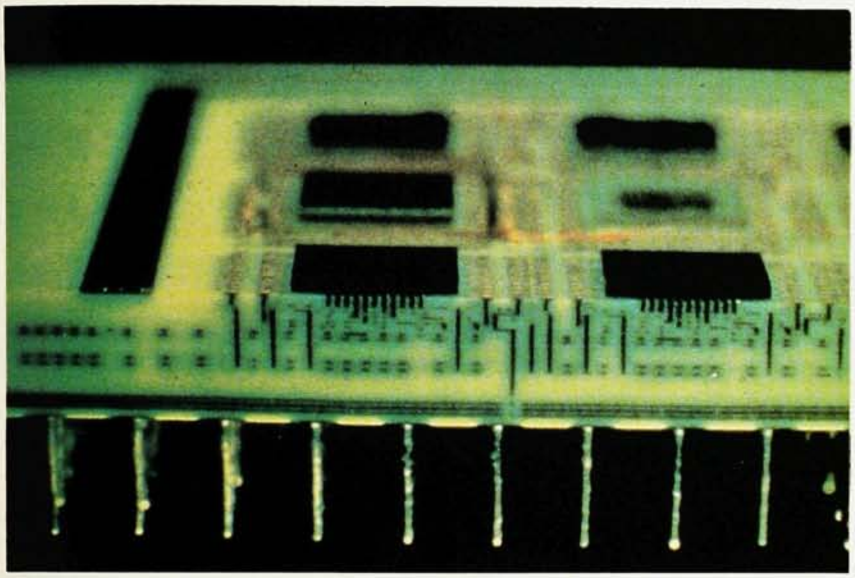

VLSI on and between chips. IBM's multilayered ceramic substrate can accommodate 320 cm of wiring per square centimeter of surface area. The foreground of this photo shows a small region of substrate (seen in cross section) with chips mounted on top. A typical substrate contains 350 000 vias (vertical pathways) for layer-to-layer connections and 130 meters of wiring. This packaging technology connects up to 45 000 circuits, the highest density yet reported for high-performance bipolar technology.

using molecular-beam epitaxy. Related techniques have long been used in building III–V devices, but only now are these methods pursued as promising means for building silicon- and germanium-based structures.

All silicon-based VLSI technologies, bipolar as well as field-effect transistor, make widespread and crucial use of various insulators, chief among them silicon dioxide. In particular, the modern 32-bit microprocessors and 4-megabit random-access memories put extraordinary demands on the purity, perfection and dielectric strength of the silicon dioxide used as an insulator in the chips. This is a classic case of technology leading fundamental science. Frank Feigl's article (page 47) explores in depth the recent progress in understanding the most basic aspects of silicon dioxide as an insulator. In large measure this progress has been motivated both by the availability of new experimental techniques (made possible by technological advances) and by the desire to understand how SiO_2 acts under the extreme conditions experienced by a modern gate oxide.

It is not unusual for VLSI chips to be used in systems containing tens of millions of transistor devices (and therefore many tens of millions of interconnections). This entire ensemble of devices must work trouble-free and without failure for thousands of hours, during which time the devices and interconnections are stressed by high electric fields, elevated temperatures, thermal gradients and often very large current densities (on the order of 10^5 amps/cm^2). Understanding the mechanisms, often at the atomic level, that govern such functioning is the task of reliability physics. Prabhakar Ghate's article (page 58) provides an introduction to this very important field. Reliability physics is constantly uncovering areas in which our supposedly satisfactory basic understanding of solid-state phenomena is in fact inadequate to account for what we observe.

I mentioned above that GaAs and related III–V semiconductors represent the primary technology under exploration as a complement, and perhaps an eventual alternative, to silicon VLSI. Lester Eastman's article (page 77) provides a wide survey of recent progress in this area. Research in III–V semiconductors is producing not only memory and logic chips with impressive performance, but also devices and structures in which novel mechanisms of electron transport are observed. Of these various possibilities, GaAs is certainly by far the most advanced. Many of its embodiments require, or profit from, operation at temperatures down to 77 K. If low-temperature operation is economically practical, silicon FET technology will be ready and able to profit from it as well. The operation of complementary metal–oxide–semiconductor chips at 77 K is well known to provide roughly a factor of two improvement in performance over room-temperature operation. But perhaps the most far-reaching effect of opening up the world of commercial feasibility to low-temperature operation would be to give new life to the search for very dense, ultra-low-power (and therefore low-voltage and low-temperature) devices. New three-terminal cryogenic devices and devices in which coherent electron transport is important are just two of the possibilities.

Whatever the main directions of future VLSI technology turn out to be, it is certain that the physical sciences will contribute strongly to the questions of both device operation and chip fabrication. Perhaps the principal contribution will be narrowing the gap that now exists between the needs of technology and our fundamental understanding of materials, processing and their interaction at the extreme level of sensitivity encountered in VLSI fabrication.

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