Chapter 3

Current Research and Development Activity

Microelectronics research and development (R&D) activities can be separated into three categories:

1. activities to improve silicon integrated circuits (ICs),
2. efforts for compound semiconductor microelectronics (primarily based on gallium arsenide (GaAs)), and
3. investigations for integrated circuits based on materials other than semiconductors.

Design activities span all three categories. Most of the work described here is aimed at making better digital integrated circuits. Other semiconductor activities, such as optoelectronics and microwave devices, are also included here because they are merging to some degree with IC technology and because all semiconductor R&D shares a common base of physical understanding and process technology.

ADVANCED SILICON INTEGRATED CIRCUITS

Efforts now underway to improve silicon-based microelectronics will be the first type of R&D to have practical applications. These efforts can be grouped in three categories of simultaneous activities:

1. the improvement of the physical circuits and packaging of integrated circuits,
2. the facilitation of the design and fabrication processes, and
3. the design of new types of ICs for specific markets.

Circuits and Packaging

The process of reducing the size of devices in ICs and increasing their packing densities has several parts. Scientists and engineers are developing devices–transistors, resistors, capacitors–that have feature sizes of less than 1 micron. Despite their small size, these devices must be designed to operate correctly and to control the required amount of power. The interconnections required to hook the devices together are also becoming increasingly harder to make. Each connection must shrink in width but still conduct electrical current with virtually no resistance. The interconnections must lie closer together but still be completely isolated from each other. Designers must lay out both the devices and the interconnections in more and more complex patterns. Finally, the package for the completed chip must allow signals to enter and leave the chip at high speed, so that the package itself does not obliterate the speed advantage of the new circuitry.

These steps have been used to scale down silicon ICs over the past 25 years. Every new reduction in feature size has been significantly more difficult to achieve than the last, and progress has been possible only through the introduction of increasingly complex manufacturing technologies and device and circuit designs. Today's R&D workers face the greatest challenges yet.

Few trends, however, can continue forever. The remarkable feature of Moore's law (the annual doubling of the number of components on a chip) is the range over which it extends before meeting unavoidable limits. Two technological factors limit growth. The sizes of the individual devices and the separations between them eventually become so small that the devices cannot function as desired. In some instances, these dimensions are a few dozen atom layers. The problems involved in interconnecting the devices on a chip also become virtually insurmountable. Together, these make a relaxation in the rapid growth of microelectronics technology inevitable. Microelectronics experts do not agree on the details and consequences of this slowdown, but they generally do agree that these limits will be reached during the next 10 to 20 years.

Design and Fabrication Processes

Activities to facilitate the IC design process are focused on design tools, which simplify circuit layout for IC designers. Particularly as the design process has grown more complex to accommodate the millions of devices, computer-aided design (CAD) systems have become virtually indispensable. Currently, there is no single standardized CAD system; rather, there are several different systems built by different groups of designers. As these systems evolve, they will simplify the design process and thereby give a wider range of users great flexibility in creating new chips.

Fabrication technology includes the processes for depositing very thin layers of different metals, insulators, and semiconductor materials on the silicon substrate; changing the impurity content in the semiconductor; etching the layers; and defining small features in the layers through lithography. Current R&D activities are exploring better techniques to carry out each of these tasks. For example, densely packed circuits may require new materials with special properties—high electrical conductivity, chemical stability, particular crystal structure—for interconnections. Also, x-ray, electron-beam, or other lithographic techniques may be needed to replace current photolithography for better definition of ultrasmall features.

Manufacturing technology is a crucial part of these advances because progress in silicon scaling is based on the introduction and improvement of highly sophisticated equipment. Some examples are chemical-vapor-deposition (CVD) and evaporation systems to grow thin films of semiconductor crystals and metals; lithography equipment and plasma etchers to define the ultrasmall features of the IC; and furnaces and ion implanters to introduce the proper impurities to the wafer.

Circuits for Specific Markets

Currently, most ICs fall into a few standard categories: logic chips, memory chips, and microprocessors. However, as the design and manufacturing capabilities of the IC industry grow and become more flexible, a range of specialized integrated circuits will play a more central role. Application-specific ICs (ASICs) are projected to grow from their current 12 to 15 percent of the total IC market to 25 to 30 percent of the 1990 market.[1] This category of integrated circuits includes custom chips, which are designed from scratch for the particular application, and chips that can be adapted by the user for the specific need. Further enhancements of the design process will expand users' ability to design their own ICs.

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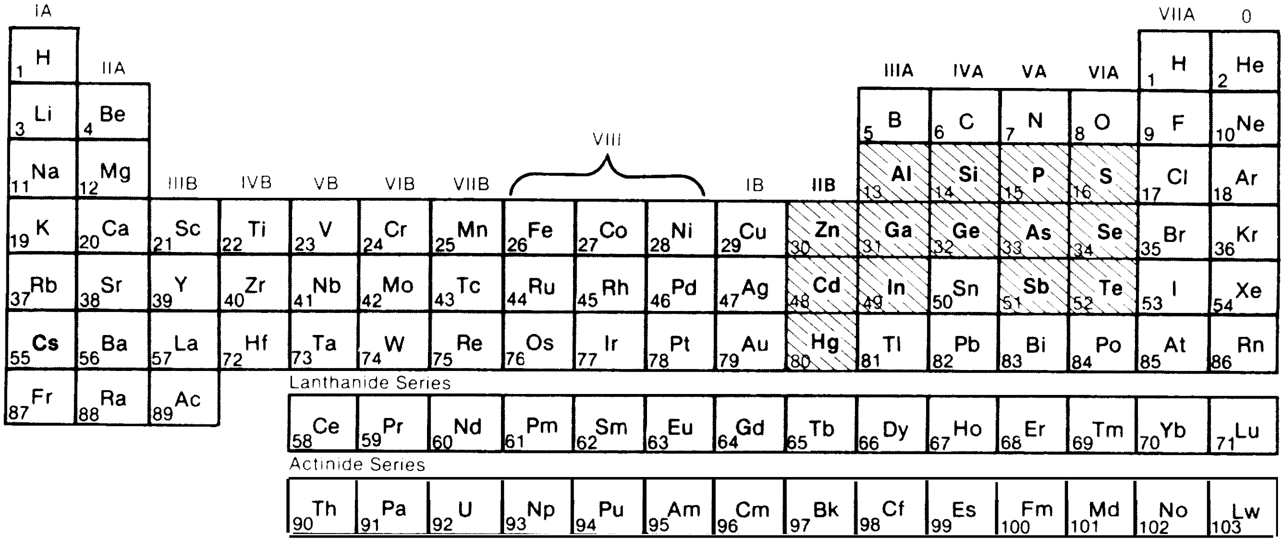
[1] “A Chip Business That Is Still Growing: Innovation Spurs Market for Application-Specific Integrated Circuits, ” *Electronics,* July 22, 1985, p. 40.

MICROELECTRONICS BASED ON GALLIUM ARSENIDE AND OTHER COMPOUND SEMICONDUCTORS

From the vantage point of the chemist or physicist, there is a logical progression of semiconductor materials in the periodic table from silicon (a column IV material), to compound semiconductors made from the columns adjacent to silicon (II I-V compounds such as GaAs), to compounds made from the next columns (II-VI compounds such as cadmium telluride). (See figure 1. In this terminology, the Roman numerals refer to the columns on the right side of the periodic table; e.g., “III-V” refers to columns 111A and IVA.) This progression is also useful for classifying the range of R&D activities in semiconductor microelec-

Figure 1 .—Periodic Table of the Elements



NOTE Elements in boldface are those commonly used to make semiconductor materials

SOURCE Office of Technology Assessment

tronics, since the most immediate development efforts focus on silicon, and longer term work usually focuses on compound materials.

GaAs and other 111-Vs are now the basis for a variety of discrete microelectronic devices, as described in appendix A. Current R&D efforts involving these materials focus on.: 1) GaAs digital integrated circuits, 2) advanced optoelectronic devices, and 3) monolithic microwave devices. R&D on design tools, which is critical in silicon technology, is also very important for these alternative technologies.

GaAs Digital Integrated Circuits

Digital integrated circuits based on materials other than silicon continue to receive attention in the research community. GaAs-based integrated circuits are currently the leading contender for next-generation technology. Even so, it is important to note that virtually no experts believe that GaAs ICs will usurp the position of silicon for most applications.

Gallium arsenide has several intrinsic physical properties that distinguish it from silicon. The typical devices made from GaAs operate faster and consume less power than silicon devices. They are also less likely to malfunction in the presence of radiation. However, since a compound semiconductor is intrinsically more complicated than a single-element semiconductor (silicon), GaAs is a much more difficult material to grow, to handle, and to use to fabricate reliable devices.

At present, many barriers impede prospects for making GaAs ICs at production capacity compared with silicon ICs, which are readily produced in quantity. Silicon ICs are currently fabricated on wafers with 5- or 6-inch diameters, while 3-inch wafers are the largest current size for GaAs. Standard silicon wafers have far fewer defects and are less brittle than the best GaAs wafers. Some processing steps for silicon IC technology can be adapted directly for GaAs ICs–portions of the lithographic procedure, wafer handling, clean-room requirements. But the steps involving other materials, such as oxides and other insulators, metals, and polycrystalline semiconductor material, must be developed specifically for GaAs. This requires a more complete understanding of the chemistry and physics of the interfaces between these materials. In addition to all of these fundamental difficulties, GaAs IC technology suffers because experience with it is very limited, relative to silicon. Many of the problems, however, will probably be solved as experience accrues.

The list of organizations supporting (and not supporting) R&D in this area reveals quite clearly the microelectronics community's views on the applicability of GaAs ICs. DOD is the leading Federal supporter of research in this field, because military applications, particularly in space, require the properties GaAs offers: high speed for large-scale signal processing, low power to minimize bulk and energy consumption, and radiation hardness for reliability in the presence of radiation. Major computer and communications companies-e. g., AT&T, IBM, and several Japanese companies —are also investigating GaAs ICs, primarily for use in the parts of their systems that require the highest speed, e.g., computer front ends. Supercomputer companies, most notably Cray, are attempting to make supercomputers based on GaAs ICS. However, the standard merchant chip makers (e.g., Intel, Fairchild Semiconductor, Advanced Micro De vices), which tend to concentrate almost exclusively on short-term development activities, have no onsite efforts in materials other than silicon. Some of these companies support longer term projects, including GaAs work, at universities and through cooperative research organizations. This balance of support indicates two things:

1. GaAs digital ICs are beginning to find niche applications in a variety of areas, and
2. they will probably not make a significant dent in the standard IC components market for several years.

Optoelectronics

As described in appendix A, compound semiconductors and their alloys are currently used to make devices that convert electrical signals to light signals and vice versa. The devices are used for optical communications and sensor applications. R&D activities in optoelectronics fall into three categories:

1. advanced discrete light sources and detectors,
2. integrated optoelectronics, and
3. superlattices and other quantum-effect structures.

The II I-V compound materials used for optoelectronics include GaAs, iridium phosphide (InP), gallium phosphide (GaP), aluminum arsenide (AlAs), iridium antimonide (InSb), and alloys of these materials, such as aluminum gallium arsenide (AIGaAs), iridium gallium arsenide (InGaAs) and iridium gallium arsenide phosphide (InGaAsP). Similarly, important II-VI materials include cadmium telluride (CdTe), mercury telluride (HgTe), and their alloy, mercury cadmium telluride (HgCdTe). These materials are designated as binary, ternary, or quaternary depending on the number of elements found in them. The alloys actually represent a range of materials; for example, half the atoms in HgCdTe must be tellurium, but the other half may be any combination of mercury and cadmium atoms. The properties of the alloy generally lie between the properties of the binary materials that compose it. The particular composition of an alloy is typically chosen to have a certain desired wavelength response. The standard approach to fabricating optoelectronic devices is to grow thin layers of ternary or quaternary alloys on a substrate of a binary material.

Discrete Optoelectronic Devices

The first optoelectronic devices for fiber optic communications were made of GaAs and AlGaAs. The best current devices, however, are based on different compositions of InGaAsP grown on substrates of InP, structures that generate and detect light over a range of wavelengths that includes those of lowest loss (1.55 microns) and lowest dispersion (1.3 microns) in optical fibers. Since these devices are relatively new, the materials and processing problems have not been completely resolved. R&D efforts in this area focus on making devices more reliable and more tolerant of extreme environments, achieving more precise control of the generated light, and developing production processes (with high throughput and yield) for the devices.

The II-VI compounds are used to fabricate long-wavelength infrared sensors because these materials (especially HgCdTe and CdTe) are sensitive to the wavelengths of interest—from around 1 micron to the 10- to 12-micron range. Currently, research on these devices centers on materials properties, which are much more difficult to control in the II-VI compounds than in other semiconductors.

Integrated Optoelectronics

Individual optoelectronic devices can be integrated and fabricated on a single substrate much as standard electronic devices are integrated on a chip to make an IC. An integrated optoelectronic device, typically built on a substrate of InP or GaAs, may be composed of lasers, devices to amplify and modulate the light signals, and light detectors. In addition, the same chip may have purely electronic devices that process electrical signals. Such an integrated chip has all the advantages of a conventional integrated circuit—miniaturization, high speed, low power, fabrication reliability—and also solves the alignment and vibrational-stability requirements for the optical elements it comprises. In addition, it brings optical and electronic devices so close together that signal delays between them are minimized, allowing high speeds to be achieved.

The basic concepts for integrated optoelectronics may be extrapolated even further in the future. Highly advanced crystal growth and processing techniques, currently in their infancy, could also open the door to the possibility of structures that would combine silicon, III-V, and II-VI devices on a single substrate. Such a scheme would allow the flexibility to use the optimal material for each portion of the complete circuit. For example, a circuit on a single chip could be composed of InGaAsP lasers, HgCdTe light detectors, and GaAs and silicon digital logic and memory circuits. Concepts of this sort are still in the speculative stage today.

Superlattices and Other Quantum-Effect Structures

By using sophisticated techniques to deposit materials very precisely, crystal growers can make layers as thin as a few layers of atoms on a semiconductor substrate. Such a layer is approximately one-thousandth of a micron thick-one-billionth of a meter. [2] Structures called superlattices are formed by growing alternating ultrathin layers of two different materials, e.g., GaAs and AlGaAs. Special methods such as molecular-beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) are necessary to achieve this extreme level of control during crystal growth. These advanced techniques open a completely new set of options for semiconductor materials. Varying the thickness of the layers and their composition can yield a superlattice material with different electronic and optical properties. Quantum mechanical effects dominate the behavior of the electrons in superlattices because the structures have such small dimensions. Thus, the electron transport processes can be dramatically different from the processes in normal material.

Currently, the range of research efforts in this area is very wide, spanning the spectrum from work in designing better systems for growing these precise layers to making devices based on superlattices. The devices include III-V and II-VI photodetectors, lasers, and transistors. The greatest overall contribution of this new breed of materials will probably stem from the fact that they can be tailor-made for a particular application. Already, they are heralded by observers from diverse vantage points as one of the most exciting areas of research today.[3]

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[2] Figure A-3 in app. A shows how small a micron is.

[3] For example, National Academy of Sciences, Committee on Science, Engineering, and Public Policy, *The Outlook for Science and Technology 1985*; and George H. Heilmeier, "Microelectronics: End of the Beginning or Beginning of the End?" International Electron Devices Meeting, December 1984.

Microwave Devices

Analog microwave devices, operating at frequencies from approximately 1 to 60 gigahertz (a gigahertz is 1 billion cycles per second), are commonly made from GaAs to take advantage of the high speed that the material offers. Currently, monolithic microwave integrated circuits (MMICs) are being developed. These circuits combine various microwave devices on a single substrate, typically GaAs. The devices are not packed as densely as silicon devices on a conventional digital IC, but the smallest dimensions are about the same as or smaller than those for silicon ICs—below 1 micron. MMICs will fill the demand for more compact and reliable microwave circuitry for applications in radar, transmission of television and telephone signals, and spectroscopy. A couple of companies have MMICs on the market already, and others plan to market them soon.[4] Most recently, the Department of Defense (DOD) announced that it will launch a major new initiative for MMICs for defense systems. The new program will be analogous to the Very High Speed Integrated Circuit (VHSIC) program, which addresses digital IC technology for DOD.

NONSEMICONDUCTOR INTEGRATED CIRCUIT TECHNOLOGIES

Integrated circuits may also be based on materials other than semiconductors. Circuits made of superconducting Josephson junctions have been heavily investigated but are not at present expected to find any large-scale applications in digital microelectronics. Bimolecular electronics is currently only a highly speculative field.

Josephson Junctions

A Josephson junction is an electronic device made by sandwiching a very thin insulator between two superconductors—materials with zero electrical resistance at very low temperatures. Like electronic devices made from semiconductors, Josephson junctions can switch or store electronic signals. Despite drawbacks such as extremely low operating temperatures, they offer several advantages over semiconductor microelectronics. Josephson junctions can switch signals at unparalleled speeds, require very little power, and can be scaled down to extremely small dimensions.

Computer systems based on Josephson-junction technology were intensively researched and developed for over two decades, most notably at IBM. However, IBM halted all but its basic research effort in this area several years ago because packaging, manufacturing, and reliability difficulties meant that the systems could not operate as well as had been originally predicted. Furthermore, while the superconducting technology was struggling to get on its feet, silicon and gallium arsenide technologies kept progressing at a tremendous rate. IBM's cutbacks in this area symbolized a significant change in the microelectronics community's view of IC technology beyond silicon. Currently, although some work on Josephson junctions continues in the United States and in Japan (especially efforts aimed at making high-speed analog circuits), these devices are considered unlikely candidates to pickup where silicon leaves off in digital ICs.

Bimolecular Electronics

In contrast to semiconductor and Josephson junction technologies, the concept of using biological systems to process electrical signals is still in its infancy. Some researchers are turning their attention to biological systems

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[4] "MMICs Save Space, Increase Reliability, and Improve Performance," *Electronics Week,* May 20, 1985, p. 52.

as the extrapolation of the trend to smaller and smaller devices leads to molecular-scale structures.

At present, large-scale bimolecular electronics is a largely speculative area. Some experts envision-a role for biological materials in the fabrication of extremely small structures on semiconductors, and in electronic sensors for medical applications. But the potential for computers based on bimolecular circuitry has not yet been demonstrated.