MOS Technology, 1963-1974: A Dozen Crucial Years

by Ross Knox Bassett

A line can be drawn from the Frosch's and Derick's work on silicon dioxide to the MOS (metal-oxide-semiconductor) transistor's dominance of semiconductor technology, but it is neither short nor straight. That line has several discernable segments, first from Frosch and Derick's work, until 1963. In this interval, by and large, no one thought seriously about a metal-oxide-semiconductor as a viable technology in its own right. The second segment runs from 1963, when the combination of integrated circuits and the planar manufacturing process had led people to see MOS transistors as a potentially promising semiconductor technology, until the mid-1970s, at which point the MOS transistor had been established as a commercially successful and sustainable technology. This article will detail that second segment, concentrating on work done by Fairchild Semiconductor Corporation and IBM, and will show that three types of work were crucial during this period: first, research on the chemistry and physics of MOS structures; second, product design and development to create integrated circuits that had some advantages over bipolar technologies; and third, organizational change to create environments where MOS technology could thrive.

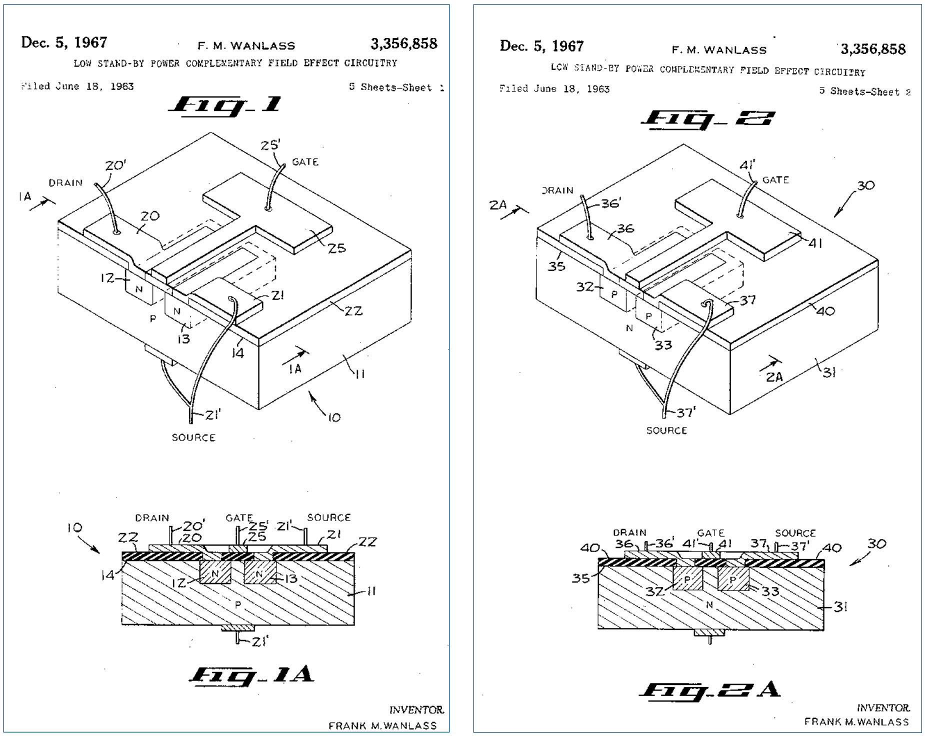

Fig. 1. *First two pages of Frank Wanlass's U.S. patent on complementary MOS transistor circuitry.*

Early Research at Fairchild

In its earliest years, Fairchild had put a lot of time and effort into studying the surfaces of bipolar transistors, but the first sustained work on the MOS transistor as a potential product came from Frank Wanlass, who joined Fairchild in August 1962 after earning a PhD in physics from the University of Utah. In a period of remarkable creativity stretching until his departure for the start-up General Microelectronics in December 1963, Wanlass explored the chemistry and physics of MOS structures, built MOS integrated circuits, and considered how various MOS phenomena could be commercially exploited. Wanlass's greatest technological contribution was the invention of CMOS (complementary MOS), which led to transistor circuits that consumed almost no power in standby operation (see Figs. 1 and 2). While the complexities of building CMOS circuits were so great in the 1960s that most firms concentrated on making *p*-channel MOS circuits, his CMOS circuitry and the low power consumption it allows has been one of the technical foundations of MOS's dominance over the last three decades. Wanlass, who often worked at the very edge of what was possible, seldom published and bounced around among marginally successful MOS companies, and is one of the vastly under-recognized figures in the history of MOS technology.[1]

After Wanlass's MOS transistor work in early 1963, Gordon Moore, then director of research and development at Fairchild, and C. T. Sah, the manager of the solid-state physics department, began putting together a team to understand the MOS structure and the silicon-silicon dioxide system in a systematic way. Moore's main reason for starting this team was to produce better bipolar transistors—Fairchild's main area of business. But this work would also be expected to address the stability problems of MOS transistors. Up to this time, the problems of MOS stability were so great—an MOS transistor's characteristics might vary by over a hundred volts over time or with changes in temperature and operating conditions—that they made MOS transistors useless as a product. If these problems could be solved, MOS transistors would be technically viable.

The first member of the group was Bruce Deal, who came to Fairchild in March 1963 with a PhD in chemistry from Iowa State University and many years researching oxidation processes. Andrew Grove joined later that spring after receiving his PhD in chemical engineering from UC Berkeley, where he had worked on fluid mechanics. Ed Snow came later that year from the University of Utah, where he had earned a PhD in solid-state physics based on the migration of ions in quartz.[2]

In October 1963 this Fairchild group made a breakthrough discovery. Snow began a project assuming that different metals applied as a gate electrode over the silicon-dioxide layer might show different levels of stability. Researchers typically evaporated aluminum onto the silicon dioxide using a tungsten filament, but because of the extremely high melting points of platinum and tantalum, Snow instead used an electron-beam evaporator to apply these metals. As he examined the stability of these platinum and tantalum structures, Snow found they were more stable than

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This article is adapted from Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies and the Rise of MOS Technology* (Baltimore: Johns Hopkins University Press, 2002).

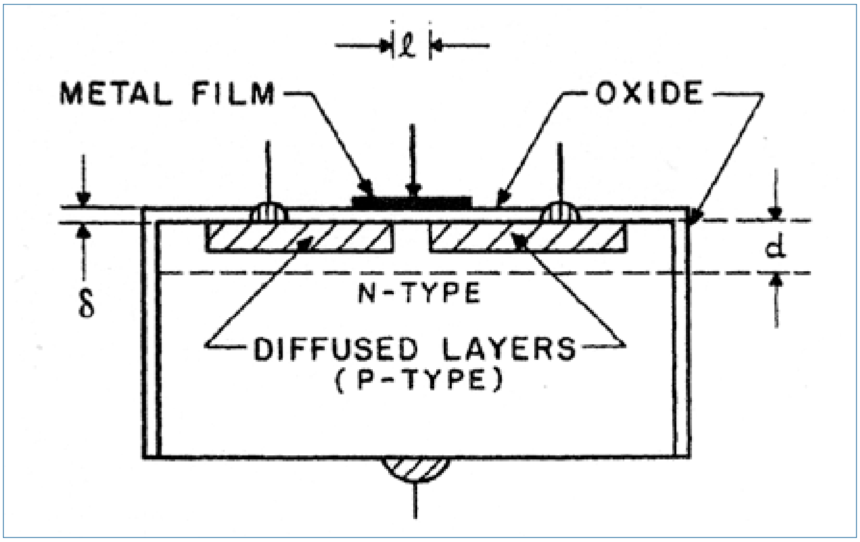

Fig. 2. *Drawing of Atalla and Kahng's "silicon-silicon dioxide surface device," now known as the MOS transistor, from a 1961 Bell Labs technical memorandum by Kahng. (Courtesy AT&T Archives and History Center)*

aluminum structures. He then tried applying aluminum with an electron-beam evaporator and discovered that the key to stability was not the particular metal used, but the method of evaporating it. He then purposely contaminated devices with sodium, lithium, magnesium, or calcium and ascertained that sodium led to the highest drifts. (Researchers later found that the tungsten filament wire used in the evaporation process had been extruded through a die lubricated with sodium, and was therefore simultaneously evaporating sodium and aluminum.) Snow's work led to an effort to search for and minimize sodium in any materials used in the MOS production process.[3]

Another focus of the group was surface states. In the late 1940s, John Bardeen had developed a theory of surface states to account for the failure of experiments suggested by William Shockley and executed by Walter Brattain and others in hopes of building a solid-state amplifying device. Bardeen proposed that the cause of the failure was surface states, charge carriers trapped at the surface of the semiconductor that prevented electric fields from penetrating beneath the surface. When Fairchild started its work, previous work on surface states usually included caveats about the difficulties of reproducibility and that results were valid only for specific cases. Deal developed a number of techniques to eliminate these surface states at the interface between silicon and the oxide layer. He later detailed various characteristics of the surface-state charge—specifically showing the role that dry-oxygen heat treatments played in reducing the surface-state density. The group published a paper claiming that the surface-state density was highly reproducible.[4]

Between 1964 and 1967 Deal, Grove and Snow, along with their manager C. T. Sah, published over two dozen papers related to the silicon-silicon dioxide interface, which to all appearances put the MOS structure on a firm scientific footing. The achievements of the trio were most clearly seen in a semiconductor physics course that they put together with other Fairchild researchers. Its centerpiece was the trio's research. Grove published the course notes as a book, *Physics and Technology of Semiconductor Devices*, which became the authoritative text in the field for a generation.[5]

But in spite of the work of this group, Fairchild was able neither to consistently make stable MOS devices throughout the organization nor to develop a successful MOS product line. Problems of technology transfer hampered Fairchild's ability to make stable devices in both its development groups and its Mountain View manufacturing facility. This would have been a serious problem if Fairchild had developed any MOS products that people really wanted to buy, but as of 1968 the company had developed MOS memory chips, arithmetic-unit chips, calculator chips, and customizable-logic chips without finding significant customers for any of them.

MOS Technology at IBM

International Business Machines was another major contributor to MOS technology. Its research group at Yorktown Heights, New York, was drawn to this technology as a way to begin work in planar silicon technology, which previously had been the exclusive domain of IBM's Components Division in East Fishkill, New York. IBM's research group had previously focused on more esoteric electronics technologies, such as gallium arsenide or superconducting electronics.[6]

One of IBM's most important contributions to MOS research came from the Components Division, which was responsible for developing and manufacturing bipolar transistors for its large computer systems and had very little interest in MOS transistors as such. As part of its work on bipolar transistors, Donald Kerr and a group of engineers had discovered that depositing small amounts of phosphorous on the silicon-dioxide surface and forming a layer of phosphosilicate glass (PSG) could limit the amount of leakage in bipolar transistors and play an important role in enhancing the stability of MOS transistors. Jerome Eldridge and Pieter Balk from IBM Research implemented this work by using thin layers of PSG to make stable MOS devices. Other important work on the physics and chemistry of MOS devices done by IBM included an examination of the important role of annealing in enhancing the surface conduction of MOS devices, and a demonstration of the advantages of using silicon with a crystal orientation (100) for making MOS devices.[7]

In spite of all the work IBM Research did on MOS technology, it faced an inherent difficulty in getting the rest of the company interested in the technology. This lack of interest occurred because MOS transistors were inherently much slower than bipolar transistors in the 1960s, given the gate lengths then achievable. IBM, which made most of its money from large computer systems, wanted transistors with speeds as fast as practically possible. Skepticism about the value of MOS technology reached the point that in October 1965, IBM's Corporate Technical Committee directed IBM Research to halt work on this technology. But IBM Research refused to do so, and the Corporate Technical Committee was unable to enforce its decree within the corporation.[8]

The doubts within IBM about MOS technology, verging on downright hostility in some quarters, led IBM Research to redouble it search for areas where the technology could prove relevant to IBM, resulting in 1966 to the program's reorientation toward semiconductor memory. At that time the typical division of labor in computers was for logic to be implemented using some kind of semiconductor technology and for memory to employ some type of magnetic technology. Computer memory was one area in which speed was not necessarily at a premium; cost was also a large factor. Here is where MOS technology found interest within IBM; in fact, memory proved to be the most receptive home to MOS technology at IBM for almost twenty years.

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In late 1966 Robert Dennard, a researcher at IBM, came up with a fundamental breakthrough in MOS memory technology (see Figs. 3 and 4). The basic unit in a semiconductor memory is the cell, a configuration that stores one bit of information. Up until then, cells had been built using four or six transistors. Dennard discovered a way to build a cell using only a single transistor. After attending an IBM Research conference and being impressed with the simplicity of the various magnetic memories proposed, he began exploring analogs to these technologies in MOS technology. Ultimately Dennard focused on the simplest possible cell structure, a capacitor that stored a charge (thus producing a voltage) and an MOS transistor that would connect or not connect the cell to the sensing circuitry. The one-device cell, as it came to be known, would occupy much less area than other cell configurations, and therefore allow a single chip to hold many more memory bits. The one-device cell was not widely used commercially until the 1970s, but since then it has been the dominant memory cell for main computer memories. In 1988 C. T. Sah called the one-device cell "the most abundant man-made object on this planet earth."[9]

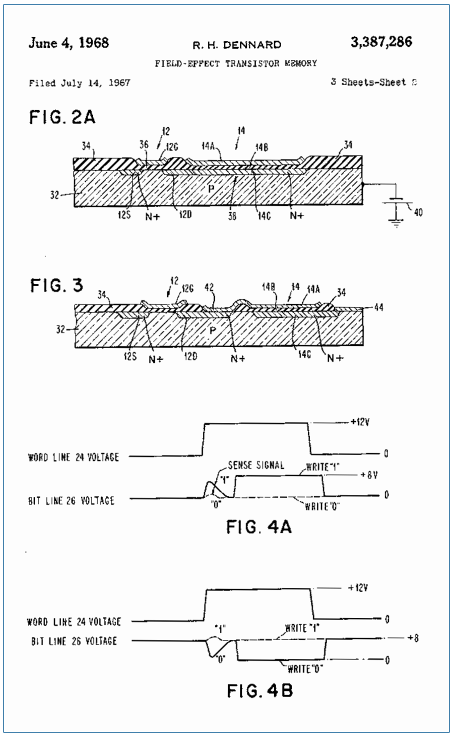

Fig. 4. *Drawing from Robert Dennard's U.S. patent on a dynamic random-access memory device. Silicon is designated by 32 in this figure and the oxide layer by 34.*

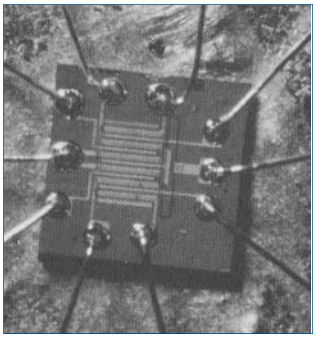

Fig. 3. *The MOS integrated circuit developed by Wanlass at Fairchild in 1963. (F. M. Wanlass, "Metal-Oxide Semiconductor Field Effect Transistor and Microcircuitry," Wescon 1963 Technical Papers, Session 13.2 Figure 6. © 1963 IEEE.)*

The MOS Community

Although the fate of the MOS transistor ultimately hinged on its success or failure at specific companies, its development was a cooperative effort, sometimes intentionally, sometimes not, between companies who were nominally competitors. This industry-wide effort benefited all who worked on MOS technology, through the transfer of information and the creation of a supportive atmosphere for the new technology. Information transfers occurred through conferences, inter-firm meetings, confidential exchange agreements, acquisition of artifacts, and the movement of personnel. Major research labs received information from new start-ups, and vice-versa.[10]

The most important conference for the description of MOS work in the first half of the 1960s was the Solid State Device Research Conference. This invitation-only conference was held every summer, typically on a university campus, and would attract around 500 attendees. The conference produced no formal publications, as intended to promote the more open exchange of information. The Solid State Device Research Conference would typically be dominated by a single topic that was of particular interest to the community of researchers; in the years 1964 and 1965, that topic was the MOS transistor. Researchers gave papers, cornered one another in the hallways, and engaged in spirited rump sessions.

Many of these conference presentations did result in journal articles at later dates. A 1967 bibliography of work in "Metal-Insulator Semiconductor Studies" showed that while there had been only five papers in that area published in 1960, by 1966 there were 181. George Warfield of Princeton University, the guest editor of a special issue on MOS structures in the 1967 *IEEE Transactions on Electron Devices* noted that "this field has progressed from its black magic phase, in which various and sundry mysterious potions coupled with assorted witchcraft were used to achieve 'good' devices, and has reached technological and scientific maturity."[11]

Information exchanges took place in a myriad of other ways besides conferences. Researchers called up their friends who worked for other firms. Companies bought devices from other companies and either put them on test or reverse engineered them to get a sense of their competitive standing. Researchers carried information with them as they moved from one company to another. In Silicon Valley, of course, workers might stop after work for drinks at the Wagon Wheel Bar near Fairchild's production facility in Mountain View. In these early years, when the future of MOS technology was uncertain, these information exchanges helped advance the cause of MOS technology throughout the semiconductor industry.

IBM, Intel, and the Establishment of MOS Technology

By 1968 there were companies such as American Microsystems or the semiconductor operations of General Instrument that were focused on MOS technology, but it was far from clear that these firms—or the technology itself—had the strength to endure. It was one large established firm, IBM, and one small new firm, Intel, that would prove to be critical in establishing MOS technology. IBM's role was important because as the world's largest computer company it set standards that other companies were likely to follow. Intel's role was to develop an assortment of innovative MOS products that opened up new markets for the technology.

In 1968 Edward Davis, an IBM manager who was responsible for developing new computer memories, made the decision that—because of the greater densities possible in semiconductor memories and what was then regarded as saturation in the performance of magnetic memories—all of IBM's computer systems would use semiconductor devices for their main computer memories. He decided further that because MOS technology offered a threefold advantage in density over bipolar technology, IBM computers would employ MOS memories after an initial phase-in period using bipolar technology. In 1972, after a successful program transferring MOS technology from IBM Research into development and manufacturing, which involved thousands of people at five sites, IBM introduced new computer systems using 1024 bit MOS memory chips; these were implemented in older, static memory cells because Dennard's one-device cell posed too many technical challenges at the time. MOS technology found an organizational home at IBM in a plant in Burlington, Vermont, that was new to semiconductor technology and not dominated by bipolar technology in the same way as IBM's East Fishkill facility.[12]

By 1968 Fairchild's MOS program was like a computer that had locked up. Fairchild had too many MOS and bipolar programs that were contending for the same commercial territory and thus squeezing each other out. When Robert Noyce and Gordon Moore left to found Intel that year, they reset the system. They would not have so many competing processes running at once. They had the ability to choose a technology or two that they considered most promising and concentrate on it. They could also choose the people and organizational structure they wanted. With so much research work having been done on MOS technology, Moore and Noyce decided that they would not need a research organization at Intel. Those who came to Intel from Fairchild Research, like Grove, arrived with a new function: they would no longer be researchers.

For their core technology, Moore and Noyce decided to concentrate on silicon-gate MOS technology, which had been described by engineers and scientists from Bell Labs. Silicon-gate technology had a self-aligning feature that gave it density advantages over other MOS processes, but it had yet to be manufactured in large quantities. Before Noyce and Moore left Fairchild, Federico Faggin at R&D had done some preliminary investigations of silicon-gate transistors. Intel took this new process, which had been described on paper and been used to make a few devices, and through a series of subtle steps made it capable of producing large numbers of consistently stable MOS devices.

But a stable process would be of little benefit without a product that customers wanted to buy in quantity. Moore and Noyce had focused the company on semiconductor memory as an area of components that customers would buy in large volumes and would not require an extensive design effort. After an unsuccessful 256 bit MOS memory chip, a team at Intel led by Robert Abbott and John Reed developed a 1 kilobit memory chip for Honeywell that struck paydirt. The 1103 chip (see Fig. 5), as it was called, became the standard semiconductor memory chip for non-IBM computer manufacturers and established Intel as a viable concern.[14]

Intel also developed a range of other products based on MOS technology, most famously the microprocessor but also the erasable, programmable read-only memory (EPROM). The advantage these products had, along with semiconductor memory, was that they were capable of almost limitless expansion into chips where each successive generation used more and more transistors, and so could follow the curve that Gordon Moore had described in 1965, now enshrined as Moore's law, suggesting that the number of transistor on an integrated circuit would double every year. [15]

Conclusion

By 1974 MOS technology was firmly established as a viable commercial technology. Intel had introduced its 4 kilobit memory chip and its second-generation microprocessor, the popular 8080. But more important than the achievements made in MOS was its future potential, as clearly described in a 1974 paper by Robert Dennard and his IBM colleagues. In it they detailed the principles of device scaling, showing that as one reduced the size of an MOS transistor by a given factor, the delay of the transistor decreased by the same factor, while the power consumption per circuit decreased as the square of that factor. Dennard's group reported its work on one-micron MOS devices, and there was good reason to think that MOS technology had a long run ahead of it.[16]

The 1960s research on the chemistry and physics of MOS structures had been necessary, but not sufficient, for the success of MOS technology. It also required the development of new products such as memories and microprocessors, where its technical advantages could come into play. And MOS technology also needed new organizational structures in which to flourish without being overwhelmed by the more mature bipolar technology. Fred Seitz called William Shockley the Moses of Silicon Valley for having a vision but being unable to get to the promised land of a broader commercial success. In much the same way, Fairchild Semiconductor Corporation became the Moses of MOS technology.

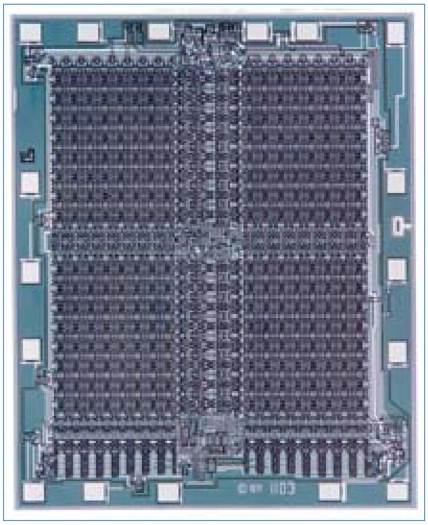

Fig. 5. *The Intel 1103 memory chip, one of the first commercially successful semiconductor memories. (Photograph courtesy of Intel Corporation.)*

About the Author

Ross Bassett, an associate professor of history at North Carolina State University (Raleigh), earned a bachelor's degree in electrical engineering at the University of Pennsylvania. After working at IBM for eight years, he left to pursue a PhD in history at Princeton, which he received in 1998. He is author of *To the Digital Age: Research Labs, Start-Up Companies and the Rise of MOS Technology* (Johns Hopkins University Press, 2002). He is currently working on the history of the Indian Institutes of Technology and the history of Indian faculty and students at MIT. He may be reached at ross_bassett@ncsu.edu.

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