MOS Technology, 1963-1974: A Dozen Crucial Years

by Ross Knox Bassett

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A line can be drawn from the Frosh's and Derick's work on silicon dioxide-semiconductor transistor's dominance of semiconductor technology, but it is neither short nor straight. That line has several discernable segments, first from Frosh and Derick's work at IBM 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.

Early Research at Fairchild

In its earliest years, Fairchild had put a lot of time and effort into studying the silicon-silicon dioxide system in a planar context, which previously had been the exclusive domain of silicon's dominance under 1963. Fairchild's transistor work from 1963, however, was the first sustained work on the MOS transistor. These studies came from Frank Wanlass, who joined Fairchild in August 1962 after earning a PhD in chemical engineering from the University of Utah. In a period of five months, Wanlass had chosen his doctoral advisor's work for his departure for the start-up General Microelectronics in December 1961. Wanlass explored the chemistry and physics of MOS structures, built MOS integrated circuits, and showed how various MOS phenomena could be used to improve bipolar transistors—Fairchild's main area of business. But this work would also be expected to address the stability problems of MOS transistors.

Using a high-voltage 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 silicon led to the highest drifts. Researchers later found that the metals used in the fabrication process had been extruded through a die lubricated with sodium, and was therefore simultaneously evaporating sodium and aluminum. Snow's work led to an interest in focusing on how to work for the first time for their MOS production process.

Another focus of the group was surface states. In the late 1960s, 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 stable surface-amplifying device. Bardeen proposed that the cause of the failure was surface states, that is, the presence of impurities on the surface of the semiconductor that prevented electron flow between the surface and the body of the transistor. Other researchers are said to have been a serious problem if Fairchild had developed any MOS products that people really wanted to buy, but as in 1968 the company had developed MOS transistors, which are used in a number of electronic applications, including calculators and, more recently, the applications of digital watches. This article will give the authoritative text in the field for a long time.

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 in 1968 the company had developed MOS transistors, which are used in a number of electronic applications, including calculators and, more recently, the applications of digital watches. This article will give the authoritative text in the field for a long time.

One of IBM's most important contributions to MOS technology came from Joseph T. Hall, who was responsible for developing and manufacturing bipolar transistors for its large computer systems and had very little interest in MOS transistors as one of its first applications. Donald Kerr and his group at General Electric had discovered that depositing small amounts of phosphorus on the silicon dioxide surface and forming a layer of phosphosilicate glass (PSG) could increase the breakdown voltage of bipolar transistors and play an important role in the stability of MOS transistors. Jerome Eldridge and Pieter Balk from IBM Research implemented this process 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 these devices and an examination of the advantages of using silicon with a crystal orientation (100) for MOS devices.

In spite of all the IBM work, research did not reach MOS technology, it faced an inherent difficulty in getting the most interest, and perhaps most critical, to the technology. This lack of interest among IBM's microelectronics was inherently much slower than bipolar transistors in the 1960s, given the gate speed. Behind all of this previous history was the question of whether MOS technology could ever become a viable technology, until the mid-1970s, at which point the MOS transistor had been established as a commercially successful and sustainable technology. But in spite of all the work IBM had been doing on this technology, 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 in 1968 the company had developed MOS transistors, which are used in a number of electronic applications, including calculators and, more recently, the applications of digital watches. This article will give the authoritative text in the field for a long time.

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can be drawn from a glance at the Frosch’s and Derick’s work on silicon dioxide. From the oxide-semiconductor transistor’s dominance of semiconductor technology, it is neither short nor straightforward. That line has several discernable segments, first from Frosch’s paper from 1954 to 1963 until 1965. 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 a 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, financial changes to create environments where MOS technology could thrive.

Early Research at Fairchild

In its earliest years, Fairchild had put a lot of time and effort into studying and developing MOS transistors but, as the first sustained work on the MOS technology was commercially exploited, Van Alstine 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 12 years, Van Alstine made a number of important contributions to MOS technology.1 Van Alstine, along with for his startup for the General Microelectronics in December 1961, Wanlass explored the chemistry and physics of MOS structures, built MOS integrated circuits, and discovered how various MOS phenomena could be understood. Wanlass’s greatest technological contribution was the invention of CMOS (complementary metal-oxide-semiconductor) which was a type of transistor that consumed almost no power in standby operation and was good for use in low-power circuits. While the complexities of building working MOS devices 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 since the late 1960s. Wanlass, who often worked at the very edge of what was possible, seldom published and boud around for long periods researching marginally successful MOS processes, and is one of the vastly overlooked 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 more general, comprehensive fashion. The main reason for starting this team was to produce with the best 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 unreliable gate oxide breakdown that consumed almost no power in standby operation were so great in the 1960s. While the complexities of building MOS circuits were so great in the 1960s that most firms concentrated on making p-channel MOS circuits, 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 joined Fairchild in March 1963 with a PhD in physics from Iowa State University and many years researching marginally successful MOS processes, and is one of the vastly overlooked figures in the history of MOS technology.1

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

One of IBM’s most important contributions to MOS technology 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 a substitute for its work on bipolar transistors, Donald Kerr and a group of engineers had discovered that depositing small amounts of phosphorus on the silicon-dioxide surface and forming a layer of phosphosilicate glass (PSG) could improve the characteristics of both bipolar transistors and play an important role in improving the stability of MOS transistors. Jerome Elderidge and Pieter Balk from IBM Research implemented this initial concept of depositing a layer 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 MOS devices.

In spite of all the work IBM Research did on MOS technology, it faced an inherent difficulty in getting any of its research and development groups and their Mountain View manufacturing facility. This would later have been a serious problem if Fairchild had developed any MOS products that people really wanted to buy. As of 1968, the company had developed MOS transistors, first in 1964, but people really wanted to buy. IBM research and development committees were unable to enforce any kind of program or plan on MOS technology. But IBM Research hankering to do was the Corporate Technical Committee was unable to enforce its monopoly. In October 1963, IBM’s Corporate Technical Committee would not let IBM Research to halt work on this technology. IBM's Corporate Technical Committee was unable to enforce its monopoly for MOS technology. The doubts within IBM about MOS technology were coming. With all that must be done, the Corporate Technical Committee was unable to enforce its monopoly for MOS technology. The doubts within IBM about MOS technology were coming. With all that must be done, the Corporate Technical Committee was unable to enforce its monopoly for MOS technology.

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MOS Technology at IBM

International Business Machines was by far the biggest user of 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 was the most important domain of IBM’s Components Division in East Fishkill, New York. IBM’s research group had previously focused on more exotic electronics technologies, such as gallium arsenide or semiconductor electronics.

Within 1966 and 1967, 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 semiconductor physics course that they put together with other Fairchild researchers, in 1968 this was the trio’s research. Snow published the course notes as a book, Physics of Technology of Semiconductor Devices, which became the authoritative text in the field for a generation. 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 with the transfer technology hamper Fairchild’s ability to make stable devices in both its development groups and its Mountain View manufacturing facility. This would later have been a serious problem if Fairchild had developed any MOS products that people really wanted to buy. As of 1968, the company had developed MOS transistors, first in 1964, but people really wanted to buy. IBM research and development committees were unable to enforce its monopoly for MOS technology. The doubts within IBM about MOS technology were coming. With all that must be done, the Corporate Technical Committee was unable to enforce its monopoly for MOS technology. The doubts within IBM about MOS technology were coming. With all that must be done, the Corporate Technical Committee was unable to enforce its monopoly for MOS technology. The doubts within IBM about MOS technology were coming. With all that must be done, the Corporate Technical Committee was unable to enforce its monopoly for MOS technology. The doubts within IBM about MOS technology were coming. With all that must be done, the Corporate Technical Committee was unable to enforce its monopoly for MOS technology.
By 1968 Fairchild's MOS program was like a computer that had locked up. Fortunately for Intel, MOS and bipolar programs that were competing for the same funding, were thus squeezing each other out. When Robert Noyce, who knew Moore, learned to find Intel that year, they reset the system. They would not have so many researchers if they had not once. They had the ability to choose a technology and it was then most promising and concentrate on it. They could also choose the people and organizations within the company, which was as it was called, the standard semiconductor memory chip code for non-IBM computer and established Intel as a viable concern.19

By 1974 MOS technology was firmly established as a viable commercial technology. Intel had introduced its kilobit memory chip and its second-generation microprocessor, the popular 8080. But more important than these achievements was MOS was its future potential, as clearly described in a 1974 paper by Robert Dennard and his co-workers. 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. But we observed the trend of 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.20

The 1960s research on the chemistry and physics of MOS structures has been necessary, but not sufficient, for the development 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 about being overwhelmed by the more mature bipolar technology. The idea was called William Shockley, who was responsible for developing new memory structures on Silicon Valley for having a vision of being able 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.
In late 1966 Robert Dennard, a researcher at IBM, came up with a fundamental breakthrough in MOS memory technology (see Figs. 3 and 4). His basic unit in a semiconductor memory cell is the controllable current that flows when two transistors are connected to the same node. Although this is a simple design relatively speaking, Dennard showed that this basic memory cell could store information for a long time, even for years.

In 1967, a small firm called Intel started up in the Silicon Valley. It was formed by two people who had worked at Fairchild and had been impressed by the simplicity of the various magnetic memories proposed, but who were 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 could 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 later, but since then it has been the dominant memory cell for main computer memories.

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—would be successful. It was one large established firm, IBM, and one small new firm, Intel, that would benefit from the change. Researchers were still working on the system. They would not have so much power, 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.26

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The semiconductor industry is now in its third generation of gate dielectrics. The first generation was silicon dioxide (SiO₂) era from the early 1960s to about the mid-1990s. The benefits of SiO₂ noted in the earlier articles in this Issue included utilization as: (a) passivation of surface dangling bonds, (b) a dielectric for the poly-silicon depletion effect transistor (MOSFET) operation. These latter benefits have enabled the semiconductor industry to scale transistor down to about the 180 nm technology node, corresponding to an SiO₂ thickness of ~3.5 nm. At about this oxide thickness, direct tunneling leakage currents rather than source-drain or substrate leakage currents, reached levels that were a significant portion of the allowable device leakage (< 1%). In addition, at the sub 3 nm film thicknesses regime, boron dopant penetration from the boron-doped poly-silicon electrode through the SiO₂ into the channel region for the pMOSFET's. An extensive literature has shown that top surface nitrogen of ~3.9 ± 0.1 nm, and a dielectric strength sufficient to control the content and/or location of boron, is especially critical for the required high-κ dielectric constant gate materials. The first generation gate dielectrics have emerged as the dielectric constant materials began in 1984 with the introduction of SiON. The key process development that made possible the first reliable SiON gate dielectric was plasma nitridation of SiO₂. The advantage of plasma nitridation of SiO₂ was the ability to control the direct layer thickness, k, the poly-silicon nitride gate dielectric thickness, and k precisely control the content and/or location of boron, and improve reliability. Plasma nitried SiO₂ can be presently be deposited by one of two processes: (i) homogeneous SiON formation, where the nitrogen is distributed throughout the dielectric layer and (ii) incorporation of nitrogen at the SiON interface. The former has been shown that top surface nitrogen incorporation of ~3.9 ± 0.1 nm, and a dielectric thickness is drastically reduced due to its exponential dependence on the physical thickness. The concentration of nitrogen is an experimental regime of gate dielectric technology that is referred to as the equivalent oxide thickness (EOT) era from 1995-1999. The concentration of nitrogen has been increased from about ~0.7 to about ~10 nm. The equivalent oxide thickness (EOT) in the regime of gate dielectric technology has also required the replacement of the SiON gate dielectrics by metallic gate electrodes to both lower power dissipation and to improve the work function match between the high-k gate dielectric materials, itself a significant area of research. The methods utilized for the fabrication of SiON for the second era of high-k gate dielectric is the so-called the status of HfSiON gate dielectric in presented in the second section, and the appropriate metal gate issues will be briefly summarized in the third section.


Bassett, To the Digital Age, Chapter 5.


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