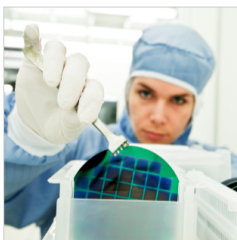


feature article



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A Brief History of the MOS transistor, Part 1: Early Visionaries

by Steven Leibson

The first wave of semiconductor companies started in April 1952 when Bell Labs held its second transistor symposium for its transistor patent licensees, which was attended by representatives from some 40 companies. After the symposium, most of those companies started manufacturing bipolar point-contact transistors within mere months or a couple of years, and many became successful commercial semiconductor vendors. A few of those vendors – including Infineon (formerly Siemens), NXP (formerly Philips), and Texas Instruments – continue to make semiconductors today. (I discussed this history in a 7-part series about the early transistor makers in EEJournal. See the reference section of this article for links to those articles.) By contrast, development of the metal-oxide-semiconductor (MOS) field-effect transistor (FET) took decades, from its conception in the 1920s to an initial working device at the very end of the 1950s, to working commercial products in the 1960s. It took years of scientific research, engineering, analysis, and a fair bit of evangelism to transform the device that almost no one wanted into today's backbone of the semiconductor and electronics industry.

Julius Edgar Lilienfeld was the first person to patent the idea for an FET. Lilienfeld was born in 1882 in the city of Lviv, now located in the western part of Ukraine. Back then, it was part of the Austro-Hungarian Empire. He received his PhD at the Friedrich-Wilhelms-Universität (now called Humboldt University) in Berlin on February 18, 1905 and then became an untenured professor at the physics institute there. His research focused on electric fields and electron emission through field induction, and his early work focused on the wonder device of the time: the x-ray tube. He also did some early work on electron behavior in high electric fields, which would eventually be thoroughly analyzed by the physicists Ralph H. Fowler and Lothar Wolfgang Nordheim.

Lilienfeld first traveled to the United States in 1921 to defend his x-ray patents against their seizure by the Alien Property Custodian in 1919. He moved to the US permanently in 1926 to escape rising antisemitism in Europe. In October 1926, he filed the first of three patent applications based on his experiments with fields in semiconductors. These patents essentially described the conceptual basis of FET operation and were issued between 1928 and 1933. Lilienfeld took an R&D position with radio parts manufacturer Amrad (the American Radio & Research Corporation) in Malden Hillside, Massachusetts. While there, he studied the electrochemistry and behavior of anodic aluminum oxide films, and his detailed analyses of these films formed the basis for manufacturing electrolytic capacitors for many decades. Although Lilienfeld's three patents described the conceptual operation of an FET, the state of the art for semiconductor processing at that time produced materials with nowhere near the purity needed to fabricate such a device.

Oskar Heil was the second person to independently conceive of the FET. He was born in 1908 in Langweiden Germany, and received a PhD from the Georg-August University of Göttingen. While at this university, he met Agnesa Arsenjewa, a Russian physicist earning her PhD. The two married in the Soviet Union in 1934 and moved to the UK's Cavendish Laboratory in Cambridge. Together, they co-wrote a pioneering paper on the generation of microwaves. They continued to pursue this work at the Physico-Chemical Institute in Leningrad. Heil then returned to the UK, without Arsenjewa. While working at Cambridge University in 1934, Heil filed a patent on controlling current flow in a semiconductor via capacitive coupling at an electrode, the essential elements that define an FET. The patent, titled "Improvements in or relating to electrical amplifiers and other control arrangements and devices," was granted at the end of 1935. However, the poor semiconductor purity available at that time and the complete absence of the necessary fabrication process technology would have again prevented the physical realization of such a device, and there's no indication that Heil ever attempted to make FETs.

When Germany's invasions triggered World War II, Heil returned to Germany and started to develop a microwave generator for C. Lorenz AG in Berlin-Tempelhof. The myth persists that Heil not only managed to manufacture FETs but made a clandestine radio with them during World War II, but there's no evidence that Heil ever attempted to make an FET. For this myth to be true, Heil would have had to figure out how to make working FETs and then would have needed to design the circuitry for an FET-based radio in the era of tube-based radios. If you wanted to build a

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clandestine AM radio set during the 1940s, it was far simpler and just as effective to assemble a crystal radio set using a variable inductor, a capacitor, a lump of galena, and a steel cat whisker to make the audio detector. Further, Heil worked in a German microwave lab. He would have had access to as many vacuum tubes as he wanted. It's highly unlikely that he'd want to build FETs so that he could then build a radio.

Although Lilienfeld and Heil both conceived of the FET, it's no more accurate to say that they invented the FET than it is to say that Leonardo DaVinci invented powered flight. According to the Smithsonian Institution's National Air and Space Museum, DaVinci produced more than 35,000 words and 500 sketches dealing with flying machines. Yet we credit the Wright brothers for inventing the first powered aircraft because they built and flew the first such aircraft.

William Shockley was born in London, UK in 1910 to American parents, went to MIT, and earned a PhD in 1936, specializing in solid-state physics. Bell Labs hired him that same year to conduct research into the possibility of building solid-state amplifiers using crystalline semiconductors. In 1939, Shockley wrote: "It has today occurred to me that an amplifier using semiconductors rather than vacuum is in principle possible." Shockley appears to have been unaware of the earlier patents granted to Lilienfeld and Heil.

Shockley and Walter Brattain attempted to develop a FET before World War II started but were unsuccessful. The war brought this work to a temporary halt, but, after the war ended, Shockley added John Bardeen to the team. Through a series of physical experiments, Brattain and Bardeen finally were able to create a working point-contact transistor with a gain of approximately 100 through the audio frequency band on December 16, 1947. However, as it happens, this first transistor was not a FET. It was a bipolar transistor that did not operate based on electric fields.

Bell Labs announced the invention of the transistor on June 30, 1948. The six-month delay gave the Bell Labs patent attorneys time to get patent applications in order. Shockley had become removed from the day-to-day work and acted more as a consultant and manager before Brattain's and Bardeen's breakthrough, but now that the feat was accomplished, he was ready to be a part of the team again and insisted that he be front and center whenever any PR photographs were taken. He also decided to work on his own patent application, which adhered to the idea that the transistor that had been created was a FET. The Bell Labs patent attorneys refused to work on Shockley's patent application because it too closely resembled Lilienfeld's patents of the late 1920s and early 1930s, and they left his name off the original Bell Labs transistor patent for the same reason.

After the transistor demonstration in June, 1948, Shockley worked feverishly for a month on a theoretical analysis of its operating mechanism. He determined that the transistor action of the point-contact device arose from P-N semiconductor junctions. Based on that insight, Shockley quickly conceived of the sandwich transistor, the first of a new breed of device called the junction transistor. If you see a simplified drawing of a bipolar transistor, it usually depicts a sandwich transistor with the base serving as the sandwich filling, positioned between the transistor's emitter and collector.

When Bell Labs announced the junction transistor in 1951, it quickly became the dominant transistor in the industry because it was superior in every way to the original point-contact device. However, it was still a bipolar transistor and not a MOSFET. In 1950, Shockley poured his analyses into the first important book about semiconductor transistors titled *Electrons and Holes in Semiconductors: With Applications to Transistor Electronics*. This book was the semiconductor industry's bible for many years. Shockley, Bardeen, and Brattain shared the 1956 Nobel Prize in Physics for their semiconductor research and their discovery of the transistor effect.

Frustrated by his lack of advancement at Bell Labs, Shockley moved to his hometown of Palo Alto, California and started his own company, Shockley Transistor Laboratory, in 1955. He did not work on MOSFET development there. He'd gone bipolar and become deeply interested in a Bell Labs project, the 4-layer diode. Shockley Transistor Laboratory had licensed the Bell Labs transistor patents, and Shockley himself continued to stay in close touch with the researchers at Bell Labs, bringing many of the semiconductor process innovations to the San Francisco Bay area, where they would quickly lead to the creation of Silicon Valley.

Mohamed Atalla and Dawon Kahng at Bell Labs became the first people to construct a working MOSFET. Atalla was born in Port Said, Egypt. He studied at Cairo University in Egypt and got his Masters and PhD from Purdue in the US. Atalla joined Bell Labs in 1949. Dawon Kahng was born in 1931 in Seoul, South Korea, which was before the country was called South Korea. He studied physics at Seoul National University in South Korea, immigrated to the US in 1955, and earned a PhD from Ohio State University in 1959. He joined Bell Labs that same year.

Atalla's and Kahng's development of the first working MOSFET was based on earlier research done at Bell Labs by Carl Frosch and Lincoln (Link) Derick, who accidentally discovered a method for growing a layer of silicon dioxide on top of silicon in 1955. By 1957, Frosch and Derick had refined this idea and added the concept of using the silicon dioxide layer as a diffusion mask for silicon doping, which they discussed in an article titled "Surface Protection and Selective Masking During Diffusion in Silicon," published in the September 1957 issue of the *Journal of The Electrochemical Society*.

Significantly, the Bell Labs practice was to remove the silicon dioxide layer after diffusion because it was considered "dirty," as in "laced with contaminants." Two months after the Frosch and Derick article appeared, Jean Hoerni at Fairchild Semiconductor realized that the silicon dioxide layer was important for several reasons and that it should be left in place. A pure silicon dioxide layer became an integral part of Hoerni's planar manufacturing process and would

be a key element of IC manufacturing.

Atalla further refined this discovery into a more formal silicon dioxide passivation technology that permitted the silicon to be doped far more precisely in specific locations when coupled with newly developed photolithographic and etching techniques. Using this technology, Atalla and Kahng managed to build a working MOSFET by the beginning of 1960, three decades after Lilienfeld first conceived of the device. Although the device worked, after a fashion, this first MOSFET had several problems. Notably, it was 100 times slower than contemporary bipolar transistors, mainly because of its relatively large channel length of 20 μm .

Because this original MOSFET was incredibly slow, Bell Labs had no interest in it, and Atalla and Kahng received little credit for the development. Despite the lack of credit and interest, Atalla and Kahng continued to work on semiconductors and developed p- and n-channel MOSFETs, the first working Schottky diode, and the first nanolayer-gate bipolar transistor, which sandwiched a thin metal gate – only a few nanometers thick – between the semiconductor base and emitter. The thin base structure allowed this transistor to operate at much higher frequencies than the bipolar transistors of the day.

Tired of the continued lack of recognition for his work, Atalla left Bell Labs in 1962 and joined the Hewlett-Packard Company. He helped the company establish its own semiconductor lab, HP Associates, and became the Director of Semiconductor Research. He then helped found HP Labs in 1966 and was the first person to direct its solid-state division. Atalla left HP in 1969 to become vice president and general manager of Fairchild Semiconductor's Microwave & Optoelectronics division, after spearheading gallium-arsenide materials research at HP.

Kahng remained at Bell Labs for many more years. He filed for a patent on the MOSFET in 1960, which was granted in 1963. Along with colleague Simon Min Sze, Kahng developed the floating-gate MOSFET in 1967. This invention is the core storage element used in EPROMs and EEPROMs. Kahng retired from Bell Labs in 1988 and became the founding president of the NEC Research Institute, now known as NEC Labs America, which is the US-based center for NEC Corporation's global network of corporate research laboratories.

Atalla and Kahng received the Stuart Ballantine Medal at the 1975 Franklin Institute Awards for their invention of the MOSFET. After decades of existing only in theory, they'd proved that it was possible to build a MOSFET. However, the original devices were problematic. They were slow, their characteristics drifted with temperature and time, and they were unreliable. No applications needed a slow, unreliable transistor. The search for better MOSFETs and suitable applications was picked up by MOSFET evangelists at several companies. Along the way, MOSFETs became faster and far more reliable. By the time the dust settled several years later, many people would contribute to the MOSFET's eventual success, but it was not an easy journey. There were many technological problems to overcome, company politics to circumvent, and business obstacles to defeat. I'll discuss these facets of MOSFET history in subsequent articles.

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