A history of the invention of the transistor and where it will lead us

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3 authors:

William Brinkman
Princeton University
75 PUBLICATIONS **8,782** CITATIONS

D.E. Haggan
AT&T Bell Labs, Murry Hill, NJ, USA
4 PUBLICATIONS **186** CITATIONS

William w. Troutman
Altera Corporation
22 PUBLICATIONS **323** CITATIONS

A History of the Invention of the Transistor and Where It Will Lead Us

William F. Brinkman, *Member, IEEE*, Douglas E. Haggan, and William W. Troutman

FIFTY years ago this November, John Bardeen and Walter Brattain discovered the transistor on the fourth floor of Building 1 at Bell Labs in Murray Hill, NJ. Fifty years later, we are still working with silicon but it is a very different silicon effort. Currently with the silicon optical bench we are trying to integrate optical components the way we did transistors over the last 50 years. So, silicon technology is still on the move. When one reads about the invention of the transistor one cannot help but note that the work of Bardeen and Brattain was truly a discovery not an invention. When they discovered transistor action, they were investigating the nature of surface states and ways to reduce their presence. It was only later that things really became clear as to what was going on. Fifty years later we celebrate that discovery, and this paper presents a brief history of the major events and the key people.

The Murray Hill site today is very different from what it was back in 1947. At that time, Building 1 was essentially the only building there. Much expansion has since taken place and today we are up to Building 15. It is now a very large complex. In much the same way, our research and development effort is much bigger and broader today than it was back in 1947. We would like to do a couple of things. We will lay out the background for the discovery of the transistor, how it came about, and then briefly cover some of the subsequent highlights. It is important to keep the following issue in mind when thinking about this discovery. The context needs to be understood, i.e., where people were in science and technology at the time of this discovery; what they knew and did not know. By looking at the context one will have a much better appreciation for what was actually accomplished. So let us take a look back in history and examine the events that occurred. Let us try to understand what was understood and what was not understood at the time of this discovery; we will then appreciate it even more.

In a certain sense, all of solid-state electronics goes back to the invention by Ferdinand Braun of the solid-state rectifier in 1874. That was a full 73 years before the discovery of the transistor. His work centered around the solid-state rectifier using a point contact based on lead sulfide. Of course, this configuration made for a very unstable device. In fact, after the invention of the vacuum tube, later in the century, this device very quickly became obsolete. But, later when people wanted to go to very high frequencies, and vacuum tubes would not work at the frequencies desired, the idea of the point contact rectifier made a comeback.

The theoretical development of quantum mechanics during the 1920's also played an important role in driving solid-state electronics. Without quantum mechanics, we would never have developed any comprehensive understanding of solids. The understanding of the differences between metals, insulators, and semiconductors was quickly developed. The concept of electronic band structure, due to quantum mechanics, was the key to that insight. Following these advances was the development of the quantum theory of solids led by Peierls, Wilson, Mott, Franck, and others, largely in England. These researchers added much to our understanding about electron conductivity in metals. Those days were truly the beginnings of establishing a picture of the electronic structure of metals. Metallic sodium is the simplest of all metals from an electronics point of view and was often studied in that era. A simple theory of Schottky barriers led to a crude understanding of the rectifiers discussed above, but the theory did not work quantitatively. These dedicated researchers brought the understanding forward; but frankly, semiconductors sat in the middle between the metal and the insulator, and in those days semiconductors were still a puzzle.

Also keep in mind the continued efforts expended toward the discovery of new devices. For example, in 1926, Lilienfeld invented the concept of a field effect transistor (FET). He believed that applying a voltage to a poorly conducting material would change its conductivity and thereby achieve amplification. He patented this concept in 1926, but no one was able to do anything with it until much later.

By the late 1930's, it was beginning to be more widely accepted that there may be opportunities to create some form of solid-state devices. At this time a man by the name of Mervin Kelly, at Bell Labs, decided in 1936 that he should start a solid-state device group. He challenged a number of people, Bill Shockley, Russell Ohl, Jack Scaff, and others, to begin work on solid-state devices. Kelly had a feeling that the vacuum tube was not going to be the ultimate answer to electronics. Its reliability and size were such that something needed to be done, besides making more efficient and smaller vacuum tubes. It is interesting to note that by 1938, two Germans (Pohl and Hilsch) described a solid amplifier made using potassium bromide that had three metal leads. However, this device turned out to have too low an operating frequency. Also, it was not a device that could be used in any true sense for electronics. That such a device came along about the same time that Kelly created the Bell Labs solid-state group

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W. F. Brinkman is with Physical Sciences Research, Lucent Technologies, Murray Hill, NJ 07974 USA.

D. E. Haggan and W. W. Troutman are with the Office of the Chief Scientist, Microelectronics Group, Lucent Technologies, Murray Hill, NJ 07974-0636 USA.

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shows that other engineers were thinking along the same lines. By 1940, Russell Ohl had done a great deal of work, along with others at Bell Labs, in an attempt to understand silicon crystals. Ohl learned that depending on how you prepared single crystals of silicon, you could get either n- or p-type silicon. What was meant by n or p type back in those days was whether it was a positive or negative rectifier. That was where the notation n or p came from. It was a question of which direction the rectification occurred; they defined these terms by that criterion. It is also interesting that a little later on, Ohl actually was able to make a sample in which the top part was a p-type region and the bottom was n type, and he found that when light was shone on it, it actually developed a voltage [1]. When Ohl took his results to his management at Bell Laboratories, they were sufficiently skeptical about this that they actually asked him if they could have a piece. They then gave the piece to Walter Brattain so that he could remeasure it. Ohl's management wanted to make sure that what he said was right. Walter was proud of the fact that he could help Russell verify that effect.

It is amusing how people figured out the character of the impurities that were causing the difference between the n type and p type. It is said that when Jack Scaff and H. C. Theuerer were cutting up silicon wafers that were n type, they could smell the phosphate as they cut the material. They therefore knew it must be phosphorus impurities. That made a lot of sense because phosphorus has the extra electron. This shows how materials were identified prior to World War II. In fact, reading through the literature from Purdue University, we see people had all sorts of odd ideas about what was important to incorporate into silicon to make p and n types. Some people thought that they were seeing helium. Later people realized that what happened was they were dragging trace impurities into the silicon with the helium and it was not the helium at all. Today we scoff at that kind of idea. But, at that time, it just simply was not so obvious.

This was the status of solid-state electronics near the beginning of WWII, and it really did not change all that much during the war except in technology areas influenced by the work on radar. Radar requirements produced a very strong desire to fine-tune solid-state rectifiers, and this resulted in some effort to try to improve silicon and germanium materials.

Radar, of course, was driven very strongly by the Radiation Laboratory at the Massachusetts Institute of Technology that was started by Lee DuBridge. Early radar was based on relatively low frequency or long wavelength. It was found that airplanes could be located in a general way but not with sufficient accuracy to make visual contact, which was especially important with the poor weather conditions over the English Channel, and it quickly became obvious that in order to get the kind of resolution desired, higher frequency or shorter wavelength radar was needed. The issue of shorter and shorter wavelengths drove system developers to look toward the gigahertz region, and this drove them to look for lower capacitance solid-state detectors [2].

In this era, there was a lot of solid-state detector work done, mostly by trial and error. Engineers probed around on the surface of crystals to find the sweet spot for the best detectors. The scientists at the Radiation Labs asked Purdue University to set up a program in which they were to look at improving both silicon and germanium crystals. At the same time, researchers at Penn State were also funded to investigate silicon. Purdue University was also asked to provide a better understanding of the work with these crystal diodes, and therefore much work was done at Purdue University. In fact, some of the work at Purdue University played an important role in John Bardeen's thinking about surface states and spreading resistance. So, in retrospect, the various investigators at Purdue University made a number of important contributions to the understanding of these two semiconductor materials during and shortly after the war.

The group of engineers and physicists that Kelly put together at Bell Labs was disbanded during the war. Shockley, who had been a part of the group, went off to the Naval Research Laboratory and became very much involved in the war effort. The people who did stay at Bell Labs moved into various projects that had to do with radar and other military efforts. When the war ended, the Radiation Lab was disbanded and there was a great reduction in most war-related efforts. At Bell Labs, the Research area was freed up once again to think more broadly, and Mervin Kelly came back to his pre-war interests.

The story was often told at Bell Labs about Mervin Kelly being a manager with much foresight. We must admit being skeptical of such stories, as managers like to have such reputations. However, after reviewing the various materials for this paper, we realized that the man had a vision. By restarting the group, it was clear that he was determined to create solid-state electronics. So by January of 1946, Kelly had assembled another team of people, this time headed by Bill Shockley and Stanley Morgan. The team included Walter Brattain, John Bardeen, John Pearson, Bert Moore, and Robert Gibney.

This group made a very important decision right at the beginning, which was that the simplest semiconductors are silicon and germanium, and that their efforts would be directed at those two elements [3]. Efforts would be made to understand them first. Effort would not be directed toward more complex materials, such as lead sulfide and copper oxide. So, the team concentrated on silicon and germanium. Second, Shockley revived (actually he independently had the idea) the idea of a field-effect device.

They began work. One of the very first and very important contributions made by Bardeen was to understand field effects. The idea that applying a voltage to a semiconductor would result in a change to its conductivity should have worked in the laboratory, but did not. Bardeen showed by very simple calculations that a relatively low concentration of surface states would screen any voltage from the interior of the semiconductor. Those working on field-effect transistors today know how true this is. We have practically spent our whole life improving the silicon–silicon dioxide interface and trying to drive out all defects to reduce this effect. What Bardeen suggested was key to getting people to think about the right things. Bardeen and Brattain immediately started investigating ways that they might clean the surface so they could reduce the effects of these surface states and make a useful device.

Fig. 1. John Bardeen, William Shockley, and Walter Brattain.

By late November 1947, Bardeen and Brattain managed to make a working transistor. It must be said that it was very crude, but they improved it from late November through the first part of December. By December 16, 1947, they had a working point-contact transistor. They were able to gradually improve it and actually make a circuit to demonstrate to Bell Labs management on Christmas Eve. Of course, this was a very big event. During the next six months at Bell Labs, Bardeen and Brattain spent a lot of time making sure they had patents filed and then clearing it for release to the public with the military. It was interesting that at one stage, the military was threatening to classify this discovery as top secret. Fortunately, Bell Labs management worked around that. By June 30, 1948, Bell Labs had a press conference in New York City which was quite elaborate. They had done a lot of work on a prototype circuit that had actual voices being amplified by the transistors. It is interesting to note that the impact of this discovery went on deaf ears as far as the public was concerned. *The New York Times* carried a very small article on a back page and did not have too much else to say about it [4]. In some sense that is understandable. It is very hard to see the full implication of something like this, unless you are a scientist or engineer, and have some appreciation for the consequences. No one could have dreamed that the transistor would have the broad social consequences it has had.

Fig. 1 shows the two inventors along with Bill Shockley. This picture and Walter Brattain's comments about it are fascinating. Walter was kind of a cantankerous person who liked to get into arguments. He said the picture was wrong in two ways. The first way it was wrong was that it was not the entire group. As we already pointed out there were other members of the group that were involved and Walter thought the publicity picture should have everybody in it. Unfortunately, it did not. The second thing that was wrong with it was this was *his* laboratory not Bill Shockley's, even though Shockley is sitting there looking as if he is actually working in the laboratory. That obviously grated on Walter, and he wanted to make this clear.

Fig. 2 shows the first transistor. It is clearly a complicated thing. The bottom electrode was the base. Seeing this tells us why the word "base" is used today. It was then the base of a germanium crystal. The other two leads were formed on the tip of the block above the germanium crystal. The tip had first a coat of metal on it, then it had some wax put over the top of it, then it had another metal layer on it, and then the bottom part was sheared off so that there was essentially an inside metal, a layer of insulating wax and a layer of metal. This was simply pressed on to the germanium surface, and the inside metal was the collector and the outside metal was the emitter. In the first experiment, the outside metal made contact to an electrolyte. So the first time they saw gain, they were actually conducting current through the electrolyte, and the gain configuration was such that the emitter to collector current was modulated by the base current. This is obviously a complex configuration.

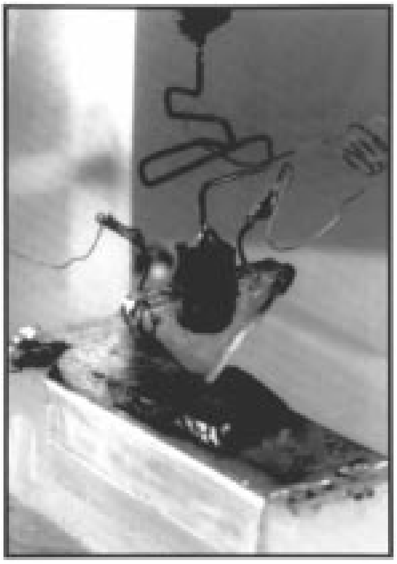


Fig. 2. The first transistor.

Today we look at this arrangement and think, "What in the world were they doing, and why would they do something like that?" Well, you have to remember that in those days a point contact device was the only device under study. People thought in terms of point contact devices and that is the way they were made. Therefore, one did not think about plating metal on the semiconductor. In fact, very quickly after this, Brattain realized that if he painted two metal stripes on the surface of the germanium very close together, he would have the same configuration. This Brattain did, and this enabled him to make a much better device than the one shown in this figure. However, the one shown here had gain, and they drew a picture of the device as shown in Fig. 3. This configuration essentially describes what they demonstrated to the "brass," as they liked to refer to the management, on Christmas Eve in 1947.

Immediately a debate broke out within the group. Bill Shockley had been away in Europe on a short sabbatical but returned around Christmas time and was chagrined to find that he was not part of the invention. He began immediately to think about the amplification effect. Bardeen was convinced that the conductivity of the surface layer was somehow being changed, and that the change in conductivity was causing the amplification.

Shockley, on the other hand, was fairly certain that the bulk of the crystal was somehow involved. It is amazing

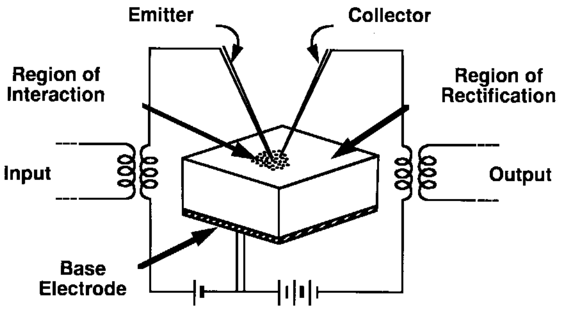


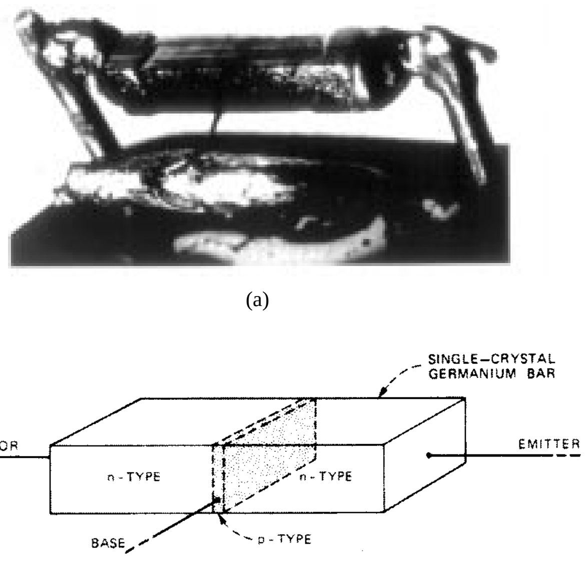
Fig. 3. Schematic diagram of the first transistor.

what happened next. In the next two months, Shockley, in a great creative burst, proceeded to write down the theory of the bipolar junction transistor. Of course, that theory very strongly depended on the introduction of minority carriers, so Shockley, in developing this theory, was the first person to both clearly see and discuss minority carrier injection into the semiconductor. Shockley, in fact, kept this idea secret for some time.

In February of that year, John Shive took a very, very thin piece of germanium and put the emitter and collector on opposite sides of the crystal, thereby eliminating surface paths between the collector and the emitter. This experiment verified the idea that what was going on was truly minority carrier injection and that the junction transistor theory of Shockley was indeed correct. It was a remarkable achievement that Shockley could derive the entire theory in such a short time. No one argues with the conclusion that Shockley made a very major contribution to the transistor's development, one that is equally important to that of Brattain and Bardeen.

By April 1950, a couple of years later, Brattain, Shockley, Teal, and Sparks actually succeeded in growing the first junction npn device [5]. In fact, the device behaved essentially as predicted by Shockley's theory. Fig. 4 is a picture of this device. The big problem, of course, in making a true bipolar semiconductor device was the need for a very thin base region. As we all know, today the base has to be on the scale of micrometers. In those days, it was very difficult to figure out how to make a crystal that changed from n type to p type and back to n type on such a scale. It was finally accomplished by 1950. Of course, none of these devices look anything like what we think of as a transistor today. That is because of a whole series of advancements that have been made to make the planar technology mainstream today.

Progress was supported by a series of important inventions that led to better and better devices. In fact, Shockley wrote a book titled *Electrons and Holes in Semiconductors*. This book became the bible for everyone who wanted to learn about semiconductors. In the engineering world, the idea of solid-state electronics was a totally new thing. Therefore, Conyers Herring taught a series of quantum mechanics courses to the staff at Bell Labs in those days. Everyone had to start learning what quantum mechanics was all about. People really did not know at the time. Remember, even though we had a true pnp transistor by 1950, engineers still really did not understand their electronic structure. That only happened later in the 1950's when experiments used cyclotron resonance to show the nature of electrons and holes in silicon and germanium.


(a)

(b)

Fig. 4. The first junction transistor.

The next improvements, in many ways, were materials improvements. By 1952, a Bell Labs team had developed a means of making high purity silicon and germanium crystals. This was done by a process called zone refining that was invented by Bill Pfann. Fig. 5 shows a picture of Pfann operating his zone refining apparatus. Basically this apparatus involved the movement of a hot zone along the tube that locally melted the germanium placed in the tube. The melt will sustain a higher concentration of impurities than the crystals, so as the heat goes through the crystal, impurities are collected in the melt, and high quality crystalline material is left behind. One of the big problems facing people was that this worked fine for germanium, but it did not work so well for silicon because of the high temperatures needed for silicon. It was only later that Henry Theuerer at Bell Labs took Pfann's idea and showed that you could turn this apparatus on end. In this vertical configuration, the surface tension of the molten silicon was sufficient to keep it from coming apart. Theuerer showed that a high-quality silicon crystal could be drawn out of a molten pool of silicon. It was silicon then that quickly became the foundation for the semiconductor industry. It was favored, at that time, because the band gap was larger in silicon so that it does not become intrinsic at as low a temperature as does germanium.

Also, by 1952, it is interesting to note that Ian Ross and George Dacey succeeded in making a unipolar device [6]. This first unipolar device was a precursor to today's FET. This configuration was made using junctions as gates rather than having the metal oxide gate structure that we have today. This junction FET worked in a pinch-off mode rather than enhancement or depletion mode as in a planar insulated gate device.

The appreciation and understanding of the transistor moved out of the Labs in the early 1950's. Because Bell Laboratories was under various consent decrees in those days, it had no choice but to license this invention. Bell Labs therefore offered all responsible parties a license to the invention of the transistor for the price of $25 000. Think back to what

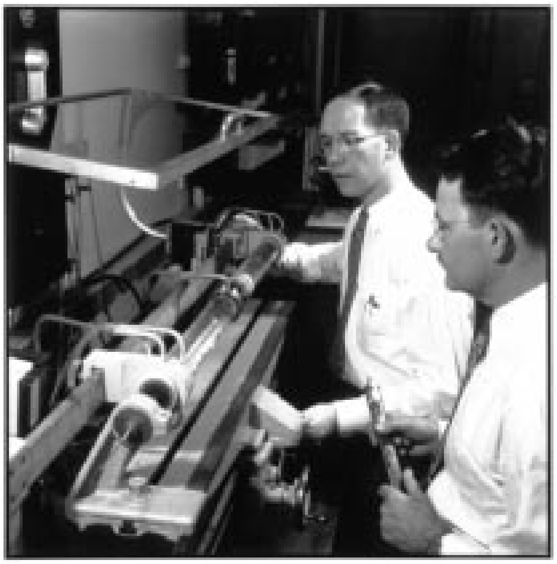


Fig. 5. William Pfann and zone refining.

a bargain this was. In fact, they did charge a royalty, but the $25 000 you paid up front was forgiven against royalty payments [7]. In April of 1952, Bell Labs held a symposium in which they invited people from a large number of different companies that took a license, and they taught them how to make and use solid-state transistors.

One of the stories that Ian Ross likes to tell occurred when, as a young man, he was asked to set up a lab with one of these new transistors so that each visitor could come in and run the currents up and down, and show gain. Ian, being from England and new to New Jersey, was surprised when our weather intervened in his demonstration. New Jersey has this tendency to go from winter to summer all in one day, and it did so on that day. When this happens, it gets really hot, and it gets extremely humid. When Ian got to work to teach these folks how to use a transistor, none of his transistors would work. So, it was kind of embarrassing that he had to put them into a test tube with a desiccant to reduce the effects of water. The famous transistor invention did not look so attractive to these people when they first came.

In 1952, Gordon Teal left Bell Labs to join a company called Geophysical Services Incorporated, which later became Texas Instruments (TI). Teal immediately began working on the transistor. About the same time, Masaru Ibuka and Akio Morita had formed the Tokyo Tsushin Kogyo. They got a transistor license, and in 1955 they renamed their company Sony. Their first transistor product, which came out in the late 1950's, was an all-transistor radio. It is important to point out that this was not the first all-transistor radio. TI had developed a transistor radio a year or two before, but Sony had a clever idea for marketing theirs. They said with this radio everyone in your family can have a radio. You do not have to just have this big mahogany box in the living room anymore. You could all have a radio of your own. Sony really created the first consumer market for transistors.

In 1955, Shockley left Bell Labs to form Shockley Semiconductors. In some sense, this company was insignificant except for the people he hired and the fact that it is the origin of Silicon Valley. He hired Gordon Moore and Robert Noyce, among others. These men later went on to form Fairchild Semiconductors, and subsequently they went on to form Intel and make DRAM's. In 1956, Shockley, Brattain, and Bardeen won the Noble Prize for physics. By this time, Bardeen was already at the University of Illinois. Therefore, two out of the three key researchers had left the Labs. The Labs of course kept on developing technologies that would later be important in making planar devices.

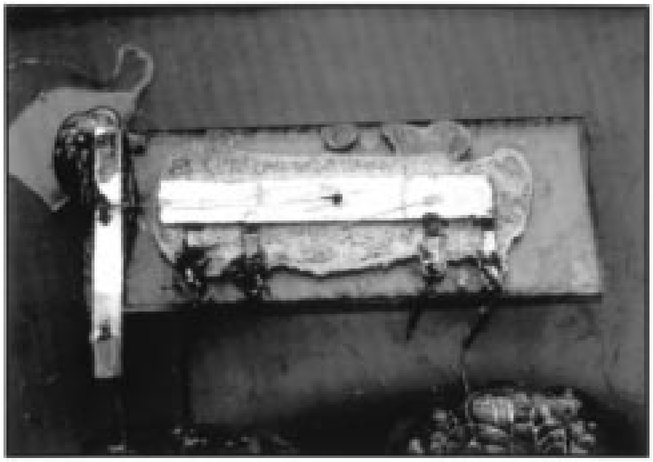


Fig. 6. Jack Kilby's first integrated circuit. (Reprinted by permission of Texas Instruments.)

In 1957, Texas Instruments developed the mesa transistor. Then came some very important events in the late 1950's. Jack Kilby of Texas Instruments developed the first IC using these mesa techniques. Kilby used discrete wire interconnection. See Fig. 6 for a picture of that device. You can see it really was a simple device by our standards today. It has one transistor, a capacitor, and resistor all together on a piece of silicon. This is the first integrated circuit, not really large scale integration. The next thing that happened was at Fairchild, where Jean Hoerni developed the planar process for transistors. In particular, the planar process offered the capability for doing thin-film metal interconnection. Bob Noyce, using this process, made an IC using vapor deposited metal connections, which became public in 1959.

Prior to this, several important things happened at Bell Labs in the late 1950's. The first event occurred when C. J. Frosch started working on the oxidation of silicon. M. M. Atalla's group extended this work, discovering that the natural oxide of silicon that occurs when you put it in a high oxygen environment has a tremendously good interface between it and pure silicon. The silicon dioxide-silicon interface is sufficiently free of surface states that you can actually make an FET. Duane Kahng joined Bell Labs at about that time, and he fabricated the first field-effect transistor using Atalla's oxidation process [8]. But, this turned out to be a pretty poor device. It took until the early 1970's, 15 years before planar FET's came into common use. The delay was due to the difficulties encountered controlling impurities. This was a materials problem, and for a long time people did not realize that sodium was the killer. Specifically, any sodium at the interface between silicon and

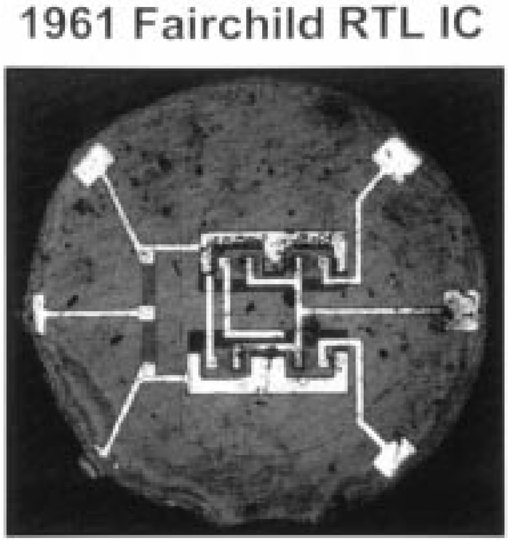


Fig. 7. Early Fairchild IC using planar process. (Reprinted by permission of Fairchild Semiconductor.)

silicon dioxide had devastating effects. It was not understood how to isolate the devices from the sodium. It was a major problem to understand the purification of this interface. As you know, we now have the very highest quality silicon-silicon dioxide interface. Today we have impurities that are less than one part in one billion, which is a tremendous accomplishment.

Another thing in the materials world that happened in the 1950's and which contributed to the development of the planar process involved providing a way to control the diffusion of acceptors and donors. This was a very, very important invention. Frosch and Derek showed that by using oxide masks you could control where you diffuse the donors and acceptors into the silicon. Then, J. Andrus and Walter Bond showed that you could use photoresist to pattern the oxide. Finally, Jean Hoerni at Fairchild put all this together into the planar process [9]. This was the process that Fairchild used to make their first IC. You can see an early Fairchild circuit in Fig. 7, which is starting to look like something we recognize today, simply because it used the planar process and one layer of metal.

In some sense, ever since 1960, it has been a story of continuous improvement. It was almost eight years between the invention of the bipolar transistor and the ideas of how to make an FET. It took from 1947 to 1960 to get all these pieces in place to start driving the planar process toward making integrated circuits. From 1960 to 1997, the industry progressed by anticipating problems and solving them. It is always interesting that at various times there were people who said, "We are running into this or that brick wall, look out!" But, the brick wall came and went, and nothing momentous happened. There are so many examples like this; sodium is just one. This was a materials problem, but we have solved that problem today. Plastic packaging played a very important role in providing low-cost components. Electrostatic discharge (ESD) was another problem and one that we still continue to battle. ESD is a static discharge through a device that can cause device degradation or even failure. Alpha particles came along in the 1970's and were a nasty problem for several years. Alpha particles caused the loss of data in DRAM's [10]. We learned how to design DRAM cells in such a way as to minimize the problem and have also improved the packaging materials for DRAM's to minimize the source of alpha particles.

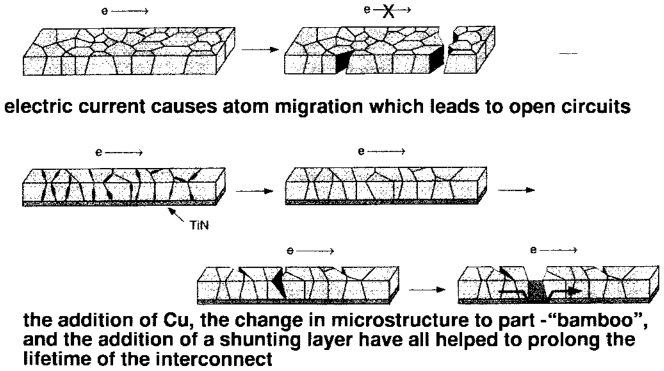


Fig. 8. Electromigration.

In 1987, there was great concern on the part of a visitor to Bell Labs. The visitor said that when we get to quarter micrometer, metal migration is going to be a killer. We just do not know how to handle that. Well, we are charging right into quarter micrometer and even beyond and nobody seems to think it is a problem; the answer of course is that we solved it. We figured out new ways to make aluminum lines by introducing titanium nitride as a sticky layer. Also, the introduction of copper strengthens the aluminum grain boundaries; see Fig. 8. Even if a grain boundary breaks, the current will divert and will go through the thin titanium nitride layer. Thus, you will not have the problem of an open circuit due to the aluminum electromigration

There is no reason why silicon technology will not go for another 10 or 15 years, maybe longer. Fig. 9 shows a device that is 120 nm on a side. It has an extremely thin oxide of less than 20 Å. Notice the thin oxide with a very smooth transition into the drain region without any kind of disruption like birds' beaks or other unwanted structures. This technology should carry us to very small dimensions. People are now saying 0.05 μm instead of 0.07 μm. Once we get there we have to remember that this is 500 Å and that is, at most, 100 atoms across. So we are going to have to think in new ways.

The next major hurdle that looks like it might be a show stopper is lithography. However, SCALPEL [11] or EUV is capable of taking us all the way down to 0.05 μm. We personally prefer SCALPEL, because we know how to make electron optics work at a high resolution. Fundamental to the SCALPEL technology is a scattering mask instead of a stencil mask; see Fig. 10. The scattering of the electrons rather than absorption produces the contrast. This invention is a major change in electron beam lithography, and a prototype tool exists now. Just to illustrate, the tool can print 0.08 μm lines and spaces without any difficulty (see Fig. 11).

We see taking this technology all the way down to the smallest dimensions we can imagine silicon working. That evolution takes us beyond 2010, when we will finally get to 0.07 μm or 0.05 μm on 12-in wafers, with 200 000 gates per

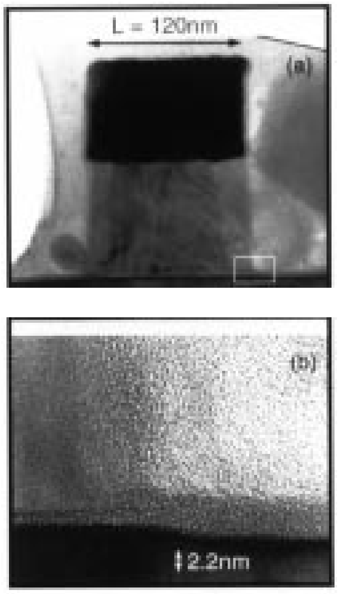


Fig. 9. Advanced FET cross section.

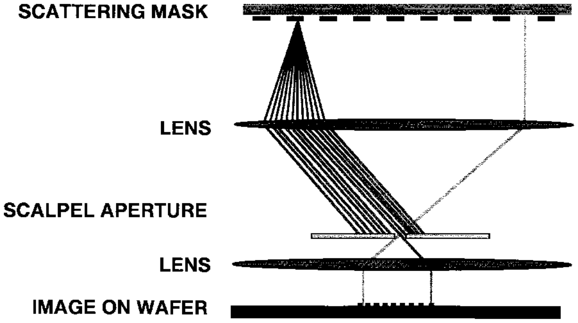


Fig. 10. SCALPEL technology.

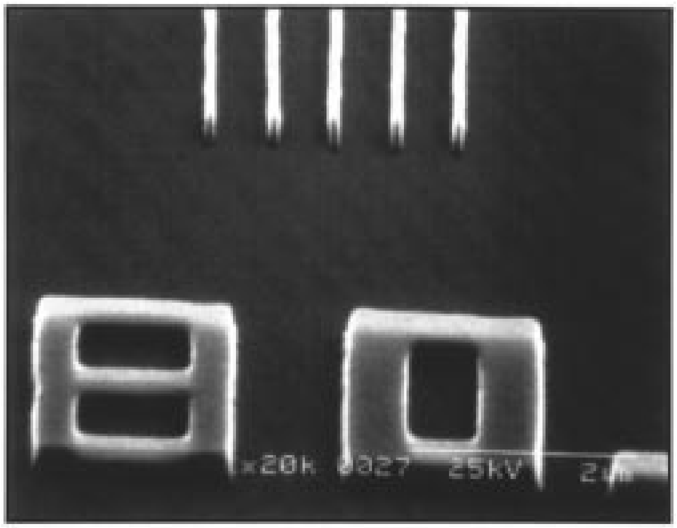


Fig. 11. 0.08-μm lines.

sq. mm density, and processor speeds way up to 1.5 GHz. We do not know what lies beyond that. However, what we do know is that when we reach this point, the subject will be extremely interesting once again. Then we will be confronted with the fact that we cannot go further unless we invent something. We personally think we have to be very careful in predicting how things will stop because it is the history of mankind, and in particular the silicon business, to invent new schemes. We look forward to see what those inventions will be.

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William F. Brinkman (M'89) was born in Washington, MS, and received the B.S. and Ph.D. (physics) degrees from the University of Missouri, Columbia, in 1960 and 1965, respectively.

He is Physical Sciences Research Vice President at Bell Laboratories, Lucent Technologies, Murray Hill, NJ. As of March 1, 1993, his responsibilities include the direction of research in physical sciences, optoelectronic and electronic devices, fiber optics, and related areas. Previous to this position he was Executive Director of the Physics Division at AT&T Bell Labs and Vice President of Research at Sandia National Laboratories in Albuquerque, NM. He joined Bell Laboratories in 1966 after spending one year as an NSF Postdoctoral Fellow at Oxford University (1965). In 1972, he became Head of the Infrared Physics and Electronics Research Department and in 1974 became the Director of the Physical Research Laboratory from 1981 until moving to Sandia in 1984. He returned to Bell Laboratories in 1987 to become Executive Director of the Physics Research Division. He has worked on theories of condensed matter and his early work also involved the theory of spin fluctuations in metals and other highly correlated Fermi liquids. This work resulted in a new approach to highly correlated liquids in terms of almost localized liquids. The explanation of the superfluid phases of one of the isotopes of helium and many properties of these exotic states of matter was a major contribution in the middle seventies. The theoretical explanation of the existence of electron-hole liquids in semiconductors was another important contribution of his and his colleagues in this period. Subsequent theoretical work on liquid crystals and incommensurate systems are additional important contributions to the theoretical understanding of condensed matter. As manager of an industrial research organization with a budget of $200M, he is strongly interested in improving technology conversion and improving the connection between research and products.

Dr. Brinkman was a Council Member of the American Physical Society and is a Fellow in the American Association for the Advancement of Science. He has served on a number of national committees, including chairmanship of the National Academy of Sciences Physics Survey and their Solid-State Sciences Committee. He serves on the Board of Editors of *Science Magazine* and the Council of the National Academy of Sciences. In addition to being a member of the NAS, he is a member of the American Academy of Arts and Sciences. He was the recipient of the 1994 George E. Pake Prize.

Douglas E. Haggan received the B.S.E.E. degree in 1958 from Bucknell University, Lewisburg, PA, and attended graduate school at the University of Delaware, Newark, and Rutgers University, Piscataway, NJ.

He worked for Burroughs Corporation for 16 years holding various engineering and management positions and then joined AT&T in 1983. At Bell Labs he worked as a supervisor in the IC Customer Service Department, the Microelectronics Account Management Organization, the Integrated Circuit Reliability Department and most recently in the Electronics Technology and Planning Center of the Office of the Chief Scientist of Lucent's Microelectronics Group, Murray Hill, NJ.

Mr. Haggan has been active in the IEEE International Test Conference and has received three US patents on electronic circuits.

William W. Troutman earned engineering degrees from Penn State University, State College, the Massachusetts Institute of Technology, Cambridge, and Cambridge University, England.

In 1966, he joined AT&T Bell Laboratories, Whippany, NJ, where he worked on the effects of electronic pulses on circuits and systems. In 1975, he moved into integrated circuit design at Murray Hill, NJ. At first, he led a design team that was responsible for various high-speed TTL functions. Later, he had design responsibility for one of the very first CMOS 4-b microcontrollers. He then led an effort that completed several highly complex, 32-b CMOS peripherals. More recently, he reports to the Chief Scientist of Lucent's Microelectronics' Business Unit, where he handles a variety of business and technical issues.