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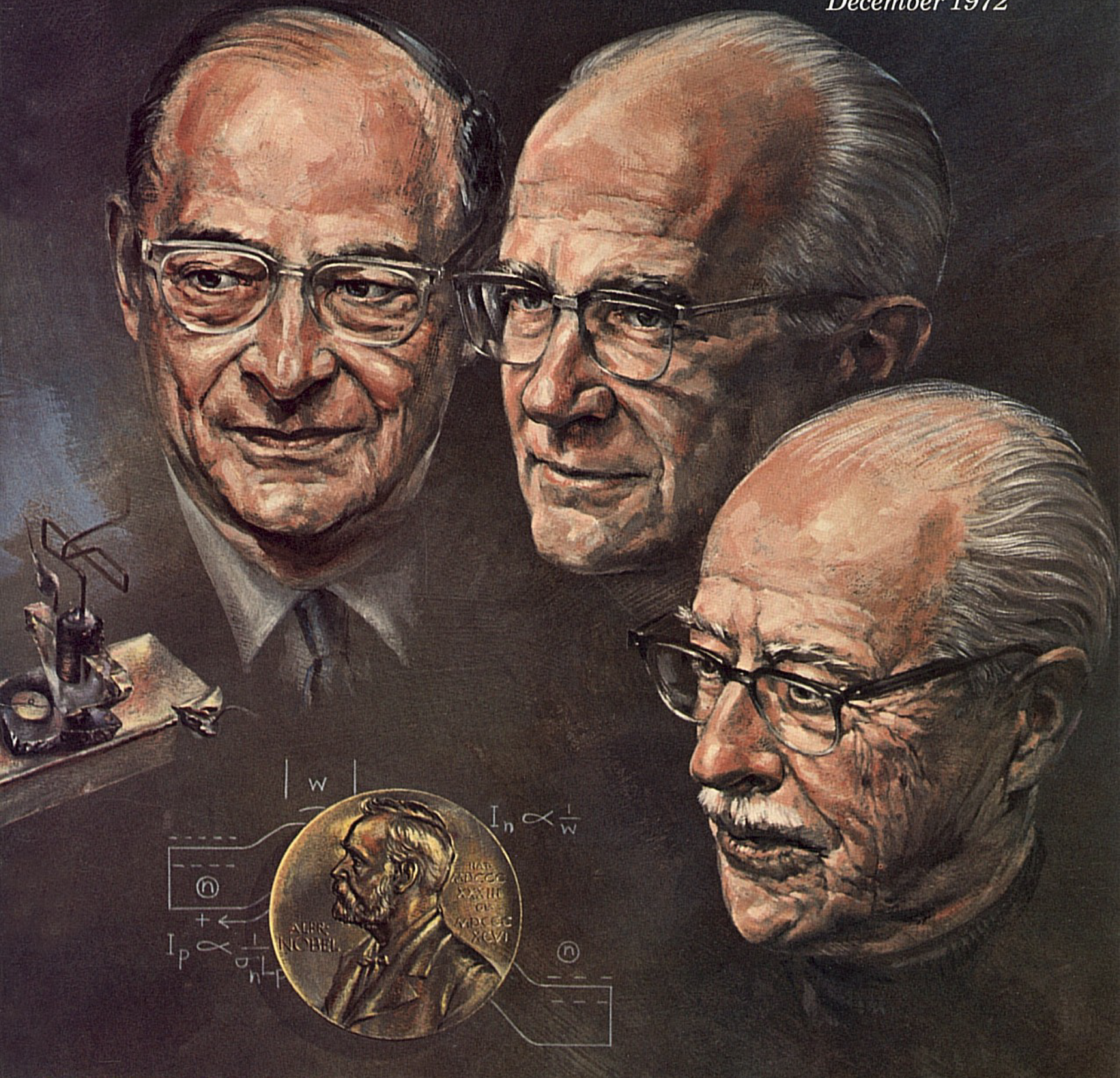

25 Years of Transistors

Bell Laboratories

RECORD

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THE TRANSISTOR—A CONSEQUENCE OF RESEARCH

The three Nobel Prize winners on our cover created the earliest transistors in their laboratories at the Murray Hill, N. J., location of Bell Labs. But, as they emphasize in their observations on the 25th anniversary of this revolutionary device (see pages 335-341), the key to their work was not any detail of fabrication or laboratory technique, but was instead the vital ingredient of understanding born of research. They knew that in all probability they could not reach a practical goal without new knowledge. So, as John Bardeen puts it (page 337), "at each stage [of the experimentation] we tried to have at least a qualitative understanding of what was going on."

A technology-dependent effort can proceed for some time on the basis of old knowledge, but in such instances efficiency soon drops off and innovations cease. What is needed for a successful technical effort is a continued influx of new knowledge, and a constant reference back to the foundations of scientific knowledge that undergird all technology.

In many cases the pursuit of research understanding—this building of firm foundations—goes largely unnoticed, since the practical results mostly appear through the work of people with the important jobs of developing, designing and producing the things society needs. But the transistor is an exception, so much so that it has become a symbol of the benefits that can flow from learning more about nature and her secrets.

Cover

Left to right, John Bardeen, William Shockley and Walter Brattain, Nobel laureates in physics, 1956. Mr. Bardeen also shared the 1972 Nobel Prize in physics for his work on the theory of superconductivity.

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Departments

"The Effecting of All Things Possible"

About 350 years ago, Francis Bacon described his "New Atlantis"—in effect a research and development establishment. He decided that 36 people could achieve his corporate goal—"the knowledge of causes, and secret motions of things; and the enlarging of the bounds of human empire, to the effecting of all things possible." Bacon's staff would "also declare natural divinations of diseases, plagues . . . tempests, earthquakes, great inundations . . . and divers other things; and . . . give counsel thereupon, what the people shall do for the prevention and remedy of them."

However ambitious, Bacon's concepts did clearly establish the direction and intent of what we now call "modern science." He realized that the understanding gained by a group of people performing basic research should lead, ideally, to applications that will benefit mankind. The invention of the transistor has done this—but not without a complex effort to realize its promise.

Since the early days, the list of specialities needed for solid-state research has grown to encompass large areas of physics, chemistry, and engineering. We have found this interdisciplinary approach vital at Bell Laboratories. And the application of the transistor and other solid-state devices in the Bell System has imposed formidable requirements on Western Electric. Western's manufacturing engineers, working side by side with our designers, have had to develop new processes and techniques. The interactions here—as well as the give and take among Bell Labs, the Operating Telephone Companies and the American Telephone and Telegraph Co.—are indispensable to our ability to help bring the benefits of solid-state technology to the communications user.

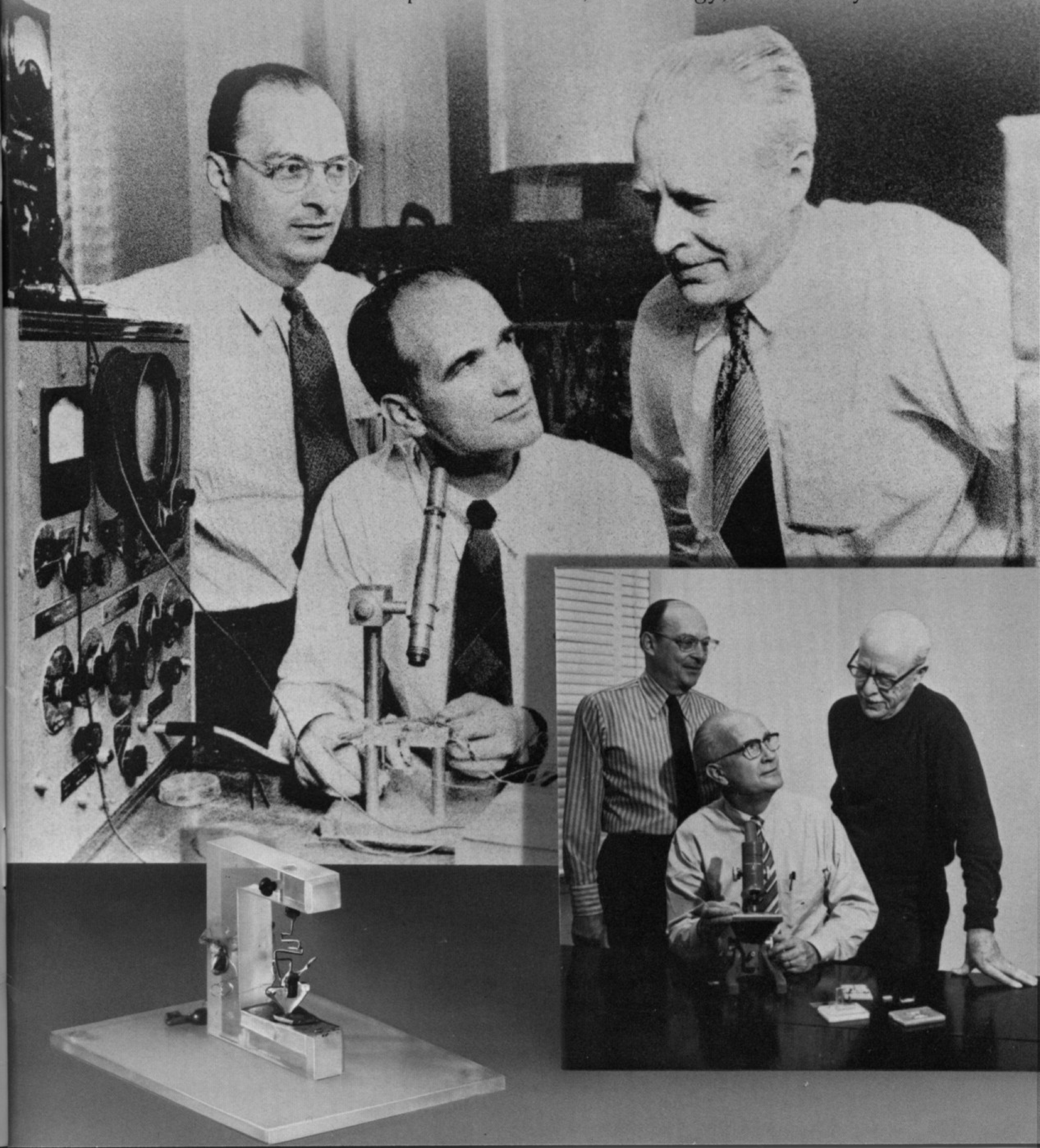
As much as it has changed our own company, however, the transistor has also changed the world. Because of this device—and others it led to—our lives have improved. Computers, made practical by these devices, manipulate previously unmanageable amounts of information to extend our knowledge and its applications—for example, in medicine, architecture, engineering, sociology, psychology, and business. Solid-state devices help physicians diagnose our illnesses and—in hearing aids and cardiac pacemakers, for example—they extend our useful lives. Solid-state devices have conquered distances through fast, reliable, and inexpensive means of communications. And such devices have helped man achieve one of his dreams—space travel.

From the perspective of the 25 years since the transistor's invention, we can assess its impact—on the Bell System, on industry, and on society at large. The transistor began with basic research, in Bacon's words, into the "secret motions of things"—the mysteries of solid-state physics—and has led to "the enlarging of the bounds of human empire." But the greatest impact of the transistor may be yet to come—if its benefits can serve as a reminder to society that solutions to many of our problems today, as well as future human progress, will depend heavily on the continued pursuit of science and its responsible application.

James B. Fisk

Three Men Who Changed Our World —25 Years Later

John Bardeen, Walter Brattain, and William Shockley, winners of the Nobel Prize in Physics, give their recollections of the transistor's invention and assess its impact on science, technology, and society.



John Bardeen

Twenty-five years ago it would have been impossible to imagine the remarkable developments that have since taken place in semiconductor science and technology. Starting with primitive diodes and transistors, a whole series of breakthroughs has occurred—single crystals, zone refining, diffusion, oxide masking, planar technology, and integrated circuits, with capabilities in large-scale integration still increasing rapidly every year. Semiconductor rectifiers are revolutionizing the electric power industry. And we have by no means reached the end of the road, as indicated, for example, by current progress in light emitting diodes and lasers, microwave oscillators and charge transfer devices.

The theory on which these developments are based dates mainly from the late twenties and thirties and is associated with such names as Frenkel, Mott, Schottky, Wagner and Wilson. Nevertheless, during this period agreement between theory and experiment was disappointing and at best qualitative. This is because semiconductors are what used to be called structure-sensitive; that is, their properties depend critically on the presence of minute amounts of impurities or other crystal imperfections. During the past quarter century we have learned how to control these structure-sensitive properties, not only in the laboratory but on an industrial scale.

My introduction to semiconductors came just after the war, in late 1945, when I joined the Bell Laboratories research group on solid-state physics which was being formed under the leadership of Stanley Morgan and William Shockley. Following a Ph.D. under Eugene Wigner at Princeton and post-doctoral years with John H. Van Vleck at Harvard, I had been much interested in the theory of metals before the war and was anxious to go back to solid-state physics after five years at the Naval Ordnance Laboratory in Washington. While at Harvard, I was a good friend of James B. Fisk (who in 1945 was Director of Research at Bell Laboratories) and also knew Shockley when he was a graduate student at M.I.T. It was they who persuaded me to join the group rather than return to my academic post at Minnesota. I was the first outsider to be recruited; the rest of the initial group had been at Bell Laboratories for some years.

Conditions were rather crowded when I arrived at the Murray Hill, N. J., Laboratory. The wind-up of World War II research was still going on. A new building was under construction but was not yet completed, so I was asked to share an office with Walter Brattain and Gerald Pearson. I had known Walter since my graduate student days at Princeton. Although at that time I had not decided what field of solid-state physics I would work in, they soon got me interested in their problems and I became deeply engrossed in trying to learn what was known about semiconductor theory.

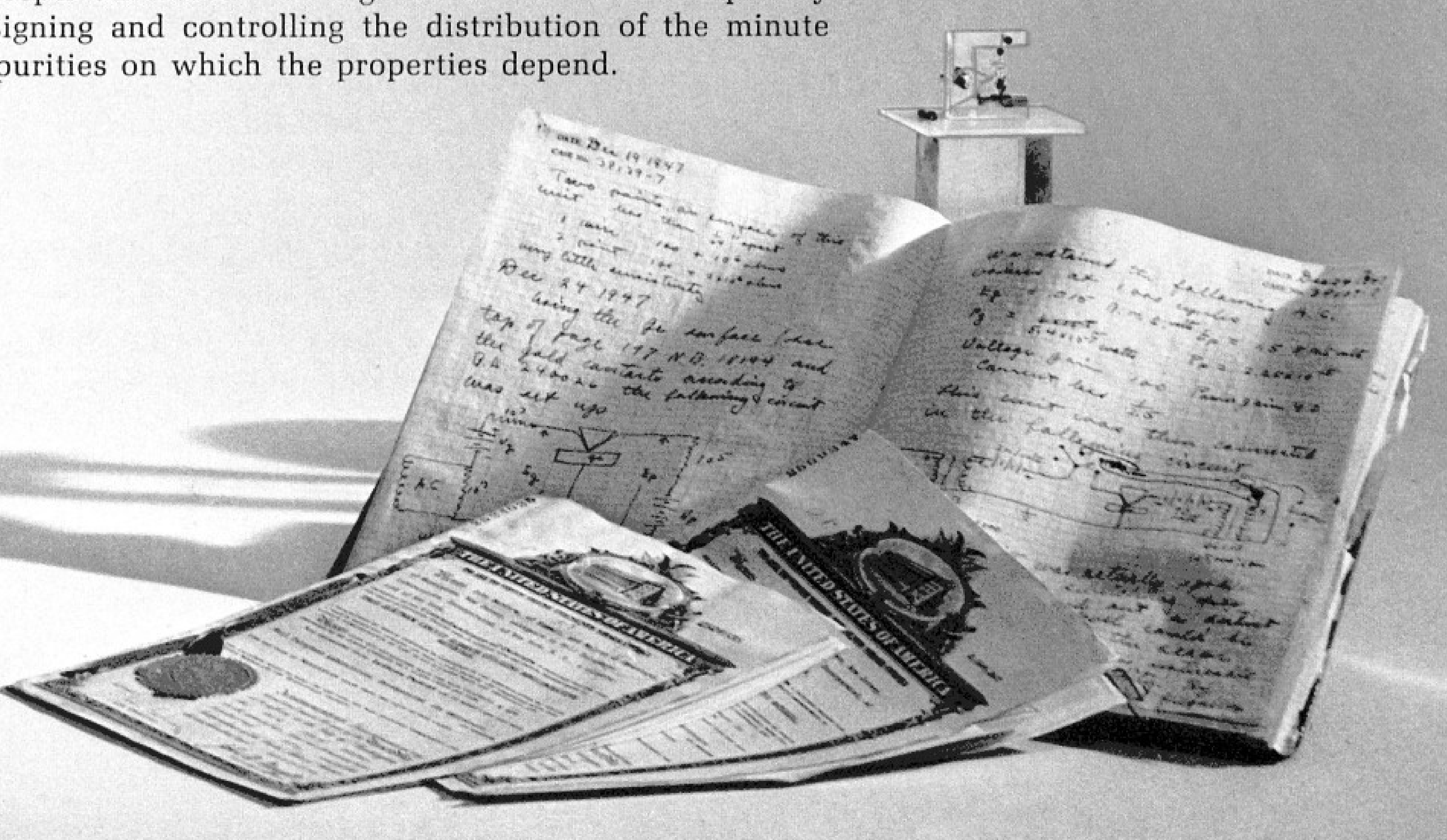
Like me, most of the group had worked in other areas during the war. Very helpful in bringing ourselves up to date were seminars and discussion groups in which we reviewed the literature. Of greatest relevance were the papers of Schottky and Spenke on semiconductor barrier layers and metal-semiconductor rectifiers, published just before the war, and reports of wartime research on silicon and germanium diodes.

My first publication after the war, with Brattain and Shockley as co-authors, was on the growth of an oxide layer on copper, as is done in forming copper oxide rectifiers. A second was on the ac impedance of a metal-semiconductor rectifier. In a third, I showed that a Schottky barrier layer could exist at the free surface of a semiconductor.

It was in following up some of the consequences of the third paper that Walter Brattain and I initiated the series of experiments that led to the invention of the point-contact transistor. Very important to these experiments were Shockley's ideas on modulating the conductance of a semiconductor by an electric field, the effect now used in MOS (metal-oxide-semiconductor) and field-effect transistors. Also vital was a close interaction between theory and experiment; at each stage we tried to have at least a qualitative understanding of what was going on.

They were very exciting days after the invention of the point-contact transistor. One of my jobs was to work with the patent attorney, Harry Hart, and we spent many hours together trying to define the invention. To get a good patent, it is necessary to have a good understanding of the basic mechanisms, and there were still questions about just how the holes flowed from the emitter to the collector. How important was the surface barrier layer in the transfer of holes from emitter to collector? Shockley initially suggested the junction transistor structure to help understand the mechanism. Independently, John Shive put the emitter and collector points on the opposite sides of a thin wafer of germanium, and found that the arrangement worked as a transistor. I can still remember the excitement I felt when I first learned of this discovery, which showed definitely that the holes from the emitter could flow appreciable distances through the bulk of n-type germanium.

The rapid exploitation of the semiconductor art has come from soundly based theoretical concepts combined with ingenious methods developed by many people for designing and controlling the distribution of the minute concentrations of impurities on which the properties depend.



Walter Brattain

The transistor and the development of solid-state electronics were technological offspring of the revolution in physics that was born with the conception of the principles E = hν and E = mc^2 by Planck and Einstein at the beginning of this century. Since I am the oldest of the three Nobel Prize winners, I can say that it all happened in my lifetime. I was fortunate to take Professor Van Vleck's course in quantum mechanics the year he first based his course on the Schrödinger wave equations and the Heisenberg-Born matrix mechanics at the University of Minnesota, 1927-28. This may have been the first such course in the U.S.A.

During this period James Franck, Irwin Schrödinger and Arnold Sommerfeld, all of whom participated in this revolution, were visitors at Minnesota. When I started work for J. A. Becker, Bell Laboratories was only four years old. The vacuum tube and thermionics were just shedding their baby teeth. It was Becker who dried my ears off as a green young Ph.D. and started me on my career as a *surface physicist*, first in thermionics and next in the study of rectification and the copper oxide rectifier.

My first experience with the impact of quantum mechanics on the understanding of solids was from Sommerfeld's lectures on the new electron theory of metals at the University of Michigan in the summer of 1931. Then came A. H. Wilson's papers on the band structure of semiconductors —the first explanation from quantum mechanical principles of what we now call n- and p-type conductivity. Hindsight makes me wonder whether the analogy between the creation of an electron-hole pair in a semiconductor and an electron-positron pair in free space might have influenced Wilson.

I vividly recall Becker's and my recognition of the close analogy between the copper oxide rectifier and the vacuum tube diode, and of our calculations of the size of the grid that one might put into the space charge layer of the rectifier to make a triode! It is an understatement to say that the results did not look promising. So I was somewhat amused when, a year or so later, Shockley came to me with an idea of making an amplifier out of copper oxide. As I remember I nevertheless told him that any means of doing this was so important that I would try to get the copper oxide device he had in mind made as near as possible to the way he wanted it. This attempt was not successful.

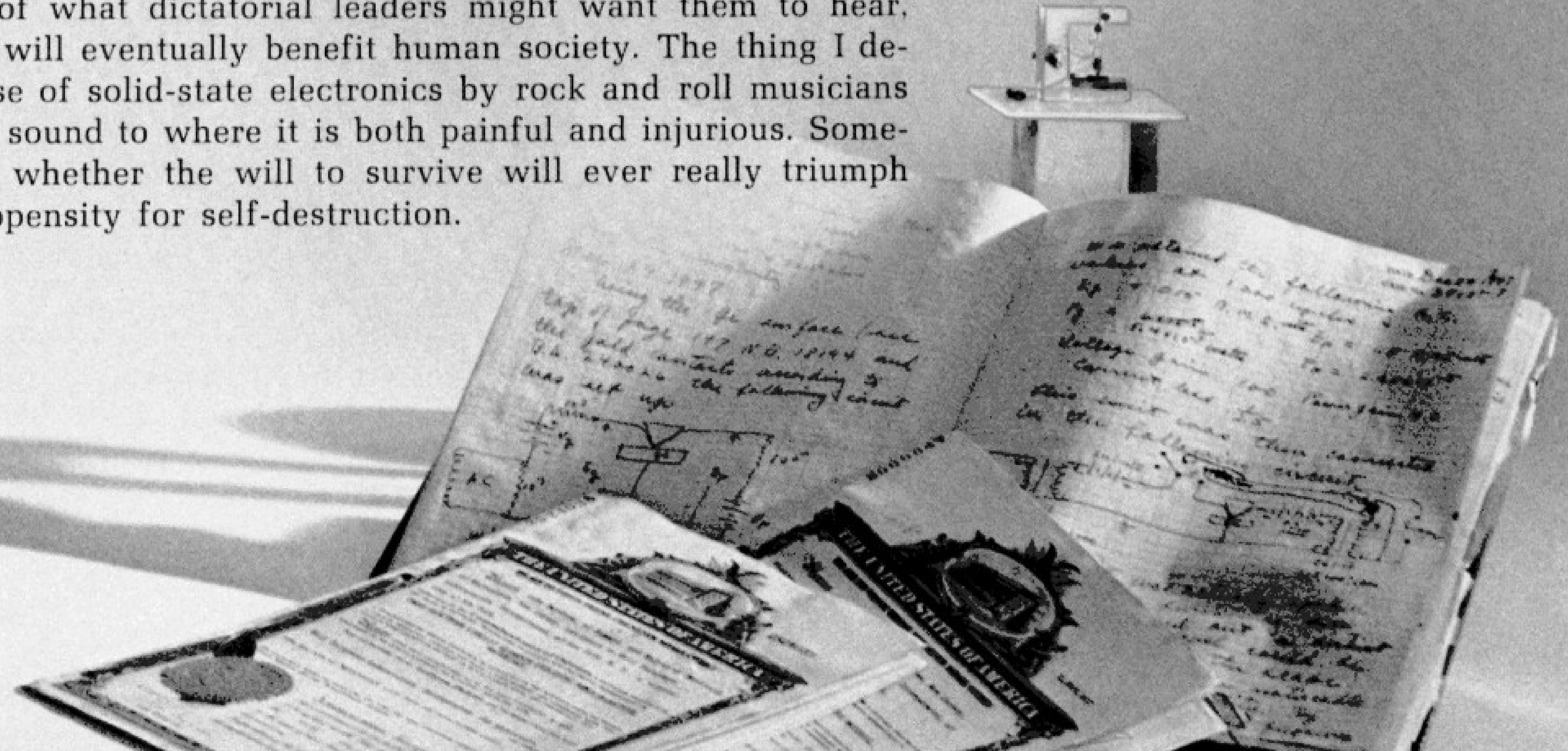
G. C. Southworth's revival of the cat's whisker detector of radio waves for microwave use and R. S. Ohl's work with silicon purified by J. H. Scaff and H. C. Theuerer leading to the first pn junction and subsequent events have been documented in several places (see for example "Genesis of the Transistor" by W. H. Brattain, *Physics Teacher*, March 1968).

The importance of an active solid-state circuit element was thoroughly recognized by anybody working in this area from about 1925 on, but I am impressed with the fact that direct attempts to make such elements were futile, whereas the research work to try to understand what was really going on in the simplest semiconductors, silicon and germanium, finally resulted in the breakthrough. One never knows beforehand, however, if one's research is going to contribute to that understanding, and after fourteen years of work I was beginning to lose faith. But I never felt any pressure from management to continue or to change fields. Perhaps the only real threat to my career came in 1932 when I, being then a bachelor, would have been the next man in my group to go if the depression had got worse. But this never happened, due to H. D. Arnold's fight to protect his research group. And later on I had to convince M. J. Kelly that I preferred research to supervising.

Another incident, never before written down, took place when my laboratory at West Street, New York City, was used to demonstrate C. J. Davisson's experiments on diffraction of electrons from a nickel crystal. This was in 1937 when it was announced that Davisson had won a Nobel Prize. The news services wanted movies and pictures. I was present, taking it all in, possibly with my hands in my pockets and my mouth open. It was hot under the klieg lights, and the news people would occasionally let Davisson cool off. During one of these breaks he walked over to me and said, "Don't worry, Walter, you'll win one someday." Little did I know that the day would come when he'd be one of the people to nominate us for the prize.

The *technological* use that society makes of the understanding that *science* gives is not always what the scientist would recommend or condone. I feel strongly, however, that the scientist has no right to dictate how his understanding is used. He does have the right to advise and to act as any other citizen when it comes to deciding what society should do, and all citizens are equally responsible for what is done.

The use of the transistor of which I am proudest is in the small battery-operated radio. This has made it possible for even the most underprivileged peoples to listen. Nomads in Asia, Indians in the Andes, and natives in Haiti have these radios, and at night they can gather together to listen. When I was a boy the idealists said that the only hope for future civilization was to see that every child learned to read and write. Even if he never learns to read or write, however, almost every human learns to speak, listen and understand. All peoples can now, within limits, listen to what they wish, independent of what dictatorial leaders might want them to hear, and I feel that this will eventually benefit human society. The thing I deplore most is the use of solid-state electronics by rock and roll musicians to raise the level of sound to where it is both painful and injurious. Sometimes one wonders whether the will to survive will ever really triumph over the human propensity for self-destruction.



William Shockley

When I think of the invention of the transistor, I think of the influences—teachers, associates, laboratories, and many, many others—that go to shape a person's career. But here I'd like to dwell on just one of them—the managerial attitudes at Bell Laboratories that stimulated my motivation to try to invent a transistor and to make it serve the telephone system.

In 1936, Mervin J. Kelly, then Director of Research for Bell Labs and later its President, made the final deal that brought me to Bell Laboratories when he visited M.I.T. just as I was winding up my Ph.D. requirements. One of the inducements was the opportunity to work under the eminent and charming physicist C. J. Davisson, who won a Nobel Prize in 1937 for his experimental confirmation, published in 1927, of the wave-particle duality of the electron. But when I reported for work, Kelly farmed me out for a training session to his own old vacuum tube department, and while I was there he gave me an eloquent pep talk on one of his own goals—to take the relays out of telephone exchanges and to make the connections electronically.

After about a year in this department, I expressed a strong leaning to resume research in the field of my Ph.D. on the behavior of electrons in crystals, and the management policy was flexible enough to allow me to make the change. This research introduced me to Walter Brattain, later to become, along with John Bardeen, one of the coinventors of the point-contact transistor, and to his problems with semiconducting copper oxide rectifiers.

Kelly's stimulus to look for new devices useful in the telephone business, plus exposure to new theories about rectification mechanisms in copper oxide, led me to invent a structure that would have worked as a transistor. With Brattain's help, I experimented with some very crude models that were total failures. Also, it was now 1940 and World War II was clearly foreseen. War-related, non-physics activities kept me busy until I returned from the Pentagon in 1945. Kelly then made me co-head of a solid-state research group, and I set as one important goal of the group the making of solid-state amplifier structures that would work. I suggested devices using principles like my pre-war idea. They would now be called field-effect transistors or FETs. They failed. But this time the failure was creative. Bardeen explained the failure in terms of the surface states that produced the Schottky barrier at the free surface.

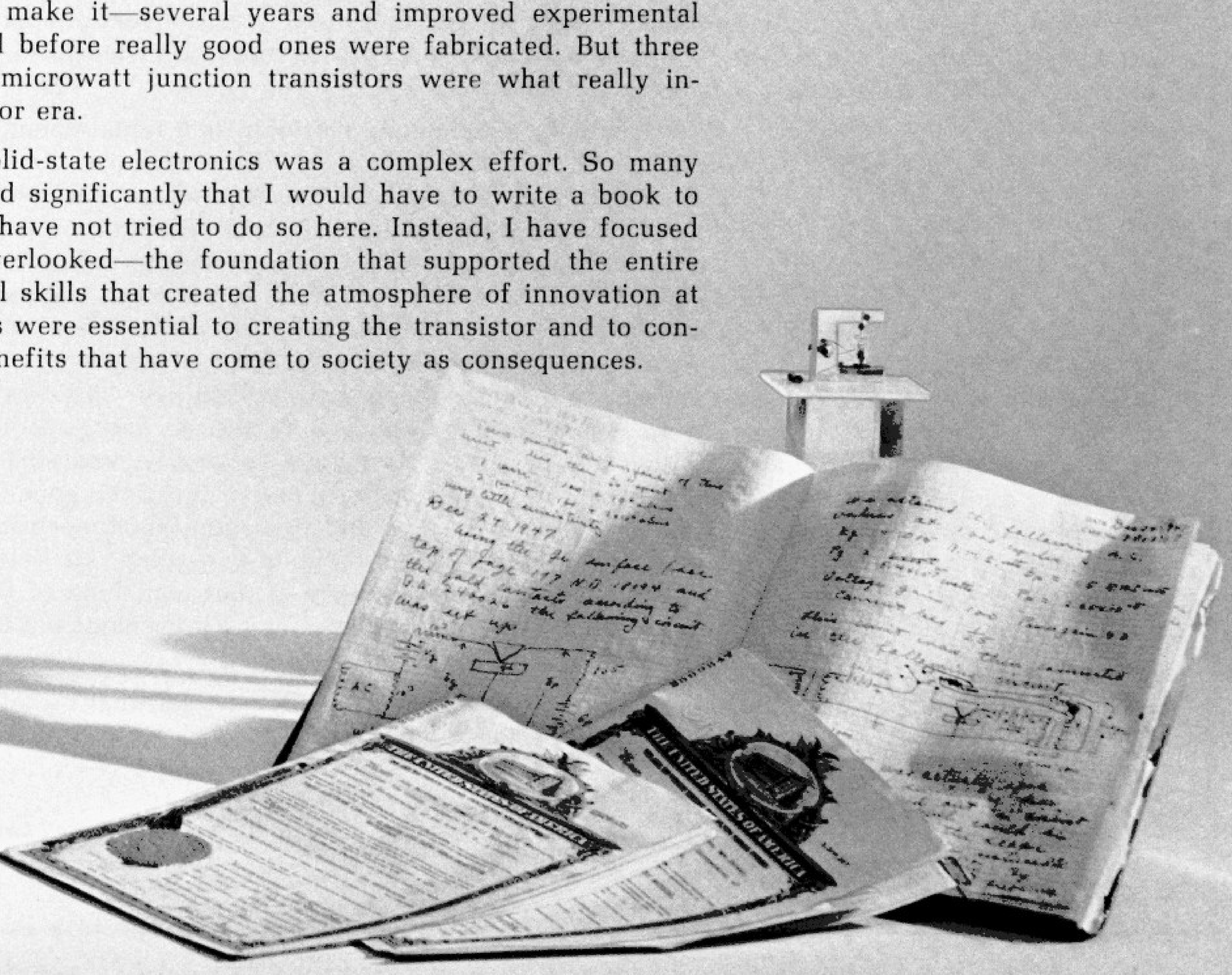
It is one of the virtues of management at Bell Labs that basic research is encouraged. Two phrases apply: "Creative-failure methodology" and "research on the scientific aspects of practical problems." Our failure to make a transistor was creative. It led to research on the scientific aspects of Bardeen's surface states. How this basic research fathered the point-contact transistor is described by Bardeen. The managerial art of optimizing the interaction between pure and applied research is what makes Bell Labs so eminent a leader in innovation.

Seven months after Bardeen and Brattain's first amplification of telephone conversation, a demonstration including television amplifiers was presented. All of us who were involved had no doubt that we had opened a door to a new important technology and were chagrined to find that *The New York Times* acknowledged the achievement on the radio program page in the concluding four of the fourteen paragraphs in the "News of Radio" column. At the time Bardeen and Brattain reported their results in the scientific literature, Gerald Pearson and I also published the first scientifically interesting but very feeble field-effect observations.

The name "transistor" selected for the invention was proposed by J. R. Pierce. The first publicly announced version had two sharply pointed wires that contacted a slab of germanium. The theory of operation and fabrication involved surface treatments carried out by team member R. B. Gibney, a chemist. I still remember one agonizing week when treatments failed and no transistors were made. Even years later, point-contact transistor technology still involved mysterious witchcraft.

Later, when I designed a basic research experiment to diagnose the surface phenomena of the original point-contact transistor, I discovered that I had an applied result. My research structure *was itself a transistor*. It was patented as the junction transistor. Exploiting its potential caused many headaches. A colleague branded it a "persistor," because persistence was what it took to make it—several years and improved experimental facilities were needed before really good ones were fabricated. But three years later, the first microwatt junction transistors were what really inaugurated the transistor era.

The creation of solid-state electronics was a complex effort. So many individuals contributed significantly that I would have to write a book to do them all justice. I have not tried to do so here. Instead, I have focused on what might be overlooked—the foundation that supported the entire effort—the managerial skills that created the atmosphere of innovation at Bell Labs. These skills were essential to creating the transistor and to contributing the many benefits that have come to society as consequences.



Morgan Sparks Reflects on . . .

25 Years of Transistors

Morgan Sparks, who joined Bell Laboratories in 1943, entered the field of semiconductor research shortly after the invention of the transistor and has followed the field closely through its 25 year history. Mr. Sparks, in fact, was the first to build a junction transistor, in 1951. Now President of Sandia Corp., Albuquerque, New Mexico, he was until recently Vice President, Electronics Technology, at Bell Laboratories. The RECORD asked Mr. Sparks to reflect on the transistor's impact on communications, how Bell Labs is changing its view of semiconductor research, and what might lie ahead for the Bell System in this field. Here are his comments:

"... not just a better mousetrap."

The transistor is a remarkable phenomenon. It's not just a better mousetrap, which so many inventions are. There have been many other outstanding inventions—those that make a lot of money, those that make big splashes—but for the most part, other inventions have been "contained"; their impact has been easily described and localized. The transistor, however, is ubiquitous.

Originally, we thought of it only as a replacement for the vacuum tube. But semiconductor technology has developed far broader implications. The refinement of vacuum tube technology did lead to greatly improved performance. But, with the principal exception of the cathode coating, the tube technology was not dominated by the subtle chemistry of materials, which is the key to semiconductor technology. Vacuum tube materials were mostly glass and metal, and improvements were achieved principally by novel and more precise geometrical arrangements. Semiconductor technology, on the other hand, has evolved over 25 years in a continuous, perhaps expanding, rate, and I don't see any let-up. It has not only improved a thousand-fold in performance, reliability, and cost—it has opened up a still expanding list of entirely new effects. It's gone far beyond what anyone thought it would be and now, transistor electronics, most recently in the form of integrated circuits, is pervading our lives in subtle ways that most people aren't even aware of. But just think of the wide expansion of our communicating and computing abilities made possible by semiconductor electronics.

Others have said this, and it's a thought that I like: the industrial revolution was an extension of muscle, through a controlled use of energy—steam power, for example. Now, the electronics revolution is an extension of the mind—new means of communications, and computers that aid in calculations, thought processes, decisions, automatic controls, etc. And this would not have happened without the transistor and the other solid-state devices that have evolved from it. Since there's no doubt that the mind is more powerful than muscle, the potential here is greater than that of the industrial revolution. In that sense, we must be just on the very first rung of the ladder.

"... amazing ... how versatile semiconductors are."

It's been amazing to me how versatile semiconductors are. There's almost no electronic function that can't be performed with semiconductors. They're amplifiers, rectifiers, thermistors, memories, oscillators, switches, particle detectors, lasers, imaging devices, photodetectors, light-emitters—the list goes on. This versatility is one reason for the cornucopia that we've had during the 25 years of this expanding technology. I can't think of a single system that's under development now at Bell Laboratories that doesn't depend in a basic way on semiconductor electronics. Electronic switching systems are the most important example in terms of people involved and dollar impact on the Bell System, and they go back to Mervin Kelly's (President of Bell Labs, 1951 to 1959) original vision that some day we'd have to escape from restrictions that electromechanical relays imposed on speed, reliability and cost. Another application that bears mentioning is the L-5 coaxial repeater, which will use new microwave transistors.

"... Bell Labs' first important policy ... was not to keep it a secret."

One way of measuring the transistor's impact is to realize that it took literally years and years, a lot of money, and many people to fill out the scientific background needed to solve the problems of making semiconductor devices. Diffusion constants, solid solubilities, band structure calculations, impurity energy levels, hole and electron mobilities—an entire technical field was established. Germanium and silicon, little more than laboratory curiosities before, became the best understood solids of all. That was the focus of our research and development from the early 1950's to about 1960. Such efforts can be made only rarely; we simply don't have enough resources.

Even though the Bell System represents only a small part of today's total semiconductor production and use, we have been dominant in technological innovations. Our developments in zone refining, zone leveling, epitaxy, diffusion, and oxide masking were important steps in bringing the devices out of the laboratory into production. Oxide masking is the development that made the planar process, and therefore, integrated circuits possible. Oxide masking, together with photolithographic techniques, extended precise dimensional control to surface patterns and made evaporated interconnections feasible.

Bell Labs' first important policy was not to keep transistor information secret. Not only was it not kept a secret, but we actively expounded the art as well as the science of practicing the technology. Several seminars were held in the early 1950's where we effectively told all we knew about transistor technology.

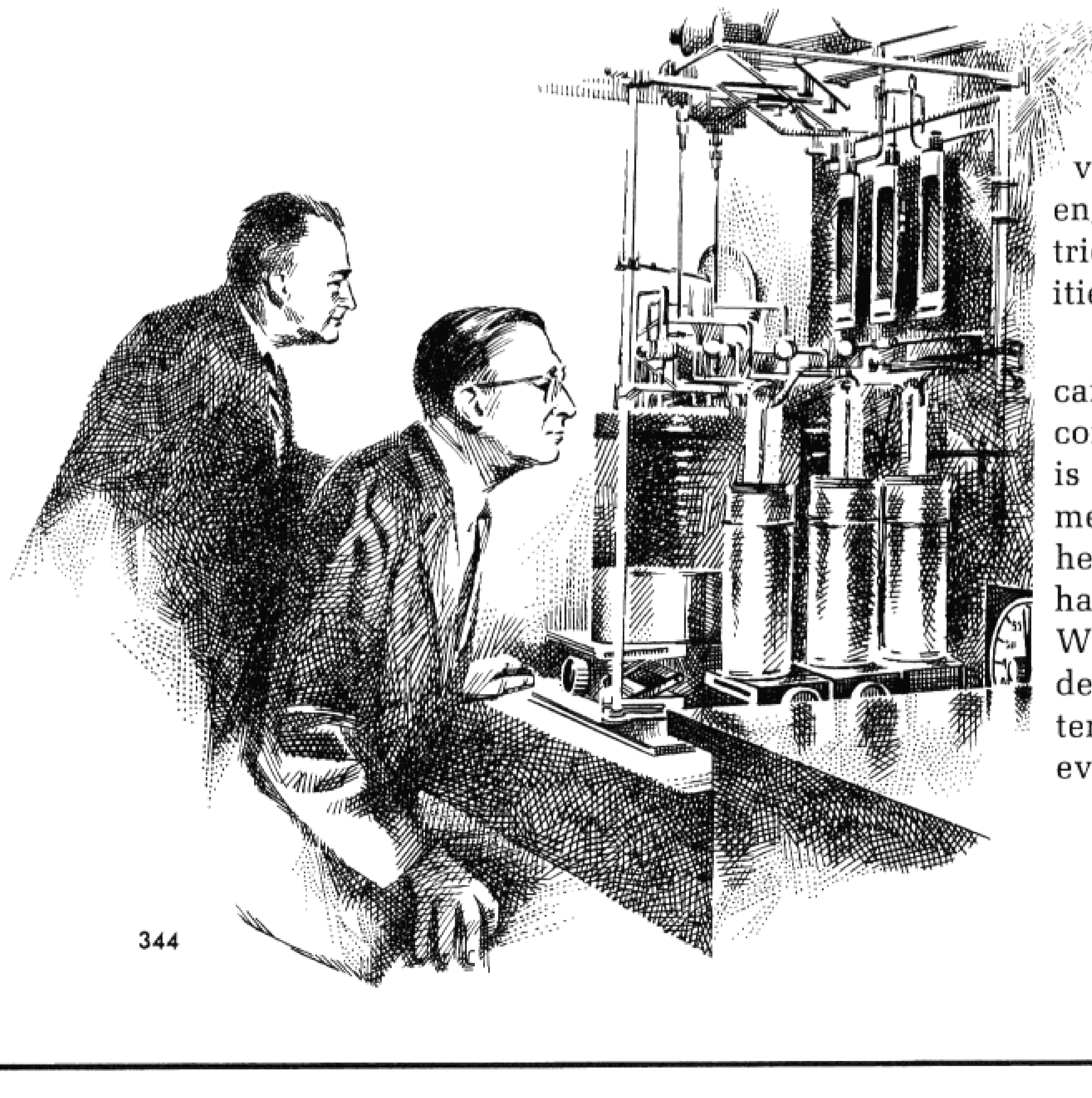
The whole tone of open information exchange within the emerging semiconductor industry was set by Bell System policies of patent licensing and publication. This industry is different from other technologically based industries in which secrecy of technical know-how is the norm. The semiconductor industry's remarkable, almost overnight, growth is due in large measure to relatively open information exchanges.

Other things, of course, helped spread the information—Wall Street, for example, became enamored with growth and glamor industries, and there was a period when investment money was readily available for semiconductor enterprises. This fostered many entrepreneurs, and in turn encouraged movement of people, who helped spread the technology from company to company. Bell Laboratories was the fountainhead; a corps of our alumni carried the word literally around the world including, importantly, the faculties of many leading universities. Back home at Bell Labs, we continued to expand the science and technology of semiconductors.

"... now is when the payoff comes."

In recent years, the emphasis in semiconductor work has changed at Bell Laboratories. The shift of this emphasis went, as one would expect, from research to development and finally to systems applications.

Our effort started with a small group of a half-dozen or so and grew rapidly until it leveled off in about the middle sixties. I would estimate that now about half of all our R & D activity on electronic phenomena is in semiconductors and that we will likely continue at this rate for the next few years.



Our present emphasis on development and applied research is reflected in the growth of our Pennsylvania Branch Lab operations, which are almost all related to semiconductors. Final development and production of semiconductor devices are so interrelated that Bell Labs design engineers must work closely with Western Electric manufacturing engineers at the actual facilities where the devices are to be made.

The important question is not whether we can perform electronic functions with semiconductors—we have shown that. The question is how can we do them more economically to meet the needs of Operating Companies and help hold down costs at the same time. We have large numbers of people working with Western Electric engineers to try to improve device yields, for example. These developments tend to be a little less newsworthy, but they're even more important in the long run.

Right now is when the payoff comes, because even small changes in the processes mean very large savings. For example, we have a rather large group now that is investigating the use of tungsten for interconnections between individual devices on a silicon chip. This might replace the three-metal system—successive layers of titanium, platinum, and gold—originally developed for the beam-lead, sealed-junction devices. The motivation for this project is fewer process steps with attendant higher yields and lower costs. This is an example of today's primary emphasis in semiconductor development—doing cheaper and with better control what we already know how to do.

"... we haven't run out of possibilities ..."

But I don't think it's at all appropriate for us to stop doing research on new devices—because we haven't run out of possibilities or ideas.

Looking into the future, we will certainly continue to have important new inventions. Charge-coupled devices (CCD's) are the most recent example. They offer many opportunities to improve systems—PICTUREPHONE®, for example, will give us an opportunity to really take a look at the CCD's as area imaging and variable-delay storage devices, but these devices have potential uses in many other systems.

Field-effect transistors built in the MOS (metal-oxide-semiconductor) structure are not now in the telephone plant, but they are committed in some major development programs. These devices are hardly new—they actually have the same theoretical basis as the devices that William Shockley proposed before the transistor effect was discovered. MOS-type semiconductor memories are under development for No. 2 and No. 3 ESS, and to replace the piggy-back twistors in the Traffic Service Position System.

I'm sure that high-frequency devices are going to get a lot of attention—there will be new inventions for use at microwave frequencies and even beyond. IMPATT diodes are another example of how we often come back to things when their time comes. One of the ideas that Shockley and Thornton Read (now in the Mathematics Analysis Department, Murray Hill) and others worked on were negative resistance devices based on transit-time principles. Such devices were analogs to a kind of vacuum tube, where device operation is directly related to the transit time of electrons from one electrode to another. Now we have IMPATT devices in silicon and gallium arsenide that are committed to some of our most important transmission systems—for example, the millimeter waveguide system.

Ion implantation is another old idea. Incidentally, Friedolf Smits (Director of the MOS Technology and Memory Laboratory, Allentown) came to Bell Labs in 1950 from Germany by way of England with the intention of working on ion implantation in germanium. However, we weren't ready for it then. Now, ion implantation is seriously challenging diffusion as the basic process for making transistor structures. Diffusion is a mass phenomenon, dominated by thermodynamics, whereas ion implantation is literally a rifle-like technique—each impurity is banged into a semiconductor one at a time. Ion implantation gives higher yields through better control over the number of impurities put in such critical structures as microwave transistors. It also allows creation of impurity profiles that are impossible by diffusion, and thus permits entirely new devices to be built.

The adaptability of ion implantation to mass production has been questioned. However, calculations indicate that this is not going to be a serious problem. Diffusion handles thousands of devices at a time, but it takes hours to accomplish. An ion beam writes a line at a time as it sweeps over a wafer surface, one at a time. But it moves rapidly and can complete a circuit in a matter of seconds.

Another contribution to the technology that's yet to come, but I think is inevitable, is the substitution of electron-beam processing for the optical methods now universally used to delineate surface patterns on semiconductor surfaces. One of the key steps in making an integrated circuit today is to expose a semiconductor wafer to light through a series of masks to define the various parts of the devices and the interconnection pattern. Electrons, with their much smaller wavelengths, have a potential of several orders of magnitude improvements in precision geometries.

Some of the processing techniques developed for the transistor have also been directly borrowed in other areas. In magnetic bubbles, for example, photolithography and epitaxy are used. The growth of thin epitaxial films for magnetic bubble devices has been the most important single advance in bringing us to the point where we're going to find out in less than a year whether bubbles really are economically competitive with other solid-state memory and logic devices. In magnetic bubbles, as in semiconductor technology, it's the control of the materials that ultimately determines the performance and, maybe even more particularly, the economics.

"...the proof that research pays off."

I think that one of the important consequences of the transistor may be that it has been heralded as the proof that research pays off. In almost every discussion of industrial research that I read, the transistor is cited as the prime example to show that it is economically advantageous for a technically-based industry to do research. And it is a valid example, although one must be careful not to oversimplify the comparisons. As I pointed out earlier, a result like the transistor has produced can occur only rarely.

As soon as some companies get into a financial squeeze the first thing they cut out is R & D: I think it's important that the Bell System didn't. In the 1930's, our owners were wise enough to recognize that improving technology was our lifeblood, and Bell Labs was supported through some difficult periods.

I spoke earlier of the way the transistor and some of its progeny have pervaded our lives. But they also have pervaded the whole fabric of this company in a way that no other new idea ever did—in our own R & D, in our relations with Western Electric and in the way we have organized and grown.

In summary, I think the whole transistor story—its discovery, its development, its continually broadening content and applications—adds up to a remarkable achievement. It is a tribute to the men and women who have done the work, to the understanding support of our management, and to the enlightened policies of the Bell System in handling such an important creation. A final observation—it has been a lot of fun to be a part of it.

A Glossary of Solid-State Electronics

Since the invention of the transistor 25 years ago, transistor technology and solid-state electronics have given rise to many new technical terms. Here for your use is a short dictionary which emphasizes the ways in which various solid-state devices and techniques may be used. Readers desiring more engineering detail should consult the IEEE Standard Dictionary of Electrical and Electronic Terms, *Wiley-Interscience, 1972.*

acceptor — an impurity that can make a semiconductor P-type by accepting valence electrons, thereby leaving "holes" in the valence band. The holes act like carriers of positive charge.

alloyed junction — a PN junction formed by recrystallization of a molten region of P-type material on an N-type substrate, or vice versa.

avalanche diode — a diode that conducts current only above a certain "breakdown" voltage, by virtue of high-field impact ionization (avalanche). Useful for voltage-limiting or microwave generation. See also IMPATT diode, avalanche multiplication.

avalanche multiplication — a high-field effect in semiconductors which leads to an increase in current. High-energy charge carriers create additional carriers by impact ionization of valence electrons. See IMPATT diode.

base — along with emitter and collector, one of the three semiconductor regions of the bipolar type of transistor. See bipolar transistor.

beam lead (for integrated circuits) — a deposited metal lead, usually of gold, which projects beyond the edge of the semiconductor chip. Used for both mechanical and electrical contact to the chip.

BIGFET — Bipolar Insulated Gate Field-Effect Transistor. A simple integrated circuit combining a field-effect transistor and a bipolar transistor. See FET.

bipolar transistor — a transistor consisting of an emitter, base and collector whose action depends on the injection of minority carriers into the base by the emitter and the collection of these minority carriers from the base by the collector. Sometimes called NPN or PNP transistor to emphasize its layered structure.

CCD — Charge Coupled Device. A semiconductor device whose action depends on the storage of electric charge within a semiconductor by an insulated electrode on its surface, with the possibility of selectively moving the charge to another electrode by proper manipulation of voltages on the electrode.

CDI — Collector Diffusion Isolation. A process for fabricating integrated circuits whereby the collector diffusion also electrically isolates the transistors from one another.

channel — a region of surface conduction opposite in type from that expected from the bulk doping. Channels are often introduced intentionally by charging external electrodes (see IGFET) or unintentionally by surface ionic contamination. See sealed junction.

charge carrier — a carrier of electrical charge within the crystal of a solid-state device, such as an electron or a hole.

chip — any small piece of semiconductor, especially one fabricated for semiconductor devices.

collector — along with the emitter and base, one of the three regions of the bipolar type of transistor. See bipolar transistor.

cutoff frequency — the frequency at which the intrinsic gain of a device falls to some predetermined value. For example, the frequency at which the gain of a bipolar transistor in a common-emitter amplifier configuration is equal to unity.

Darlington pair — a circuit, often integrated, consisting of two bipolar transistors with the collectors connected together and the emitter of one connected to the base of the other. The combination behaves like a very high gain transistor. See supergain transistor.

depletion layer — the region in a semiconductor where essentially all charge carriers have been swept out by the electric field which exists there.

diffusion — spontaneous intermingling of substances, as, for example, the diffusion of an impurity into a semiconductor at high temperature to create a desired concentration of N or P charge carriers.

DIP — Dual In-line Package. A circuit package somewhat longer than it is wide, with the leads coming out of the two long sides.

donor — an impurity that can make a semiconductor N-type by donating extra "free" electrons to the conduction band. The free electrons are carriers of negative charge.

doping — the introduction of an impurity into the crystal lattice of a semiconductor to modify its electronic properties—for example, adding boron to silicon to make the material more P-type.

drain — along with the source and gate, one of the three regions of a unipolar or field-effect transistor. See FET.

emitter — along with the base and collector, one of the three regions of the bipolar type of transistor. See bipolar transistor.

energy gap (of a semiconductor) — the region, according to quantum mechanics, of forbidden electron energies. The gap lies between the energy band for valence electrons and the energy band for conduction electrons.

epitaxial layer — a deposited layer of material having the same crystallographic characteristics as the substrate material.

extrinsic conductivity — electrical conductivity dependent on the impurities in the material. (Compare intrinsic conductivity.)

FET — Field-Effect Transistor. A transistor consisting of a source, gate, and drain, whose action depends on the flow of majority carriers past the gate from source to drain. The flow is controlled by the transverse electric field under the gate. See unipolar transistor, IGFET.

FIC — Film Integrated Circuit. See thin-film integrated circuit.

gate — along with the source and drain, one of the three regions of the unipolar or field-effect transistor. See FET.

grown junction — PN junction made by controlling the type of impurity in a single crystal while it is being grown from a melt.

Gunn oscillator — microwave oscillator based on the velocity dependence of charge carriers as a function of electric field in some semiconducting materials such as gallium arsenide. Invented by J. B. Gunn.

HIC — Hybrid Integrated Circuit, consisting of an assembly of one or more semiconductor devices and a thin-film integrated circuit on a single substrate, usually of ceramic.

hole — the absence of a valence electron in a semiconductor crystal. Motion of a hole is equivalent to motion of a positive charge.

IC — see integrated circuit.

IGFET — a field-effect transistor whose gate is insulated from the semiconductor by a thin intervening layer of insulator, usually thermal oxide.

IMPATT diode — Impact Avalanche and Transit Time diode. An avalanche diode used as a high-frequency oscillator or amplifier. Its negative resistance depends upon the transit time of charge carriers through the depletion layer.

ingot — material prepared by solidification from a melt.

injection — in a semiconductor, the introduction of excess minority carriers. Injection can take place at a conducting PN junction or in a region illuminated by light.

integrated circuit — a circuit in which many elements are fabricated and interconnected by a single process, as opposed to a "nonintegrated" circuit in which the transistors, diodes, resistors, etc. are fabricated separately and then assembled.

interface states — extra donors, acceptors, or traps that may occur at a boundary between a semiconductor and some other material.

intrinsic conductivity — electrical conductivity of an apparently pure material—i.e., without the presence of any significant impurities.

ion implantation — introduction into a semiconductor of selected impurities in controlled regions (via high-voltage ion bombardment) to achieve desired electronic properties.

JFET — Junction Field-Effect Transistor (see FET), in which the gate electrode is formed by a PN junction.

junction — the interface between two semiconductor regions of differing conductivity. Usually refers to a PN junction, at which the conductivity changes from P-type to N-type.

junction transistor — a bipolar transistor constructed from interacting PN junctions. The term is used to distinguish junction transistors from other types, such as field-effect and point-contact transistors. See bipolar transistor, PN junction.

LASER — Light Amplification by Stimulated Emission of Radiation. In the laser, excited electrons give up their excitation in step with the light that is passing by to add energy to the transmitted light. Some lasers can generate or amplify extremely pure colors, in very narrow beams, often with very high intensity.

LED — Light-Emitting Diode. A semiconductor device in which the energy of minority carriers in combining with holes is converted to light. Usually, but not necessarily, constructed as a PN junction device.

lifetime — term used to describe the life of a minority charge carrier in a semiconductor crystal—for example, how long a free electron exists in a P-type material before it combines with a hole and is neutralized.

LPE — Liquid Phase Epitaxy. The formation of an epitaxial layer by placing the substrate in contact with a molten liquid and allowing crystallization onto the substrate to take place. See VPE and epitaxial layer.

LSA diode — Limited Space-charge Accumulation diode. A microwave oscillator diode similar to the Gunn diode (see Gunn oscillator) but attaining higher power or higher frequency by avoiding the formation of "domains" or regions of nonuniform distribution of charge.

majority carrier — the mobile charge carrier (hole or electron) that predominates in a semiconductor material—for example, electrons in an N-type region.

mask — pattern or template used in photolithographic-like processes employed in making integrated circuits. The pattern prescribes regions of the circuit, electrical leads, etc.

mesa — a device structure fabricated by selective etching which leaves flat portions of the original surface ("mesas") projecting above the neighboring regions. The mesa technique is often used to limit the extent of the electronically active material to the area of the mesa. (Compare planar structure.)

minority carrier — the nonpredominant mobile charge carrier in a semiconductor—for example, electrons in a P-type region.

monolith — a semiconductor chip containing a multiplicity of devices interconnected into an integrated circuit. The term is contrasted with hybrid circuitry.

MOSFET — a field-effect transistor containing a metal gate over thermal oxide over silicon. The MOSFET structure is one way to make an IGFET.

multicrystalline — see polycrystalline.

NPN — a semiconductor structure consisting of a layer of P-type material sandwiched between layers of N-type material, as commonly used in the bipolar type of transistor.

N-type — semiconductor material in which the majority carriers are electrons and are therefore negative.

ohmic contact — contact to a semiconductor or other part of a device having low electrical resistance and not showing rectifying behavior. See rectifying contact.

oxide masking — use of an oxide on a semiconductor to create a pattern in which impurities are diffused or implanted.

OXIM — Oxide-Isolated Monolith. A method of making integrated circuits in which an oxide layer is introduced to insulate semiconductor regions from each other.

passivation — treatment of a region of a device to prevent deterioration of electronic properties through chemical action or corrosion. Usually passivation protects against moisture or contaminants.

photodiode — an optically sensitive diode. Often the current is accurately proportional to the intensity of the incident light.

photolithographic process — technique used in making integrated circuits, which uses light and selective masking to develop a fine-scaled pattern of areas in a semiconductor; analogous to processes using photo negatives in offset printing.

photoresist — a photosensitive material which, after selective exposure to ultraviolet light, resists the action of a chemical. Used in conjunction with a mask to selectively process certain areas of a semiconductor device.

PIN diode — diode constructed of an I-type (intrinsic) layer between P and N layers and used in high-speed or high-power microwave switching.

planar structure — a flat-surfaced device structure fabricated by diffusion and oxide-masking, with the junctions terminating on a single plane. The structural planarity is often advantageous for photoresist processing. (Compare mesa structure.)

PN junction — within a crystal, an interface between a P region that conducts primarily by holes and an N region that conducts primarily by electrons.

PNIP — semiconductor crystal structure consisting of layers that are P-type, N-type, Intrinsic, and P-type. Used for high-voltage, high-frequency bipolar transistors.

PNP — semiconductor crystal structure consisting of an N-type region sandwiched between two P-type regions, as commonly used in bipolar transistors.

PNPN — a semiconductor crystal structure in which the layers are successively P-type, N-type, P-type and N-type. When ohmic contacts are made to the various layers, a silicon controlled rectifier (SCR), or thyristor, results.

point-contact transistor — the original transistor, invented at Bell Laboratories, which was made by placing sharp metal points in contact with the surface of an N-type semiconductor crystal.

polycrystalline — descriptive of a material that consists of many small crystallites rather than a single crystal.

P-type — semiconductor material in which the majority carriers are holes and are therefore positive.

quasi-intrinsic — descriptive of a semiconductor material whose conductivity is kept low, close to the intrinsic value, by doping with impurities which create carrier-traps lying near the center of the energy gap.

recombination — in a semiconductor, the combining of holes and electrons. Recombination tends to reduce the minority carriers to their equilibrium number after injection has taken place. See lifetime.

rectifying contact — an electrical contact through which current flows easily in one direction (the "forward" direction), but with difficulty or not at all in the reverse direction.

rise time — for an instantaneous change in voltage applied, the time required for the steady-state current to rise from 10 percent to 90 percent of its maximum value.

SBC — Standard Buried Collector. A method of making integrated circuits in which diffused collector areas are "buried" by overlying layers.

Schottky barrier — a potential barrier formed between a metal and a semiconductor. The term usually refers to a barrier which is high enough and thick enough to serve as a rectifier but which avoids the slowing-down effects that result from injection of charge in PN junction rectifiers.

SCR — Silicon Controlled Rectifier. A PNPN device useful for switching and power applications because it can have both high breakdown voltage and high current-carrying capability. See PNPN, thyristor.

sealed junction — a PN junction sealed by covering it with an inert material which does not allow troublesome impurities to reach the junction and cause changes in its electrical characteristics. See passivation.

semiconductor — an element such as silicon or germanium (or equivalent compounds; see III-V compounds) that is intermediate in electrical conductivity between the metals and insulators.

SIC — Silicon Integrated Circuit. An integrated circuit where all the elements such as transistors, diodes, resistors and capacitors are successively fabricated in or on the silicon and interconnected.

silicon controlled rectifier — see SCR.

single-crystal material — a material all of which consists of a single crystal, as distinct from most materials, which are polycrystalline.

slice — a thin slab of semiconductor, sawed from an ingot for the purpose of making semiconductor devices.

snap-back diode — a kind of diode which, when switched from a forward to a reverse direction, passes current for a short time and then very rapidly turns off. The sudden change in current is very rich in harmonics. Used as frequency multiplier or pulse generator.

solar cell — large-area diode in which a PN junction close to the surface of a semiconductor generates electrical energy from light falling on the surface.

solid-state electronics — designation used to describe devices and circuits fabricated from solid materials such as semiconductors, ferrites, or films, as distinct from devices and circuits making use of electron tube technology.

source — along with the gate and drain, one of the three regions of the unipolar or field-effect transistor. See FET.

space charge — the electrical charge of carriers in the depletion layer of a semiconductor.

spreading resistance — the ohmic resistance of a small ohmic contact to a large volume of semiconductor material.

storage time — the time required to withdraw the minority carriers from both sides of a PN junction when the junction is switched from a forward to a reverse bias.

substrate — the underlying material upon which a device, circuit, or epitaxial layer is fabricated.

supergain transistor — a transistor with a common emitter current gain of about a thousand or more, usually fabricated as a Darlington pair.

surface states — extra donors, acceptors or traps, usually undesired, which may occur on a semiconductor surface because of crystal imperfections or contamination and which may vary undesirably with time.

thermal oxide — on silicon semiconductor devices, an oxide fabricated by exposing the silicon to oxygen at high temperatures. The resulting interface is outstandingly free of ionic impurities and defects. See surface states.

thin-film integrated circuit — a circuit consisting of patterns of tantalum or other materials laid down on a substrate of glass or ceramic, typically larger than silicon integrated circuits. Sometimes designated FIC.

thyristor — a PNPN device useful as a controlled rectifier that can conduct high currents by injection of a highly conducting hole-electron plasma. So-called by analogy to a thyratron electron tube. (Same as SCR).

transistor — a semiconductor device that uses a stream of charge carriers to produce active electronic effects. The name was coined from the electrical characteristic of "transfer resistance." As compared with electron tubes, transistors are usually advantageous because of their greater efficiency, lifetime, reliability and compactness.

transit time — the time a charge carrier takes to go from one part of a semiconductor to another. For example, in a reverse-biased diode the time a carrier requires to move through the depletion region.

TRAPATT — Trapped Plasma Avalanche Transit Time diode. A diode used as microwave oscillator in a manner analogous to the IMPATT diode.

traps — impurities or defects in a semiconductor that can capture an electron or hole and hold it for a period of time. After trapping, the carriers may be released or recombined, with probability depending on trap energy. Recombination of minority carriers is expedited by the presence of "deep" traps, so the lifetime of a minority carrier can be varied by varying the type and concentration of trap impurities.

tunnel diode — a diode that exhibits negative resistance because of tunneling through a thin depletion layer.

tunneling — in quantum mechanics, a process that explains how charge carriers can penetrate insulating regions that are sufficiently thin.

unipolar transistor — a transistor such as an FET whose action depends on majority charge carriers only.

varactor diode — a diode making use of the variation of capacitance that takes place as reverse bias is varied. Can be used as a frequency multiplier, as a tuning element in a tuned circuit, or as a low-noise parametric amplifier.

VPE — Vapor Phase Epitaxy. The formation of an epitaxial layer by deposition from the vapor phase onto the substrate. See LPE and epitaxial layer.

wafer — same as chip.

Zener diode — a voltage-limiting diode with high impedance at low voltages but low impedance above a "breakdown" voltage. Most voltage-limiting diodes break down by impact ionization ("avalanche") rather than by cold-field emission (the Zener effect).

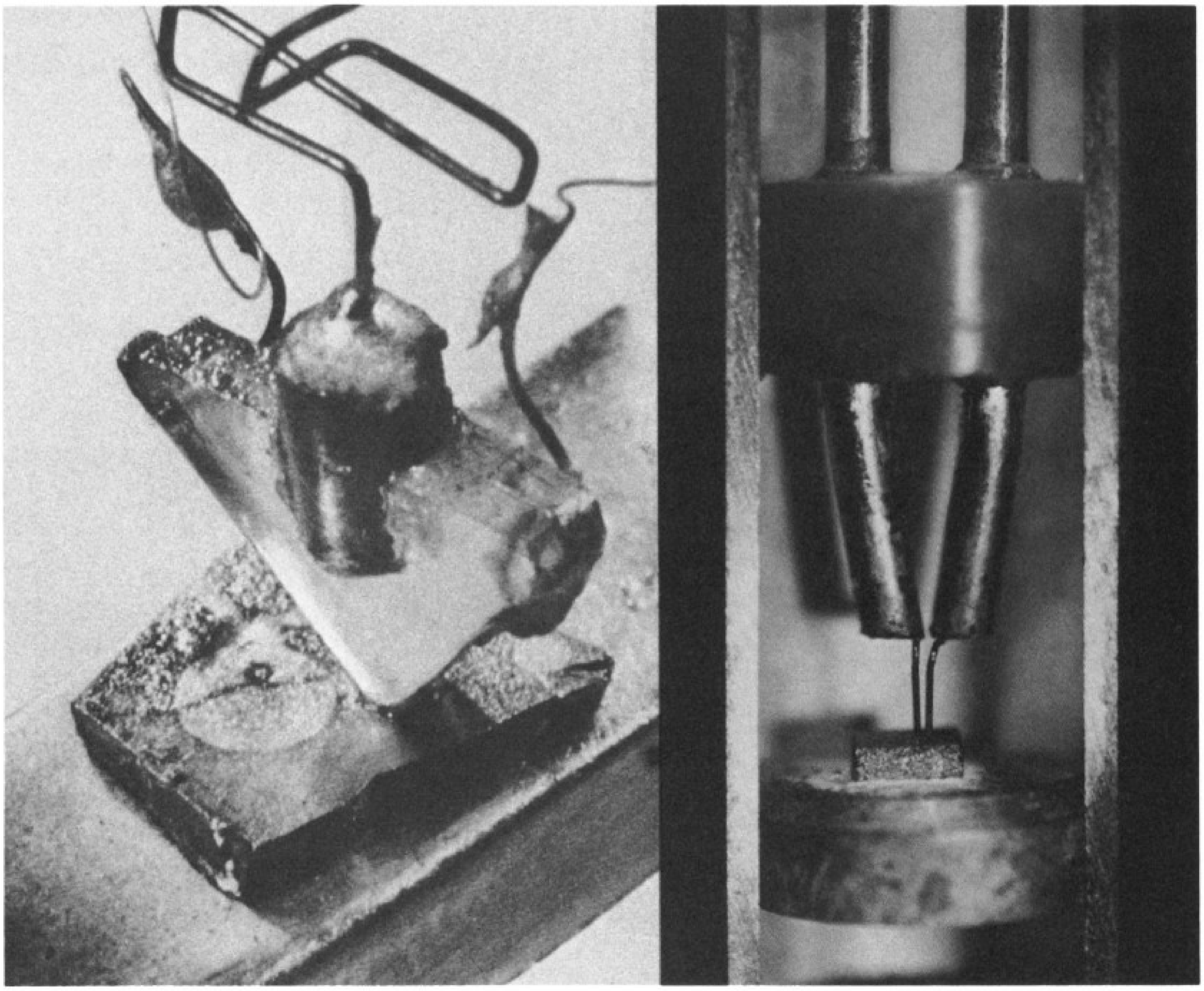
zone refining — technique of purifying a semiconductor or other substance by "sweeping" or passing a molten zone through the otherwise solid material.

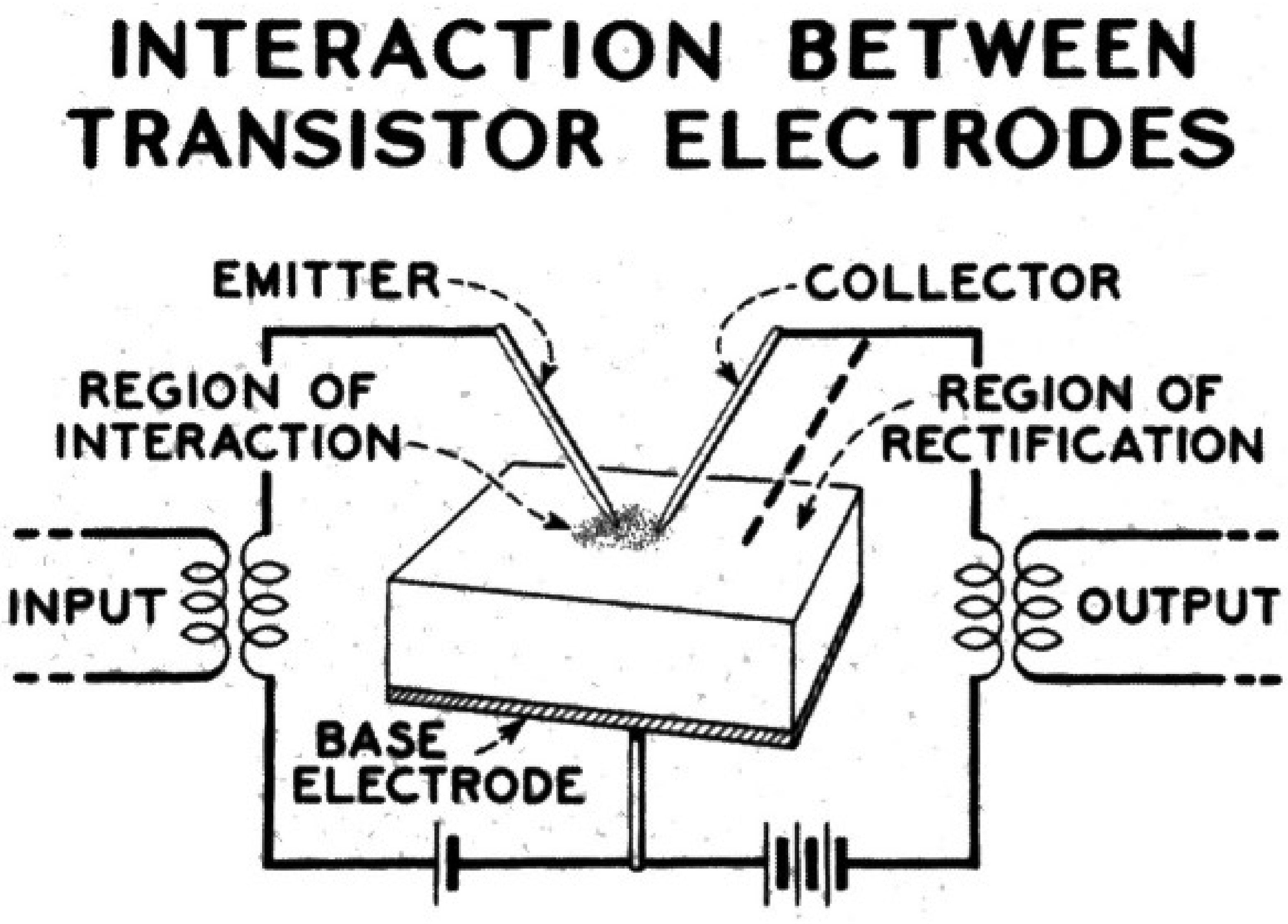
III-V compound — a compound consisting of an element from column III of the periodic table and an element from column V, as distinct from semiconductor elements like silicon and germanium from column IV. Several III-V compounds are advantageous for semiconductor devices such as oscillators, lasers, or light-emitting diodes.

The Growth of a Technology — A Look at the RECORD

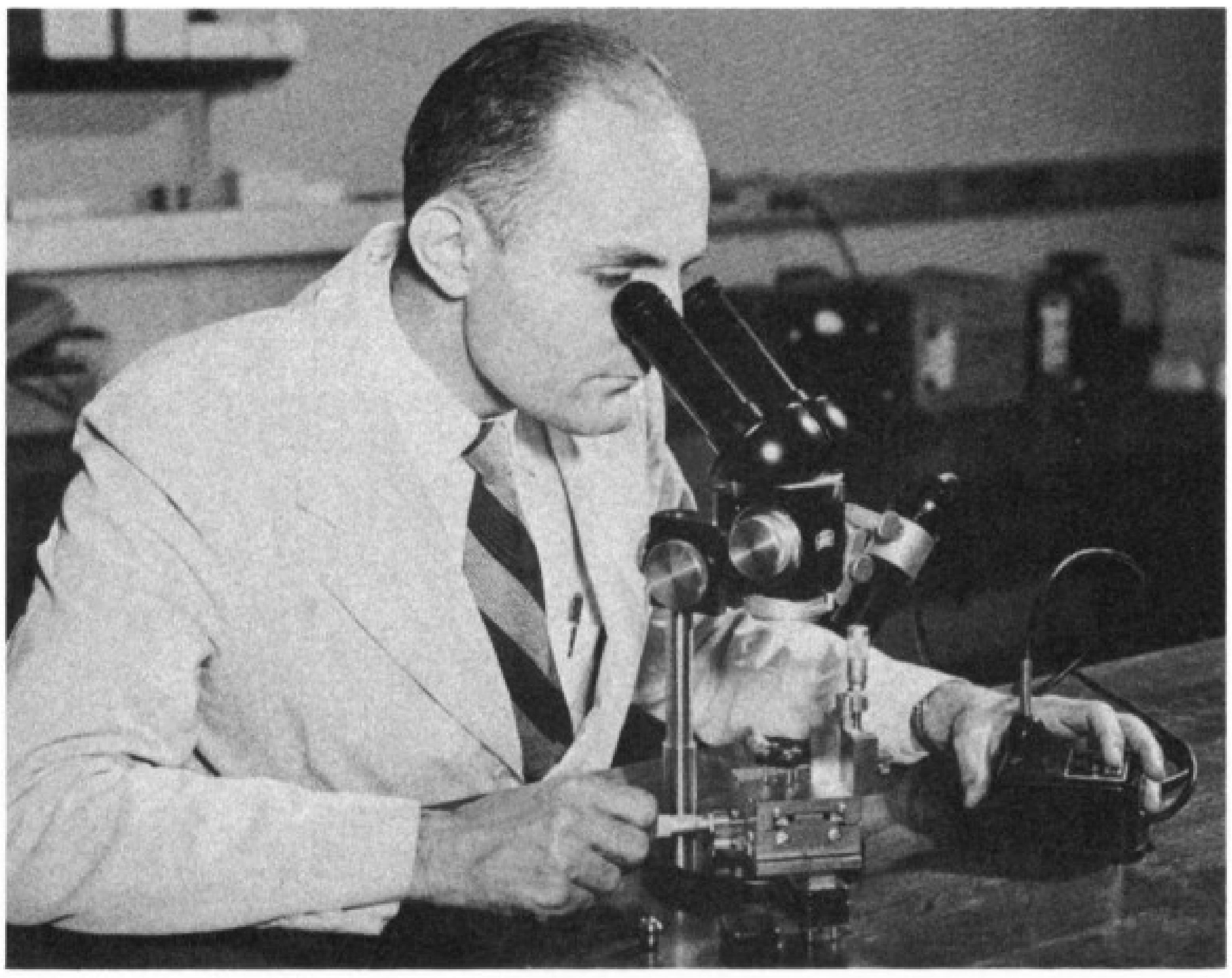
In the 25 years following the invention of the transistor, Bell Laboratories scientists and engineers continued to advance solid-state technology, with developments in materials processing and device fabrication, as well as in new devices. Here are some of their major innovations—as described in the Bell Laboratories RECORD.

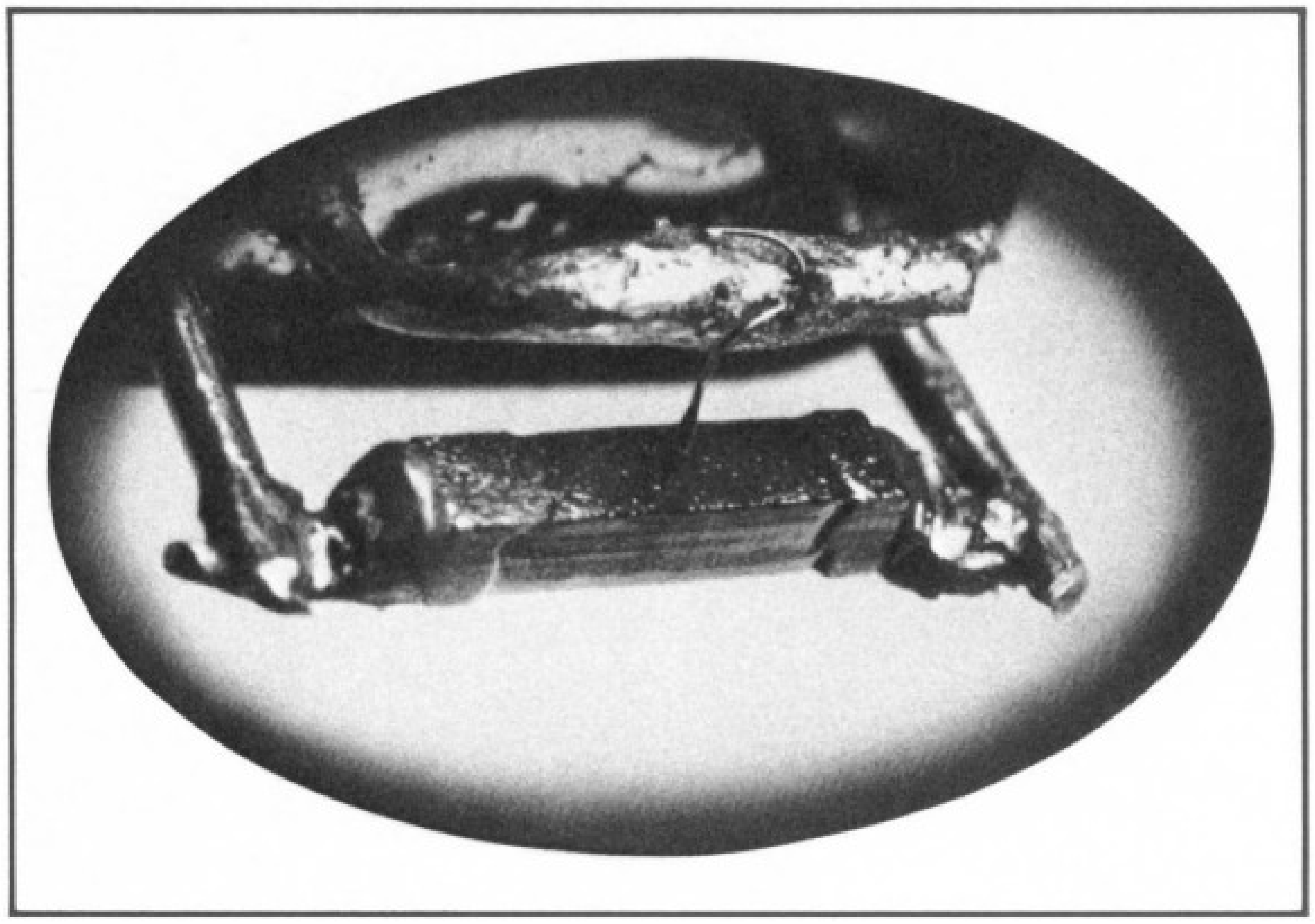
Point-contact transistor. *"An amazingly simple device, capable of performing efficiently nearly all the functions of an ordinary vacuum tube, was demonstrated publicly for the first time on June 30 (1948) in the auditorium of Bell Labs' West Street, New York location. Known as the transistor, the device works on an entirely new physical principle discovered in the course of fundamental research into the electrical properties of solids. Although the device is still in the laboratory stage, it is expected to have far-reaching significance in electronics and electrical communication."* (August, 1948). *Right, one of the first experimental transistors, and far right, an early version of a point-contact transistor.*



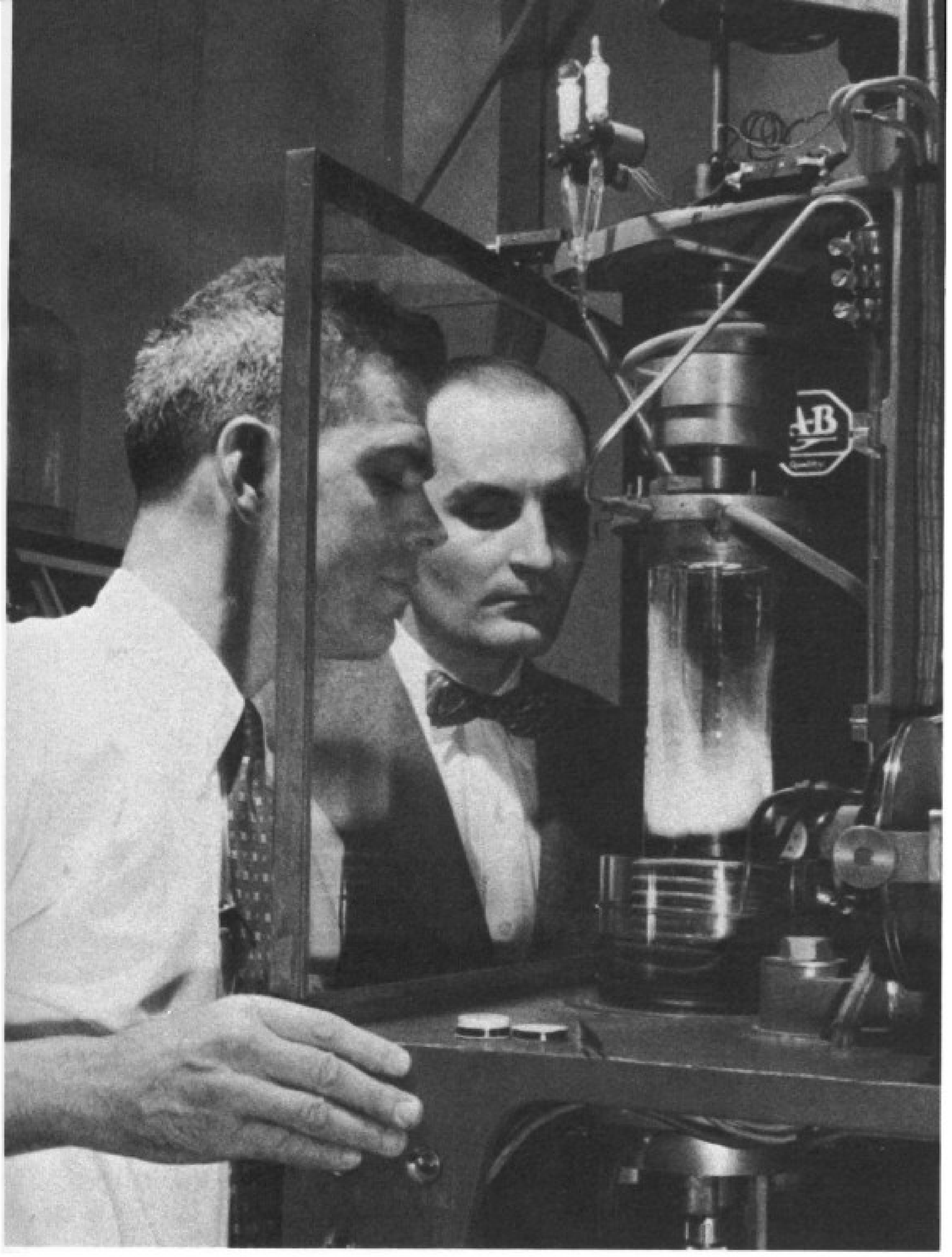


Point-contact transistor. "*The transistor's amplification process can be understood in terms of the discovery of Dr. Bardeen and Dr. Brattain that the input point is surrounded by an 'area of interaction.' Within this area the electronic structure of the semiconductor is modified by the input current. Now, if the output point is placed in this area, the output current can be controlled by the input current. This control of output current by input current is the basic mechanism of amplification.*" *(August, 1948). Left, a sketch used at the first demonstration to help explain the concept of transistor action.*

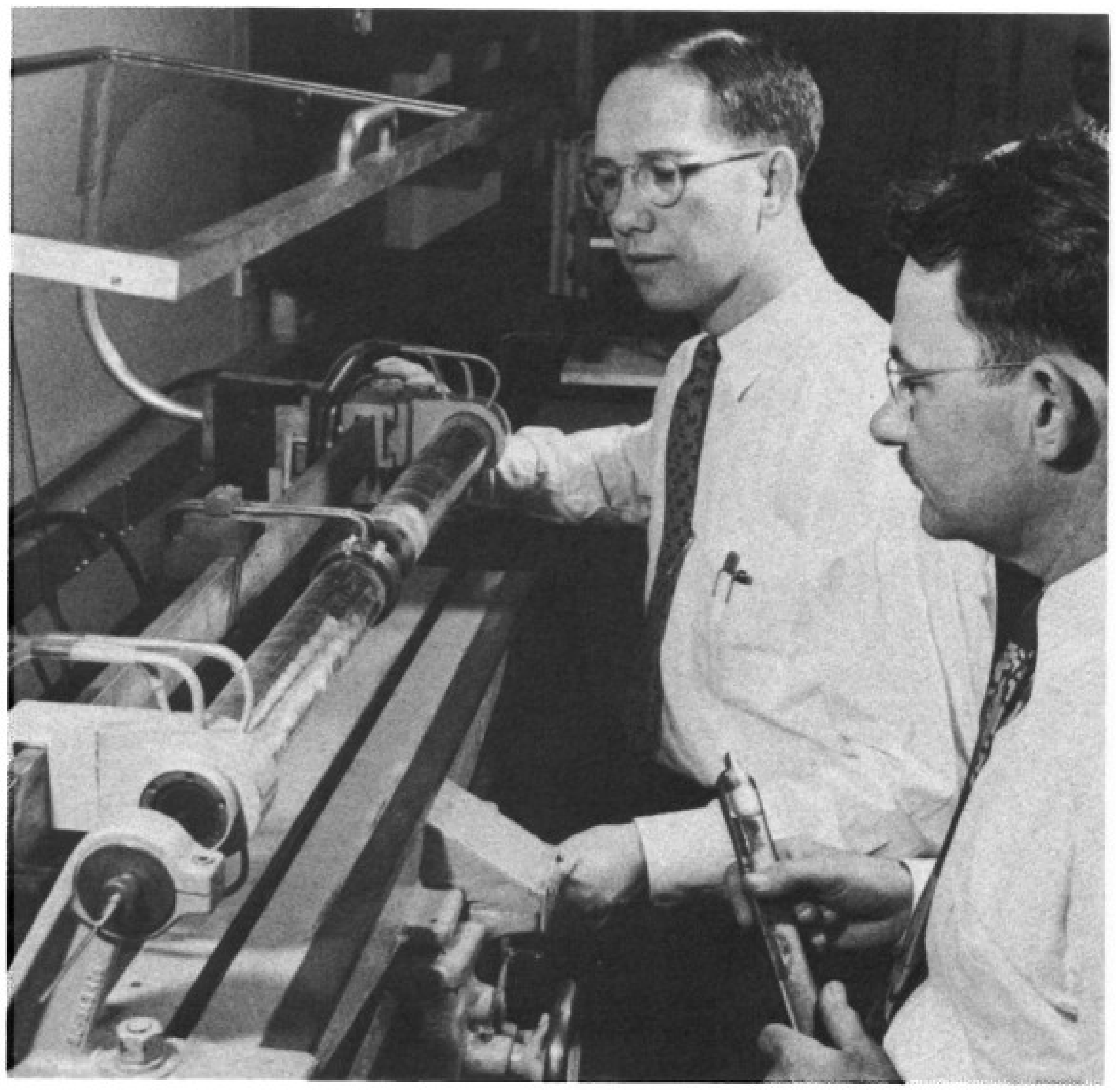




Junction transistor. "*Researchers have now developed a radically new, and in many ways more effective, type of amplifier called a junction transistor. This transistor has no point contacts; instead, it consists of a tiny rod-shaped piece of germanium, treated so that it embodies a thin electrically positive layer sandwiched between the two electrically negative ends. The new transistor, unlike any earlier amplifier, can be operated on about a millionth of a watt, which is just sufficient to carry the signal without waste.*" *(August, 1951). Left, an early version of a junction transistor; left above, Morgan Sparks, one of the device developers, examines a section of germanium to locate a layer having the desired structure and type of conductivity.*

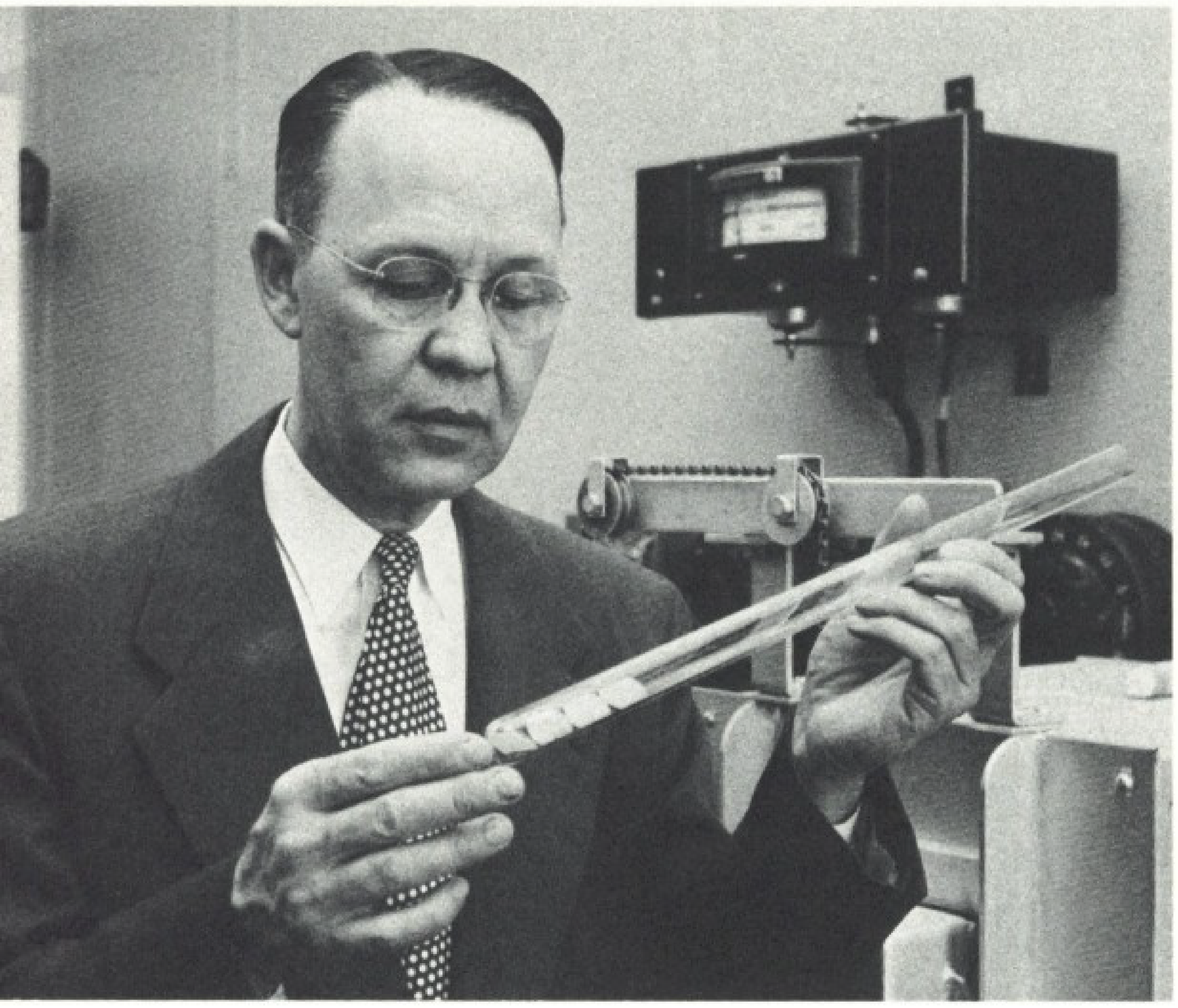


Single-crystal silicon. *"The science learned with germanium predicted that p-n junctions built into very pure silicon single crystals would perform many functions for which germanium was not ideally suited: for computers and switching elements, for solar-energy conversion, and for all kinds of transistor action at higher temperatures. To apply this new knowledge to devices, the first successful step was taken by G. K. Teal and Ernest Buehler, who grew silicon single crystals." (June, 1954). Above, Ernest Buehler and Morgan Sparks view crystal growth.*

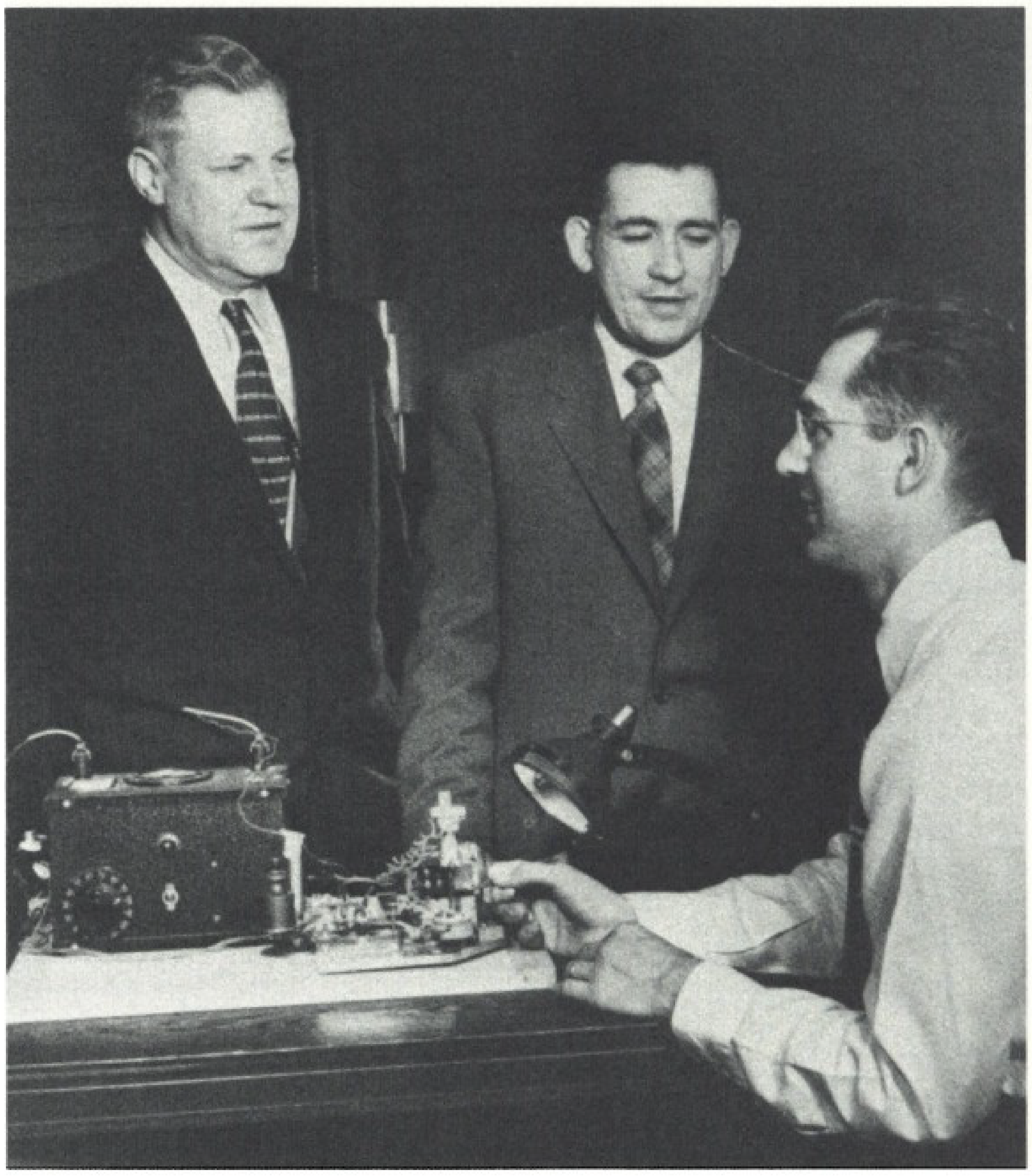


Zone refining. *"Faced with the challenge of supplying single-crystal germanium of ultra-high purity for the transistor, metallurgists at Bell Laboratories devised a new approach. The method of zone refining consists of slowly passing a series of molten zones through a relatively long charge, or ingot, of impure solid. As a molten zone advances, impure solid melts at its leading interface, and purified solid freezes at its trailing interface. Each molten zone which passes through the charge carries a fraction of the impurity toward the end of the charge. The purification increases with the number of zone passes. Germanium purified by zone refining is probably the purest known manufactured material." (June, 1955). Above, W. G. Pfann, left, inventor of the process, is shown operating the equipment while J. H. Scaff, who was closely associated with the development of zone refining, holds a large single crystal of germanium that was purified by this basic technique.*

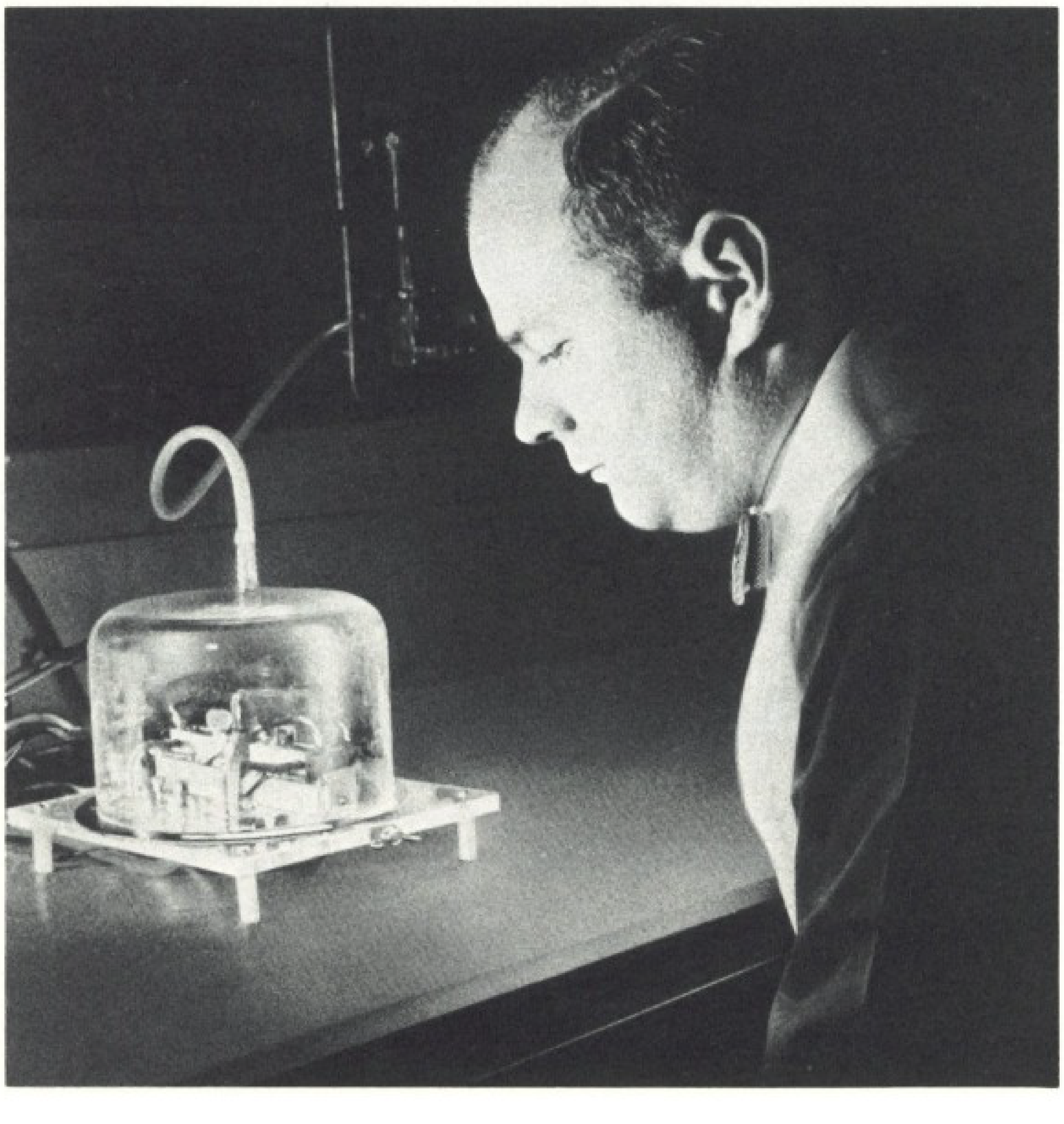
Bell solar battery. *"New silicon devices for use in communications, including the Bell solar battery—the first successful device to convert useful amounts of the sun's energy directly and efficiently into electricity—were demonstrated by Bell Laboratories late in April at the annual meeting of the National Academy of Sciences in Washington. In its present experimental form, the solar battery can achieve a six percent efficiency in converting sunlight into electricity. This approaches the efficiency of steam and gasoline engines, in contrast with other photoelectric devices which have never achieved more than one percent. Developed by a three member team of Bell Laboratories scientists—G. L. Pearson, C. S. Fuller and D. M. Chapin, physicist, chemist, and electrical engineer, respectively—the experimental device uses strips of silicon about the size of razor blades." (June, 1954). Left, G. L. Pearson, D. M. Chapin and C. S. Fuller examine the response of experimental devices.*



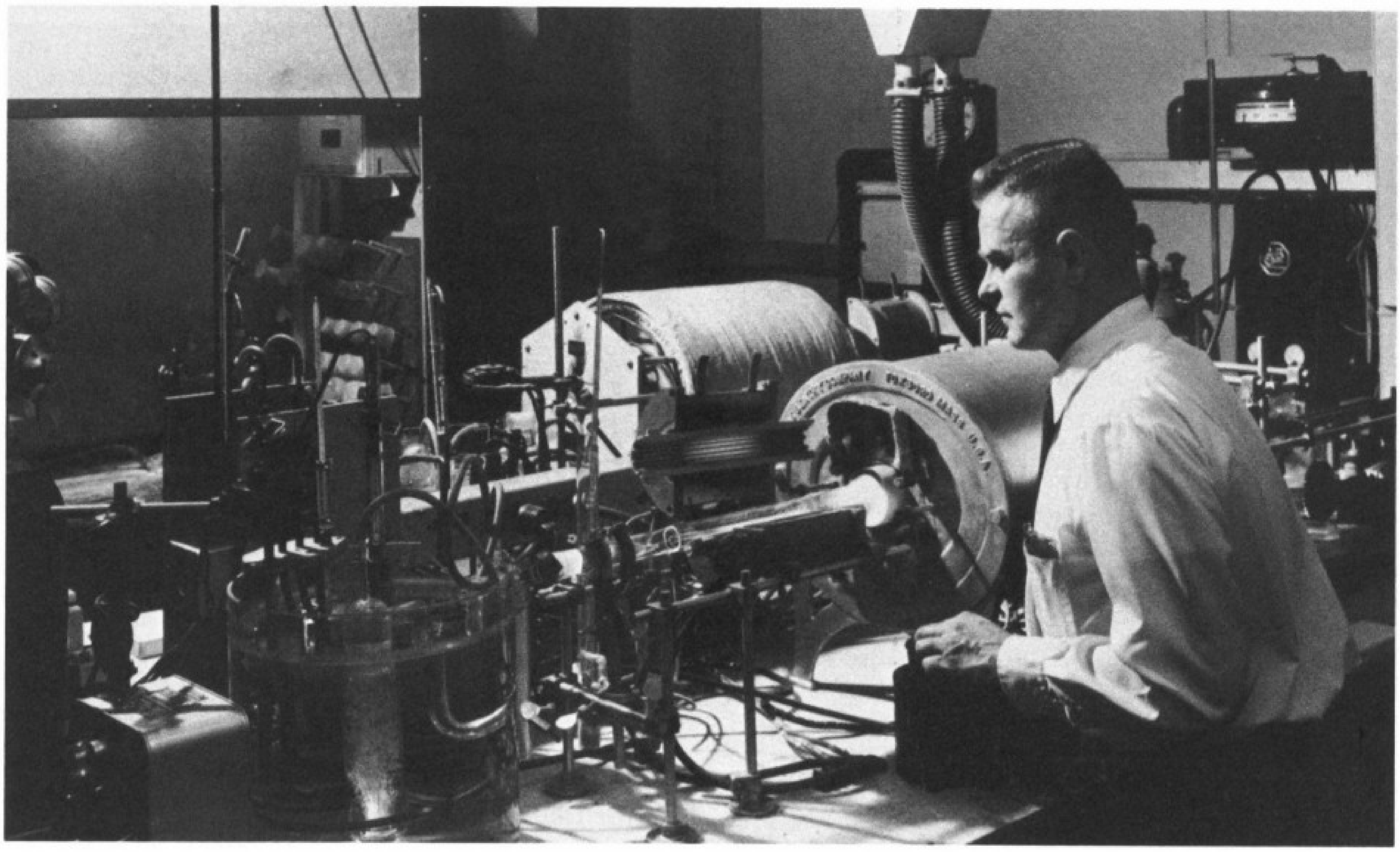
Diffusion. *"A technique developed by C. S. Fuller, which has been successfully used in a variety of silicon devices, consists of the preparation of p-n junctions by diffusing impurities into the surface of a silicon wafer. These diffusion techniques show great promise of being widely applicable to many kinds of semiconductor devices made from both germanium and silicon. The process consists simply of heating the semiconductor wafer in the presence of a suitable impurity vapor. In this way, p- or n-type layers of controlled thickness are formed just below the semiconductor surface." (June, 1954). Above, C. S. Fuller holds a tube used to prepare silicon for the Bell solar battery.*



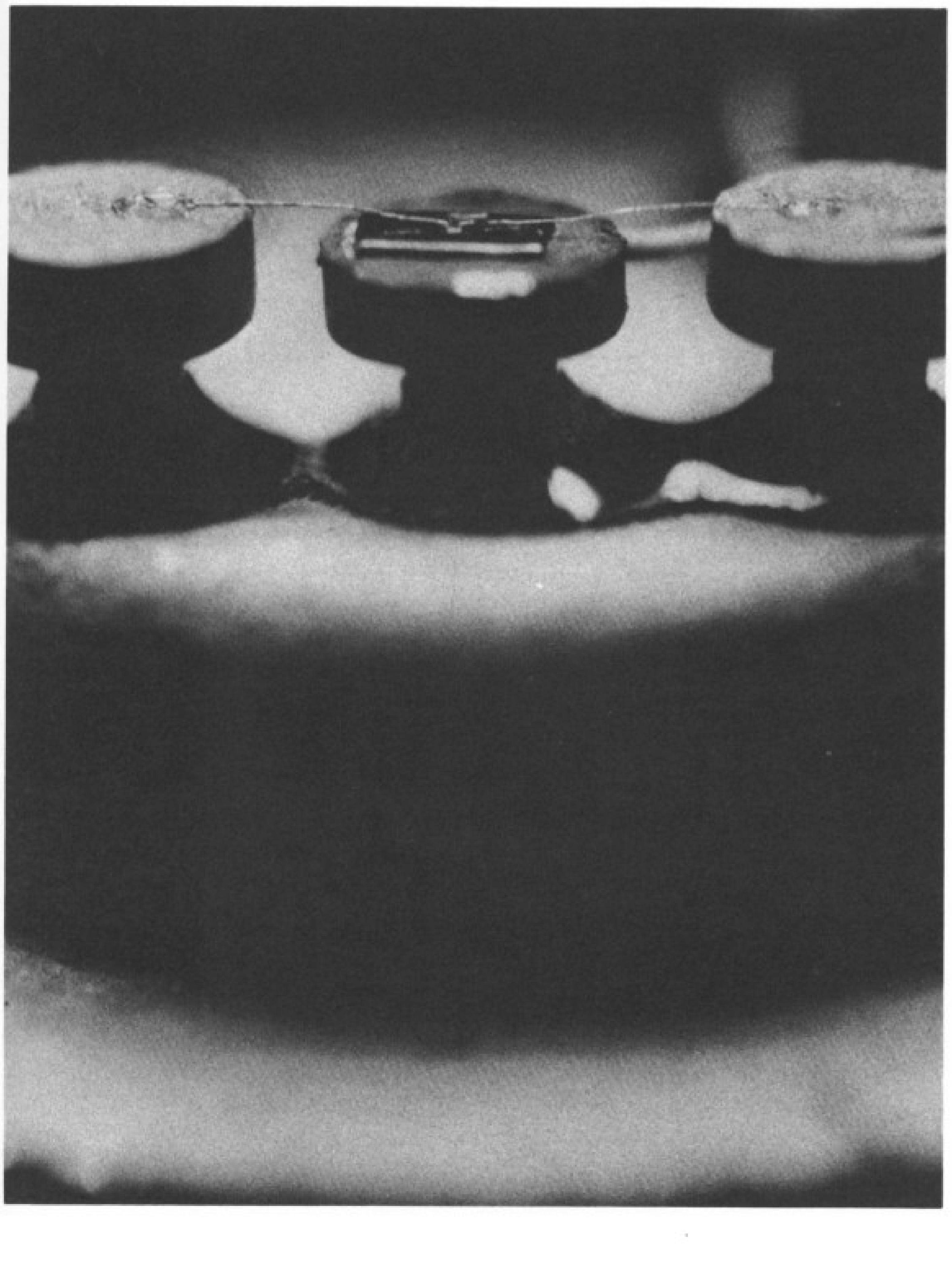
Thermocompression bonding. *"A significant break-through in the technique of attaching electrical leads to semiconductor devices has been achieved at Bell Laboratories. Research by O. L. Anderson, H. Christensen, and P. Andreatch has shown that a combination of heat and pressure can be employed to provide a firm bond between various soft metals and clean, single-crystal semiconductor surfaces. Called thermocompression bonding, the new technique provides a bond that is stronger than the lead itself. Temperatures and pressures required are not high enough to affect the properties of the semiconductor." (September, 1957). Above, O. L. Anderson, H. Christensen, and P. Andreatch are shown with the experimental equipment.*



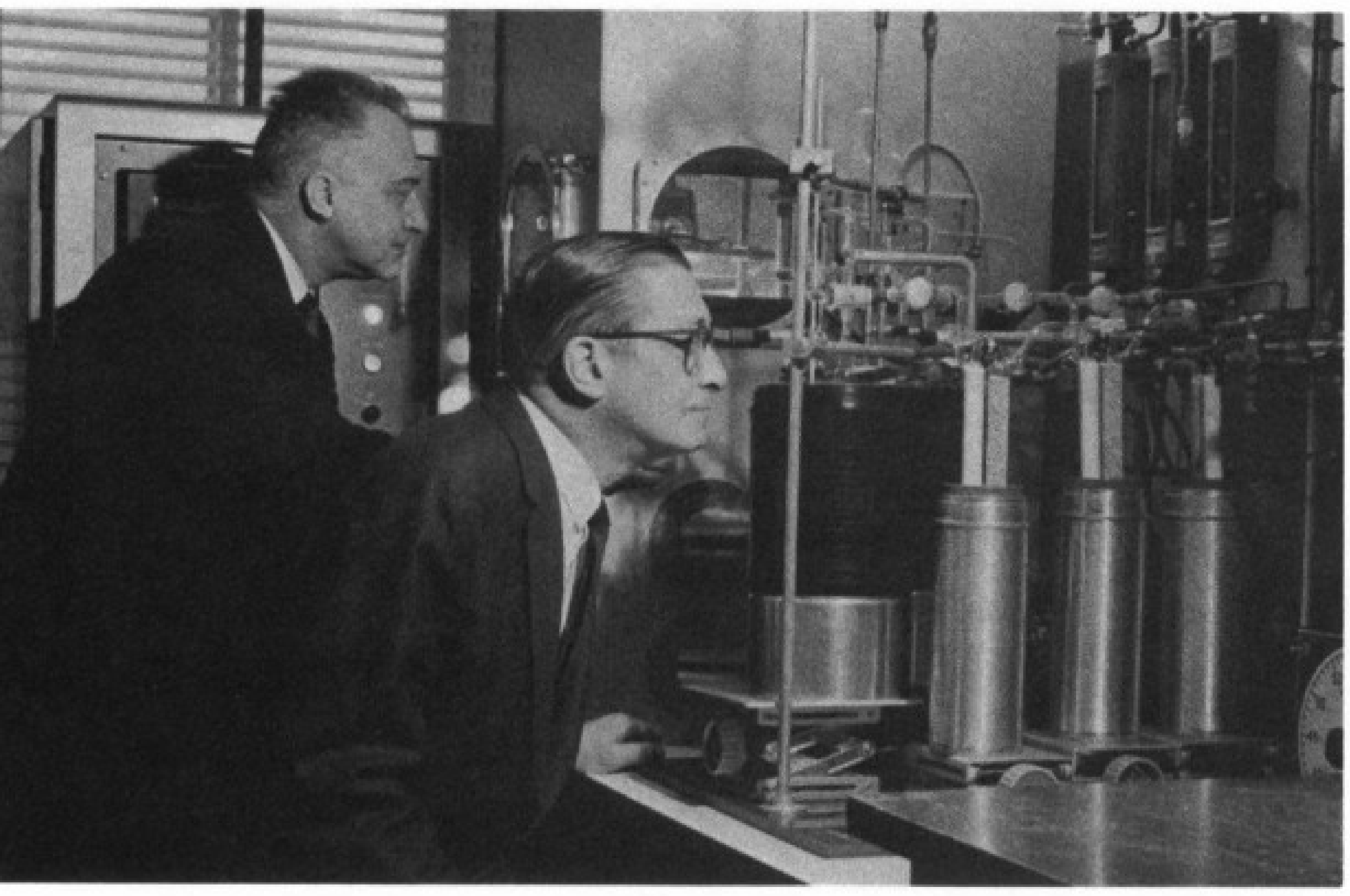
Junction field-effect transistor. *"The 'field-effect' transistor is one of the latest additions to the transistor family. Although it operates on a principle quite different from that of the point-contact or junction type, it is capable of performing many of the same functions such as amplification or oscillation, and it has the advantages of small size and low power consumption common to the others. Field-effect transistors have been made at Bell Laboratories and in every respect their performance has been found to be in good agreement with theory." (May, 1955). "FET's using a reverse-biased p-n junction as the control electrode were proposed by W. Shockley in 1952 and later fabricated by G. C. Dacey and I. M. Ross." (September, 1968). Left, P. W. Foy operating a heater used in making junction FET's.*



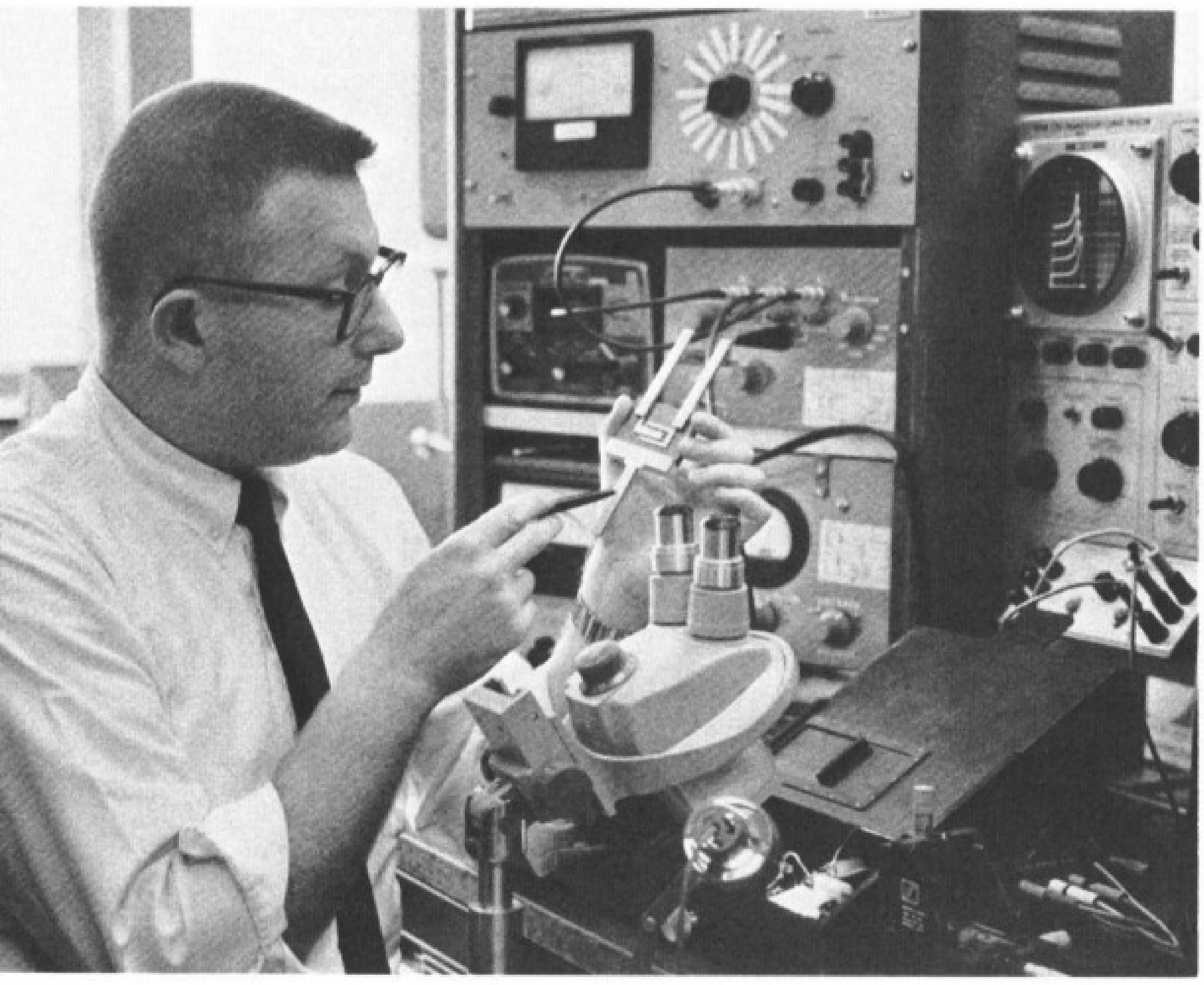
Oxide masking. "*Oxide masking is a proven process step for a new silicon transistor currently in production at the Western Electric Company at Allentown, Pennsylvania. In the oxide masking technique, silicon dioxide is used to mask silicon from certain impurity diffusants, while permitting others to pass through. Masking is basically a simple process that is economical and compatible with mass production. Therefore, it can take its place with those techniques required to meet industry's demands for transistors.*" *(November, 1960). Above, L. Derick observes a masking set-up.*

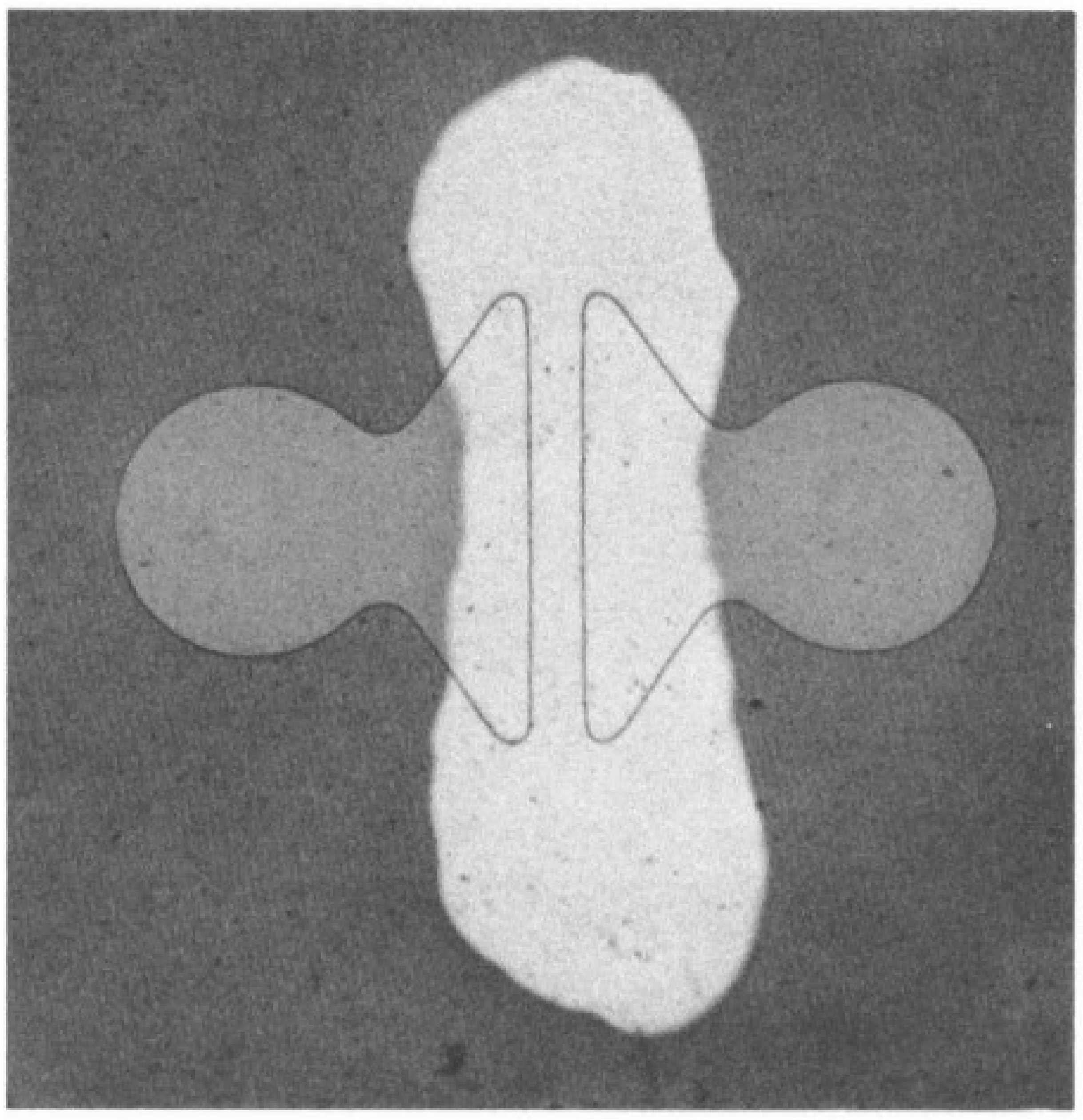


Diffused-base transistor. "*A major advance in transistor technology—new fabricating techniques for an entirely new kind of transistor, technically known as the diffused-base transistor—was recently announced by Bell Laboratories. The new techniques involve the adaptation of the chemical process of diffusion used in treating silicon for the Bell solar battery. Diffusion is a process by which controlled minute amounts of impurities are introduced into a material. In the new transistor, an impurity is introduced only once into the growing crystal. The fully grown crystal receives two other doses of impurity in easily controlled diffusion processes.*" *(February, 1956). Left, an early diffused-base germanium transistor.*



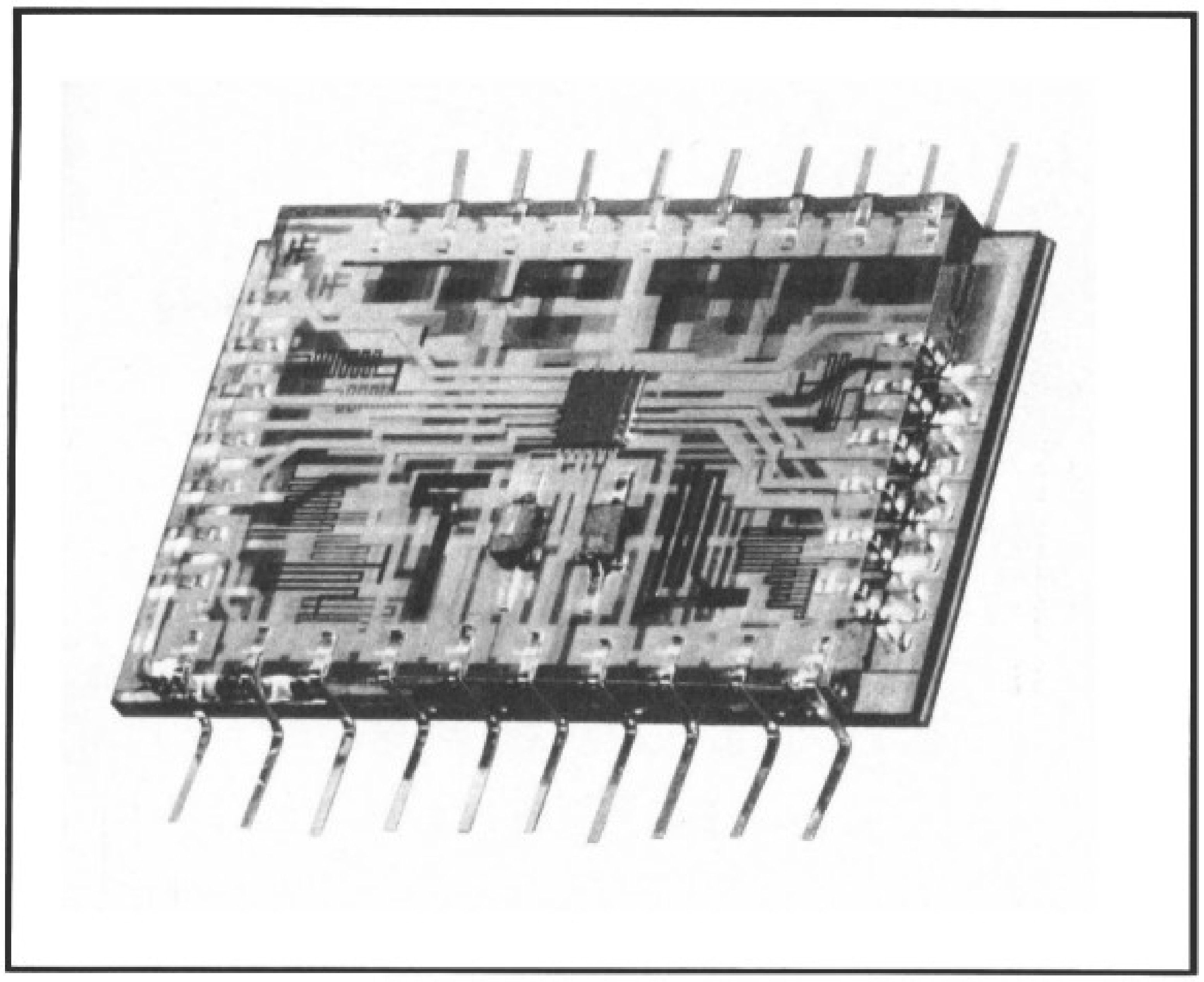
Epitaxy. "Research at Bell Laboratories has recently brought about major improvements in the diffused-base transistor through the use of the epitaxial technique. Epitaxial films—those formed on the surface of a crystal—are identical to the crystal in structure of the lattice. These films have made possible silicon transistors whose switching times are less than a tenth of those made previously, and which have a comparable reduction in the collector resistance. The development is expected to have far-reaching implications in both the fabrication and application of semiconductor devices. The addition of the epitaxial film technique to the well established diffusion technology gives the device engineer an extra degree of freedom in design which should result in new devices, formerly difficult or impossible to achieve." (July, 1960). Above, Joseph J. Kleimack, left, and Henry C. Theuerer observe epitaxial growth.



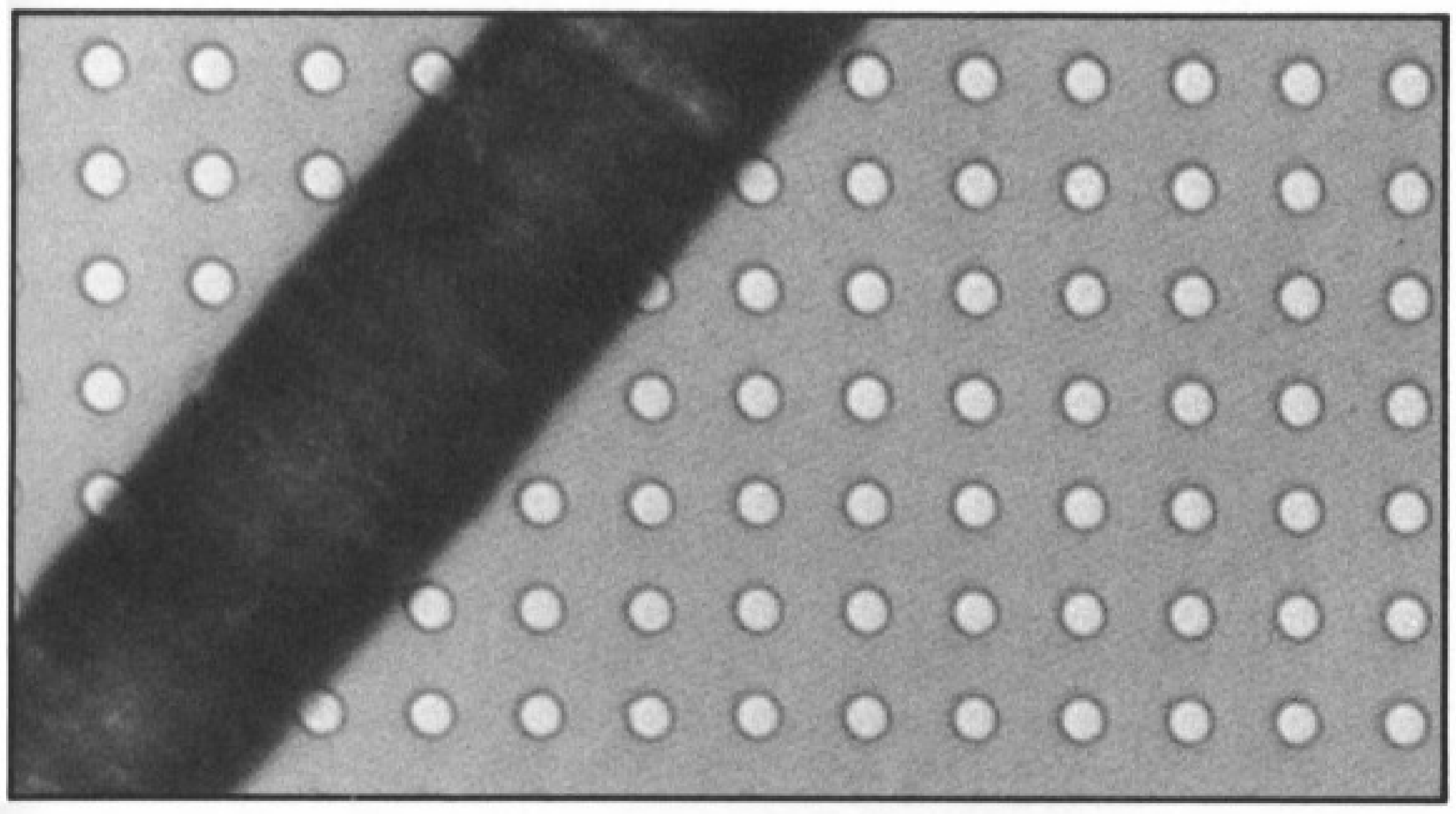


Insulated-gate field-effect transistor. "In the late 1950's and early 1960's, advances in silicon transistor technology paved the way for the insulated-gate field-effect transistor (IGFET). The control electrode, or gate, in this device is a metallic film applied to the surface of the semiconductor but separated from it by a thin layer of insulating material. D. Kahng and M. M. Atalla, both of Bell Laboratories, reported the first IGFET in 1960. It is possible to fabricate many IGFET's simultaneously on the same substrate without having to perform an operation to isolate them from each other. A number of highly complex circuits are now under development for Bell System applications. These include shift registers and memory arrays containing up to several hundred components per chip and operating up to several megahertz." (September, 1968). Above, a magnified view of one of the first silicon insulated-gate FET's that use silicon dioxide as the insulator.

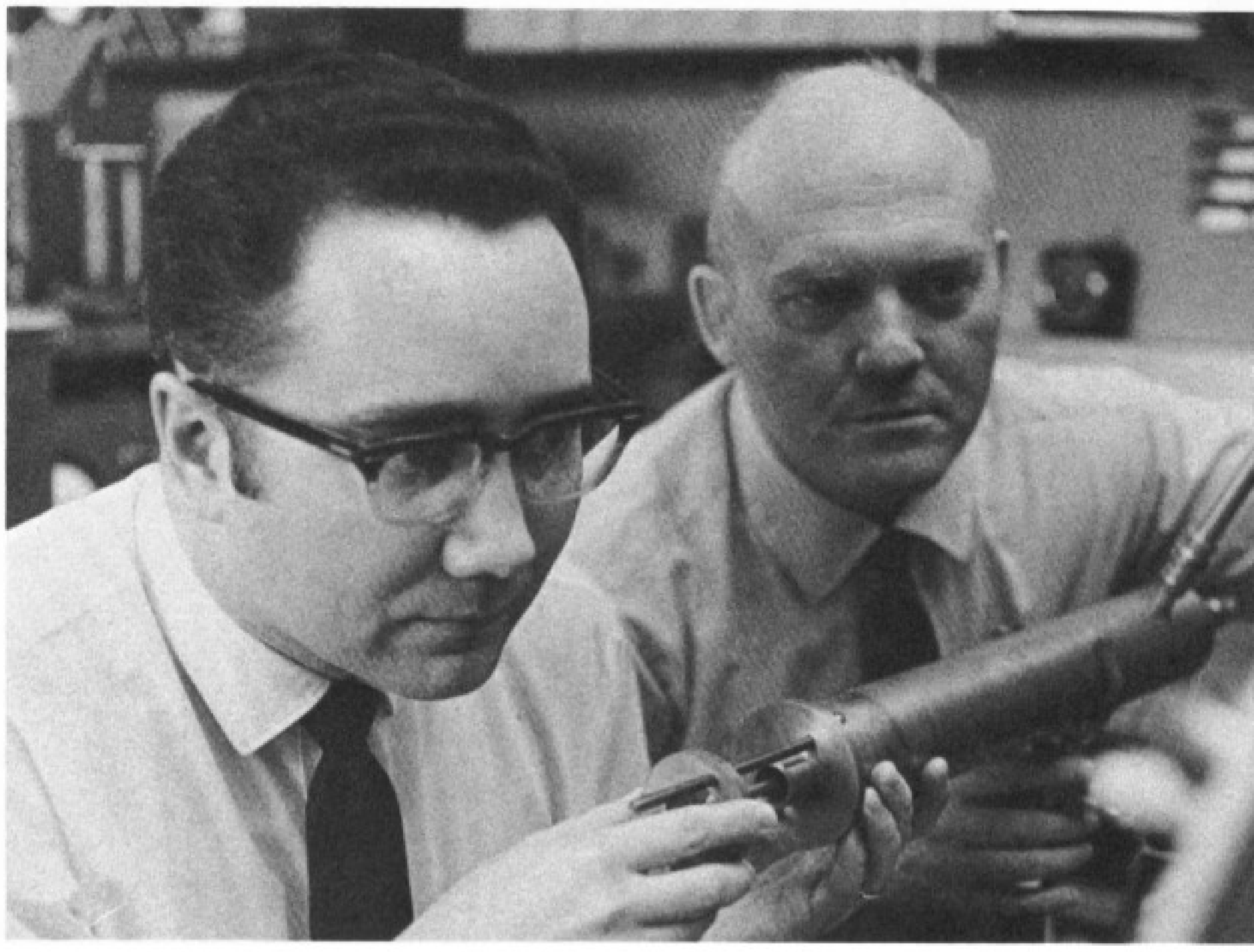
Beam-lead, sealed-junction device. "A new type of structure for semiconductor devices and circuits has been devised at Bell Laboratories. The structure uses strong electrical leads—called beam leads—to provide mechanical support for the semiconductor and to make electrical connections. This development is expected to simplify fabrication and assembly procedures for many types of semiconductor devices and circuits—including transistors, diodes, and integrated circuits. Beam leads are integral parts of the devices and circuits and extend out from the structure like cantilever beams." (January, 1965). Left, M. P. Lepselter holds a model of a beam-lead transistor.



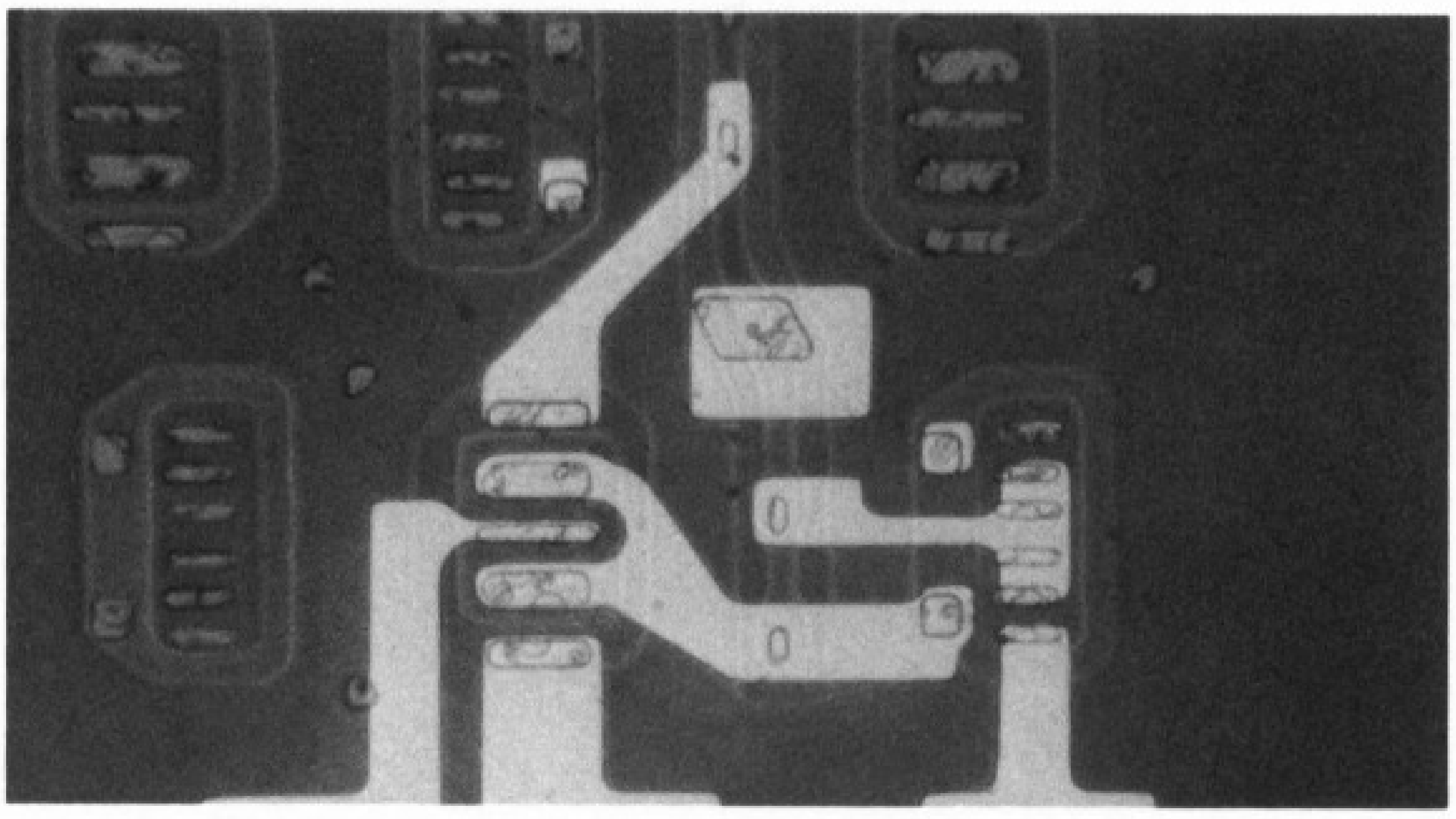
Hybrid integrated circuit. *"Beam-lead, sealed-junction chips containing many components will be interconnected with thin-film circuits, thereby eliminating complex wiring and bulky circuit boards. This will lower costs, improve performance, increase reliability, and save space. In addition, as the fabrication costs decrease, it will become economical to eliminate such outsize components as transformers, inductors, and large capacitors." (October-November, 1966). Above, a hybrid integrated circuit used for tone generation in the* TOUCH-TONE® *set.*



PICTUREPHONE® camera tube target. *"A new camera tube for the* PICTUREPHONE® *visual telephone combines some of the best features of the 'old' and the 'new' arts of electron device design. From electron tube technology it takes the low cost and simplicity of electron beam scanning; from integrated circuit technology, the reliability and sensitivity of a silicon photodiode array. The target structure is an array of reverse-biased diodes on a silicon wafer about the size of a nickel. A typical array contains close to 300,000 individual diodes. The result is a vidicon-type camera tube far more sensitive than any now being used." (June, 1967). Above, an enlarged portion of the image-sensing area with a human hair shown for comparison.*



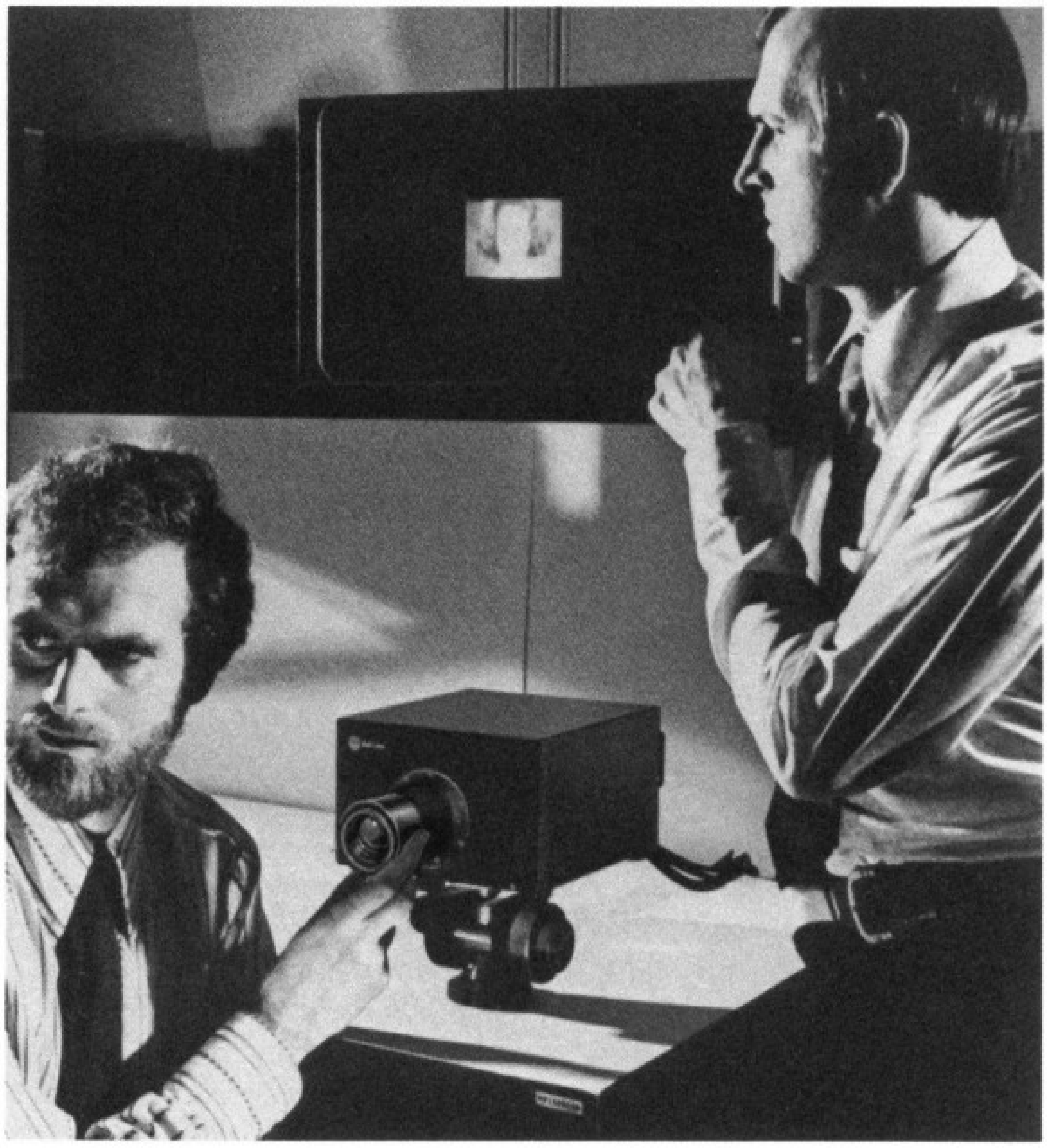
IMPATT. *"Researchers have sought a usable solid-state source of microwave frequencies for many years. One of the most promising devices so far developed is the IMPATT (IMPact Avalanche and Transit Time) diode. There are three basic IMPATT diode structures: the Read diode (proposed in 1958 by W. T. Read of Bell Labs), the p-i-n diode, and the p-n junction. IMPATT operation was first achieved in 1964, at Bell Labs, using a p-n junction diode." (May, 1967). Above, Bernard C. DeLoach and Ralph L. Johnston adjust an IMPATT power source.*



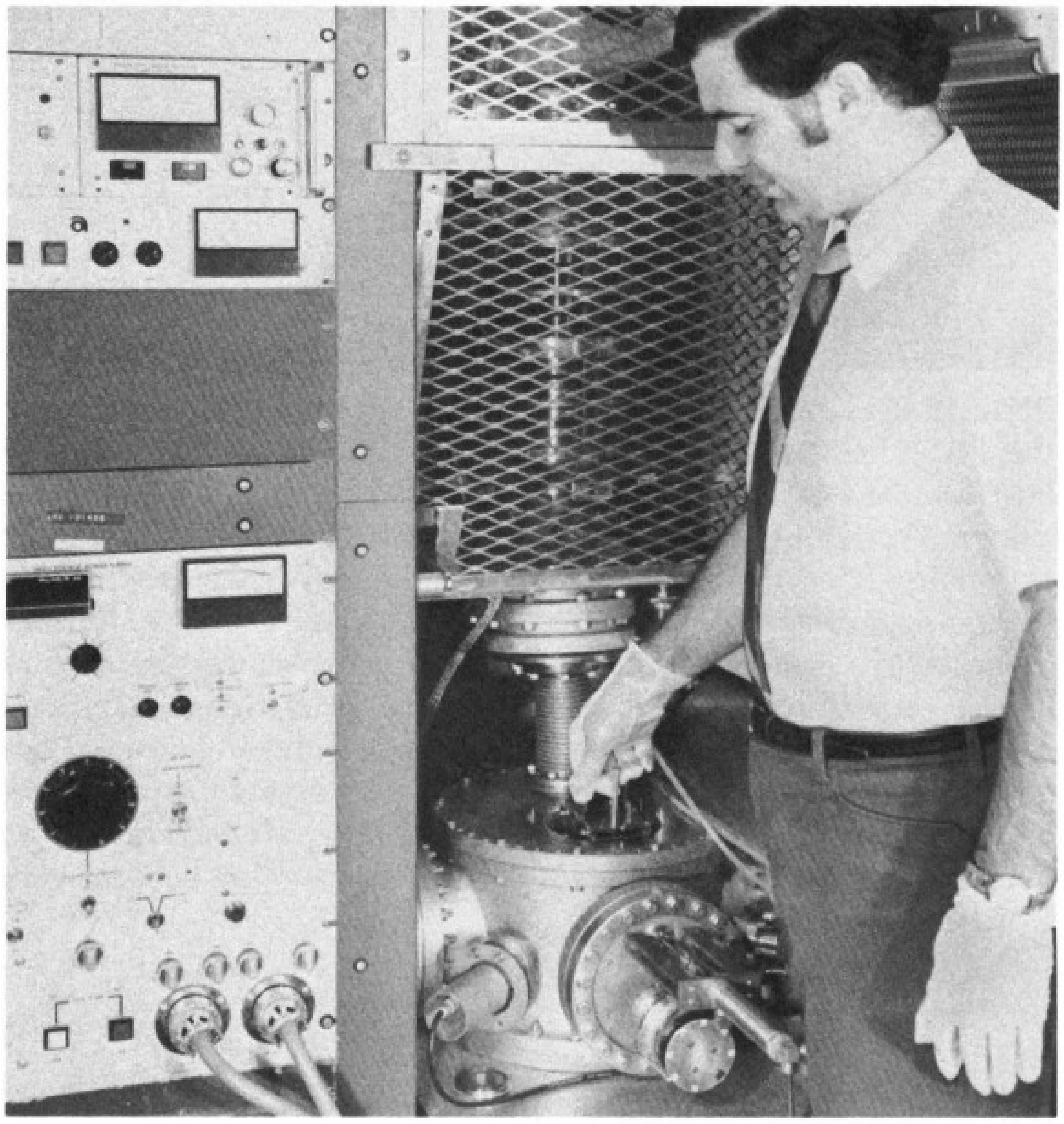
Collector diffusion isolation. *"New structures that promise to reduce the cost of bipolar integrated circuits have been developed at Bell Labs. In all integrated circuits, the individual components have to be electrically isolated. In the past this has been done in bipolar structures with special processing steps. Naturally, these processing steps raise the cost of the circuits. Bell Labs scientists have found new ways of making bipolar circuits without the extra steps. Instead, components are isolated as an integral part of the process of making them. The first of the new methods is called collector diffusion isolation (CDI). With CDI, costly operations are eliminated." (April, 1969). Above, an enlarged portion of an integrated circuit made with CDI.*

Primary Pattern Generator. *"Bell Laboratories engineers have designed and developed an entire system to create the masks that are used in the fabrication of integrated circuits. The system features a computerized laser in a high-speed scan to 'write' the primary patterns for the masks. The new system includes a primary pattern generator (PPG) which gives a combination of speed and precision exceeding anything previously used in mask making. It takes the PPG about 10 minutes to write a pattern, or small array of patterns, on a photosensitive glass plate. Loading the pattern plate on the PPG and taking it off when the pattern is complete takes another two minutes. Many of the new complex interconnection patterns, while requiring only 12 minutes on the PPG, would take 24 hours with the previous method." (May, 1970). Above, Alfred Zacharias shows an integrated circuit mask made in minutes by the PPG.*

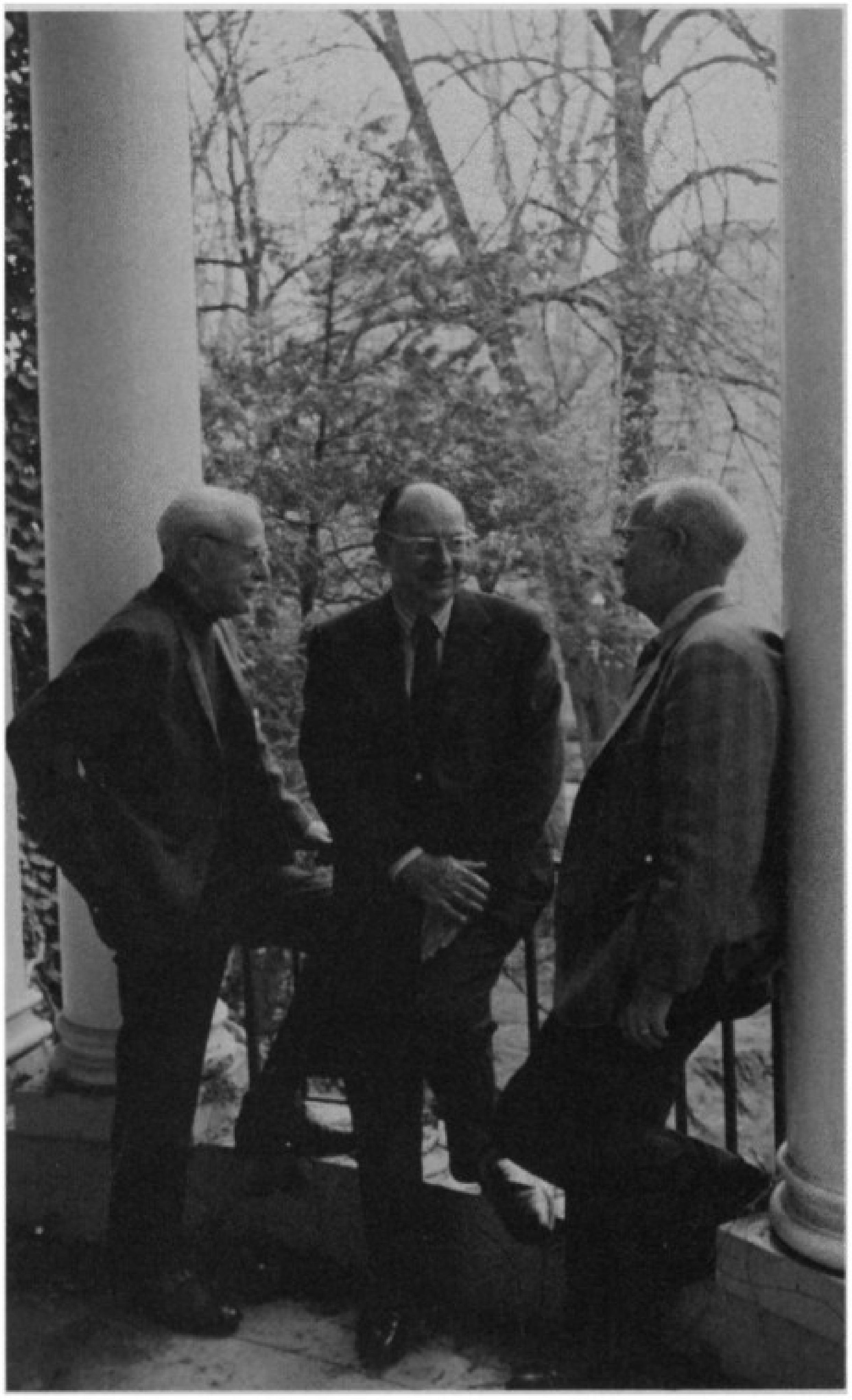
Ion implantation. *"Schottky-barrier diodes may be the key to faster, low-power, integrated circuit memories and other logic circuits in economical, small packages. The low and high energy diodes are formed on lightly doped p- and n-type silicon, respectively. The desired doping levels can be attained by bombarding the silicon with boron or phosphorus ions in a process known as ion implantation." (July, 1969). Right, A. U. MacRae inserts semiconductor wafers into the implantation chamber of Bell Laboratories ion implantation equipment, which is being used to form semiconductor devices with electrical characteristics superior to those obtained by conventional impurity diffusion techniques.*



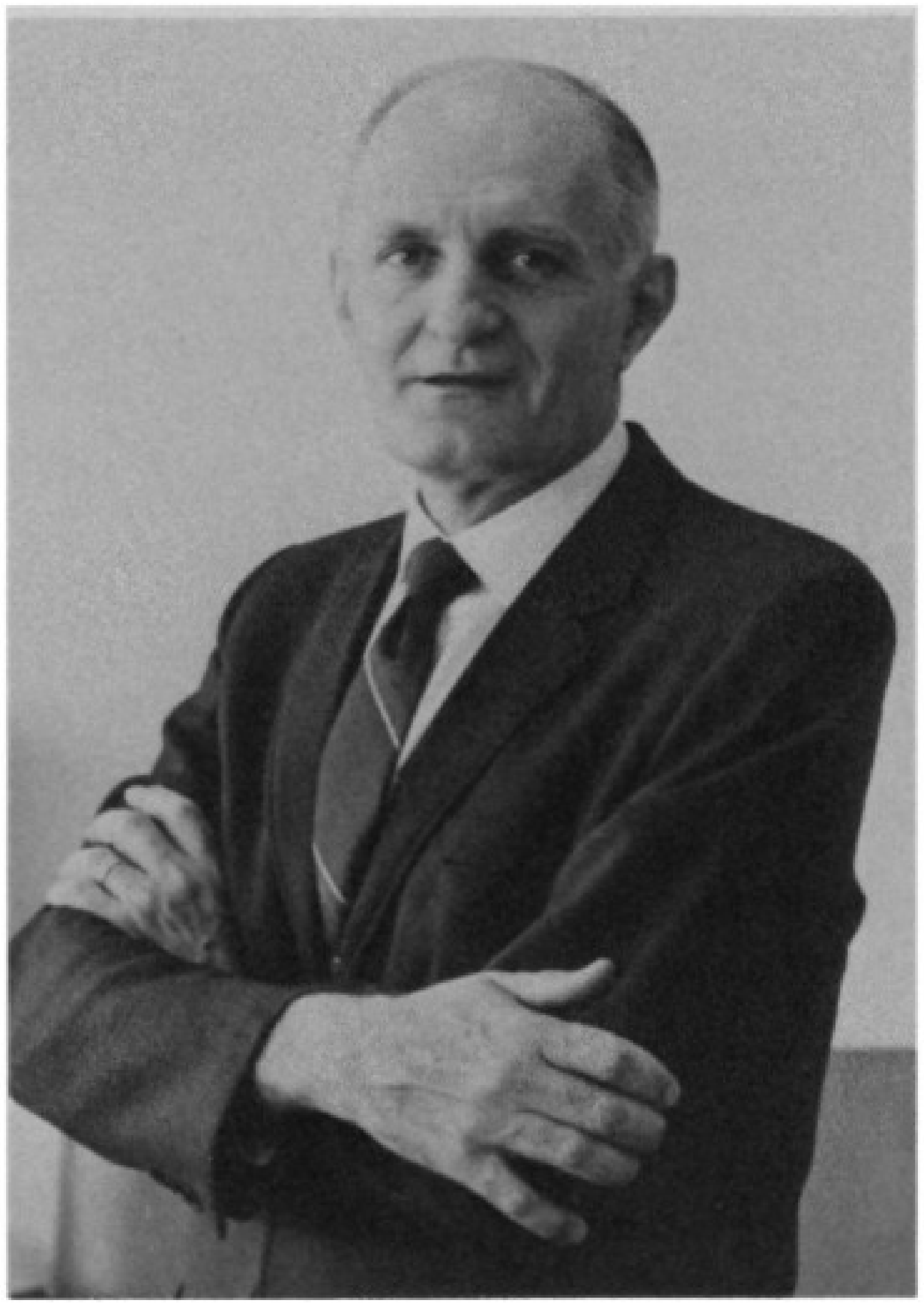
Charge-coupled device. *"Scientists at Bell Laboratories have created a new class of simple semiconductor devices. Called Charge-Coupled Devices (CCD's), these three-layer structures can be used for imaging, logic, and memory functions. According to the inventors, W. S. Boyle and G. E. Smith, the ultimate usefulness of the CCD's is still difficult to assess. As a result of the CCD's inherent simplicity, small size, and fewer critical processing steps, the cost of information processing may be reduced." (June/July, 1970). Above, Michael Tompsett and Edward Zimany test a color TV camera using CCD image sensors.*



THE AUTHORS



Walter H. Brattain *William Shockley*
John Bardeen



Morgan Sparks

John Bardeen received the 1956 Nobel Prize in Physics jointly with William Shockley and W. H. Brattain for their contributions to transistor physics. He joined Bell Labs in 1945 as a research physicist and was co-inventor with Mr. Brattain of the point-contact transistor. In 1972, he received his second Nobel Prize in Physics, jointly with L. N. Cooper and J. R. Schrieffer, for a theory of superconductivity.

He received the B.S. and M.S. degrees in 1928 and 1929 from the University of Wisconsin and the Ph.D. in 1936 from Princeton University. He is the recipient of honorary Doctor of Science Degrees from Rose Polytechnic Institute, Western Reserve, Princeton University, Union College, the University of Wisconsin, and Rensselaer Polytechnic Institute and of honorary LL.D. degrees from the University of Glasgow and the University of Notre Dame.

He is a Fellow, and former President, of the American Physical Society and a member of the National Academy of Sciences, the American Association for Advancement of Science, the American Academy of Sciences, and the American Philosophical Society. Mr. Bardeen served on the President's Science Advisory Committee from 1959 to 1962 and currently is Professor of Electrical Engineering and Physics at the University of Illinois. He also serves as consultant and member of the Board of Directors for Xerox Corp.

Walter H. Brattain joined Bell Labs in 1929 as a research physicist in the field of surface properties of solids and subsequently worked in the field of semiconductor surfaces. These studies resulted ultimately in the invention, with John Bardeen, of the point-contact transistor. For this invention and other contributions to the field of physics he was awarded, jointly with John Bardeen and William Shockley, the 1956 Nobel Prize in Physics.

Mr. Brattain received the B.S. degree in Physics and Mathematics in 1924 from Whitman College, the M.A. in 1926 from the University of Oregon, and the Ph.D. in 1929 from the University of Minnesota. He has been awarded honorary Doctor of Science degrees from Portland University, Whitman College, Union College, the University of Minnesota, Gustavus Adolphus and the L.H.D. from Hartwick College.

During World War II, he was associated with the National Defense Research Committee at Columbia University. He is a member of the National Academy of Sciences, the Franklin Institute, Phi Beta Kappa, and Sigma Xi and is a Fellow of the American Physical Society, the American Academy of Arts and Sciences, and the American Association for Advancement of Science.

William Shockley, presently serving as Executive Consultant to Bell Laboratories, is the inventor of the junction transistor. He joined the Bell Labs staff in 1936 and, after serving with the U. S. Navy in antisubmarine warfare research during World War II, became co-head of the solid-state physics research program. As the result of his work in this area he received, jointly with John Bardeen and Walter Brattain, the 1956 Nobel Prize for Physics.

In 1955 he established Shockley Semiconductor Laboratory at Palo Alto, California, which subsequently became a subsidiary of Beckman Instruments. He continued his work in the transistor field with Clevite Transistor until 1965.

Mr. Shockley has served as visiting lecturer at Princeton University and California Institute of Technology and became the first Alexander M. Poniatoff Professor of Engineering Science at Stanford University in 1963. He has contributed to several scientifically oriented groups within the armed services and was awarded the Air Force Association Citation of Honor. He has received honorary Doctorate Degrees from the University of Pennsylvania, Rutgers University and Gustavus Adolphus College. He has been awarded more than 70 patents, has contributed many articles to scientific journals, and is the author of the book *Electrons and Holes in Semiconductors* (1950). He is a Fellow of the IEEE and of the American Academy of Arts and Sciences. He received the Bachelor of Science degree from the California Institute of Technology in 1932 and the Ph.D. from the Massachusetts Institute of Technology in 1936.

Morgan Sparks, former Vice President, Electronics Technology of Bell Laboratories, is now President of Sandia Corporation, a Western Electric subsidiary.

Mr. Sparks joined Bell Labs in 1943 and for five years engaged in electrochemical research on primary batteries, electrolytic capacitors and rectifiers. In 1948 he entered the field of semiconductor research, specializing particularly in research into the properties of PN junctions and junction devices.

He was appointed Director of Solid State Electronics Research in 1955; Director of Transistor Development in 1958; Executive Director, Components and Solid State Device Division in 1959; Executive Director, Semiconductor Components, Electronic Materials and Processes in 1966; Executive Director, Semiconductor Components in 1968; Vice President, Technical Information and Personnel in March 1969; Vice President, Electronics Technology in December 1971; and assumed his present position in October 1972.

Mr. Sparks received the B.A. and M.A. degrees from Rice University in 1938 and 1940, respectively. He was awarded a University of Illinois Rockefeller Foundation Fellowship for 1940-42 and received the Ph.D. degree from Illinois in 1943.

He has written numerous technical articles on transistors, PN junctions and the properties of semiconductors, and has been granted ten patents in the general area of semiconductor electronics.

He is a Fellow of the American Physical Society, the Institute of Electrical and Electronics Engineers and the American Institute of Chemists. He is also a member of the American Chemical Society, Phi Beta Kappa, Sigma Xi, Gamma Alpha and Phi Lambda Upsilon.

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