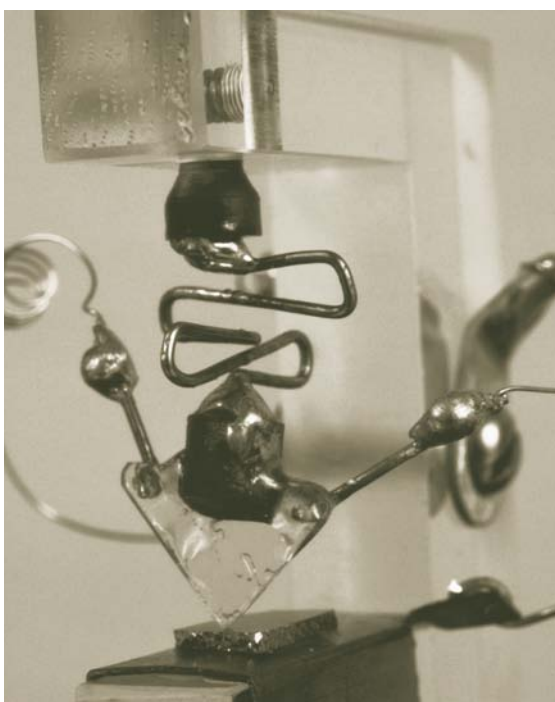
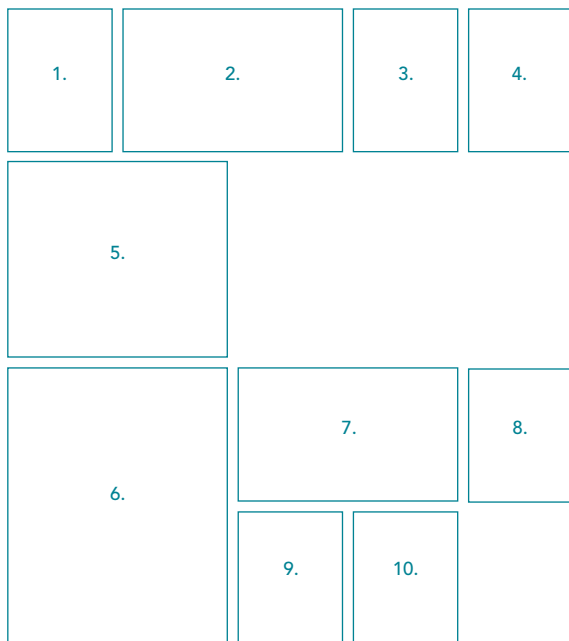


# 50 YEARS OF ELECTRON DEVICES

The IEEE Electron Devices Society  
and Its Technologies

1952-2002





1. **Russell Varian, klystron co-inventor, co-founder of Varian Associates, EDS Administrative Committee Member 1955 - 1956** *(Courtesy of Ansel Adams)*
2. **Early klystron** *(Courtesy of Varian Medical Systems)*
3. **Zhores Alferov, 2000 Nobel Prize "for developing semiconductor heterostructures used in high-speed and opto-electronics"** *(Zhores Alferov)*
4. **Herbert Kroemer, 2000 Nobel Prize "for developing semiconductor heterostructures used in high-speed and opto-electronics"** *(Courtesy of Hans Mehlin, Nobel e-Museum, copyright the Nobel Foundation 2001)*
5. **John Bardeen, William Shockley and Walter Brattain, 1956 Nobel Prize "for their researches on semiconductors and their discovery of the transistor effect"** *(Courtesy of Lucent Technologies Bell Labs Innovations)*
6. **The original point-contact transistor** *(IEEE/EDS)*
7. **An integrated circuit with the silicon dioxide etched away to reveal the metal interconnections** *(Courtesy of Julie Lee and Tom Way, IBM Corporation)*
8. **Leo Esaki, 1973 Nobel Prize "for experimental discovery of tunneling phenomena in semiconductors"** *(Courtesy of IBM Research Division)*
9. **Jack Kilby, 2000 Nobel Prize "for his part in the invention of the integrated circuit"** *(IEEE History Center)*
10. **Bob Noyce, co-inventor of the integrated circuit, co-founder of Intel Corporation.** *(IEEE History Center)*

# 50 YEARS OF ELECTRON DEVICES

## Table of Contents

2	Foreword
3	The Electron Tube Legacy
8	From Tubes to Transistors
16	The Decade of Integration
25	New Light on Electron Devices
33	Focus on Manufacturing
40	Toward a Global Society
45	Into the Third Millennium

## Foreword

**T**HE FORMATION OF THE IRE PROFESSIONAL GROUP ON ELECTRON Devices in 1952 followed shortly after the most important invention of the past century, the transistor. The work of Bardeen, Brattain, and Shockley and subsequent developments by other giants in the field of electron devices have indeed revolutionized the way we live and the way we think. In the past fifty years, we have witnessed how the results of these developments dramatically and irreversibly improved our lives and livelihood. In his narrative, Michael Riordan captures both the principal events marking these technological advances and the evolution of the Electron Devices Society in its first fifty years. He has succeeded in making the critical connections between the two, and the resulting history is of great value to our members as well as to historians of technology. I cannot think of a better means of commemorating the fiftieth anniversary of our Society than this historical account. As the information technology revolution continues and as we approach the limit of Moore's Law, we breathlessly await what will unfold in the next fifty years.

The Electron Devices Society is grateful to former President Craig Casey for shepherding this important project from the start. Not only did he provide effective leadership to the 50th Anniversary Booklet Committee, he was also the principal researcher of most of the contents. His committee members, Jim Early, Tak Ning, Lew Terman, Richard True, and I, have contributed valuable contents to the manuscript, as well as proofread its numerous revisions. Our Society is indebted to staff member Laura Riello for her excellent work in coordinating the editorial and production activities among the Committee, the author, and the IEEE Marketing Department. She was indeed principally responsible for the timely completion of the final product.

It was not the purpose of this booklet to cite all the inventions in the field of electron devices or all the volunteer leaders of the Society. There are electron device topics and significant contributions by EDS members to the Society and device technology that were not included due to space limitations. I hope that regardless of one's professional affiliation and expertise, the reader will be fascinated by the key historical elements along the evolutionary and revolutionary path of the technology made possible by the invention of electron devices.

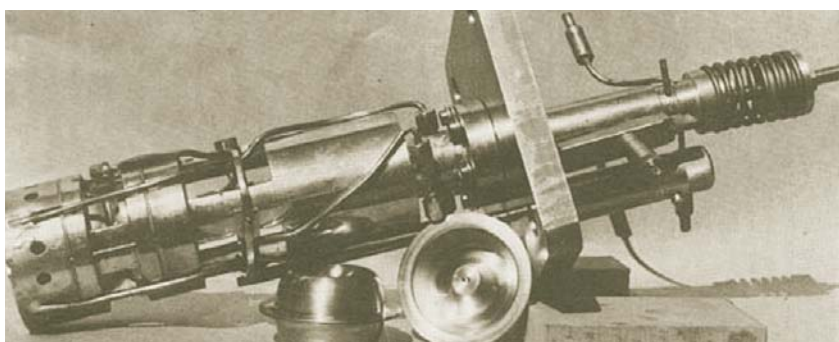
Cary Y. Yang  
EDS President, 2000-2001



50 YEARS OF ELECTRON DEVICES

**1930s and 1940s**

# THE ELECTRON TUBE LEGACY



## The Electron Tube Legacy



Lee de Forest and Bell Labs President Mervin Kelly holding an electron tube.

**E**LECTRON DEVICES HAVE PLAYED A CENTRAL ROLE in electrical engineering almost since the birth of the profession near the end of the nineteenth century. Indeed, the first article published in the initial 1884 volume of the *Transactions of the American Institute of Electrical Engineers* (AIEE), one of the IEEE's parent organizations, was "Notes on Phenomena in Incandescent Lamps," by Edwin Houston. Over a decade before the discovery of the electron, he discussed the Edison effect, a curious trickle of current through the lamps that was to become the physical basis of electron tubes. Working for the Marconi Company in 1905, British physicist John Ambrose Fleming employed this effect in his "oscillation valve," which served as a detector of wireless transmissions. In America, Lee de Forest and Reginald Fessenden soon adapted this valve to function as an amplifier in radio transmitters by inserting a third electrode to serve as a modulating grid. With the much improved physical understanding of electrons achieved by 1912, scientists at AT&T and General Electric developed high-power electron tubes, which were being used a few years later for transcontinental and transatlantic radio and telephone communications.

In parallel with these developments, a professional organization emerged devoted to the interests of electrical engineers specializing in radio applications. Formed from the union of two smaller societies, the Institute of Radio Engineers (IRE) held its first official meeting in 1912. The following year, it established offices in New York City and began publishing its widely read journal, the *Proceedings of the IRE*. For the next fifty years, the AIEE and IRE served as dual representatives of the electrical engineering profession in America — at a time when radio and television broadcasting

grew into major industries and electronics became an integral part of modern life. Beginning in the 1920s, RCA, Sylvania, Western Electric and other companies began manufacturing an almost bewildering variety of electron tubes for a steadily growing list of applications. At the heart of all this economic activity was the manipulation of streams of electrons flowing from cathode to anode in myriads of different configurations. In fact, the word "electronics" itself emerged during the 1920s to describe the bold new technology.

The Electron Devices Society can trace its own origins back to the 1930s, when the Technical Committee on Electronics coordinated IRE activities in the field. In 1938 it sponsored the first Conference on Electron Tubes, held at the Pennsylvania Hotel in New York, under the leadership of Frederick Lack, Frederick Llewellyn and Browder J. Thompson. The meeting was so successful that two more Electron Tube Conferences were held the following year at the Stevens Institute of Technology in Hoboken, New Jersey, again under auspices of the IRE Committee on Electronics. Attendance swelled to over a hundred.

Wartime secrecy prevented further Electron Tube Conferences until the 1946 meeting, when microwave devices developed during World War II were the focus of attention (see Sidebar 1.1). Particularly noteworthy among them was the traveling-wave tube invented by Rudolf Kompfner and dramatically improved by John Pierce, which was first discussed at this meeting, held at Yale University. Traveling-wave tubes headed the list of topics at the 1947 Syracuse meeting, while magnetrons and klystrons received top billing at the 1948 Cornell meeting. Jack Morton and George O'Neill were especially active in organizing these meetings.





Russell Varian,  
co-inventor of the klystron.



John Pierce and Rudolf Kompfner discussing  
the theory of traveling-wave tubes.

## Sidebar 1.1 Microwave Tubes

During the 1930s, the Bell Telephone Laboratories began investigating the use of shortwave electromagnetic radiation for long-distance communications. The high bandwidths that could be achieved, as well as the potential for line-of-sight transmissions over many miles, was promising. The U.S. Army and Navy were also interested in shortwave electromagnetic waves as navigational aids and for aircraft detection systems. But progress was hampered by the lack of electron tubes able to function at the necessary frequencies of a gigahertz or more.

Then in 1937, working at Stanford University with his brother Sigurd, Russell Varian invented the klystron; the first successful microwave tube, it could oscillate and amplify signals at frequencies as high as 3 GHz, corresponding to a wavelength of 10 centimeters. Klystrons modulate a stream of electrons traveling along the tube axis into bunches that generate microwave radiation at an output resonator gap. Like all microwave tubes, their high-frequency operation does not depend on small device dimensions.

A bit later, Henry Boot and John Randall invented the cavity magnetron

at Birmingham University. These British physicists employed a resonant cavity structure in a magnetron for the first time. It was a huge success, generating kilowatts of microwave power at 10 cm — far more than klystrons could then achieve. Soon after U.S. physicists and engineers learned about this surprising electron device in 1940, the MIT Radiation Laboratory was established to develop comprehensive radar systems with the cavity magnetron as the core element. Small klystrons served as local oscillators in these systems, which eventually operated above 10 GHz by the end of World War II. Radar proved crucial to the Allied victory.

Originally trained as an architect, Austrian émigré Rudolf Kompfner invented another kind of microwave tube, the traveling-wave tube, at Birmingham in 1943. After he learned about this invention during the War, Bell Labs engineer John Pierce developed a working theory of its operation, based on the interaction between an electron beam and slower electromagnetic waves traveling within the tube. His theory contributed to the tube's stability and the realization of its broadband capabilities. Pierce developed other new features that vastly

improved these tubes — such as a convergent electron gun now named after him. Kompfner came to Bell Labs in the early 1950s and worked with Pierce to adapt traveling-wave tubes for satellite communications, which began in the 1960s with the *Echo* and *Telstar* satellites. Traveling-wave tubes are the only electron devices able to supply the proper combination of high output power and bandwidth needed for satellite communications.

Today, modern traveling-wave tubes are still used extensively in microwave and satellite communications systems because of their high efficiency, long lifetimes and excellent reliability. And modern klystrons can produce astonishing levels of peak and average power — more than 100 MW peak and 1 MW average. They power particle accelerators used for physics research and cancer therapy, and are employed in high-resolution radar systems. Magnetrons are also widely-used today because they are efficient, low-cost sources of microwave power. Every commercial microwave oven contains a magnetron.

## The Electron Tube Legacy

*The work at Bell Labs is just great  
We sure find it hard to berate  
With papers galore  
They cover the floor  
Two sessions with six out of eight.*

*Old-timers' limerick  
from Device Research Conference*

The microwave tubes and crystal rectifiers used in radar systems had helped the Allies win World War II. Now these and other electron devices found their way into the commercial marketplace. The postwar decade witnessed dramatic changes occurring in the field of electrical engineering, partly in response to all the pent-up consumer demands. Electronics technology was growing rapidly: television, FM radio, computers, solid-state components and military applications. Electronics began attracting the lion's share of electrical engineering students, offering them good jobs in industry and academe. The IRE membership rolls more than tripled between 1947 and 1957, surpassing the AIEE membership, which had doubled. To address the needs of its members who shared a common technical specialty and wanted to interact more directly, the Institute in 1948 established its Professional Group system, with "Audio" and "Broadcast Engineers" as the first two groups. Many more would follow in the ensuing decade.

Solid-state electron devices were also beginning to attract major attention. The vastly improved understanding of semiconductor physics and technology, particularly involving germanium and silicon, that had emerged from wartime radar programs spawned several new devices during the postwar years. The flood gates burst in 1948 after the invention of the transistor at Bell Labs by John Bardeen, Walter Brattain and William Shockley (see Sidebar 1.2).

Given all this interest, the purview of the IRE Electron Tube Committee was extended in 1949 to include solid-state electron devices. Renamed the Committee on Electron Tubes and Solid State Devices, its first Chairman was Leon S. Nergaard of RCA, who would serve in that position until 1951. This was the IRE committee that in ensuing decades would grow into the IEEE Electron Devices Society.

### Sidebar 1.2 The Invention of the Transistor

Solid-state electron devices originated with the crystal rectifiers that were commonly used as detectors in radio receivers until displaced by vacuum diodes during the 1920s. Such nonlinear electron devices convert AC radio signals into DC waveforms. When microwave transmissions became possible during the late 1930s, scientists and engineers turned increasingly to silicon rectifiers to serve as detectors of these signals because vacuum diodes then available could not operate at gigahertz frequencies. The radar systems of World War II used such crystal rectifiers — based on a chip of silicon or germanium with a metal point contact stabbing into its surface — in the superheterodyne circuits of their receivers.

Well before the War, scientists and engineers dreamed of inventing solid-state amplifiers using the semiconductors then available. At Bell Labs, William Shockley had several ideas for fashioning such a device; he convinced Walter Brattain to try to fashion one of them out of copper oxide, but it proved a failure. However, a vastly improved understanding of semiconductors — particularly



germanium and silicon — emerged from the radar program during the War. In 1945, Bell Labs set up a new Solid State Physics department with Shockley as leader to take advantage of all the new knowledge and push back the scientific frontiers even further.

In the spring of that year, Shockley conceived what he called a “field-effect” amplifier based on the new semiconductors, but attempts by Brattain and others to make such a device using silicon failed completely. Examining the theory of this device in 1946, theoretical physicist John Bardeen conjectured that electrons trapped on the semiconductor surface were blocking the electric fields, keeping them from penetrating into the material and modulating the flow of electrons inside. Working together over the next two years, Bardeen and Brattain verified this theory and stumbled upon a way to overcome the blocking effect of the surface electrons. In December 1947 they invented the first solid-state amplifier, called the “point-contact transistor.” (The word “transistor” was actually coined by John Pierce in May 1948.) This device closely resembled the



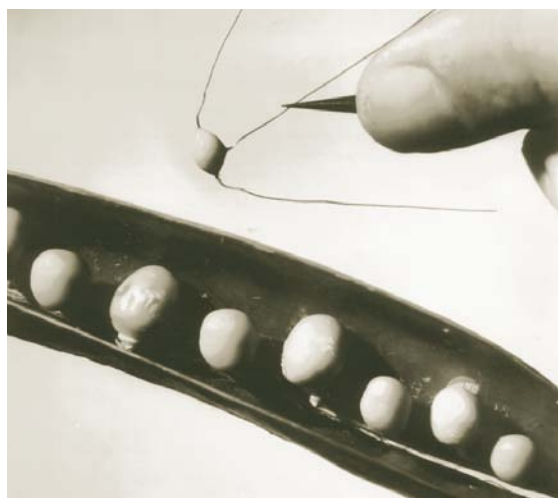
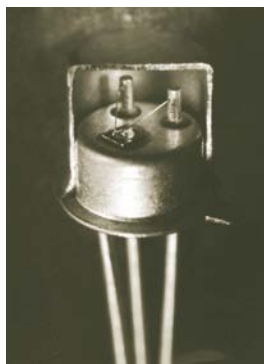
**Bardeen, Shockley and Brattain with the point-contact transistor.**

crystal rectifiers of World War II radar receivers, with two very closely spaced metal points (instead of one) poking into the surface of a germanium chip. One point contact carried the input signal, which modulated the output signal flowing through the other contact. By the time Bell Labs announced the invention in mid-1948, its engineers had already developed prototype radio and telephone circuits based on point-contact transistors.

Meanwhile, in January 1948, Shockley conceived yet another idea for a transistor, called the “junction transistor.” It was essentially a sandwich made of three adjacent layers of germanium or silicon “doped” with different impurities to induce radically different electrical characteristics among them. Electrical signals applied to the central layer would modulate currents flow-

ing through the entire sandwich from one end to the other. Shockley figured that his junction transistor would be much easier (than the point-contact transistor) to manufacture with uniform, reliable characteristics. But it took several major advances in materials science (see Sidebar 2.1) before Bell Labs scientists and engineers finally succeeded in making one, proving Shockley’s insights and precise mathematical theory to be indeed correct.

In the 1950s, junction transistors produced by GE, RCA, Transitron, Texas Instruments and Japan’s SONY Corporation began to be employed as amplifiers in commercial devices such as hearing aids and transistor radios. By the early 1960s, they had displaced electron tubes in most computer circuits. The manipulation of electrons in semiconductors had begun to have a major impact upon commerce and industry. And it would become truly immense by the end of that decade.



50 YEARS OF ELECTRON DEVICES

**1950s**

FROM  
TUBES TO  
TRANSISTORS



## From Tubes to Transistors

**A**LTHOUGH ELECTRON TUBES ALMOST COMPLETELY dominated the marketplace for electronic devices as the 1950s began, ten years later they were fighting a losing battle with solid-state devices. This was the decade in which transistors fought their way into consumer electronics, computers and other circuitry, starting with hearing aids in 1953 and the famous transistor radio the following year. Shockley's invention of the junction transistor led this invasion — establishing a beachhead from which myriads of steadily improving transistors could swarm inland, capturing nearly every market in their path. Just about the only redoubts were high-fidelity audio electronics, television and microwave systems, which operated at high power or high frequencies that transistors could not (yet) attain.

With the onset of the Cold War between the United States and Soviet Union, government support for the development of advanced electronics — especially solid-state devices and microwave tubes — was not hard to obtain. The Korean War resuscitated military procurement of these devices, which had seriously lapsed in the late 1940s. And as the Eisenhower Administration strove to develop the Atlas intercontinental ballistic missile and the Distant Early Warning system (the “DEW Line”) of radar defenses in response to the perceived Soviet threat, there was no shortage of jobs for electronics and electrical engineers.

This was a decade in which the principal theme was the steady drumbeat of process innovations. Rapid improvements in materials science and manufacturing techniques — as well as novel structural approaches — continually expanded the operating characteristics of transistors and

their solid-state kin. Development of zone refining at Bell Labs gave researchers and engineers ultrahigh-purity germanium and silicon to work with. Gordon Teal demonstrated how to grow large crystals of both semiconductors, ensuring the necessary materials uniformity that would result in controllable, predictable behavior of the electrons flowing through them. Working with Morgan Sparks at Bell Labs and then Willis Adcock at Texas Instruments, he adapted this technique to grow junction transistors that found ready applications in portable radios and military electronics (see Sidebar 2.1). A special transistor issue of the *Proceedings of the IRE* in November 1952 described much of this R&D activity.

Others were pursuing different approaches. John Saby at General Electric developed the alloy-junction transistor, which proved easier to manufacture than grown-junction devices. GE, RCA and a host of other, smaller companies were producing hordes of alloy-junction transistors by mid-decade. Robert Noyce was attempting to push their performance levels to higher frequencies at Philco when Shockley came by in early 1956 to recruit the bright young physicist for a company devoted exclusively to silicon semiconductors that he was about to establish near Palo Alto.

Sensing the rapid changes occurring in electron devices, the IRE Committee on Electron Tubes and Solid State Devices (often referred to as “Committee 7”) moved quickly. In 1951 discussions began about forming a new IRE Professional Group on Electron Devices. By the end of the year, the proposal had been approved by the IRE Executive Committee and the group — the antecedent of the present IEEE

## From Tubes to Transistors



George D. O'Neill, the first Chairman of the Administrative Committee of the IRE Professional Group on Electron Devices.

Electron Devices Society — was launched. Its Administrative Committee (AdCom) held its first meeting on March 5, 1952, at IRE headquarters in New York City. At the helm was Chairman George D. O'Neill of Sylvania, who had served in many capacities on previous committees since the late 1930s. Leon Nergaard was the founding Vice Chairman and John Saby served as the first Secretary. During its difficult formative years, the new Professional Group on Electron Devices (PGED) would find itself in highly experienced hands.

One of the early areas of concentration for the Group was the formation of local chapters around the country. These efforts met with mixed success, as many metropolitan areas did not possess a sufficient number of interested engineers to support a chapter, while others were dominated by a single electronics company and saw no need for such a chapter. By the mid-1950s, however, there were active chapters in Boston, Los Angeles, New York City, Philadelphia, San Francisco and Washington, as well as struggling groups in other areas. By December 1953, paid membership in the full Professional Group exceeded 1,000 engineers and scientists.

Of major importance during those formative years were the tireless efforts of Yale professor Herbert J. Reich and Saby, as the successive Chairmen of the AdCom subcommittee on publications, to pull together and publish a quarterly journal for the group, called the *Transactions of the IRE Professional Group on Electron Devices*. First appearing in October 1952, it was published on an irregular basis for a few years, as good papers became available, often from conferences or symposia that did not publish a proceedings. There was only a single issue in 1952, three in 1953 and four in 1954, when AdCom agreed to begin publishing the *Transactions* on a regular quarterly basis the following year. In 1955, Earl Steele of General Electric took over from Saby as its first real Editor, a position he would hold until 1961.

### Sidebar 2.1 Bipolar Junction Transistors

Although Bardeen and Brattain's invention of the point-contact transistor came first, it was the bipolar junction transistor conceived by Shockley a month later that really made these electron devices a commercial reality. In January 1948 he had the key insight of "minority carrier injection" — that electrons and holes can briefly coexist in the bulk semiconductor material and flow in the intimate presence of one another. In July 1949 Shockley published his ideas in an article, "The Theory of *P-N* Junctions in Semiconductors and *P-N* Junction Transistors." He further elaborated these ideas in his 1950 book, *Electrons and Holes in Semiconductors*, which became the bible of the new field read by thousands of practitioners.

Important advances in materials science helped get junction transistors out of the laboratory and into production. William Pfann's invention of zone refining at Bell Labs provided ultrapure germanium samples with impurity levels of less than a part per billion. Meanwhile, chemist Gordon Teal perfected a technique for growing large single crystals of germanium; he and Morgan Sparks



**Gordon Teal and Morgan Sparks, who fabricated the first grown-junction transistors.**

then figured out how to introduce small impurities into the melt and form *pn* junctions as well as three-layer structures directly in the resulting crystals. Announced in July 1951, such “grown-junction” transistors were used in hearing aids and radios by the mid-1950s. Texas Instruments manufactured the germanium transistors used in the first transistor radio, the Regency TR1, which reached customers by Christmas 1954.

Another approach to making junction transistors had been invented by John Saby at General Electric laboratories in Schenectady, New York, and developed for mass production by RCA. In 1951, he fabricated the so-called alloy-junction transistor by melting pellets of indium on the opposite sides of a thin slab of germanium; the molten indium alloyed with the germanium to form two *pn* junctions astride a narrow intervening layer of *n*-type germanium. Alloy-junction transistors proved easier to manufacture than the grown-junction variety; many transistor producers, large and small, adopted this approach rather than set up elaborate crystal-growing equipment. Philco, for example, made high-frequency alloy-junction

transistors by narrowing their base layers as much as technically possible at the time.

One serendipitous outgrowth of these transistor-fabrication efforts came at SONY, which began selling transistor radios in 1955. In 1957, while experimenting on heavily doped germanium *pn* junctions as part of efforts to reach high frequencies above 100 MHz, Leo Esaki invented the tunnel diode; he observed that some of the electrons were actually traversing the barrier due to quantum-mechanical tunneling. He shared the 1973 Nobel Prize in physics for this fundamental scientific discovery.

Meanwhile, researchers at Bell Labs and other institutions had begun to recognize the limitations of germanium and were turning to silicon as the element of choice for transistors and other semiconductor devices. While much more difficult to purify due to its higher melting temperature and great reactivity, silicon has a significantly larger gap between its valence and conduction bands. This higher band gap means that silicon transistors are far less sensitive to temperature changes — and that their leakage

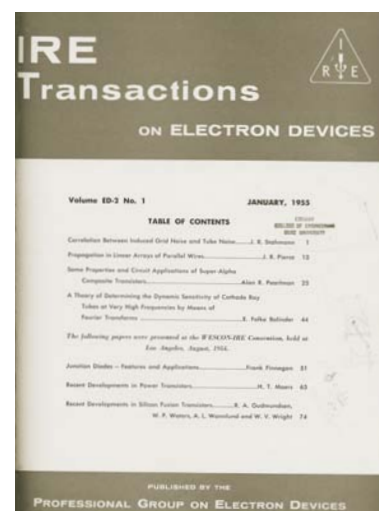
currents are far lower than for germanium devices.

Having joined Texas Instruments in 1953, Gordon Teal zealously pursued the quest of making silicon transistors. Before leaving Bell Labs, he had adapted his crystal-growing techniques to work with silicon; at TI he hired physical chemist Willis Adcock to lead a group aimed at developing silicon transistors. In April 1954 they succeeded in making a grown-junction transistor using high-purity silicon. Although Morris Tanenbaum also fabricated silicon transistors at Bell Labs that same year, the TI devices were the first silicon transistors to reach market.

The knotty problem of purifying the silicon was finally solved by Bell Labs metallurgist Henry Theurer, who developed the float-zone refining technique in 1955. This breakthrough and the fabrication of *pn* junctions by impurity diffusion (see Sidebar 2.2) were the technological advances that pushed the doors open wide for silicon semiconductor devices. By the end of the 1950s, germanium was in decline.

## From Tubes to Transistors

Two of the earliest issues of the *IRE Transactions on Electron Devices*.



Efforts to publish a monthly newsletter and bulletin were not as successful. The idea rose and fell in AdCom meetings, with little to show for the discussions. By the middle of the decade, lacking a champion to advocate it, the idea had been effectively tabled.

The Professional Group on Electron Devices actively sponsored parallel sessions at the annual IRE meeting in New York and the WESCON conference on the West Coast. Typically, there were sessions on electron tubes, microwave tubes and transistors. All were very well attended, especially the transistor sessions, which often had to turn away listeners because of a lack of available seating. In addition, the Group often cosponsored more specialized meetings of interest to its members with other IRE professional groups — for example, a Symposium on Microwave Radio Relay Systems held in November 1953, and a Symposium on Fluctuation Phenomena in Microwave Sources the following year.

IRE Committee 7 continued in existence all the while, maintaining control over and sponsorship of the annual electron device research conferences. In 1952, this gathering bifurcated into a pair of annual meetings: the Conference on Electron Device Research (CEDR) and the Solid-State Device Research Conference (SSDRC). They were both free-wheeling, by-invitation-only, off-the-record meetings in which advanced, cutting-edge research could be discussed openly without violating the proprietary concerns of employers. No proceedings were published; if individual authors wished to see their papers in print, they could always send them to Reich, Saby or Steele for publication in the *Transactions*.

By 1954 strong sentiments were emerging that the Professional Group on Electron Devices should sponsor its own annual meeting. A poll of the membership revealed widespread support for the idea of holding such a technical meeting every fall in an eastern city. At the January 1955 AdCom meeting, George O'Neill agreed to serve as the Chairman of the first annual meeting. He was authorized to begin to make the necessary arrangements to hold it that fall in Washington, DC, supported by the local PGED chapter. The letter calling for papers emphasized that the meeting was principally intended “to provide an outlet for presentation of material covering areas between research and process engineering.” The gathering was to be a “Conference on Electron Devices, as distinguished from their circuit applications.” It occurred on October 24-25, 1955, at the Shoreham Hotel near Rock Creek Park, with over 600 in attendance — the first of many annual meetings held at this hotel. The following October, when the meeting attracted more than 1,000 attendees, Shockley delivered the luncheon speech.

As Saby stepped in as AdCom Chairman in mid-1955, rapid changes were occurring in the field of solid-state devices. At the June Solid-State Device Research Conference held in Philadelphia, Bell Labs researchers revealed that they had just succeeded in making transistors using diffusion techniques to incorporate impurities into the germanium and silicon (see Sidebar 2.2). The operating frequencies of the diffused-base transistors made with this technique soon exceeded 100 MHz — making them competitive with electron tubes in the FM radio range. What's more, Bell Labs had succeeded in extending zone-refining purification





**John Saby, who helped to launch the *IRE Transactions on Electron Devices* and developed the alloy-junction transistor.**

techniques to silicon, a far more refractory element than germanium. It was only a year earlier that a Texas Instruments team led by Willis Adcock and Gordon Teal had fabricated the first successful silicon transistor to reach the market. Diffusion and silicon were truly the hits of the 1955 SSDRC, through which rumors circulated that Shockley was about to leave Bell Labs and set up a California semiconductor company concentrating on these technologies.

With the deepening Cold War and the urgent needs it created for advanced electronic systems, electron device developers found strong support among the U.S. armed services for their advanced research activities. Silicon transistors had much smaller leakage currents than germanium transistors and more uniform operating characteristics over large temperature ranges. Military purchasing agents, who soon preferred silicon over germanium, were willing to pay as much as a hundred dollars for a single transistor. The eager market for these and other “mil-spec” electron devices helped to build a solid foundation under the young semiconductor industry.

Its intellectual roots also received a strong affirmation in late 1956 with the announcement that Bardeen, Brattain and Shockley would receive the Nobel Prize in physics for their invention of the transistor. The three men headed for Stockholm in December to accept their awards from the Swedish king. This would not be the last time that a Nobel prize was given for the invention of an electron device.

As the decade came to an end, major developments in science, technology and world affairs augured well for the future of research on electron devices. The October 1957

launch of *Sputnik* redoubled military interest in and support for the field, while President Eisenhower established the National Aeronautics and Space Administration (NASA) to pursue civilian R&D in space. Photovoltaic cells and transistors made by Bell Labs and Texas Instruments powered radio transmitters in the U.S. *Vanguard* and *Explorer* satellites sent up in response to the Soviet challenge. The new field of satellite communications required highly efficient microwave tubes, especially traveling-wave tubes; their electronic circuits absolutely demanded use of ultralight semiconductor devices, no matter what the cost.

Meanwhile, Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor Company in California invented the integrated circuit (See Sidebar 3.1). Over the next few decades, this revolutionary breakthrough would promote drastic reductions in the size and weight of electronic circuitry. Along with other advances in computers and communications, the integrated circuit would open up an era we now refer to as the Information Age.

The IRE Professional Group on Electron Devices somehow managed to cope with all the dramatic changes and mature into an active, responsive organization. Under Saby's tenure as Chairman, AdCom even considered splitting the Group into two independent professional groups — one focused on electron tubes and the other on solid-state devices. The idea was to accommodate better the differing needs of these two disciplines, each of which contained about half the total membership. But the idea was fortunately rejected, and the Group continued its steady growth. By the decade's close in December 1959, its membership exceeded 5,000, including students.

## From Tubes to Transistors

*T.I. the market to claim,  
Has produced a transistor of fame.  
It aptly addressed  
As the snowflake, attest:  
Because no two are the same.*

**Old-timers' limerick  
from Device Research Conference**

*An AdCom member expressed the opinion that in the semiconductor field there has not been the major break-throughs the tube field has had and it might be timely to consider abolishing the Semiconductor Research Conference.*

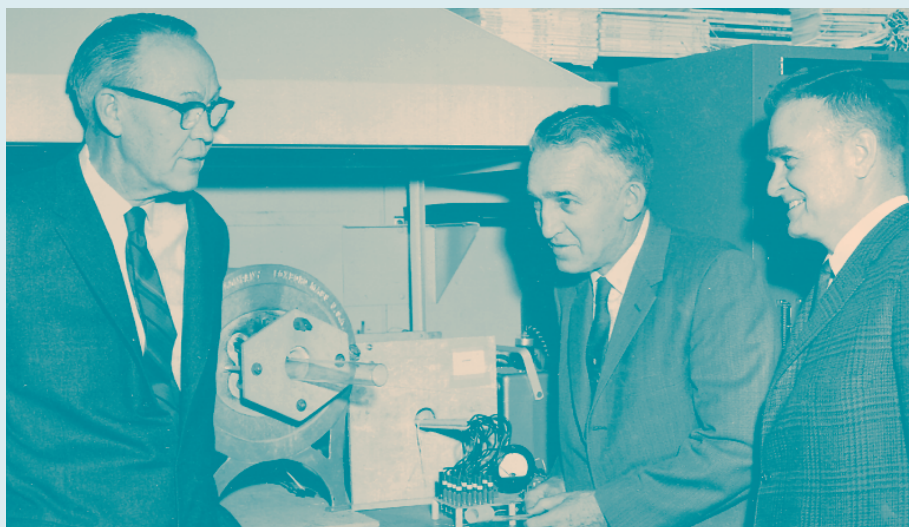
**AdCom minutes, IRE Professional Group on Electron Devices,  
September 13, 1957**

### Sidebar 2.2 Photovoltaic Cells and Diffused-Base Transistors

Ever since Russell Ohl's 1940 discovery of  $pn$  junctions in silicon, scientists had recognized that these devices could convert light to electricity with fairly high efficiency, an order of magnitude better than for the selenium photocells then used in light meters. But it took until the early 1950s to develop a relatively inexpensive process to produce large-area  $pn$  junctions. Calvin Fuller was experimenting at Bell Labs on the use of diffusion to introduce trace impurities into germanium and silicon, forming  $pn$  junctions just beneath the semiconductor surface. Gerald Pearson soon recognized that this approach might yield the large-area  $pn$  junctions required for photovoltaic cells; in 1954 he worked with Fuller and Darryl Chapin to develop the Solar Battery, a boron-doped silicon photovoltaic cell that could convert sunlight to electricity at efficiencies up to 6 percent.

Announced to the public in April 1954, the solar cell became an overnight sensation, with the media heralding its supposedly cheap, non-polluting energy. But due to their high manufacturing costs, these cells

Calvin Fuller, Carl Frosch and Link Derick  
with an early diffusion furnace.



were not competitive with conventional sources of electricity except in remote applications well off the electric-power grid. Fortunately, an application emerged in the late 1950s for which silicon photovoltaic cells were ideal: powering space satellites. By then, further development had pushed their energy conversion efficiencies above 10 percent. Photovoltaic cells powered the *Vanguard* and *Explorer* satellites, which first orbited in 1958 — and almost every Earth satellite since then.

As their costs came down gradually over the ensuing decades, these cells have been used to power pocket calculators, emergency roadside telephones, and many other remote, off-grid applications. Large arrays of silicon photovoltaic cells are now beginning to appear on the rooftops of homes, schools and businesses — generating electricity for the inhabitants and feeding excess power to the grid.

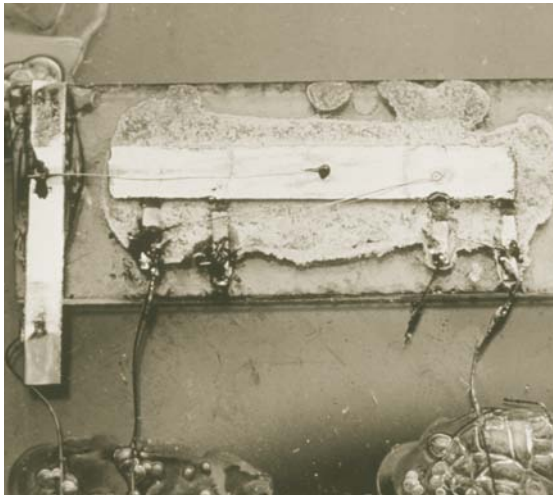
Bell Labs had also vigorously pursued applications of diffusion in fabricating high-frequency transistors able to operate above 100 MHz, which

required that they have very narrow base layers only microns thick. In early 1955, Morris Tanenbaum made the first diffused-base silicon transistor. Together with the development of the float-zone refining process, this breakthrough convinced Vice President Jack Morton that the manufacture of semiconductor devices would soon depend almost entirely on silicon and diffusion.

Another key advance in 1955 was the development of oxide masking at Bell Labs by Carl Frosch and Link Derick. They learned how to form a glassy, protective  $\text{SiO}_2$  layer on the silicon surface and use it as a selective mask against the diffusion of impurities. Employing these techniques, one could now etch intricate patterns in the oxide layer for use in producing tiny, diffused-base transistors. The Fairchild Semiconductor Company and Texas Instruments were manufacturing such “mesa” transistors by 1958. These transistors found a ready

market in military applications and began appearing in computers and other circuits that required high-frequency amplifiers and switches.

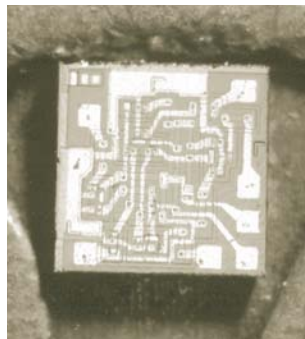
As the decade ended, Jean Hoerni and his Fairchild colleagues invented the “planar” manufacturing process that would soon revolutionize the semiconductor industry. Instead of making mesa transistors with precariously exposed *pn* junctions that could easily be contaminated, he embedded the junctions in the silicon *beneath* the oxide layer, where they were naturally protected. Within a year, Robert Noyce figured out how to employ this planar process in the manufacture of silicon integrated circuits (see Sidebar 3.1).



50 YEARS OF ELECTRON DEVICES

1960s

THE  
DECADE OF  
INTEGRATION



## The Decade of Integration

**IN TERMS OF BOTH CIRCUIT GEOMETRIES AND THE** organizations devoted to the electrical engineering profession, the 1960s was truly the “decade of integration.” Fairchild and Texas Instruments made the first commercially available integrated circuits in 1961; these miniature electronic circuits on a single chip of silicon found ready applications in ballistic-missile and portable electronic systems for military purposes. At about the same time, the IRE and AIEE recognized that their constituencies had increasingly overlapped — with needless duplication of staff, publications and activities. The two organizations merged into a single one, the Institute of Electrical and Electronic Engineers (IEEE), in 1963, the year after the IRE celebrated its 50th (and last) anniversary. Both of these sweeping changes have fundamentally altered the practice of electrical engineering in this country and throughout the world.

They also occurred at a time when the “missile gap” and “space race” were on almost everyone’s mind. After the Soviet Union managed to put the first man in orbit, Yuri Gagarin, the United States responded quickly with the sub-orbital flight of Alan Shepard in May 1961. President John F. Kennedy then committed the nation to land a man on the Moon by the end of the decade. Because the existing American rockets had much less thrust than their Soviet counterparts, U.S. engineers had to scrimp everywhere possible on the weight of their payloads, which placed a huge premium on solid-state components and integrated circuitry. The high cost of these devices was of little concern when the nation was spending \$20 billion to reach the Moon first.

The idea of integrated circuitry had been in the air since the mid-1950s, with the U.S. armed forces promoting three different approaches to miniaturization. The Navy had its Project Tinkertoy, the Army Signal Corps its MicroModule Program, and the Air Force its Molecular Electronics. Various techniques that could make miniature circuits possible, such as diffusion technology, planar processing, and photolithography, had been developed by the end of the decade. But it took the genius of two men, first Kilby in July 1958 and Noyce the following January (see Sidebar 3.1), to envision how these techniques could be employed to fabricate an electronic device that their companies would be able to manufacture reliably and in quantity.

Still, it required another two years of development before integrated circuits were ready for market. There were significant problems of materials processing and engineering that had to be solved, such as exactly how to isolate individual circuit elements on a chip by introducing additional *pn* junctions into the silicon substrate. The actual yields of successful circuits at first were abysmally low — only fractions of a percent. And the “market” for the devices was extremely limited at first. About the only customers willing to pay over a hundred dollars apiece for these integrated circuits were the armed services and their defense contractors. North American Aviation, which had contracted to design and manufacture Minuteman missiles for the Air Force, was a crucial early customer that provided a steady demand for these miniature electronic devices. The Army Signal Corps was another, promoting the applications of integrated circuits in portable electronic units, such as helmet radios for footsoldiers.

## The Decade of Integration

In parallel with these important technological advances, the nation's two major electrical engineering societies were contemplating a sweeping integration of their own. Extending as far back as 1957, and perhaps well before that, discussions had occurred along these lines; a 1959 report recommended fusion of the AIEE and IRE into a single professional society covering all the interests of electrical engineers. Similar discussions also took place at the level of the individual Professional Groups; for example, the PGED AdCom often contemplated and approved joint projects with corresponding units in AIEE.

Such efforts became official policy in 1961, when the IRE Executive Board authorized President Pat Haggerty to pursue a merger with the AIEE. In a special election held the following year, 87 percent of the IRE membership approved the merger. On January 1, 1963, the two societies formally became one, the IEEE. On the very same day, the IRE Professional Group on Electron Devices became the IEEE Professional Technical Group on Electron Devices — a cumbersome name that lasted only two years. In 1965, it was renamed the IEEE Electron Devices Group.

Leading AdCom during much of the pre-merger activity was Willis Adcock, a colleague of Haggerty's at Texas Instruments who had previously served as PGED Secretary/Treasurer and Vice Chairman. The first AdCom Chairman with both feet firmly planted in the solid-state devices community, Adcock worked closely with Haggerty to promote and maintain the Group's interests in the merger. One major proposal under discussion at the time, going back as far as 1959, was the possible formation of a separate IRE professional group devoted to "atomic and molecular electronics." The matter was finally resolved by establishing another section within the existing Group devoted to the new field of microelectronics — broadening the Group's focus and bolstering its overall strength.

### Sidebar 3.1 Integrated Circuits

Miniaturization of electronic circuits was a frequent topic of discussion in the late 1950s, especially in the U.S. armed services because of their needs for compact, lightweight electrical equipment. But it took the inventive genius of electrical engineer Jack Kilby to come up with a practical way to achieve this goal. On July 24, 1958, he penned a prophetic entry into his Texas Instruments logbook: "Extreme miniaturization of many electrical circuits could be achieved by making resistors, capacitors and transistors & diodes on a single slice of silicon."

By September Kilby had built and operated a phase-shift oscillator on a chip of germanium having a transistor, capacitor and the resistors on it linked by gold wires. This crude prototype oscillated at 1.3 MHz, demonstrating that integrated circuits were indeed achievable. That autumn Kilby began refining his designs and working with Jay Lathrop to adapt the techniques of photolithography for defining intricate circuit elements in chips of both germanium and silicon.

That same year Jean Hoerni invented the planar manufacturing process at





**Jack Kilby, the inventor of the first integrated circuit, and Jay Lathrop.**

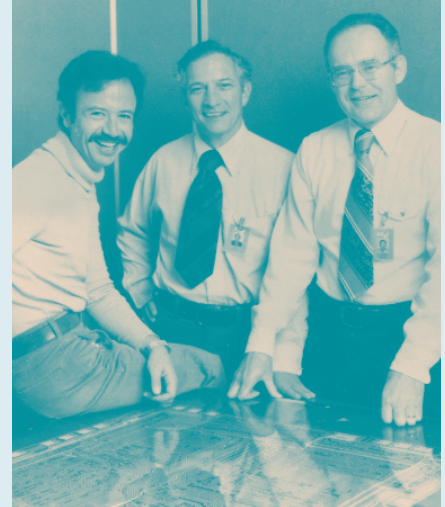
Fairchild Semiconductor Corporation in California (see Sidebar 2.2). In January 1959, while thinking about other possible uses for this process, Robert Noyce conceived another way to fabricate integrated circuits. “In many applications,” he wrote, “it would be desirable to make multiple devices on a single piece of silicon in order to be able to make the interconnections between them as part of the manufacturing process.” Noyce’s distinctive approach used fine aluminum lines deposited directly upon the silicon-dioxide protective layer to connect circuit elements defined in the underlying silicon by Hoerni’s planar process. Fairchild scientists and engineers under Gordon Moore quickly began working out the many details of manufacturing such an integrated circuit.

By 1961 both companies had silicon integrated circuits ready for market — TI’s family of Solid Circuits and Fairchild’s Micrologic series. At first, however, the only customers interested were the armed forces and other companies supplying them lightweight electronics and computers. The Air Force’s Minuteman program was

an important driving force, as was NASA’s Apollo project later that decade.

In producing these integrated circuits, both companies used bipolar junction transistors impregnated into silicon by diffusion processes. At Fairchild, meanwhile, a group of researchers that included Bruce Deal, Andrew Grove, Chih-Tang (“Tom”) Sah, and Ed Snow began addressing the problems of manufacturing metal-oxide-semiconductor (MOS) field-effect transistors, which had been invented at Bell Labs and further developed at RCA. One of the big problems they faced was the stability of these transistors; they eventually solved it by depositing a thin silicon nitride layer atop the silicon dioxide and scrupulously eliminating any sources of sodium ions in the microchip manufacturing process. By the decade’s end, MOS transistors were beginning to displace bipolar transistors in many integrated circuits.

It was Moore who envisioned the immense potential that integrated circuits held for electronics. He began a far-sighted article in the April 1965 issue of *Electronics* by stating,



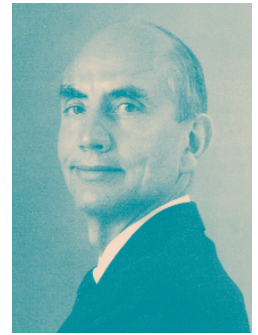
**Andrew Grove, Robert Noyce and Gordon Moore.**

“The future of integrated electronics is the future of electronics itself.” Moore foresaw a day in the not-too-distant future when that integrated circuits would permeate home computers, portable communications devices, and automobile control systems. Since the number of circuit components on a microchip had grown from ten to about fifty in only four years, he boldly extrapolated this exponential growth for another decade and predicted that integrated circuits would contain 65,000 components by 1975. This prediction, which has come to be known as Moore’s Law, turned out to be true; it has governed the explosive growth of the semiconductor industry ever since.

## The Decade of Integration



Willis Adcock.



Glen Wade, Editor of *Transactions on Electron Devices* from 1961 to 1971.

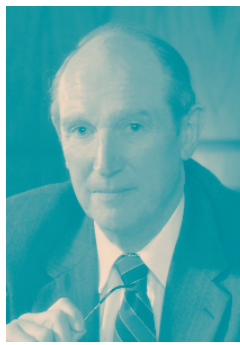
The new IEEE Electron Devices Group subsumed the functions of the AIEE's technical committees on electron devices and energy sources; the original IRE Tubes Standards Committee and Solid-State Standards Committee also fell under its sway. The responsibility for consolidating all these professional activities under one roof fell largely on the shoulders of Ray Sears, AdCom Chairman from July 1963 to June 1964, and Earl Thomas, Chairman the following year. "This was a slow and at times a difficult process," Thomas observed in his departing report, "since it was necessary to make sure in setting up the organization and [its] procedures . . . that none of the worthwhile technical activities previously carried on by the groups and committees being merged would be lost." By the time that he stepped down in June 1966, Group activities had been reorganized into five associated subfields under five technical committees: Electron Tubes, Solid-State Devices, Energy Source Devices, Integrated Electronics, and Quantum Electronics.

The Group's principal publication, renamed the *IEEE Transactions on Electron Devices* in 1963, was also rapidly evolving and diversifying during the decade. In 1961, Earl Steele resigned as Editor and in stepped Glen Wade, an engineer who had worked on traveling-wave tubes at a lengthy list of institutions, including Cornell, Stanford and General Electric. Wade served cheerfully as the Editor for a decade, bringing on associate editors and incorporating numerous changes. Under his able leadership, the *Transactions-ED* became bimonthly in 1961 and a monthly journal in 1964. One reason for this expansion was the improvement in quality of the journal under Wade's

editorship, which induced many more authors to submit good papers for publication. Another was the increasing number of articles being received on "quantum electronic devices" such as masers and lasers, whose physical operation can be adequately described only by invoking quantum mechanics.

So great was the interest in quantum devices, in fact, that a new technical committee of the Group had been formed devoted explicitly to this subfield during the 1963 reorganization. And in October 1964, the IEEE agreed to begin publishing a new professional journal devoted to quantum electronics — just before the Royal Swedish Academy announced that Charles Townes was to share the Nobel Prize in physics for his research on masers and lasers. The new publication, named the *IEEE Journal of Quantum Electronics*, was cosponsored by the Electron Devices Group and the Group on Microwave Theory and Techniques; Wade and Robert Kingston served as its co-editors for the first few years, beginning in January 1965.

Quantum devices were increasingly discussed in technical papers presented at conferences. The development of semiconductor lasers and light-emitting diodes in the 1960s (see Sidebar 3.2) added fuel to this rapidly burning fire. Special sessions devoted to quantum electronics began to be held at the Electron Device "Halloween Meeting" in Washington at the end of October. By the mid-1960s, sessions of this annual meeting were typically devoted to electron tubes, solid-state devices, energy-conversion devices, integrated circuits, and quantum devices. And a new area of professional specialization also began to emerge



**Ian Ross, Bell Laboratories President from 1979 to 1991.**



**Jan M. Engel, the first editor of the Electron Devices Group Newsletter.**

in this decade — imaging displays and sensors. Three sessions of the 1967 Washington meeting, for example, were devoted to these topics.

The annual device research conferences, one devoted to solid-state devices and another to electron tubes and other devices, continued their separate existence until 1969. That year they merged back into a single Device Research Conference, which continued to be held annually every June. In order to maintain their unique characteristics, these conferences were managed by their own special committees, which coordinated their plans and activities with the Electron Devices Group.

One such memorable gathering was the 1960 Solid-State Device Research Conference at the Carnegie Institute in Pittsburgh, at which Bell Labs researchers revealed important new results. Led by Ian Ross, one group had pioneered the techniques to grow very thin germanium and silicon layers “epitaxially” by chemical vapor deposition. This process allowed them to fabricate layers of semiconductor material that were just microns thick and to control precisely the electrical properties of each layer. Another group led by John Atalla and Dawon Kahng revealed the first practical, successful field-effect transistor, known as the metal-oxide semiconductor (MOS or MOSFET) transistor. By carefully growing an oxide layer on the silicon surface, they managed to passivate the frustrating “surface-state” electrons that had previously blocked external electric fields from affecting the behavior of electrons within the underlying material; they then deposited an aluminum lead atop the oxide layer to introduce the fields. By the end of the 1960s,

these MOS transistors were replacing junction transistors in electronic circuits, especially for lower-power applications. It was certainly a meeting to remember.

Two years later, at the Solid-State Device Research Conference held at the University of New Hampshire, researchers from MIT Lincoln Laboratory revealed surprisingly high efficiencies, over 85 percent, for conversion of electricity to light in gallium arsenide *pn* junction diodes. This discovery spurred intense work on GaAs semiconductor lasers by groups at MIT, General Electric and IBM (see Sidebar 3.2). That fall, these groups published papers on their successful efforts.

The transition years of the mid-1960s, when various electron-device groups from the IRE and AIEE were merging under the auspices of the IEEE, proved to be a challenging but rewarding time for the Group. With expansion of *Transactions-ED* to a monthly journal and the publication of the new journal on quantum electronics, it operated on a deficit basis for a few years, managing to get back in balance by 1966. That year, the long-envisioned goal of publishing a quarterly newsletter was finally realized; the first edition of the Newsletter of the Electron Devices Group appeared in June. Edited by Jan M. Engel of IBM Research in San Jose, California, it provided a convenient forum for recent news of the organization and other matters that could not be covered well in the *Transactions* — such as highlights of AdCom meetings, reports from the device-research conferences and other professional gatherings, as well as notices of future meetings of interest to the membership.

## The Decade of Integration

Integration was happening across the full spectrum of the IEEE, too, reflected best in the 1964 launch of the Institute's flagship publication, *Spectrum*. On a more specialized note, the Electron Devices Group began cooperating in 1966 with three other professional groups — on Circuit Theory, Computers, and Microwave Theory and Techniques — to cosponsor yet another publication, the *IEEE Journal of Solid State Circuits*. Chairing the joint council overseeing the new journal was Stanford's John Linvill; Vice Chairman that first year was Gordon Moore of Fairchild, who had just published a prophetic article in *Electronics* introducing Moore's Law (see Sidebar 3.1) predicting the exponential growth of components on integrated circuits. The founding Editor was James Meindl, then of the Army Signal Corps. "In solid-state circuits a confluence of disciplines must be integrated to provide coverage and perspective," noted a brief item in the first EDG Newsletter. "The *Journal of Solid State Circuits* represents a new level of intergroup activity in the IEEE, bringing groups with mutual interests together for unified action in an area of growing importance."

As the decade of integration ended, integrated circuits and light-emitting diodes were finding their way increasingly into commercial applications, such as computers and pocket calculators. By then, MOS transistors had proved superior to junction transistors in many applications. Moore's Law was being borne out in actual practice as the component densities on microchips continued to grow exponentially.

And electron devices played a crucial role in landing the first man on the Moon. With their computers based on integrated circuits and their communications systems relying on traveling-wave tubes, Apollo 11 and its lunar module reached this destination in July 1969. Thanks to these marvelous electron devices, millions watched Neil Armstrong live on television as he stepped onto its surface, uttering the soon-famous words, "One small step for man, one giant step for mankind."

### Sidebar 3.2

#### Early Semiconductor Lasers and Light-Emitting Diodes

The fact that semiconductors can emit light in response to electric currents has been recognized at least since the early 1930s, when Russian researcher Oleg Losev noticed such emissions from silicon carbide — at what probably were naturally occurring *pn* junctions. Another two decades elapsed, however, before this curious phenomenon was understood to be due to electron-hole recombination at these interfaces. But research on such light-emitting diodes initially took a back seat to other electroluminescent techniques at companies interested in developing flat-panel television displays.

The advent of III-V compound semiconductors (see Sidebar 4.2) dramatically altered this situation during the early 1960s, when scientists at Bell Labs, GE, IBM, MIT, RCA and Texas Instruments began examining the infrared and visible-light emissions from gallium phosphide and gallium arsenide. At the 1962 Solid-State Device Research Conference, Bob Keyes and Ted Quist from MIT Lincoln Laboratory reported observing over 85 percent quantum efficiency for the production of infrared radiation at *pn*



**Robert N. Hall.**

junctions formed in GaAs. This announcement encouraged several groups to try to generate stimulated, coherent radiation at these junctions. Within just a few months, three teams succeeded in achieving such laser action. That autumn a General Electric group led by Robert Hall, one from IBM headed by Marshall Nathan, and an MIT group under Robert Rediker reported observing infrared laser radiation from GaAs junctions at liquid-nitrogen temperatures (77 K).

In October 1962, a GE team led by Nick Holonyak observed visible laser light at 77 K in alloys of GaAs and GaP (commonly written  $\text{GaAs}_{1-x}\text{P}_x$ , where  $0 < x < 1$ ). This achievement stimulated researchers at Hewlett Packard led by Egon Loebner to employ such solid solutions, formed epitaxially by chemical-vapor deposition on gallium-arsenide substrates, in their attempts to mass-produce light-emitting diodes (LEDs). While TI developed infrared-emitting GaAs diodes and Bell Labs pioneered red-emitting GaP LEDs, HP and Monsanto pursued the manufacture of numeric displays for scientific equipment.

By 1968 these companies were mass-producing red-emitting GaAsP alloy LEDs; HP briefly dominated the market for displays in watches and pocket calculators — which was taken over in the 1970s by liquid-crystal displays.

These early LEDs generated only 0.1 lumen per watt, while gallium phosphide LEDs managed to achieve 0.4 lumen per watt. While at Monsanto in the early 1970s, George Craford introduced nitrogen into GaAsP and GaP LEDs, thereby generating red and green emissions at about 1 lumen per watt. During the 1970s and 1980s, the increasing use of liquid-phase epitaxy, metal-organic chemical-vapor deposition techniques and semiconductor heterostructures (see Sidebar 4.2) steadily boosted LED efficiencies. High-brightness green and blue LEDs emerged during the 1990s after a group at Nichia Chemical Industries led by Shuji Nakamura fabricated heterojunctions based on gallium nitride, indium gallium nitride, and aluminum gallium nitride.

LED efficiencies have thus improved to the point where they now exceed the performance of halogen lamps,



**Nick Holonyak.**

and the best available laboratory devices generate over 100 lumens per watt. High-brightness LEDs are available today in all three of the primary colors needed for full-color displays. Light-emitting diodes are finding rapidly-growing applications in traffic lights, automobile taillights, and outdoor lighting displays such as the towering, eight-story high NASDAQ billboard in New York's Times Square, which contains over 18 million LEDs.

## The Decade of Integration

*Now National got a new boss  
To Fairchild it wasn't a loss  
All managers proud  
Not a brain in the crowd  
And rolling stones gather No MOS(s).*

***Old-timers' limerick  
from Device Research Conference***

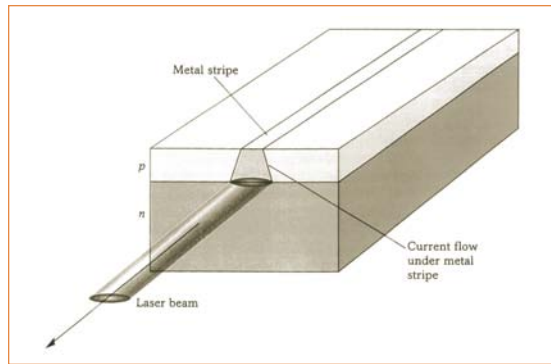
As the new decade dawned, the IEEE Electron Devices Group found itself in healthy condition. With total membership soaring past 9,300 — including 32 percent student members and another 16 percent from overseas — it was among the largest of the IEEE's professional groups. The monthly *Transactions-ED* was now flourishing under Wade's editorship, and the Electron Devices Group was cosponsoring two other successful journals, on quantum electronics

and solid-state circuits. And a quarterly newsletter kept the burgeoning membership informed of its many sprawling activities. AdCom even had its own man on the White House staff — Hubert Heffner, who in 1969 had been appointed by President Nixon to serve as Deputy Director of the Office of Science and Technology Policy. The future of the Electron Devices Group indeed seemed solid and bright.

*T.I. is having a shake-up  
They are changing their structure and make-up  
Their Shepard on high  
Now higher can fly  
The farther to fall when they break-up.*

***Old-timers' limerick  
from Device Research Conference***

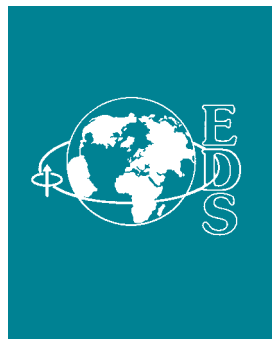
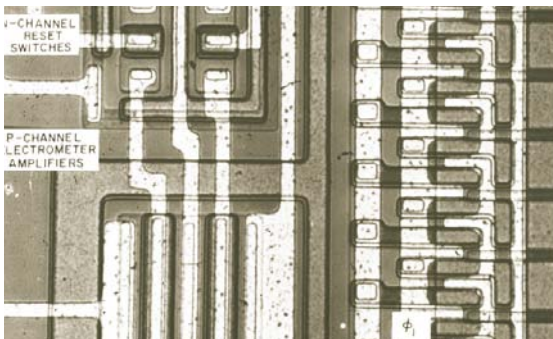




50 YEARS OF ELECTRON DEVICES

1970s

NEW LIGHT  
ON ELECTRON  
DEVICES



## New Light on Electron Devices

Jewel James Ebers.



John L. Moll, the first Ebers Award winner.

**A**S THE 1970s BEGAN, THERE WAS STRONG AND growing interest among electrical engineers and materials scientists in the new field of opto-electronics. It arose largely in response to the invention of the semiconductor laser during the previous decade. Devices that emit, convert or detect light became a focus of extensive activity among members of the Electron Devices Group. Visual electronic displays were another; the charge-coupled device, or CCD, revealed at IEEE meetings in 1970 (see Sidebar 4.1), was an instantaneous sensation. Devices that generate and absorb electromagnetic radiation had of course been used since the beginning of the century, but the major emphasis was now on the visible and infrared portions of the spectrum. The promise of broadband communications via networks of glass fibers soon became a potent force driving research and development efforts.

Solid-state integrated circuits, then becoming widely known as microchips, was another area of major activity, as component densities continued to follow the exponential growth curve enunciated by Moore in the mid-1960s. It was in fact the planar techniques used in the manufacture of MOS field-effect transistors that had made CCDs possible. In 1970 Marcian “Ted” Hoff, working at the Intel Corporation established two years earlier by Moore and Noyce, invented the microprocessor — in effect, a complete computer on a single chip of silicon. This was also the year that the sobriquet “Silicon Valley” was coined to describe California’s Santa Clara Valley, which had become the global epicenter of the semiconductor industry. And in that very same year, President Nixon awarded Jack Kilby the National Medal of Science for his pioneering work on

integrated circuits. It was indeed a good year!

Hand-held pocket calculators also emerged in the early 1970s, based upon a single microprocessor and a semiconductor memory chip. They created a rapidly growing demand for numeric displays that was satisfied by light-emitting diodes (see Sidebar 3.2) and organic liquid-crystal displays — electron devices that had been invented and developed during the previous decade. Some calculators were even powered by silicon photovoltaic cells (see Sidebar 2.2); this was one of the first successful commercial applications of these semiconductor devices, which had been introduced in 1954.

An important change in the IEEE organization as the 1970s began was the alignment of all the professional groups and societies into six divisions reflecting what were called “interest clusters.” Each division elected one Director to represent it on the IEEE Board of Directors, and a seventh Director was responsible for new technologies and interdivisional activities. The Electron Devices Group found itself in Division IV, together with professional groups on Antennas and Propagation; Magnetics; Microwave Theory and Techniques; Parts, Materials, and Packaging; and Sonics and Ultrasonics.

During the 1970s, the IEEE Electron Devices Group reached maturity and expanded its activities beyond the borders of the United States. These efforts had actually begun back in the mid-1960s, when the annual Washington meeting was renamed the International Electron Devices Meeting. Over the rest of that decade, non-U.S. membership swelled from

## J. J. EBERS AWARD WINNERS

1971	John L. Moll	1982	Arthur G. Milnes	1993	Karl Hess
1972	Charles W. Mueller	1983	Adolf Goetzberger	1994	Alfred U. Mac Rae
1973	Herbert Kroemer	1984	Izuo Hayashi	1995	Martin A. Green
1974	Andrew S. Grove	1985	Walter F. Kosonocky	1996	Tetsushi Sakai
1975	Jacques I. Pankove	1986	Pallab K. Chatterjee	1997	Marvin H. White
1976	Marion E. Hines	1987	Robert W. Dutton	1998	B. Jayant Baliga
1977	Anthony E. Siegman	1988	Al F. Tasch, Jr.	1999	James T. Clemens
1978	Hung C. Lin	1989	Tak H. Ning	2000	Bernard S. Meyerson
1979	James M. Early	1990	Yoshiyuki Takeishi	2001	Hiroshi Iwai
1980	James D. Meindl	1991	Simon M. Sze		
1981	Chih-Tang Sah	1992	Louis C. Parrillo & Richard S. Payne		

less than 1,000 to just over 1,500 — representing about 16 percent of the total membership. The largest foreign contingents were in Canada, Europe and Japan; the Tokyo Section alone boasted nearly 300 members in 1969. European members took increasing part in the activities of the Group, which occasionally cosponsored meetings such as the European Microwave Conference and the Symposium on Solid-State Device Technology. There were also frequent exchanges of information with the Japan Society of Applied Physics. And in 1972, the annual Device Research Conference took place in Edmonton, Canada, at the University of Alberta — the first time this popular gathering had ever been held beyond the borders of the United States.

Reflecting this maturity and the increasing stability of the Electron Devices Group, AdCom in 1975 petitioned the IEEE Technical Activities Board to ordain it as a full-fledged Society. Under the Institute's general practices, such a designation indicates that a Group's financial resources are deemed strong enough to survive on its own as a completely independent organization. The petition cited the group's field of interest as "electron and ion devices including electron tubes, solid-state and quantum devices, energy sources, and other devices which are related technology." The request was quickly granted. On February 17, 1976, the Electron Devices Group formally became the IEEE Electron Devices Society — the name that has survived over a quarter century to the present day.

As the professional interests of members expanded beyond traditional tube and solid-state devices, AdCom added new

technical committees to accommodate them. By the mid-1970s, the Electron Devices Society had new committees devoted to the Computer Aided Design and Applications of Devices, Electrography and Electroprinting, and Power Electronics. Meanwhile, it continued to serve as a core participant in the Quantum Electronics Council and Solid-State Circuits Council, which coordinated the joint activities of several groups and societies — especially the publication of professional journals on these subjects.

In 1970 members of AdCom decided that the time had arrived to establish a special award for major achievements in the field of electron devices. In March 1971, the IEEE Awards Board approved an award "for outstanding technical contributions to electron devices," to be presented every year at the Washington meeting. It was named the J. J. Ebers Award to honor the exemplary life and work of Jewel James Ebers, who had met an untimely death in 1959 after making important contributions to electron-tube technology and the semiconductor device art. John Moll, his Bell Labs colleague during the early 1950s, received the first Ebers Award in the fall of 1971.

In 1974, the IEEE established an Institute-level technical field award for electron-device contributions, named the Jack A. Morton Award to commemorate Morton's lifelong achievements in the development of electron tubes and solid-state devices. This award was presented annually to an individual or group for outstanding contributions to the field of solid-state devices. (In 2000 it was replaced by the Andrew S. Grove Award.) In 1976 Robert Hall received the first Morton Award for "outstanding achievement

## New Light on Electron Devices

Bill Boyle and George Smith demonstrating a TV camera that uses a CCD.



in solid-state physics and chemistry and the invention and development of semiconductor devices.” The next year it went to Morgan Sparks for “contributions to solid-state devices technology and the management of research and development.”

Members of the Electron Devices Society (or Group) were also the frequent winners of the IEEE’s distinguished general awards. For example, the IEEE Medal of Honor, the Institute’s highest and most prestigious award, was awarded to Rudolf Kompfner in 1973 and to John Pierce in 1975 for their pioneering work on traveling-wave tubes and satellite communications. In 1973, Nick Holonyak won the Morris N. Liebmann Award, given for recent developments in emerging technologies, for his “outstanding contribution to the field of visible light emission diodes and diode lasers.” The following year Willard S. Boyle and George E. Smith shared this award for “the invention of the charge-coupled device and leadership in the field of MOS device physics.”

The *IEEE Transactions on Electron Devices* also reached maturity in the 1970s. When Glen Wade stepped down as Editor in 1971, he was quickly replaced by John Copeland of Bell Labs, who served until 1974. There was now an extensive Editorial Board, with associate editors on such subfields as bipolar devices, display devices, energy sources, electron tubes, and solid-state power devices. Thus a new Editor could be readily drafted from these ranks whenever the existing one decided to retire. So Copeland was replaced by Ronald H. Haitz of Hewlett-Packard in 1974, Haitz by Karl H. Zaininger of RCA in 1977, and Zaininger by Stephen

Knight of Bell Labs in 1979 — all without any noticeable lapse in the quality of the journal.

One highlight of the decade was the publication in July 1976 of a special issue of the *Transactions* on the history of electron devices. With Gerald Pearson serving as guest editor together with Haitz, it commemorated the 200th anniversary of the founding of the United States and coincided roughly with the 25th anniversary of the Society (taking the 1952 origins of the IRE Professional Group on Electron Devices as the starting point). Its authors included such luminaries as Rudolf Kompfner writing on “The Invention of the Traveling Wave Tube,” William Shockley on “The Path to the Conception of the Junction Transistor,” and Jack Kilby on the “Invention of the Integrated Circuit.” If ever there was a collector’s item among the many fine issues of this journal, this was certainly it!

The Newsletter also continued without interruption after its founding Editor Jan Engel stepped down in 1970. In fact, it even began coming out bimonthly for a few years under his successor, John Szedon of Westinghouse, but reverted back to a quarterly in 1974. It, too, sported an Editorial Board with associate editors.

Among the annual Device Research Conferences, the 1970 Seattle meeting at the University of Washington was a particularly memorable one, with participants from Bell Labs, Fairchild and other companies revealing surprising new applications of MOS technology such as dynamic random-access memory (DRAM) and the charge-coupled



Jim Early.

## Sidebar 4.1 Charge-Coupled Devices

Soon after the charge-coupled device was invented at Bell Labs in 1969, the knee-jerk reaction of many semiconductor researchers was, “I should have thought of that!” Almost all the required MOS fabrication techniques had been available for nearly a decade; what was needed in addition was the inspiration to apply them in assembling the appropriate configuration. This encouragement came in part from Jack Morton, who prodded his colleagues to develop a semiconductor device that was analogous to the then-popular magnetic-bubble memory. Contemporaneous work on the silicon diode array camera tube also played an important role.

That autumn, Willard S. Boyle and George E. Smith busted this conceptual block by suggesting that a linear array of MOS capacitors could be used as charge-storage and transfer devices. In October the first CCD was fabricated, a simple array of ten MOS capacitors; it performed much as predicted. Boyle and Smith published their work the following spring in the *Bell Labs Technical Journal* and presented it in a few IEEE meetings — including Smith’s memorable talk at

the 1970 Seattle Device Research Conference.

Modifications of the basic CCD idea quickly followed, including a serious but short-lived application to computer memory. With a Bell Labs engineer, Boyle and Smith conceived the “buried channel” approach, whereby the charge is stored in the bulk silicon rather than at its interface with the silicon-dioxide surface layer. Marvin White and his colleagues at Westinghouse developed techniques to reduce noise, which eliminated a “bottleneck” in low-light-level imaging devices.

When Jim Early (who had left Bell Labs for Fairchild in 1969) encountered the buried-channel approach in 1971, he became convinced that this was the best way to proceed, as it could surmount the potential problem of charge trapping by surface-state electrons. He hired Gilbert Amelio from Bell Labs to work on buried-channel CCD’s under a Fairchild contract with the U.S. Navy. The resulting devices had high sensitivity and extremely low noise. Other companies such as GE, Hughes Aircraft, RCA

and Texas Instruments were involved in the race to develop CCDs, but it was Fairchild that succeeded in bringing these devices into the commercial marketplace.

This research and development led to many of the charge-coupled devices commonly in use today. Sporting millions of pixels per square inch, CCD’s can now be found at the heart of digital cameras, camcorders, and professional TV cameras. They are also employed in a growing variety of scientific applications, such as at the focus of large optical telescopes like the Hubble Space Telescope and at the heart of gigantic particle detectors used in high-energy physics.

## New Light on Electron Devices

*We look with respect on Ma Bell  
And the patents she's willing to sell  
Plus the people that go  
To help companies grow,  
They leave with their know-how and tell.*

*Old-timers' limerick  
from Device Research Conference*

device (see Sidebar 4.1). Actually, one of the surprising things about the CCD, said one EDS stalwart, was that it had not been invented years earlier, when the technology to make it first became available. Yet another revelation at the 1970 DRC was an announcement by Bell Labs researchers that they had developed semiconductor lasers able to operate continuously at room temperature (see Sidebar 4.2). These heterostructure lasers are now the basis of optical-fiber communications and consumer products such as laser printers, CD players and digital video disks.

One meeting that gained prominence among the various gatherings was the International Solid-State Circuits Conference (ISSCC), which benefited from active participation of EDS members. Sponsored by the Solid-State Circuits Council, of which the Electron Devices Society was a member, it was held in Philadelphia every February until 1978, when the meeting took place in San Francisco. Due to its close proximity to Silicon Valley, the attendance that year surged above 2,400, over a thousand more than the previous year. After that, the ISSCC began alternating between the east and west coasts — and eventually moved permanently to San Francisco.

Perhaps because of the popularity of sessions on silicon technology at the annual IEDM, the Device Research Conference declined in attendance during the decade, hitting a low of about 200 in 1975. This fall-off also may have reflected a decline in the electron-device field in the mid-1970s, as an editorial in the June 1974 Newsletter noted “a reduction in electron device research activity in the United States during the past years.” In part to raise the attendance, the 1976 DRC in Salt Lake City was held in tandem with the Electronic Materials Conference sponsored by the American Institute of Metallurgical Engineers (also called The Metallurgical Society). Attendance revived and began hitting traditional levels of about 500 by the decade end.

### Sidebar 4.2 Compound Semiconductor Heterostructures

Researchers have long recognized that so-called III-V compounds such as GaAs, AlSb and InP make excellent semiconductors. Possessing equal numbers of atoms of elements in the third and fifth column of the Periodic Table, they have the same tetrahedral crystal structure as carbon and silicon — and therefore similar physical properties. Working at Siemens-Schuckert research laboratory in Erlangen, Germany, Heinrich J. Welker pioneered the understanding of these compounds in the 1950s. He and his colleagues established that they often have wider band gaps and greater carrier mobilities than semiconductors made of germanium and silicon. Although III-IV compounds are not likely to displace silicon in traditional semiconductor uses, their versatile band structures have been widely exploited for high-frequency oscillators and optoelectronic devices.

After the invention of semiconductor lasers in 1962 (see Sidebar 3.2), it took almost another decade to achieve room-temperature devices. In 1963 Herbert Kroemer, then at Varian, and Zhores Alferov in Leningrad suggested





Izuo Hayashi and Mort Panish.

that higher-performance lasers could be realized using a three-layer “double heterostructure” in which a narrow-band-gap semiconductor is sandwiched between two wide-band-gap layers. For example, a thin layer of *p*-type GaAs might be sandwiched between *n*- and *p*-type layers of AlGaAs. Higher populations of electrons and holes can be confined within the inner layer, which also serves as a waveguide for radiation from electron-hole recombination. At the 1967 Solid-State Device Research Conference in Santa Barbara, Jerry Woodall reported that his IBM group had developed liquid-phase epitaxy to grow such AlGaAs layers on GaAs substrates. Using such an approach, Izuo Hayashi and Mort Panish of Bell Labs built a successful double-heterostructure laser that operated at room temperature, announcing their breakthrough at the 1970 Device Research Conference in Seattle. At about the same time, Alferov’s group at the Ioffe Physico-Technical Institute reported similar results.

Improved techniques since then have allowed researchers to grow extremely thin layers on GaAs and InP sub-

strates. In the late 1970s and early 1980s, Al Cho pioneered molecular-beam epitaxy at Bell Labs, while Russell Dupuis and Harold Mansevit developed metal-organic chemical vapor deposition at Rockwell. Extremely delicate, detailed heterostructures (often with one or more dimensions measured in nanometers) have been fabricated using these techniques. To describe the movement of electrons and holes in such tightly confined spaces requires use of quantum mechanics, hence these structures are often called quantum wells.

Practical applications of these heterostructures began to emerge in the 1980s. With the thin-layer control that had become available, multiple-cavity quantum-well lasers and vertical-cavity surface-emitting lasers were now possible. In the latter devices, cavity mirrors are formed by alternating layers of compound semiconductors with substantially different refractive indices. These heterostructure-growth technologies also permitted a rich field of device research and the production of a new family of high-frequency transistors. In addition to the heterojunction bipolar transistor, a variety

of high-electron-mobility transistors found use in microwave applications.

The highest expression of the heterostructure art developed so far is the quantum cascade laser developed in the mid-1990s by a Bell Labs team led by Federico Capasso. This structure contains hundreds of ultrathin layers of gallium indium arsenide and aluminum indium arsenide, each at most a few nanometers thick, laid down by molecular-beam epitaxy. The result is a sequence of many similar quantum wells, each with a precisely determined energy level. A single electron descending this “quantum staircase” emits dozens of identical photons at infrared wavelengths.

Today semiconductor lasers flash away at the heart of opto-electronic devices ranging from CD and DVD players to laser printers and bar-code scanners. Along with a great variety of semiconductor photodetectors, they are the critical active elements in fiber-optic systems that span the globe, providing broadband telecommunications on vast highways of light.

## New Light on Electron Devices

*An M-O-S-T is inferior  
Because it has no damned interior  
It's only the surface  
That serves any purpose  
And a surface just can't be superior.*

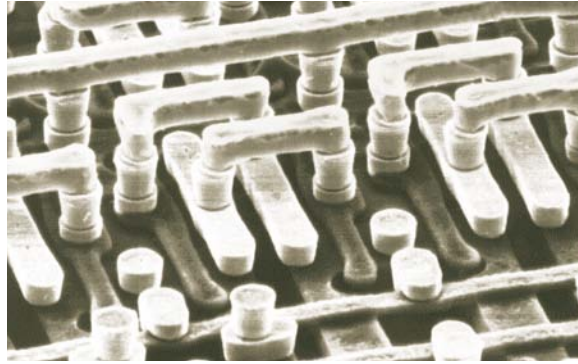
**Old-timers' limerick  
from Device Research Conference**

The Electron Device Society was itself experiencing worrisome membership losses in the mid-1970s. Part of this decrease could be attributed to success, since the members of the Society's Quantum Electronics Council reorganized as a separate IEEE Group on Quantum Electronics and Applications in 1977, resulting in a loss of about 600 EDS members. But this loss could not account for the entire decline from more than 9,000 members at the beginning of the decade to less than 7,000 in 1978. Renewed attention to the needs of members and efforts to increase their numbers brought the total back above 8,000 by the end of the 1970s; over a quarter of them now worked outside the United States. And the financial condition of the Electron Devices Society also improved, with more than \$300,000 cash reserves in the bank as the decade ended.

Due to the energy crisis of the mid-to-late 1970s and the emphasis placed on renewable energy by the Administration of President Jimmy Carter, photovoltaics had received a lot of attention. The EDS technical committee on energy sources (or energy-conversion devices) was reinvigorated by the millions of federal dollars pouring into research and development on solar cells. Although the cost of solar electricity was usually prohibitive due to the high expenses for manufacturing these cells, it was cost-effective for many remote applications off the electric-power grid, and its long-range future looked promising. Instead of only electricity making light, light was now also making electricity.

The component densities of microchips, in the dawning era of very large-scale integration (VLSI), continued their relentless exponential climb. Introduced at the beginning of the decade, dynamic random-access memory (DRAM) chips by 1979 contained over 100,000 transistors and offered 64K bits of memory. As Noyce had observed in his leadoff article for a September 1977 special issue of *Scientific American* concerning the "microelectronic revolution," the doubling period for this relentless growth had increased somewhat from Moore's original one year to about 18 months. But one could still foresee a day in the not-distant-future when there would be millions of transistors on a single microchip.

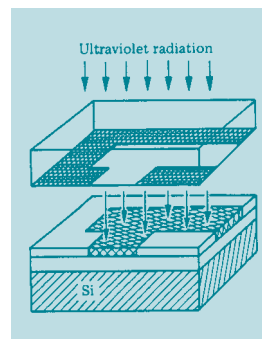
Unwilling to wait that long, however, computer hobbyists had already seized upon the Altair 8800 microcomputer, whose architecture was built around an Intel 8-bit microprocessor. Two of them — Steve Jobs and Steve Wozniak — had even founded their own brash new microcomputer company, the Apple Computer Company, in a Silicon Valley garage. That very same September of 1977, the fledgling company began selling the Apple II personal computer. The world would never be the same again.



50 YEARS OF ELECTRON DEVICES

**1980s**

FOCUS  
ON  
MANUFACTURING



George E. Smith, founding Editor  
of *IEEE Electron Device Letters*.



**T**HERE WAS DEEP AND WIDENING CONCERN ABOUT the economic health of the United States as the 1980s began. Oil embargoes of the previous decade had ignited two energy crises and touched off the fires of rampant inflation. Heavy industries such as steel and automaking had responded languidly while their European and Japanese competitors grabbed market share. And the U.S. electronics industry was on the ropes, too, while such giants as SONY and Panasonic cornered the consumer market. Amidst this worrying sense of decline, Jimmy Carter lost the Presidency to Ronald Reagan, who entered office bent upon turning the foundering ship around.

There were widespread fears that even the U.S. computer industry was in trouble. Japanese electronics firms had begun to dominate the market for memory chips and were expected to target microprocessors next. So great were the fears of foreign competition in the semiconductor industry that the Reagan Administration eventually took the unprecedented step of partially funding a consortium of U.S. chipmakers — including such heavyweights as IBM, Intel, Motorola and Texas Instruments — to do cooperative R&D on microchip manufacturing technologies. With Noyce at the helm, SEMATECH began operations in Austin, Texas, in July 1988.

Two other events of major significance for the electron-device field occurred during the early 1980s. In 1981 IBM began manufacturing and selling its personal computer, based on an open architecture that other firms were free to copy. And in 1984, the nationwide AT&T communications system was broken up by a judicial consent decree into

a long-distance telephone carrier plus regional “Baby Bells.” The ferocious competition stimulated by these events was to have a profound impact on the computer and telecommunications industries — with many small electronics companies successfully challenging the hegemony that the two behemoths had once enjoyed in their respective domains.

The principal goal of microchip manufacturing in Europe, Japan and the United States was to make the component parts of integrated circuits — transistors, capacitors and their interconnections — ever smaller and to pack them ever more densely on the chip surface (see Sidebar 5.1). Such unrelenting miniaturization helps ensure that microchips offer ever-increasing computational power and do their appointed tasks at ever-greater speeds. As the 1980s began, semiconductor industry leaders championed the goal of very large-scale integration, in which the microchip features would have to become as small as a micron, or a millionth of a meter. By the mid-1980s, VLSI pioneers were beginning to breach this barrier and work toward the submicron scale.

The IEEE Electron Devices Society strongly supported these efforts, often working in tandem with the Solid-State Circuits Council and Japanese counterparts. In 1979 a special VLSI issue was published jointly by the *Transactions on Electron Devices* and the *IEEE Journal of Solid-State Circuits*, edited by AdCom member Walter Kosonocky of RCA, Takuo Sugano of the University of Tokyo and Hans Friedrich of Siemens. In 1980 the Society cosponsored a VLSI Workshop and the following year cosponsored the first Symposium on VLSI Technology, held in Maui, with the Japan Society of



**Friedolf Smits, Treasurer of the Electron Devices Society, 1980-87, and recipient of the first EDS Distinguished Service Award.**

Applied Physics. The *Transactions-ED* published special issues on VLSI technology and simulations in 1980, 1982 and 1983.

Sessions on CMOS technology for VLSI attracted large crowds at the annual EDS gatherings. For example, a big hit at the 1982 meeting in San Francisco — the first IEDM held outside Washington — was a paper by several Toshiba researchers that demonstrated how to achieve 1.2 micron *n-p* spacing between elements. And the very next year, scientists at the Nippon Telegraph and Telephone (NTT) Corporation revealed new CMOS technologies to obtain submicron features in DRAM chips, the first memory chips to offer megabit storage capacities.

With all the fast-moving progress occurring in electron-device technologies, the slow rate of publication in *Transactions-ED* became a growing concern of AdCom. Typically it took some forty weeks from submission of an article to its publication in the journal. To address this problem, publications committee chair Eugene Gordon proposed publishing a new, quick-turnaround journal called *IEEE Electron Device Letters*, and AdCom enthusiastically supported the idea. With George E. Smith of Bell Labs serving as the Editor, the inaugural issue of the new journal appeared in January 1980, containing five brief papers. *Electron Device Letters* proved a hit with Society members; its circulation of more than 9,000 was about twice that of *Applied Physics Letters*. Thanks to Smith's efforts, it now required an average of 19 days after submission for authors to learn whether their papers had been accepted; the time to publication correspondingly dropped to 10–13 weeks. But the extra service did not come without a price. The

Society ran a large budget deficit in 1980 that could be attributed mainly to the costs of publishing the new journal. Its healthy cash surplus of \$360,000 as the decade began was in danger of plummeting if measures were not taken to stem the losses. Fortunately, Friedolf Smits of Bell Labs began serving as Treasurer in 1980. Effectively acting as executive director of the Society, he tackled the problem of getting its finances back on a firm footing. The solution was achieved in 1982 largely by “unbundling” the cost of the *Transactions-ED* from the annual dues for membership, which was henceforth to include only the quarterly Newsletter and *Electron Device Letters*. But that year 80 percent of the membership enthusiastically signed up to continue their *Transactions* subscriptions on a voluntary, paid basis. With this improvement and a large surplus from the 1982 San Francisco IEDM gathering, the Electron Devices Society was once again operating in the black.

The success of this San Francisco meeting — in terms of both attendance and finances — convinced AdCom to hold the IEDM on the West Coast every other year. This decision benefited not merely the large concentrations of California members, especially in Silicon Valley, but also the growing membership in Japan and on the Asian rim of the Pacific. Such members were much more inclined to attend meetings in California than in Washington, DC. In 1984, when the IEDM again occurred in San Francisco, a record 2,900 attended, and the Society received a \$70,000 surplus to add to its coffers, a major part of the big EDS surplus of \$175,000 that year. Except for 1986, when it was held in Los Angeles, the IEDM has ever since returned to San Francisco in the even years.

## Focus on Manufacturing



Takuo Sugano.



Cyril Hilsum.

During the 1980s, AdCom also began to include Japanese representatives on its roster of elected members. Takuo Sugano joined in 1984, followed by Yoshiyuki Takeishi in 1987, making it a truly world-wide committee. There had previously been two Europeans on the committee, Adolf Goetzberger and Cyril Hilsum, but these were the first times that Asian members served. With reimbursement of their travel costs, such non-U.S. members soon became a regular and continuing feature of AdCom.

The roster of technical EDS committees continued to expand into new areas of activity such as opto-electronics, as proposed by Frederick Dill in 1979. James Harris of Rockwell chaired this technical committee when it first met in 1980. Three years later, reflecting the surging interest in fiber-optic communications, EDS joined with nine other IEEE societies and the Optical Society of America to begin publishing the *IEEE/OSA Journal of Lightwave Technology*. This journal became one of the leading publications on optical fibers, components, networks and systems.

In 1983 AdCom approved a new award named after Paul Rappaport, who had served on the committee during the early 1970s and as EDS President in 1975. He had worked on photovoltaics research at RCA before becoming Director of the National Renewable Energy Center in the late 1970s. This award is given annually at the IEDM to the author or authors of the best paper that appeared in one of the Society's publications during the previous year. At the 1984 San Francisco meeting, Jaroslav Hyneczek of Texas Instruments received the initial Paul Rappaport Award for his article on "Electron-Hole Recombination

Anti-blooming for Virtual-Phase CCD Imager," which had been published in the August 1983 issue of *Transactions-ED*.

In 1984 the IEEE was undergoing a major divisional realignment. That year the Electron Devices Society joined three other IEEE societies to form Division I: Circuits and Systems; Components, Hybrids and Manufacturing Technology; and Lasers and Electro-Optics — as well as the Solid-State Circuits Council. One upshot of this reorganization was that the quarterly EDS Newsletter was to be replaced by a new Division I publication, *Circuits and Devices Magazine*, which began publication in 1985 and appeared bimonthly. AdCom devoted considerable time and effort to making this magazine successful, but it never really caught on.

The publishing activities of the Society had become pretty overwhelming by 1986. Not only had EDS started one new professional journal and cosponsored two other publications, but it was about to begin joint publication with The Metallurgical Society (later renamed The Minerals, Metals and Materials Society) of the *IEEE/TMS Journal of Electronic Materials*. By then, *Transactions-ED* was publishing around 2,600 pages annually, with *Electron Device Letters* adding another 700 and expected to level off at 750 pages per year. And that year AdCom member David Hodges of the University of California, Berkeley, proposed yet another new journal concerning the manufacture of complex microelectronic components — mostly for VLSI applications. The first issue of *IEEE Transactions on Semiconductor Manufacturing* appeared in February 1988, cosponsored by the EDS, the Solid-State



David Hodges, founding Editor  
of *IEEE Transactions on  
Semiconductor Manufacturing*.



Circuits Council, the Components, Hybrids and Manufacturing Technology Society, and the Reliability Society.

The costs of all these new publications put a huge strain on the Society's finances. The EDS share of *Circuits and Devices Magazine* was eating up much more money than had been projected, and its share of startup costs for the new *Transactions-SM* was enough to wipe out what had been healthy budget surpluses in the mid-1980s. Add to this the fact that the annual Photovoltaic Specialists Conference was then encountering big losses, and a possibly serious financial problem once again loomed. And it came just as Friedolf Smits stepped down as EDS Treasurer because he had been elected Director of IEEE Division I, with his term scheduled to start in 1988.

During 1987, discussions began on the need to hire permanent professional staff to manage the day-to-day operations of the Society, as a few of the other IEEE societies had already done. Its operations had become too complex and far-reaching for an all-volunteer organization, which now embraced over 10,000 members and had an annual budget exceeding a million dollars. EDS published two professional journals of its own and cosponsored four others; it sponsored almost 20 conferences a year and cooperated with other societies on nearly as many more. But with likely budget deficits looming over the next two years, due mainly to the costs of the new publications, such a major step forward was impossible until the Society could get itself on a sounder financial footing. These problems fortunately dissipated under the new Treasurer, Lu Kasprzak of IBM, who applied the lessons he learned from Smits. The expected

1988 deficit turned into a large surplus of \$162,000 due to much higher conference proceeds and somewhat lower publication costs than anticipated. That year AdCom also decided to unbundle the costs of *Circuits and Devices Magazine* from the membership dues; starting in 1990, any member who wanted to receive this magazine had to pay a separate fee.

With the finances in much better condition, AdCom could seriously consider the question of hiring professional staff. The day before its June 1989 meeting, EDS President Craig Casey of Duke University, Michael S. Adler of General Electric, Kasprzak, and several past presidents met to discuss this issue. They concluded that such management was indeed required and that the Society could now afford it. The needed office space was available at the new IEEE Operations Center in Piscataway, New Jersey. That October Adler, Casey, Kasprzak, Smits and the incoming EDS President Lewis Terman of IBM met at the Center and decided to recommend the creation of the new, full-time position of EDS Executive Officer. At the subsequent December meeting, AdCom unanimously endorsed their recommendation.

Thus the Electron Devices Society ended the 1980s on an extremely sound footing and with bright prospects for the future. Its finances were in fine condition, with annual surpluses often coming in well above \$100,000 and reserves exceeding \$1.5 million. The total paid membership, including students, was up again — to more than 11,000 members. And the Society could now look forward to having its sprawling activities managed by a full-time staff of salaried employees.

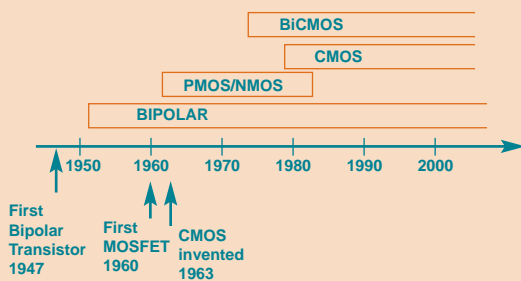
When the first Charles Stark Draper Prize was awarded by the U.S. National Academy of Engineering as the decade ended, Jack Kilby and Robert Noyce shared it for their “independent development of the monolithic integrated circuits.” Given biennially for “outstanding achievements in all fields of engineering and technology that contribute to human welfare and freedom,” the Draper Prize has since become recognized as the world’s leading award for engineering excellence. The two EDS members who received it in 1989 richly deserved this honor.

Tremendous changes were then underway in world affairs, especially in Eastern Europe, where a decade of unrest that had begun with the Solidarity movement in Poland ended with the fall of the Berlin Wall in November 1989. With the long Cold War finally drawing to its close, major transformations were also occurring in the United States, which under President George Bush was beginning to shift resources out of the military-industrial complex and into the civilian economy. More and more, a U.S. company’s success or failure would be determined by its performance in the commercial marketplace. Computer and telecommunications firms had responded aggressively to the competitive stimuli that were introduced during the 1980s and were now on much better footings as the decade ended. In particular, the U.S. microelectronics industry was back in excellent condition and growing steadily as the 1990s began.

### Sidebar 5.1 **Microchip Manufacturing**

Microchip manufacturing has evolved rapidly since the invention of the integrated circuit (see Sidebar 3.1). Silicon rapidly became the material of choice for fabricating microchips because a high-quality insulating and passivating layer is easily formed on its surface by thermal oxidation. This oxide layer can be readily patterned to serve as an isolation layer, as masks for diffusion and ion-implantation, as well as for the critical transistor components.

Silicon-device technology development took off on several fronts after the 1960 demonstration of MOS field-effect transistors and the 1963 invention of CMOS (Complementary MOSFETs), which dissipate very little power in standby operation. Circuit designers used bipolar transistors for their speed, *p*-channel and *n*-channel MOSFETs for their process simplicity, and CMOS for their low power dissipation. BiCMOS combined bipolar and CMOS transistors on the same silicon chip. As their dimensions have become ever smaller over the years, breaching the micron level during the 1980s, CMOS devices steadily improved in speed while maintaining their low



Evolution of semiconductor technology since the invention of the transistor.

power dissipation. Since the early 1990s, CMOS has become the technology of choice for digital devices; bipolar and BiCMOS transistors are primarily used for analog and microwave applications.

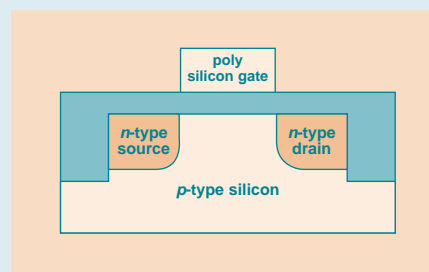
Microchip fabrication involves the sequential application of many processing steps. For example, CMOS manufacturing employs literally hundreds of individual steps — of a few basic types. The most important is photolithography, in which a pattern is created on the chip surface by exposing a light-sensitive layer (photoresist) with an image of this pattern; the developed image in the photoresist is then used as a selective mask in removing the underlying material. The resolution of this process determines the minimum size of the transistors that can be fabricated and hence the density of components on the resulting microchip. By the end of the 20th century, individual features of CMOS transistors were about 250 nanometers across, and gigabit microchips had become possible.

Another basic process entails the formation of insulating or conductive

films. Silicon dioxide films are readily formed by thermal oxidation or deposition, while films of other materials can be formed using various processes such as chemical vapor deposition. By employing a combination of lithography and etching, microchip manufacturers can then pattern these films as desired. Local oxide films, for example, can be formed by masked oxidation of silicon.

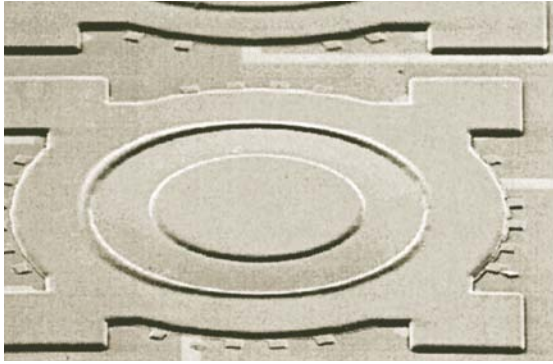
A third basic microchip manufacturing process involves increasing the level of certain impurities in selected areas of the silicon. This is achieved by diffusing these impurities from a source material or by implanting ions of them. Silicon-oxide or silicon-nitride films are commonly used as diffusion masks, while the layers of photoresist or other films serve as masks for ion implantation. These processes can be used to change the conductivity types of selected regions from *p*-type to *n*-type, or vice-versa, thus creating *pn* junctions in the silicon.

The fabrication of a microchip typically has two main parts, the front-end and the back end. The former consists of forming individual devices in the



Schematic diagram showing the cross section of an *n*-channel MOS field-effect transistor, as used in a modern CMOS microchip. Metal contacts and wiring are not shown.

silicon, while in the latter metal wires are added to interconnect them into the desired circuit and system functions. The silicon wafer is then sliced into individual microchips, which are placed on a module or board containing wires whose purpose is to make interconnections among the microchips and to other system components.



50 YEARS OF ELECTRON DEVICES

1990s

TOWARD  
A GLOBAL  
SOCIETY



**S**PURRED BY A DRAMATIC THAW IN INTERNATIONAL relations, the world became a much closer and more intimate place during the 1990s. The Cold War stumbled to a dramatic end in 1991, when the Soviet Union collapsed after a bungled August coup. Germany was reunited after more than three decades of division, while China and Eastern Europe hastened to rejoin the world economy. Trade relations warmed as tariffs fell in many parts of the world. And the U.S. Congress began vying with the next President, Bill Clinton, to slash the swollen annual budget deficits and reduce the mountainous national debt — helping stimulate the longest period of economic growth in the nation's history.

At the throbbing heart of this expansion was a great boom in the computer, semiconductor and telecommunications industries that occurred in large part due to the impact of the Internet and World Wide Web upon business and everyday life. Improvements in computers and communications relied heavily upon advances in electron devices — and increasingly upon improved electro-optical devices. Market pressures for smaller, faster and better devices prodded these technologies onward. The miniaturization of microchip components continued its relentless march toward submicron dimensions — leading to microprocessors having millions of transistors and memory chips approaching gigabit storage capacities by the century's close. In part due to increasingly high costs, multinational microchip manufacturers began to form strategic alliances to develop products and technologies jointly. Semiconductor foundries also emerged, mainly in the Asia-Pacific region, providing manufacturing services to chip-design firms



Bill Van Der Vort (back row, left) with the EDS staff.

as well as established chipmakers. The semiconductor industry itself became increasingly globalized.

During the 1990s, one increasingly began to encounter the terms “nanoscale” and “nanotechnology,” as it became possible to envision producing device features — and perhaps even entire electron devices — that could be measured in tens of nanometers. Prior to this decade, such possibilities had been largely regarded as science fiction or the wild ravings of futurist ideologues. But after the discovery of spherical carbon-60 molecules (better known as “Buckyballs”) and cylindrical carbon nanotubes, as well as the development by various research groups of single-electron transistors, these ideas no longer seemed so far-fetched. Features were beginning to approach the size where the quantum-mechanical behavior of electrons could not be ignored any more (see Sidebar 4.2).

With the Electron Devices Society in great financial condition in 1990 and AdCom's enthusiastic approval, the EDS leadership set out to hire an Executive Director. A search committee that included Casey, Smits and Terman interviewed candidates that summer and offered the position to Bill Van Der Vort, who had worked at IEEE since 1977, most recently as Manager of the Systems Department. Accepting this offer, he started as EDS Executive Director in August 1990 and has been serving in this capacity ever since. He has led a growing team at the Society's Executive Office in Piscataway, New Jersey, that now includes nine people. They manage the Society's business and finances, coordinate its myriad meetings, and support the editing and publishing of its newsletter and professional journals.

## Toward a Global Society



**Lew Terman, EDS President  
from 1990 to 1992.**



**Michael Adler, EDS President  
from 1992 to 1994 and  
IEEE President-elect 2002.**

One major thrust of the early 1990s was to complete the efforts begun during the prior decade to convert the Society into a truly international organization. In 1990, Roger Van Overstraeten of Belgium was elected to AdCom, its first European member in more than a decade. Shortly after, it became standard EDS policy to have at least two elected AdCom members from Region 8 (Europe, Africa, and the Middle East) and another two from Region 10 (Asia-Pacific, Australia, and New Zealand). To accommodate this policy, AdCom's total membership grew from 18 to 22 — the first of several increases in the 1990s. And to make its growing activities more effective, an Executive Committee was established consisting of the elected officers, the junior and senior past presidents, the chairs of key committees, and the Executive Director.

Under the leadership of Terman and Michael Adler, who served as EDS Presidents in the early 1990s, the Society's efforts at globalization moved into high gear. During their tenure in office, new chapters were established in Australia, Canada, China, Egypt, France, and Germany, as well as in other countries. This rapid expansion was aided by the appointment of Cary Yang as Chairman of a new Regions/Chapters Committee. Executive Committee members occasionally visited these chapters and regions to help foster better communications and membership services. By the time Adler stepped down in 1994, there were 59 EDS chapters in all, with 26 of them located beyond U.S. borders; by the end of 1996, more than half the chapters, 48 out of 85, were outside the U.S. The new EDS logo, as redesigned by Terman in 1992, reflects the Society's broad international character — sporting a lone electron, represented by a spin vector, circling the globe.

In 1990, the Society also began to consider publishing a new journal about microelectromechanical systems (MEMS) with the American Society of Mechanical Engineers. These devices, which have features as small as a micron, are fabricated with many techniques (such as photolithography and molecular-beam epitaxy) that are used to produce microchips, but they possess mechanical as well as electrical behavior. At the end of 1990, AdCom approved such a new publication, which had been proposed by Richard Muller of the University of California at Berkeley. The *IEEE/ASME Journal of Microelectromechanical Systems* began publication in March 1992, with the IEEE Robotics and Automation Society collaborating on the effort.

In its December 1993 meeting, AdCom decided to reinstitute publication of a quarterly newsletter for EDS members, to begin with 12 pages and grow as needed. Ever since 1990, when the Division I magazine *Circuits and Devices* was unbundled from the standard membership package, communications between the Society's directorate and its increasingly far-flung membership had often been difficult. To address this problem, the Executive Office began publishing the EDS Newsletter again in 1994, with six regional editors and Krishna Shenai as Editor-in-Chief.

In 1993 AdCom also approved the establishment of another award, the EDS Distinguished Service Award, to be presented every year to an individual member "to recognize and honor outstanding service to the Electron Devices Society and its sponsored activities." In 1994, the first award was presented to Friedolf M. Smits, who had served as EDS Treasurer during much of the 1980s and managed to put the Society on the stable financial footing it achieved



**EDS Region 10 Chapters Meeting in Kyoto, June 1999,  
held in conjunction with the first EDS AdCom  
meeting held outside the United States.**



by decade's end. Subsequent winners of the award have included Adler, Terman, Al Mac Rae, George Smith, Dexter Johnston, John Brews, and Craig Casey.

During the latter half of the decade, the Society continued to support the publication of a growing diversity of professional journals while placing increased emphasis on electronic editions. The new *IEEE Journal of Technology Computer Aided Design*, approved by AdCom in 1995 and published beginning in 1997, was the first completely electronic EDS publication. For those who wanted to receive them in digital format rather than on paper, the Society's two leading journals — *Electron Device Letters* and *Transactions on Electron Devices* — became available on CD-ROM in 1997. That year the Science Citation Index, Inc., which evaluates the professional impact of scientific and technical publications, rated these two EDS journals near the top of its overall listings: fifth and eighth, respectively, out of 171 in all.

That same year, AdCom approved an agreement with the Electrochemical Society to copublish and market yet another journal, the *IEEE/ECS Electrochemical and Solid-State Letters*. Like *Electron Device Letters*, it featured brief articles and had a similarly rapid turn-around time from submission to publication. Published in both paper and electronic editions, the first issue of this journal appeared in July 1998.

The list of professional meetings supported (at least partially) by the Electron Devices Society also continued to grow and diversify. Where EDS had supported 39 meetings at the beginning of the 1990s, the total grew to 68 by 1996 and continued to climb for the rest of the decade. The annual

Symposium on VLSI Technology had become so popular that AdCom occasionally held its spring meeting there rather than at the Device Research Conference. This once-favorite gathering had steadily declined in attendance, to about 300 by the late 1990s, in part due to the competition from all the specialized technical meetings then going on. The growth and diversification of EDS meetings underscored the great wisdom of establishing a full-time, professional management team, for the Society could never have supported all these meetings — more than one per week — without it.

The booming finances of the Electron Devices Society bore out this foresight, too. Its annual surpluses averaged more than \$200,000 during the first half of the decade, so that by 1995 the Society held reserves of about \$2.5 million — most of it securely lodged in long-term investment funds. Many of these surpluses came from the International Electron Devices Meeting, which had begun to offer short courses on cutting-edge technologies for additional registration fees. But the best years were yet to come. During the latter half of the decade, the annual surplus averaged more than \$800,000. In 1999 alone, it reached a whopping \$1.5 million, about equal to the Society's entire reserves when the decade began! By the turn of the century, the EDS reserves had swollen to more than \$7.2 million.

In superb financial condition, the Society could now easily afford to support many more activities — and do them better — than it had previously. Travel funds to encourage visits of Executive Committee members to chapters in Europe and Asia were established early in the decade.



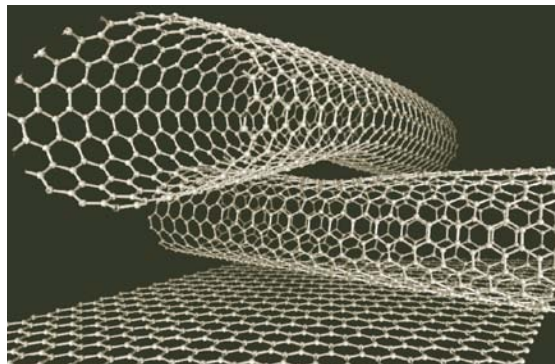
Third EDS Region 8 chapters meeting at The Hague, September, 1995.

AdCom approved substantial increases in the cash prizes for the various EDS awards and instigated a new Chapter of the Year Award in 1997. It also agreed to support the Jack Morton Award (which had until then been funded by AT&T and Lucent Technologies). And the Society started to fund some of the activities of the new IEEE History Center at Rutgers University, with a total contribution of \$65,000 during the 1990s. In turn, the Center began to do a series of oral-history interviews with key EDS officers and members in preparation for the EDS golden jubilee celebrations scheduled for 2002.

As the twentieth century (and second millennium) ended, the IEEE Electron Devices Society found itself in an enviable intellectual and financial condition. The roster of EDS chapters now numbered 99, spread widely across the globe, and the total membership exceeded 13,000 — including more than 5,000 outside the United States. The Society published or copublished nine professional journals, two of them rated among the best in the world, and two of which were electronic journals. And it now sponsored or cospon-

sored over a hundred professional meetings, one of which (the annual IEDM) had an attendance that usually exceeded 2,000.

As the third millennium began, the impact of electron devices upon modern life was impressive indeed. During the previous decade, the world had effectively become much smaller and faster paced, due in large part to light-speed voice-and-data communications over global networks of copper and glass, which owed their very existence to electron and electro-optical devices that had been pioneered largely by the Society's members. Broadband satellite and wireless communications relied heavily on these devices, too. And the march of miniaturization continued toward device features at and even below the 100 nanometer scale — much smaller than the wavelength of visible light. As the number of components on microchips continued to double every 18 months, following Moore's apparently inexorable Law, it seemed inevitable that this relentless progress would continue for at least another decade.



50 YEARS OF ELECTRON DEVICES

**2000s**

INTO  
THE THIRD  
MILLENNIUM



## Into the Third Millennium



EDS Millennium Medalists in attendance at the International Electron Devices Meeting, December 10, 2000.

### THE INITIAL YEARS OF THE THIRD MILLENNIUM

provided an excellent opportunity for reflection upon the impact that electron devices have had on the world over the past century — and upon the contributions of the individuals and institutions that invented and developed them. Telephone and wireless communications were in their infancy a century ago, and electronic computation did not even exist. Today, thanks in large part to electron devices, people can witness via satellite events on the far side of the globe at almost the moment of occurrence. They can converse over cellular phones from a rapidly growing variety of locations throughout the world. And they can afford to purchase computers whose microprocessors churn away at over a billion cycles per second. Members of the IEEE Electron Devices Society have made crucial contributions to enable all these marvelous possibilities.

To honor some of its leading members, especially those who had generously dedicated their time and efforts to its success over the past five decades, the Society awarded 45 Millennium Medals at the 2000 International Electron Devices Meeting. EDS members and former officers — including many individuals mentioned in this brief history — came to San Francisco from around the world to accept their medals. They were honored for all their “outstanding contributions to the Electron Devices Society and to the field of electron devices” in general.

The new EDS-sponsored Andrew S. Grove Award was also presented for the very first time at this gathering — to Wolfgang Fichtner of the Swiss Federal Institute of Technology in Zurich, for his “outstanding contributions

to semiconductor device simulations.” Financial support for this prize, which replaced the Jack A. Morton Award, had been approved by AdCom in 1999; it is given to an individual or group (of not more than three persons) “for outstanding contributions in the field of solid-state devices and technology.” The following year, Al Tasch of the University of Texas, Austin, won the award for his “contributions to MOS technology, and ion implantation and device modeling.”

In June 2000, Grove had received the Institute’s highest distinction, the IEEE Medal of Honor, for “pioneering research in characterizing and modeling metal-oxide-semiconductor devices and technology, and leadership in the development of the modern semiconductor industry.” He joined such luminaries as Bardeen, Esaki, Kilby, Noyce, Shockley and Townes — as well as George Heilmair, Rudolf Kompfner, Donald Peterson, John Pierce, and John Whinnery — in being recognized for his exceptional contributions to the field of electronics. And together with Bill Gates of Microsoft, Grove was honored by the first IEEE President’s Award, given annually for distinguished leadership and public contributions, “for continuing to create untold opportunities in the fields of interest of the IEEE, its members and society, and for his profound impact on the semiconductor industry and the computer industry worldwide.”

But the crowning recognition of achievement in electron devices came that October, when the Royal Swedish Academy of Sciences announced that Jack Kilby, Zhores Alferov and Herbert Kroemer had won the Nobel Prize in physics. Kilby was honored “for his part in the invention of the integrated circuit,” while Alferov and Kroemer were



Herbert Kroemer (left)  
receiving his Nobel Prize  
from the King of Sweden.

recognized “for developing semiconductor heterostructures used in high-speed- and opto-electronics.” (Although he clearly deserved to, Robert Noyce could not share in this prize, since he had died in 1990.) Reflecting the increasingly global nature of the discipline, a Texas electrical engineer born in Kansas, a German-born California physicist (both of them long-standing EDS members), and a Russian physicist from St. Petersburg would share science’s most prestigious prize.

On December 10 — at almost the same time EDS members were accepting their Millennium Medals a third of the way around the globe — Kilby, Kroemer and Alferov marched onto the stage of Stockholm’s Concert Hall to the accompaniment of trumpet fanfares. As Bardeen, Brattain and Shockley had done over four decades earlier, they followed a pair of student marshals bedecked in blue and gold sashes, walking before two phalanxes of previous Nobel laureates. With an audience of over half a billion watching on television screens across Europe and around the world, Tord Claeson, Chairman of the Nobel physics committee, delivered the charge. “I have briefly described some consequences of your discoveries and inventions,” he said, wrapping up his brief encomium. “Few have had such a beneficial impact on mankind as yours.” Following that, the three men accepted their citations and gold medals from the King of Sweden, joining such illustrious figures as Albert Einstein, Enrico Fermi, and James Watson in the Pantheon of science. It had been a very good year for electron devices.

“The advanced materials and tools of microelectronics are being used for studies in nanoscience and of quantum

effects,” Claeson had noted in concluding his speech. He confidently predicted that “there will be continued development, as we may be only halfway through the information technology revolution.” The events of that year and the next were already beginning to prove him right. The scientific and technological breakthroughs that these three men and others had achieved were still yielding penetrating insights and potentially revolutionary electron devices.

Existing techniques are actively being applied to the fabrication of nanoscale devices such as quantum corrals, wells, wires and dots — in which electrons move in only one or two dimensions, or are trapped around a single point. The explicitly quantum behavior imposed by such a close confinement promises important new applications. The quantum cascade laser developed by Bell Labs is just one example of nanotechnology already being put to practical use, such as measuring the levels of atmospheric pollutants (see Sidebar 4.2).

Other researchers have managed to fabricate nanoelectromechanical systems (NEMS) in silicon. One such device is an electromechanical transistor developed by University of Munich scientists, in which a single electron shuttles from source to drain upon a silicon pendulum vibrating at frequencies up to 100 MHz. And in June 2001, researchers at Intel announced the fabrication of silicon-based transistors with features measuring only 20 nanometers across. With such ultramicroscopic electron devices, companies can envision one day manufacturing silicon microchips sporting billions of transistors. That very same summer, Motorola scientists announced that they had developed

## Into the Third Millennium

a revolutionary way to mate heterostructures made of gallium arsenide and other III-V compounds with silicon microstructures. This advance promises a whole new generation of microchips that can offer both computational and optoelectronic functions.

Still other scientists and engineers are pushing the electron-device frontiers into domains where they no longer rely on silicon. In April 2001 IBM researchers announced that they had fabricated large arrays of transistors made from carbon nanotubes. The following August, the same group reported the successful operation of a logic circuit built solely out of

such nanoscale components. Meanwhile, Hewlett-Packard scientists have been developing custom-designed carbon-based molecules that can serve as on-off switches. Such “molecular electronics” devices may offer dramatic increases in the performance of the electronic circuits of the future.

The “information technology revolution” spawned by the 1947 invention of the transistor clearly has a long way to go before it runs its full course. The flood of striking innovations that have occurred over the past fifty years, in the wake of this epochal electron device, still shows little sign of letting up.



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