The Transistor Turns 40

The enduring, innovative transistor enters yet another age

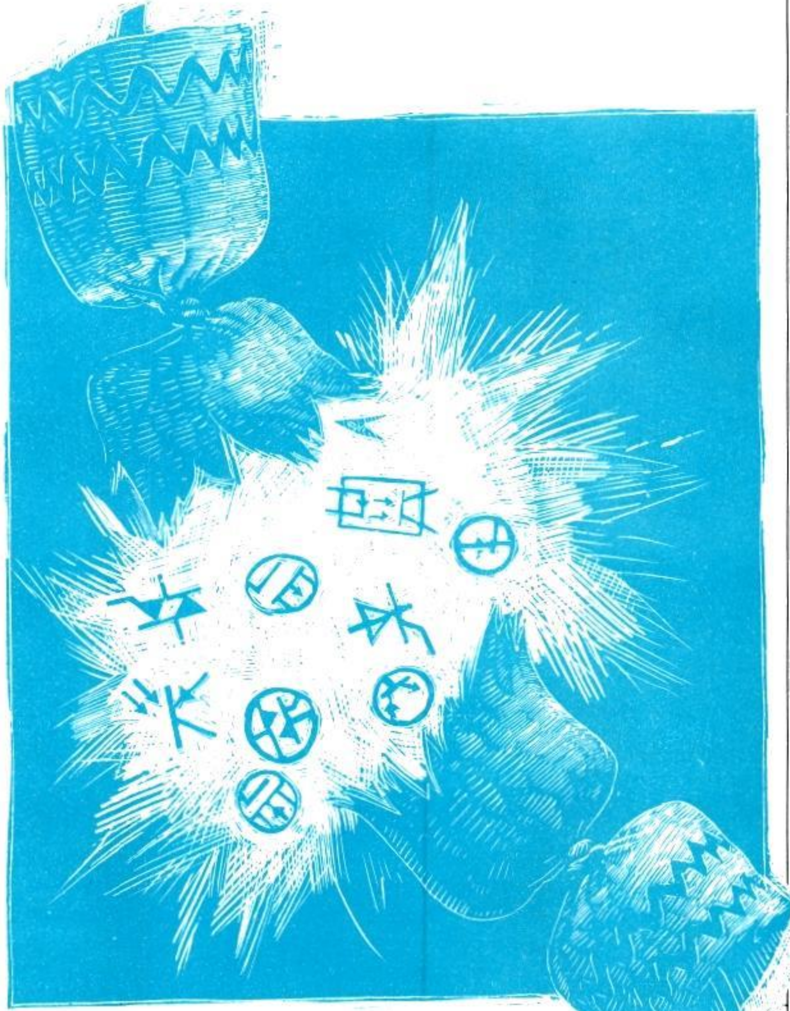
By Mar Jean Olson, Assistant Editor

Imagine your life today had American physicists Brattain, Bardeen, and Shockley not gathered on a cold December day in a New Jersey Bell Telephone Laboratory. Can you see yourself at work surrounded by anodes, cathodes, grids, and vacuum tube amplifiers? Heralded as "a new rival of the vacuum tube", that "tiny marvel"--the transistor--is currently celebrating its 40th anniversary.

"Not much larger than the tip of a shoelace" the transistor ushered in the solid-state revolution. It inaugurated the semiconductor electronics industry and brought dramatic changes in fields ranging from communications, computing, medicine, and space exploration. By demonstrating the "transistor effect" (the amplification of a voice signal by a semiconductor crystal in an electrical circuit) and by making their observation known to the public, those three men—Walter Brattain, John Bardeen, and William Shockley--altered the course of our lives and received the 1956 Nobel Prize in physics for their discovery.

At first the scientific community did not know what to make of the transistor development. Some viewed it as a flash-in-the pan oddity. Popular hobbyist journals included it next to other earth shattering inventions like the "raincoat fabric that breathes", "stainless-steel clad copper kitchenware", "permacrystal radios", and "pocket-sized picture tube reactivators." Some pundits adamantly declared, "The transistor will not replace the vacuum tube". Others, like those at *Radio & Television News*, made cautious concessions, " Although the little germanium devices open the door to many potential electronic applications, do not restructure your projects because it is highly improbable that they will eventually replace the vacuum tube." Even Dr. Ralph Bown, then the director of Bell research, insisted, "The transistor will not make obsolete all vacuum tubes." But the test of time shows that the transistor was hardly a gimmick.

For the roots of the transistor we have to turn the clock back to 1906 when a young American electrical engineer named Lee de Forest made a startling discovery. He found that by placing an electrified wire grid across the path of a stream of electrons in a vacuum tube, the flow of electrons could be controlled (interrupted, reduced, or stopped entirely). A feeble current entering at one end could even be amplified to make a powerful egress. De Forest's simple invention gave birth to the technology of electronics. From it came radio, television, radar, X-ray cameras, electron microscopes, guided missiles, electronic calculators and burglar alarms, and robot machine tenders, to name just a few. Most importantly de Forest's tri-



ode tube paved the way for another deceptively simple discovery--that of the transistor at Bell Labs.

TRANSFERRING RESISTANCE

Shockley's colleague John Pierce (whom some credit over Arthur C. Clarke for the idea of the first practical communications satellite—a project unthinkable without transistors) coined the term *transistor* because it *trans*fers an electrical signal across a re*sistor*. The transistor pared down de Forest's delicate tube to a basic rig consisting of a couple of fine wires (*cat's whiskers* to the radio aficionado) and a small crystal. No vacuum needed! No heating necessary! No warm-up delay!

The original experimental model at Bell was "almost vanishingly small" (about the size of a pencil eraser) and operated on a miniscule amount of power (about one tenth that used by an ordinary flashlight bulb). This reduced bulk was of great early importance in the infantile stages of transistor development since the size of the tube largely determined the size of the apparatus. The trendy television receiver required at least two dozen tubes while the celebrated computing machine at the University of Pennsylvania known as *ENIAC* used 18,000! Through painstaking labour, researchers produced "subminiature" vacuum tubes less than an inch long for special purposes, but the transistor halted further research into low-power vacuum tube applications by virtually turning the world upside down. It used so little power so effectively. As a radio amplifier for example, its efficiency rated 25% against the vacuum tube's 10%. It cried out for smaller sized batteries to operate portable devices. It made possible discrete hearing aids, handy portable radios, and compact electronics for aircraft, and it promised endless possibilities when joined in marriage to the printed circuit.

The transistor was the outcome of purely scientific curiosity. At first glance it looks extremely simplistic in design—a germanium crystal soldered to a metal disk, contacted on its other face by two tungsten wires slightly more than a thousandth of an inch apart--but it resulted from an elaborate experiment. Shockley stumbled upon the principle while investigating the behaviour of semiconductors. These substances (of which germanium is one) behave unlike familiar electrical conductors such as copper or silver or familiar insulators such as rubber. Shockley found a way to alter the conductivity of germanium so that it let current flow rapidly in response to a signal. To understand its conception, it helps to review the functions of the electronic tube and the way in which electric current is conducted by a solid.

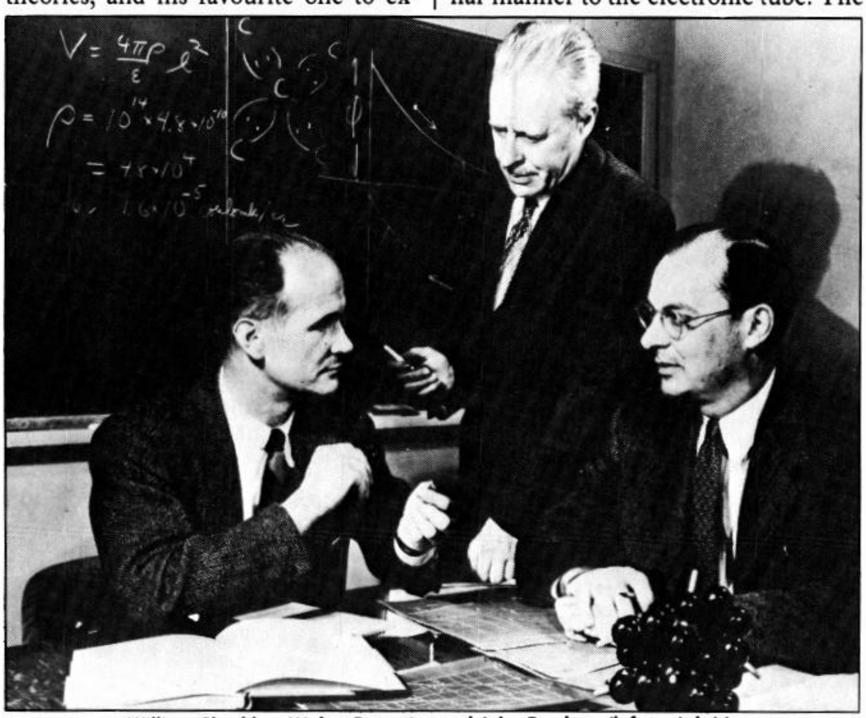
The electronic tube itself was invented in 1905 by English physicist John Ambrose Fleming who passed an alternating current to a filament inside a vacuum tube and observed that the electrons would boil off the end of the filament as free particles and would then travel across the vacuum to a positively charged plate at the opposite end. This phenomenon, known as the *Edison effect*, had been noticed much earlier by Thomas Edison, but Edison found neither explanation nor practical use for it. Fleming called his tube a *diode* because of its two electrodes—the filament and the plate—which could be used for detecting radio signals. De Forest's addition of the grid to manipulate the electrons made the tube a triode and was the crucial step into versatility and usefulness.

WATCH THAT SPACE

Shockley liked to call upon rudimentary analogies to illustrate sophisticated theories, and his favourite one to explain the mysterious electrical properties of semiconductors follows. "To see how semiconductors let electricity flow backward, picture this: You are driving on a crowded highway, packed with cars, bumper to bumper. Since there is an open space near the front of the line, each vehicle ahead of you takes its turn moving up. Now jump up above the traffic as an observer airborne in a heliocopter. Seen from above, the empty space will appear to move backward. So it is with the transistor's germanium surface; there is an occasional atom with an 'incomplete' quota of electrons. An electron moves in from the next atom making room for another, and this replacement is so rapid that the movement spreads from one contract point to the next in a ten-millionth of a second." This then was Shockley's rough picture of the theory: the ability of a crystal semiconductor to conduct electricity is due to the presence of 'impurities' that free some of the electrons which would otherwise have been occupied in bonding atoms.

THEORETICAL SNAGS

Bardeen became intrigued by a snag in the basic semiconductor theory. When a semiconductor is placed between two metallic contacts in an electrical circuit (one the point of a fine wire and the other a metal block), the arrangement acts as a rectifier in a similar manner to the electronic tube. The

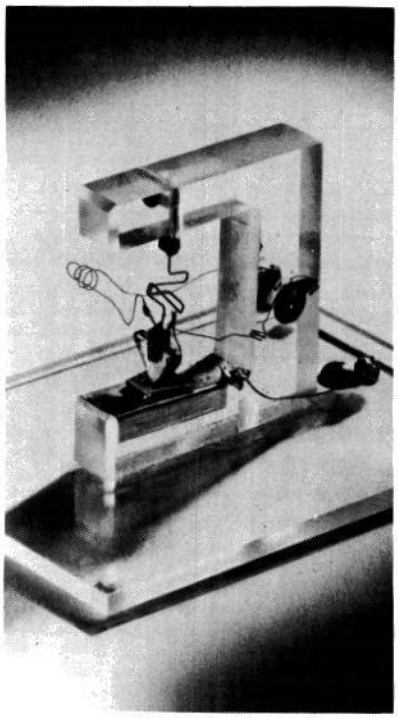


William Shockley, Walter Brattain, and John Bardeen (left to right) in 1948, just shortly after their discovery of the transistor effect.

reason? The point contact between the semiconductor and the cat's whisker has a lower resistance to electrical flow in one direction than in the other. This difference in resistance accounts for the rectifying action of a crystal. Bardeen supposed the resistances to current would vary with the physical properties and materials forming the contacts. His experiments, however, showed otherwise. Since the properties of the materials made much less difference than the theory predicted, Bardeen decided that something unexplained must be occurring at the surface of the crystal. Under Shockley's direction, Bardeen undertook his theoretical study of the conditions at the surface of a semiconductor.

Bardeen's modifications of the theory proved correct in Shockley's laboratory. He hypothesized that there were localized states on the surface of a semiconductor which differed from those on the interior and predicted the number of states to be equal to the number of surface atoms. Like impurities in a crystal, these states produced holes capable of carrying current, and the holes consisted of spaces on the exposed side of the atoms which normally would have been filled by electrons from adjacent atoms. Thus Bardeen made clear the central concept that the surface of a semiconductor is a better carrier of electricity than its interior. His theory also satisfactorily accounted for the fact that the rectifying action of a crystal occurred independently of the particular metal composing the cat's whisker. Shockley reasoned that an externally applied electric field should increase the conductivity of a crystal by inducing the electrons out of the bonds. So he placed a sheet of germanium in an intense electric field. The increase in conductivity of the germanium was less than the original theory proposed, but nevertheless, it supported Bardeen's modified theory. The conductive layer of electrons or holes on the surface of the germanium acted as a shield against penetration of the material by the electric field, just as metallic shields around parts of radio sets kept away stray electric fields.

Colleague Brattain joined Bardeen and Shockley to refine the work which indicated a method of controlling the electrons or holes in a crystal, and voilà--the transistor. The "harried scientists" demonstrated their transistor as an amplifier for voice, television picture, pulse and oscillator. They even constructed a superheterodyne radio receiving set operating completely without vacuum tubes. Transistors were used in the set's amplifiers and in the local oscillator while conventional germanium crystal detectors served as mixer and detector and selenium rectifiers in the power supply. This set performed as well as a conventional five-tube superheterodyne receiver—the transistor was on its way to stardom. Soon the US Army and Navy commenced testing with the immediate goal of miniaturization in mind—Would the walkie-talkies and handy-talkies of the Second World War be obsolete? Would Dick Tracy's wrist-watch shortly be a reality?



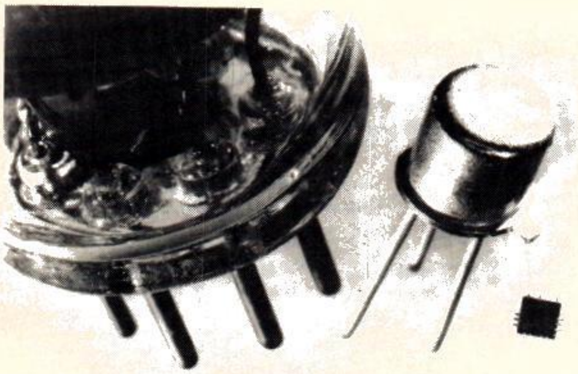
The first transistor ever assembled.

FUTURE DEVELOPMENTS

Following those early days of investigating the holes in the crystal lattices of atoms, germanium was quickly upstaged by the more abundant and less temperature-sensitive silicon with its natural ability for converting light into electricity. Most importantly, the transistor's switching ability proved magnificent. It produces electromagnetic waves of ultra-high frequency and opens and closes circuits in billionths of a second. This valuable switching power of the transistor provided the technology for the computer revolution because without transistors to replace cumbersome vacuum tubes, there would be neither pocket calculators nor handy battery-operated radios. Transistors are the ghosts in such varied machines as heartbeat regulators, stereo systems, and electronic guitars. These miniscule powerhouses are also the driving force behind satellite communications.

Perhaps the most far-reaching impact of transistors is in the field of communications because they form the key components in telephones, PBXs, terrestrial microwave radio relay systems, and undersea and terrestrial cable systems. Back in 1962 the launch of Telstar 1 paved the way for live satellite broadcasts, and now the next evolutionary step in telecommunications is the Integrated Services Digital Network (ISDN)—the new network inconnection standard that permits voice, data, and video information to be transmitted digitally as easily as today's handling of voice traffic. In the words of Tony Lash, president of TIL Systems in Toronto and participant in Canada's first public application of ISDN conducted out of Ottawa by Bell Canada, "ISDN is the future."

In addition to ISDN developments, the transistor has made possible experimental optical switches which operate at speeds measured in picoseconds (trillionths of a second)—the time it takes for light to traverse the period at the end of this sentence. Physicists are now working with femtosecond speeds (one-quadrillionth of a second) with the hope that photonics technology will one day lead to a practical optical computer at least 1,000 times more powerful than today's best supercomputers. Transistors have even entered the healthcare sphere where biochemists are building neural networks on chips that mimic the way brain cells retrieve stored information and solve problems. Test chips have already recalled stored memories using incomplete data and have done so within a few millionths of a second—about one thousand times faster than biological neurons can perform a comparable memory task. This sampling of examples shows the tremendous influence that Shockley, Brattain, and Bardeen's "tiny marvel" had on the direction of electronics. From its humble beginnings as a flash-in-the-pan oddity to its 40th birthday celebration, the transistor altered the course of our lives and continues to define the world of electronics, packaged in their thousands as integrated circuits. CEE



30 YEARS OF ELECTRONICS HISTORY IS represented in this photo; from left to right, a vacuum tube, a transistor, and an early integrated circuit.

On June 30, 1948, Mr. Harvey Gernsback and the author were among a group of science writers and other members of the press that attended a historic press conference and demonstration at the Bell Telephone Laboratories in New York City. The conference was called to announce the invention of the transistor by Drs. John Bardeen and Walter H. Brattain of Bell Labs.

The transistor, as demonstrated, was a revolutionary device; hardly larger than the tip of a shoelace, it could do many of the things a vacuum tube could do, and many other things as well—all with incredibly small amounts of power. Of miniscule size in comparison with the smallest vacuum tube, the transistor is exceptionally rugged. It has no vacuum, no grid, no plate, and no cathode. Further, it has no warm-up delay.

The first amplifying semiconductor was the point-contact transistor. As shown in Fig. 1, it consists of two thin wires spaced only a few thousandths of an inch apart with their ends touching the surface of a thin wafer of germanium. The flow of current in one of the wire points controls the flow of current through the other.

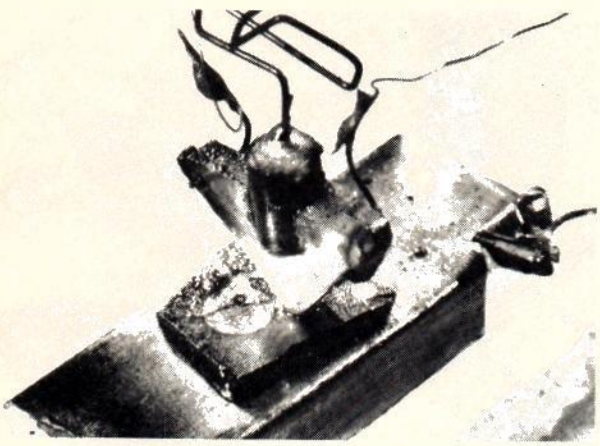


FIG. 1—THE FIRST TRANSISTOR consisted of two thin wires, spaced only a few thousandths of an inch apart, with their ends touching a wafer of germanium.

The next breakthrough from Bell Telephone came in March 1950 with the announcement that Dr. J. N. Shrive had invented a new transistor controlled by light rather than by electric current.

In July of the following year, the junction transistor, invented by Dr. William Shockley, shown in Fig. 2, was announced. It was extremely small for its time, occupying only about 1/400th of a cubic inch, and consumed even less current than the earlier point-contact device.

In the ten years following the invention of the first transistor, the world of the semiconductor did not stand still. Nor did all the exciting inventions come from Bell Labs. The germanium diode had been invented long before the transistor; the 1N34, 1N60 and similar diodes from Sylvania and GE were the latest toys of the electronics experimenter and hobbyist.

FIG. 2—TWO SEMICONDUCTOR PIONEERS. Dr. William Shockley is shown at the right; Mr. F.E. Blount is at the left.

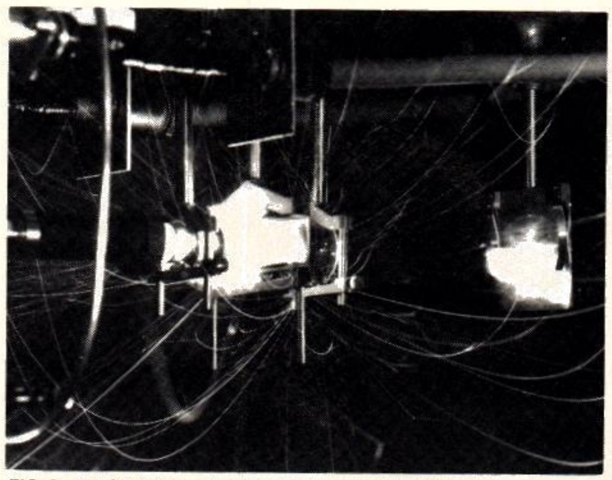


FIG. 3—THIS LASER, developed by Raytheon in the early 1960's, could deliver more than 350 joules of energy.

The selenium rectifier replaced the copper-oxide tungar rectifiers in battery chargers and low-voltage power supplies. And, pretty soon, the selenium rectifier replaced the rectifier tube in AC-DC radios.

The germanium power rectifier was used for a while, but it was soon pushed aside by the silicon rectifier—a device that has held its place in electronics ever since, both as a small-signal detector and as a power-handling rectifier.

Those (and many other) developments from the early days of semiconductors were not the only things making electronics news. FM, TV, high-fidelity, and the laser, shown in Fig. 3, were all in their infancy then, and scarcely a week passed without the announcement of a new and revolutionary development.

Doubtless, old-timers who followed **Radio-Craft** and **Radio-Electronics** can recount many tales of exciting headline-making advances in electronics. **R-E**