THE INDUSTRIAL STRENGTH

by MICHAEL RIORDAN

MORE THAN A DECADE before J. J. Thomson discovered the electron, Thomas Edison stumbled across a curious effect, patented it, and quickly forgot about it. Testing various carbon filaments for electric light bulbs in 1883, he noticed a tiny current trickling in a single direction across a partially evacuated tube into which he had inserted a metal plate. Two decades later, British entrepreneur John Ambrose Fleming applied this effect to invent the “oscillation valve,” or vacuum diode—a two-terminal device that converts alternating current into direct. In the early 1900s such rectifiers served as critical elements in radio receivers, converting radio waves into the direct current signals needed to drive earphones.

In 1906 the American inventor Lee de Forest happened to insert another electrode into one of these valves. To his delight, he discovered he could influence the current flowing through this contraption by changing the voltage on this third electrode. The first vacuum-tube amplifier, it served initially as an improved rectifier. De Forest promptly dubbed his triode the audion and applied for a patent. Much of the rest of his life would be spent in forming a series of shaky companies to exploit this invention—and in an endless series of legal disputes over the rights to its use.

These pioneers of electronics understood only vaguely—if at all—that individual subatomic particles were streaming through their devices. For them, electricity was still the fluid (or fluids) that the classical electrodynamicists of the nineteenth century thought to be related to stresses and disturbances in the luminiferous æther. Edison, Fleming and de Forest might have been dimly aware of Thomson’s discovery, especially after he won the 1906 Nobel

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Prize in physics. But this knowledge had yet to percolate out of academic research labs such as the Cavendish and into industrial workshops. Although he had earned a Ph.D. in physics from Yale, in his daily practice de Forest remained pretty much a systematic tinkerer in the Edisonian vein, trying endless variations on his gadgets in his halting attempts to improve their performance.

VOLUMES COULD be written about the practical applications that owe their existence to the understanding of electricity as a stream of subatomic particles rather than a continuous fluid. While the telephone clearly antedated the discovery of the electron, for example, its modern manifestations—cellular and touchtone phones, telefax machines, satellite communications—would be utterly impossible without such knowledge. And the ubiquitous television set is of course just a highly refined version of the cathode-ray tube that Thomson used to determine the charge-to-mass ratio of his beloved corpuscle. The field of electronics, a major subfield of electrical engineering today, grew up in the twentieth century around this new conception of electricity, eventually taking its name in the 1920s from the particle at its core. (We are perhaps fortunate that Thomson did not prevail in his choice of nomenclature!)

In parallel with the upsurge of electronics, and in some part due to it, came a sweeping transformation of industrial research in America. Once the main province of highly individualistic inventors searching for a fruitful breakthrough, technology development slowly became an organized practice performed by multidisciplinary teams of salaried scientists and engineers working in well-equipped industrial labs. As the century waxed and quantum mechanics emerged to explain the mysterious behavior of electrons, atoms and molecules, these researchers increasingly sported advanced degrees in physics or chemistry. A deeper understanding of the scientific principles governing the behavior of matter gradually became indispensable to the practice of industrial research. As the noted historian of technology Thomas Hughes put it, "Independent inventors had manipulated machines and dynamos; industrial scientists would manipulate electrons and molecules."

Few examples illustrate this evolutionary transformation better than the case of the vacuum-tube amplifier. For almost a decade after de Forest invented it, his audion found little use beyond low-voltage applications in wireless receivers—as a detector of weak radio signals. He simply did not understand that the gas remaining in his tube was impeding the flow of electrons from filament to plate. At the higher voltages required for serious amplification, say in telephone communications, the device began, as one observer noted, "to fill with blue haze, seem to choke, and then transmit no further speech until the incoming current had been greatly reduced."

One corporation extremely interested in amplifying telephone signals was the American Telephone and Telegraph Company, then seeking to develop a suitable "repeater" for transcontinental phone service.

J. J. Thomson inspecting electron tubes in 1923 with Frank Jewett, the first president of Bell Labs. (Courtesy AT&T Archives and AIP Niels Bohr Library)

Among its leading scientists was Frank Jewett, then working in the engineering department of its Western Electric Division. In 1902 he had earned a Ph.D. in physics from the University of Chicago, doing his research under Albert Michelson and befriending Robert Millikan. Harboring a hunch that the electrical discharges in evacuated tubes might serve as the basis for a suitable repeater, Jewett approached his old chum, who in 1911 sent one of his brightest graduate students, Harold Arnold, to Western Electric. Here was a young man steeped in the new thinking, who had just spent several years measuring the charges of individual electrons on oil droplets.

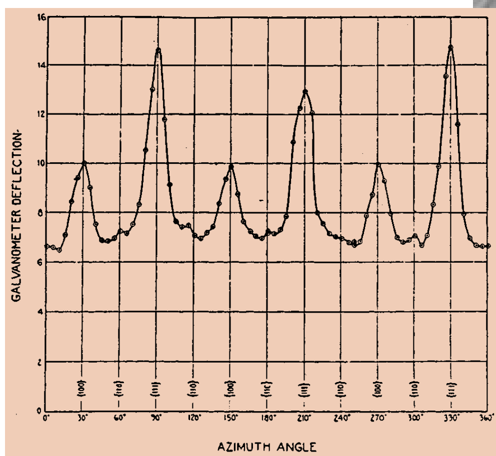
When de Forest demonstrated his audion to Western Electric scientists and engineers in October 1912, Arnold was present. He diagnosed the blue haze as due to the recombination of gas molecules that had been ionized by energetic electrons. Then he solved its problems by use of high vacuum, an oxide-coated filament, and other modifications dictated by a superior understanding of the electronic discharge. (A similar development occurred simultaneuosly at General Electric, but it lost the ensuing patent fight to AT&T, which had wisely purchased the appropriate rights to de Forest's patents.)

Within a year Western Electric was making "high-vacuum thermionic tubes" that served as active elements in excellent telephone repeaters. At the grand opening of the Panama-Pacific Expositon held in San Francisco on January 15, 1915, Alexander Graham Bell inaugurated the nation's first coast-to-coast telephone service, talking to his former assistant Thomas Watson in New York. Recalling this event in his autobiography, Millikan observed that "the electron—up to that time largely the plaything of the scientist—had clearly entered the field as a patent agent in the supplying of man's commercial and industrial needs."

Thus convinced of the value of scientific research in an industrial setting, Western Electric incorporated its engineering department as a separate entity—the Bell Telephone Laboratories—in 1925, naming Jewett its first president. The very next year, as an outgrowth of their research on the performance of vacuum tubes (also called electron tubes), Clinton Davisson and Lester Germer established the wave nature of electrons, which had been predicted a few years earlier by Louis de Broglie. For his pivotal work on electron diffraction, Davisson was to share the 1937 Nobel Prize in physics with the British scientist George Thomson, son of J. J.

Quantum mechanics soon explained the behavior not only of electrons in atoms but of the large ensembles of them that swarm about freely within metals. Based on the theoretical work of Enrico Fermi and Paul Dirac, Bell Labs physicists eventually figured out why an oxide-coating worked so well on tungsten filaments of vacuum tubes. It helped to lower the work function of the

Right: Clinton Davisson and Lester Germer with the apparatus they used to establish the wave nature of electrons. *(Courtesy AT&T Archives)*



Bottom: Graph from their 1927 Nature *article showing diffraction peaks observed in electron scattering from a nickel crystal.*

metal, thereby making it easier for electrons to escape from the surface—and substantially reducing the amount of power needed to heat a filament. Such a fundamental understanding of the physics of electrons proved crucial to further engineering advances in vacuum tubes that saved AT&T millions of dollars annually.

IN THE LATE 1920S and early 1930s, Felix Bloch, Rudolph Peierls, Alan Wilson and other European physicists laid the foundations of modern solid-state physics in their theoretical studies of how waves of electrons slosh about within the periodic potentials encountered inside crystalline materials. Their work resulted in a theory of solids in which there are specific allowed (or forbidden) energy levels—called "bands"—that electrons can (or cannot) occupy, analogous to the Bohr orbitals of early quantum theory. Combined with practical methods of calculating these band structures in actual substances, pioneered by Eugene Wigner, band theory fostered a better understanding of why certain materials act as electrical conductors and others as insulators. And, in a decade when electron tubes reigned supreme as the active components of electronic circuits, band theory began to elucidate the properties of intermediate materials called semiconductors, whose myriad spawn would eventually supplant these tubes throughout electronics.

World War II spurred tremendous practical advances in the technology of semiconductors, largely due to the fact that microwave receivers needed rectifiers able to operate above a few hundred megahertz, where electron tubes had proved useless. Crystal rectifiers, with a delicate metal point pressed into a germanium or silicon surface, filled the gap nicely. By the end of the War, methods of purifying and doping these substances to make easily controlled, well-understood semiconductors had been perfected by scientists at such secret enclaves as the Rad Lab at MIT and Britain's Telecommunications Research Establishment at Great Malvern.

No laggard itself in these pursuits, Bell Labs led the way during the postwar years in applying wartime insights and technologies to the creation of practical new semiconductor components. "The quantum physics approach to structure of matter has brought about greatly increased understanding of solid-state phenomena," wrote its vice president Mervin Kelly—another of Millikan's grad students—in 1945, authorizing formation of a solid-state physics group. "The modern conception of the constitution of solids that has resulted indicates that there are great possibilities of producing new and useful properties by finding physical and chemical methods of controlling the arrangement of the atoms and electrons which compose solids."

The most important postwar breakthrough to occur at Bell Labs was the invention of the transistor in late 1947 and early 1948 by John Bardeen, Walter Brattain, and William Shockley. And a key to their interpretation of transistor action was a new physical phenomenon Shockley dubbed "minority carrier injection"—in which electrons and positively charged quantum-mechanical entities called "holes" can flow by diffusion in the presence of one another. Once again, a detailed scientific understanding of how individual subatomic particles (and what, in certain respects, act like their antiparticles) behave proved crucial to a pivotal advance in electronics.

The transistor happened along at a critical juncture in technological history. For the electronic digital computers that also emerged from wartime research could not have evolved much further without it. The thousands of bulky, fragile electron tubes used in such early,

Lee de Forest, inventor of the vacuum-tube amplifier, and Bell Labs President Mervin Kelly. (Courtesy AT&T Archives)

room-filling computers as the ENIAC and UNIVAC burned out with all-too-frustrating frequency. Only large corporations, the armed services and government agencies could afford these massive, power-hungry monstrosities and the vigilant staff to keep them operating. "It seems to me," Shockley conjectured in December 1949, "that in these robot brains the transistor is the ideal nerve cell."

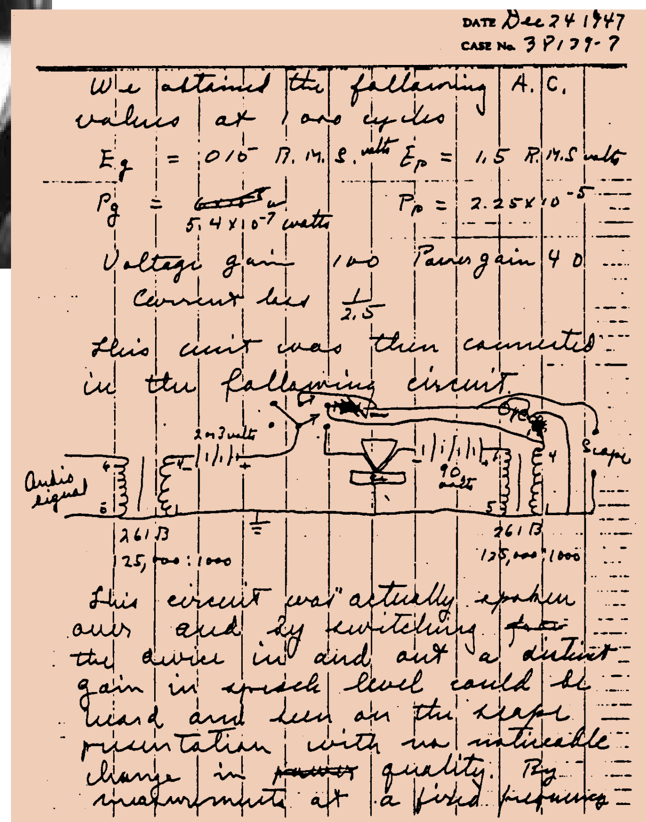
But the transistor has proved to be much more than merely a replacement for electron tubes and electromechanical switches. Shrunk to less than a ten-thousandth of its original size and swarming by the millions across the surfaces of microchips, it has opened up entirely unexpected realms of electronic possibility, which even the most farsighted could not have anticipated during those booming postwar years. The transistor was, as historians Ernest Braun and Stuart MacDonald observed, "the harbinger of an entirely new sort of electronics with the capacity not just to influence an industry or a scientific discipline, but to change a culture."

Characteristically, particle physicists were among the first to glimpse the potential ramifications of this revolutionary new solid-state amplifier. "I would be very anxious to do some experimenting to learn about the techniques of your new Germanium triods," wrote Fermi to Shockley in early January 1949 (misspelling the final word). After receiving a few samples and testing them at his University of Chicago laboratory, Fermi replied, "They really are very fine gadgets, and I hope very much that they might be useful in our work."

THOMSON'S DISCOVERY triggered a spectacular century of innovation in both science and technology. Paced by increasingly detailed knowledge of the electron's properties and behavior, scientists and engineers developed many other advanced devices—lasers, light-emitting diodes, microwave tubes, solar cells and high-speed microprocessors, to name several—that are essential to modern computing and global communications. Today we know the mass and charge of the electron to better than seven significant figures. Aided by quantum mechanics, we can accurately calculate its energy levels in all kinds of atoms, molecules and solid-state substances. Largely taken for granted, such information is crucial for the precision control of electrons at the submicron scales that characterize many leading-edge technologies.

Of critical importance in attaining this deep understanding was the ease with which electrons can be detached from other forms of matter and manipulated using electromagnetic fields. Such features were readily apparent in Thomson's landmark experiments, for example, and Millikan exploited them in his research. In certain key instances the energy required corresponds to that of photons in visible light. This unique partnership between the electron and photon (whose centennial we will also celebrate in the not-too-distant future) is central to much of

Left: John Bardeen, William Shockley, and Walter Brattain, who shared the 1956 Nobel Prize in physics for the invention of the transistor. (Courtesy AT&T Archives)



DATE Dec 24 1947
CASE No. 38139-7

We obtained the following A.C. values at 1000 cycles

E_g = .015 R.M.S. volts E_p = 1.5 R.M.S volts

P_g = 5.4×10⁻⁷ watts P_p = 2.25×10⁻⁵

Voltage gain 100   Power gain 40

Current loss 1/2.5

This unit was then connected in the following circuit

This circuit was actually spoken over and by switching the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in quality. By measurements at a fixed frequency

Bottom: Page from Brattain's lab notebook that records the 23 December 1947 demonstration of the first transistor. (Courtesy AT&T Archives)

advanced technology. Perhaps this complementary relationship is one reason why, during the past decade or so, we have witnessed the emergence of a "photonics" industry that threatens to supplant electronics in some commercial sectors.

No comparable partnership exists, for example, between quarks and gluons. Quarks are *not* detachable, at least not yet, and gluon fields do not extend to infinity like the electromagnetic. It makes all the difference in the world. We still have only rough values for the quark masses, especially the up and down quarks that make up the bulk of ordinary matter. Only a few wild-eyed speculators dare to mention the possibility of "quarkonics" or "gluonics" industries. Maybe one day soon we will manipulate quarks for practical benefit, say by using high-energy electron beams. Perhaps, but I seriously doubt it will ever amount to much of an industry. For now, quarks and gluons remain the playthings of pure physics.

Just a hundred years after its discovery, the electron sits at the core of modern life. Where previous generations of writers, for example, used chemical inks and mechanical devices to cast their ideas onto paper (and deliver them to readers), I have composed this article while staring at a luminous screen—behind which a blazing stream of electrons traces out my fumbling thoughts as my fingertips tap keys that activate transistor-laden microprocessors deep within my computer. And some of you now read my words on luminous screens of your own, conveyed to your desks by surging rivers of electrons and photons pulsating as ones and zeroes through an intricate network that stretches into almost every corner of the globe. The only paper involved in the exchange is the pages marked with red ink that now lie crumpled in my wastebasket.

We all owe a debt to J. J. Thomson—and the scientists and engineers who followed the path that he pioneered—for taming the first subatomic particle and adapting its unique properties for the practical applications that are relentlessly redefining what it means to be human.