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The First Ten Years of the Transistor

A Guest Editorial

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The technology in which it was to be used was already about 35 years old when Bardeen, Brattain and Shockley discovered the transistor ten years ago. This circumstance has led to an unusual course of development and application. The transistor has affected the technical and commercial growth of electronics and communications more quickly than might have been expected from the somewhat offhand newspaper comments of July 1, 1948. (The news story about the transistor was carried on page 46 in one famous case).

The quick growth of the transistor art after the original discovery came about because electronics based on an elaborate functionality of the vacuum tube as amplifier, modulator, oscillator and such in our technology was already preeminent. The transistor provided an alternative to the vacuum tube in these functions, so electrotechnology, one of the most elegant intellectual attainments of history, was ready for any and all transistors.

This was as though Faraday's capacitors and dielectric principles had been first reported to a meeting of the A. I. E. E., or antibiotics had been announced in finished form to a congress of bacteriologists and clinicians who had already established therapeutic procedures for dealing with all classes of germs. Actually, electrical capacitors, inductors, resistors and thermionics were extensively explored before any uses were known for them; bacterial inhibition by antibiotics was studied for decades before medical application was worked out; even with war-time haste, several years of intensive effort separated Hahn and Strassmann's discovery of nuclear fission from the production of significant energy by the process. Thus, in each of these cases there was time to ponder, to try, but most of all to imagine, beyond any known framework of use, what the discovery would come to.

Much of this was denied the transistor in its early years. To a degree, perspective was lost in the astoundingly rapid exploitation of transistor function. In late 1952 there were commercial transistorized hearing aids. Their performance now surpasses Dr. Bell's highest hopes for comfort for the deaf. About 100,000 transistors for defense use studies were made the same year. Three million were made annually for auto radios by 1957, in the United States alone. The cost of this being a child prodigy, of this growing old in infancy, was early made clear by crises in reliability. An article in *Time* for September 7, 1953, said, "Still neither . . . nor other scientists have lost all hope concerning the difficulties then widespread in production and performance of the device." Satisfactory yields from production have been erratic, and economics consequently often frenzied.

But other costs may have been far greater, costs incurred because the world of electronics foolishly thought it knew all about the possible uses and the possible consequences of the transistor through experience gained long before the transistor was created. Because of this, we must at the end of this first decade give thought to what the discovery of the transistor means in a larger frame of reference than that even all of the present wonders of electrotechnology—communications, automation, control—can give it.

The transistor discovery has in many ways altered our age-old ideas about the electrical behavior of matter. For example, we are accustomed to the idea that positive and negative charges of electricity accessible to each other will amost immediately neutralize one another, and that common fluid media, for example, contain charged particles of opposite sign only because of stabilization as ions and the continuing replenishment of the supply by thermal agitation. In the crystals of which transistors are made, however, positive and negative charges do coexist for appreciable times in both the so-called p and n regions. Thus, p-type crystals having a multitude of positive charges contained in their rigid atomic skeleton also have electrons "free" among them. Such long-life times of opposite charges for recombination suggest an abundance of new effects, in addition to transistor action across junctions. For instance, the controlled recombination can give light emission which may itself some day be useful, and which already has revealed much about electrical charge interactions. The conductivity modulation of semiconductors contrasts them with metals.

Further, and equally exciting, are the phenomena related to the mobility of the charged particles. We find that, although the conditions for this new control of electric charges are indeed built firmly into the crystal lattice by the substitution of foreign atoms, a remarkable mobility of charge remains. Thus, responses of these systems to electromagnetic waves are lively.

Significantly, this liveliness is different from the acceleration of electrons in the vacuum tube, which is proportional to an electric field, and it is also different from the behavior of the electron cloud conceived to be in metals. For instance, in the crystals preferred for transistors, electrons move at about 1/1000th the speed of light and hit some atom and bounce off in a way that corresponds to a new motion in each distance of about 1000 atom diameters. They can keep this spirited pace over such long distances because of the perfect periodic arrangement of atoms in the crystal. Through such an array of atoms, electrons can proceed like waves, as Davisson and Germer discovered at Bell Telephone Laboratories more than 25 years ago. These electron movements are such that the speed and not the acceleration is proportional to the applied electric field. A pressing challenge now is discovery of some principle which will give us other ways of controlling this speed and thus, in effect, raise the frequency response of transistors from a few hundred megacycles up to thousands and tens of thousands. Existing knowledge seems inadequate.

The second main aspect of the transistor discovery which is influencing nearly all modern science and technology of solids is the novel forms of matter it evoked. Pfann's zone refining produced germanium and silicon crystals of such purity and relative perfection that the ideal simplicity of solid state theory was at last approximated. It can, in fact, be argued that silicon and germanium are the best understood solids. At least they were understood perfectly enough so that, in them, imperfections (in crystal order) were first identified. Thus a mystery as old as science and as crystals was exposed. It is because of such imperfections that the strength of metals and solid matter is generally so much less for both yield and fracture than the forces between the atoms of the ideal crystals would allow. The explanation is, as long guessed but not before shown, that wires and girders and bridges and wheels have to be the extra size they are because the atoms are missing from some places they ought to be in; that is, dislocations and vacancies limit the properties of real solids.

Such meaningful findings as these coupled directly back to the transistor technology itself, since imperfections control directly certain performance of the devices. This all shows what a few new ideas can mean to the entirety of science and engineering.

Likewise, of course, these exquisite refinements in the knowledge of what electrons and their positive equivalents or "holes" could do in suitable crystals have engendered new families of devices, of deep import for the future. Thus, in the past decade, have been created junction devices yielding nearly perfect rectifiers, electronic switches, photo and solar cells and lightning protectors or nondestructive fuses. Indeed, such controlled breakdown has been made to give out visible light associated with microplasmas, with implications for visual communication which are just now being pondered.

These aspects of the transistor discovery have fired the imaginations of engineers and scientists throughout the world. While substitution for the vacuum tube has itself attracted many licensees of patents through the Western Electric Company, including agreements in England, France, Germany, Switzerland, Sweden, Italy, the Netherlands, Japan, as well as North America, the recognition also of additional features is seen in the accompanying active and historic exchange of technical information, which is growing rapidly. Thus, beginning with a couple of international symposia early held at Bell Telephone Laboratories, there has now arisen a vigorous worldwide system of conferences in this new field. This may be illustrated by the Solid State School held at Varenna on Lake Como, Italy, in 1957, the International Conference on Solid State Physics in Electronics and Telecommunications in Brussels in 1958, and the forthcoming International Conference at Rochester. One should also mention the formation of a new division of solid state physics of the American Physical Society which provided 18 of 24 sessions at the Chicago meeting of the Society in March of 1958. Publication has been equally strong evidence that the transistor has had a bearing on modern science far beyond that of a specific electronic device. Several thousand papers have now been published in journals all around the world, including the Indian *Journal of Physics*, the Czech *Slaboproudy Obzor* and the Russian *Uspekhi Fizicheskikh Nauk*.

The results of this world-wide interest and attention have in ten years, as in the case of transistor technology, spread transistor science far beyond its original scope. Thus the most perfect solids, the nearly ideal crystals, have enabled qualities of separate electrons rather than characteristics of electron swarms to be studied and eventually to be exploited. Paramagnetic systems arise from the unpaired electron spins in germanium and silicon crystals containing certain well-known donor atoms. These exhibit resonance of the thermal motion of the isolated magnetic electrons with radio frequency or microwave frequency fields, in the presence of an external magnetic bias. A great new realm of behavior of electric waves has been revealed. This is in their interaction with electron spins in which energy, and hence signals, can be exchanged among waves and crystals not by the movement of electric charges, but by the reorientation of the magnetic moments of electrons. These may be distributed in nonconductors easily accessible to the penetration of even microwaves and, of course, this realm extends far beyond semiconductors. Solid state MASERS, as some of the devices embodying these principles have come to be called, promise a new freedom from noise in electronic amplifiers, so that signals from outer space, and indeed the signals from the stars which radio astronomers study, will be exactly received. Further, the international scientific interest in both the concept and the compositions of transistors has recently succeeded in identifying, by the methods of cyclotron resonance, that electronic charge carriers, the essence of all communications and electrical engineering, can exhibit even in metal systems more than one effective mass. This means that knowledge of conductors is being sharply revised and extended, since details of the band structure concept are being revealed in formerly unimagined detail. This study has indeed finally illuminated the detailed structure of graphitic carbon—the patriarch of electronics—in filaments, microphones, resistors, electrodes and contacts.

But finally, what does all this replacement of the vacuum tube at one end and advancement of the frontiers of science at the other during the decade of the transistor mean for communications itself? Any comment, and especially any comment looking to the future, ought to be related to the shape and philosophy of electrical communications expected to come. Therewith a certain harmony in time appears, because this is also the tenth anniversary of Shannon's *Mathematical Theory of Communication* and of Wiener's *Cybernetics*, as well as the 30th anniversary of Hartley's forerunner of modern analysis of the communication of information. Shannon's monumental theory is particularly rich in its applications to situations involving discrete coding, as in the so-called "digitalization" of sight and sound. That is, instead of using electromagnetic waves whose amplitude or frequency are analogues to acoustic or visual signals, these same signals are represented by pulses, giving on-or-off, 1-or-0 conditions. Such pulse systems are particularly suited to modern wideband transmission media.

The transistor and its associated devices are perfectly proportioned for communications and data handling, for control and sensing, based on pulses. The pulse code modulation now developed for exchange trunk carrier in telephony seems destined also for widespread video transmission by sending 70 million pulses per second. This now seems possible over ordinary pairs of wires, providing that simple transistor amplifiers are frequently inserted in the lines. Important new uses of existing plant facilities may soon appear. But a still greater unity of communications systems based on binary signal processes is forthcoming. Switching and the related logical elements of computing comprise extensive digital operations. While most of the work here may be well done by improved diodes, which came along with transistor technology, the transistors themselves are, as in transmission, elegantly suited for the amplifiers, inverters, pulse stretchers, power regulators and tone generators necessary in the new schemes of communications, in which at last the technical essences of transmission and switching are joined.

Junction devices seem uniquely suitable for digital operations; on-or-off, plus-or-minus now look like the alphabets of communication—through neurons, minds, telegraphs. Will it come to pass, that, after all, the vacuum tube electronics will not be converted to transistor electronics, but rather, that it will just be forgotten? Perhaps transistors will next enjoy Shaw's kind of childhood—one too wonderful to have been wasted on the young.