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Bell Laboratories
RECORD

THE TRANSISTOR
1948—1958

Ten Years of Progress at
BELL TELEPHONE
LABORATORIES

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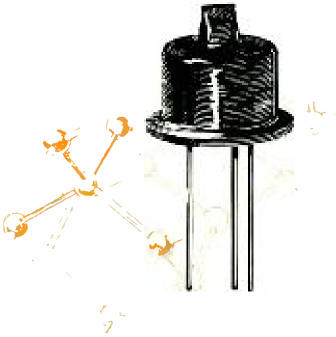
Contents

Cover *Internal structure of a diffused-base germanium transistor (magnification about 40 diameters). For details of connections to germanium crystal, see drawing on page 205. (Photograph by M. J. O'Brien.)*



The Transistor — Ten Years of Progress

M. J. KELLY
President, BELL TELEPHONE LABORATORIES

The invention of the transistor in our Laboratories about ten years ago initiated a completely new era in communications technology. All the transmission, switching, signaling, station and power systems employed in the telephone service of today will be affected by this invention. Since Bell's invention of the telephone more than eighty years ago, scientists and engineers in ever-increasing numbers contributed to the growth of a rich and comprehensive communications technology. Through this technology distance was conquered, for it was technically possible at the time of the transistor's invention for any two people, wherever they were in the world, to be interconnected for telephone conversation. This technology was so complete that contributions of new scientific knowledge and invention would largely be in providing lower cost levels, improvement in existing services and new services.

The transistor, a completely new oscillator, modulator and amplifier, gave early promise of large contribution to lower cost levels and to improved and new services. This promise justified the large research and development effort of our Laboratories during these past ten years. The initial transistor invention resulted from a basic research program carried out by a small team of scientists. The large rewards promised by this invention were at once recognized and led to a steady expansion and extension of effort in our Laboratories until today almost one-third of the Laboratories' work for the Bell System is devoted to building a new communications technology in which the transistor is the central element and applying it in the development of new facilities for communications.

The large rewards to service that were envisioned are made possible by the inherent properties of this new semiconducting device. The principal ones are:

> *The availability of the electrons to meet the operating needs of transistors and diodes without the use of power to energize a hot cathode.* Cathode power for the most generally used electron tubes varies from 0.5 watt to 5.0 watts.

The low anode voltage required in the functioning of transistors and diodes. Anode potentials of 10 volts are frequent, while anode potentials of 50 volts are rare. Corresponding hot-cathode tubes most frequently require anode potentials of 100 volts, while potentials as low as 50 volts are rare.

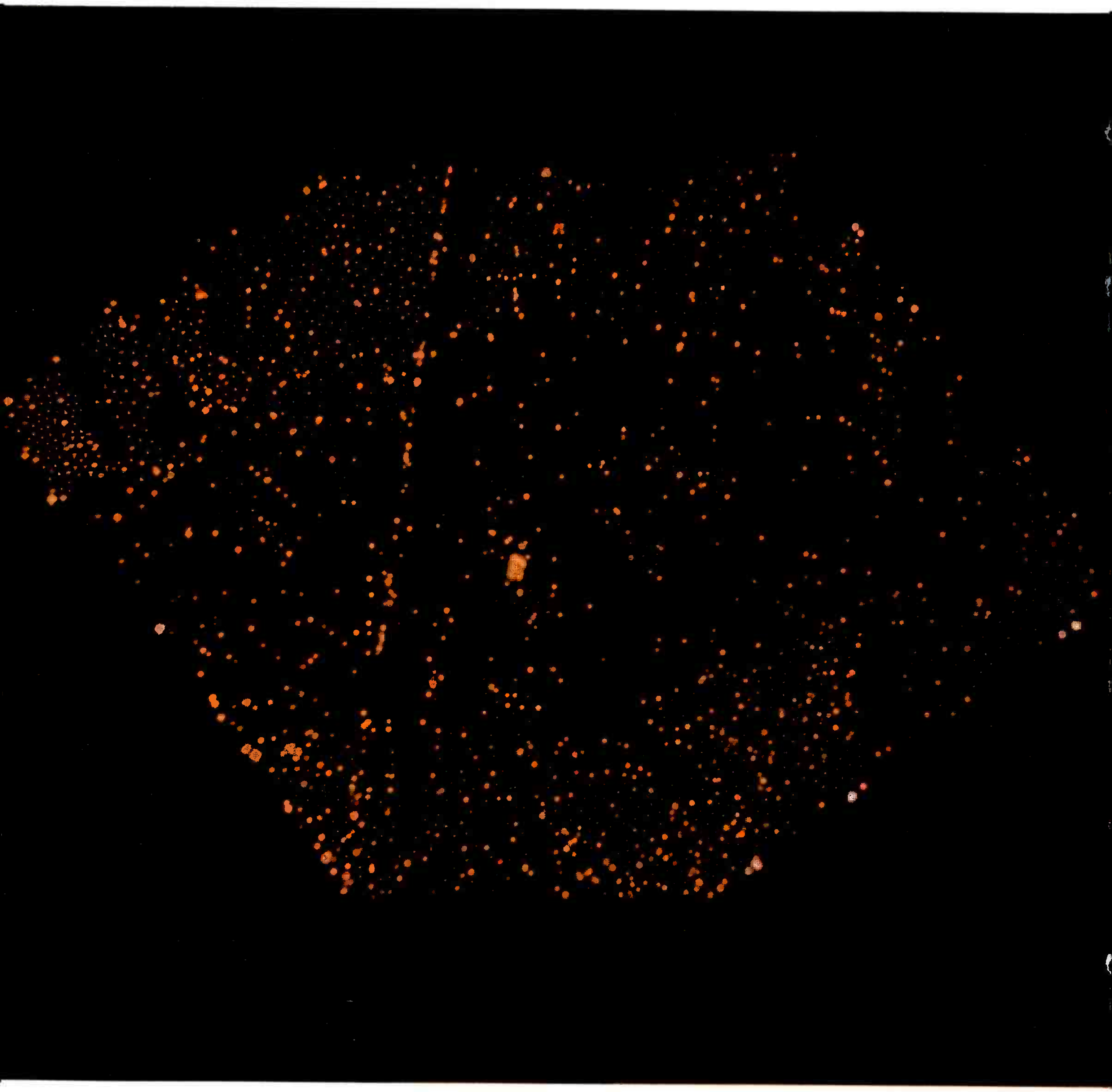
The miniature size of the transistor and diode. Their semiconducting active element varies from the size of a pinhead to some five times this size. These active elements may be enclosed in containers varying in size from that of the smallest electron tube down to containers one-fifth that size. Their small size, low energy consumption and low anode potentials made it possible to associate them with components much smaller in size than those required by electron tubes.

The scientifically possible indefinite life of the transistor and diode. The ideal transistor or diode does not deteriorate with use as do electron tubes. While significant progress has been made in realizing this ideal, much research and development must still be done before we have attained the goal of indefinite trouble-free life.

Finally, when the technology has matured, the manufacturing cost of transistors and diodes should be well below the level of corresponding electron tubes when produced in the same quantities.

Basic and applied research are providing new knowledge that is making it possible to develop transistors that exhibit most of their inherent properties. Transistors with functional properties of a sufficiently wide range are now available for application in almost all the communications systems implementing Bell System service. Significant progress has been made in realizing the reliability and long life required for telephone service. Manufacturing process developments are in progress that give promise of low cost in quantity production. Development of transmission and switching systems, signaling and station facilities employing transistors and other solid-state devices are now in progress. Some have been completed, placed in manufacture and in service.

The nine papers of this issue of the RECORD review progress in selected areas of research and development. The story they present is not comprehensive. It is, however, typical of the accomplishments of the period. A completely new communications technology is evolving; in time it will replace that of the pre-transistor period. We can look forward to the next decade with confidence of large and expanding contributions to communications service by new solid-state electronic facilities that the transistor's invention pioneered.



In studies of electrical breakdown (page 194), voltage across silicon p-n junction causes luminescent spots. This phenomenon was first observed at the General Electric Laboratory. Using the solar battery configuration (thin top layer), Bell Laboratories scientists showed that the emission was a body property and that all of the breakdown was channeled into small regions (light spots). This large-area junction was photographed by its own light. Magnified about 50 diameters.

The transistor is a direct result of basic research at Bell Telephone Laboratories. Its invention triggered a burst of activity which, in only ten years, has established the study of semiconductor materials as a mature branch of contemporary science, and it has also launched a new technology of great importance to all communications.

Morgan Sparks

SEMICONDUCTOR RESEARCH

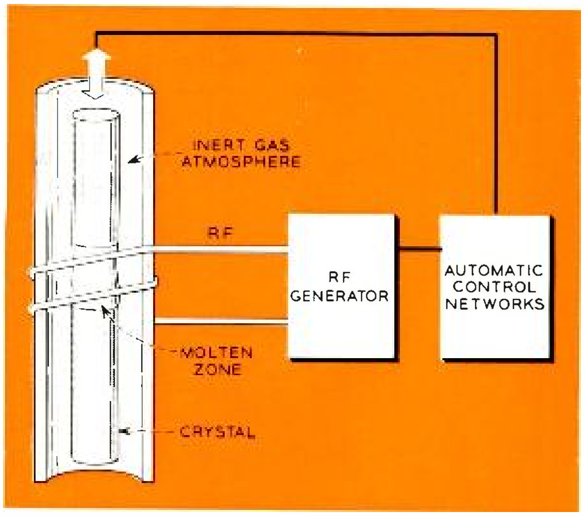
Prior to World War II only a few people had ever seen a piece of germanium. It received its first real attention in the scramble to develop better materials for microwave diodes, and at the end of the War polycrystalline germanium of high purity (by the standards of the day) was available. During a basic research study at Bell Laboratories of the surface properties of this germanium, the transistor was invented (RECORD, *August*, 1948).

The scientific importance of this work by J. Bardeen, W. H. Brattain and W. Shockley was recognized by the award of the 1956 Nobel Prize in Physics. The impact of the discovery on work at the Laboratories was profound and almost immediate; this was one invention that did not have to wait for appreciation. Within a few months, a sizable group of people with diversified backgrounds was at work—physicists, chemists, metallurgists and engineers. Semiconductor research continued to increase, and it now represents a major activity of the last decade.

Consider first where we stand with respect to the semiconductor materials themselves. Almost all of the effort has been put into germanium and silicon, in that order. This is surprising, since by conservative estimate there are at least a thousand semiconducting substances. In hindsight, it is fortunate that transistor action was first observed on germanium — it is one of the simplest of all solids. Greatly aided by this simplicity, steady and impressive progress has been made in understanding its properties. Today, germanium is probably the most completely understood of all solid materials.

Both germanium and silicon are now available as the purest and most perfectly formed crystals which scientists have had for their study. Even more important, this purity and structural perfection can be altered in a controlled way by a number of techniques; the electrical effects of these alterations are the distinguishing features of semiconductors. The invention of zone refining (RECORD, *June*, 1955) has removed most of the usual limitations of the purification of solids. The present problems are mostly concerned with recontamination from the vessels and chemicals used in the subsequent processing. This invention has such universal application that its importance transcends the semiconductor field. It is surely one of the important metallurgical developments of our time.

Zone refining was immediately successful for purifying germanium, but molten silicon is so reactive that no really satisfactory material has been found to serve as a container. An ingenious variation called floating-zone refining has solved this problem by circumventing it. A vertical rod



"Floating-zone" refining process prevents contamination of semiconductor crystal. Molten zone heated by RF *coil is held in place by surface tension, touches no solid material except the crystal.*

of silicon is supported at the top and bottom and the molten zone is formed between, usually near one end. The molten zone is kept small enough so that surface tension will keep it in place; thus the molten silicon is supported only by solid silicon. By this method, together with a specially developed chemical process for removing boron —an unfortunate example of one of the few cases where zone refining does not work efficiently— silicon has recently been prepared which surpasses even the best germanium in purity.

Single crystals may be grown by either variation of the zone-refining process by placing a seed crystal at one end and starting the molten zone where it will just touch the seed. The first successful method for producing single crystals was the pulling technique, where a seed is slowly pulled up after touching the surface of a melt. This method is still widely used for both silicon and germanium. Some of the best crystals produced by these methods have had dislocation densities as low as ten per square centimeter; some areas large enough to study are apparently entirely free of dislocations. A dislocation is a structural flaw on an atomic scale—a plane of atoms which terminates somewhere within the crystal. Most materials, in their best crystalline forms, have a million or more dislocations per square centimeter (RECORD, *August*, 1955; *April*, 1956).

The whole theory of dislocations in crystals — they were depicted as playing an important role in crystal growth and in the strength of materials — was on quite tenuous grounds until the last few years. Experiments performed on germanium and silicon, in which dislocations were first definitely delineated and later produced under control, were invaluable in establishing the present sound position of the theory.

NEW KNOWLEDGE

As better and better silicon and germanium became available, more accurate measurements were made of the known properties. One of the basic characteristics of a semiconductor is the mobility of its charge carriers — that is, its holes and electrons. Mobility is the speed with which a charge carrier moves in an electric field of one volt per cm. It was shown in a humorous graph in 1950 that the mobility of electrons in pure germanium, which should be a constant, actually gave a smooth, linearly increasing curve when plotted against the year of measurement in the interval 1945-1950. There was nothing wrong with the measurements; mobility is a structure-sensitive property, and the measurements, made after crystals of nearly perfect structure were available, are in substantial agreement. Electrons in germanium at room temperature move about 4000 cm/sec in a unit field.

Many of the experiments now performed on semiconductors rely on transistor-based properties, that is, on properties and ideas which were not known prior to the transistor. One of these is the injection of minority carriers in excess of their equilibrium numbers, which can be done in a controlled way with a forward biased p-n junction. The trapping of electrons has been studied in this way. In some cases, where excess electrons and holes recombine through traps in silicon with the emission of radiation, a complete set of self-consistent data has been obtained. The traps have been identified chemically as ordinary donors and acceptors, and the wavelength of the radiation has been correlated with the independently measured electrical properties of the silicon crystal (the width of the forbidden energy gap) and the traps (their ionization energy as donor or acceptor). As a final touch of elegance, it is found that one must include the proper absorption or emission of phonons in the crystal in order to achieve a precise energy balance. A phonon is a progressive wave of lattice vibrations of the crystal; in this case the phonons and photons cooperate to conserve momentum as well as energy. The energy of the phonons is only about 5 per cent of the total energy involved in the event.

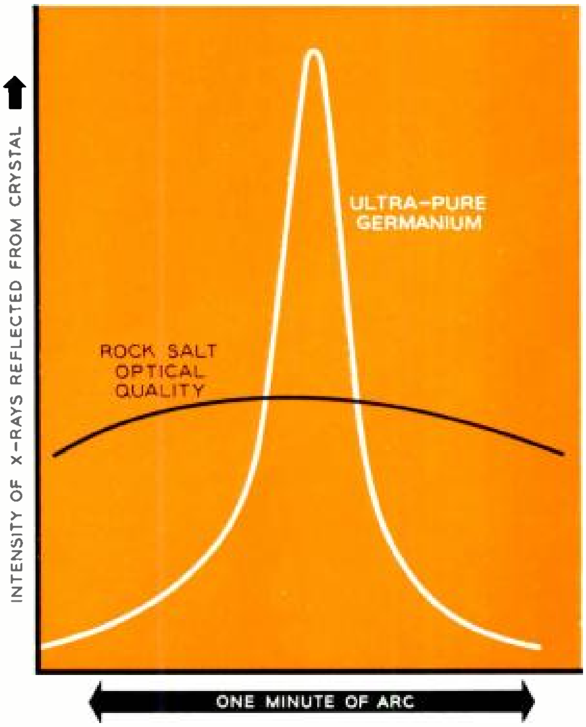
One of the most interesting investigations has been that of the elementary processes of dielectric breakdown (RECORD, *February*, 1958). In the localized fields of reverse-biased junctions, collision ionization processes can be studied with great precision. It was found that true breakdown by avalanche multiplication occurred without damage to the crystal in both germanium and silicon. Another mechanism of breakdown, also nondestructive, has been observed under conditions somewhat more difficult to realize experimentally. This involves the creation of holes and electrons by internal field ionization; electrons are literally torn out of the crystal bonds. It is the first evidence of an effect predicted over twenty years ago, and is of considerable theoretical significance. In both instances, there is an emission of light from the breakdown region of the crystal. In the avalanche case, the light and breakdown current occur in separate spots (see photograph facing page 193). For breakdown by field emission, the light appears to come uniformly from relatively large areas of the crystal.

One of the most fruitful areas of semiconductor research has been the study of surfaces (RECORD, *November*, 1957). Surfaces have been historically one of the most difficult fields of study in both physics and chemistry. Their important properties are usually determined by fractional atom layers or at most a few atom layers of some foreign material that is extremely difficult to remove, identify, or reproduce. For surface studies, semiconductors offer the advantages that their electrical properties are influenced by small numbers of foreign atoms, and that there are many surface properties which may be measured on the same sample under the same conditions — surface photovoltage, photoconductivity, surface recombination of holes and electrons, contact potential, and the modulation of conductivity by a surface field (the field effect). The data of such experiments have been interpreted in terms of electronic surface states and in terms of the space-charge layers associated with them. Reproducible results, which can be characterized with surface states of known electrical properties, have been obtained for several procedures of preparing the surface. For the most part, however, the chemical nature of these surfaces is not known in detail.

The discussions so far have been restricted to the main stream of research on the distinguishing features of semiconductors themselves. In the continuous interaction of various branches of science, however, the ideas and techniques of semiconductor crystals have helped to add other new knowledge. For example, the electrons which freeze out on donor impurity atoms in semiconductors at low temperatures are well suited for electron spin resonance experiments. Particularly in silicon, considerable information about the nature of the wave functions of the electrons on donor atoms has been obtained by this method.

The acoustoelectric effect has recently been observed for the first time and in a germanium crystal. In this experiment, a standing sound wave is produced in the crystal. Since sound waves disturb the atoms of the crystal as they pass, standing waves produce periodic stresses in the crystal. There is a corresponding variation in the electrostatic potential within the crystal, and under certain conditions electrons tend to bunch slightly in some regions. The corresponding voltage fluctuation (very small) in the crystal is called the acoustoelectric effect.

Chemical thermodynamics is especially suitable for application to dilute solutions—just the composition of greatest interest for semiconductors. It has been shown that electrons and holes must be included as independent variables in the equilibrium considerations of semiconductors. Thus the solubility of lithium in germanium can be changed by several orders of magnitude merely by changing the number of conduction electrons in the germanium. This is a "common ion effect" familiar in chemistry; it applies in this case because lithium ionizes and contributes a conducting electron when it dissolves in germanium. Silicon is the most abundant element in the earth's crust, excepting oxygen, and it is therefore surprising that in 1948 there were almost no reliable thermodynamic data such as melting point, heat of fusion, volume change during



As a crystal sample is rotated through a small angle, intensity of reflected x-rays is measured to reveal structural qualities. Sharp peak for germanium sample carefully prepared at the Laboratories shows its near-perfection compared to a typical crystal of optical-quality rock salt.

fusion, and vapor pressure for either silicon or germanium. All of these values have now been accurately measured.

There are a number of other fields that have been advanced through experiments on semiconductors, but these will merely be mentioned. The pure and nearly perfect crystals so frequently referred to are excellent diffraction gratings for x-rays and neutrons. They are also being used to study the conductivity of heat, the nucleation and precipitation of a second solid phase, solid-state chemistry such as the association of ions into pairs, and heat-treatment effects. Other subjects in which semiconductor research has caused important repercussions are radiation damage in solids, electroluminescence, noise in conductors, and electronic energy bands in solids—particularly the existence of several anisotropic effective masses for electronic carriers.

DEVICE RESEARCH

Research on devices themselves has also been intensive. It was a challenge to understand the original transistor and find better ways to make it. The rapidly evolving theory of p-n junctions, together with new techniques of crystal growth and impurity control, focused most of the device attention on junction structures (RECORD, *June*, 1954). The newly acquired understanding of semiconductor p-n junctions was the most powerful single stimulant for the improvement and invention of transistors and related devices.

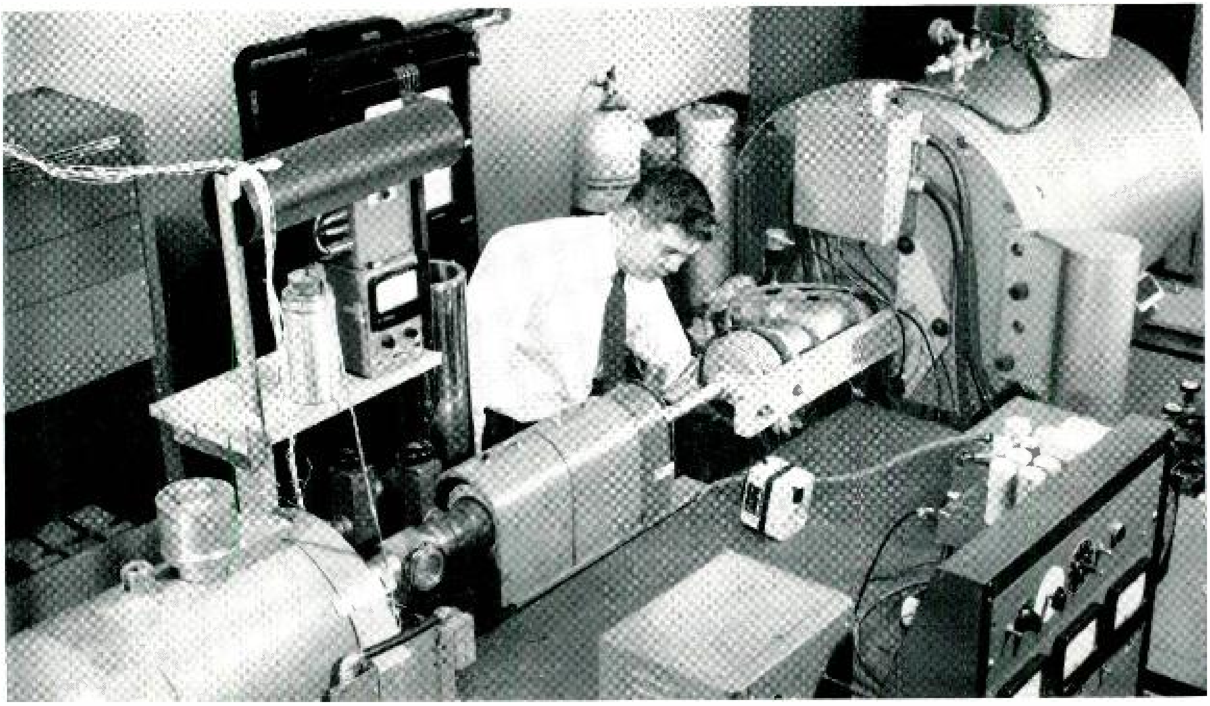
A p-n junction is one of the least complicated structures possible in a semiconductor. It is not unduly difficult to make, and it can be analyzed mathematically in terms of straightforward semiconductor ideas. It nevertheless embodies a remarkable set of useful properties. The injection of minority carriers has been mentioned; this is the principal requirement of the emitter of a transistor. A reverse-biased p-n junction is a collector for minority carriers, a radiation detector, a means of creating space-charge layers with very high electric fields, and a voltage variable capacitance. An unbiased p-n junction is a rectifier, a photovoltaic element, and a sensitive thermoelectric couple. All of these features of p-n junctions have been used directly. They have also been employed to construct more complicated structures for other purposes. For example, one of the earliest ideas for a solid-state amplifier was to modulate the lateral conductivity of a thin sheet by changing the charge on the surface — much as a vacuum-tube triode may be considered to operate by modulating the space current by changing the charge on the grid.

Many such structures were built, but none was successful because the electronic surface states mentioned in the previous section soaked up the charge and left the electrons within the sheet essentially unaffected. By putting a p-n junction on the surface of a germanium sheet, so that the space charge of the reverse-biased junction penetrated into the material, an amplifier was made which performed as predicted by a well developed theory which included, of course, p-n junction principles. This device is called a field-effect transistor (RECORD, *May*, 1955) although it is fundamentally different from junction and point-contact transistors. It is an example of a class of devices called unipolar transistors, in which only one kind of current carriers, holes or electrons, is involved in carrying a signal through. These devices have received relatively little attention so far, probably because the great potential of the versatile junction transistors has been so rapidly realized. Their characteristics are different from junction transistors, however, and they are likely to be properly evaluated in the future.

Another idea which originated in the early work on p-n junctions was to obtain a bistable structure which would exhibit either the high impedance characteristic of a reverse-biased junction or the low impedance of a forward-biased junction—depending on the imposed voltage. Such a device would be an electronic switch with enormous potentialities for massive applications in such places as telephone switching and computers. The p-n-p-n diode was invented for this purpose, again by extending and combining the ideas of simple p-n junctions.

The first really successful high-frequency transistor, the germanium tetrode, was invented by realizing through circuit considerations that the frequency limitations of junction transistors as then constructed was determined by the magnitude of the capacitances and resistances involved. These parameters were then made smaller by recourse to semiconductor principles and the addition of a fourth electrode to decrease the active area of the emitter junction (RECORD, *April*, 1955).

Device research is by no means confined to the theories of device operation. Of great importance is the creation of an improved technology, and research efforts have been most productive toward this end. Crystal growing and zone refining have been discussed. The first controlled p-n junctions were made when methods were found to change accurately the impurity balance in the melt during crystal growth. Some other examples are a staining technique to delineate p-type areas in a silicon crystal, a method for measuring accurately the thickness of surface layers which may be only one ten-thousandths of an inch thick (RECORD, *January*, 1957), surface cleaning procedures, and a method for the "electroless" plating of nickel on silicon surfaces for use as contacts. It is in such projects that the close cooperation between research and development, between those whose interests are primarily



In study of solid-state materials, electron-bombardment of samples is one of many basic research tools at Bell Laboratories. W. L. Brown using Van de Graaff accelerator for research experiment.

to understand and those who bear the responsibility for prescribed applications, is greatest. In many of these projects the work is done jointly by the two groups. This close relationship has characterized the semiconductor field from the beginning, and is due in part to the fact that the techniques were changing so rapidly. There simply wasn't a substantial, well-tested technology on which to plan development work several years ahead. Development engineers were forced to evaluate new techniques immediately; this made their jobs more difficult.

The best example of an improved technique which evolved from research is solid-state diffusion. The diffusion constants and solid solubilities of donors and acceptors were being studied, and a troublesome stumbling block was contamination by uncontrolled impurities during the diffusions. This sometimes completely masked the effects under study. Several years were required to identify the contaminants and eliminate them. Ultimately, diffusion in both germanium and silicon was mastered and meant an improvement of about tenfold in the precision of placing impurities in the crystal. During the same interval, methods were being worked out for the preparation of even purer silicon. The Bell Solar Battery (RECORD, *July*, 1955) was the almost immediate product of these two advances in technology. It was known that p-n junctions are good photovoltaic cells, and the inventors of the Bell Solar Battery calculated that the properties of silicon are almost ideally matched to the solar spectrum. Diffusion offered a practical means for making a structure designed to optimize the conversion of the absorbed light into electricity.

Diffusion was next applied to reduce the critical dimensions of junction transistors, with a resultant increase of their high-frequency limit by about one hundred times. It is now the preferred method for producing the intricate crystal compositions demanded by the newest semiconductor devices. The Bell System is depending heavily on it for the new telephone system of the years ahead.

The study of semiconductors other than germanium and silicon is progressing and will certainly expand. Some of these substances, particularly a group called the III-V intermetallic compounds (RECORD, *July*, 1956) are almost as simple as germanium and silicon although their preparation is more difficult. Zinc oxide has been grown in small single crystals, and the electronic properties of several impurities determined. This material is a representative of another group of semiconductors called the II-VI compounds. They are more complicated than germanium and silicon in almost every way.

It has been an exciting decade of feverish activity and progress. Semiconductors have emerged from obscurity to a respected place in modern physics, and in addition have launched a new technology of great importance to communications.

Frequently, the true worth and potential of an invention are only determined after working models are fabricated and incorporated into experimental circuits. From a very early date, research versions of transistor equipment have been under study at Bell Telephone Laboratories to give advance indications of their potentialities.

R. L. Wallace, Jr.

Research in Circuits and Systems

For many years the transmission of telephone messages over very long distances has been possible only because vacuum tubes were available to produce the enormous amount of amplification required. A large part of the electrical energy fed into one end of a long pair of wires is unavoidably wasted in heating the wires and for this reason does not reach the intended destination at the other end of the pair.

In a circuit from New York to Los Angeles, for example, the factor by which the signal power is reduced in this way is a number so large that its significance is hard to imagine. The number can be written approximately in a representative case as a three followed by three thousand zeros. To make up for this loss, the signal in such a circuit is passed through about 10,000 vacuum tubes distributed in amplifiers located at intervals along the way.

Although research, development and improvements in manufacture have made these vacuum-tube systems remarkably reliable and economical, considering that the amplifiers are complicated and expensive to produce and maintain, there has been a continuing effort to find newer and better solutions to the transmission problem.

Just ten years ago a group of Laboratories members was called together and told quietly about a startling new amplifier. The discovery that amplification could be produced by a slab of crystalline germanium with two pointed wires pressed against it was of obvious potential importance in the transmission of telephone messages, so the group was given the assignment of studying this new effect and finding out what use it might have.

EARLY DESIGNS

There was obviously no supply of transistors in these early days. Each member of the group was given a small sliver of germanium, a few words of advice, and the instruction to go back to his bench, make a transistor, and find out what it was good for. The first transistors, though they were not yet christened with this name, bore little resemblance to the devices which are so well known today. One of the first experimental versions resembled a mousetrap and enjoyed only a few days of popularity. It was adequate to demonstrate the phenomenon of amplification but was not sufficiently stable to permit serious study.

Within a very few weeks, much better mechanical designs began to evolve and to be used for experiments. These newer versions produced electrical properties which were stable enough to be measured and used in the computation of circuit performance. Experience with such transistors inspired the rapid invention and improvement of circuits for performing all sorts of electrical functions, and the results attained were so interesting that the number of workers assigned to the problem was steadily increased.

Within a few months after the initial discovery, a transistor development group was organized. One of the functions of this group was to supply small quantities of transistors to various members of the Laboratories who had use for them. This was the beginning of the sort of orderly path of development on which the commercial exploitation of a device must necessarily rest. However, the early "make-your-own" experience had disclosed a valuable avenue of quick research progress in the application of transistors in transmission. In those early days, improvements came so fast that many transistors became obsolete before they were ever connected into a circuit. Thus, several members of the original transistor group chose to meet the problem of transistor supply by continuing to make their own devices. In some isolated cases this early practice has been profitably continued to this day.

The early studies undertaken in the Transmission Research Department, particularly as they related to the junction transistor, revealed some remarkable and useful properties. Among the first to be noted was the exceedingly small amount of power which the transistor required from a battery or other source to enable it to amplify small signals. Some rough calculations showed, in fact, that if a suitable treadmill and generator could be devised, a flea could easily supply the power required to operate one transistor by doing an amount of work equivalent to making one good-sized jump per minute.

ADVANTAGE IN POWER CONSUMPTION

With respect to economy of power consumption in small signal applications, the transistor was found to be many times better than any vacuum tube. This was obviously important in portable equipment requiring batteries. To demonstrate this, the first transistorized hearing aid was built in the Laboratories and was shown to provide ten times as great battery life as a comparable vacuum-tube model. In this application the transistor has now completely replaced the vacuum tube.

Economy of power consumption is also of vital importance in many telephone applications. In some cases, important advantages can be obtained by essentially replacing vacuum tubes with transistors, but of far greater importance are new applications which would be completely impractical if tubes were used. For example, it has never generally been practical to provide vacuum-tube amplification in customers' telephone sets, principally because of the difficulty of supplying the required power over telephone lines.

Despite its extremely small size, this amplifier built for research study contains a broadband transistor and fourteen other circuit elements.

With the advent of the transistor this situation was radically changed. Already telephone customers with impaired hearing are using sets in which transistors provide the amplification required to make voices audible to them. In the research and development departments of the Laboratories, there are many new telephone circuits and services under study which have a chance of being practical only because it is possible to supply power to transistors over telephone lines.

Another obviously desirable attribute of the transistor which was recognized from the very beginning was that it could be made about as small as need dictated. This fact led many to imagine a whole host of applications which were made possible principally because of the minute space into which they imagined transistor circuits could be put. It was thought, for example, that telephone repeaters could be made so small that they would fit into a cable splice. These dreams of ultraminiaturization have been slow in coming true for a reason which was painfully obvious to the first people who tried to make miniature transistor circuits. The vacuum tubes in a telephone repeater, radio set, or television set occupy a very small fraction of the total volume. Replacing them with transistors did not make an impressive difference in the size of the equipment.

In spite of this, miniaturization was a real possibility not only because transistors could be made small, but also because they can be operated at very small voltages and currents and do not get hot as vacuum tubes do. This makes it possible to use very small resistors, capacitors, transformers, and the like in transistor circuits and to pack them together very tightly. But just as transistors themselves were not available for such studies in the early days, so miniature passive components were not available. Like the transistors, they had to be made by the circuit man whose principal interest was in the electrical performance of the circuit, not in the details of the components.

EXPERIMENTAL EFFORTS

The illustration on page 199 shows the results of an all-out effort at miniaturization. This is a broadband amplifier only about 0.15 inch in diameter and 1.5 inches long. It contains some fifteen circuit elements including two transformers and one inductor.

An example of miniaturization in which the components have not been made quite so small is shown in the illustration on this page. This package, only a little bigger than a package of king-size cigarettes, contains a seventeen-transistor radio receiver of very high performance capabilities and a battery adequate to operate the receiver eight hours a day for two weeks. It contains also the selective circuitry which would permit this receiver to be used for personal radio signaling. A customer carrying this package in his pocket could be advised, by a buzz from the receiver, that he was wanted on the telephone.

In spite of the many desirable properties of the transistor, it had in the early days certain limitations which precluded its use in many important transmission applications. Not the least of these was that no transistors capable of amplifying very high frequencies or very broad bands were available. Efforts to improve this situation led to the discovery of the junction tetrode transistor (RECORD, *April*, 1955) and to the fabrication and use of about two thousand of these devices in experimental transmission circuits.

Another project showing the possibilities of transistorized circuits is a very simple transistor carrier system capable of transmitting high-quality television pictures over distances up to a few miles. This system uses a carrier frequency of 10 megacycles and transmits a double-sideband, amplitude-modulated signal extending from five megacycles to fifteen megacycles. As designed, the repeaters could be spaced at two-mile intervals on 3/8-inch coaxial cable or at closer intervals on smaller cables. In a demonstration model, the repeaters are spaced at half-mile intervals in a 3/16-inch cable, though they can be separated as much as one mile in this size cable by using two repeaters at each repeater location.

Another example of miniaturization: radio signaling receiver includes seventeen transistors and has high performance with long battery life.

To consider the telephone transmission plant from a somewhat broader point of view, it seems reasonable to say that the transistor arrived at a very appropriate time. In the L3 carrier system the science of design and the art and science of manufacture of vacuum-tube carrier systems had been carried to such a high degree of sophistication and perfection that it seemed hard to imagine that further refinements of this approach could yield substantial advantages.

PULSE-CODE MODULATION

Clearly, a completely new approach to the transmission problem was needed. In fact, such an approach had already been evolved and studied extensively in the research department. It involved converting the signal, whether it be a television picture signal or a group of voice signals, into a series of pulses and transmitting the signal in this form. At the receiving end of the line, the signal would be reconverted to the original form and delivered to the customer in such a way that he would be quite unaware that pulse transmission had been involved.

This method, called Pulse Code Modulation or simply digital transmission, offered very important advantages. The circuits had very simple jobs to do — to recognize the presence or absence of a pulse, to generate new pulses to replace those which had been somewhat degraded in transmission, and to perform other straightforward manipulations of the pulses. This could all be done with very simple circuits which did not require precise adjustment and could therefore be cheap. Furthermore, signals could be transmitted over very great distances by these techniques without suffering any of the progressive deterioration of signal quality which is inherent in other carrier systems. And such signals were shown to be relatively insensitive to interference as compared to other forms of signal.

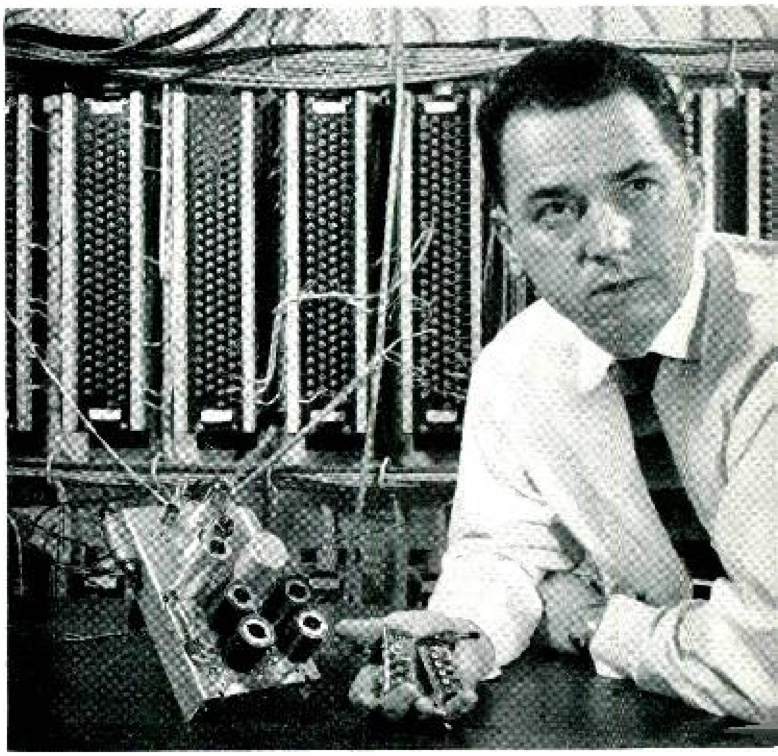
The principal disadvantages of this approach arise from the fact that it requires pulses to be generated and transmitted at very high rates. For example, about three-quarters of a million pulses per second are required to transmit a bank of twelve telephone message channels, and about seventy million pulses per second are required to transmit a television picture. Pulses at these high rates are attenuated very rapidly as they travel down a pair of wires or a coaxial cable and therefore have to be regenerated by repeaters which are spaced relatively close together as compared to the spacings used in older carrier systems. The fact that the repeaters are exceedingly simple and cheap is therefore partially offset by the fact that more of them are required.

Studies of PCM systems using vacuum-tube repeaters showed that the cost of supplying power to the large number of vacuum tubes required was so great as to make the system unattractive in all but a few special cases.

The advent of the transistor, and particularly of transistors capable of very rapid operation — first the tetrodes, and later the even better diffused-base transistors — makes digital transmission systems look exceedingly attractive for a great many kinds of application in the Bell System. A comparison of the two repeaters seen at the right shows why this is so. The larger unit is a pair of experimental vacuum-tube repeaters designed for regenerating pulses at a rate of about three-quarters of a million pulses per second (adequate for 12-channel voice transmission). Each of the two repeaters requires 18.5 watts of power. The smaller unit is an experimental regenerative repeater using diffused-base transistors specially fabricated for the purpose. It is designed for a pulse rate of ten million per second — adequate for more than a hundred and fifty voice channels — and requires only 0.6 watt of power. Even so, the transistor repeater delivers twice as much peak pulse power to the line as does the vacuum-tube model. A great many of the transistor repeaters in tandem can be powered over the same pair of wires used to carry the signal.

Much research and development needs to be done before digital transmission systems will find widespread use in the telephone plant. For some of the systems under consideration, it will be necessary to find ways of making even faster transistors, diodes, and transformers than are at present available to the transmission-research worker, and it will be necessary to evolve new circuit techniques and perhaps other new circuit elements. Much remains to be done in finding better ways of converting signals into pulse form and back again. Methods of encoding leading to pulse sequences which are easier to transmit are being sought, and so on. Experience has indicated the value of tackling such problems experimentally at the earliest possible moment.

Some important digital systems are, however, within the range of what has already been demonstrated in the research laboratory, and may find their way into the telephone plant in the fairly near future. Others will come later and finally, transistorized digital transmission systems may find widespread use in the telephone plant.



R. L. Carbrey holding two small regenerative repeater circuits. These do the same job as the large vacuum-tube version on the table at the left.

In the fast-moving field of transistor technology, important advances have been made on all fronts: frequency of operation and reliability have steadily increased; speed and efficiency of operation have improved significantly; and corresponding gains have been registered for a wide range of related semiconductor designs.

W. J. Pietenpol

TRANSISTOR DESIGNS
The First Decade

It is pointed out in the previous articles that research at Bell Laboratories led to the invention of the transistor, and that electronics scientists immediately recognized that this discovery would lead to a revolution in their field. With semiconductors it was expected that, in many applications, vacuum tubes could be replaced, and the result would be lower power consumptions, smaller size and better reliability of both electrical and mechanical properties.

In many cases it was also expected that the transistor class of device would make possible new and yet unimagined advances in electronic circuitry. The tremendous importance of this discovery and the views of those scientists have been confirmed by the rapidity of developments of the past decade. Discoveries and improvements of processes and structural design have, in this short space of time, led to a series of transistors and semiconductor diodes which exhibit a wide variety of properties.

The first structure to be developed and, therefore, logically the first to be introduced into manufacture, was the so-called "point-contact" transistor. As in the original work, this structure consisted of a small wafer of germanium soldered to a metallic base, with two point contacts on the opposite surface spaced approximately 0.001 inch apart. The first design to go into manufacture was not sealed to exclude the atmosphere, but was rather designed into a cartridge structure. It was designated the type "A" transistor (RECORD, *February*, 1956).

To give high gain and good stability, it was necessary with this transistor to "form" or electrically pulse the phosphor-bronze collector point. This procedure introduced impurities and imperfections in the immediate area of the collector point in a way that it made possible not only voltage amplification but current amplification as well. This forming process is by no means simple and, even now, many aspects of the procedure are not understood from a physical point of view. The time from the first invention to manufacture was relatively short, and in 1951, the first point-contact transistors were made by Western Electric in Allentown, Pennsylvania. *(See article on transistor manufacture, page 226 this issue.)*

GROWN-JUNCTION AND ALLOY TYPES

The first design in which the physics of operation was well understood was the grown-junction transistor (RECORD, *October*, 1955). Crystals of germanium or silicon are grown from molten material by dipping a single crystal seed into the melt and gradually withdrawing it. Impurities to form base and emitter regions are introduced into the

View of model shop at Murray Hill, N. J., location, where developmental versions of transistor structures are fabricated at Bell Laboratories.

molten material as the crystal is being withdrawn. After cooling, the crystal is cut into bars about 0.020 by 0.020 inch in cross section and ⅛ inch long. Contact is made by welding a fine gold wire to the base region. A variety of codes of grown-junction transistors have been made with power dissipation up to 50 milliwatts and with frequencies of operation to several megacycles per second. One of the big Bell System applications of grown-junction transistors was found in the telephone handset where there was a need for more amplification *(page 216)*. The circuit in this application is designed for a power gain of about 20 decibels. By adding a fourth electrode and by using transistor bars of very small cross section (to reduce collector capacitance), it is possible to raise the operating frequency of the grown-junction structure to the 100-mc range (RECORD, *April*, 1955).

Outside of the Bell System, millions of grown-junction transistors have been manufactured, mainly for use in personalized radio sets where battery life may be improved as much as a factor of 10 over conventional vacuum-tube receivers.

Another important structure, called the alloy transistor (RECORD, *January*, 1956) is fabricated by melting impurities into the surface of a thin wafer of semiconductor material and recrystallizing the molten portions in such a fashion that junctions are created on either side of the wafer. Most alloy transistors have been made of germanium with indium as the impurity. The alloying process makes possible a major improvement over grown-junction transistors—a reduction in series resistance of the collector and emitter contacts.

In most switching applications, the voltage drop across the transistor in the "on" condition must be held to a minimum. Thus, the alloy transistor is particularly suited to various types of computer and switching-logic circuitry. A variety of transistor codes of this class have been developed for a number of Bell and military systems. For example, the experimental electronic switching system discussed on page 215 of this issue employs a pair of n-p-n and p-n-p alloy transistors with a frequency cutoff of 7 mc per second and a power dissipation of 250 milliwatts (RECORD, *April*, 1958).

Even in the early days it was recognized that impurities proper for the creation of p-n junctions might be diffused into the solid semiconductor material with major advantages of dimensional control. As mentioned in the first article in this issue, years of research were necessary to identify and eliminate minute amounts of undesirable impurities which diffused into the material and resulted in a loss of charge-carrier lifetime and gross changes in resistivity. By 1954, a major breakthrough in the identification and isolation of these impurities had made possible diffusion as a technique for creating p-n junctions in both germanium and silicon (RECORD, *December*, 1956). The undesired impurities were found to be traces of various residues left on the surface after chemical etching and washing.

DIFFUSION

Several variations of the diffusion technique are used to obtain proper impurity density, distribution, and conductivity type. However, the basic technique can be imagined from the schematic reproduced on page 204. The semiconductor material to be diffused is placed in a furnace inside a quartz or ceramic liner. The temperature of the furnace may be accurately regulated and is maintained at 100-300°C below the melting point of the semiconductor. The impurities to be diffused into the semiconductor are introduced either as a gas flowing through the furnace or by evaporation from "doping" agents within the furnace.

Among the first of the devices resulting from this new technology was the Bell Solar Battery. Others made possible were power rectifiers (typical units have ratings of 0.5, 1.0, and 10 amperes) and a series of voltage limiters (rated in steps from 6.2 to 150 volts). For example, one of the rectifiers rated at 0.5 ampere continuous current or 10 amperes peak, with a power dissipation of 0.5 watt at 65°C, is fabricated from a wafer of silicon only 0.045 by 0.045 by 0.007 inch in dimension. It is interesting to note that the current density through this wafer of silicon at the peak current rating is 1000 amperes per square inch —almost the same as that allowable by the Underwriters' Code for copper wire used in home wiring systems.

With diffusion technology, germanium transistors have been fabricated which will amplify electrical signals to frequencies above 500 megacycles per second. One code of germanium diffused-base transistor designed as an oscillator and now in manufacture by Western Electric has a minimum rating of 50 milliwatts of 250 megacycles power output. Units of this type have given usable power output at frequencies over 1000 megacycles per second. This is 10 to 50 times higher than the amplifying frequencies previously obtainable with transistors. Other units of this general type have been designed for use in the logic and switching circuits of very high speed computing systems.

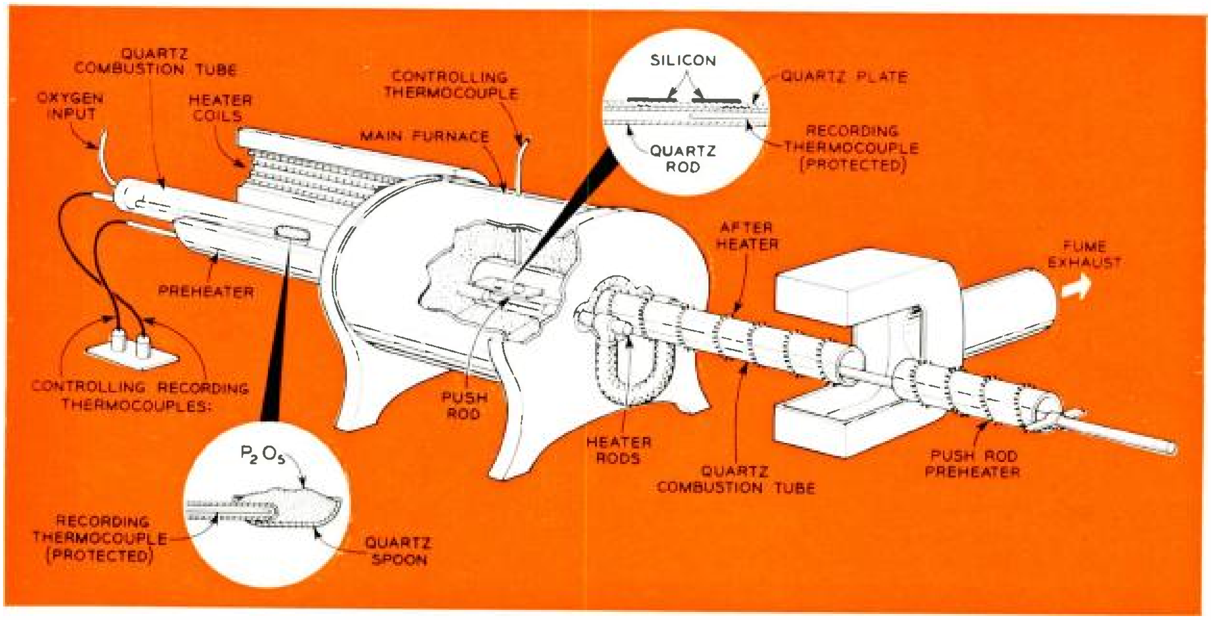
The photograph on the cover of this issue shows a diffused-base germanium transistor with emitter and base stripes only 0.001 by 0.002 inch in size and spaced less than 0.001 inch apart *(see drawing on next page showing details of this structure)*. Electrical contact is made to these stripes by a wire bonded to the stripes and welded to the header lead-through wires. Diffused germanium transistors of this general type are now circling the earth in the "Explorer" and "Vanguard" satellites.

Diffused silicon transistors have also been developed and are being manufactured by Western Electric Co. Although their amplifying frequencies are somewhat lower than those of their germanium counterparts, the silicon units will find a useful place because of their operation at higher ambient temperatures and attendant reliability. Another important property of the silicon units is that when used as electronic switches they have extremely high values of impedance in the nonconducting or "off" condition. Thus, silicon transistors are being used in computer and switching applications where the very highest speeds are not required.

Today the circuit designer has at his command a broad range of structures and characteristics. Transistors are commercially available in all of the designs mentioned above. It is not possible here to compare all of their electrical characteristics, but it is instructive to show in the illustration on page 206 the frequency range as a function of power dissipation presently covered by available transistors. The frequencies plotted are the alpha cutoff frequencies for the various types. For video or broadband amplifiers, the usable range would be somewhat below the cutoff frequency, while, for oscillators, one can often get usable power outputs well above the frequency cutoff.

GROWTH OF AN INDUSTRY

The growth of the transistor from its birth in 1948 to its present maturity has been rapid indeed. With the critical need for electronic components in the world today, and with the many advantages offered by transistors, it is not surprising that such a revolution has occurred. The management of nearly every major electronic laboratory has

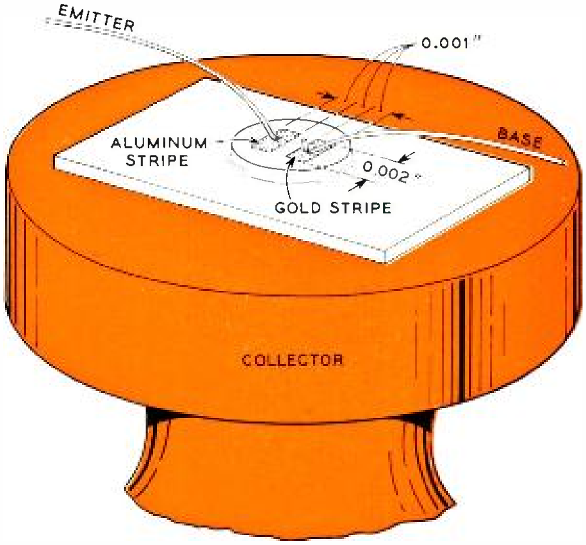


Diffusion processes have been a major breakthrough in device fabrication: representation of diffusion furnace for introducing precise amounts of donor and acceptor impurity atoms into crystal.

directed teams of their most competent research and development people toward the design of these semiconductor devices. As early as 1951 Bell Laboratories conducted a symposium on the properties and applications of transistors.

About eighteen months later, to disseminate information on device-design theory and technology more widely, Bell Laboratories conducted a second symposium for licensees of the Western Electric Co. in the semiconductor field. Representatives of many companies attended this eight-day symposium to learn in detail the steps by which current transistors were fabricated. Also, members of the teaching staffs of many of the major universities were invited in 1952 to attend a series of lectures concerned with the theory of semiconductors. Then, in January, 1956, a second symposium for the licensees of the Western Electric Co. was conducted to bring them up to date on the advances in semiconductor technology. A major portion of this latter symposium was spent describing the breakthrough in diffusion and the control of the properties of silicon.

By concerted effort, most of the basic problems associated with semiconductor devices have been solved; and today transistors are being used in many industrial and military systems, particularly where low power, small size, and high reliability are dominant factors. The sales of transistors alone in the U.S. have risen from a level of essentially nothing in 1952 to sixty-nine million dollars in 1957. Forecasters predict that these sales will go to over three-hundred million by 1965. If one adds to this the sale of semiconductor diodes, it is predicted that combined sales will reach 550 million by 1965. By that time it is expected that the dollar volume of semiconductor sales will exceed that of the older electron tube. In 1957 the sale of transistors and diodes was 29 million and 62 million units, respectively. A further indication of the growth can be seen by the fact that the Joint Electron Tube Engineering Council (JETEC) had issued 600 transistor and 1300 diode industry codes by the end of 1957.



Details of structure seen in cover photograph: germanium crystal has raised area or "mesa", on which are evaporated two tiny metal stripes. Wires from headers are bonded to these stripes to form the transistor's base and emitter connections.

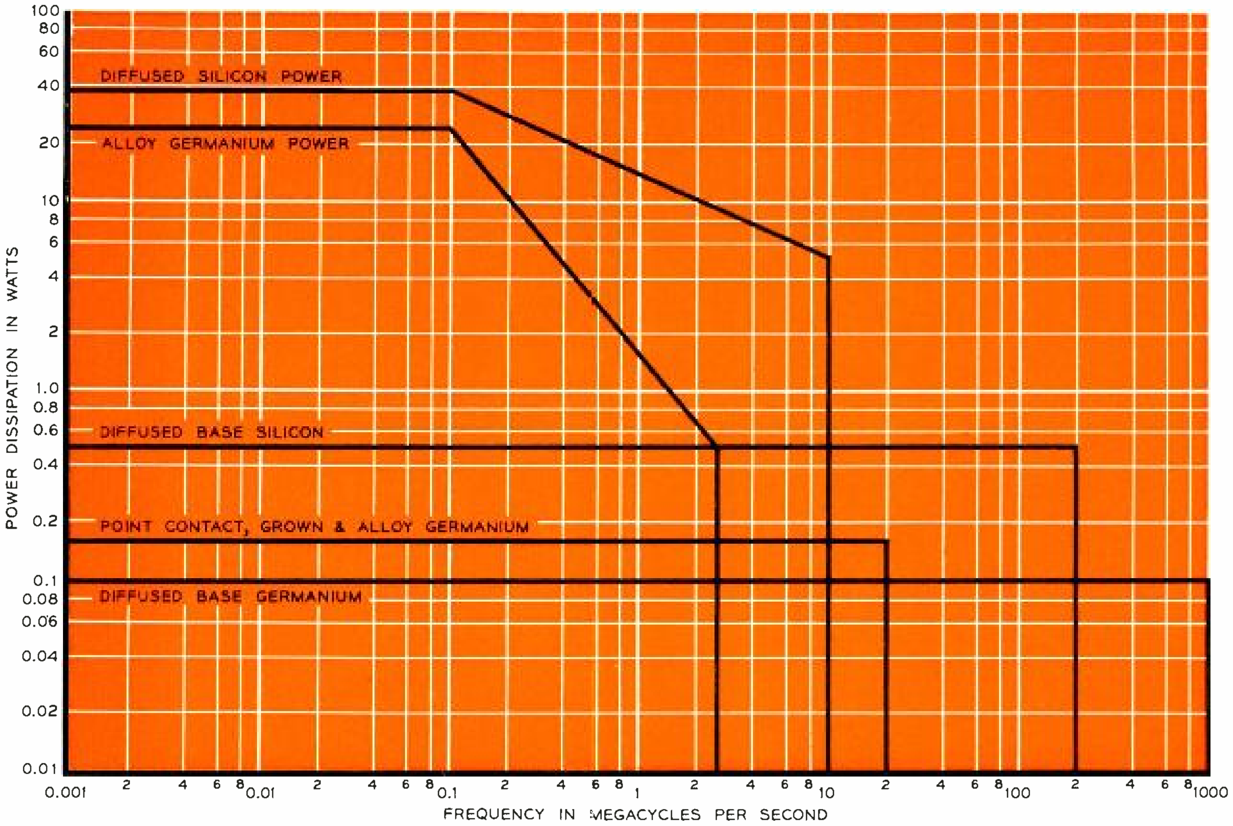
New Designs

In the laboratory stage there are a number of new designs which will extend the range of electrical performance of the devices presently in manufacture. One which will soon be in pilot production is the 4-region switching diode. The electrical characteristics of this device are similar to those of a cold-cathode gas tube. However, the silicon device requires a great deal less power and can operate at speeds 1000 times faster than the gas tube. The active part of the unit is a silicon wafer 0.020 by 0.020 by 0.004 inch in size. The wafer is mounted in a ceramic or glass capsule 0.1 inch in diameter and 0.1 inch long. The impurities used in diffusing the n and p layers are phosphorus and boron.

It is interesting to note that this small device requires precise control of almost every bulk and surface property known to semiconductors. That is, it is necessary to control accurately the density of impurities throughout the bulk material, the width of the various layers, and the density of imperfections in the bulk material, which in turn controls the lifetime of minority carriers. It is necessary to control not only the density of these imperfections but also the type of imperfections (the energy level within the forbidden gap). On the surface, one must control and add impurities in such a manner that the density and type of surface states are within reasonably narrow limits. The surface must be carefully cleaned and oxidized so that the device will be electrically stable over long periods of time. In addition, the atmosphere around the device must be controlled so that there are no ions present to alter the electrical properties of the crosspoint. Even with these requirements, however, the crosspoint will be economical in production.

Another two-terminal device soon ready for manufacture is a very high speed silicon computer diode. By a controlled reduction of carrier lifetime, minority carrier storage has been reduced to less than 5 millimicroseconds.

Other new designs of semiconductor devices are being made in the laboratory by reducing the



Frequency of operation plotted as a function of power dissipation for various types of transistors presently available. In this illustration, values of alpha cutoff frequencies are used; thus, for oscillator applications, higher values of frequency are possible, while lower values would apply for broadband applications. Areas under the curves show the continuing trend of transistor device development toward the latest types of structures with wider ranges of operating characteristics.

thickness dimension of the base layer, by reducing the spacing between electrodes, and by reducing the cross-sectional areas of the devices. In this manner, the operating frequency range of germanium and silicon transistor units can be extended by a factor of ten. Several possible designs for improving the frequency response and the power dissipation of these devices are also being explored.

MICROWAVE AMPLIFIERS

For some time it has been known that a variable reactance can serve as an amplifier. But it is only recently that this principle has been put to practical use. The dependence of capacitance of a p-n junction upon the voltage applied across it makes possible a rapidly variable capacitance when an appropriate high-frequency voltage drive is used. Furthermore, this device should have extremely low noise. In particular, an amplifier of exploratory design has a measured gain of 15 db at a frequency of approximately 6000 megacycles per second and a measured noise figure of 4.5 db. In this case, the driver was a 12-kilomegacycle reflex klystron. Thus, it now seems possible that amplifiers can be designed for operation at frequencies as high as, or even higher than, those possible with advanced-design vacuum-tube and traveling-wave structures.

The first decade of transistor technology has brought with it a revolution to the electronics industry. A broad range of solid-state devices is now available to the circuit designer, and a multi-million dollar industry has been born.

In the Bell System, transistors are finding their first transmission applications in short-distance systems. These systems are able to profit quickly from the transistor's unique characteristics, but in the coming years, it is expected that both local and long-distance systems will benefit from the properties of many solid-state devices.

M. B. McDavitt

Transmission Applications

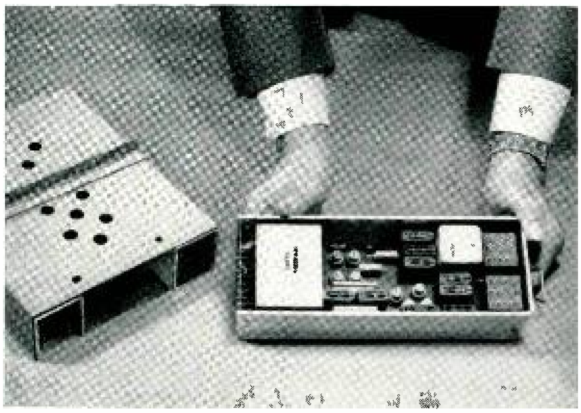
Since the transistor can perform many of the functions of the vacuum tube, it might appear logical for the new device to find its initial application in the long distance telephone plant, which is essentially dependent on amplifying devices because of its extensive use of carrier techniques. It is interesting to note, therefore, that transistors for transmission purposes have conformed to an early prediction by Dr. Ralph Bown, former Vice President of Bell Laboratories, that transistors would first find their way into the local plant. Why has this been the case, and will the transistor also become an important factor in long distance transmission?

As soon as the transistor appeared on the scene, transmission development people started thinking about applications. Because of certain limitations in linearity and noise performance, the early point-contact transistor was more useful as a digital or ON-OFF device than as an analog device—that is, one that would faithfully reproduce a weak signal at greater power. However, discussion of these limitations with research and device development people was one stimulus of many that spurred them to bring into being transistors of progressively greater sophistication. This is a good example of the constant interplay in the Laboratories amongst the people responsible for the devices and those concerned with their systems applications.

While the more sophisticated types of transistors were being born, studies showed that it was going to be difficult to achieve significant economic gains by transistorizing existing frequency-division carrier systems which had been through many years of cost-reduction attention. Furthermore, many of the newer carrier systems had pushed into higher frequencies beyond the range of available transistors. It thus appeared that new techniques were needed for the general case, and that there would have to be special circumstances to make transistors attractive in the frequency-division field.

RURAL CARRIER

The first such case arose in providing a carrier system for increasing the call-carrying capacity of open-wire pairs serving rural customers. Here, low power consumption is all-important. Commercial power, where it is available, is inexpensive. Communication may be most needed during power failures, however, and standby facilities to keep the equipment operating at such times can be kept low in cost only by keeping the oper-



Transistorized negative - impedance repeater (cover at left). In addition to advantage of small size through use of transistors and other small components, savings are expected in power drain.

ating current drain very small. Where commercial power is not available, the system would have to operate from primary batteries. Transistors make it possible to meet these requirements.

The P1 carrier system uses solid-state devices throughout both the carrier equipment and power supply; germanium transistors of both the grown junction and alloy junction types are employed (RECORD, *August*, 1956; *October*, 1956). The P1 system is of the double-sideband type, operating in the relatively low frequency range of 12-96 kilocycles. It provides four two-way carrier channels, for both voice and signaling, in addition to the normal physical channel on one pair of wires. Printed wiring building blocks are plugged into convenient housings. One terminal is normally in the central office, and the other is mounted in a metal case on a pole at the point of physical distribution to the customers it serves. Repeaters are also pole-mounted. Multi-party line service is available. During the idle condition, the pole-mounted terminal draws about two thirds of a watt from the 20-volt direct current supply; during conversation, this rises to 2 watts, and, during ringing spurts, to 10 watts. As a part of the field trial in Georgia, one terminal was operated experimentally for a prolonged period with a Bell Solar Battery as the primary power source.

NEGATIVE-IMPEDANCE REPEATER

The negative-impedance repeater is another case where substitution of transistors is justified because low operating voltage and low power consumption are of great importance (RECORD, *February*, 1952; *January*, 1956). In the Bell System's program to raise the general level of transmission, the demand for negative-impedance repeaters (E2-E3) for reducing the transmission loss in local and toll connecting trunks has climbed rapidly to where it is measured in hundreds of thousands per year. The energy saved by transistors can be significant in annual operating costs; furthermore, in many local central offices where these negative-impedance repeaters will be used, the installation of a 130-volt dc power supply needed for the vacuum-tube version can be avoided.

Use of a pair of transistors in the so-called piggy-back circuit configuration, in both the series and shunt-type repeaters, allows the use of transistors that individually would not give high and stable amplification. By easing the performance requirements, the cost of transistors is minimized.

Printed wiring, miniaturized components and the use of resistance-type building-out networks rather than impedance matching makes a 2:1 reduction in size of the repeater possible as compared to the vacuum-tube version, with corresponding savings in floor space. Experimental use in the field was recently initiated, and production is planned in 1959.

PERSONAL RECEIVER

The personal-signaling radio receiver is an application which would be out of the question with vacuum tubes, because of power consumption. The personal radio system (RECORD, *January*, 1958) effectively gives the customer an extension of his telephone bell in vest-pocket form. This tiny radio receiver must meet exacting technical requirements as to sensitivity and selectivity and must operate for several days without replacement of the small battery. Early versions operated in the 30 to 40-megacycle range — a part of the frequency spectrum that severely limits the number of customers that can be served in a given city. The Laboratories has demonstrated models that operate in the 150-megacycle mobile band — a frequency region that makes it possible to serve many more customers in a locality.

This development was made possible by the advent of the diffused-base transistor that can readily amplify and oscillate at 150 megacycles. The selectivity of the superheterodyne circuit is adequate for the so-called split-channel operation, that is, 30-kilocycle channel spacing, recently proposed by the Federal Communications Commission. (Public Notice 43395, Docket No. 11995, released April 9, 1957.) Its audio output power is ample to operate three small tuned-reed selectors that give a number combination unique to the customer. The reeds, in turn, activate an audio transducer which emits a clear signal when the customer is wanted, and none of the others on the same radio channel is aware of it. A number of these receivers are expected to be in experimental field use early in 1959.

PULSE MODULATION

Earlier, it was stated that new techniques were needed to prove in transistors for the more general case in carrier applications. Pulse modulation — an old concept implemented with fresh tools — appears to be the answer.

In frequency-division carrier systems, most of the apparatus is in the portions directly associated with the individual channels. The individual channel components are, in turn, mainly accounted for in filters, compandors and signaling facilities. Carrier supplies, grouping equipment, and the maintenance and alarm features are about all that can be made common. Over the years, filters in this class have reached a high degree of sophistication and, hence, are unlikely candidates for radical cost reduction. Companding and signaling are amenable to other treatment. The planner and the designer consequently turned to a technique that could use less individual and more common equipment.

Time division or pulse modulation is a transmission technique that meets this specification and that is highly amenable to transistorization.

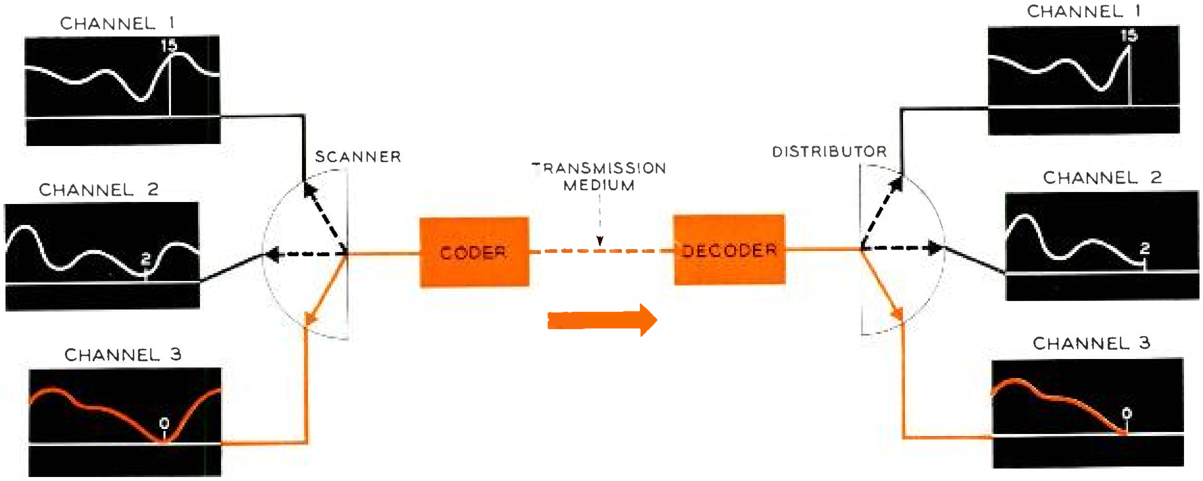
EXCHANGE TRUNK CARRIER

The first concerted effort, based on a pressing economic need, has been to develop a carrier system suitable for increasing the call-carrying capacity of existing cable pairs in exchange trunks. Congestion of existing conduits and the cost and other problems associated with building new ones make the exchange trunk plant a fertile field for carrier exploitation. The N carrier system — the lowest cost frequency-division type for general use — has proved economical on the longer exchange trunks, but there is a large field of application for a substantially less expensive type that would prove in on shorter exchange trunks.

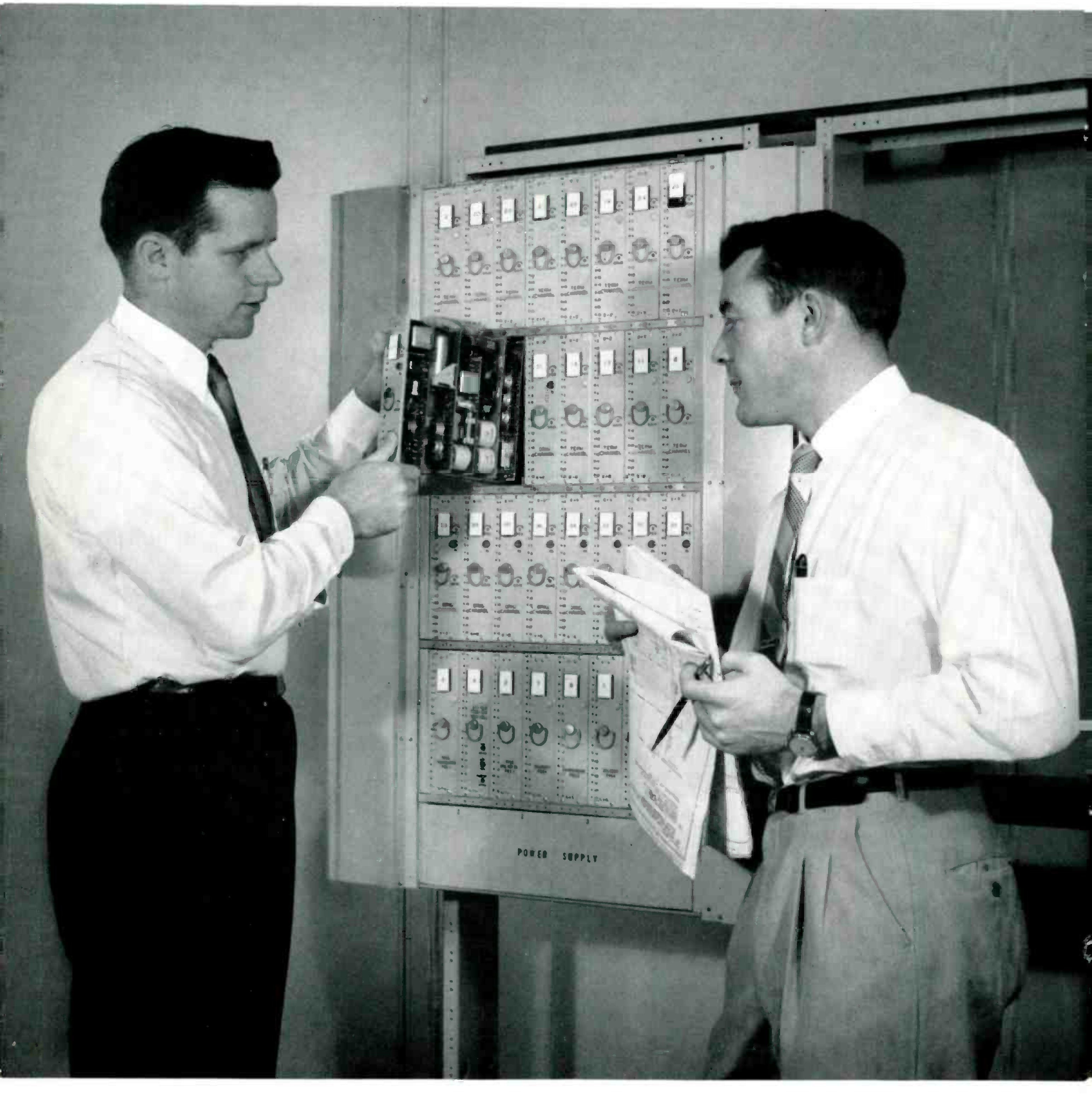
But exchange cable poses a tough problem. It was designed for voice-frequency operation and is a rather poor transmission medium for the high frequencies associated with carrier. There are several forms of pulse modulation, but one in particular — pulse code modulation, or PCM — has the virtue of being very "rugged." The ruggedness lies in its ability to operate in the face of high loss, crosstalk, noise and distortion in the transmission medium. Its disadvantage is that it occupies a wider frequency spectrum than other forms of pulse modulation, but its ruggedness makes this tolerable.

The specific PCM system now approaching the final stage of development in the Laboratories uses solid-state devices throughout and provides 24 voice channels on two cable pairs — a 12:1 gain in capacity. Transmission on each pair is in one direction only. Signaling as well as voice will be transmitted if this proves desirable.

At the terminal, the portion individual to each voice channel consists essentially of a hybrid coil, simple diode and transistor circuits serving as transmitting and receiving gates and gain elements, and small low-pass filters. Somewhat similar equipment, but of an even simpler nature



Representation of a pulse-code modulation system. The speech signals at the left in this illustration are sampled and, at the right, reconstituted. The information is sent over the transmission medium in the form of coded pulses. This type of system has the advantages that it is relatively immune to various signal degradations and that it permits using more equipment units in common.



A twenty-four channel pulse-code modulation terminal currently under test at Bell Laboratories. C. G. Davis (at left) removes a channel unit from the frame as J. J. Shanley checks the circuit.

since the basic information is digital, is used for signaling. The rest of the equipment is common to 24 channels.

At the talker's end, an electronic "commutator" opens the gate of each channel and measures the instantaneous speech intensity 8,000 times per second. The measured sample is encoded into a 7-digit binary code representing any one of 128 speech intensities. An eighth digit is added for signaling, and, at every complete turn of the "commutator," a single framing or synchronizing pulse is added.

At the receiving end, the 7-digit signal is decoded, a pulse is created reproducing the intensity of the one measured at the sending end, and this pulse is injected at the right time through the receiving gate. From these pulses, the low-pass filter in the receiving arm produces a continuous speech signal that, for all practical purposes, duplicates the one sent.

Compandor features are included in the common sending and receiving equipment.

The cable inserts both attenuation and distortion in the pulses, so that repeaters are necessary. Here, another advantage of PCM is realized. Since the signals are in coded form, as long as they can be recognized at all, they can be freshly reconstituted or regenerated in the repeater in substantially perfect form as to pulse shape and spacing. The transistor circuit for accomplishing this, though quite subtle in design, is simple and small, and is suitable for location in manholes in enclosures similar to loading-coil cases. Because of the high pulse rates — in excess of 1.5 million per second — loading coils must be removed. The system design has been adapted to existing manhole intervals, and repeaters will be spaced at an average of 6,000 feet. Power for the repeaters will be transmitted over the cable pair from the central office.

A field experiment is now in progress. The amount of apparatus in the PCM system is substantially less than in a frequency-division system that would do the same job. Consequently, the lower initial cost, floor space and heat dissipation seem likely to generate extensive application in the exchange trunk plant.

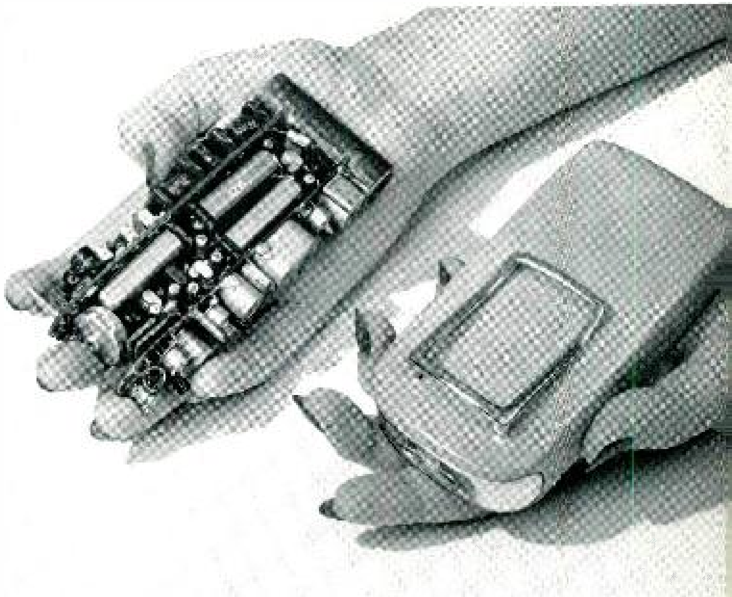
OTHER APPLICATIONS

What about other future applications of transistors in transmission systems? The ultimate capabilities of the diffused-base structure have yet to be determined, but it is already clear that the boundaries imposed by earlier structures have been immensely widened.

Transoceanic submarine cable systems require both passive and active components in submerged repeaters of almost unique reliability. With many such repeaters in tandem, powered from the shore ends, low operating voltage and power consumption in the individual amplifying elements are of great importance. Future systems will want to have much greater frequency bandwidth for carrying more telephone messages and possibly data and television. Transistors have the desired inherent qualities and are being actively considered in long range plans.

Exploratory laboratory work has demonstrated the technical feasibility of achieving broad-band feedback-type video amplifiers and intermediate frequency (70 megacycles) amplifiers with transistors, equaling the best vacuum-tube versions in linearity or distortion performance. Where and when they will be incorporated in systems depend on a number of problems not yet resolved, but their use is probably only a matter of time.

For ultimately superseding long-haul broad-band systems, such as L3 carrier, and for multiplexing in a manner to exploit the enormous bandwidth capabilities of waveguides, the greatest promise appears to lie in the extension of pulse-code modulation techniques. Serious attention in this direction is being given by the Laboratories in research and planning and in device and systems development. Transistors capable of substantial and continuous power outputs at microwave and higher frequencies are not in sight at this time. It is evident, however, that transistors and numerous other solid-state devices are highly attractive for most of the remaining functions involved, and there is little doubt that they will pervade both the local and toll telephone transmission plant of the future.



A developmental model of personal signaling receiver (right) and chassis without case (left). The unit is actually a transistorized telephone bell.

In telephone switching systems, transistors are now aiding in the automatic routing of long-distance calls and in certain signaling functions necessary in establishing telephone connections. In coming years, however, full exploitation of the transistor's capabilities will require the design of entirely new electronic switching systems.

A. E. Ritchie

APPLICATIONS IN TELEPHONE SWITCHING

Telephone switching is that application of the switching art which provides for interconnecting, on demand, a particular set of transmission paths that will permit any customer to communicate with any other. Depending on the type of system, the operations involved can be divided into several functional parts—for example, the determination of information regarding the destination requested by the customer; logical operations upon the information to permit setting up the call in some reasonable manner; signaling among various elements of the system concerned with the call; and finally, establishing of a series of connections between the source and the destination.

Thus, a switching system includes not only a method of interconnecting telephone lines, but also, in its modern form, computer-like controls and signaling arrangements of varying degrees of complexity. Typically, these functions are performed by equipment located in central offices, with the information presented to the system in the form of pulses generated by the telephone dial. The central offices are connected together either directly or through tandem and toll offices to form a nationwide—in some respects even worldwide—integrated system.

The basic switching functions — in particular, logic, memory and connecting—can be performed by the correct association of devices capable of opening and closing electrical circuits under external control. In telephone switching systems now in service, these devices performing these functions are generally relays, crossbar switches and similar electromechanical elements.

The transistor, however, can also perform the basic functions of switching, since it too can close and open an electrical circuit under the control of a small input signal. In fact, the low resistance of a conducting transistor is not unlike a relay contact in that sizable currents can be carried at a low voltage drop. This means that the transistor can switch electrical power at high efficiency—much higher efficiency than vacuum tubes, another electronic device which can perform switching functions. Furthermore, transistors require no heater power. The gain of a transistor permits the control signal to be small compared to the load power being switched. This also allows the overall power level to be low and reduces the power consumption required to perform a given switching function.

Although relays are used in many of the signaling circuits associated with switching systems, vacuum tubes have been effectively used in ac signaling equipments employed on longer-range and carrier-derived trunks. Here the transistor has characteristics as an amplifier and oscillator which make it a useful tool for such applications.

Switching circuits in telephone offices are rather complex and tend to require large numbers of devices. Thus, the small size of transistors is of real value for miniaturization. These advantages of transistors for switching applications are obtained in the presence of one other advantage in the control and connecting area—high-speed operation. Relays take milliseconds to operate, often many milliseconds, while transistors operate in microseconds, often fractions of a microsecond. Thus, transistors can increase the speed of operation by thousands of times over relay circuits. This reflects itself in switching systems by allowing more telephone traffic to be handled by less equipment.

With one notable exception, application of transistors in present electromechanical switching systems has been for signaling purposes. The exception, a machine which performs a true control function, is the card translator in the 4A toll crossbar system (RECORD, *June*, 1955).

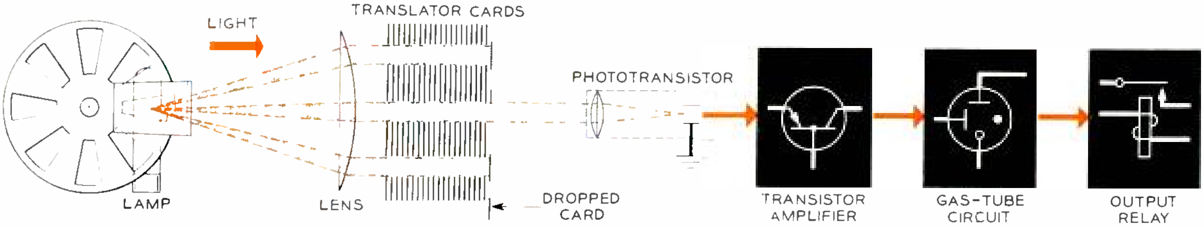
E. M. Hoffman of Special Developments Department inspecting a single-frequency signaling unit. Transistors allow small size and low power drain.

THE CARD TRANSLATOR

The 4A toll offices are the key switching centers in the present nationwide dialing system, which permits nationwide dialing by customers as well as operators. In this capacity, these offices require certain translating functions of a complexity not heretofore encountered. In particular, equipment must be able to translate six digits (area code plus central office code) into information permitting easy and rapid change of routes combined with multiple automatic alternate routing of calls to any destination within the telephone system. This latter information refers to the successive selection and testing of many possible different routes until an idle trunk is found to advance the call. The solution to the problem was found in the card translator, a machine which employs punched metal cards, an optical system and transistor sensing devices.

In operation, the translator displaces one card in a stack of about 1200 in accordance with a six-digit (or sometimes a three-digit) input. By means of a coded arrangement of holes, the displaced card either blocks or transmits light through a set of "tunnels" in the card stack. Transmitted beams of light, interrupted at 400 cps, fall upon a selected number out of over 100 phototransistors, each of which serves as an input to a transistor amplifier. The amplifier in turn controls a gas-tube relay circuit which provides the final output data.

In the five years since its introduction, this application of transistors, vital to direct distance dialing, has given excellent performance in all

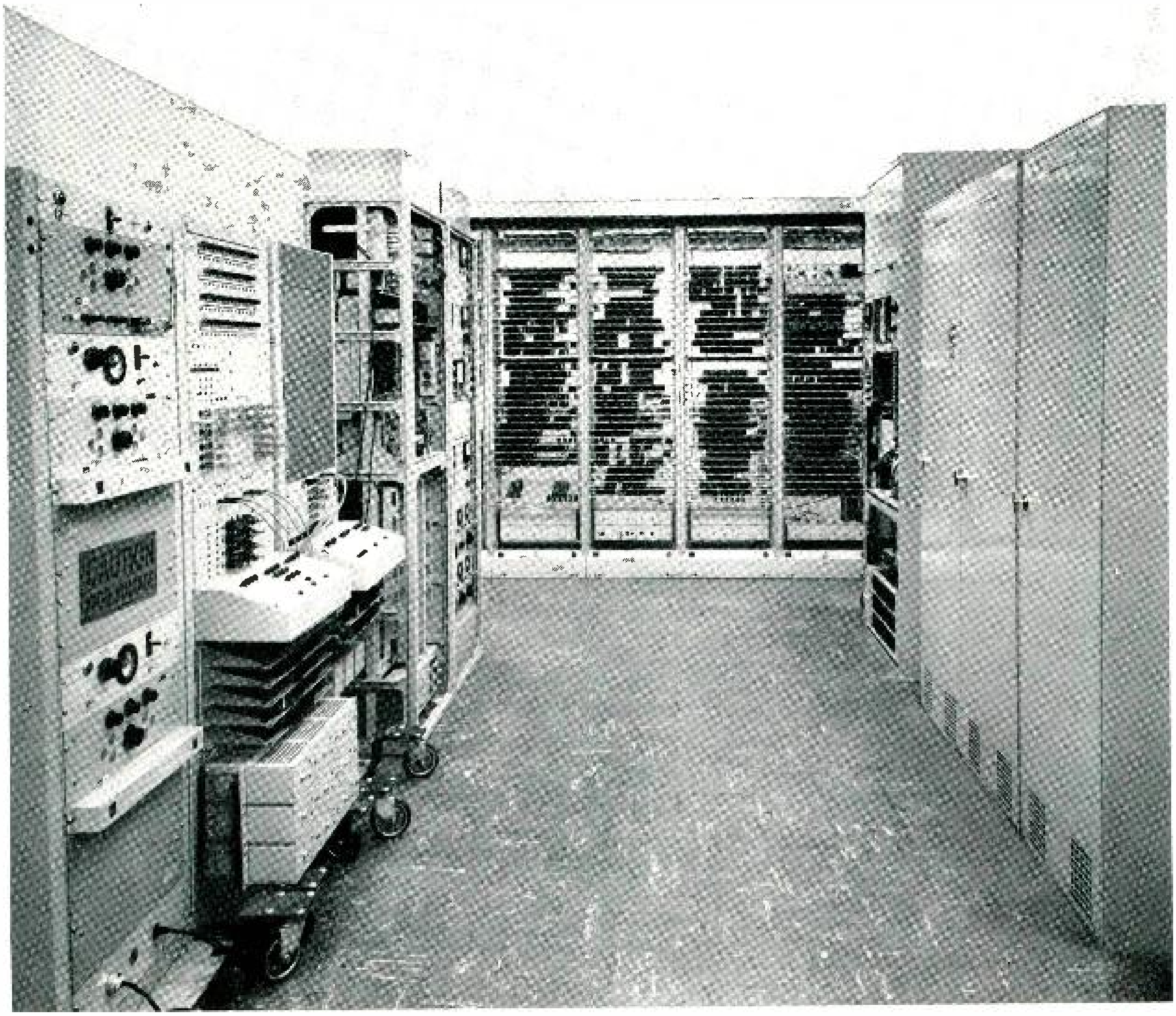


In the card translator, beams of light fall on a stack of metal cards, and certain beams are transmitted through the stack, depending upon which card is dropped. Phototransistors detect the light and transistor circuits provide amplification for signals used in later steps of the switching process.

respects. It has also provided a good background of experience in the use of transistors in telephone switching, and has served to introduce these new devices to the Operating Companies.

SIGNALING CIRCUITS

In signaling, there are two current uses of transistor circuits. Signaling provides for the transmission and reception of information between offices for control and supervision of connections. Such information—when a trunk is seized, what number is being called, when a customer answers, and finally when the talkers hang up or disconnect—is important to the process of setting up and taking down telephone connections and of recording information for billing. Over short ranges dc signals can transmit the required information; for longer distances and on carrier and radio channels, ac signals are necessary. In this latter category, a type of system known as the single frequency (SF) system employs a 2600 cps tone which is turned on or off or interrupted to convey the required dial, control and supervisory information.



Experimental equipment at the Whippany, New Jersey, location of Bell Laboratories, used for preliminary studies of electronic switching systems. In this photograph, switching network and barrier-grid store memory are in the bays at the left; central control section is in rear; and flying-spot store is in right-hand bay. Although transistors have been used in circuits incorporated into electromechanical equipment, exploitation of advantages requires design of true electronic systems.

In the past, vacuum tubes have been relied upon in this type of circuit. However, transistors have replaced tubes in a newly designed series of signaling circuits and, together with other solid-state devices and with component miniaturization techniques, have resulted in equipment units requiring only one-third the space and one-half the power of previous designs.

Another signaling system, which has the specific function of transmitting digital information from office to office or from operator to office, is known as the multi-frequency (MF) system. In this system, each of the 10 digits is formed by a simultaneous combination of two out of a set of five tones. A sixth tone is combined with certain of the first five to provide additional control signals. The tone combinations are transmitted in rapid sequence by "sender" circuits or operator keysets.

Generally, central offices have been equipped with common vacuum-tube MF oscillators to supply all senders and keysets. However, some senders are now being equipped with individual oscillators using transistors for supplying current for pulsing. In many cases this type of arrangement has proven to be more economical than the use of the common supply using vacuum tubes. Individual oscillators employing vacuum tubes are impractical, primarily because of the high cost of power required to keep the tubes ready for instant use. In addition, the long life expectancy of transistors reduces maintenance costs in comparison to tubes.

TRANSISTORS IN ELECTRONIC SWITCHING

From the above examples it can be seen that transistors have a number of attractive features for use in telephone switching. But it should also be apparent that we have only begun to take advantage of their full potentialities. Transistors, semiconductor diodes and other electronic devices, in fact, have made feasible a fully electronic switching system. Such a system is now under development at Bell Laboratories. A preliminary model capable of performing all the basic system functions is under test in the laboratory, and manufacture of an experimental system has been started to provide experience under Bell System service conditions.

Both the electronic devices themselves and the organization of the system represent major changes in the art of telephone switching. The design goes far beyond substitution of electronic circuits for the corresponding relay circuits of conventional systems. Rather, the system is organized in ways which exploit the advantages of the electronic technology.

The system consists basically of a switching network employing electronic voice-frequency switches for interconnecting telephone lines and trunks, and electronic memory and logic units for performing the control functions. The logic and memory units send orders directly to the switching network to set up a particular connection. They make use of a scanner to detect call requests and dial pulses by sampling periodically the electrical condition of each customer's line. Outgoing information is steered to the appropriate trunk through a selector. Both the scanner and selector are assemblies of electronic elements which act like single-pole, multithrow switches.

The high-speed operation afforded by electronic devices permits one set of controls to direct all operations necessary for handling the traffic in the office. At any instant, the central control is usually engaged in handling only a small part of a single call. It progresses from line to line, observing the situation on each line. When it finds a new call being originated or a dial pulse received, it takes appropriate action and moves on. Each single memory, logic or scanner operation takes an exceedingly short period of time—only a few millionths of a second—so one set of controls suffices, even though a number of such operations are required for most tasks that the system performs. To the telephone customer, the system appears to present its undivided attention, but actually the controls are time-shared among all of the customers.

Thousands of transistors and semiconductor diodes are used in the electronic switching system, and they fill some role in nearly every type of functional unit. It is in the central control that the largest number of transistors is found. Logic operations are performed by semiconductor diodes. Transistors are used as amplifiers to maintain signal levels through chains of logic and to drive other circuits. Additional transistors are used as signal inverters, emitter followers, and pulse stretchers. Others are used for such varied purposes as regulating power voltages and generating dial tone, busy tone and other signals required by the system.

In each case, choice of the transistor or diode means that at the present time it is the device best suited to the purpose. In some cases, other electronic devices have been employed. Gas tubes are used in the switching network for the talking connection. The transient memory uses a barrier-grid storage tube for recording information, and the permanent memory uses a cathode-ray tube to read information stored on photographic plates. Use of semiconductor devices in these applications may be expected to increase with further advances in the art.

The transistor, with its dual role of switch and amplifier, is therefore of great significance to switching systems, as it is to the many other areas of telephone technology discussed in this issue. Its inherent advantages point inevitably to widespread use in the coming years.

Since transistors can perform so many different circuit functions, they naturally are finding use in many different types of electronic apparatus and special equipment. These range from small voice amplifiers with relatively few components to extensive systems for high-speed data processing and data transmission.

W. A. Depp and L. A. Meacham

Station Apparatus, Power and Special Systems

When the fact first became evident that a tiny bit of mineral at the junction of three conductors could actually amplify electrical signals, those who knew of it were at once aware of its potential practical importance. Following a pattern that is traditional in the Laboratories, a planned development program began to take form immediately. Within a few days, circuit engineers had been informed of the discovery and were busy examining characteristics of the first crude examples of the "surface states phenomenon" (as it was called before the word "transistor" was coined). They were filling pages of their notebooks with possibilities for its use in oscillators, amplifiers, modulators, multivibrators and other basic circuits, and were considering with the device people how its properties could be improved.

These beginnings led into a vast effort of research, development, and engineering, the difficulties of which, and the successes as well, have undoubtedly been far greater than was originally anticipated. Although the promise offered by solid-state devices has continually grown with increasing knowledge, an interval of time measured in years was required for realization of even the simplest Bell System applications. Because of stringent performance and reliability requirements, large-scale uses had to await a fairly advanced state of development of both the device and its technology of use.

In the present article it is proposed to survey the results of the first ten years of the solid-state program in the fields of station apparatus, power and special systems. Because so many projects come within this scope, only a few can be given more than the briefest attention.

TELEPHONE STATION APPARATUS

The first large-scale use of transistors in the Bell System was in "amplifier-equipped telephone sets." There are several varieties of these, each using a single transistor as an amplifier of voice signals. Two types employ the amplifier in receiving—one to benefit people with impaired hearing, the second to improve service at noisy locations. Another design uses it in transmitting, for customers with very weak or impaired voices. In still another new design, the transistor makes it possible to employ a common-battery station set (that is, a telephone set powered over the line from the central office) on extremely long lines. Previously, such long lines from the central office demanded the use of local-battery telephones in spite of their high maintenance expense.

Experimental electronic telephone instrument: this trial model contains transistor circuits for both speech transmission and tone ringing, and uses pushbuttons instead of the usual dial. Pushbuttons send multifrequency tones in place of the usual direct-current pulses to the central office.

Specific development of these station applications began in 1952, and production of one set by Western Electric Company started in 1954. At the present time, more than 100,000 amplifier-equipped telephones are in the field, mostly of the type to aid impaired hearing. With grown-junction germanium transistors, they are showing a remarkably high degree of reliability.

Beyond these improvements for special situations, far more fundamental changes in the telephone are under intensive study. In the development of electronic switching systems, it has been found that important advantages may be derived from transistorized telephones with radically new features. One of these possible new features is a transistorized speech network which permits a major reduction in the direct current required to power the set. The change would scarcely be noticed by the customer, but it offers real advantages to the system, such as saving power and permitting the use of miniature components to terminate the line either at the central office or at a line concentrator.

Another new experimental feature is the tone ringer (RECORD, *February*, 1957), intended to replace the bell. This transistor-operated unit summons the customer with a more pleasant and seemingly softer sound, but one that he can hear further from his telephone. Even if he is on an eight-party line, he hears only his own ring, for the tone ringers are frequency-selective, and each party can have his own frequency. This change will benefit the electronic switching system by the use of ringing signals which are in the same ranges of frequency and amplitude as those of speech, and which can therefore be transmitted through the same switching circuitry, including transformers and coupling capacitors.

In a third new feature under study, the dial is replaced by a set of ten or possibly twelve pushbuttons, arranged to send multifrequency tones instead of the usual direct-current pulses to convey the called number to the central office. This promises a new high in convenience and speed to the calling customer. It may also make possible new services in which he transmits pushbutton signals over any established telephone connection—to control unattended equipment, to place orders, to make reports, and so on.

These and other new features of tomorrow's telephone owe their feasibility in large part to the transistor and the closely related diode.

In the trial of electronic switching scheduled to begin at Morris, Illinois, in late 1959, the new telephones to be used will have conventional dials, but will employ both low-current operation and tone ringing. To prepare for this there has been a preliminary trial during 1956 and 1957 of some 300 of the low-current tone-ringer (LCTR) sets at Crystal Lake, Illinois, with encouraging results as to both performance and user reaction. The addition of pushbutton operation, along with other revisions of ESS and its telephones to take advantage of latest advances, is being studied for "post-Morris."

Possible use of transistors in pushbutton telephones is not confined to electronic switching systems. Also in progress are development and engineering studies aimed at economically replacing rotary dials with pushbutton units in existing dial telephones and economically adapting the standard electro-mechanical switching systems to accept either the dc pulses of rotary dials or alternating-current pushbutton signals. Among the benefits anticipated for these systems is an eventual reduction in the amount of common-control equipment required at the central office. With pushbuttons the average dialing time is nearly halved, and holding times for the originating register-sender apparatus are materially reduced.

As an especially convenient variation of "dialing" with alternating-current signals, a so-called "repertory dialer" is also under study. Here the signals corresponding to some fifty frequently-called telephone numbers may be recorded. The number is to be selected by moving an index to the name of the called party and then transmitted by pressing a single "call" button.

These uses of solid-state elements involve neither high frequencies nor extremely fast pulsing; in this respect they tend to be unusual in modern technology. They do demand extreme reliability, however. Their commercial feasibility depends upon the low costs that are promised by automation in their manufacture. The number of transistors prospectively involved is of the order of ten million per year, and the number of solid-state diodes is several times as great.

ELECTRONIC PBX

The most recent development in the field of private branch exchanges has been the 756A PBX (RECORD, *December*, 1957) to provide dial service in the 20- to 60-line range. This PBX — designed as a small, attractive unit for use in a modern office — is simple to install and provides many new service features for the customer. These design objectives have been met and the system is being enthusiastically accepted by the Operating Companies and their customers.

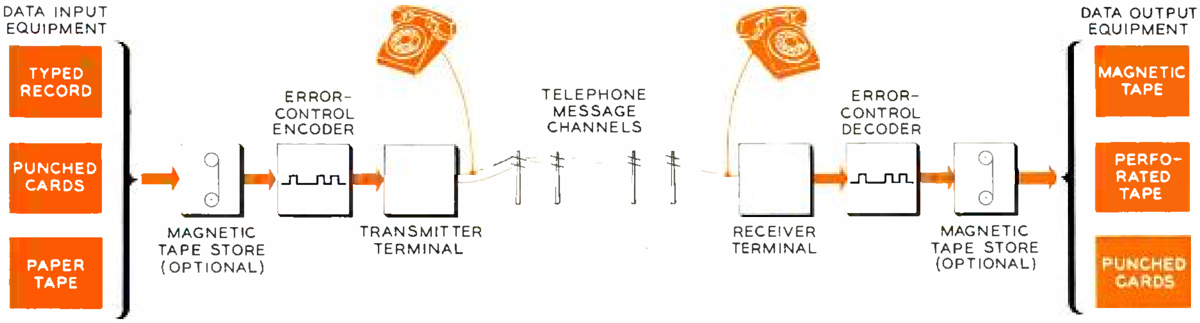
The developments of the next few years should continue with these objectives. But any attempt to provide for a greater number of lines and more new service features, without substantial increase in the size of the present package, is met with severe limitations imposed by the size, power requirements and noise of the present electromechanical devices. Therefore, exploratory work is in progress using new solid-state electronic devices to provide effective solutions to the PBX development problems of the future.

In the electronic PBX development work, the available solid-state devices now allow the instrumentation of time-division electronic switching. In the last century, time-division multiplex was applied to telegraph, and more recently this principle has been applied to multiplexing a number of pulse-modulated telephone conversations onto one transmission medium. But a number of proposals made during the last ten to fifteen years to construct time-division switching systems from various vacuum tubes, electron-beam tubes and other devices have met with only moderate success. For the smaller sizes of PBX, these proposals are basically to provide samples of a customer's conversation of a few microseconds' duration, and to deliver them periodically at the rate of about 8,000 samples per second via a common bus to another customer. Small low-pass filters in each customer's line circuit ensure a continuous flow of energy to the telephone receiver, even though the customers are actually connected to each other for only a few microseconds out of each 125-microsecond sampling period. During the remainder of this period, the other pairs of customers may be interconnected in turn.

This time-division system eliminates the many links (one per conversation) necessary for the space-division system now being used. More importantly, this system eliminates the many switches (10 to 20) necessary to interconnect each of the lines or trunks to these links. Instead, only one switch is used per line or trunk. Obviously, the requirements on the switch are quite severe. Since it closes for only a few microseconds, it must pass enough energy to keep the conversation continuously flowing. The peak currents that flow may be a sizable fraction of an ampere. These currents must be passed with little loss, since it is uneconomical at present to use amplifiers on each line. When the switch is open, it must present a very high impedance to insure that the crosstalk level is about 65 db or more below the normal speech levels. Finally, the switch must be capable of being turned on or off by a low-level power source within a small fraction of a microsecond. The outlook for obtaining these characteristics by the use of conventional vacuum tubes or by special electron-beam tubes was discouraging, but today experimental systems using transistor switches are in operation at the Laboratories.

It is evident that more than a set of switches is needed to complete a PBX. A central memory

T. P. Nenninger of the Station Apparatus Development Department testing an experimental transistorized repertory dialer under study at Bell Laboratories. A list of some fifty frequently called telephone numbers is pre-set into the instrument; pushing a single button dials number from list.



One possible arrangement of a versatile high-speed data transmission system. Many types of data input and output equipment could be served with a system of this type, and data could either be stored on tape or be transmitted directly over the line. Businesses having large amounts of information to be made available at branch locations scattered over a wide area could speed operations significantly with such services. Solid-state components will help to make them possible.

is needed to remember which customers are talking, and logic circuits are needed to write information into this memory and later to read the information from the memory and to act upon it. For the memory, ferrite and other new solid-state memory devices are contemplated. For the logic circuits, both transistors and magnetic cores may be used. These new solid-state devices combine to form a set which is compatible from the standpoints of size, power requirements and operating speeds. These new tools make it possible to design PBX's that will provide many new optional services such as direct inward dialing, abbreviated dialing, "add-on" conference connections, and station-controlled transfer of incoming calls. In general, many of the services now performed by an attendant could be done by the PBX.

DATA TRANSMISSION

Data transmission is another new service being supplied to the customer. In the past, data was thought of as information related to laboratory experiments, telemetering, military systems or scientific computing. Certainly the largest data transmission network at present is that provided by the Bell System for the SAGE continental defense system. But the most extensive flow of data is likely to be associated with the business world. Information on ordering, shipping, scheduling, accounting, inventory control and personnel administration is flowing in increasing amounts across our nation.

Much of this information is flowing over our TWX and private-line telegraph systems, but the need for higher speed and increased flexibility has led to the recent trial of a Dataphone service. Electrical signals derived from storage media such as paper tapes, magnetic tapes, punched cards, or directly from business machines may be connected to the telephone system by way of a Digital Subset. Through Bell System switching and transmission facilities, digital data delivered to this subset could be carried to thousands of customers throughout the country.

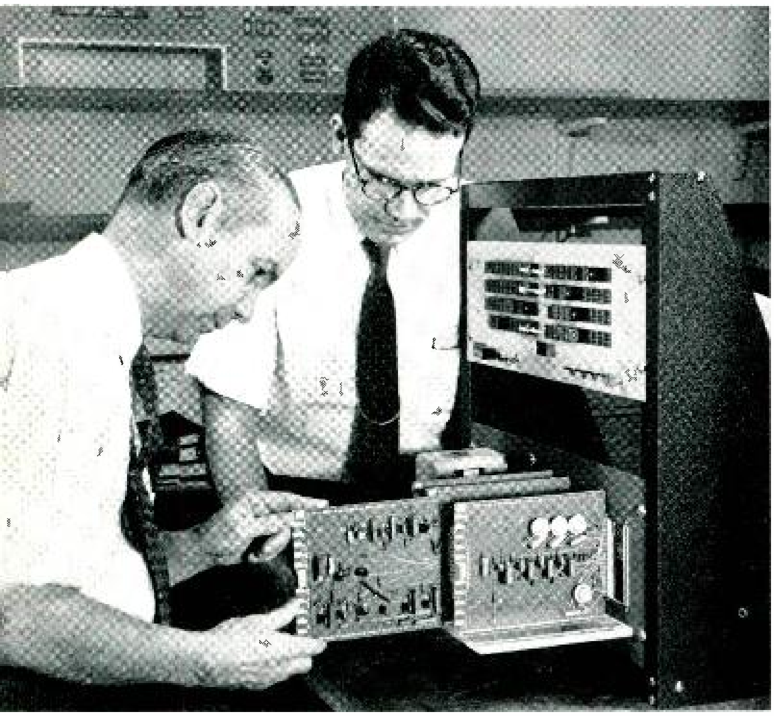
The Digital Subset is only one of several equipment units resulting from research and development effort in this field. Recently a "data subset" was demonstrated that showed the possibility of recording the outputs of several kinds of business machines on a single type of "common-language" magnetic tape (RECORD, *April*, 1957). This tape could then be reproduced at the far end of a telephone connection for operation of other business machines. By proper encoding of the input data to these transmission systems, errors due to noise or other causes may be greatly reduced. All of these systems are dependent upon solid-state devices to provide the compactness and reliability necessary in equipment to be used in the customer's office.

BELL SYSTEM DATA PROCESSING

So far, we have been considering new services provided directly for the customer. Now we wish to consider some of the special systems being developed for use "behind the scenes." One of the more spectacular systems of this type is the Bell System Data Processing (BSDP) system which is being designed to mechanize the Operating Companies' revenue accounting. Performing these operations with increased speed, efficiency, economy and accuracy will be of benefit both to the Bell System Companies and to their customers.

Through special converters the system will take input data from Automatic Message Accounting tape, punched cards, teletypewriter tape, toll tickets and customer payment stubs. A calculator will perform the arithmetical and logical operations, as well as the sorting, arranging, merging, extracting and deleting operations. Long-term storage will be on magnetic tapes. The output—including bills, toll statements, reports and lists—will appear on highspeed printers. All of these processing machines will be under the control of a stored program of daily operations.

In the design of BSDP and in the design of all large computer-like machines, it is advantageous to depend upon the newer solid-state devices. They use so little power that inexpensive power rectifiers and temperature-regulating equipment will suffice. In addition, they provide the reliability and ruggedness required where enormous quantities of data are passed rapidly through single machines and where even occasional errors may prove costly. Newer types of transistors will be used in the logic circuitry and in association with the quick-access memory. The latter will use magnetic cores or one of the newer solid-state memory devices under development.



S. T. Meyers (left) and A. B. Brown, Special Systems Exploratory Development Department, working with an experimental error-control circuit applicable to data-transmission equipment. Transistors and printed-wiring circuit cards are typical of much new apparatus now under study.

POWER SYSTEMS

The introduction of new switching and transmission systems based on the application of solid-state devices could profoundly affect the telephone power plant. Two trends are evident.

The first is the decentralization of locations at which power is required, as active equipment tends to move out of the telephone central office. The second is the increased complexity of energy-processing due to the increase in both the number of voltages needed and the more severe requirements on the precision of regulation of individual power supplies. Many of the new solid-state devices are finding applications in power plants. Thus, they are providing important new tools with which to solve the new problems that they themselves have raised.

Because of the many different voltages required by some of the new systems, the central office battery is yielding to a source of alternating current, which must compete with a battery in reliability. Rotating machinery, normally driven from commercial power but automatically switched to a standby battery during periods of commercial power failure, is provided. In this area, the new solid-state devices are affecting even equipment as old as the alternating-current generator. Our suppliers of power equipment have shown that by incorporating solid-state power rectifiers in the machines themselves, often rotating with the armature, it is possible to eliminate both the commutator and slip rings, perhaps the most troublesome parts of a rotating machine from the point of view of reliability and maintenance. As a result, simpler and more reliable rotating machinery is in prospect.

Junction diodes are used both as rectifiers and as sources of reference voltage, in relation to which outputs are regulated. Transistors are used either as linear amplifiers, in feedback systems that perform the regulation, or as periodically operating switches that provide efficient power conversion. Because of the many voltages required and the severe requirements on regulation, it is often necessary to integrate the power supplies with the switching or transmission equipment they serve. Here again, by virtue of the small size and efficiency of the new devices, such an integration can be accomplished much more readily when solid-state rectifiers and regulators are employed.

As seen from this discussion and from the previous articles in this issue of the RECORD, solid-state devices are pervading almost every area of telephone technology. Their promise is great, and this promise is already partly fulfilled.

In the interests of national security, transistors have made deep inroads into military equipment—sometimes at a faster pace than is possible for commercial systems. Many of the special problems of military applications of transistors have been solved, and the result has been a significant contribution to defense.

J. A. Baird

MILITARY APPLICATIONS

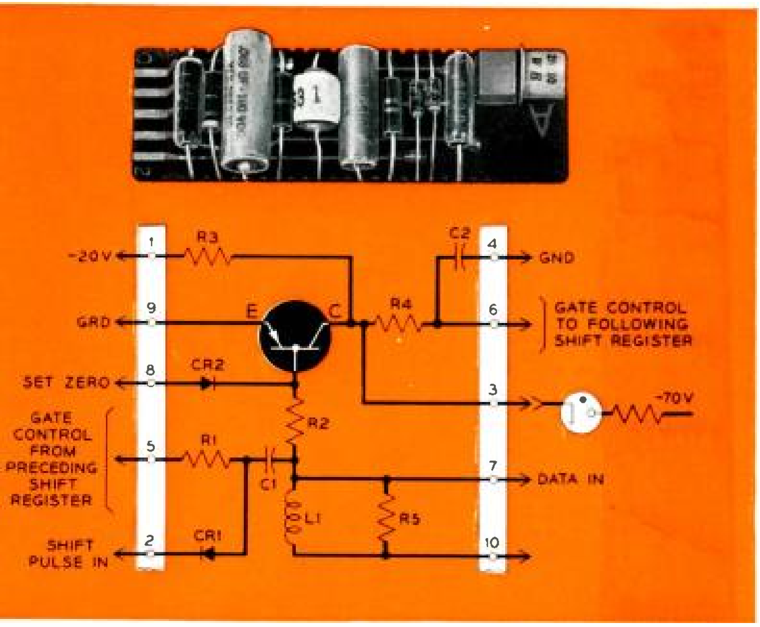
Military applications of electronic equipment pose interesting and frequently frustrating environmental problems. Many of these arise because most military equipment must be movable and often must operate while in motion. It may be carried on a man's back, in a tank, or more recently in an earth-circling satellite. In such applications—where equipment must be rugged, and where size, weight and power consumption must be minimized—it is easy to understand how the transistor can and will play an important role.

Some of the secondary benefits which the military designer expects from the use of transistors may not be so obvious, but in many cases they are extremely important to the over-all military effort. We are told, for example, that in World War II a certain type of communication company used more than ten tons of batteries in a single month for its communications equipment. Use of transistors can easily reduce that type of logistics problem many fold.

There have been some problems, however, which have prevented a switch from vacuum tubes to transistors from occurring as rapidly as many of us predicted. In particular, sensitivity to temperature variations is one of these difficulties. Field equipment may have to operate in a tropical jungle or in the sub-zero temperatures of the arctic. An airplane may go from the blazing sun on a desert runway to very high altitudes in a matter of minutes—a maneuver which obviously results in extremely wide temperature variations. Many of these conditions have been difficult to meet with germanium transistors, but the newer units fabricated from silicon should allow considerable improvement.

While weight and power are of great importance, the strongest urge to use transistors comes from the expectation that equipment reliability in an adverse environment can be improved significantly. The trend in military equipment is toward large systems. With the great increase in speed of aircraft and missiles, many of the jobs of data gathering, processing and evaluation which were done in World War II by human operators must in the future be done by electronic data processors and digital computers. These will be located in remote places, all tied together by data links. In order to make such large systems successful, it will be necessary to take full advantage of the inherent reliability of solid-state devices.

Improvement in equipment reliability can come from more than just the advantage in reliability that transistors may have over the vacuum tube. Of considerable importance is the fact that associated components are operated at low voltage and power levels, which increase their reliability. With low dissipation, packaging techniques can be used which are less vulnerable to vibration. Furthermore, with the small size and low power consumption, more critical circuits can be duplicated or paralleled to insure system operation in the event of individual component failure.



Circuit package for a military data-transmission system. Such compactness is made possible through the use of transistors, other miniaturized components, modern packaging techniques.

The planners of military systems, both in the services and at Bell Laboratories, recognized very early the potential impact of the transistor on military equipment. Starting about 1951 with feasibility studies and exploratory developments, an increasing number of military projects have used transistors until at present there are hardly any new systems which will not use them extensively. Security regulations prevent publishing descriptions of many of these applications, particularly the newer ones and those still being developed. With that limitation, some of the applications will be described briefly.

Digital Techniques

It is not surprising that many of the applications which have been investigated and carried through the model stage have been primarily digital in their operation. The first transistors available to the system designer were point-contact transistors whose characteristics were much better suited to switching or regenerative pulse-type circuits than they were to linear operation. There are other more fundamental reasons, however, why the applications are predominantly digital. Digital computing and related fields were advancing at a tremendous rate when the transistor made its appearance. The point was rapidly being approached as systems increased in size where power and weight limitations posed serious problems for many military applications of digital systems. The transistor and other solid-state devices have opened new doors for advancement. In many of the systems described here, application of transistors has been accompanied by development of new system techniques.

Transistors in Data Sets

The first military equipment units to get into production in the Western Electric Company using large quantities of transistors were the Coordinate Data Sets AN/TSQ-7 and AN/TSQ-8. These sets, developed for the Signal Corps, are used in a defense network to transmit radar target data over telephone channels. At the radar, three dc voltages represent the rectangular coordinates of an aircraft with respect to the radar site. These dc voltages cannot be transmitted long distances over telephone channels. The data transmitter converts the coordinate voltages into digital numbers and transmits them at a rate of 750 bits per second as modulation of a 1,500 cycle per second carrier. The receiver converts the digital numbers back to dc voltages, reproducing the original inputs. TSQ-8 transmits data on only a single target. TSQ-7 handles data on as many as 48 targets and also transmits velocity as well as position data.

The TSQ-8 was designed to do about the same job as the earlier TSQ-1 which used 370 vacuum tubes. But TSQ-8, like the TSQ-7, takes advantage of the transistor to give a more compact design which uses less power. Although the state of the art would not allow elimination of all tubes within the time schedule, TSQ-8 shows significant reductions over TSQ-1. With 40 tubes and 200 transistors, TSQ-8 occupies one-fifth the volume (0.5 cubic feet) and weighs only one-fifth as much (250 pounds) as TSQ-1. The TSQ-7 with 57 tubes and 235 transistors is twice the size and weight of TSQ-8.

In both sets, all digital operations are performed with point-contact transistors. Junction-type transistors are used for linear operations. Only in the encoding and decoding circuits which change the dc voltages to digital numbers and vice-versa, and in the automatic gain-control of the receiver, are vacuum tubes used.

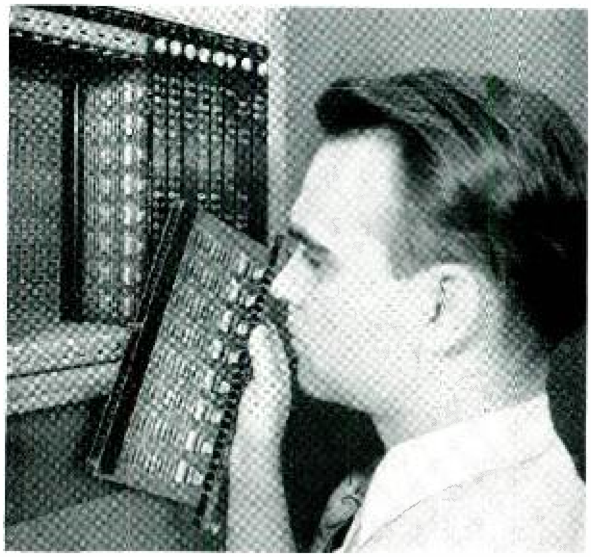
While this development was under way, considerable progress was being made in the transistor art. Schedules prevented taking advantage of some of the newer devices to eliminate the remaining vacuum tubes, but sufficient work has been done to conclude that any subsequent data-transmission sets could use solid-state art completely. This would further cut the volume of TSQ-8 by a factor of two or more and the power by a factor of ten.

This type of digital data-transmission is new enough that there has been no standardization of "language." The organization of the digital message, and the synchronization and the rate at which digits are transmitted, are not the same for all systems. The TSQ-7 and TSQ-8 receivers will not accept data from the Air Force SAGE Direction Centers. To allow the systems to work together, Bell Laboratories was asked by the Signal Corps to design a Digital Data Converter (DDC) which would convert SAGE data into the form acceptable to the TSQ receivers.

Original plans called for the DDC to use TSQ transistor circuits. In the course of development, however, some modifications were made to improve operating margins, but in general the circuits are quite similar. In all, one hundred and sixty-eight transistors are used, most of which are of the point-contact type. One of the interesting developments in the DDC is the packaging of the transistor circuits, which uses three-dimensional printed wiring. Not only are individual packages placed on printed wiring boards, but these packages are plugged into a backboard on which the wiring is also printed.

Representative of a system which would be difficult to build without transistors because of space and weight requirements is the Data Communications System AN/USC-2, better known as the Discrete Address or DA System. Data are transmitted over a single radio channel between a Navy surface vessel and as many as 100 aircraft. Data transmitted from ship to aircraft provide directions for interception of targets and for returning to land on a carrier deck. Transmission from aircraft to ship includes acknowledgments and information as to distance and direction from ship, altitude, headings and speed. The system makes it possible to direct individual orders from a ship to the proper aircraft and to identify their messages of acknowledgment and information.

The first experimental system, AN/USC-2 (XN-1), used point-contact transistors, and a subsequent development, AN/USC-2 (XN-2), uses newer junction types. The airborne equipment has about 220 transistors and the surface-based equipment has about 300.



J. H. Helfrich shown inserting circuit board into a digital data-converter unit. Printed wiring in back makes assembly into three-dimension unit.

DATA PROCESSING

The previous examples have been concerned with data transmission. Closely related insofar as basic techniques are concerned is the field of digital computing and data processing. In defensive systems, computers must handle large amounts of data from which they must predict future target positions so that other computers can direct defensive aircraft or missiles to intercept the attack. In offensive weapons like a ballistic missile or a bomber, computers must compute the trajectory to the target or the proper position from which a bomb should be released.

Until transistors became a factor in military systems, most of these jobs were done with analog computers. Now, however, they are or will be predominantly digital. Typical of an application in which the use of transistors and the application of digital techniques have gone hand-in-hand is the TRADIC (RECORD, *April*, 1955). Sponsored by the Air Force, TRADIC has had as its goal the development of techniques for the use of transistors in a bombing and navigation computer. A significant result of this program was the TRADIC Phase One Computer completed in January, 1954. It was the first all solid-state digital computer in operation.

This first computer demonstrated techniques which could be used for the bombing problem. It also provided valuable life-test data on a relatively large collection of transistors. Even though the transistors were early models which were not hermetically sealed, approximately 700 transistors operating nearly continuously for two years gave a failure rate of only 0.07 per cent per thousand hours. This gave some early confirmation to the expectation that transistors would provide reliable operation.

With techniques developed for this computer, a second computer has been designed to be tested in an airplane. Known as the Flyable Model TRADIC Computer, it was designed to operate with the K5 Bombing and Navigation System in place of an existing analog computer. In addition to the purely computing functions, a number of circuits associated with the radar, such as the radar range unit, used transistors. The first of two models was installed in a C131 airplane in the fall of 1957 and has operated successfully.

Both of the TRADIC computers are serial synchronous machines operating at a pulse rate of one megacycle per second. Semiconductor diodes perform the logic operations and point-contact transistors are used in circuits to retime and reshape pulses distorted by the logic networks. Both machines require cooling of the transistors.

Closely related to the TRADIC computers in basic circuit configuration, but faster in its operation, is a computer developed for the Navy. A task frequently required in air defense, such as protecting a fleet against bomber attacks, is the tracking of a number of aircraft targets using data obtained from a continuously rotating radar antenna. This is called track-while-scan. Position data on each of the various targets must be stored for several revolutions of the antenna. Each piece of data must be examined to see whether it is a new target or a new position of a target already being tracked. This can be accomplished by a computer in much the way a human would do it. If a target position is a logical extension of a previous track, then it is accepted as a new position in that track. This kind of operation requires a relatively large number of similar operations on large amounts of data in a short time.

To establish the feasibility of doing the track-while-scan with a digital computer using transistors, Bell Laboratories has developed for the Navy a computer which does the basic track-while-scan job. In addition, for demonstration purposes, it provides means for an operator with a joy stick to "fly" a target which the computer then tracks. This computer has the capacity to track up to 50 targets simultaneously.

THREE-MEGACYCLE PULSE RATE

To keep the amount of equipment to a minimum, the computer uses serial synchronous techniques. This, with the large number of operations which must be performed, requires a high pulse rate. One of the outstanding achievements of this project is the three-megacycle pulse rate obtained with point-contact transistors. Another feature worthy of mention is that the circuits associated with the ultrasonic quartz delay lines, which provide the large amount of storage, use transistors for all active elements. This is the first known application of transistors to do this job. In all, about 1,000 transistors are used.

Probably the largest number of transistors which Bell Laboratories has assembled in one unit of equipment in its military work has been in the Leprechaun computer. Leprechaun represents the second major step in the TRADIC exploratory development program. It uses more than 5,000 alloy-junction transistors in a computer designed primarily for laboratory evaluation and research in military computer organiza-

F. W. Hodde (right) feeds a problem into the Leprechaun transistorized digital computer while N. J. Powell prepares the machine for computations. Leprechaun has over 5,000 transistors, yet is hardly larger than a console television set. The transistors draw only twenty watts of dc power.

C. W. Green holding a transistorized power supply developed for a military system. The four transistors can be seen along the right side of the unit.

tion and programing. The transistors are operated at very low voltage (0.3 volt maximum on the collector) and low power (0.5 milliwatts dissipation). They provide both the logic or switching functions as well as the gain in a system called Direct-Coupled Transistor Logic (DCTL). This is a good example of a use of transistors which takes advantage of inherent characteristics of the semiconductor junctions and which would not be possible with vacuum tubes. The resulting circuits are extremely simple combinations of transistors and resistors, and they allow a very orderly mechanical arrangement. The 5,000 transistors require only about twenty watts of dc power.

Another feature of Leprechaun is its magnetic-core memory, which is the first large scale (1,024 eighteen bit words) core memory in which the switching currents are supplied by transistors. This was made possible by the development of a transistor that switches relatively high currents (170 ma) in a short time (1.5 microseconds).

CIRCUIT RELIABILITY

All of these applications have been primarily digital in their operation. Other transistor applications which are not digital have had as their primary goal an increase in reliability. This is illustrated by an application in the Nike Hercules missile. When a missile is fired, it is of utmost importance that the warhead not be exploded accidentally near the launching site where operating personnel might be injured. To prevent malfunctions from causing a premature explosion, circuits are provided which prevent complete arming of the warhead until it is safely on its way. Elements in these circuits themselves may fail and it is imperative that such failures shall not cause an explosion. With the small size and low power required by transistors, a multipath or redundant circuit has been developed which prevents individual component failures from making the missile unsafe but still allows it to complete its mission in the normal way. This would be difficult to do within the missile with other components. Use of transistors to improve the reliability of the electronic guidance section of Nike has been the goal of another development program. With Nike Ajax as the test vehicle, a number of models have been built and test fired with success.

Within the limits of security regulations, some generalizations in terms of circuit types can be made. Practically all digital operations to be performed in the foreseeable future will use transistor and/or other solid-state devices. Considerable experience has been accumulated by Bell Laboratories and its subcontractors on a variety of digital techniques. On projects like those already described, enough experience has been gained to allow the confident undertaking of large systems of data processing, data transmission and computing.

The problem of converting from physical or analog quantities to digital numbers is always associated with digital-type operations. Techniques have been developed to do most of these conversions at least as accurately as existing equipment using vacuum tubes. These will all use solid-state devices. Likewise, circuits which provide the tie between computers and radar sets in measurement of range, pointing of an antenna and other similar functions will all use transistors.

Equipment for supplying power to transistor circuits is now being made with all solid-state components. Where regulation is needed, transistors either provide the regulation or control magnetic amplifiers which regulate the output. Transistors of the newer types allow the operation of oscillators in the hundreds-of-megacycles range. Radar intermediate-frequency amplifiers and video circuits have been developed. In the laboratory, most of the common circuits in military systems except those requiring high power can now be made with transistors. Getting them into production, and achieving a full realization of the reliability which the transistor is capable of providing, have awaited a stabilizing of the transistor art — an art that has been changing rapidly during the past five years. The development background is available, and with the advent of the diffusion process, which promises reliable transistors at low cost, the military applications can be expected to increase greatly.

A critical test of the transistor is economical manufacture to an exacting set of physical and electrical specifications. In this article, contributed by J. E. Genther of the Western Electric Company, the difficult problem of manufacture is discussed, along with the promising solutions afforded by new techniques adaptable to automation.

J. E. Genther

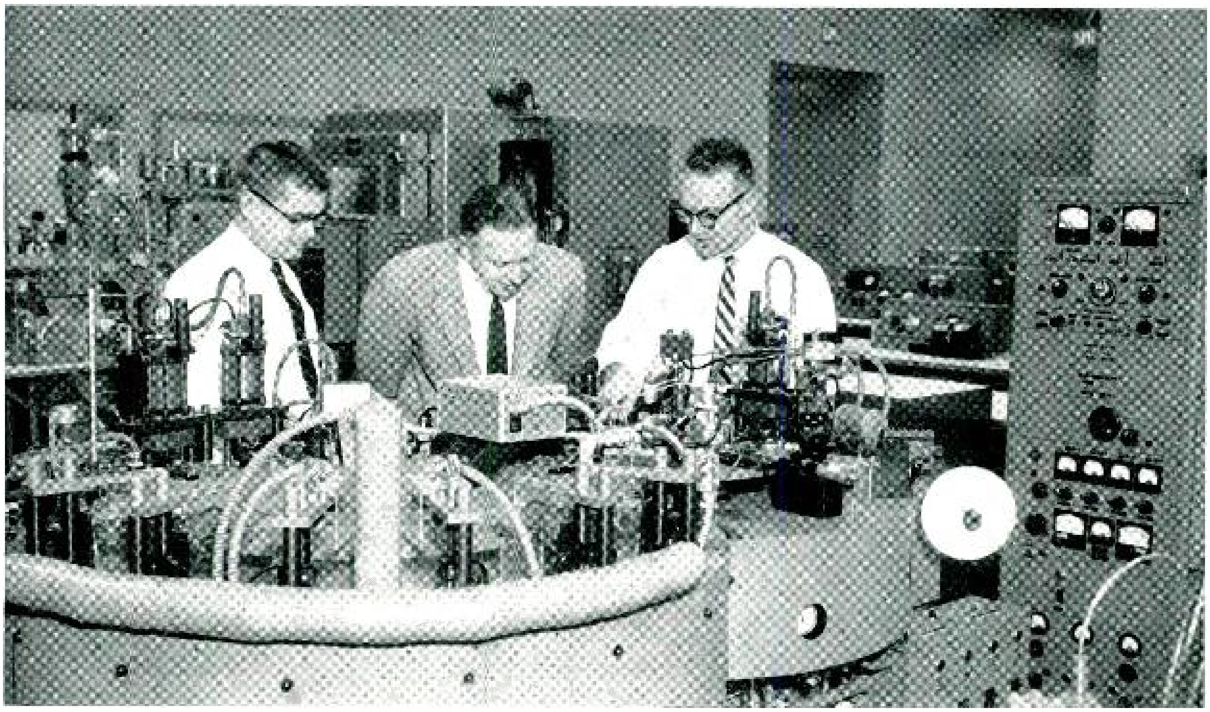
TRANSISTOR MANUFACTURE

When Western Electric Company started to manufacture transistors in 1951 it was faced with a completely new technology and a new set of manufacturing problems. The manufacturing engineer's first view of the transistor was one of excitement and anticipation. As he studied the original point-contact transistor, he saw a product simple in structure, rugged, and enclosed in plastic so that it would easily lend itself to mass production. However, it did not turn out quite that way. Problems were soon encountered in the areas of reliability, reproducibility, and range of performance.

Fortunately, a Bell Laboratories group had already been established at the Allentown, Pa., Western Electric Works, and the Laboratories device engineers and the Western Electric manufacturing engineers were advantageously located for work on common problems. It was well they were for those were the days when the Gate House of the Works was made part of the experimental manufacturing facilities: transistors were placed in this non-airconditioned area to determine whether or not their electrical characteristics would change under conditions of wide temperature and humidity ranges. They did. They were not reliable. Neither were they completely reproducible. It seemed that no two point-contact transistors behaved alike. In addition, not nearly enough transistors produced by the process met exacting Bell System requirements. It was found that the manufactured device was being asked to perform at the peak of its capability.

These problems and other experiences were fed back to the other members of what Dr. M. J. Kelly has termed an "organized creative technology" team. As a result, point-contact transistors ultimately became manufacturable. Although they are not being made on a mass-production basis and although they cost more than originally expected, these new devices do satisfy certain customer demands, and their reliability in service has been quite good. For example the transistor's first Bell System application was in the card translator *(see discussion of card translator on page 213)*. The point-contact transistors used in this system since 1952 have a reliability history of 1,000,000 socket-hours per failure.

The grown-junction transistor announced in 1952 was of considerable interest from a manufacturer's viewpoint for several reasons. In the first place, it had new ranges of parameter properties and extended the applications possibilities. In addition, grown junctions, which were understood and reasonably controlled, were substituted for the art-techniques of forming. Finally, and perhaps best of all, the manufacturing engineer was able to visualize an electronic product whose properties could be determined by test at an early stage of the manufacturing process.



At the Allentown, Pennsylvania, Works of the Western Electric Company, J. O. Hinkle (left), the author and R. C. Shafer inspecting machine for the automatic assembly of transistors. Full realization of the transistor's economy demands that the techniques be adaptable to automation.

The grown-junction transistor brought with it a new technology to be learned, involving a whole new set of processes, tests, and in many respects a new language in which "junction" was the common term. An operator could learn forming techniques in a few days, but it took engineers months to learn to grow single crystals with doped layers a thousandth of an inch thick between junctions to the precision and control needed for this work. As grown-junction devices were put into manufacture, changes were made which improved them and their manufacturing processes. Nor were grown-junction transistors without their early reliability problems, which necessitated many changes and adoptions of new processes; and as the extreme surface sensitivity was learned, the simple concept of plastic encasement was dropped in favor of a vacuum-tight, metal-to-glass sealed container.

W. E.-LABORATORIES PROBLEMS

Working together, Western Electric and Bell Laboratories device engineers solved these and many other problems. They developed electroetching, thus making unnecessary the costly solutions of hydrofluoric, nitric, and acetic acids which could be hazardous to both man and machine. Automatic bonding of the base contact was visualized, and a machine was built by the Laboratories to establish that this could be done. A round can design was introduced in place of the initial oval design as an aid to ultimate automatic manufacture. A machine for making these devices was planned and built. In spite of problems with reproducibility (in the junction grown in the bar) and range of performance (frequency and power), which affects demand, the machine produces units, and automatic semiconductor production is a step on the way to reality.

The grown-junction transistor has an excellent field record in an application where it is operating well within its range of performance. As used in the hard-of-hearing set amplifier, the 70,000 units in the field have resulted in only one known failure in two years of operation.

In 1955 a new transistor technology, the alloy process, was introduced to meet the needs of systems employing digital techniques for which the grown-junction transistor was not suitable. The very first projects for experimental electronic switching required transistors having greater reliability and better performance than any semiconductor device yet devised.

As manufacturing experience was gained on these devices on a production basis, it became clear that the alloy technology processes, though involved, were capable of the requirements requested of them. Quick feed-back of information, obtained by development and manufacturing engineers working under a common roof, indicated that these alloy transistors could be process tested at many points during manufacture and that controls could be initiated which would make the devices reproducible and reliable.

In the manufacture of alloy-junction transistors, for the first time in semiconductor manufacture, art was being eliminated in favor of process controls. Material could be selected for optimum yield, alloying pellets could be sized and sorted for use with wafers of measured thickness to produce uniformity at alloying, alloyed wafers could be process tested, and feed-back data was used to correct alloying time and temperature. The resulting uniform sub-assemblies reduced the number of fall-outs at later processing test points so that work was not performed on defective units and little material was discarded. The result—transistors were produced which satisfied the requirements of reproducibility, reliability, and range of performance. The electronic switching systems people report that they have tested, under operating conditions, more than 400 of the units for over a year without a failure. New applications have arisen and more are expected as increasing volume and continuous effort reduce costs.

Low cost is not a problem of the manufacturing engineer alone. Designs and processes which can lead to low cost are to a large extent related to the original concepts in research and development. The effort of the "organized creative technology" team fails if it cannot produce a suitable end product at a reasonable cost. To produce transistors at a low cost, stabilized designs and high yields are required, and until these considerations are met, low-cost devices produced on a mechanized basis are not possible. If one has a stabilized design, the "organized creative technology" team will refine that design and its processes, increase the yields, and achieve low cost.

Applying what was learned from production of transistors for the electronic switching system units, a process has been developed to load alloying jigs semi-automatically and, as an alternative technique, alloying pellets are also being attached by a rapid "tacking" operation. Cumbersome base-wafer mounting brackets have been eliminated to produce a simple structure capable of handling more power than its prototype. New techniques for making electrode contacts, presently a tedious hand process, have been developed. These and other refinements lead to a low-cost transistor processed on a semi-mechanized basis.

In the meantime, the development engineers have introduced junction formation by the diffusion process. This appears as an additional technology to be learned and controlled, but with an encouraging and stabilizing note: it suggests common material, common technology, and control through understanding and measurement.

We have already mentioned that in the "early days" — ten years ago — the transistor was envisioned as a simple, rugged, low-cost device which was to be easily mass produced with reproducible, reliable, and wide range of performance characteristics. With what we have learned collectively over the past ten years, plus what is promised by the diffusion technique, it appears that the goal is at hand. The uniform basic material may well be silicon, which is less affected by temperature and which is readily available on the earth's surface. The common technology will be diffusion. Slices instead of wafers will be processed so that the cost per junction becomes small. Controlled and very thin diffused layers can be produced, thereby extending the range of operation. The number of different device types will be reduced and commonized. As a result, fewer processes and techniques will be needed and high yields will more quickly result. Then more complete mechanization will be possible and lower-cost semiconductor devices will be a reality.

The manufacturing engineer's work becomes increasingly more important, for transistors are being made in growing numbers to satisfy demand for initial systems applications, and more particularly for use in development circuitry for radical new electronic telephone systems. With the growth in production, he will continue to develop the techniques of manufacturing so that standardized design and processes will be adaptable to the mechanized facilities needed to meet the large scale demands of the future.

The many demands of semiconductor technologies have been challenging to all of us, not the least to the manufacturing engineer. He has had to strike a balance between the present — to provide adequate facilities for existing techniques — and the future — to be prepared for the new and better way in this rapidly evolving field. Above all, he has had to resolve new and unknown techniques with cost and scheduling requirements. It is significant that in ten years the transistor has been developed to the point where it can compete performance-wise and cost-wise in many applications with its forty-two-year-old competitor, the vacuum tube. In many instances, the manufacturing engineer has had to sacrifice low cost for better device performance. In this respect, the challenge of the field has multiplied as the manufacturing processes have become more complex and the manufacturing engineer has had to sharpen his imagination to keep his cost competitive and at the same time keep pace with the changing techniques. Added processes and piece parts and more precise fabrication techniques required to produce the desired reliability and performance may not allow him to produce a device as low in cost as he had originally desired. The customer, however, will be obtaining more transistor performance per dollar.

Despite its many attractive features, the transistor is not used merely because it is a transistor. It is, in fact, in close competition for circuit and systems use with many other types of electronic devices, some of them at a very high state of development with many years of background experience in economical systems design.

D. F. Hoth

SYSTEMS PLANNING

When the transistor was announced ten years ago, predictions were made of a revolution in electronics. Up till now, however, transistors have had only a minor impact on the telephone plant. This may seem a startling statement in view of the many applications discussed in this issue, but only a few of these developments are in actual use and, where they are, quantities are still quite small. The revolution is still to come.

Will there be a revolution? How rapidly will it take place? In attempting to answer these questions, let us start by examining three of the important underlying facts.

A MULTI-FACETED TECHNOLOGY

The first fact is that the revolution will not come from transistors alone. There is much other new technology which, even without the transistor, would have an important effect on the telephone plant. In addition, new services to our customers are needed, many of which could be provided even without transistors. This new technology includes other devices, both semiconductor and non-semiconductor, miniaturization techniques, automatic manufacturing techniques and new techniques for the design of systems.

The development of other semiconductor devices has, of course, been closely related to the development of transistors, being dependent on the same fundamental research and much of the same applied research and development. The semiconductor devices include highly efficient power rectifiers, junction diodes for performing logic and switching functions, the Bell Solar Battery and the photo-transistor. Other new devices include the square hysteresis loop magnetic-core memory device, the recently announced "twistor" magnetic memory, the barrier-grid storage tube, the traveling-wave tube, the ferrite microwave isolator, and a great many others. Some of these, such as the magnetic memory core and the twistor are, like the transistor, results of extensive research in solid-state physics.

The development of miniaturized equipment was already on the way when the transistor was invented. However, the transistor has provided much added impetus because of its small size and low power consumption. The fact that it dissipates little heat permits compact assemblies. Its low voltage and current requirements allow the use of small circuit components with low ratings. For these reasons a whole line of miniature circuit components has been developed.

Automatic manufacturing (automation) is a trend which today extends throughout all industry. In the electronics field, new assembly techniques such as printed wiring help to make automation practical. The trend toward automation is not really dependent on the use of transistors in the equipment being manufactured, although it benefits greatly from the miniaturization which the transistor makes possible. Military needs and military-sponsored research and development have accelerated both miniaturization and automation.

New system techniques are many and varied. Perhaps the most notable, from the point of view of the transistor, is the development of electronic pulse techniques used in electronic switching and pulse-type transmission systems.

Thus, the revolution in electronics will not be wholly a transistor revolution. It will depend on a large group of new developments of which the transistor is merely a leading member.

THE TRANSISTOR AS A COMPETITOR

The second underlying fact is that the vacuum tube exists and will perform any function the transistor will perform. From the point of view of application, the difference between the transistor and the tube is usually more of degree than of kind. Transistors are smaller, consume less power and are potentially cheaper and more reliable than vacuum tubes. The tube, however, is a highly developed device and is made in thousands of different types which will perform a wide variety of circuit functions.

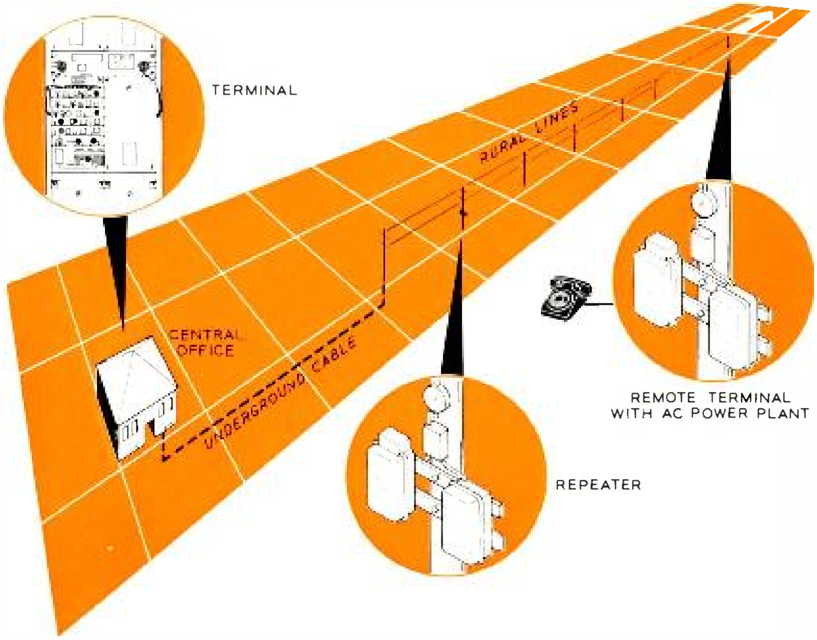
Here the situation is different than it was when the vacuum tube was invented. At that time, there was no other practical device for performing the same functions. Thus, when transcontinental telephone service was instituted in 1915, it was the vacuum tube that made it practicable. Even the comparatively crude tubes of the day had no serious competitor in making this service possible. The tube was also vital in the development of radio-telephony and carrier-telephony.

To compete with the tube today, the transistor must, in most applications, compare favorably in cost, reliability and performance. Exceptions are those cases where small size and low power consumption are overriding considerations.

After ten years of development, prices of transistors are broadly comparable to those of tubes. Further development and large-scale use can be expected to bring prices down to considerably lower levels within the next few years.

In carefully designed circuits, good transistors are now more reliable than the best vacuum tubes. The Leprechaun computer, described on page 224 of this issue, has run up over 15 million transistor hours without a transistor failure. However, we are only just beginning to understand all of the factors affecting transistor life, and failures often occur for unexpected reasons.

While transistors will do many jobs as well as tubes, they do not yet have as much versatility. For example, tubes are available which will operate at thousands and even tens of thousands of megacycles. As yet, transistors are limited to a few hundred megacycles at best. Tubes are available which will amplify large amounts of power.



Layout of the P-carrier rural system: reliability and low power requirements of transistors meant that carrier techniques could be applied where systems of this type were formerly impracticable.

With this system, telephone terminals are placed on poles near the customers' premises; one pair of wires carries regular voice-frequency channel with four channels stacked at higher frequencies.

At present transistors are limited to a few watts.

While it is a great deal slower than the transistor, the electromagnetic relay is valuable for many switching applications and, indeed, forms the building block of all present-day telephone switching systems. Like the vacuum tube, it is a highly developed device. In many applications where high speed is not a requirement, it is and probably will remain preferable to transistors.

Thus, the value of the transistor is not its ability to perform new functions which could not formerly be accomplished, but its potential ability to perform old functions more efficiently. In most telephone applications, high reliability and low cost are important, if not dominant, factors in making the transistor attractive. In many cases, such factors as high frequency response or high power handling capacity are also important. Thus, transistors have had to reach a high state of development before they could find widespread use in the telephone plant. A designer does not use transistors to be fashionable; he considers them merely additional items in his bag of techniques.

The third underlying fact is that the really revolutionary effect of the transistor on the telephone plant will not result from simply replacing tubes with transistors in new models of old types of systems. Some of this has been and will continue to be done, and with worthwhile results. But, while the cumulative savings in space, power consumption and reliability may be substantial, the really important advantages will only be realized in new applications or radically different types of systems which, while they could be built with vacuum tubes, were never found to be advantageous before transistors were available. These radically new designs, to compete with older designs, require the high state of transistor development discussed above.

OPPORTUNITIES

Let us next take a broad look at the opportunities for improving the telephone plant which the transistor affords. These can be grouped into three general categories:

1. Opportunities for saving power and space and improving reliability in more or less conventional equipment which formerly used vacuum tubes.
2. Increased freedom in locating electronic equipment where we would like to put it.
3. The ability to design practical electronic pulse systems such as electronic switching systems and pulse-modulation transmission systems.

The first of these opportunities is so obvious as to require little comment. An example is the transistorized negative-impedance repeater now in development. It will save power, space and maintenance when used in place of its vacuum-tube counterparts (types E1, E2 and E3 repeaters).

The second, increased freedom in locating electronic equipment, is an important advantage greatly desired by all telephone system planners. Many situations have arisen where more efficient systems could have been designed if it were not for the practical necessity of concentrating the electronic equipment at central locations like telephone buildings where plenty of power was available, the equipment was readily accessible for maintenance and size was not a controlling consideration. In some cases, of course, where there was enough to be gained, these considerations were overlooked. In more, however, less efficient system designs were used. The transistor, while it does not remove these limitations entirely, greatly reduces them.

In transmission, this means that we can design systems with closely spaced repeaters. We can get more use out of existing cables by operating to higher frequencies where attenuation is high. The experimental pulse-code modulation system for exchange trunks described on page 209 of this issue transmits frequencies up to about 2 megacycles over ordinary exchange cables. It uses manhole or pole-mounted repeaters only 6000 feet apart.

Sometimes we want to locate other transmission equipment on poles. In type-P carrier, terminals are located on poles near rural customers. Small storage batteries supply the terminals when commercial power fails. Where commercial power is not available, primary batteries will supply power for the equipment for long periods between replacements.

We have always avoided the use of electronic equipment in telephones because we do not want telephone service to fail when commercial power fails and because maintenance visits to customers' premises are expensive. With transistors available, electronic circuits are being used in telephones in a number of ways *(see article beginning on page 216)*. Electronic circuits are being used to amplify the speech signals, to reduce the amount of direct current which must be supplied from the central office, to eliminate a watt or more of 20-cycle power now used for ringing (replacing it with low-level, voice-frequency tones) and for a possible push-button calling circuit to replace the dial. Some of these developments, in addition to their more obvious advantages, provide new opportunities in the design of the switching and transmission systems with which they will be used.

In switching, the ability to locate equipment where we want it allows the system planner to consider more efficient systems. Electronic remote line concentrators allow a group of customers to share the same lines to the central office, with a consequent saving of cable pairs.

In addition to switching, transmission and station equipment, there are also other applications where we want to locate telephone equipment outside of central locations. A good example is the personal radio signaling service. Transistors allow us to develop a compact, efficient pocket-radio receiver with long battery life.

ELECTRONIC PULSE SYSTEMS

The third opportunity afforded by transistors is practical electronic pulse systems. These systems perform logical or switching functions like those performed in electromechanical switching systems but at much higher speeds. Generally, the signals handled are binary in character.

Such systems can be built with either vacuum tubes or transistors. Vacuum-tube circuits are at present faster, but even transistor circuits are a thousand times as fast as relay circuits. Transistor systems operate at much lower power levels than tube systems, may require fewer circuit elements and have advantages of compactness and reliability.

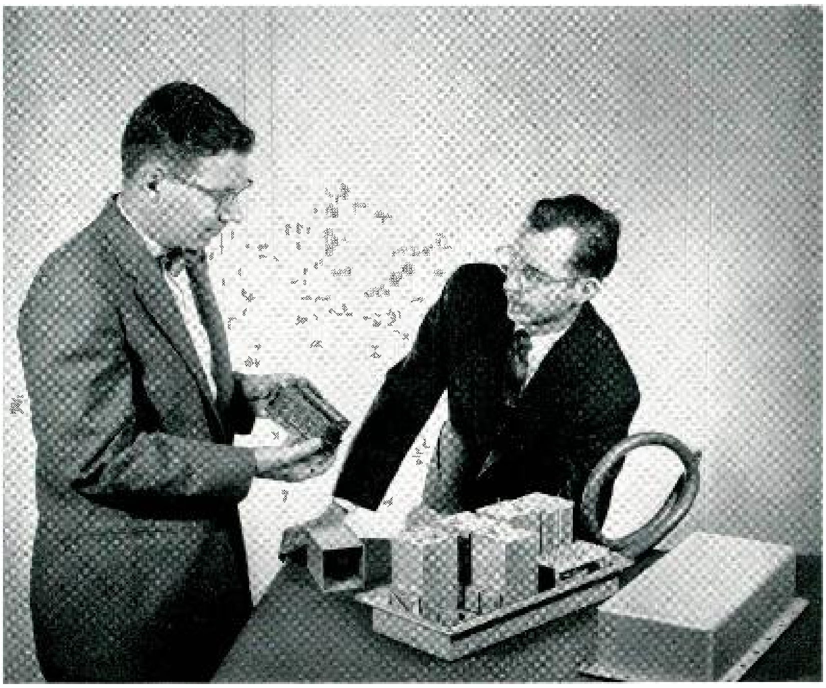
In telephone switching, the speed of electronic circuits allows much greater time-sharing of common functions, resulting in savings of equipment. In spite of this, vacuum-tube systems have been unable to compete with electromechanical systems. This is primarily because of the large continuous power required by vacuum-tube heaters to insure instant availability, though each tube may be used only part of the time. With transistors, the balance is shifting and electronic switching will become practical. In these new switching systems, an additional opportunity is being exploited—that of providing large quantities of low-cost electronic memory. Service features and other operating characteristics of the system can be changed at will by merely changing the contents of the memory. This results in a highly flexible system that can be readily altered to accommodate new types of services and changing conditions.

These high-speed pulse techniques are also being extended to transmission in pulse-code modulation systems. PCM systems can operate on lines having more distortion and noise than conventional transmission systems. They allow us to get more out of existing cables and to use new types of transmission media not suited for other types of transmission. The PCM system for exchange trunks now being tested by the Laboratories is a first example. Other PCM techniques are being considered for toll applications.

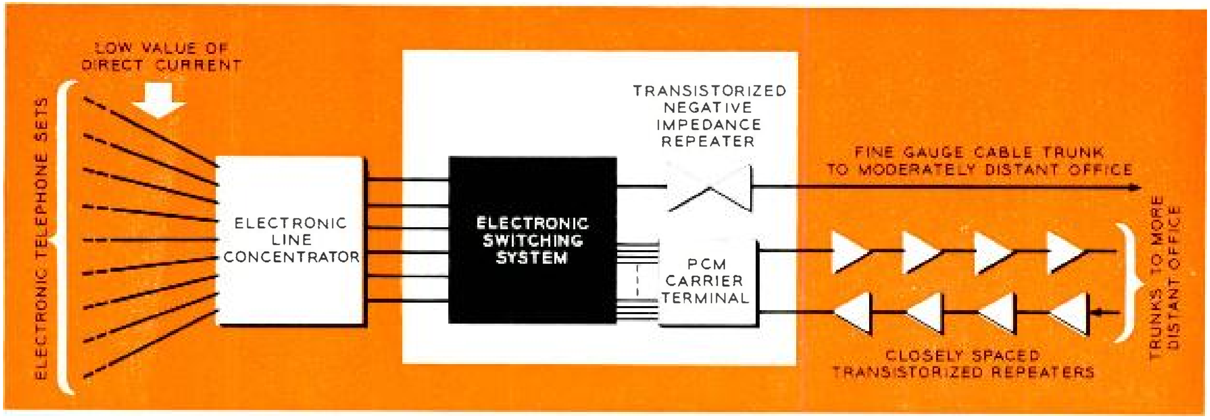
THE TELEPHONE PLANT OF THE FUTURE

Let us now return to our original questions. Will there be a revolution? How rapidly will it take place? Taking the usual risk of the prophet, let us explore these questions by trying to picture the telephone plant of the future.

This future plant will undoubtedly include many services which are non-existent or in rudimentary form at present. These include such things as



F. T. Andrews (left) and L. C. Thomas inspecting repeater for experimental pulse-code modulation system. Repeaters can be installed about every 6,000 feet through urban areas.



Simplified schematic representing a number of possible applications of electronic systems in the telephone plant of the future. Electronic devices —predominantly transistors and semiconductor diodes, but also including many other types — can mean better service and greater economy. Degree of success depends on realism of systems planning, plus the large coordinated effort of research and development in many fields and efficient manufacture and operation to meet needs.

visual communications and high-speed data transmission. While much could be said about these services, let us restrict our discussion to regular telephone service.

Let us start with the local plant. Up till now, it has been largely non-electronic. Whereas, in toll, vacuum tubes have been widely used and are indeed essential for the long transmission circuits required, the same has not been true in the local plant. In recent years, type E repeaters and type N carrier have made inroads, but only a small part of the plant has become electronic.

In the future, we can expect electronic systems to be as large a factor in local transmission as in toll. While it will probably be many years before this is fully realized, the next ten years should see a several-fold increase in the use of electronic transmission facilities in the local plant. The new electronic art, including the transistor, coupled with the increasing cost of cables will make this economically advantageous. Improvements in transmission will be another benefit.

The largest use of electronic transmission facilities is expected to be in interoffice trunks. The longer trunks will use carrier methods, including the new PCM system. Medium-length trunks will use smaller conductors than at present with transistorized negative-impedance repeaters. The trend toward more tandem switching will be aided by the improved transmission quality of the new types of facilities.

The situation in the case of customer lines and concentrator trunks is less clear. Some type of electronic facility, however, will undoubtedly begin to appear in this area also.

Electronic switching systems will be used. It will be a long time, however, before all switching is electronic, since we have some very good electromechanical systems. Electronic line concentrators and electronic PBX's will also appear. The line concentrator will be a start toward a new pattern of switching with larger centers and more small satellite units.

More and more telephone sets will become electronic, particularly in areas served by electronic switching systems. We will have sets requiring much less direct current and equipped with tone ringing and push-button calling. Some extension of loop length will be possible. Special sets for special purposes will become more general: the speakerphone, sets for the hard of hearing, etc.

Special services such as mobile radio and radio paging will be extended and improved with obvious help from the transistors.

In toll, the effect of transistors will perhaps be less obviously revolutionary. Still, it can be expected that new transmission systems will use transistors. Transistorized pulse-code modulation systems may come into use. Electronic switching will certainly be applied with the "brains" available used to provide more flexible rerouting of traffic to accommodate changing loads or circuit out of service time.

It seems safe to conclude that a revolution, or at least a rapid evolution, is in the offing. It will be fashioned out of transistors, other devices both new and old, pulse techniques and other new art. It will also be fashioned out of new and broad concepts of planning systems for maximum efficiency and economy of Bell System use.

THE AUTHORS


J. A. Baird

J. A. Baird ("Military Applications"), was born in Omaha, Texas, and received the B.S. degree in Electrical Engineering from Texas A&M in 1943. After service in the U. S. Navy, he joined Bell Laboratories in 1946 and spent several years engaged in the development of military radar and communications systems, during this time doing graduate work and receiving the M.S. degree from Stevens Institute of Technology in 1950. He then returned to Texas A&M, from which he received the Ph.D. degree in Electrical Engineering in 1952. Upon rejoining the Laboratories, Mr. Baird again entered the military development field, with particular emphasis on the applications of transistors and other solid-state devices, and in 1955 was appointed Military Development Engineer. This spring he was appointed Assistant Director of Military Systems Development. He is a member of the Institute of Radio Engineers.

W. A. Depp ("Station Apparatus, Power and Special Systems"), was born in Kentucky and received his college education at the University of Illinois. After being awarded the B.S. and M.S. degrees in Electrical Engineering in 1936 and 1937, he joined the Laboratories in the latter year, and was initially concerned with problems in the design of electron tubes. During World War II, he worked on tubes for radar and other military equipment, and he was subsequently placed in charge of the basic development of all types of gas-filled tubes. Later, Mr. Depp transferred to the Transmission Systems Development Department with responsibility for several telephone carrier systems projects, and in 1955 he was appointed Director of Special Systems Exploratory Development. He is a member of the A.I.E.E., a senior member of the I.R.E., and a member of Eta Kappa Nu, Tau Beta Pi, Phi Kappa Phi and Sigma Xi.


W. A. Depp

J. E. Genther ("Transistor Manufacture"), is a native of Easton, Pennsylvania, who received his B.S. degree in Chemistry from Lafayette College in 1940. He then joined the U. S. Navy in which he served throughout the years of World War II, and joined Western Electric in 1945 as Assistant Engineer in Manufacturing at the Hudson Street Tube Shop. Subsequently he has been Assistant Engineer working on copper oxide varistors and on resistors and Engineer associated with chemical services and further work on varistors and transistors, and then became Department Chief with responsibility for transistors and varistors. Presently Mr. Genther is Assistant Superintendent, Varistor Engineering, in the Allentown Works of the Western Electric Company, where he works closely with Laboratories personnel on Bell System projects.


J. E. Genther

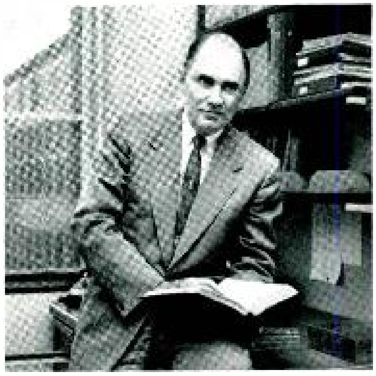
D. F. Hoth ("Systems Planning"), Transmission Studies Engineer at Bell Laboratories, was born in Arlington, N. J., and attended Stevens Institute of Technology, from which he received the degree of Mechanical Engineer in 1935. A member of the Laboratories since 1936, he initially engaged in studies of local


D. F. Hoth

plant transmission and of room noise in relation to telephone transmission. In 1942 he was commissioned in the U. S. Army Signal Corps for military development work, and returned to the Laboratories in 1946. Since the war, Mr. Hoth has been active in the radio field, including work on mobile radio systems, and in the planning of development projects for wire and radio systems. He was appointed to his present position in 1953, and is currently responsible for long-range planning studies and new transmission systems. He is a member of Sigma Phi Epsilon and of the Institute of Radio Engineers.

M. B. McDavitt ("Transmission Applications"), a native of Texas, holds an E.E. degree from the University of Virginia and an M.S. in E.E. degree from Massachusetts Institute of Technology. He joined the Development and Research Department of A.T.&T. in 1925, where he worked on dial systems, and continued in this field after transferring to the Laboratories in 1934. During World War II he was associated with various military projects, and later served as Director of the Bell Laboratories School for War Training. He was named Radio Transmission Engineer in 1945, Assistant Director of Switching Engineering in 1948, and in 1949 became Director of Switching Development. He has been Director of Transmission Development since 1952. Mr. McDavitt is currently responsible for the development of all transmission systems for Bell System use. He is a Fellow of the A.I.E.E. and a Senior Member of the I.R.E.

M. B. McDavitt



L. A. Meacham

L. A. Meacham ("Station Apparatus, Power and Special Systems"), who is Station Development Engineer at the Laboratories, is a native of Denver, Colorado. He received the B.S. degree in electrical engineering at the University of Washington in 1929, and the following year he pursued graduate studies at Cambridge University in England, where he received the Cambridge "Certificate of Research" in 1930. That year he joined Bell Laboratories and worked on problems concerned with constant-frequency currents. One of the results of this work was his development of the bridge-stabilized oscillator. In 1939, he received the Eta Kappa Nu Recognition of Outstanding Young Electrical Engineers.

With the approach of World War II, Mr. Meacham engaged in radar developments, during which time he designed a precision timer that became nationally standardized for the measurement of range in military radar equipment. A prolific inventor with 48 issued patents to his credit, Mr. Meacham is presently engaged in exploratory development of electronic telephones. He is a member of Phi Beta Kappa, Sigma Xi, Eta Kappa Nu and Tau Beta Pi.

W. J. Pietenpol

W. J. Pietenpol ("Transistor Designs—the First Decade"), Director of Development—Semiconductor Devices, has been a member of Bell Laboratories since 1950. He was born in Boulder, Colorado, and received his undergraduate education at the University of Colorado, where he was awarded both the B.A. and B.S. degrees in 1943. After a period with the Radio Corporation of America, he continued his studies at Ohio State University, where he was awarded three fellowships—Eastman Kodak, Westinghouse, and Research Foundation—and received his doctorate

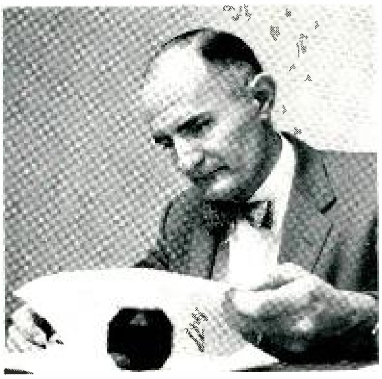
AUTHORS (CONTINUED)

degree in 1949. At Bell Laboratories, Mr. Pietenpol has been primarily concerned with the development of p-n junction diodes and transistors. He was appointed Transistor Development Engineer in 1953, and was appointed to his present position in 1955. He is a member of Sigma Xi, Tau Beta Pi, Phi Beta Kappa and the I.R.E.

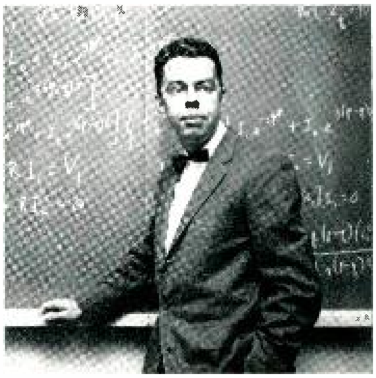
A. E. Ritchie

A. E. Ritchie ("Applications in Telephone Switching"), Systems Planning Engineer at Bell Laboratories, is a resident of Summit, New Jersey, who received the A.B. degree from Dartmouth in 1935. He received the A.M. degree in Physics, also from Dartmouth, in 1937 and joined Bell Laboratories in July of that year. He was initially engaged in the testing of switching circuits, subsequently set up and taught courses in Laboratories educational programs, and conducted a graduate course in switching circuits at M. I. T. He is co-author with W. Keister and S. H. Washburn of *The Design of Switching Circuits*, published by Van Nostrand in 1951. More recently, Mr. Ritchie was concerned with traffic measuring equipment, and in 1952 was appointed a sub-department head in charge of various military and government projects. He was appointed to his present position in the Switching Engineering Department in 1955, and is presently engaged in studies of pushbutton calling sets, a military communication system and line concentrators. Mr. Ritchie is an associate member of the A.I.E.E.

Morgan Sparks ("Semiconductor Research"), a native of Pagosa Springs, Colorado, received his B.A. and M.A. degrees from Rice Institute in 1938 and 1940, and was awarded a University of Illinois Rockefeller Foundation Fellowship for the years 1940 to 1942. While studying at the University of Illinois, he was employed by the National Defense Research Committee, and in 1943 he was awarded the doctorate degree. Upon joining the Laboratories in this year, Mr. Sparks engaged in electrochemical research with emphasis on primary batteries, electrolytic capacitors and rectifiers, and later entered the field of semiconductor research into the properties of p-n junctions and junction devices. In 1955 he was appointed Director of Solid State Electronics Research at the Laboratories. He is a member of the American Physical Society, the American Chemical Society. Phi Beta Kappa and Sigma Xi.



Morgan Sparks



R. L. Wallace, Jr.

R. L. Wallace, Jr. ("Research in Circuits and Systems"), is a native of Callina, Texas, and received the B.A. degree, summa cum laude, from the University of Texas in 1937. Continuing his education, he received the M.A. degree in Physics from the same university, and then went to Harvard where he combined study and teaching. In 1941 he accepted a position with the National Defense Research Committee as a Special Research Associate in the field of military communications, and he joined Bell Laboratories in 1946. At the Laboratories, Mr. Wallace has been active in a number of fields, particularly acoustics research and, since the invention of the transistor, research in transistor circuits and systems. He was appointed Director of Transmission Research in 1955. He is a member of the Acoustical Society of America, Phi Beta Kappa and Sigma Xi, and is a Fellow of the I.R.E.