The frequency-production index can be expressed in dimensionless form and is then the number of oscillations at the alpha cutoff frequency of the highest frequency transistor during the average time required to produce a transistor in the U.S.A. In dimensionless form I_fP is 2×10^{11} cycles per unit. This measures the simplicity of the transistor compared to man.

Since transistor production depends on years and men, I have used in Table I the well established ratio[2] of 70 between them in predicting frequency from volume and frequency-production index. The production estimates are based on conventional methods of estimating growth.

No business essay is complete without a reference to money. Assuming that the cost per unit varies as $P_y^{-0.33}$, my estimate of average transistor prices for 1958, 1959, and 1960, is $1.80, $1.40, and $1.20. The corresponding sales volumes are $125, $210, and $300 million.

In closing this essay, I should like to acknowledge the assistance that has made it possible to carry out the extensive research involved. The significant data published by the Electrical Industries Association[3] has been essential. Special thanks are due to the encouragement and assistance of my friends at Bell Telephone Laboratories; without it, the completion of the investigation would have been difficult.

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[2] This number will be recognized as 3 (10) in the customary score system.

[3] *Wall St. J.*, p. 11; October 14, 1957.

The Technological Impact of Transistors*

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Summary—**During the past ten years the transistor has invaded every phase of the electronics industry. Its important features are its high efficiency at low power levels, its reliability, and its potential low cost.**

Presented here are the major milestones and problems which were overcome and led to devices that cover a broad field of electronic technology, and to the growth of a new industry.

ELECTRONICS is an increasingly important part of modern technology. It merits this distinction because it pervades our economy as water does a sponge. Since electronics has to do with the high speed transmission and processing of information, it becomes a wonderful extension of man's mind.

Electronics has the potential of affecting every aspect of our modern industrial world through communication, entertainment, transportation, power, manufacturing, and business. If we can measure the transistor's effect in expanding the breadth and versatility of electronics, by imaginative implication, we can define its impact on the whole of modern technology.

The bulk of present day electronics has to do mostly with the *transmission* of information. In some 45 years it has grown from the original deForest vacuum triode and modulation theory to the fifth largest American industry comprised largely of consumer, military, and industrial transmission functions.

For some time now, through applications of information and switching theory to functions such as pulse-code modulation, memory, and logic, electronic man has known how *in principle* to extend greatly his visual, tactile, and mental abilities to the digital transmission and processing of all kinds of information. However, all these functions suffer from what has been called "the tyranny of numbers." Such systems, because of their complex digital nature, require hundreds, thousands, and sometimes tens of thousands of electron devices. The large amount of power used inefficiently and the high cost of reliability of the electron tube have prevented these expansions of electronics in all but a few cases where the high cost could be tolerated, even though not desired.

This is where the transistor comes in. The really important aspects of the transistor are its very high-power efficiency at low-power levels and its potential reliability. Because of its relatively simple mechanical features, it is potentially low cost—another basic requirement of "the tyranny of numbers."

So the story of the transistor to date has really been the struggle to realize these potentialities of high performance with high reliability and low cost. Let us take a quick look at the major milestones and problems that have been passed leading to today's transistor technology.

To measure the present and future stature of transistor electronics, we will glance at a few of the many system functions which transistors are now performing

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or are committed to do. These examples cannot be inclusive—there are too many. Many of them will be drawn from the Bell System since the facts are more readily available to the authors. But some military, consumer, and industrial applications must be mentioned.

HISTORY

The era from the announcement of the invention of the point-contact transistor in mid 1948 until mid 1951 can be likened to early childhood. In this era, key items in advancing the device technology and research understanding came through the development of pulling and zone-melting methods for growing single crystals of germanium of unprecedented purity and uniformity.

Work by the inventors of the transistor and their colleagues during this era, resulted in improved theoretical understanding and physical realization of the junction transistor with greatly improved performance. Fabrication of junction diodes, triodes, and phototransistors was accomplished by both growing and alloying techniques. The micropower, high gain, and low noise predicted for such devices was proved.

From mid 1951 to mid 1952, a period reminiscent of adolescence was experienced. Gains in performance encouraged further applications. However, as for an adolescent youngster, so too for the transistor, from day to day we were impressed with new performance possibilities—yet, at the same time, new reliability difficulties were brought to light.

These reliability problems were shown to be surface dependent, research and development programs on surface physics and reliability were initiated throughout the industry. This heralded the "young manhood" period of 1952 to mid 1955.

During this period, larger responsibilities and definite commitments were undertaken. For example, point transistors went to work in an operator tone-dialing trial in October of 1952. The first over-the-counter sales of alloy and grown-junction-transistor hearing aids took place around the end of 1952. A few years later no manufacturer produced tube hearing aids.

In March, 1953, point-contact phototransistors and transistors were employed in the card translator portion of direct distance-dialing equipment. In a reliability study over 100 million transistor hours of operation were attained in this application with an indicated failure rate of less than 0.04 per cent per 1000 hours. TRADIC, the first transistorized military computer, was demonstrated in January, 1954, and later in the same year, the first all-transistor personal radio became available in time for the Christmas market.

Other equipment developed during this era included the first all-transistor industrial computer, and transistorized telephone sets for the hard of hearing and for use in noisy locations. Transistorized rural carrier and line concentrator tests were successfully undertaken.

On the military side, digital data transmission and processing systems, computers, and missile-control systems relied wholly or in part on transistors for their successful development and trial.

This sudden expansion in applications called for a wide variety of types of transistors. Techniques for germanium were pushed to their limits. Germanium crystals of almost perfect physical and chemical properties were developed to improve manufacturing yields.

Diodes, triodes, tetrodes, and power units of a wide variety were developed and put into manufacture. Silicon entered the field as an alloy-junction diode of greatly improved properties; silicon became an important bread and butter business.

Gains in understanding of the surface effects in reliability were put to work successfully in the form of improved surface treatment and capsulation techniques. Reliability surpassed that of all but the best telephone tubes. In fact, one hearing aid transistor manufacturer complained bitterly and frequently over the disappearance of his replacement business.

Where then did transistor electronics stand near the end of this era of early manhood?

The wide variety of applications called for a staggering range of characteristics. Point, grown, alloy, and surface-barrier techniques on germanium and silicon were close to their capability limits. Each structure and technique had serious limitations. Transistor designers and manufacturers were forced to develop a large number of compromise designs—about 200. The resulting manufacturer's nightmare inhibited large-scale economical manufacturing of any one prototype. This was reflected in still high costs, from $2.00 to $45.00 per transistor.

Meantime, research people were busy pushing ahead the frontiers of understanding of materials, structures, and techniques. Toward the end of this era they made a triple breakthrough of such magnitude that it started a new era—the "Era of Maturity." This work demonstrated the possibility of removing most of the limitations which forced design compromises to a multiplicity of types.

By proving the feasibility of purifying silicon to transistor requirements, by solving the problems of solid-state diffusion as a technique, and by devising the diffused-base structure, they demonstrated the possibility of making diffused silicon transistors with cutoff frequencies of 50–100 mc, 5 to 10 times faster than the older germanium transistors while at the same time retaining the silicon advantages of high power, temperature, and efficiency. Application of similar structures and techniques to germanium pushed the frequency frontier into the low-microwave region.

The magnitude of these research accomplishments dictated a re-evaluation of most transistor development-application programs starting in mid 1955. It was realized that further refinements of growing, alloying, and surface barrier techniques were possible but only at large development and manufacturing costs. However, the dramatic demonstrations of potentiality of these new diffusion techniques, based as they were on more complete scientific understanding, clearly showed that maximum effort should be devoted to their development. The eventual economies of a single prototype diffusion technique and diffused structure, with heavy emphasis on silicon, were the goals.

PRESENT STATUS

Where then has this diffusion breakthrough brought us today? Either in, or just entering, production are the following diffused devices:

1) Silicon-power rectifiers ranging from 0.5 ampere up to 100 amperes which will handle reverse breakdown voltages up to several hundreds of volts.
2) Silicon-voltage limiters with closely controlled breakdown voltages ranging from 4.2 volts up to 200 volts.
3) Diffused-base silicon transistors with frequency cutoffs in the 50–100-mc range. As switching transistors they will provide 10-mc switching rates with attendant power dissipation up to one-quarter watt.
4) Diffused-base germanium transistors with frequency cutoffs as high as 1000 mc. One code of this prototype designed as an oscillator has a minimum rating of 50 mw output power at 250 mc. Other codes designed for very high speed switching provide switching rates as high as 50–100 mc.

Today the circuit designer has at his command a broad range of structures and characteristics. These new devices in combination with improved versions of the older structures greatly extend the range of performance formerly possible. It is not possible here to compare all of their electrical characteristics, but it is helpful to show in Fig. 1 the frequency range as a function of power dissipation covered by presently available types. The frequencies plotted are the grounded-base-alpha cutoff frequencies for each prototype. For video or broad-band amplifiers, the useable range would be somewhat below the cutoff frequency depending upon the mode of application. However, for oscillators, useful power outputs can be achieved to well above the frequency cutoff.

The availability of such complete performance range from present semiconductor devices has profoundly affected the kinds and numbers of system applications.

In transmission systems, pulse-code modulation carrier, personal radio paging, and VHF communications are depending upon diffused germanium devices. Although transistors have not yet found their way into commercial television receivers, laboratory developments indicate this to be highly probable with attendant savings in size, power, and maintenance costs.

In power systems, the new diffused silicon rectifiers, voltage regulators, and lightning protectors are essential components for success. By applying diffusion to cheap silicon, it has been possible to design a much smaller and better telephone click reducer than the copper-oxide unit now in use for many years but dependent upon an uncertain supply of unique copper.

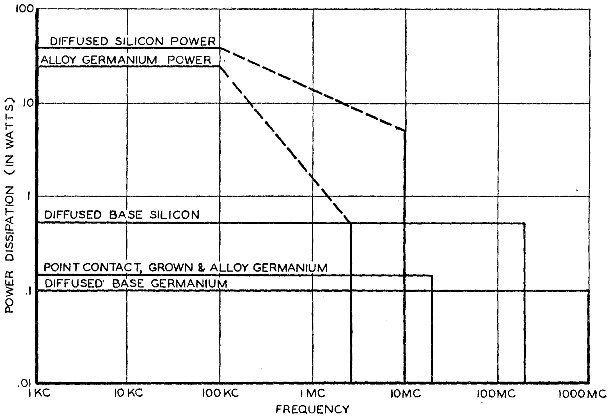

Fig. 1—The curves indicate the power-frequency spectrum covered by various prototypes of transistor structures.

In electronic switching, computers, and digital data processing, the new diffused diodes and triodes are greatly extending the speeds and reliability while at the same time greatly reducing the size and power required for such large and complex machines.

In the military area too this new line of devices is gaining acceptance in computers, missile systems, servosystems, fuses, radar, communications, and power supplies. In fact, diffused germanium transistors are now circling the earth in the EXPLORER and VANGUARD satellites.

All in all today's variety of old and new transistors are finding their way into a staggering variety of tube and nontube replacement equipment. To round out the list with a few more, there should be mentioned binaural hearing aids, portable radios, phonographs and dictating machines, auto radios and fuel-injection systems, portable cameras, paging receivers and instruments, machine-tool controls, clocks and watches, toys, and even a guidance system for a chicken feeding cart.

As of this date, there are approximately seventy domestic and foreign manufacturers of transistors and related diodes. Production figures abroad are not available but it is known that essentially every major Western nation, as well as Japan, is very active. It is believed, however, that they are somewhat behind the United States in application and production. We have no authoritative technical information on Russia's status but *Pravda* assures us that Russia is well in the forefront—as usual?

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 is now entering production, is the four-region *p-n-p-n* silicon 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 one thousand times faster than the gas tube. Thousands of these diodes will be used in the switching network of all-electronic telephone systems. Other major applications will doubtless be found in military and commercial digital computers.

It is interesting to note that this small device requires precise control of almost every bulk and surface property known to semiconductors. It is necessary to control accurately the density of impurities throughout the bulk material, the width of the various layers, and the density of the 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 diode. Recent technological developments have made possible such precise control of each of these properties.

With the ever-advancing speeds of electronic computers go requirements for faster and faster computing diodes. By a controlled reduction of carrier lifetime, minority carrier storage and recovery times have been reduced to less than 2 mμsec. These designs, which are ready for pilot manufacture, will extend the speed of computer diodes by a factor of 10.

New diffused transistor structures are being made in the laboratory by reducing the thickness of the base layer and by reducing electrode spacing and cross-sectional area. In this way the frequency range of germanium and silicon transistors can be extended another factor of 10 over that of present designs. It is expected that diffused germanium transistors will soon be made which will oscillate at frequencies as high as 10,000 mc per second.

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 microwave use. The dependence of the capacitance of a *p-n* junction upon the voltage across it makes possible a rapidly variable capacitance, when an appropriate high-frequency voltage drive is used. Furthermore, theory predicts that this device should have extremely low noise. In actuality, an amplifier of exploratory design has a measured gain of 15 db at a frequency of approximately 6000 mc per second and a measured noise figure of 4.5 db. In this case the driver was a 12-kmc reflex klystron. It now seems possible that amplifiers can be designed for operation at frequencies as high as, or possibly higher than, those possible with advanced designed vacuum tube and traveling wave structures with properties competitive in many ways.

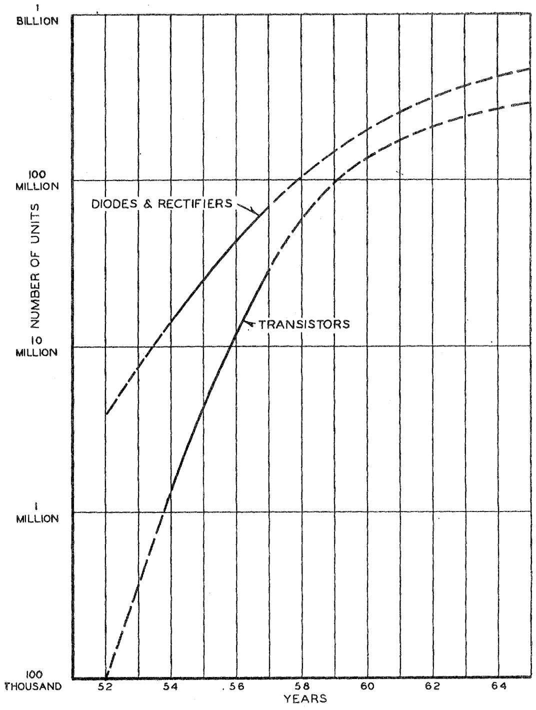

Fig. 2—The solid portions of the curves indicate the number of units sold in the United States by the year. The dotted portions of the curves represent estimates.

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 today's world 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 directed teams of their most competent research and development people toward the design of these semiconductor devices.

Through the years, meetings and symposia have been held for scientists to exchange information on the most recent technology developments. By concerted effort, many of the basic problems associated with semiconductor devices have been solved; today, transistors are being used in many industrial and military systems, particularly where low power, small size, and high reliability pay off. In the United States the sale of transistors alone has risen from a level of essentially nothing in 1952 to 29 million units in 1957. Forecasters predict that these sales will go to over 250 million units by 1965. If one adds to this the sale of semiconductor diodes, it is predicted that combined sales will reach 600 million by 1965. (See Fig. 2.) In 1957, the dollar volume of transistors and semiconductor diode sales was 69 million dollars and 103 million dollars, respectively. By 1965, it is expected that the dollar volume of semiconductor sales will exceed that of the older electron tube. A further indication of the growth can be seen by the fact that the Joint Electron Tube Engineering Council had issued 600 transistor and 1300 diode industry codes by the end of 1957.

During its short ten years of life, the transistor, through its inherent low-power requirements, small size, and high reliability has permeated the entire electronics industry. It has already captured large sections of the market. With materials, structures, and techniques presently in the laboratory and currently in manufacture, the transistor will play an increasingly important part in modern electronic technology.

By basic scientific contributions and imaginative inventions, scientists and engineers have laid the foundation on which is being built a truly great technological industry. It may well be that the extension to man's mind, that transistor electronics makes possible, will yet have a greater impact on society than the nuclear extension of man's muscle.

The Status of Transistor Research in Compound Semiconductors*

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Summary—**New semiconductors capable of competing with germanium and silicon in transistor applications must be looked for among the compound semiconductors, and more specifically among the III-V and IV-IV compounds. Gallium arsenide and indium phosphide are the most promising all-round materials for high-frequency as well as high-temperature performance. Indium antimonide and indium arsenide may be of interest for extremely high-frequency transistors operating at low temperatures. The aluminum compounds, gallium phosphide and silicon carbide, are potentially useful for very high operating temperatures at the cost of high-frequency performance. Some of the unusual properties of the compound semiconductors have led to novel methods of junction preparation and new junction structures, such as the surface-diffusion and the wide-gap junction. Bipolar and unipolar surface-diffusion transistors have been demonstrated in indium phosphide, and the wide-gap emitter principle for high injection efficiency has been experimentally verified in gallium arsenide transistors. Electron lifetimes in these two compound semiconductors are estimated from the transistor results.**

INTRODUCTION

THE ADVENT of the germanium transistor in 1948, and the silicon transistor shortly thereafter, raised the inevitable question whether there are other semiconductors capable of exhibiting transistor action. Research in this direction was primarily stimulated by the hope of finding a semiconductor with superior properties for transistor applications. A glance at the periodic table and the electrical properties of the elements shows immediately that such a material would scarcely be found among the elemental semiconductors, except possibly diamond which has some obvious disadvantages. Therefore, the search for a competitor to germanium and silicon in the transistor field was concentrated on the *compound semiconductors*.

Compound semiconductors, in contrast to the elemental semiconductors, are true chemical compounds of two or more elements with characteristic stoichiometric compositions. Representatives of this vast class of semiconductors are found throughout the entire range of chemical compounds from the simple binaries to the most complex organic structures. The elemental semiconductors, such as α-tin, tellurium, selenium, germanium, and silicon are, in effect, only special cases of the compounds. Although by far the major systematic research efforts, both theoretical and experimental, have heretofore been concentrated on germanium and silicon, the compounds have played an important role in semiconductor research from the beginning. In fact, the earliest evidence for a conduction mechanism different from that in metals was Faraday's observation of a negative temperature coefficient of the resistivity in the compound, silver sulfide, in 1833. Rectification at a contact between dissimilar materials was discovered by Braun with pyrites and galena, and almost simultaneously by Schuster with "tarnished" copper, or copper oxide, in 1874. Silicon carbide and lead sulfide attained some importance as detectors in the early radio days, but they were soon displaced by the vacuum tube. Copper oxide has been one of the most important solid rectifier materials to this day, particularly in power applications. The practical importance of these compounds stimulated some early fundamental research, but, due to the lack of a satisfactory model of semiconduction, little significant information was gained. In 1931, after quantum mechanics had come into its own, Wilson laid

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