VOLUME 46, NUMBER 6

June, 1958

published monthly by The Institute of Radio Engineers, Inc.

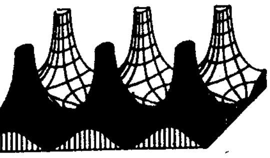
Proceedings of the IRE®

contents

June, 1958
Vol. 45 *No. 6*

Proceedings of the IRE

Poles and Zeros



We Do It Again. This page is the introduction to another IRE PROCEEDINGS Special Issue. These tomes have now, we hope, achieved such a reputation that were the covers not already a healthy IRE blue, we would be justified in binding them in a truly royal purple to signify the special contents. While continuing to pat ourselves on the back, may we also point out to all bill-paying members that the January Special Issue on Radio Astronomy contained 402 editorial pages, and here is another of equivalent size and import in the same year, yet.

The subject selected for this issue—Transistors—made choice of the date of issue automatic. June, 1958 marks the tenth anniversary of the first announcement of the invention of the transistor by the Bell Telephone Laboratories. Production of these devices will this year exceed 45 million in the United States; in 1916, ten years after the invention of the vacuum triode, the tube was still far from any form of quantity production. The transistor cannot take credit for the rapidity of its own development; it arrived in an era already catalyzed by prior vacuum tube art. It still speaks well for the breadth of scientific training of the electronic engineer that, rather than being put out of business by the transistor, he has taken it in stride, learned to think of energy levels and holes and active circuits, and has made the transistor the basis for a whole new era in electronics.

Many of our members may not be aware of the steps undertaken in the conception, gestation, and birth of a Special Issue. Certainly these brain children do not just arrive by stork nor do they burgeon as a result of fortuitous circumstances. They are actually the result of a great amount of work by a great many people, and the occasion of the birth of this latest Brobdingnagian infant seems propitious to review the procedure and give a nod of thanks to various hard working people along the way.

Conception of this issue occurred during an early 1957 meeting of the IRE Editorial Board, where it was agreed that progress since the November, 1952 issuance of Special Issue Transistor I amply warranted another compendium of scientific and engineering thought on the subject. Experience has shown that the very necessary first step in the process of gestation is to identify a sponsoring group and more particularly, an organizer of the issue or an issue editor. In the case of this number the joint IRE-AIEE Committee on Semiconductor Devices undertook the sponsorship, and its chairman, Stephen J. Angello, of the Westinghouse Research Laboratories, became the issue editor. He and his committee, which operates within the IRE as a subcommittee of the IRE Committee on Solid-State Devices, planned the contents of the issue to provide appropriate coverage of the field, and to insure that the issue would conform to requirements as a classic reference in the field, as had Transistor I.

Now it is a well recorded fact in the publishing field that all authors will submit their papers on time, and there are only infrequent delays due to typing difficulties or the mails which delay the arrival of papers beyond the promised dates, or even beyond the editor's true expectations. In such few isolated cases editors have been known to write letters of considerable solicitude fearing for the author's future state of health and general fitness, always couched in language which remains polite, or at least mailable. Finally, somehow, the desired papers are in hand and the presses roll, bringing us to the glorious natal day of another Special Issue—Transistor II.

Such an issue could not properly be introduced without a few words from the transistor's co-inventors and Nobel Prize winners, Shockley, Bardeen, and Brattain, and so the lead articles go to them. There follow 37 additional papers covering the field as of today.

To Steve Angello, James Early, and the others who contributed, many thanks for a fine job. To those who wrote, and wrote, and did meet the deadlines, no matter how many times removed—more commendations. In the winnowing process 20 other papers fell by the wayside, but these authors also contributed because they made the first team work the harder, and their time will come. Rejection of 20 papers from a field of 57 submitted is a good score these days. Would that some other journals could also make that claim.

Engineering Surplus? Since 1951 our eyes and ears have reacted to the ceaseless repetitions of the engineering shortage. In publicizing the situation the ivory hunters have all too often used a shot gun rather than a rifle, and have attracted to the engineering colleges a considerable percentage of ill-prepared and non-adapted students, rather than the selectively chosen students of high intellect who will contribute to the advancement of our scientific world.

We are now seeing the other team prowling the jungle—those using similar publicity devices and statistics to prove there is now a surplus of engineers, and we are going to see the results of their work in the next several years' input to our engineering schools.

The subject of guidance of qualified students into engineering careers is a psychological and public relations matter, and we feel it has been handled without sufficient recourse to experts in those fields. We hope that we have not thereby created a system whose damping constant is less than unity.

—J.D.R.

William H. Doherty

Director, 1958-1960

William H. Doherty was born on August 21, 1907 at Cambridge, Mass. A student at Harvard University, he received its B.S. degree in electric communication engineering in 1927, and the M.S. degree in engineering the following year.

His early work at Bell Laboratories began in 1929 and was in high-power transmitter development for transoceanic telephone service and broadcasting. This work led to the invention of a high-efficiency power amplifier now extensively used in broadcasting, for which the IRE awarded him the Morris Liebmann Memorial Prize in 1937.

Later he participated in pioneering work in the fire-control radar field, and throughout World War II supervised a development group which was responsible for the design of a number of radars used on naval surface ships and submarines for gunfire and torpedo control.

Mr. Doherty continued in military electronics work until 1949, when he became Director of Electronic and Television Research. He was appointed Director of Research in Electrical Communications in 1951 and continued in that post until he went to the American Telephone and Telegraph Company in 1955 as an Assistant Vice-President. Last year he returned to Bell Telephone Laboratories as Assistant to the President.

On June 1, 1958, Mr. Doherty assumed the post of Manager of Government Sales with the Radio Division of Western Electric Co., Inc.

He is a member of Tau Beta Pi and Sigma Xi, and he holds an honorary Doctor of Science degree from the Catholic University of America. He also is President of the Harvard Engineering Society.

Mr. Doherty joined the IRE as an Associate member in 1929. He became a Member in 1936, a Senior Member in 1943, and Fellow in 1944. He served on the following IRE Committees: Editorial Review, during 1954–55; Membership, from 1943 to 1946; Nominations, during 1952–53; Policy Development, in 1951; Policy Advisory, during 1952–53; and Professional Groups, from 1948 to 1951. He was chairman of the Nominations Committee in 1953, and an IRE Director from 1951 to 1953.

Scanning the Transistor Issue*

STEPHEN J. ANGELLO†, SENIOR MEMBER, IRE

THIS special issue of PROCEEDINGS commemorates the tenth anniversary of the announcement of the invention of the transistor by the Bell Telephone Laboratories. Since the publication of the first technical news of this invention,[1] the field has expanded truly high and wide. Diffused base transistors made at Bell Laboratories are oribiting around the earth in the Explorer and Vanguard satellites, and there is scarcely a country in the world not making some kind of effort on transistor and semiconductor device development.

The most exciting thing about the invention is that the operation of the transistor depends upon a new concept in the physics of the solid state. It was known for many years before the transistor that solids can be found which conduct electricity by positive electronic charge carriers as well as by negative electrons. There is some interesting historical reading in the development of the concept. Experimenters who normally were very careful made mistakes in determining the sign of the Hall effect, because it was hard to believe that an electron could have a positive charge. About 1939, W. Schottky in Germany gave a complete theoretical discussion of the equilibrium of electrons and holes in semiconductors, particularly in the region of a semiconductor adjacent to a large area metal contact.

W. H. Brattain and J. Bardeeen discovered that a metal point upon a germanium crystal when carrying forward current could influence the reverse current in a similar point contact nearby. This was interpreted as injection of minority current carriers from the metal into the germanium. These injected charge carriers were collected by the other probe, hence the names "emitter" and "collector" which are still in general use. Since the collector had to be close to the emitter, it was evident that the emitter influence region was small. These phenomena were interpreted correctly by W. Shockley who proceeded to develop a new theory of conduction in semiconductors of the germanium (valence crystal) type, introducing the concept of finite minority carrier density above the equilibrium density and the associated lifetime. Furthermore, he postulated a *p-n* junction rectifier and a type of transistor which was two *p-n* junctions separated by a narrow base region. This was a radical departure from the original point-contact device, and many months passed before the theory was checked by experimental devices.

The Solid-State Devices Committee of the IRE and AIEE which organized this issue felt it proper to honor the co-inventors of the transistor. To this end we have asked each gentleman to write a short essay, and these are given first place in the body of this issue. We delight in paying tribute to the superb experimental technique of Dr. Brattain, the deep theoretical understanding of Dr. Bardeen, and the creative genius of Dr. Shockley.

Our appreciation of this discovery will be enhanced if we imagine for the moment that the lifetime of an excess of minority charge carrier density is essentially zero. We would be restricted then to the phenomenon of a charge carrier density depletion layer in the boundary region adjacent to a metal or semiconductor contact. We dare not presume to name all possible devices which can be created with the space-charge depletion layer as a basis, but we can enumerate devices known at this time. This list may be compared with the existing devices based upon minority carrier injection with useful lifetime. The size and importance of the latter list makes the point of this discussion, namely, that the discovery of the transistor introduced a fertile concept into solid-state device development. Not only is the left-hand list longer, but also the commercial market for devices in this list eclipses the right-hand list. Only metal-semiconductor rectifying cells have been important in the depletion layer type devices, and this market is being decimated by *p-n* junction rectifying cells.

TABLE I

COMPARISON OF DEVICES DEPENDING UPON SPACE-CHARGE DEPLETION LAYER AND MINORITY CARRIER INJECTION

Minority Carrier Injection	Space-Charge Depletion Layer
p-n junction diodes	Metal-semiconductor rectifying cells
p-n-p and *n-p-n* junction transistors	Field effect transistor
Junction tetrode transistor	Field effect resistor
p-n-i-p and drift types	Variable capacitance diode
Double base diodes	Voltage regulator diode
p-n-p-n diode	
p-n-p-n triode	
Stepping transistor	

Requests have come to us from a number of people prominent in semiconductor research and development to take this opportunity to reaffirm a basic truth. This is that all device development is dependent upon the properties of the starting materials which are available. Therefore, device development ought to be coupled with a vigorous research and development program upon basic materials. Consider again that the transistor depends upon the minority current carrier lifetime. The discovery of the transistor was made only when the careful metallurgical work of W. G. Pfann had resulted in germanium of sufficient quality to show the

* Original manuscript received by the IRE, April 29, 1958.
† Westinghouse Research Labs., Pittsburgh 35, Pa.
[1] J. Bardeen and W. H. Brattain, "The transistor, a semiconductor triode," *Phys. Rev.*, vol. 74, pp. 230–231; July 15, 1948.

necessary conduction effects. Diffusion, alloying, etching, magic surface coatings, point contact forming, or any other device fabrication technique is of no avail to produce a transistor if the basic material is not of sufficient quality. Perhaps other exciting basic discoveries await careful research upon new semiconducting materials. Along this line, we believe that the field would benefit if someone who was closely associated with the Bell Laboratories' transistor discovery and development would describe the historical events in detail. We already know from Dr. Bown's preface to Dr. Shockley's classic text that there was a vigorous program under-way with the broad aim of developing a solid-state amplifier. We suspect that their success was related to the close relation between basic materials research and device development. The results of device development can feed back valuable information to materials research to give them a *raison d'être* and to guide them into fruitful channels of thought and experiment.

Before scanning the papers of the issue in detail, it is fitting to explain that there are sixteen invited papers. The honor to the authors of these papers is enhanced by the method by which they were chosen. A letter survey was conducted asking nationally prominent men in the field to suggest authors for topics we considered desirable to cover in this issue. In most cases the authors were selected by popular vote in this survey. Our list of topics also was enhanced by the same survey. Many thousands of man hours have gone into the preparation of this issue and we hope it will serve the field for many years to come as an important reference work.

The first invited paper following the essays of Brattain, Bardeen, and Shockley is by J. A. Morton and W. J. Pietenpol. They have surveyed the technological impact of the transistor during the past decade. In an interesting narrative they trace the development of transistor types and applications. This article is required reading for the executive responsible for the guidance of solid-state development in his organization.

Although the commercial exploitation of the transistor has been mainly with germanium and silicon, we have asked Dietrich Jenny to survey the interesting results which have been obtained in the III–V compounds and other compound semiconductors. These new materials already have resulted in a new device feature—the wide-band gap emitter. This summary will serve to orient anyone interested in the future possibilities of this field.

There are other semiconductor devices in addition to transistors and diodes, and S. J. Angello has surveyed these with the idea of organizing the large number known by certain logical classifications. Criteria for "important" devices are attempted and descriptions and references are given for some devices which we predict will become important.

Dr. Shockley was invited to contribute an original paper, and appropriately he chose to push back further the frontier of knowledge of "Electrons, Holes, and Traps." This knowledge will be useful because certain devices such as the four-layer diode require trap level control in fabrication.

Because of the importance of recombination in device technology, we asked G. Bemski to prepare a tutorial article on this subject. The paper covers theory, basic experimental methods, and discussion of results.

Two experts were asked to survey the difficult field of electrical noise. K. M. van Vliet and A. van der Ziel divided the field between them into bulk semiconductors and junctions, respectively. It is our belief that these papers will serve as the textbook on electrical noise in semiconductors for a long time in the future.

An important source of recombination centers is the dislocations in crystals caused by neutron irradiation. G. C. Messenger and J. P. Spratt have contributed a paper which gives a theoretical discussion of the effect of neutrons upon the grounded emitter current gain of a transistor. Observed changes in transistor parameters are explained and some basic quantities of the recombination theory for germanium are given.

Another variation of the general theme of recombination is provided by a paper contributed by R. Gremmelmaier on irradiation of a *p-n* junction by γ rays. The diffusion length of minority carriers can be estimated by the effects of irradiation and results are given for Si, GaAs, and InP.

As Morton and Pietenpol state, the development of diffusion techniques in silicon and germanium was an important breakthrough in the technique of semiconductor device fabrication. F. M. Smits, who has contributed much to the development of this subject, was asked to summarize the state of the art. He has favored us with a very complete and valuable paper.

Major techniques such as diffusion are always fruitful sources for valuable modifications. Herbert Nelson has contributed one such modification in a paper on preparation of semiconductor devices by lapping and diffusion techniques.

Another important variation of the original diffusion technique is "outdiffusion." J. Halpern and R. H. Rediker describe this technique for the fabrication of narrow base germanium computer diodes. Feasibility of the process has also been shown for *n-p-n* graded-base transistors.

We proceed to the very important topic of the single *p-n* junction. John Moll has responded to our invitation and provided us with an historical survey of the theory of the *p-n* junction. This will be a reference paper for students entering the field.

Some extensions of the theory involve complicated depletion layer configurations. L. J. Giacoletto has contributed an analog model solution to such problems which is an aid to visualization.

Only a few years passed from the theoretical description of *p-n* junctions to commercial application of silicon and germanium rectifying cells. H. Henkels was asked to summarize the state of the art with respect to these devices. The result is a rich mine of device development information, part of which was generated by Dl. Henkels' original work.

At the low-power end of the scale *p-n* junction devices often are referred to as "diodes." Recently, some very interesting developments have been carried out upon diodes in microwave systems. Of special interest is the feasibility of obtaining power gain. We asked A. Uhlir, Jr., who has contributed much original work to this subject, to prepare a status report. The number of applications possible for the new *p-n* junction diode which are found in this paper will surprise those who have not had occasion to follow developments in this field.

A contribution by G. C. Messenger rounds out the discussion of diodes by describing new approaches to extend the frequency capability of radar crystal mixers and to improve sensitivity.

A special use of diodes is in detection of light. D. E. Sawyer and R. H. Rediker have made noteworthy contributions with respect to speed of response of such diodes. Their paper describes the operation of 75-mμsec germanium diodes.

The natural extension from single *p-n* junctions is the configuration of two *p-n* junctions separated by a narrow base region. R. L. Pritchard has been invited to survey the progress of *p-n* junction triode theory to which he has contributed much. This paper is one reason why we feel that this transistor issue will be a reference work of some importance.

Electrical engineers often feel that they have a better understanding of a theoretical model if they can form equivalent circuits which approximate the theory. J. G. Linvill has made a contribution to this topic which may appeal to many device engineers.

One of R. L. Pritchard's original contributions to transistor theory is presented in his paper on current flow in junction transistors at high frequencies. He extends the theory to a two-dimensional model.

Having covered the theory of *p-n* junction triodes, we move on to the technology for providing real representations of theoretical models. An alloy-diffusion method for high-frequency germanium transistors is described by P. J. W. Jochems, *et al.* C. C. Thornton and J. B. Angell contribute to the technology of micro-alloy diffused transistors. D. E. Thomas and J. L. Moll have contributed a very interesting paper concerned with measurement of transistor characteristics. They prove that a junction transistor fits a certain general network theorem given by Bode. This enables complicated frequency characteristics to be determined by relatively simple measurements.

A special class of transistors which is enjoying increasing application in industry is the group capable of controlling power. We have asked M. A. Clark to survey this field. Workers interested in design theory and practice in the areas of high current densities and high voltage will find much valuable information here.

Two contributed papers concerned with thermal resistance measurements upon transistors are pertinent to power transistors and the general problem of rating transistors. These are by B. Reich, and J. T. Nelson and J. E. Iwersen.

Extension of power transistors to high frequency is highly desirable. J. T. Nelson *et al.* describe a 5-watt 10-megacycle transistor which is fabricated in silicon by the diffusion technique.

Emeis and Herlet have checked parts of the theory of power transistors by fabricating an extensive series of alloy transistors with a wide range of basic material parameters. Measurements upon these transistors are compared with theory. Emeis, Herlet, and Spenke describe an alloyed power transistor of cylindrical geometry which provides an emitter and base with very long perimeter. This perimeter can be varied in length, and further checks of power transistor theory are obtained.

The papers now progress into more complicated transistor structures with a paper contributed by I. M. Mackintosh on *p-n-p-n* triodes. These devices are rapidly becoming important in switch-type application. A complementary paper on this same subject is contributed by R. W. Aldrich and N. Holonyak, Jr.

Computers represent a very important use of transistors which will become more important as time progresses. R. A. Henle and J. L. Walsh were asked to survey the kinds of application of transistors in computers. Their review will be found very educational by those who wish to be brought up to date in this field.

It is probably fair to say that there is not a facet of electronics circuits which has not been affected by transistors. In an invited survey, D. D. Holmes describes one of these facets: the field of commercial communication equipment.

Two papers were contributed which are strictly circuits design papers. These are by J. J. Suran on the analysis and design of transformerless pulse generators, and by D. F. Page, who discusses oscillator circuit design and a unified approach to the design of instability.

Finally, a popular demand prompted us to ask Esther Conwell to bring her 1952 Transistor Issue paper up to date to provide the field with an accurate compendium of silicon and germanium properties. In addition to tabular data, she has supplied a lucid explanation of the concepts applicable to this field.

I wish to take this opportunity to thank certain persons who contributed much to the preparation of this issue. It was a pleasure to work with E. K. Gannett, the Managing Editor, and we acknowledge his cordial cooperation. James E. Early acted as co-organizer and contributed many valuable ideas to the planning of the issue.

The members of the IRE-AIEE Solid-State Devices Committee provided an able team of reviewers to supplement the normal IRE Review Board. Credit for any success which this issue might achieve belongs directly with the authors whose papers are recorded herein.

Comments on Implications of Transistor Research*

JOHN BARDEEN†

IN looking back over the past ten years of research associated with transistor development, I am most impressed by the tremendous strides made in our understanding of the effects of minute physical imperfections on the physical properties of solids. In large part, this is an unanticipated by-product, made possible by the production and control of nearly perfect single crystals of germanium, silicon, and related materials.

This control has not only made it possible to design and fabricate devices with remarkable properties but has greatly aided the scientific study of crystal imperfections.

Ten years ago we felt that prospects for commercial development of transistors were excellent, even though great problems had to be overcome. However, both the large scale of the effort required to achieve this and the great degree of success which has been obtained in overcoming frequency, power, and other limitations were not foreseen, at least by me. The junction transistor has of course played a key role in these developments.

Many properties of solids of scientific and technological interest other than semiconductivity are dependent on impurities or other imperfections present in parts per billion or less. These include, for example, photoconductivity, luminescence, and even plastic flow. Controlled very perfect single crystals have provided, in a sense, a laboratory for study of such processes. Research on the physics of surfaces has also been stimulated. Advances in theory have kept pace with experiment so that in many cases a detailed quantitative understanding is possible. Thus research stimulated by transistor applications is having an impact in many other areas of science and technology.

The growth of solid-state physics, already well underway when the transistor was discovered, has undoubtedly received a strong impetus. There has been rapid expansion in both the number of laboratories doing research in this area and the number of scientific publications.

We were very lucky to be in on a major discovery of the sort that cannot be predicted in advance. But it is the cumulative advance in scientific understanding, made by many people in many countries, which has made it possible to realize the potentialities of semiconductor devices and to make striking progress in many other areas dependent on crystal imperfections.

* Original manuscript received by the IRE, April 29, 1958.
† Dept. of Physics, University of Illinois, Urbana, Ill.

Essay on the Tenth Anniversary of the Transistor*

WALTER H. BRATTAIN†

As far as I am concerned the advent of the transistor is one of those developments that come along when general background knowledge has developed to such a stage that human minds are prepared to take a new step in the understanding of phenomena that have been under observation for a long time. In the case of a device with such important consequences to technology it is notable that the break-through came from work dedicated to the understanding of fundamental physical phenomena rather than from the empirical cut and try efforts of producing a useful device.

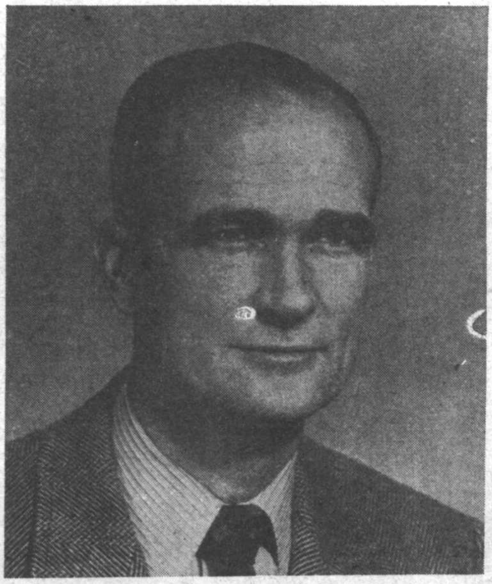
This general understanding of the physics of solids, semiconductors in particular, was dependent on the development of quantum mechanics. To understand how electrons and nuclei react together to form the aggregates we call solid crystals we had to understand first how they react individually to form atoms. The type of solid binding most characteristic of the semiconducting crystals—the covalent bond—was just the type that can only be understood from a quantum mechanical standpoint.

The picture of a semiconductor as a medium in which electrons and holes, as dissociated covalent bonds, can exist in thermodynamic equilibrium was the necessary conceptual idea. It is closely analogous to the quantum mechanical concept of electrons and positrons in vacuum. Another close analogy is to the theory of dissociation in electrolytes. On hindsight one wonders why this essential concept was not grasped sooner. Why did physicists and chemists have to wait until they could understand "defect" as well as "excess" conductivity from first principles before seeing the light?

In conclusion, I would like to point out that while a well thought out experiment may always give good results, nevertheless the really important experiment is the one that leads to new and unexpected results regardless of the original reason or expectation that inspired it. While lightning only strikes occasionally one should be cautious in discouraging the urge to do an experiment no matter how hazy the reason or how sure one is that the result may be trivial.

* Original manuscript received by the IRE, May 5, 1958.
† Bell Telephone Labs., Murray Hill, N. J.

An Invited Essay on Transistor Business*



WILLIAM SHOCKLEY†, FELLOW, IRE

IN 1950, I finished writing a book[1] by placing at the end of the last chapter a prediction about the future of transistor electronics. In the interest of establishing my position as a prophet of transistor business, I shall quote this prediction:

> "It may be appropriate to speculate at this point about the future of transistor electronics. Those who have worked intensively in the field share the author's feeling of great optimism regarding the ultimate potentialities. It appears to most of the workers that an area has been opened up comparable to the entire area of vacuum and gas-discharge electronics. Already several transistor structures have been developed and many others have been explored to the extent of demonstrating their ultimate practicality, and still other ideas have been produced which have yet to be subjected to adequate experimental tests. It seems likely that many inventions unforeseen at present will be made based on the principles of carrier injection, the field effect, the Suhl effect, and the properties of rectifying junctions. It is quite probable that other new physical principles will also be utilized to practical ends as the art develops."

* Original manuscript received by the IRE, April 28, 1958. This research has been supported in its entirety by E. L. Shockley, who has contributed major portions of one weekend towards its completion.

† Shockley Semiconductor Lab., Beckman Instruments, Inc., Mountain View, Calif.

[1] W. Shockley, "Electrons and Holes in Semiconductors," D. Van Nostrand Co., Inc., New York, N. Y.; 1950.

Now for the future! In the course of carrying out the research for this essay, I have discovered a new and significant law of growth in the transistor field. This is the Shockley frequency-production index. In effect, it is a measure of the simplicity of the transistor, compared to the man. Men produce transistors, and transistors in their purest action (sinusoidal oscillation) produce cycles. The ratio is the frequency-production index and is defined by

$$f_{\alpha co}/P_y \equiv I_f P \tag{1}$$

where $f_{\alpha co}$ is the alpha cutoff frequency of the highest frequency transistor produced in a given year, and P_y is the volume of transistor production. The value of the ratio, when expressed in units of years/sec, lies between 50 and 100 as may be seen from Table I.

TABLE I

Year	$f_{\alpha co}$ sec^{-1}	P_y year^{-1}	$I_f P$ year/sec
1949		10^4	
1950	7×10^6	10^5	70
1951		2×10^5	
1952	5×10^7	4×10^5	100
1953		6×10^5	
1954	1.2×10^8	1.3×10^6	90
1955		3.5×10^6	
1956	8×10^8	1.3×10^7	62
1957	1.5×10^9	2.9×10^7	50
1958	5×10^9	7×10^7	70
1959	10^{10}	1.5×10^8	70
1960	1.7×10^{10}	2.5×10^8	70

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 $I_f P$ 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.

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

No business essay is complete without a reference to money. Assuming that the cost per unit varies as $P_t^{-0.33}$, 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.

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

The Technological Impact of Transistors*

J. A. MORTON†, FELLOW, IRE, AND W. J. PIETENPOL†, MEMBER, IRE

***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.

* Original manuscript received by the IRE, March 5, 1958.
† Bell Telephone Labs., Inc., Murray Hill, N. J.

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 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.

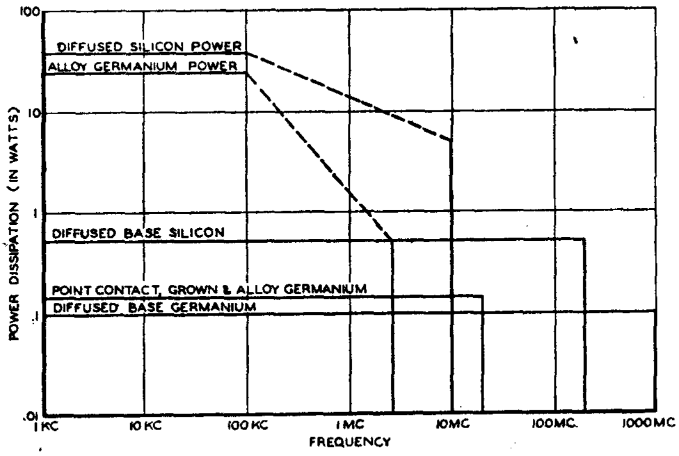


Fig. 1—The curves indicate the power-frequency spectrum covered by various prototypes of transistor structures.

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, servo-systems, 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.

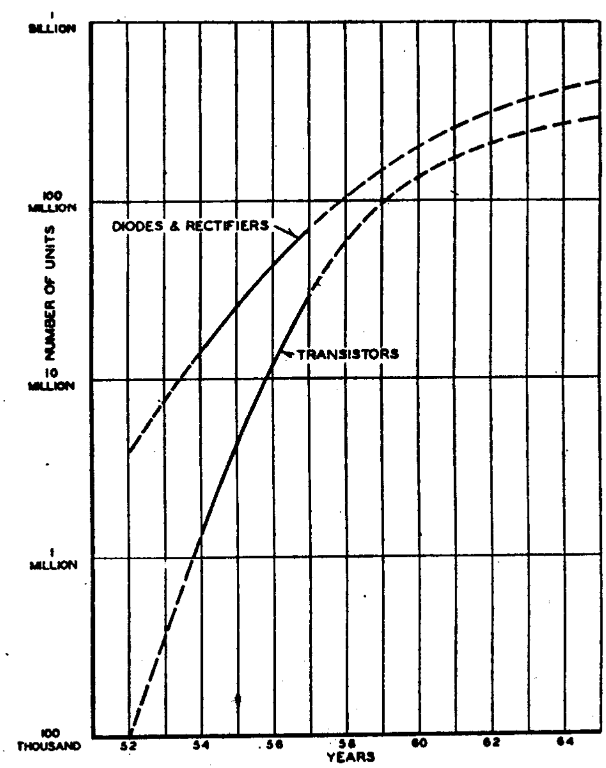


Fig. 2—The solid portions of the curves indicate the number of units sold in the United States by the year. The dotted portions of the curves represent estimates.

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*

DIETRICH A. JENNY†, MEMBER, IRE

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

* Original manuscript received by the IRE, April 10, 1958. The work reported in this paper was supported in part by the U. S. Air Force, Wright Air Dev. Center, Dayton, Ohio.

† RCA Labs., Princeton, N. J.

down the groundwork for modern semiconductor theory in the form of the energy band model.[1] Sporadic experimental research was subsequently carried out with many compound semiconductors in an effort to study them in terms of the Wilson theory, but technological and reproducibility problems precluded satisfactory conclusions. The renewed interest in point contact diodes as radar and general high-frequency detectors during World War II marked the beginning of intensive theoretical and experimental research on germanium and silicon. Tremendous progress in the understanding and application of semiconductors was made during this period as evidenced by the discovery of the transistor by Bardeen and Brattain in 1948[2] and the *p-n* junction transistor by Shockley in 1949.[3]

Stimulated by these events, compound semiconductor research received renewed attention which resulted in the demonstration of a point contact transistor with lead sulfide by Gebbie, Banbury, and Hogarth.[4] However, it was Welker's contribution in 1952, pointing out the semiconducting properties of aluminum antimonide and indium antimonide, that sparked extensive and systematic research in the compound semiconductor field.[5] It became clear that the study of compound semiconductors could contribute much to the fundamental understanding of semiconductors in general, and that new applications as well as improvements of the devices already known would ultimately result. Systematic compound semiconductor research is still in its infancy and much remains to be done until the understanding of the compounds has reached a stage comparable to that of germanium and silicon. However, a host of fundamental information is already available in certain compound semiconductor classes, such as the III-V compounds, the II-VI compounds, and the only known IV-IV compound, silicon carbide. Work is progressing rapidly towards the realization of certain practical devices with some of these new semiconductors. Galvanomagnetic devices of indium antimonide and indium arsenide, utilizing the Hall and magnetoresistance effect, have recently appeared on the market. Diodes and rectifiers made from gallium arsenide, indium phosphide, aluminum antimonide, gallium phosphide, and silicon carbide are under development. Compound semiconductor transistors are still in the research stage, but their feasibility has been experimentally established in indium phosphide and gallium arsenide.

The following is a brief summary of the evaluation of compound semiconductors for transistor applications based on information from the literature and original work by the author.

Semiconductor Properties and Transistor Performance

In the search for new transistor materials certain fundamental semiconductor properties must be evaluated in comparison with those of germanium and silicon. The forbidden energy band gap (band gap), the impurity activation energies of donors and acceptors, the charge carrier mobilities of electrons and holes, and the dielectric constant are of primary importance. Other physical and chemical properties have to be taken into account due to their effect on the material and device technology, and device stability. The following shall be restricted to the discussion of the electronic properties directly affecting the performance of transistors, whereas other physical and chemical properties of secondary importance will be largely neglected.

The first-order relations between transistor performance and the important semiconductor properties are summarized in Table I, where the unipolar as well as the bipolar transistor types are considered. The unipolar relations are equally applicable to high-frequency diodes and general rectifiers with minor modifications.[6] The upper frequency limit of unipolar transistors is determined by the RC time constant of the junction capacitance and the series resistance, as shown by Dacey and Ross.[7] The upper frequency limit relation for bipolar transistors is that derived by Giacoletto.[8]

A high band gap is conducive to high-temperature operation, whereas low impurity activation energies are of importance for low-temperature operation. High mobilities and a low dielectric constant are desirable for high-frequency performance. However, it must be borne in mind that these properties are to some extent interrelated, so that certain compromises are unavoidable. For instance, the dielectric constant affects not only the high-frequency performance through its effect on device capacitances, but enters also into the impurity activation energy (hydrogenic model)[9] and the impurity scattering mobility (Conwell-Weisskopf and Brooks-Herring relations).[10] Without going further into these details, it

[1] A. H. Wilson, "The theory of electronic semiconductors," *Proc. Roy. Soc.*, vol. 133, pp. 458–491; October, 1931.

[2] J. Bardeen and W. H. Brattain, "The transistor, a semiconductor triode," *Phys. Rev.*, vol. 76, p. 459; July, 1958.

[3] W. Shockley, "The theory of *p-n* junctions in semiconductors and the *p-n* junction transistor," *Bell Sys. Tech. J.*, vol. 28, pp. 435–489; July, 1949.

[4] H. A. Gebbie, P. C. Banbury, and C. A. Hogarth, "Crystal diode and triode action in lead sulphide," *Proc. Phys. Soc.*, vol. 63B, p. 371; February, 1950.

P. C. Banbury and H. K. Henisch, "On the frequency response of lead sulphide transistors," *Proc. Phys. Soc.*, vol. 63B, pp. 540–541; April, 1950.

C. A. Hogarth, "Crystal diode and triode action in lead selenide," *Proc. Phys. Soc.*, vol. 64B, pp. 822–823; June, 1951.

H. K. Henisch, "Transistor experiments on binary lead compounds," *Phys. Rev.*, vol. 91, p. 213; July, 1953.

[5] H. Welker, "Ueber neue halbleitende Verbindungen," *Z. Naturf.*, vol. 7a, pp. 744–749; November, 1952.

[6] D. A. Jenny, "A gallium arsenide microwave diode," Proc. IRE, vol. 46, pp. 717–722; April, 1958.

[7] G. C. Dacey and I. M. Ross, "Unipolar field-effect transistor," Proc. IRE, vol. 41, pp. 970–979; August, 1953.

——, and ——, "The field-effect transistor," *Bell Sys. Tech. J.*, vol. 34, pp. 1149–1189; November, 1955.

[8] L. J. Giacoletto, "Comparative high-frequency operation of junction transistors made of different semiconductor materials," *RCA Rev.*, vol. 16, pp. 34–42; March, 1955.

[9] H. A. Bethe, "Theory of the Boundary Layer of Crystal Rectifiers," M.I.T. Rad. Lab., Cambridge, Mass., Rep. No. 43-12; November, 1942.

[10] E. Conwell and V. F. Weisskopf, "Theory of impurity scattering in semiconductors," *Phys. Rev.*, vol. 77, pp. 388–390; February, 1950.

H. Brooks, "Scattering by ionized impurities in semiconductors" (abstract), *Phys. Rev.*, vol. 83, p. 879; August, 1951.

TABLE I
SEMICONDUCTOR PROPERTIES AND TRANSISTOR PERFORMANCE

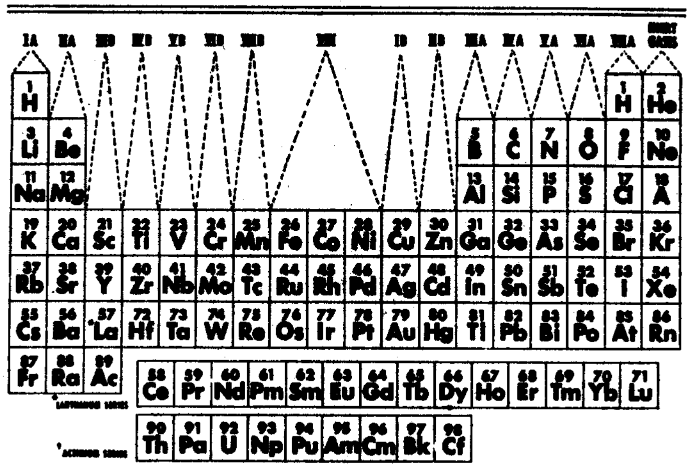
Transistor Performance		Pertinent Semiconductor Properties	First-Order Relation
Operating temperature range	Upper temperature limit T_u	Band gap E_g	$T_u \propto E_g$
	Lower temperature limit T_l	Impurity activation energy E_i	$T_l \propto E_i$
Upper frequency limit F	Unipolar transistors	The higher of the two mobilities μ_{high}; dielectric constant κ	$F \propto \frac{\mu_{high}}{\kappa^{1/2}}$
	Bipolar transistors	Electron and hole mobility, μ_n and μ_p; dielectric constant κ	$F \propto \sqrt{\frac{\mu_n \times \mu_p}{\kappa^{1/2}}}$

TABLE II
EXAMPLES OF COMPOUND SEMICONDUCTORS

Compound Class	Compound	Band Gap (ev)	Electron Mobility (cm^2/volt per second)
Elemental	α-Sn	0.08	~3000
	Ge	0.7	3900
	C (diamond)	6.7	1800
Binary	InSb	0.18	65,000
	GaAs	1.35	>5000
	SiC	2.8	>100
Ternary*	$AgTlTe_2$	0.1	—
	$CnInSe_2$	0.9	~1000
	$CnAlS_2$	2.5	—
Organic*	Cynanthron	0.2	10^{-8}
	Indanthracene	0.66	10^{-12}
	Anthracene	1.64	10^{-2}

* U. Winkler, "Die elektrischen Eigenschaften der intermetallischen Verbindungen Mg_2Si, Mg_2Ge, Mg_2Sn and Mg_2Pb," *Helv. Phys. Acta*, vol. 28, pp. 633–666; December, 1955.

TABLE III
PERIODIC TABLE OF THE ELEMENTS



is now possible to evaluate new semiconductors in comparison with germanium and silicon on the basis of the first-order relations between transistor performance and semiconductor properties of Table I.

THE NEW COMPOUND SEMICONDUCTORS

Semiconductors are not confined to the elements, but a vast number of representatives are found among the chemical compounds. A few representative examples of compound semiconductors with increasing chemical complexity and some of their properties are listed in Table II.

Each class of compounds contains a large number of semiconductors with band-gap values from a small fraction of an electron volt to several electron volts. On the other hand, the mobilities seem to fall within characteristic ranges for each compound class, whereby the binary compounds exhibit the highest absolute mobility values as well as the highest mobilities for a given band gap. The favorable band-gap and mobility combinations together with the relatively simple chemistry of the binary compounds have led to concentration of the research effort on this compound class.

The evaluation of binary compound semiconductors for transistors and related applications has indicated that most of the numerous binary compound groups must be ruled out for various reasons. Table IV shows the results of this evaluation which was compiled from the literature and from an experimental investigation of over 200 different compounds carried out at RCA Laboratories. This table is arranged according to the columns of the periodic table of the elements of Table III. The reasons for discarding most of the binary compound groups are indicated in the respective boxes of Table IV, where the symbols and abbreviations are: low melting point (low *MP*); low band gap (low E_g); low mobilities (low μ), chemical, thermal, or mechanical instability (unstable); and technological difficulties in preparation, purification, and crystal growth (technology).

The compound groups in the two boxes framed with heavy lines contain at present the most promising representatives, and are the well known column IV elemental semiconductors including germanium, silicon and the compound silicon carbide, and the III-V compound semiconductors. The boxes framed in heavy dashed lines contain compound groups which could not be investigated satisfactorily because of technological difficulties in preparing materials suitable for measurements. The

TABLE IV
BINARY COMPOUND SEMICONDUCTOR EVALUATION

COLUMNS OF THE PERIODIC TABLE	IIIA B Al Ga In Tl	IVA C Si Ge Sn Pb	VA N P As Sb Bi	VIA O S Se Te Po	VIIA F Cl Br I (At)
IA Li Na K Rb Cs Fr	low MP unstable metallic	low MP unstable	low MP unstable	low μ, MP unstable	low μ
IIA Be Mg Ca Sr Ba Ra	low E_g metallic	technology low μ, E_g	technology low μ, E_g	low μ	low μ
IIIB Sc Y La RARE EARTHS	low E_g metallic	technology	technology	low μ	low μ
TRANS. ELEMENTS ACTINIUM SERIES	low E_g metallic	technology low E_g metallic	technology low E_g metallic	low μ	low μ
IB Cu Ag Au	low E_g metallic	low E_g metallic	low μ	low μ, E_g	low μ
IIB Zn Cd Hg	low E_g metallic	no compounds	low μ	low μ, E_g	low μ
IIIA B Al Ga In Tl	low E_g metallic	technology metallic	III-V COMPOUNDS	low μ, E_g	low μ
IVA C Si Ge Sn Pb		C Si Ge α-Sn SiC	technology unstable	low μ, E_g	low MP
VA N P As Sb Bi			low MP	low μ, E_g	low MP
VIA O S Se Te Po				low μ, E_g	low MP
VIIA F Cl Br I (At)					low MP

pertinent properties of the members of the two interesting compound groups are shown in Table V opposite, as far as they are known at present.

This table contains measured values of the various properties with indications for the future trends expected from theory, and experience with germanium and silicon. The mobility values for the compounds in Table V are Hall mobilities, whereas the mobilities for germanium and silicon are the drift mobilities.

Gallium arsenide and indium phosphide clearly stand out as the most promising representatives in terms of the first-order relations between transistor performance and semiconductor properties of Table I. For very high-temperature devices the aluminum compounds, gallium phosphide and silicon carbide, are of interest due to their high band gaps, if a sacrifice in high-frequency performance from low mobilities can be tolerated. Very high frequencies should be attainable with indium arsenide and indium antimonide because of their high electron mobilities, but the low band gaps require operation below room temperature.

Besides the interesting electronic properties of some of these single compounds, it is well worth mentioning that many representatives form solid solutions throughout the entire mixture range with a monotonic band gap transition between the two band gaps of the components. Table VI shows three examples of such mixtures with their band gap coverage which extends from 0.33 ev to 2.25 ev without interruption.

The mixture of gallium arsenide and gallium phosphide shown in Fig. 1 is of particular interest and will be discussed later.[11]

The III-V compounds crystallize in the zincblende structure which is geometrically identical to the diamond lattice of germanium and silicon. The atoms of each component element are contained in their own face-centered cubic sublattices. This similarity between the diamond and the zincblende structure is of significance in comparing the properties of the III-V compounds with elements of column IV (germanium, silicon, diamond) as Herman has indicated.[12]

THEORETICAL TRANSISTOR PERFORMANCE IN COMPOUND SEMICONDUCTORS

Experience with germanium and silicon has shown that single crystal material with extremely high purity and crystal perfection is imperative for successful transistor experiments. Therefore, the evaluation of a new semiconductor for transistor applications must be made at an early stage of material research, to avoid an unnecessary waste of effort on the technology of purification and crystal growth with possibly unsuitable materials. Transistor research has, fortunately, progressed to the point where such an evaluation can be made on the basis of the few fundamental properties pointed out earlier. The results of an evaluation of several promising compound semiconductors in comparison with germanium and silicon is briefly discussed below for the unipolar and the bipolar transistor types. The two device properties of major interest are high-frequency performance and operating temperature range with particular emphasis on the upper operating temperature limit.

The temperature limitations of the various semiconductors is best represented in comparison with germanium. Assuming that devices made from germanium are operable up to a temperature of 100°C, as established by practical experience, the upper operating temperature limit, T_u, of devices made from other semiconductors can be estimated from the expression for the intrinsic carrier concentration. Here the actual concentration is set equal to that of germanium at 100°C:

$$T_u = \frac{E_g}{k \log (N/n_i^{Ge})} = 533E_g - 273; \text{ (°C)} \qquad (1)$$

where E_g is the band gap of the new semiconductor, k is the Boltzmann constant, N is the averaged density of states in the conduction and valence bands, and n_i^{Ge} is the intrinsic hole and electron density of germanium at

[11] O. G. Folberth, "Mischkristallbildung bei $A^{III}B^{V}$-Verbindungen," *Z. Naturf.*, vol. 10a, pp. 502–503; June, 1955.

[12] F. Herman, "Speculations on the energy band structure of zincblende-type crystals," *J. Electronics*, vol. 1, pp. 103–114; September, 1955.