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Development of Silicon Crystal Rectifiers for Microwave Radar Receivers

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INTRODUCTION

TO THOSE not familiar with the design of microwave radars the extensive war use of recently developed crystal rectifiers¹ in radar receiver frequency converters may be surprising. In the renaissance of this once familiar component of early radio receiving sets there have been developments in materials, processes, and structural design leading to vastly improved converters through greater sensitivity, stability, and ruggedness of the rectifier unit. As a result of these developments a series of crystal rectifiers was engineered for production in large quantities to the exacting electrical specifications demanded by advanced microwave techniques and to the mechanical requirements demanded of combat equipment.

The work on crystal rectifiers at Bell Telephone Laboratories during the war was a part of an extensive cooperative research and development program on microwave weapons. The Office of Scientific Research and Development, through the Radiation Laboratory at the Massachusetts Institute of Technology, served as the coordinating agency for work conducted at various university, government, and industrial laboratories in this country and as a liaison agency with British and other Allied organizations. However, prior to the inception of this cooperative program, basic studies on the use of crystal rectifiers had been conducted in Bell Telephone Laboratories. The series of crystal rectifiers now available may thus be considered to be the outgrowth of work conducted in three distinct periods. First, in the interval from 1934 to the end of 1940, devices incorporating point contact rectifiers came into general use in the researches in ultra-high-frequency and microwave communications techniques then under way at the Holmdel Radio Laboratories of Bell Telephone Laboratories.

¹ A crystal rectifier is an asymmetrical, non-linear circuit element in which the seat of rectification is immediately underneath a point contact applied to the surface of a semiconductor. This element is frequently called "point contact rectifier" and "crystal detector" also. In this paper these terms are considered to be synonymous.

At that time the improvement in sensitivity of microwave receivers employing crystal rectifiers in the frequency converters was clearly recognized, as were the advantages of rectifiers using silicon rather than certain well known minerals as the semi-conductor. In the second period, from 1941 to 1942, the advent of important war uses for microwave devices stimulated increased activity in both research and development. During these years the pattern for the interchange of technical information on microwave devices through government sponsored channels was established and was continued through the entire period of the war. With the extensive interchange of information, considerable international standardization was achieved. In view of the urgent equipment needs of the Armed Services emphasis was placed on an early standardization of designs for production. This resulted in the first of the modern series of rectifiers, namely, the ceramic cartridge design later coded through the Radio Manufacturers Association as type 1N21. In the third period, from 1942 to the present time, process and design advances accruing from intensive research and development made possible the coding and manufacture of an extensive series of rectifiers all markedly superior to the original 1N21 unit.

It is the purpose of this paper to review the work done in Bell Telephone Laboratories on silicon point contact rectifiers during the three periods mentioned above, and to discuss briefly typical properties of the rectifiers, several of the more important applications and the production history.

CRYSTAL RECTIFIERS IN THE EARLY MICROWAVE RESEARCH

The technical need for the modern crystal rectifier arose in research on ultra-high frequency communications techniques. Here as the frontier of the technically useful portion of the radio spectrum was steadily advanced into the microwave region, certain limitations in conventional vacuum tube detectors assumed increasing importance. Fundamentally, these limitations resulted from the large interelectrode capacitance and the finite time of transit of electrons between cathode and anode within the tubes. At the microwave frequencies (3000 megacycles and higher), they became of first importance. As transit time effects are virtually absent in point contact rectifiers, and since the capacitance is minute, it was logical that the utility of these devices should again be explored for laboratory use.

The design of the point contact rectifiers used in these researches was dictated largely, of course, by the needs of the laboratory. Frequently the rectifier housing formed an integral part of the electrical circuit design while other structures took the form of a replaceable resistor-like cartridge. A variety of structures, including the modern types, arranged in chronological sequence, are shown in the photograph, Fig. 1. In general, the

principal requirements of the rectifiers for laboratory use were that the units be sensitive, stable chemically, mechanically, and electrically, and

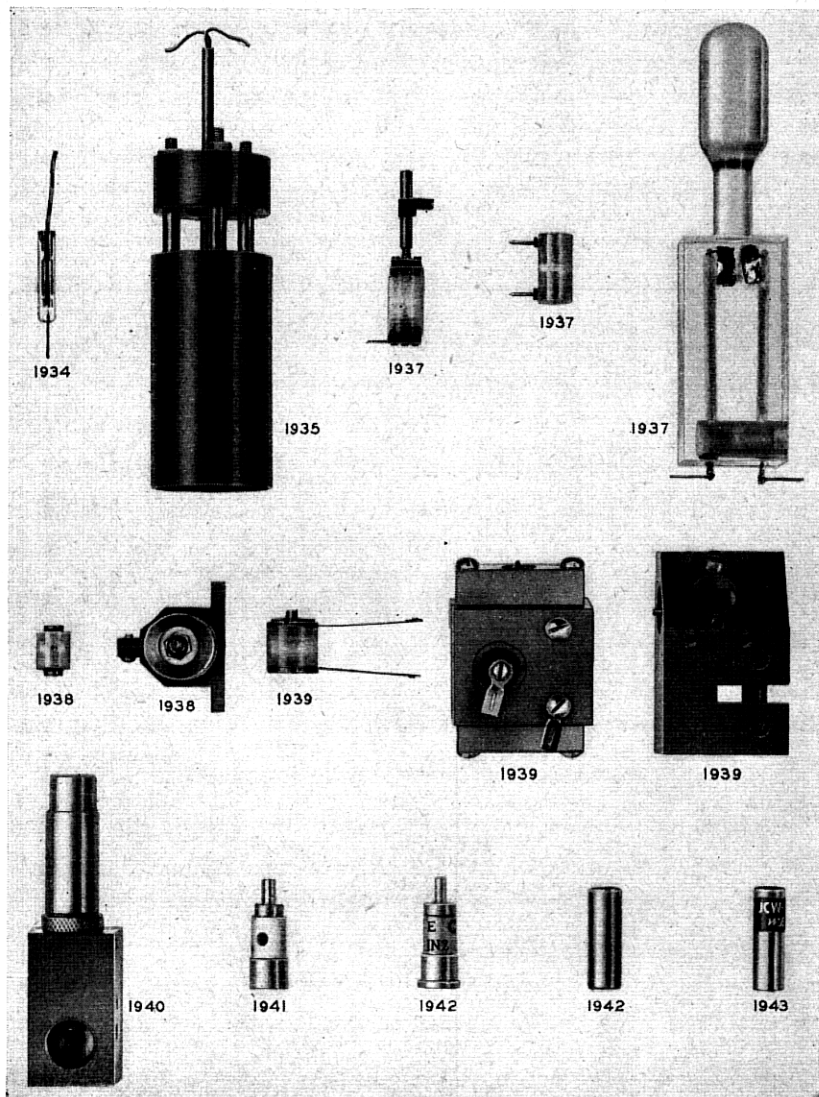


Fig. 1—Point contact rectifier structures. 1934-1943. Approximately $\frac{2}{3}$ actual size.

that they be easily adjusted. Considering the known vagaries of the device's historical counterpart, it was considered prudent to provide in the structures means by which the unit could be readjusted as frequently as might prove necessary or desirable.

As the properties of various semi-conductors were known to vary widely, an essential part of the early work was a survey of the properties of a number of minerals and metalloids potentially useful as rectifier materials. There were examined and tested approximately 100 materials, including zincite, molybdenite, galena, iron pyrites, silicon carbide, and silicon. Of the materials investigated most were found to be unsuitable for one reason or another, and iron pyrites and silicon were selected as having the best overall characteristics. The subsequent studies were then directed toward improving the rectifying material, the rectifying surface, the point contact and the mounting structure.

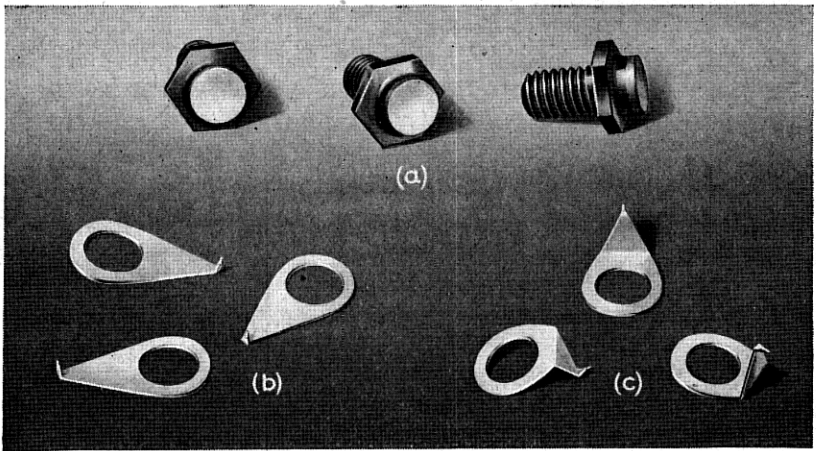


Fig. 2—Rectifier inserts and contact points for use in early 3000 megacycle converters. Overall length of insert $\frac{3}{16}$ -inch approximately.

For use at frequencies in the region of 3000 megacycles standard demountable elements, consisting of rectifier "inserts" and contact points, were developed for use in various housings or mounting blocks, depending upon the particular circuit requirements. The rectifier "inserts" consisted of small wafers of iron pyrite or silicon, soldered to hexagonal brass studs as shown in Fig. 2a. In these devices the surface of the semi-conductor was prepared by grinding, polishing, and etching to develop good rectification characteristics. Our knowledge of the metallurgy of silicon had advanced by this time to the stage where a uniformly active rectifier surface could be produced and searching for active spots was not necessary. Furthermore, it was possible to prepare inserts of a positive or negative variety, signifying that the easy direction of current flow was obtained with the silicon positive with respect to the point or vice versa. Owing to a greater nonlinearity of the current voltage characteristic, the n-type or negative

insert tended to give better performance as microwave converters while the p-type, or positive insert, because of greater sensitivity at low voltages, proved to be more useful in test equipment such as resonance indicators in frequency meters. In certain instances also, it was advantageous for the designer to be able to choose the polarity best suited to his circuit design. In contrast, however, to the striking uniformity obtained with the silicon processed in the laboratory, the pyrite inserts were very non-uniform. Active rectification spots on these natural mineral specimens could be found only by tediously searching the surface of the specimen. Moreover, rectifiers employing the pyrite inserts showed a greater variation in properties with frequency than those in which silicon was used.

In addition to providing a satisfactory semi-conductor, it was necessary also to develop suitable materials for use as point contacts. For this use metals were required which had satisfactory rectification characteristics with respect to silicon or pyrites and sufficient hardness so that excessive contact areas were not obtained at the contact pressures employed in the rectifier assembly. The metals finally chosen were a platinum-iridium alloy and tungsten, which in some cases was coated with a gold alloy. These were employed in the form of a fine wire spot welded to a suitable spring member. The spring members themselves were usually of a wedge shaped cantilever design and were made from coin silver to facilitate electrical connection to the spring. Several contact springs of two typical designs are shown in the photograph, Figs. 2b and 2c.

A typical mounting block arranged for use with the inserts and points is shown in Fig. 1 (1940) and in Fig. 3. This block was so constructed that it could be inserted in a 70 ohm coaxial line without introducing serious discontinuities in the line. The contact point of the rectifier was assembled in the block to be electrically connected to the central conductor of the coaxial radio frequency input fitting, while the crystal insert screwed into a tapered brass pin electrically connected to the central conductor of the coaxial intermediate frequency and d-c output fitting. The tapered pin fitted tightly into a tapered hole in a supporting brass cylinder, but was insulated from the cylinder by a few turns of polystyrene tape several thousandths of an inch thick. This central pin was thus one terminal of a coaxial high-frequency by-pass condenser. The capacitance of this condenser depended upon the general nature of the circuits in which the block was to be used, and was generally about 15 mmfs. The arrangement of the point, the crystal insert and their respective supporting members was such that the point contact could be made to engage the surface of the silicon at any spot and at the contact pressure desired and thereafter be clamped firmly in a fixed position by set screws. Typical direct current characteristics of the positive and negative silicon inserts and of pyrite inserts assembled and adjusted in this mounting block are shown in Fig. 4.

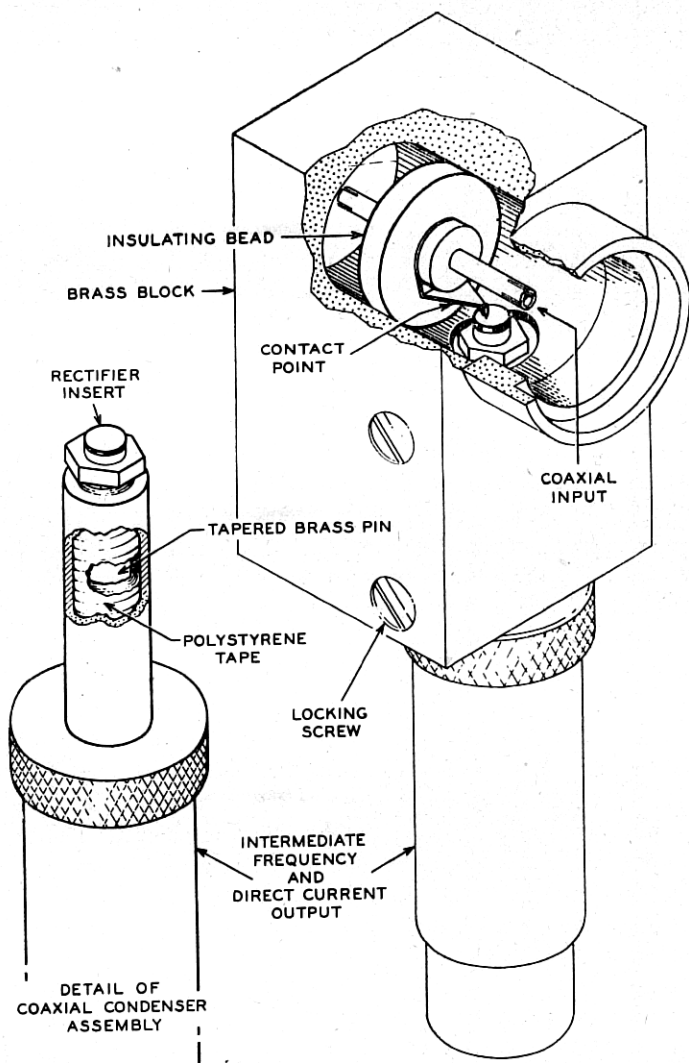


Fig. 3—Schematic diagram of one of the early crystal converter blocks.

The inserts and points in appropriate mounting blocks were widely used in centimeter wave investigations prior to 1940.² The principal laboratory uses were in frequency converter circuits in receivers, and as radio fre-

²G. C. Southworth and A. P. King, "Metal Horns as Directive Receivers of Ultra-Short Waves," *Proc. I. R. E.* v. 27, pp. 95-102, 1939; Carl R. Englund, "Dielectric Constants and Power Factors at Centimeter Wave Lengths," *Bell Sys. Tech. Jour.*, v. 23, pp. 114-129, 1944; Brainerd, Koehler, Reich, and Woodruff, "Ultra High Frequency Techniques," D. Van Nostrand Co., Inc., 250-4th Avenue, New York, 1942.

quency instrument rectifiers. They were also used to a relatively minor extent in some of the early radar test equipment. Moreover, the availability of these devices and the knowledge of their properties as microwave converters tended to focus attention on the potentialities of radar designs employing crystal rectifiers in the receiver's frequency converter. Similarly, the techniques established for preparation of the inserts tended to orient subsequent manufacturing process developments. For example, the methods now generally used for preparing silicon ingots, for cutting the rectifying element from the ingot with diamond saws, and for forming the

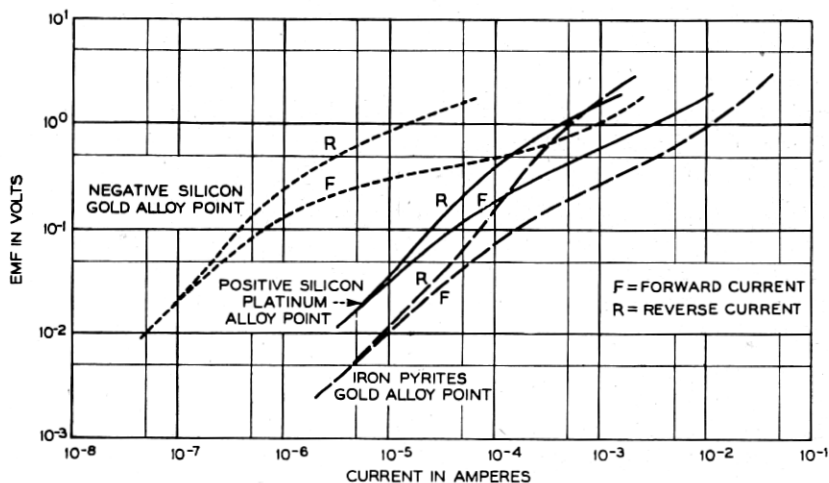


Fig. 4—Direct-current characteristics of silicon and iron pyrite rectifiers fabricated as inserts, 1939.

back contact to the rectifying element by electroplating procedures, are still essentially similar to the techniques used for preparing the inserts in 1939. As a contribution to the defense research effort, this basic information, with various samples and experimental assemblies, was made available to governmental agencies for dissemination to authorized domestic and foreign research establishments.

DEVELOPMENT OF THE CERAMIC TYPE CARTRIDGE STRUCTURE

The block rectifier structure previously described was well adapted to various laboratory needs because of its flexibility, but for large scale utilization certain limitations are evident. Not only was it necessary that the parts be accurately machined, but also the adjustment of the rectifier in

the block structure required considerable skill. With recognition of the military importance of silicon crystal rectifiers, effort was intensified in the development of standardized structures suitable for commercial production.

In the 1940-1941 period, contributions to the design of silicon crystal rectifiers were made by British workers as a part of their development of new military implements. For these projected military uses, the problem of replacement and interchangeability assumed added importance. The design trend was, therefore, towards the development of a cartridge type structure with the electrical adjustment fixed during manufacture, so that the unit could be replaced easily in the same manner as vacuum tubes.

In the latter part of 1941 preliminary information was received in this country through National Defense Research Committee channels on a rectifier design originating in the laboratories of the British Thomson-Houston Co., Ltd. A parallel development of a similar device was begun in various American laboratories, including the Radiation Laboratory at the Massachusetts Institute of Technology, and Bell Telephone Laboratories. In the work at Bell Laboratories, emphasis was placed both on development of a structure similar to the British design and on exploration and test of various new structures which retained the features of socket interchangeability but which were improved mechanically and electrically.

In the work on the ceramic cartridge, the external features of the British design were retained for reasons of mechanical standardization but a number of changes in process and design were made both to improve performance and to simplify manufacture. To mention a few, the position of the silicon wafer and the contact point were interchanged because measurements indicated that an improvement in performance could thereby be obtained. To obviate the necessity for searching for active spots on the surface of the silicon and to improve performance, fused high purity silicon was substituted for the "commercial" silicon then employed by the British. The rectifying element was cut from the ingots by diamond saws, and carefully polished and etched to develop optimum rectification characteristics. Similar improvements were made in the preparation of the point or "cats whisker", replacing hand operations by machine techniques. To protect the unit from mechanical shock and the ingress of moisture, a special impregnating compound was developed which was completely satisfactory even under conditions of rapid changes in temperature from -40° to $+70^{\circ}\text{C}$. All such improvements were directed towards improving quality and establishing techniques for mass production.

In this early work time was at a premium because of the need for prompt standardization of the design in order that radar system designs might in

turn be standardized, and that manufacturing facilities might be established to supply adequate quantities of the device. The development and initial production of the device was accomplished in a short period of time. This was possible because process experience had been acquired in the insert development, and centimeter wave measurements techniques and facilities were then available to measure the characteristics of experimental units at the operating frequency. By December 1941, a pattern of manufacturing techniques had been established so that production by the Western Electric Company began shortly thereafter. This is believed to have been the first commercial production of the device in this country.

As a result of the basic information on centimeter wave measurements techniques which was available from earlier microwave research at the Holmdel Radio Laboratory, it was possible also, at this early date, to propose to the Armed Services that each unit be required to pass an acceptance test consisting of measurement of the operating characteristics at the intended operating frequency. This plan was adopted and standard test methods devised for production testing. Considering the complexity of centimeter wave measurements, this was an accomplishment of some magnitude and was of first importance to the Armed Services because it assured by direct measurement that each unit would be satisfactory for field use.

The cartridge structure resulting from these developments and meeting the international dimensional standards is shown in Fig. 5. It consists of two metal terminals separated by an internally threaded ceramic insulator. The rectifying element itself consists of a small piece of silicon (p-type) soldered to the lower metal terminal or base. The contact spring or "cats whisker" is soldered into a cylindrical brass pin which slides freely into an axial hole in the upper terminal and may be locked in any desired position by set screws. The spring itself is made from tungsten wire of an appropriate size, formed into an S shape. The free end of the wire, which in a finished unit engages the surface of the silicon and establishes rectification, is formed to a cone-shaped configuration in order that the area of contact may be held at the desired low value.

The silicon elements used in the rectifiers are prepared from ingots of fused high purity silicon. Alloying additions are made to the melt when required to adjust the electrical resistivity of the silicon to the value desired. The ingots are then cut and the silicon surfaces prepared and cut into small pieces approximately 0.05 inch square and 0.02 inch thick suitable for use in the rectifiers. The contact springs are made from tungsten wire, gold plated to facilitate soldering. Depending upon the application, the wires

may be 0.005 inch, 0.0085 inch, or 0.010 inch in diameter. After forming the spring to the desired shape, the tip is formed electrolytically.

In assembling the rectifier cartridge, the two end terminals, consisting of the base with the silicon element soldered to it, and the top detail containing the contact spring, are threaded into the ceramic tube so that the free end of the spring does not engage the silicon surface. An adhesive

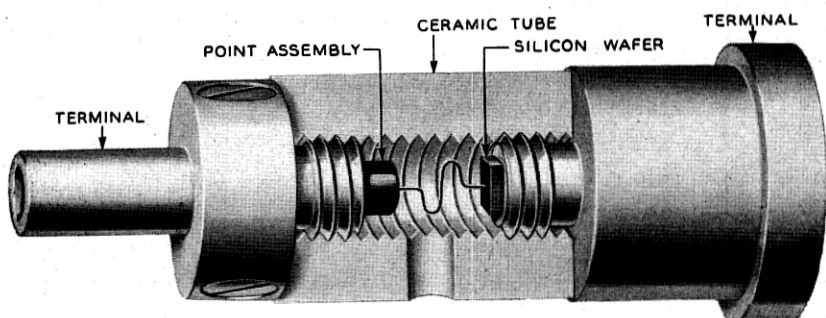
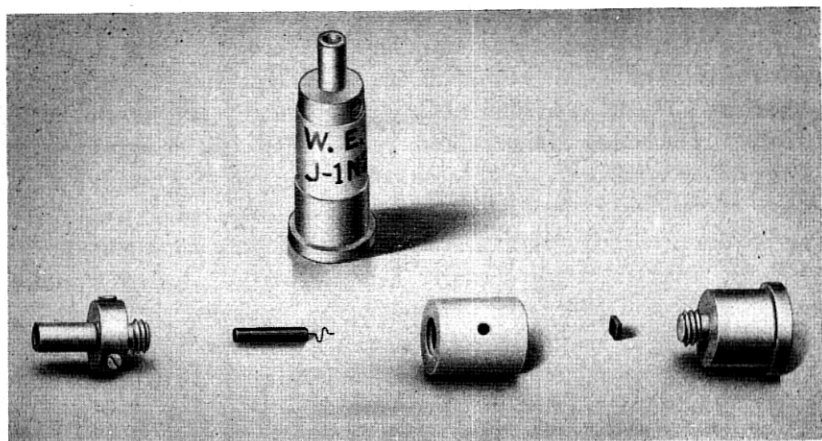


Fig. 5—Ceramic cartridge rectifier structure and parts. Overall length of assembled rectifier is approximately $\frac{1}{4}$ inch.

is employed to secure the parts firmly to the ceramic. The rectifier is then "adjusted" by bringing the point into engagement with the silicon surface and establishing optimum electrical characteristics. Finally the unit is impregnated with a special compound to protect it from moisture and from damage by mechanical shock. Units so prepared are then ready for the final electrical tests.

The adjustment of the rectifier is an interesting operation for at this

stage in the process the rectification action is developed, and to a considerable degree, controlled. If the point is brought into contact with the silicon surface and a small compressional deflection applied to the spring, direct-current measurements will show a moderate rectification represented by the passage of more current at a given voltage in the forward direction than in the reverse. If the side of the unit is now tapped sharply by means of a small hammer, the forward current will be increased, and, at the same time, the reverse current decreased.³ With successive blows the reverse current is reduced rapidly to a constant low value while the forward current increases, but at a diminishing rate, until it also becomes relatively constant. The magnitude of the changes produced by this simple operation is rather surprising. The reverse current at one volt seldom decreases by less than a factor of 10 and frequently decreases by as much as a factor of 100, while the forward current at one volt increases by a factor of 10. Paralleling these changes are improvements in the high-frequency properties, the conversion loss and noise both being reduced. The tapping operation is not a haphazard searching for better rectifying spots, for with a given silicon material and mechanical assembly the reaction of each unit to tapping is regular, systematic and reproducible. The condition of the silicon surface also has a pronounced bearing on "tappability" for by modifications of the surface it is possible to produce, at will, materials sensitive or insensitive in their reaction to the tapping blows.

In the development of the compounds for filling the rectifier, special problems were met. For example, storage of the units for long periods of time under either arctic or tropical conditions was to be expected. Also, for use in air-borne radars operating at high altitudes, where equipment might be operated after a long idle period, it was necessary that the units be capable of withstanding rapid heating from very low temperatures. The temperature range specified was from -40° to $+70^{\circ}\text{C}$. Most organic materials normally solid at room temperature, as the hydrocarbon waxes, are completely unsuitable, as the excessive contraction which occurs at low temperatures is sufficient to shift the contact point and upset the precise adjustment of the spring. Nor are liquids satisfactory because of their tendency to seep from the unit. However, special gel fillers, consisting of a wax dispersed in a hydrocarbon oil, were devised in Bell Telephone Laboratories to meet the requirements, and were successfully applied by the leading manufacturers of crystal rectifiers in this country. Materials of a similar nature, though somewhat different in composition, were also used subsequently in Britain. Further improvements in these compounds have been made recently, extending the temperature range 10°C at low

³ Southworth and King; loc. cit.

temperatures and about 30°C at high temperatures in response to the design trend towards operation of the units at higher temperatures. The units employing this compound may, if desired, be repeatedly heated and cooled rapidly between -50°C and +100°C without damage.

Use of the impregnating compound not only improves mechanical stability but prevents ingress or absorption of moisture. Increase of humidity would subject the unit not only to changes in electrical properties such as variation in the radio frequency impedance, but also to serious corrosion, for the galvanic couple at the junction would support rapid corrosion of the metal point. In fact, with condensed moisture present in unfilled units corrosion can be observed in 48 hours. For this reason alone, the development of a satisfactory filling compound was an important step in the successful utilization of the units by the Armed Services under diverse and drastic field conditions.

TABLE I
Shelf Aging Data on Silicon Crystal Rectifiers of the Ceramic Cartridge Design

Storage Conditions	Initial Values		Values After Storage for 7 Months	
	Conversion Loss (Median) (L)	Noise Ratio (Median) (N _r)	Conversion Loss (median) (L)	Noise Ratio (median) (N _r)
	<i>db</i>	<i>db</i>	<i>db</i>	<i>db</i>
75°F. 65% Relative Humidity.....	6.8	3.9	6.7	4.3
110°F. 95% Relative Humidity.....	6.9	3.9	6.9	4.3
-40°C.....	7.0	3.9	6.8	3.9

The large improvement in stability achieved in the present device as compared with the older crystal detectors may be attributed to the design of the contact spring, correct alignment of parts in manufacture and to the practice of filling the cavity in the unit with the gel developed for this purpose. Considering the apparently delicate construction of the device, the stability to mechanical or thermal shock achieved by these means is little short of spectacular. Standard tests consist of dropping the unit three feet to a wood surface, immersing in water, and of rapidly heating from -40 to 70°C. None of these tests impairs the quality of the unit. Similarly the unit will withstand storage for long periods of time under adverse conditions. Table I summarizes the results of tests on units which were stored for approximately one year under arctic (-40°), tropical (114°F—95% relative humidity), and temperate conditions. Though minor changes in the electrical characteristics were noted in the accelerated tropical test, none of the units was inoperative after this drastic treatment.

DEVELOPMENT OF THE SHIELDED RECTIFIER STRUCTURE

Rectifiers of the ceramic cartridge design, though manufactured in very large quantities and widely and successfully used in military apparatus, have certain well recognized limitations. For example, they may be accidentally damaged by discharge of static electricity through the small point contact in the course of routine handling. If one terminal of the unit is held in the hand and the other terminal grounded, any charge which may have accumulated will be discharged through the small contact. Since such static charges result in potential differences of several thousand volts it is understandable that the unit might suffer damage from the discharge. Although damage from this cause may be avoided by following a few simple precautions in handling, the fact that such precautions are needed constitutes a disadvantage of the design.

Certain manufacturing difficulties are also associated with the use of the threaded insulator. The problem of thread fit requires constant attention. Lack of squareness at the end of the ceramic cylinder or lack of concentricity in the threaded hole tends to cause an undesirable eccentricity or angularity in the assembled unit which can be minimized only by rigid inspection of parts and of final assemblies. At the higher frequencies (10,000 megacycles), uniformity in electrical properties, notably the radio frequency impedance, requires exceedingly close control of the internal mechanical dimensions. In the cartridge structure where the terminal connections are separated by a ceramic insulating member, the additive variations of the component parts make close dimensional control inherently difficult.

To eliminate these difficulties the shielded structure, shown in Fig. 6, was developed. In this design the rectifier terminates a small coaxial line. The central conductor of the line, forming one terminal of the rectifier, is molded into an insulating cylinder of silica-filled bakelite, and has spot welded to it a 0.002-inch diameter tungsten wire spring of an offset C design. The free end of the spring is cone shaped. The rectifying element is soldered to a small brass disk. Both the disk, holding the rectifying element, and the bakelite cylinder, holding the point, are force-fits in the sleeve which forms the outer conductor of the rectifier. By locating the bakelite cylinder within the sleeve so that the free end of the central conductor is recessed in the sleeve, the unit is effectively protected from accidental static damage as long as the holder or socket into which the unit fits is so designed that the sleeve establishes electrical contact with the equipment at ground potential before the central conductor. The sleeve also shields the rectifying contact from effects of stray radiation.

The radio frequency impedance of the shielded unit can be varied within certain limits by modifying the diameter of the central conductor. For

example, in the 1N26 unit, which was designed for use at frequencies in the region of 24,000 megacycles, a small metal slug fitting over the central conductor makes it possible to match a coaxial line having a 65-ohm surge impedance. For certain circumstances this modification in design is advantageous, while in others it is a disadvantage because the matching slug is effective only over a narrow range of frequencies.

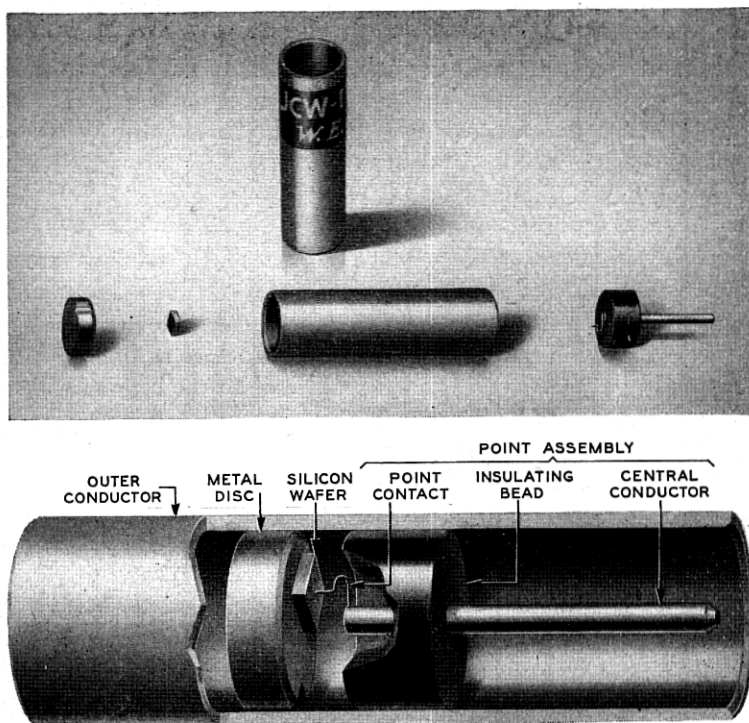


Fig. 6—Shielded rectifier structure and parts. Overall length of assembled rectifier is approximately $\frac{3}{4}$ inch.

The shielded structure was developed in 1942 and since it was of a simplified design with reduced hazard of static damage, it was proposed to the Armed Services for standardization in June of that year. However, because of the urgency of freezing the design of various radars and because the British had already standardized on the outline dimensions of the ceramic type cartridge, Fig. 5, the Services did not consider it advantageous to standardize the new structure when first proposed. In deference to this international standardization program, plans for the manufacture of this

structure were held in abeyance during 1942 and 1943. However, an opportunity for realizing the advantages inherent in the shielded design was afforded later in the war and a sufficient quantity of the units was produced to demonstrate its soundness. As anticipated from the constructional features, marked uniformity of electrical properties was obtained.

TYPES, APPLICATIONS, AND OPERATING CHARACTERISTICS

Various rectifier codes, engineered for specific military uses, were manufactured by Western Electric Company during the war. These are listed in Table II. The units are designated by RMA type numbers, as 1N21, 1N23, etc., depending upon their properties and the intended use. Letter suffixes, as 1N23A, 1N23B, indicate successively more stringent performance requirements as reflected in lower allowable maxima in loss and noise ratio, and, usually, more stringent power proof-tests. In general, different codes are provided for operation in the various operating frequency ranges. For example, the 1N23 series is tested at 10,000 megacycles while the 1N21 series is tested at 3,000 megacycles and the 1N25 at 1000 megacycles, approximately. Since higher transmitter powers are frequently employed at the lower frequencies, somewhat greater power handling ability is provided in units for operation in this range.

One of the more important uses of silicon crystal rectifiers in military equipment was in the frequency converter or first detector in superheterodyne radar receivers. This utilization was universal in microwave receivers. In this application the crystal rectifier serves as the non-linear circuit element required to generate the difference (intermediate) frequency between the radio frequency signal and the local oscillator. The intermediate frequency thus obtained is then amplified and detected in conventional circuits. As the crystal rectifier is normally used at that point in the receiving circuit where the signal level is at its lowest value, its performance in the converter has a direct bearing on the overall system performance. It was for this reason that continued improvements in the performance of crystal rectifiers were of such importance to the war effort.

For the converter application, the signal-to-noise properties of the unit at the operating frequency, the power handling ability, and the uniformity of impedance are important factors. The signal-to-noise properties are measured as conversion loss and noise ratio. The loss, L , is the ratio of the available radio frequency signal input power to the available intermediate frequency output power, usually expressed in decibels. The noise ratio, N_R , is the ratio of crystal output noise power to thermal (KTB) noise power. The loss and noise ratio are fundamental properties of the

TABLE II
Performance Specifications—Silicon Crystal Rectifiers

Code	W.E. Spec. No.	Structure	Nominal Operating Frequency	Test Power	Max. Conversion Loss	Max. Noise Ratio ⁷	Int. Freq. Impedance	Min. Figure of Merit	Low-Level Resistance	Proof Test Method, Note	Test Level	Normal Use
1N21	D-163366	Cartridge	mega-cycles 3000	milli-watts 0.4	db 8.5	4.0	ohms		ohms	5	0.3 erg	Converter
1N21A	D-168355	"	"	0.4	7.5	3.0				5	2.0 ergs	"
1N21B	D-169113	"	"	0.5	6.5	2.0	375 ¹			5	0.3 erg	"
1N23	D-168356	"	10000	1.0	10.0	3.0	"			5	1.0 erg	"
1N23A	D-169304	"	"	1.0	8.0	2.7	"			5	0.3 erg	"
1N23B	D-169305	"	"	1.0	6.5	2.7	"			6	12.5v ³	"
1N25	D-170247	"	1000	1.25	8.0	2.5	100-400 ²			6	6.ω ⁴	"
1N26	D-168707	Shielded	24000	1.0	8.5	2.5	300-600 ²	60	4000 max. at 1 mv	5	0.1 erg	Low-Level Detector
1N27	D-172981	Cartridge	3000	.005 max.								Converter
1N28	D-168030	"	"	0.4	7.0	2.0	300 ¹	55	6000-23,000 at 5 mv max.	5	5.0 erg	Low-Level Detector
1N31	D-171936	Shielded	10000	.005 max.						6	25.ω ⁴	

¹ Average values under conditions of production test—not limited directly by specifications.

² Values limited by specifications.

³ Pulse generator voltage.

⁴ Pulse generator impedance.

⁵ Single D.C. spike.

⁶ Multiple square pulse.

⁷ Numerical ratio.

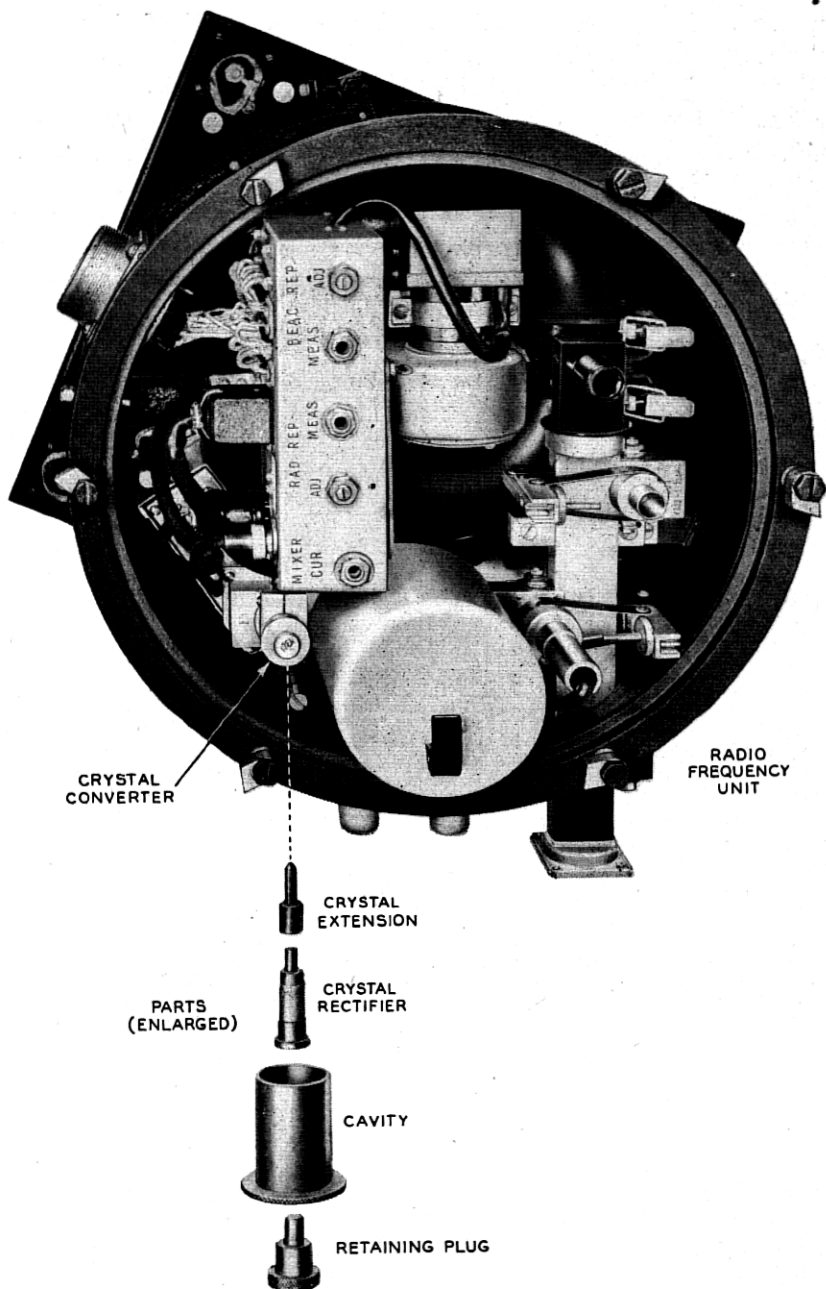


Fig. 7—Converter for wave guide circuits as installed in the radio frequency unit of the AN/APQ13 radar system. This was standard equipment in B-29 bombers for radar bombing and navigation.

converter. From these data and other circuit constants, the designer may calculate⁴ expected receiver performance.

For operation as converters,⁵ crystal rectifiers are employed in suitable holders. These may be arranged for use with either coaxial line or wave guide circuits, depending upon the application. Figure 7 shows a converter for wave guide circuits installed in the radio frequency unit of an air-borne radar system. A typical converter designed for use with coaxial lines is shown in the photograph Fig. 8. A schematic circuit of this converter is shown in Fig. 9. In such circuits the best signal-to-noise ratio is realized when an optimum amount of beating oscillator power is supplied. The optimum power depends, in part, on the properties of the rectifier itself, and, in part, on other circuit factors as the noise figure of the intermediate

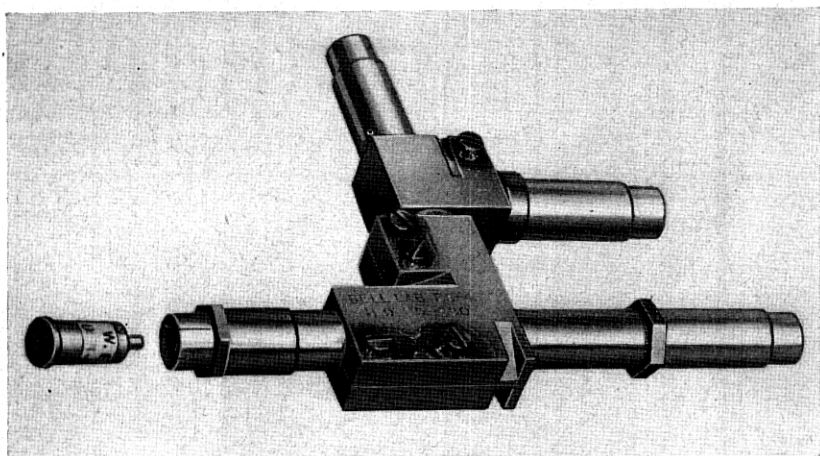


Fig. 8—Converter for use at 3000 megacycles. The crystal rectifier is located adjacent to its socket in the converter.

frequency amplifier. For a well designed intermediate frequency amplifier with a noise figure of about 5 decibels, the optimum beating oscillator power is such that between 0.5 and 2.0 milliamperes of rectified current flows through the rectifier unit. Under these conditions and with the unit matched to the radio frequency line, the beating oscillator power absorbed by the unit is about one milliwatt. For intermediate frequency amplifiers

⁴ The quantities L and NR are related to receiver performance by the relationship

$$F_R = L(NR - 1 + F_{IF})$$

where F_R is the receiver noise figure and F_{IF} is the noise figure of the intermediate frequency amplifier. All terms are expressed as power ratios. A rigorous definition of receiver noise figure has been given by H. T. Friis "Noise Figures of Radio Receivers," *Proc. I. R. E.*, vol. 32, pp. 419-422; July, 1944.

⁵ C. F. Edwards, "Microwave Converters," presented orally at the Winter Technical Meeting of the *I. R. E.*, January 1946 and submitted to the *I. R. E.* for publication.

with poorer noise figures, the drive for optimum performance is higher than the figures cited above. Conversely, for intermediate frequency amplifiers with exceptionally low noise figures, optimum performance is obtained with lower values of beating oscillator drive. If desired, somewhat higher currents than 2.0 milliamperes may be employed without damage to the crystal.

The impedance at the terminals of a converter using crystal rectifiers, both at radio and intermediate frequencies, is a function not only of the rectifier unit, but also of the circuit in which the unit is used and of the

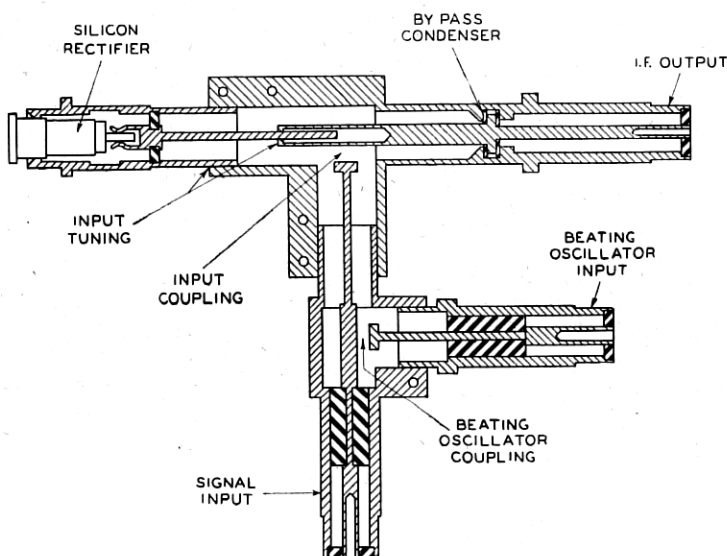


Fig. 9—Schematic diagram of crystal converter.

power level at which it is operated. Consequently the specification of an impedance for a crystal rectifier is of significance only in terms of the circuit in which it is measured. Since the converters used in the production testing of crystal rectifiers are not necessarily the same as those used in the field, and since in addition there are frequently several converter designs for the same type of unit, a specification of crystal rectifier impedance in production testing can do little more than select units which have the same impedance characteristic in the production test converter. The impedances at the terminals of two converters of different design but using the same crystal rectifier may vary by a factor of 3 or even more, with the intermediate frequency impedance generally varying more drastically than the radio frequency impedance. The variation is also a function of the con-

version loss. Crystals with large conversion losses are less susceptible to impedance changes from reactions in the radio frequency circuit than are low conversion loss units.

The level of power to which the rectifiers can be subjected depends upon the way in which the power is applied. The application of an excessive amount of power or energy results in the electrical destruction of the unit by rupture of the rectifying material. Experimental evidence indicates that the electrical failure may be in one of three categories. The total energy of an applied pulse is responsible for the impairment when the pulse length is shorter than 10^{-7} seconds, the approximate thermal time constant of the crystal rectifier as given by both measurement and calculation. For pulse lengths of the order of 10^{-6} seconds the peak power in the pulse is the determining factor, and for continuous wave operation the limitation is in the average power.

In performance tests in manufacture all units for which burnout tolerances are specified are subjected to proof-tests at levels generally comparable with those which the unit may occasionally be expected to withstand in actual use, but greater than those to be employed as a design maximum. The power or energy is applied to the unit in one of two types of proof-test equipment. The multiple, long time constant (of the order of 10^{-6} seconds) pulse test is applied to simulate the plateau part of a radar pulse reaching the crystal through the gas discharge transmit-receive switch.⁶ This test uses an artificial line of appropriate impedance triggered at a selected repetition rate for a determined length of time. The power available to the unit is computed from the usual formula,

$$P = \frac{V^2}{4Z},$$

where P is the power in watts, V is the potential in volts to which the pulse generator is charged, and Z is the impedance in ohms of the pulse generator. In general, where this test is employed, a line is used which matches the impedance of the unit under test at the specified voltage.

The second type of test is the single discharge of a coaxial line through the unit to simulate a radar pulse spike reaching the crystal before the transmit-receive switch fires. The pulse length is of the order of 10^{-9} second. The energy in the test spike may be computed from the relation

$$E = \frac{10^7}{2} CV^2,$$

where E is the energy in ergs, C the capacity of the coaxial line in farads, and V the potential in volts to which the line is charged.

⁶A. L. Samuel, J. W. Clark, and W. W. Mumford, "The Gas Discharge Transmit-Receive Switch," *Bell Sys. Tech. Jour.*, v. 25 No. 1, pp. 48-101, Jan. 1946.

Specification proof-test levels are, of course, not design criteria. Since the units are generally used in combination with protective devices, such as the transmit-receive switch, it is necessary to conduct tests in the circuits of interest to establish satisfactory operating levels.

In general, however, the units may be expected to carry, without deterioration, energy of the order of a third of that used in the single d-c spike proof-test or peak powers of a magnitude comparable with that used in the multiple flat-top d-c pulse proof-test. The upper limit for applied continuous wave signals has not been determined accurately, but, in general, rectified currents below 10 milliamperes are not harmful when the self bias is less than a few tenths of a volt.

The service life of a crystal rectifier will depend completely upon the conditions under which it is operated and should be quite long when its ratings are not exceeded. During the war, careful engineering tests conducted on units operating as first detectors in certain radar systems revealed no impairment in the signal-to-noise performance after operation for several hundred hours. A small group of 1N21B units showed only minor impairments when operated in laboratory tests for 100 hours with pulse powers (3000 megacycles) up to 4 watts peak available to the unit under test.

Another important military application of silicon crystal rectifiers was as low-power radio frequency rectifiers for use in wave meters or other items of radar test equipment. Here the rectification properties of the unit at the operating frequency are of primary interest. Since units which are satisfactory as converters also function satisfactorily as high-frequency rectifiers special types were not required for this application.

Units were also used in military equipment as detectors to derive directly the envelope of a radio frequency signal received at low power levels. These signals were modulated usually in the video range. The low-level performance is a function of the resistance at low voltages and the direct-current output for a given low-power radio frequency input. These may be combined to derive a figure of merit which is a measure of receiver performance.⁷

Typical direct-current characteristics of the silicon rectifiers at temperatures of -40° , 25° and 70°C are given in Fig. 10. It will be noted in these curves that both the forward and reverse currents are decreased by reducing the temperature and increased by raising the temperature. The reverse current changes more rapidly with temperature than the forward current, however, so that the rectification ratio is improved by reducing the temperature, and impaired by raising the temperature. The data shown are for typical units of the converter type. It should be emphasized, however,

⁷ R. Beringer, Radiation Laboratory Report No. 61-15, March 16, 1943.

that by changes in processing routines the direct-current characteristics shown in Fig. 10 may be modified in a predictable manner, particularly with respect to absolute values of forward current at a particular voltage.

MODERN RECTIFIER PROCESSES

When the development of the type 1N21 unit was undertaken, the scientific and engineering information at hand was insufficient to permit intentional alteration or improvement in electrical properties of the rectifier. In these early units, the control of the radio frequency impedance, power handling ability and signal-to-noise ratio left much to be desired. Within a short time, some improvements in performance were realized by process improvements such as the elimination of burrs and irregularities from the point contact to reduce noise. Substantial improvements were not obtained,

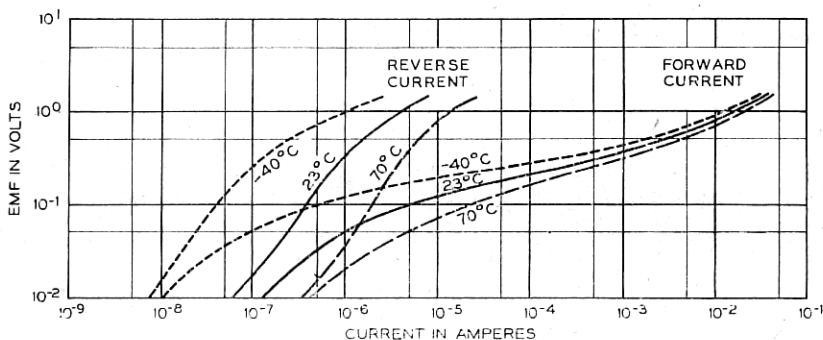


Fig. 10—Direct-current characteristics of P-type silicon crystal rectifier at various temperatures.

however, until certain improved materials, processes, and techniques were developed.

In the engineering development of improved crystal rectifier materials and processes, basic data have been acquired which make it possible to alter the properties of the rectifier in a predictable manner so that the units may now be engineered to the specific electrical requirements desired by the circuit designer in much the same manner as are modern electron tubes. This has led not only to improvements in performance but also to a diversification in types and applications.

The simplified equivalent circuit for the point contact rectifier, shown in Fig. 11, provides a basis for consideration of the various process features. In Fig. 11, C_B represents the electrical capacitance at the boundary between the point contact and the semi-conductor, R_B the non-linear resistance at this boundary, and R_s is the spreading resistance of the semi-conductor

proper, that is the total ohmic resistance of the silicon to current through the point. The capacitance C_B being shunted across the rectifying boundary, decreases the efficiency of the device by its by-pass action because the current through it would be dissipated as heat in the resistance R_S . Losses from this source increase rapidly with increased frequency because of the enhanced by-pass action. It would appear, therefore, that to improve efficiency it would be important to minimize both R_S and C_B by some method such as reducing the area of the rectifying contact and lowering the body resistance of the silicon employed. For a given silicon material, the impedances desired for reasons of circuitry and considerations of mechanical stability place a limit on the extent to which performance may be improved by reducing the contact area. R_S may be reduced by using silicon of lower resistivity, but this generally results in poorer rectification. This impairment is due apparently to some subtle change in the properties of the rectifying junction resulting from decreasing the specific resistance of the silicon material.

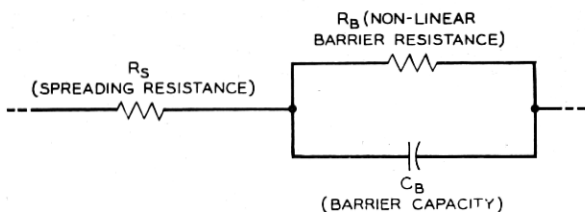


Fig. 11—Simplified equivalent circuit of crystal rectifier.

The answer to this apparent dilemma lies in the application of an oxidizing heat treatment to the surface of the semi-conductor. This process derives from researches conducted independently in this country and in Britain, though there was considerable interchange of information between various interested laboratories. In the oxidizing treatment, apparently the impurities in the silicon which contribute to its conductivity diffuse into the adhering silica film, thereby depleting impurities from the surface of the silicon. When the oxide layer is then removed by solution in dilute hydrofluoric acid, the underlying silicon layer is exposed and remains intact as the acid does not readily attack the silicon itself.

Since decreasing the impurity content of a semi-conductor increases its resistivity, the silicon surface has higher resistivity after the oxidizing treatment than before. Thus by oxidation of the surface of low resistance silicon it is possible to secure the enhanced rectification associated with the high resistance surface layer, while by virtue of the lower resistivity of the underlying material the I^2R losses through R_S are reduced.

In actual practice the properties of the rectifier are governed by the resistivity of the silicon material, the contact area, and the degree of oxidation of the surface. By the controlled alteration of these factors units may be engineered for specific applications. The body resistance of the silicon is controlled by the kind and quantity of the impurities present. Aluminum, beryllium or boron may be added to purified silicon to reduce its resistivity to the desired level. Boron is especially effective for this purpose, the quantity added usually being less than 0.01 per cent. As little as 0.001 per cent has a very pronounced effect upon the electrical properties. The contact area is determined by the design of contact spring employed and the deflection applied to it in the adjustment of the rectifier. The degree of oxidation is controlled by the time and temperature of the treatment and the atmosphere employed.

In the development of the present rectifier processes, certain experimental relationships were obtained between the performance and the contact area on the one hand, and the power handling ability and contact area on the other. These show the manner in which the processes should be changed to produce a desired change in properties. For example, Fig. 12 shows the relationship between the spring deflection applied to a unit and the conversion loss at a given frequency. The apparent contact area, (i.e., the area of the flattened tip of the spring in contact with the silicon surface, as measured microscopically) also increases with increasing spring deflection. It will be seen in Fig. 12 that for a given silicon material, the conversion loss at 10,000 megacycles increases rapidly with the contact area. The curves tend to reach constant loss values at the higher spring deflections. It is believed that this may be ascribed to the fact that for a given spring size and form, the increment in contact area obtained by successive increments in spring deflection would diminish and finally become zero after the elastic limit of the spring is exceeded.

The losses plotted in Fig. 12 were measured on a tuned basis, that is, the converter was adjusted for maximum intermediate frequency output at a fixed beating oscillator drive for each measurement. Were these measurements made on a fixed tuned basis, that is, with the converter initially adjusted for maximum intermediate frequency output for a unit to which the minimum spring deflection is applied, and the units with larger deflections then measured without modification of the converter adjustment, even greater degradation in conversion loss than that shown in Fig. 12 would be observed. This results from the dependence of the radio frequency impedance upon the contact area. In loss measurements made on the tuned basis, changes in the radio frequency impedance occasioned by the changes in the contact area do not affect the values of mismatch loss obtained, while on the

fixed tuned basis they would result in an increase in the apparent loss because of the mismatch of the radio frequency circuits.

While the conversion loss is degraded by increasing the contact area, the power handling ability⁸ of the rectifiers is improved, as shown in Fig. 13.

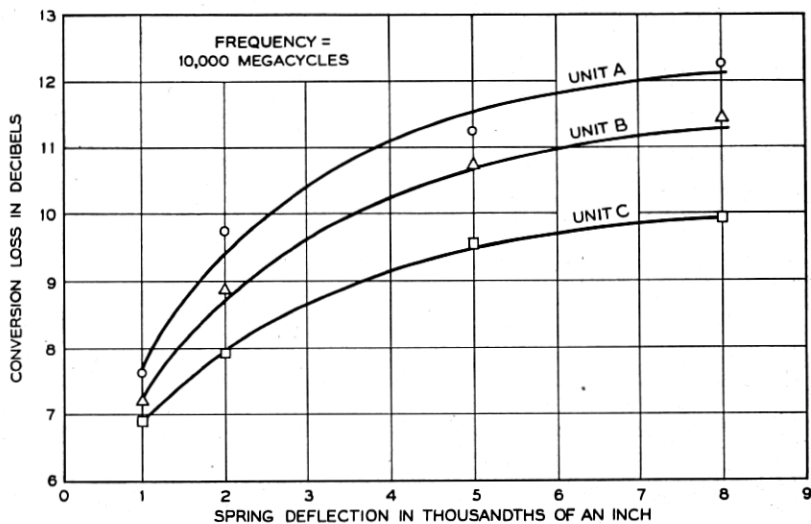


Fig. 12—Relationship between spring deflection and conversion loss in silicon crystal rectifiers.

This is not surprising because the larger area contact gives a wider current distribution and thus minimizes the localized heating effects near the contact. Generally, therefore, in the development of units for operation at a

⁸The measurement of power handling ability of crystal rectifiers by application of radio frequency power is complicated by the fact that the impedance of the unit under test varies with power level. If a unit is matched in a converter at a low-power level and power at a higher level is then applied, not all of the power available is absorbed by the unit but a portion of it is reflected (due to the change in impedance). This factor has been called the self protection of the unit and it necessitates the distinction between the power absorbed by and the power available to the unit under test. The data for Fig. 13 were acquired by first matching the unit in converters at low powers (about 0.3 milliwatts CW 3000 mcs) and then exposing it for a short period to successively higher levels of pulse power of square wave form of 0.5 microseconds width at a repetition rate of 2000 pulses per second, measuring the loss and noise ratio after each power application. The power handling ability is then expressed as the available peak power required to cause a 3 db impairment in the conversion loss or the receiver noise figure. This method was employed because in radar receivers the units are matched for low-power levels. In this respect the method simulates field operating conditions, but the "spike" of radar pulses is absent.

The increase in power handling ability with increasing area shown in Fig. 13 is confirmed by similar measurements with radio frequency pulse power with the unit matched at high-level powers, by direct-current tests, and by simple 60-cycle continuous wave tests. The magnitude of the increase depends, however, upon the particular method employed for measurement.

given frequency, a compromise must be effected between these two important performance factors. Because of increased condenser by-pass action a smaller area must be used to obtain a given conversion loss at a higher frequency. For this reason the power handling ability of units designed for use at the higher frequencies is somewhat less than that of the lower-fre-

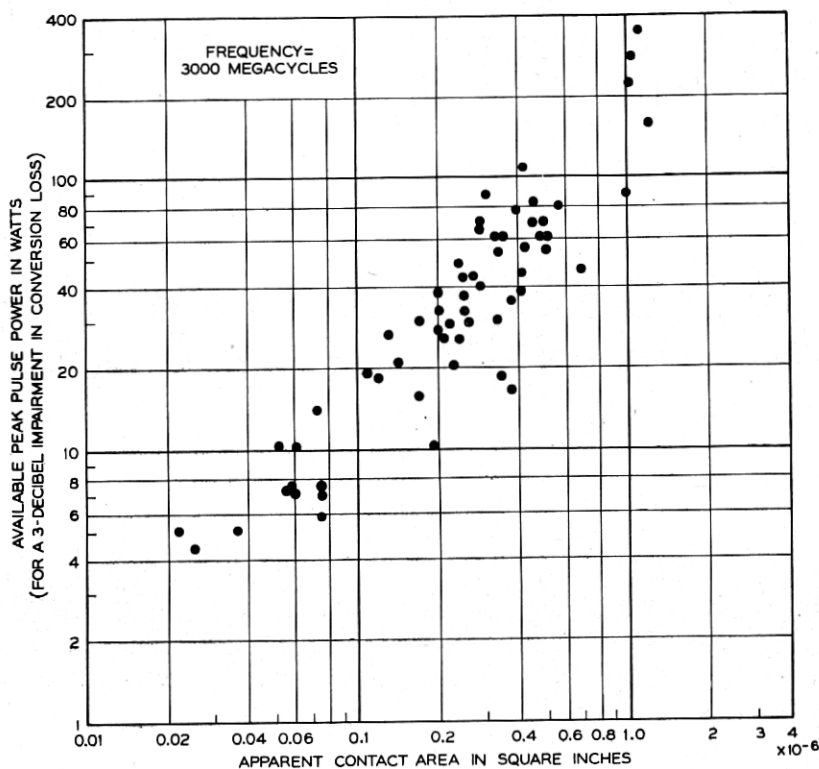


Fig. 13—Correlation between power handling ability measured with microsecond radio frequency pulses and contact area in silicon crystal rectifiers.

quency units because emphasis has been placed upon achieving a given signal-to-noise performance in each frequency band.

Use of the improved materials and processes produced rather large improvements in the d-c rectification ratio, conversion loss, noise, power handling ability, and uniformity. Typical direct-current rectification characteristics of units produced by both the old and the new processes are shown in Fig. 14. These curves show that reverse currents at one volt were decreased by a factor of about 20 while the forward currents were increased by

a factor of approximately 2.5 giving a net improvement in rectification ratio of 50 to 1. The parallel improvement in receiver performance resulting from process improvements is shown in Fig. 15. A comparison in power handling

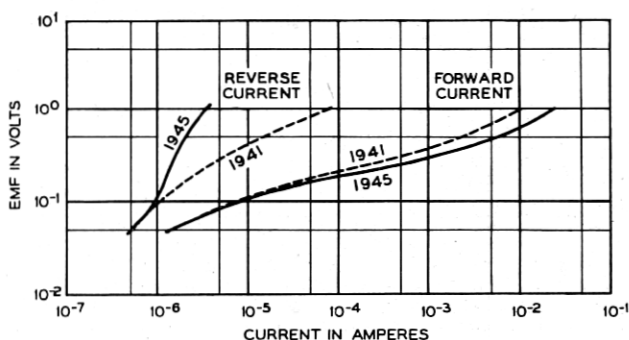
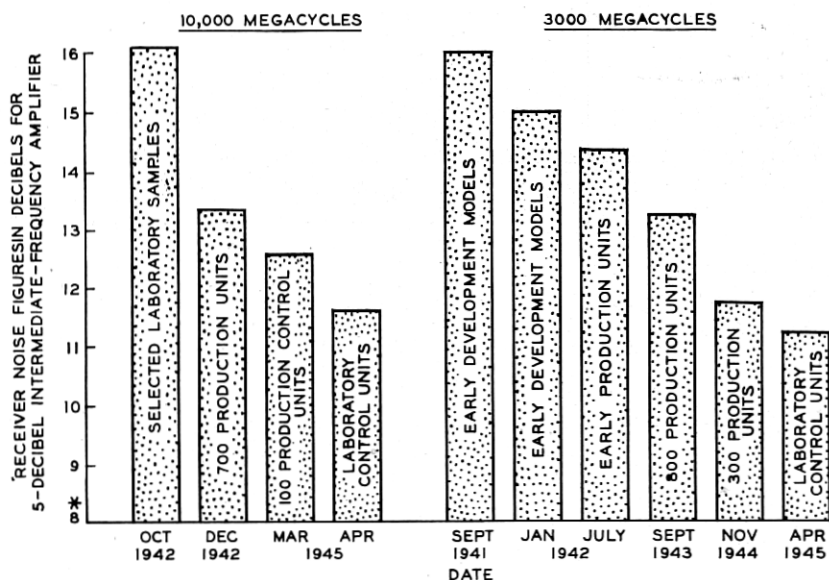


Fig. 14—Improvement in the direct-current rectification characteristics of silicon crystal rectifiers in a four-year period.



* NOTE: — 8 DECIBELS IS THE MINIMUM RECEIVER-NOISE FIGURE ATTAINABLE WITH A DOUBLE DETECTION RECEIVER EMPLOYING A CRYSTAL CONVERTER AND A 5-DB INTERMEDIATE-FREQUENCY AMPLIFIER.

Fig. 15—Effect of continued improvement in the crystal rectifier on the microwave receiver performance. The noise figures plotted are average values.

ability of the 3000-megacycle converter types made by the improved procedures and the older procedures is shown in Fig. 16.

The flexibility of the processes may be illustrated by comparison of two

very different units, the 1N26 and the 1N25. Though direct comparison of power handling ability is complicated by the fact that the burnout test methods employed in the development of the two codes were widely different, it may be stated conservatively that while the 1N26 would be damaged after absorbing something less than one watt peak pulse power, the 1N25 unit will withstand 25 watts peak or more. The 1N26 unit is, however, capable of satisfactory operation as a converter at a frequency of some 20 times that of the 1N25. These two units have been made by essentially the same procedures, the difference in properties being principally due to modification of alloy composition, heat treatment, and contact area.

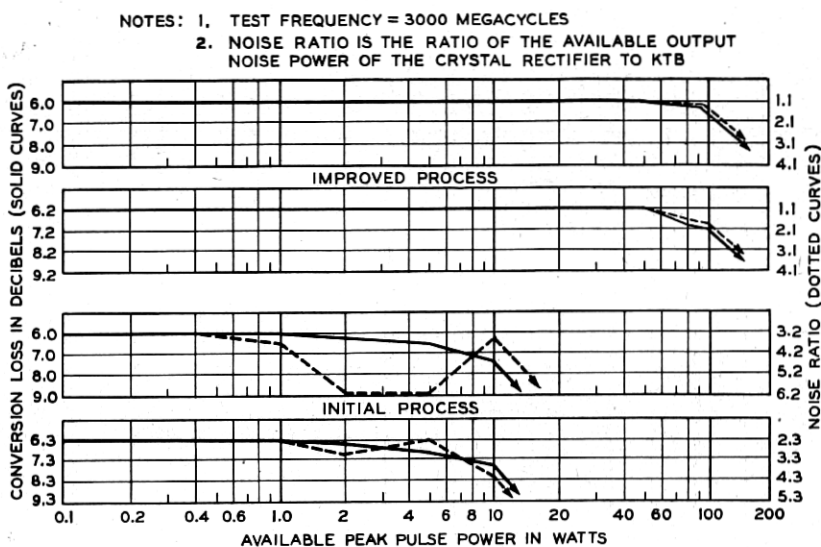


Fig. 16—Comparison of the radio frequency power handling ability of silicon crystal rectifiers prepared by different processes.

Prior to the process developments described above, in the interests of simplifying the field supply problem one general purpose unit, the type 1N21, had been made available for field use. However, it became obvious that the advantages of having but a single unit for field use could be retained only at a sacrifice in either power handling ability or high-frequency conversion loss. Since the higher power radar sets operated at the lower microwave frequencies, it seemed quite logical to employ the new processes to improve power handling ability at the lower microwave frequencies and to improve the loss and noise at the higher frequencies. A recommendation accordingly was made to the Services that different units be coded for operation at 3000 megacycles and at 10,000 megacycles. The decision in the matter was

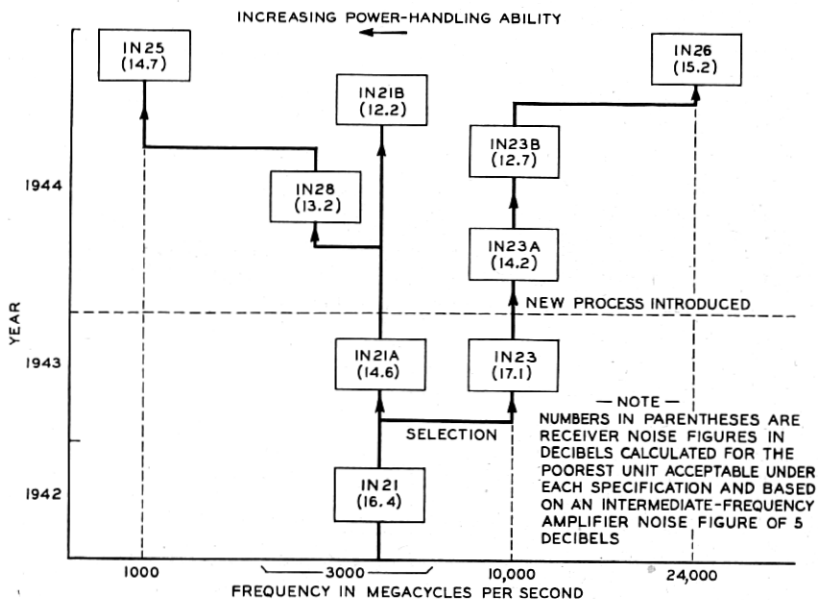


Fig. 17—Evolution of coded silicon crystal rectifiers.

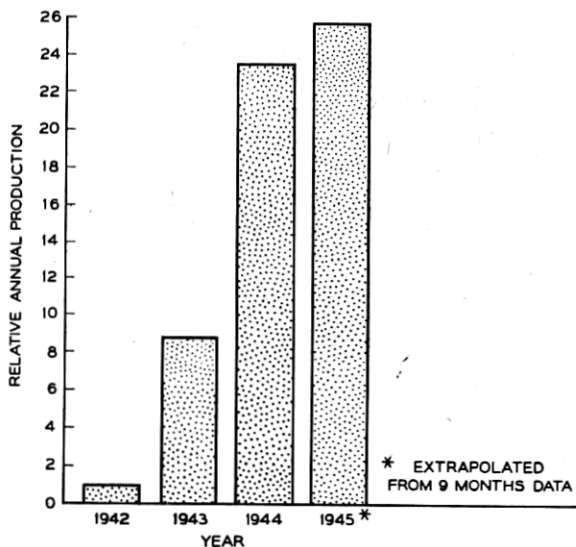


Fig. 18—Relative annual production of silicon crystal rectifiers at the Western Electric Company 1942-1945.

affirmative. The importance of this decision may be appreciated from the fact that it permitted the coding and manufacture of units such as the 1N21B and 1N28, high burnout units with improved performance at 3000

megacycles, and the 1N23B unit which was of such great importance in 10,000 megacycle radars because of its exceptionally good performance. From this stage in the development the diversification in types was quite rapid. The evolution of the coded units, of increasing power handling ability for a given performance level at a given frequency, and of better performance at a given frequency is graphically illustrated in Fig. 17. The large improvements in calculated receiver performance are again evident, especially when it is considered that the receiver performances given are for the poorest units which would pass the production test limits.

EXTENT OF MANUFACTURE AND UTILIZATION

An historical resumé of the development of crystal rectifiers would be incomplete if some description were not given of the extent of their manufacture and utilization. Commercial production of the rectifiers by Western Electric Company started in the early part of 1942 and through the war years increased very rapidly. Figure 18 shows the increase in annual production over that of the first year. By the latter part of 1944 the production rate was in excess of 50,000 units monthly. Production figures, however, reveal only a small part of the overall story of the development. The increase in production rate was achieved simultaneously with marked improvements in sensitivity, the improvements in process techniques being reflected in manufacture by the ability to deliver the higher performance units in increasing numbers.

The recent experience with the silicon rectifiers has demonstrated their utility as non-linear circuit elements at the microwave frequencies, that they may be engineered to exacting requirements of both a mechanical and electrical nature, and that they can be produced in large quantities. The deficiencies of the detector of World War I, which limited its utility and contributed to its retrogression, have now been largely eliminated. It is a reasonable expectation that the device will now find an extensive application in communications and other electrical equipment of a non-military character, at microwave as well as lower frequencies, where its sensitivity, low capacitance, freedom from aging effects, and its small size and low-power consumption may be employed advantageously.

ACKNOWLEDGEMENTS

The development of crystal rectifiers described in this paper required the cooperative effort of a number of the members of the staff of Bell Telephone Laboratories. The authors wish to acknowledge these contributions and in particular the contributions made by members of the Metallurgical group and the Holmdel Radio Laboratory with whom they were associated in the development.