High-Frequency Gallium Arsenide Point-Contact Rectifiers

By W. M. SHARPLESS

(Manuscript received September 11, 1958)

Gallium arsenide, one of the Group III–V intermetallic compounds, appears to be an excellent semiconductor for use in point-contact devices. This paper describes some recent work in which single-crystal gallium arsenide, with resistivity adjusted to fit the application, is used for point-contact rectifiers which operate efficiently as frequency converters at frequencies as high as 60 kmc, and for switching diodes which show no minority carrier storage effects for switching time of the order of 10^{-10} seconds. These devices will operate over a considerable range in temperature.

I. INTRODUCTION

Silicon and germanium semiconductor materials have been used in point-contact rectifiers for many years and numerous types of rectifiers employing these two materials are commercially available today. Technical papers too numerous to mention have been published covering the important features of these Group IV semiconductor materials.

More recently, there has been increased interest in some of the semiconductor materials generally referred to as the intermetallic compounds. These are formed by a combination of some of the Group III and Group V elements and tend to possess some of the better properties of both silicon and germanium.* Due to the higher energy gaps, higher electron mobilities and, in some cases, the lower dielectric constants of some of these III–V compounds, theoretically they should make efficient high-frequency rectifiers and should be able to operate at higher temperatures than either silicon or germanium.†

Gallium arsenide (GaAs), one of the III–V intermetallic compounds, appears to be very attractive for high-frequency point-contact rectifiers.

* A good review of the work that has been done on the Group III-V compounds appears in a recent book.[1]

† The importance of the semiconducting compounds was perhaps first discerned by H. Welker in Germany early in the 1950's.[2]

In a recent paper, Jenny[3] reports that GaAs point-contact rectifiers have operated efficiently as first detectors at frequencies as high as 6 kmc.

This paper describes some of the work on gallium arsenide point-contact rectifiers which is currently in progress at Bell Telephone Laboratories, Holmdel, N. J. By controlling the resistivity of the single-crystal gallium arsenide and by the selection of the proper point material and processing technique, rectifiers intended for either high-frequency first detectors or lower-frequency high-speed switching devices have been produced. Measurements have been made of conversion loss, output noise ratio and intermediate-frequency impedance of GaAs rectifiers operating as first detectors in the millimeter wave band (55 kmc) and in the X-band (11 kmc). High-speed switching diodes have been made which showed no carrier storage effects for switching times of the order of 10^{-10} seconds. Rectifying characteristics have been taken on test diodes over a temperature range between $-320°$ F and $+237°$ F.

II. GENERAL PROCESSING OF GaAs RECTIFIERS

Some variations in the general processing techniques have been found necessary in order to produce the several different types of rectifiers desired. There are, however, several steps in the processing that are common to all types and these will be discussed first.

It is of prime importance to obtain a good ohmic back contact to the GaAs sample. Experience at our laboratory has indicated that one of the best ways to accomplish this is to deposit a thin tin-and-nickel coating on the flat, clean back surface of the GaAs. The sample is then heated in a vacuum furnace to a temperature at which the tin will start to diffuse into the GaAs. This forms an excellent ohmic back contact to the GaAs and leaves a tough nickel external surface which may be used for subsequent soldering. Back contacts made in this way are very uniformly adherent. This becomes most important when the samples are diced into miniature squares suitable for soldering to the small supporting structures needed in very high frequency devices.

The surface of the sample which is later to be used for the point contact is finished either by grinding with M305 abrasive or by polishing to a smooth, mirror-like finish with a one-micron sapphire dust abrasive. We have found that the polished surface results in a more reproducible, lower-capacity point-contact area than any of the ground surfaces tested. In either case, just before the rectifiers are assembled, the GaAs contact surfaces are given a light chemical etch with a dilute solution of hydrofluoric and nitric acids.

An exhaustive study of all the materials which might be used for point-contact springs was not made, but, of the metals tested, our best results have been obtained with spring-tempered phosphor bronze wires. The "S" springs are welded to their supports and sharply pointed electrolytically. For very high frequency work the use of a very sharp point is desirable and the pressure applied to the contact area is kept small. For lower frequency and higher power switching applications, the strength of the springs is increased and the sharpness of the points becomes of lesser importance.

When a metal point is brought into contact with a prepared semiconductor surface, the initial rectification pattern is usually poor compared to the desired static characteristic but can be improved by further contact conditioning.* In the case of p-type silicon rectifiers, it has generally been found possible to bring about this improved rectification ratio by mechanically tapping the rectifier case. For n-type germanium rectifiers this conditioning or forming may be accomplished by applying electrical pulses directly to the rectifier terminals.

N-type GaAs responds to contact area forming in much the same way as do n-type germanium rectifiers. The forming technique consists of applying a series of fairly high-level pulses of energy to the rectifier terminals after point contact has been established. We have found that 60-cycle sine-wave pulses are quite satisfactory for this forming, and the low-frequency static characteristic may be observed on an oscilloscope while the forming is taking place. Arrangements are provided for separately controlling the magnitude of the voltage applied in either the positive or negative direction, or both voltages may be applied simultaneously. The resulting current is controlled by adjusting the value of a series resistor. A considerable amount of latitude in forming is thus provided.

III. CONTROLLED-RESISTIVITY GALLIUM ARSENIDE MATERIAL

The rectifiers described in this paper have all been made from specially doped GaAs material obtained from single-crystal ingots prepared by J. M. Whelan of Bell Telephone Laboratories at Murray Hill, N. J. Preparation of the compound and growth of single crystals by the floating zone method have been previously described.[4] In a private communication, Whelan describes the method used to prepare single crystal GaAs of controlled resistivity as follows: Zone refining was used to

* An exception is found for semiconductor materials which have had their surfaces previously conditioned by ionic bombardment. In such cases further surface conditioning is not necessary or, in general, desirable.

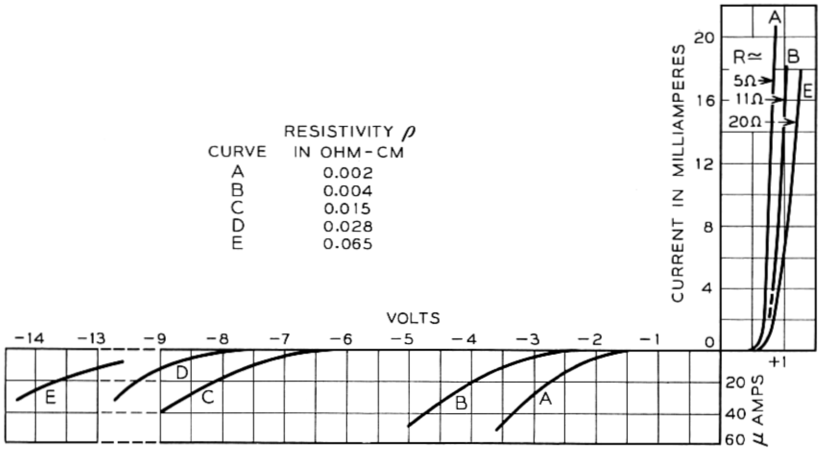

Fig. 1 — Typical static characteristics of GaAs point-contact rectifiers as a function of semiconductor resistivity.

increase the resistivity of the GaAs above that required for diodes. The purified material was then doped to the desired resistivity, 0.002 to 0.07 ohm-cm, by regrowing the crystal in an arsenic atmosphere containing one of the following donor impurities: sulphur, selenium or tellurium. Overdoping was corrected, when necessary, by subsequent floating zone passes in a "pure" arsenic atmosphere.[5]

The effect of varying the resistivity of the GaAs material used in a point-contact rectifier is shown in Fig. 1. Typical static characteristics are shown for rectifiers made from doped GaAs materials, ranging from 0.065 ohm-cm for a lightly doped sample to 0.002 ohm-cm for heavily doped material. The data presented in Fig. 1 were obtained using the same size pointed phosphor bronze springs and the same contact pressure in each case. The contact surface preparations were also the same. The forming techniques were optimized insofar as possible for each rectifier, and thus the curves show the typical static characteristics that result when rectifiers are processed using different resistivity GaAs materials. Depending on the particular application intended, the spreading resistance and other characteristics of the rectifiers may thus be varied over a considerable range by the selection of the properly doped material. Further, depending on the type of rectifier desired, the frequency characteristic and power handling capacity may be varied by controling the size of the point-contact area and the contact pressure.

3.1 *Millimeter Wave Rectifiers*

As mentioned earlier, GaAs rectifiers have been prepared for use as first detectors in both the millimeter and X-band range. Measurements have been made of conversion loss, output noise ratios and IF impedance for typical operating conditions.

GaAs rectifiers intended for operation as first detectors at millimeter waves (50 to 90 kmc) are assembled in the wafer-type millimeter wave mounting shown in Fig. 2. For very high frequency first detector rectifiers, it is important to keep the product of the barrier capacity and the spreading resistance as small as possible; thus, the lowest resistivity (ρ = 0.002 ohm-cm) material is selected for this application (see Fig. 1). A 0.001-in. diameter phosphor bronze wire spring is selected to give the low contact pressure desired and the wire is sharply pointed to give the small contact area needed. The rectifier is mechanically assembled in much the same way as are the silicon millimeter wave wafer rectifiers described in a previous paper.[6] A light contact pressure is applied by advancing the point one-half mil after contact between the polished surface of the GaAs and the phosphor bronze point has been established. A low ac voltage (4–6 volts peak) is then applied for viewing the static characteristics on an oscilloscope. Arrangements are provided for limiting the voltage and current, as mentioned earlier. Rectifiers intended for operation at millimeter waves are given no contact forming other than that which takes place when the low-voltage ac is applied through a 1000-ohm series resistor while the static characteristic is being viewed.

Table I gives the measured performance figures for the best point-contact wafer-type millimeter wave rectifiers we have made using either silicon, germanium or gallium arsenide as semiconductor materials. Conditions of operation have been optimized for the best output signal-to-noise ratio for each type of rectifier measured. Both the germanium

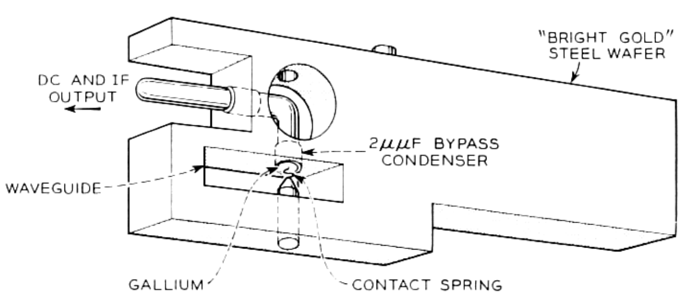

Fig. 2 — Millimeter-wave wafer unit using GaAs.

TABLE I

Rectifier Type	Semiconductor Material	Conversion Loss, db	Noise Ratio, N_R	Z_{IF}, ohms (60 mc)
Wafer	p-type silicon	6.4	1.6	260
Wafer	n-type germanium	6.6	2.0	300
Wafer	n-type gallium arsenide	5.6	2.1	325

and GaAs units were given a few tenths of a volt positive bias. Measurements were made at a frequency of 55.5 kmc using a 60-mc intermediate frequency.

From the table it can be seen that the lowest first detector conversion loss figure measured at millimeter waves was obtained using a GaAs rectifier. One would expect low conversion losses for GaAs units due to the high mobility and low spreading resistance of the basic GaAs materials used, but the actual measurement of a conversion loss below 6 db at a frequency of 55 kmc is gratifying. The noise outputs from millimeter wave rectifiers all tend to be higher than those measured for similar types of rectifiers designed for and used at longer waves. It is believed that this is at least partly due to the lighter point-contact pressures that are required in these very high frequency units. Further experience may be helpful in reducing these noise ratios.

3.2 *Microwave Rectifiers*

GaAs rectifiers intended for operation in the microwave bands have been assembled in the small low-capacity cartridge case shown in Figs. 3 and 4. These units use contact points and semiconductor wafers of approximately the same size as the millimeter wave units described

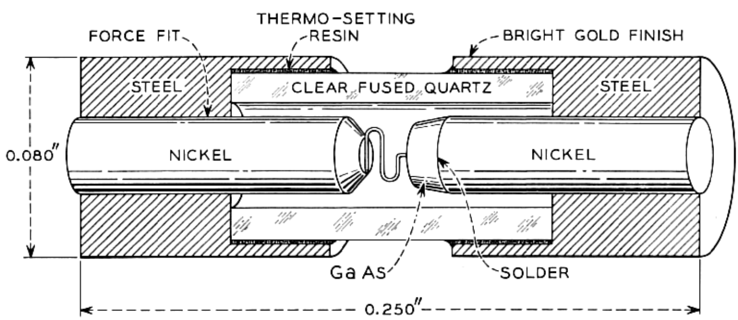

Fig. 3 — Cross section of microwave low-reactance cartridge-type GaAs rectifier holder.

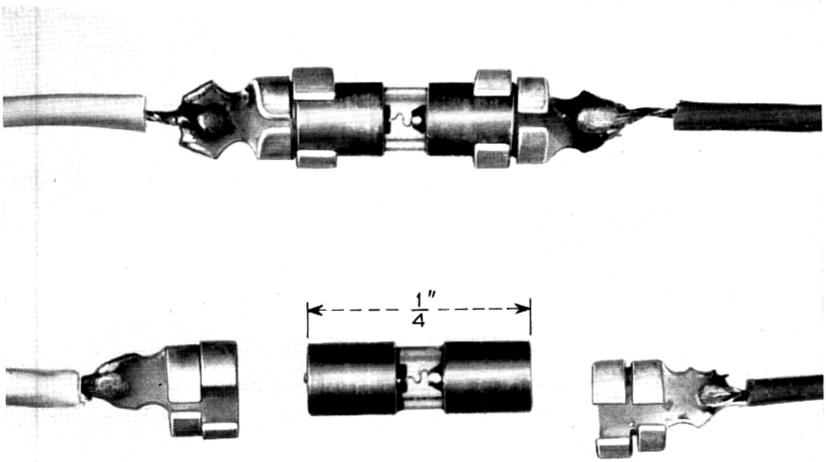

Fig. 4 — Photograph of cartridge-type GaAs rectifier holder, with pigtail leads for use at low frequencies (magnified 8 times).

above, and since the inductance and capacity of the rectifier components are very small — as they must be for millimeter waves — the unit is easily adaptable to broadband designs in the kilomegacycle range.

The cartridge rectifiers intended for operation at X-band (11 kmc) are assembled by first pressing in the GaAs detail and then the phosphor bronze point detail until contact is established. The pointed wire "S" spring, approximately 0.002 in. in diameter, is then advanced seven-tenths of a mil and the contact area lightly formed in the same manner as for the millimeter wave first detectors. GaAs material in the low resistivity range between 0.002 and 0.004 ohm-cm is used for these rectifiers.

In the microwave region, the cartridge-type rectifiers may be mounted directly in waveguides in the conventional manner. The cartridge, because of its small size, also adapts itself to special types of broadband arrangements such as those provided by coaxial lines or by ridged or stepped waveguides. Fig. 5 suggests one such possible microwave mounting arrangement, where the impedance of the regular waveguide is lowered by reducing the E-plane guide height until it presents an impedance the same as the resistive component of an average rectifier. The remaining reactance may be tuned out with a waveguide shorting section, which follows the rectifier. Since both ends of the cartridge are the same physical size, the rectifiers may be turned end for end when a change in polarity is desired.

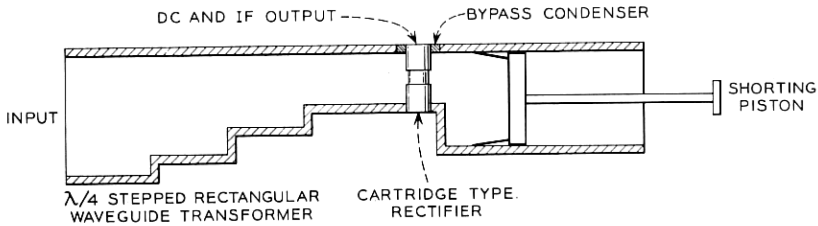

Fig. 5 — Broadband waveguide arrangement for use with cartridge-type rectifiers.

Table II gives some measured broadband first detector performance figures for several point-contact cartridge-type rectifiers that we have made using samples of our best silicon and best gallium arsenide materials. Conditions for operation were optimized insofar as possible for each group of rectifiers measured, with the GaAs units given a few tenths of a volt positive bias. Measurements were made at a frequency of 11 kmc employing a 60-mc intermediate frequency. A beating oscillator drive of one milliwatt was used in all cases.

From the table below it can be seen that the measured output noise ratios of GaAs point-contact rectifiers operating as first detectors at 11 kmc are at least as good as those for similar units employing silicon as the semiconductor material. Further, the average conversion loss of the GaAs units is at least one db better than that of the silicon group measured, which would mean that, conservatively, the over-all noise figure of an 11-kmc receiver would be improved at least one db by using GaAs in place of the silicon. If we used a GaAs first detector having the best conversion loss and noise ratio in Table II together with an IF amplifier having a noise figure of $1\frac{1}{2}$ db, the resulting over-all receiver noise figure at 11 kmc would be 6.0 db. It appears that the reproducibility of the GaAs units is good and that the variation between one unit and the next will be small; this is evidenced by the small difference between the average and best conversion loss listed in Table II.

Table II

Semiconductor Material	Number of Units	Conversion Loss, db		Noise Ratio, N_R		Range of Z_{IF}, ohms
		Average	Best	Average	Best	
p-type silicon	18	5.8	5.1	1.47	1.36	300–500
n-type gallium arsenide	8	4.2	4.0	1.35	1.20	275–580

IV. SWITCHING RECTIFIERS

GaAs rectifiers intended for high-speed switching applications are assembled in much the same way as are the microwave diodes, using the same low-capacity case shown in Fig. 4. In general, these units operate at higher power levels and at frequencies in the lower kmc region; thus a heavier contact pressure may be applied, and a 0.003-in. diameter phosphor bronze wire spring is used with a spring advance after contact of up to one and one-half mils. These units are given a more intensive ac forming by increasing the peak driving voltage to about 20 volts and reducing the value of the series current limiting resistor to 300 ohms.

GaAs material in the resistivity range from 0.02 to 0.04 ohm-cm is used for general-purpose switching rectifiers. It is obvious that, depending on the exact requirements regarding forward and reverse impedances at a given driving voltage, one might use resistivity values different from the range mentioned above. In general, the GaAs material for switching applications is selected on the basis of using the lowest resistivity material that will allow a satisfactory reverse characteristic (see Fig. 1). During the forming process, the forward resistance tends to decrease rapidly, as desired, but, at the same time, the contact area tends to increase, which is in the direction of limiting the efficiency of operation at the higher frequencies. Thus, as in all point-contact devices, several factors must be considered in the processing of the rectifiers and, in general, a compromise is adopted which will arrive at the best rectifier for a particular application. In the case of the switching rectifiers, a resistivity of about 0.03 ohm-cm is used, together with a forming technique which gives a good compromise between low capacity, low forward resistance and very high back impedance up to, say, -10 volts. Measurements made on switching rectifiers of this type show no minority carrier storage effects up to switching times of the order of 10^{-10} seconds, which is the limit of our present measuring equipment.

V. TEMPERATURE EFFECTS

Since GaAs possesses a relatively high energy gap (1.34 ev) it tends to be more suitable for stable operation at higher temperatures than are possible for either silicon or germanium. Fig. 6 is a multiple photograph of a cathode ray oscilloscope display showing the low-frequency static characteristic of a point-contact GaAs rectifier as the temperature was varied from $-320°$ F to $+237°$ F. It will be noticed that the static characteristics changed only slightly over this large temperature range, the

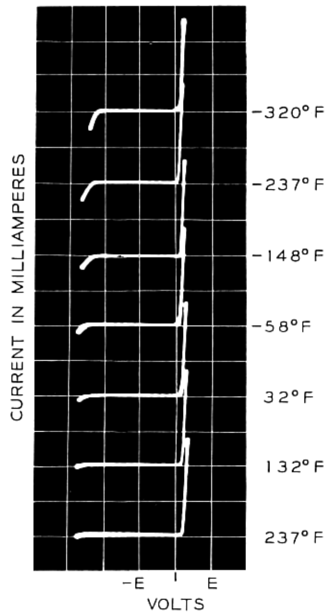

Fig. 6 — Effect of temperature variation on the static characteristic of a GaAs point-contact rectifier.

principal change being in the location of the knee of the reverse current characteristic. It is obvious that the temperature limit for good rectification was not reached at either extreme of the range covered. Experimental evidence has been published[1] which indicates that certain samples of n-type GaAs were found to show very small changes in Hall coefficient, resistivity or mobility up to a temperature near 600° F. This indicates that GaAs rectifiers would probably operate efficiently at temperatures this high if a temperature-stable mounting were provided.

Groups of GaAs point-contact rectifiers have now been in storage at room temperature in our laboratory for periods of several months. There is no evidence to date that the normal changes in relative humidity and temperature experienced in the laboratory have had any effect on the rectifying properties of the units.

VI. CONCLUDING REMARKS

It appears that gallium arsenide semiconductor devices may well enjoy a very bright future. The relative insensitivity of gallium arsenide point-contact rectifiers to rather large changes in operating temperatures will be important in many diode applications. Extensive burn-out tests were not made, but gallium arsenide rectifiers appear to possess as good burn-out properties as similar types of rectifiers made with either silicon or germanium. Efficient operation of gallium arsenide rectifiers as first detectors at frequencies extending upward into the millimeter wave band has been demonstrated. Gallium arsenide high-speed switching diodes have been made which show no carrier storage effects for switching times of the order of 10^{-10} seconds.

VII. ACKNOWLEDGMENTS

The author is greatly indebted to J. M. Whelan, who developed the process for making the single-crystal gallium arsenide and prepared all the GaAs materials used in the work described. Helpful suggestions regarding details of the processing techniques were received from R. S Ohl. Assisting in the work were E. F. Elbert and S. E. Reed.

REFERENCES

1. Cunnell, F. A. and Saker, E. W., *Progress in Semiconductors, Vol. II*, John Wiley & Sons, New York, 1957, pp. 37–65.
2. Welker, H., Z. Natur., **7a,** 1952, p. 744.
3. Jenny, D. A., A Gallium Arsenide Microwave Diode, Proc. I.R.E., **46,** April 1958, pp. 717–722.
4. Whelan, J. M. and Wheatley, G. H., J. Phys. Chem. Solids, **6,** 1958, p. 169.
5. Struthers, J. D., Whelan, J. M. and Ditzenberger, J. A., to be published.
6. Sharpless, W. M., Wafer-Type Millimeter Wave Rectifiers, B.S.T.J., **35,** November 1956, pp. 1385–1402.