Backward Diodes for Low-Level Millimeter-Wave Detection*

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Summary—Backward diodes (low peak current tunnel diodes) suitable for small-signal detection applications in the millimeter-wave region have been fabricated from *n*-type germanium. The diodes have the dimensions and geometry of point-contact diodes. For millimeter-wave signal levels below about −20 dbm, the current sensitivity of these units is an order of magnitude greater than that of selected existing diodes for this frequency range. When employed as millimeter-wave frequency converters, the minimum conversion loss is comparable to that of conventional diodes, but the beating oscillator power requirements may be somewhat reduced. The diode noise factor at megacycle IF frequencies is comparable to that of conventional units, and in the low audio IF range it is expected to be markedly decreased. The fabrication of these diodes is described and their initial performance at selected frequencies from 11 Gc to 300 Gc is discussed.

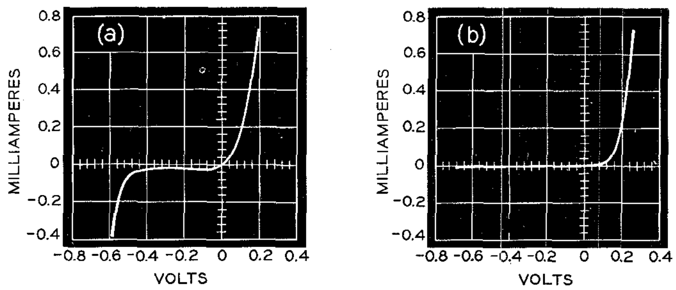

Fig. 1—Comparison of the *I-V* characteristics of (a) a germanium backward diode and (b) a silicon point-contact microwave diode. In (a), the forward current (quadrant I) is the reverse tunnel current of the normal Esaki diode; it is usually plotted in quadrant III.

TUNNEL DIODES[1] suitable for use well into the millimeter-wave region now have been fabricated on an experimental basis from a number of semiconductors.[2–5] These diodes have been made in the mechanical form of point-contact diodes, and the requisite narrow *p-n* junctions have been produced by electrically "forming" a contact between the semiconductor surface and a suitable metal point.

If the peak current of such diodes is kept very low, a few hundred microamperes or less, the shape of the *I-V* characteristic suggests that these so-called *backward diodes* might be sensitive detectors of low-level microwave signals. That this conclusion is resonable, assuming comparable junction capacitance, can be seen by comparing the characteristic of a germanium backward diode [Fig. 1(a)] with that of a conventional silicon point-contact microwave diode [Fig. 1(b)]. The forward conduction current of the backward diode[6] (*i.e.*, reverse tunnel current of the usual tunnel dide) increases more rapidly near zero voltage then does that of the conventional diodes, and thus, the backward diode can be expected to yield a larger rectified current output for a given small input voltage. However, the "reverse breakdown voltage" (*i.e.*, beginning of the tunnel diode forward injection current) is quite low and restricts the usefulness of the diode to relatively small signals. It is also apparent that the reverse current is almost never insignificant.

Eng[7] has compared the performance of germanium backward diodes and conventional diodes operating as baseband (video) current detectors and as frequency converters at 6 and 13 Gc, with particular attention to noise characteristics. Follmer[8] has carried out rather similar experiments, primarily at somewhat lower frequencies. In general, backward diodes of germanium were found to be superior low-level baseband current detectors, to require less local oscillator drive than conventional diodes when used as mixers, to at least equal the noise performance of conventional mixer diodes at megacycle IF frequencies, and to offer markedly lower noise output in the audio IF range.

This paper describes the fabrication and initial microwave performance of backward diodes suitable for use in the millimeter-wave region.

Diode Fabrication

Although backward diodes can be made from a number of semiconductors, two factors favored the initial

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[1] L. Esaki, "New phenomenon in narrow germanium *p-n* junctions," *Phys. Rev.*, vol. 109, pp. 602–603; June, 1958.

[2] C. A. Burrus, "Gallium arsenide Esaki diodes for high frequency applications," *J. Appl. Phys.*, vol. 32, pp. 1031–1036; June, 1961.

[3] C. A. Burrus, "Gallium antimonide Esaki diodes for high frequency applications," PROC. IRE (*Correspondence*), vol. 49, p. 1101; June, 1961.

[4] C. A. Burrus, "Germanium and silicon high frequency Esaki diodes," PROC. IRE (*Correspondence*), vol. 50, pp. 1689–1690; July, 1962.

[5] C. A. Burrus, "Indium phosphide Esaki diodes," *Solid-State Electronics*, vol. 5, pp. 357–358; September/October, 1962.

[6] In this work a tunnel diode is called a backward diode, regardless of its peak current value, if it is working as a positive resistance device in such a way that the reverse tunnel current provides the forward, or lower impedance, diode conduction. The term Esaki diode would be used to denote the usual tunnel diode operated in such a way as to make use of its negative resistance characteristics. Note that, for many values of i_p, the diodes may be physically identical.

[7] S. T. Eng, "Low noise properties of microwave backward diodes," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-9, pp. 419–423; September, 1961.

[8] W. C. Follmer, "Low frequency noise in backward diodes," PROC. IRE (*Correspondence*), vol. 49, pp. 1939–1940; December, 1961.

use of n-type germanium for the millimeter-wave diode application. First, the forward conduction current (reverse tunnel current) of germanium backward diodes increases more rapidly at small applied voltages than does that of similar diodes made of gallium arsenide or silicon, for example; second, the formation of tunnel junctions approximating the dimensions of pont-contact units was a relatively simple and reproducible operation with this material. Since, for high-frequency diodes, minimum junction capacitance (and, therefore, maximum current densities) was desired, the selected germanium was the most heavily doped n-type material available in some quantity; it contained 7–7.5×10^{19} arsenic atoms/cc ($\rho=0.00056$ ohm-cm), and was supplied by Trumbore.[9]

Normally, gallium was employed as the acceptor source for the junction. Since this metal is brittle at room temperature and liquid a little above room temperature, it was electroplated onto points of other materials.[4,10] The narrow p-n junction was formed by application of a current pulse, in the reverse normal diode direction, to a contact between the gallium plated point and the n-type semiconductor surface. A consistently successful junction-forming (alloying) process was as follows.[4] A very light mechanical contact was established between the appropriate metal point and the chemically etched (111) germanium surface. A suitable contact was indicated when the 60-cps diode curve tracer, having a 1000-ohm current-sensing resistor, showed an I-V characteristic similar to that of Fig. 2(a). The 60-cps voltage was then increased until first the characteristic of Fig. 2(b) then that of Fig. 2(c), was observed. Next, a succession of 10–15 microsecond pulses was applied, one at a time, beginning at a low voltage (1–1.5 volt) where no alloying occurred. The amplitude of each succeeding pulse was increased by 0.1 to 0.2 volt until a backward diode characteristic with a readily discernible negative resistance region began to develop, Fig. 2(d). Further applications of this pulse, or one of greater amplitude and/or duration, resulted in an increased value of the diode peak current [Figs. 2(e)–2(g)]. The pulse generator had an internal impedance of 5–10 ohms.

Pulse alloying seldom was successful unless the characteristics of Figs. 2(a)–2(c) had been achieved. Failure to obtain the characteristic of Fig. 2(a) upon initial contact normally appeared to indicate dirty surfaces or excessive contact pressure, and failure to achieve the characteristics of Figs. 2(b) and 2(c) by ac forming was most often traced to excessive contact pressure. With a sufficiently low contact pressure and clean surfaces, it was relatively simple to produce, in this way, diodes with values of peak current predetermined and reproducible to less than 10 per cent. No etching of the junctions has been attempted.

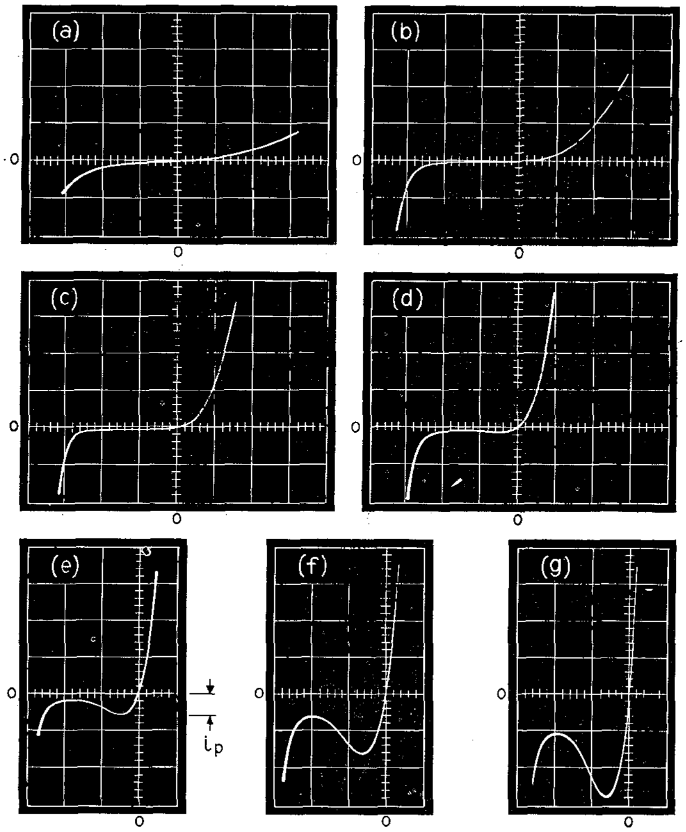

Fig. 2—I-V characteristics of typical backward diodes made by electrically "forming" a gallium point contact on n-type germanium. (a) Initial contact, no intentional forming. (b)–(c) AC forming. (d)–(g) Pulse forming. Scale: 0.2 volt/cm horizontal, 0.2 ma/cm vertical.

By increasing the pulse power, use of germanium with lower donor concentrations, 4–5×10^{19}/cc, has resulted in diodes with good dc characteristics. Excellent dc characteristics have also been obtained quite readily, without increasing the pulse power, by substituting aluminum for gallium as a point acceptor source. However, the millimeter-wave performance of these units has not equalled that of diodes made by forming gallium point contacts on the more heavily doped germanium, and it is inferred that this latter combination has yielded diodes with the largest peak current densities. In general, any change in fabrication techniques which could reasonably be expected to lower the diode current density (raise the junction capacitance), degraded the millimeter-wave sensitivity of the final diodes.

The junction capacitance at the I-V curve valley and the spreading resistance of one presumably typical diode, fabricated as described earlier, have been measured at 55 Gc. The values were 0.038 pf and 7.3 ohms, respectively,[11] for a 0.14-ma peak current diode. This result implies that the capacitance of diodes having peak

[9] F. A. Trumbore, W. G. Spitzer, R. A. Logan and C. L. Luke, "Solid solubilities of antimony, arsenic and bismuth in germanium from a saturation diffusion experiment," *J. Electrochem. Soc.*, vol. 109, pp. 734–738; August, 1962.

[10] C. A. Burrus, "High frequency silicon varactor diodes," *J. Appl. Phys.*, vol. 32, pp. 1166–1167; June, 1961.

[11] B. C. DeLoach, "A New Microwave Measurement Technique to Characterize Diodes, and an 800 Gc Cut-Off Frequency Varactor Diode at Zero Volts Bias," presented at Nat'l Symp. on Microwave Theory and Techniques, Santa Monica, Calif.; May 20–22, 1963.

currents of 0.04 ma and less did not exceed 0.01 pf at the valley, and was somewhat less at the low-level operating point of the diodes.[12]

Diodes for microwave evaluation have been fabricated in various existing holders designed for use with silicon point-contact units in the frequency range of interest, and the physical dimensions of the crystal dicings, spring contact probes, etc., were determined in each case by the particular holder design. In general, the point probes have been made from fine wires 0.5 to 1 mil in diameter or thin foil tapes about 0.2×3 mils in cross section,[14] usually copper with gallium-plated points. Where necessary for mechanical stability, the points have been set in a thin layer of an epoxy resin[2] whose presence, at least in the small quantities required, has not increased the microwave loss by a measurable amount.

Diode Performance

Baseband Detection

One class of microwave detection involves the use of a diode as a simple rectifier, either 1) to reduce a CW microwave signal to a rectified dc current or voltage, or 2) to remove the modulated signal from an amplitude modulated microwave carrier. The first application often consists of a diode connected to a dc meter or dc amplifier to monitor microwave power; the second, depending upon the specific circumstances, has been called baseband detection, single detection, second detection, video detection, envelope detection, etc. We have included all such rectifier uses, 1) and 2), under the term *baseband detection.*

The minimum signal recorded as detected was that peak power, from a 100-cps square-wave modulated klystron, which resulted in a detected signal twice the noise level as viewed on an oscilloscope. This power level, determined by a somewhat subjective observation with the aid of a high impedance, high gain broadband amplifier, has been referred to as the tangential signal,[15] or as the tangential signal sensitivity (TSS) of a detector. It is a useful measure of detector sensitivity if the amplifier characteristics are known. The amplifier employed in this work was a Tektronix-type 122 preamplifier having a 10-megohm input resistance and a frequency range of 0.2 cps to 40 kc. The amplifier, while not a particularly low noise device, did allow some qualitative observation of diode noise, at least in the conventional diodes. We have designated the tangential signal sensitivity of a diode measured with this amplifier at its full bandwidth as TSS(10 megohm). However, we have stretched the definition to include the same minimum recorded signal for a diode shunted by a 50-ohm resistor, and have noted the "tangential signal sensitivity" for this case as TSS(50 ohm). Here the output noise level was determined at all times by the amplifier; thus the observed TSS(50 ohm) for all the diodes would be improved if a lower noise amplifier were employed. Note that the measured values quoted here were for a signal modulated at an audio rate and viewed against a background of noise extending essentially to dc; and that different numbers would have been obtained, for example, with a short-pulse modulated signal viewed against noise having a low-frequency cutoff in the megacycle region (a common radar case), or for a small decremental signal superimposed on a relatively large, constant received-power level (a common situation in observing microwave resonance phenomena).

Microwave power measurements were made with precision rotary-vane attenuators in conjunction with a 1-mw power level. In the millimeter-wave region, this power level was set by diodes calibrated against Sharpless' secondary standards,[16] at 11 Gc the 1-mw level was set by a Hewlett-Packard power meter. Diodes under test were matched for maximum rectified output, and, although reflections from the diodes were not monitored continuously, all indications were that a good impedance match was readily attained.

Baseband Detection—55 Gc: Diodes intended for use in the 5–6 millimeter-wave region were incorporated in wafer holders designed by Sharpless.[13] The performance of these diodes working as baseband detectors was measured at 55 Gc under three dc load impedance conditions (a few ohms, 50 ohms, megohms) and compared, under similar conditions of operation, with the performance of the *best available* conventional diodes. These conventional diodes were selected examples of the millimeter-wave silicon point-contact units originally developed by Sharpless;[13] they were grouped into two reference samples of about 10 diodes each. One sample contained diodes which delivered the largest rectified current into a low impedance load, and its composite performance served as a comparison "standard" for diodes working as current detectors. The second sample, composed of the best voltage detectors, was used in a similar way with megohm load impedances. It is to be noted that the composite plots of dc output vs microwave input of the various reference samples (Figs. 3–7) are not made up, necessarily, of parallel curves; very frequently the most sensitive low-level detectors were relatively poorer at the 1-mw input level.

Low Impedance Diode Load: Net rectified current through a 50-ohm resistive load is plotted as a function of microwave input power in Fig. 3. Curves for several representative values of diode peak current are shown. In general, maximum small signal current sensitivity, TSS(50 ohm) $= -44$ to -46 dbm, has been obtained

[12] For comparison, the average zero-bias junction capacitance of the 55 Gc silicon point-contact reference diodes was 0.04–0.05 pf.[13]

[13] W. M. Sharpless, "Wafer-type millimeter wave rectifiers," *Bell Sys. Tech. J.*, vol. 35, pp. 1385–1402; November, 1956.

[14] First suggested to us by R. F. Trambarulo.

[15] C. G. Montgomery, Ed., "Technique of Microwave Measurements," McGraw-Hill Book Co., New York, N. Y., pp. 228–230; 1947.

[16] Calibrated, in turn, against a calorimeter. W. M. Sharpless, "A calorimeter for power measurements at millimeter wavelengths," IRE Trans. on Microwave Theory and Techniques, vol. MTT-2, pp. 45–47; September, 1954.

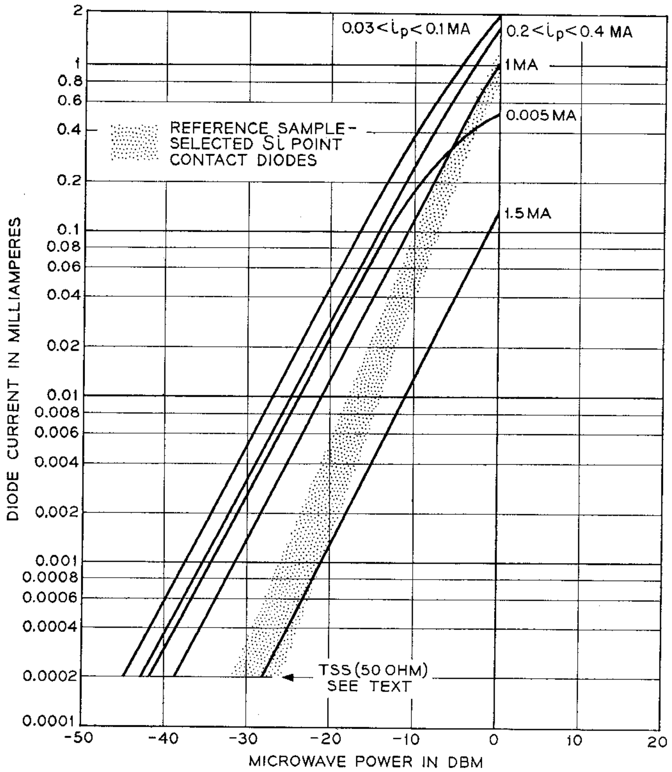

Fig. 3—Backward diode dc current vs 55-Gc (5.4 mm) microwave power. Diode load=50 ohms, amplifier bandwidth=40 kc.

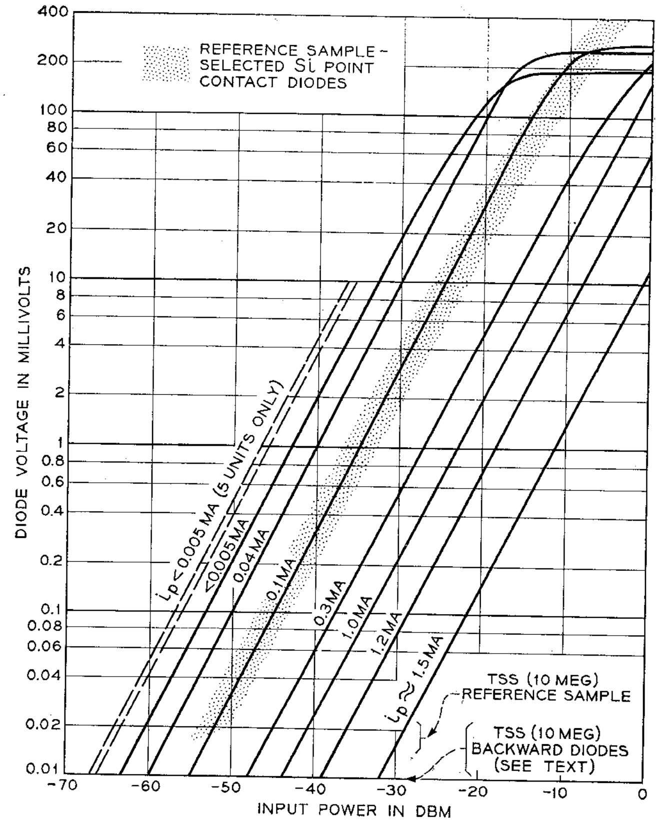

Fig. 5—Backward diode dc voltage vs 55-Gc microwave power. Diode load=10 megohms, amplifier bandwidth=40 kc.

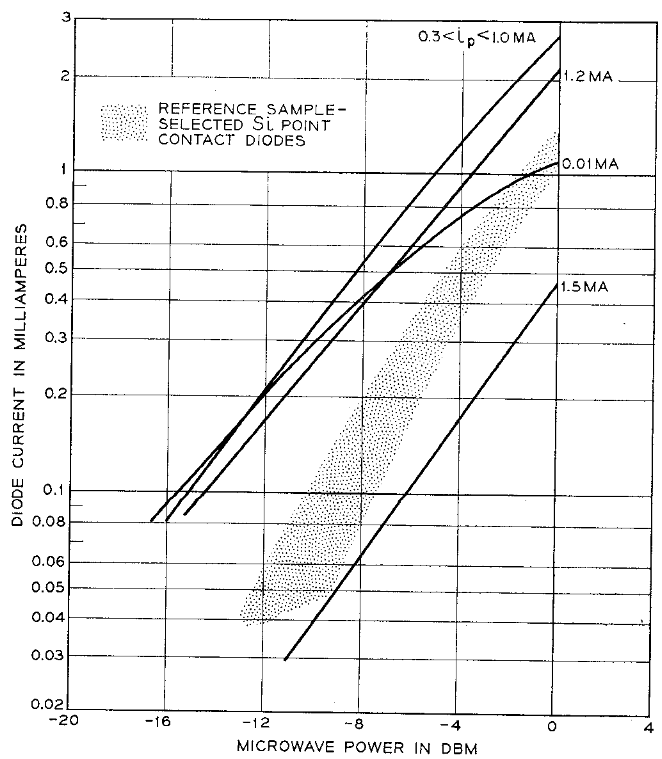

Fig. 4—Backward diode dc current vs 55-Gc microwave power. Diode load=5 ohm meter.

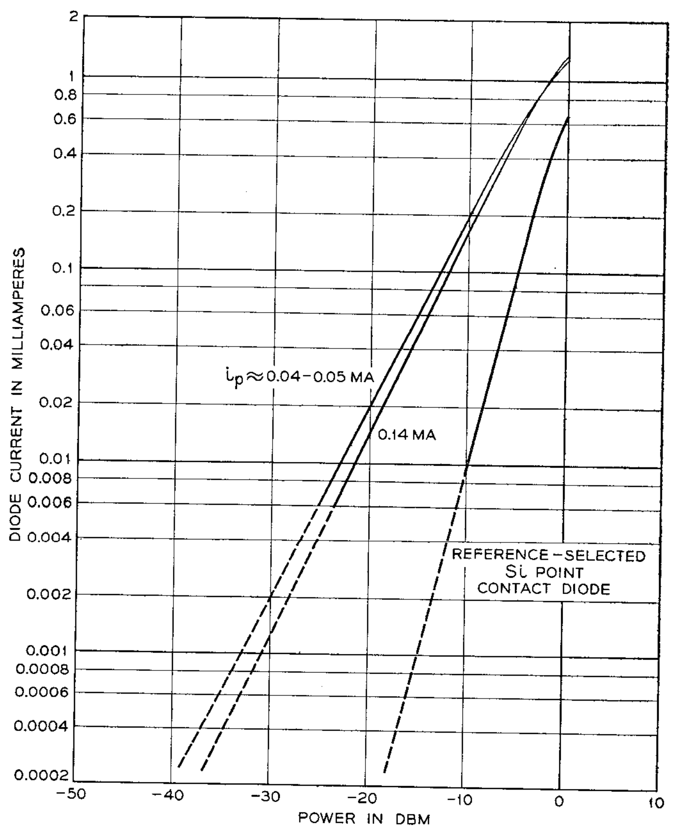

Fig. 6—Backward diode dc voltage vs 115-Gc (2.6-mm wavelength) microwave power. Diode load=50 ohms, amplifier bandwidth =40 kc.

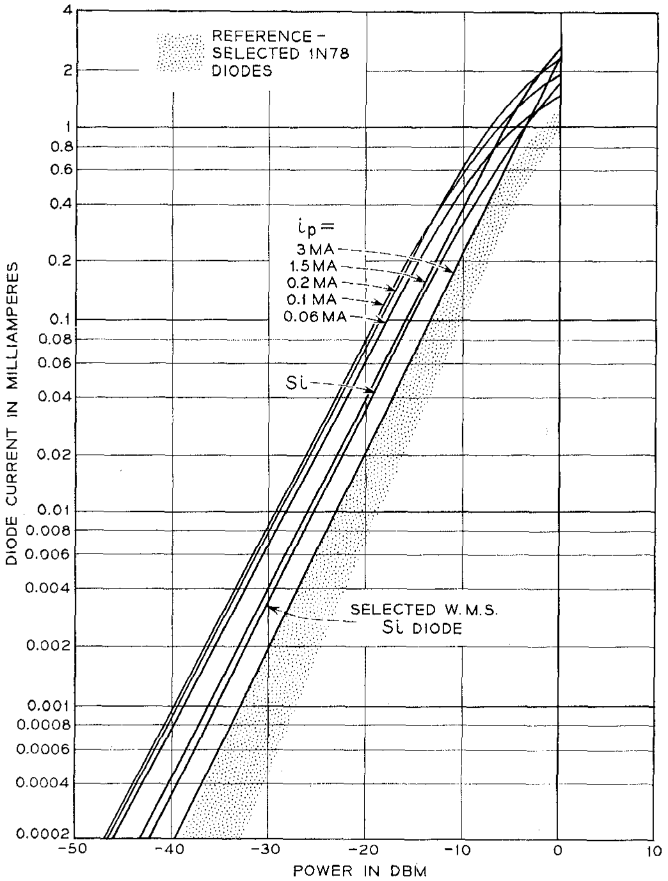

Fig. 7—Backward diode current vs 11.2-Gc (2.7-cm wavelength) microwave power. Diode load = 50 ohms, amplifier bandwidth = 40 kc.

with backward diodes having peak currents from about 0.03 to 0.1 ma. Diodes with peak currents substantially above or below this value tended to exhibit somewhat decreased values of TSS(50 ohm), although the diode peak current could be raised well above 1 ma before TSS(50 ohm) fell into the range typical of the reference sample, -24 to -32 dbm. Within the range $0.01 \lesssim i_p \lesssim 1$ ma, the rectified current at 1-mw input power was at least comparable to that from the reference sample. Any group of backward diodes made on the same sample of germanium and having nominally identical values of peak current could be expected to exhibit a spread of less than ± 1 dbm in TSS(50 ohm), and to deliver dc current at 1-mw input power not less than 85 per cent of the maximum observed for the group. Also of interest was the consistently uniform square-law behavior at the lower power levels.

Fig. 4 compares rectified current as read by a low resistance (5 ohm) meter for a rather similar set of diodes. It is seen that the low impedance meter required a somewhat lower impedance diode ($i_p \approx 0.3$ to 1 ma) for optimum milliampere-to-milliwatt ratios; otherwise, the results were substantially those of the 50-ohm case.

High Impedance Diode Load: The high impedance base-band voltage detection results are illustrated in Fig. 5, where diode voltage vs input power is plotted for representative diodes. Since microwave diodes operating into high resistance baseband loads are always mismatched, or matched through lossy transformations, the net output voltage is sensitive not only to the junction parameters but also to variations in the mechanical structure. The detection sensitivity of individual diodes thus showed somewhat larger deviations from the average than did diodes with 50-ohm loads. While it has been possible to make backward diodes with measured TSS(10 megohm) of -58 to -63 dbm with reasonable reproducibility by minimum ac forming [Fig. 2(b)], in only a few units has a measured TSS(10 megohm) significantly higher been achieved. These figures are to be compared with a TSS(10 megohm) of -50 to -57 dbm for the reference sample. However, it is pointed out again that the signal display system appeared to be limited consistently by diode noise only with the conventional units, and that noise from the backward diodes usually was not discernible. Thus the minimum observed sensitivity of the backward diodes presumably would be improved by use of a lower noise amplifier, while that of the conventional units probably would not.

Also, it should be noted that by reducing the contact pressure, and, therefore, the junction capacitance, the low-level high impedance sensitivity of millimeter-wave silicon point-contact diodes can be increased at some expense in low-frequency noise. In cases where gross mechanical instability can be tolerated (as, for example, in certain microwave spectrometers where the point contact can be readjusted frequently)[17] a substantial gain in sensitivity, perhaps approaching 10 db, can sometimes be realized. The advantage of the backward diode would seem to be that neither stability nor noise performance appears to be significantly degraded by lowering the peak current to obtain high impedance units.

Baseband Detection—Higher Frequencies: Rectified current as a function of 115-Gc microwave power is shown in Fig. 6.[18] Background pickup in the system, not involving the diodes themselves, limited the minimum recorded signal to about 0.005 ma, and thus, the curve has been extrapolated to lower values for comparison with Fig. 3.

Work at frequencies significantly higher than 100 Gc has been limited by the available components, and the results were not conclusive. Some indication of the backward diode performance near 1-mm wavelength, relative to silicon point-contact units, has been obtained from baseband detection of the output of a harmonic generator[19] driven by a 25-Gc klystron. At 300 Gc, the TSS(10 megohm) of the best backward diodes was esti-

[17] W. C. King and W. Gordy, "One-to-two millimeter wave spectroscopy. IV. Experimental methods and results for OCS, CH_3F, and H_2O," *Phys. Rev.*, vol. 93, pp. 407–412; February, 1954.

[18] Measurements by W. M. Sharpless.

[19] R. S. Ohl, P. P. Budenstein, and C. A. Burrus, "Improved diode for the harmonic generation of millimeter and submillimeter waves," *Rev. Sci. Instr.*, vol. 30, pp. 765–774; September, 1959.

mated to be about 3 db worse than the best silicon point-contact unit, with all diodes fabricated in a 10×50-mil waveguide.[17,19] At 200 Gc, where sufficient power was available for the measurement, the backward diode TSS(50 ohm) was approximately 5 to 10 db better than that of the best silicon diode.

Baseband Detection—11 Gc: Diodes for evaluation at 11 Gc were mounted in a quartz cartridge package.[20] For comparison, all available silicon point-contact diodes in this package (9 units)[20] and a sample of Sylvania and Microwave Associates type 1N78 units (about 50 diodes) were measured. Fig. 7 summarizes the results for a 50-ohm diode load. The effects of junction capacitance on the performance of high-frequency diodes is illustrated nicely by comparing the sensitivity of the higher peak current diodes at 11 Gc, shown in this figure, with that of similar diodes at 55 Gc (Fig. 3).

The measured TSS(10 megohm) of the single best silicon diode made by Sharpless,[20] type 1N78 diode and backward diode was about −64, −62, and −63 dbm, respectively. These small differences were fairly representative of the relative values obtained with high impedance loads at 11 Gc for the entire samples.

Frequency Conversion

Fairly extensive measurements of the power loss incurred in converting from 59 Gc to 11 Gc, using wafer-mounted germanium backward diodes in a converter circuit designed for silicon point-contact diodes, have been made.[21] The results, in general agreement with those of Eng at 13 Gc,[7] are indicated in Fig. 8, which shows the measured conversion loss, 59 Gc to 11 Gc, as a function of 48-Gc beating oscillator (BO) power for two backward diodes having different values of peak current with no dc bias, and for a selected silicon point-contact diode with and without added bias. The effect of an added bias on the conversion loss of the backward diodes is not shown in the figure; however, a dc bias sufficient to raise the total backward diode current to 150–200 per cent of the rectified current due to the applied BO power was found to decrease the conversion loss by an amount approaching 2 db in some cases. The bias was most effective when applied to the higher impedance, lower peak current (<0.1 ma) diodes, and was usually of no value for higher peak current (>0.2 ma) units. The bias appeared to act as an impedance matching device, lowering the diode impedance to match the existing microwave circuits.

The 55 Gc to 60 Mc conversion loss of about 25 backward diodes having peak currents from 0.3 to 1 ma also has been measured.[22] The lowest observed conversion loss was 6.7–6.8 db, comparable to the losses reported for

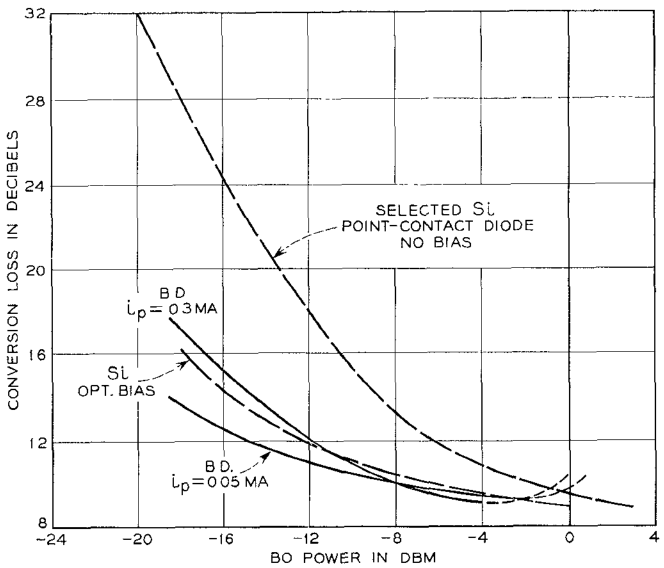

Fig. 8—Conversion loss vs beating oscillator power; $f_{sig}=59$ Gc, $f_{bo}=47.8$ Gc, $f_{if}=11.2$ Gc, $\text{Power}_{sig}=-35$ dbm. (Data by courtesy of R. C. Shaw.)

the best silicon point-contact diodes.[13,23]

At 115 Gc, where only 0.6-mw BO power was available at the diode, the loss in converting to 60 Mc was found to be comparable to that of silicon point-contract units when optimum bias was applied to both diodes.[24]

Noise

The noise output of the germanium backward diodes has been compared at 11 Gc and at 60 Mc with that of conventional silicon diodes.[25] It was observed, in general agreement with Eng,[7] that at high frequencies the noise factor of the unbiased backward diodes and that of the conventional diodes were quite comparable, with perhaps a small difference in favor of the backward diode. A comparison of the noise factor for the two types of diodes at various BO power levels, but with dc bias for optimum conversion efficiency, has not been made.

Noise measurements at low frequencies have not yet been made directly. However, it is expected[7,8] that the audio frequency noise should be at least several db below that of conventional diodes.

Acknowledgment

Several persons in these Laboratories (noted in the text and references) have supplied materials, made measurements for us, or allowed us to quote results of measurements on diodes supplied by us for their own work. We are grateful for their assistance. We also are grateful to D. H. Ring and S. E. Miller for encouraging this investigation, and to C. F. Chapman for assistance in the diode fabrication.

[20] W. M. Sharpless, "High-frequency gallium arsenide point-contact rectifiers," *Bell Sys. Tech. J.*, vol. 38, pp. 259–270; January, 1959.

[21] R. C. Shaw, unpublished work.

[22] B. R. Cheo, unpublished work.

[23] In general, biased gallium-arsenide varactor diodes with point-contact geometry, used as resistance devices, can be expected to show values of conversion loss about 1 db below that for the silicon units at 1-mw BO power.[20]

[24] W. M. Sharpless, unpublished work.

[25] R. C. Shaw, B. C. DeLoach, and B. R. Cheo, unpublished work.