Millimeter-Wave Semiconductor Devices

N. B. KRAMER, MEMBER, IEEE

Invited Paper

***Abstract*—Special techniques used in the construction of various types of millimeter-wave diodes are presented. The performance of millimeter Gunn and IMPATT devices is reviewed and other factors influencing the application of these diodes are discussed. The performance and characteristics of small-area diodes used for millimeter-wave modulation, mixing, and detection are also reviewed. Several shortcomings in the present design and application of millimeter diodes are pointed out with suggestions for further work.**

INTRODUCTION

THE KEY to the recently increased use of millimeter waves is improved semiconductor device technology for signal generation, modulation, and detection. Progress has been made in many areas: basic device physics, semiconductor materials, processing technology, packaging and circuit mounting techniques. New devices, components, and circuitry at millimeter frequencies have usually come about as an extension of techniques proven at lower microwave frequencies. In many cases this "frequency scaling" is straightforward; in other cases important modifications or new techniques are required. This paper will cover some of the special techniques used in the construction and application of millimeter-wave diodes. Active diode characteristics important for applications will be discussed: power, efficiency, reliability, impedance, pulsed behavior, tuning, and noise. Performance of various passive diodes will also be reviewed and summarized.

DIODE MOUNTING

The importance of technological progress in handling, mounting, connecting, and protecting the semiconductor chip is often overlooked. At UHF through *Ku* band (microwave frequencies) diodes are bonded directly into the microwave circuit in chip form and connected with ribbon leads or are similarly mounted in sealed metal–ceramic packages. Because of the advancements made in mounting/packaging techniques, the mount/package will not usually be a limitation to performance at microwave frequencies except for broad-band circuit designs. However, at millimeter wavelengths (30 GHz and upward) the mounting parasitics usually are a limitation even in narrow-band circuits, and it is often useful to be able to tailor the mount/package design to achieve the desired performance. Moreover, to be able to adequately limit and control the parasitics, it is necessary to work within inconveniently small volumes.

Manuscript received February 26, 1976; revised May 4, 1976.
The author is with the Electron Dynamics Division, Hughes Aircraft Company, Torrance, CA 90509.

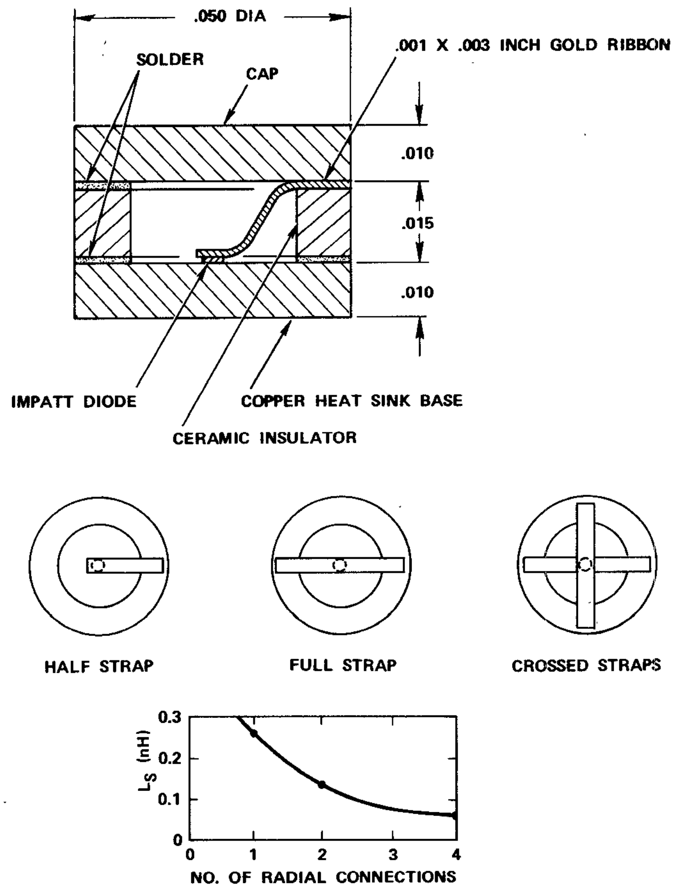

Fig. 1. Package used for 30–50-GHz IMPATT, p-i-n, and varactor diodes showing alternative ribbon connections for the purpose of varying series inductance. Dimensions are in inches.

It is often stated that an optimum package design has minimum parasitics. This is not altogether true. It is desirable to minimize resistive loss associated with the chip and its mounting connections, and it is also desirable to minimize capacitance that shunts the chip in order to reduce circulating RF currents that are dissipated in the resistive parasitics. However, the inductance of the connecting lead often has a nonminimum optimum value. As an example, see Kerr's analysis [1] of the classic Sharpless wafer diode mount [2]. As another example, half, full, and crossed strapped samples (see Fig. 1) are made up from a lot of IMPATT diodes for evaluation in a standard cavity design [3] to meet specific oscillator or amplifier requirements; in many cases a package with larger inductance provides superior performance to that obtainable by means of cavity alterations and tuning adjustments using a lower inductance package.

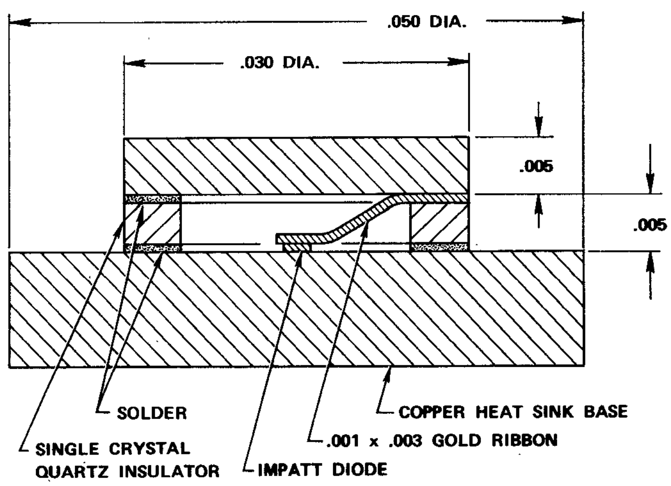

Fig. 2. Package for 50–100-GHz IMPATT diodes. Dimensions are in inches.

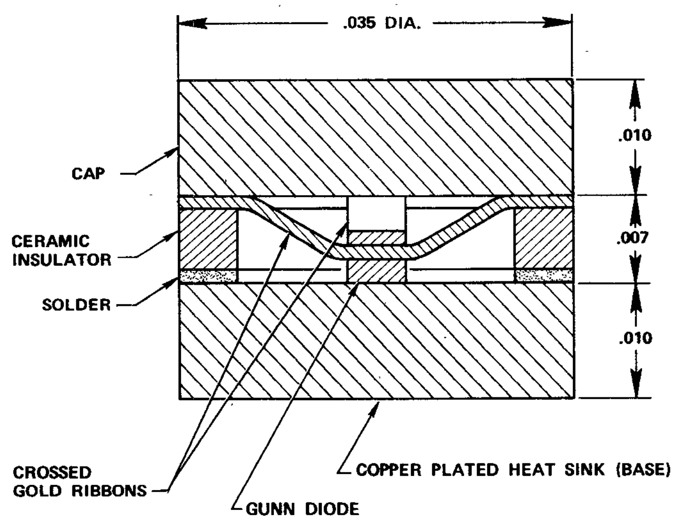

Fig. 3. Package for millimeter-wave Gunn diodes. Dimensions are in inches.

In summary, a package should be designed to have a shunt capacitance value that is a small fraction of the operating diode capacitance and to have means for varying the inductance of the connecting lead(s) prior to assembly.

Packages for Diodes Requiring Power Dissipation

For diodes in which dc or RF power must be dissipated, a mounting scheme is required that provides adequate heat removal and that also has the necessary mechanical strength to withstand thermal expansion and contraction. The package of Fig. 1 has these features but has a shunt capacitance value that limits diode performance above 50 GHz. At frequencies above 50 GHz further package miniaturization is used to reduce parasitic shunt capacitance and to allow a lower range of inductance values. A smaller package that has proven useful for IMPATT diodes from 50 to 100 GHz is shown in Fig. 2. The insulating rings are ultrasonically cut from a single crystal quartz plate. The quartz crystal can be oriented to closely match the thermal expansion characteristics of the copper package base. The low dielectric constant of quartz contributes to the reduced shunt capacitance of this package.

The miniature ceramic–metal package shown in Fig. 3 has been used with good results for 30–40-GHz Gunn diodes [4]. A similar package has been successfully used for Gunn diodes from 20 to 95 GHz [5]–[7].

For frequencies in the neighborhood of 100 GHz and upward the shunt capacitance of any type of ring insulator becomes intolerable. One approach is to use quartz standoffs [8] as shown in Fig. 4. This type of diode mounting arrangement has been used for IMPATT devices from 50 to 170 GHz [3], [10]. At the higher frequencies the position and geometry of the standoff and the connecting ribbon are critical factors in circuit performance. With the single standoff mount the parasitic shunt capacitance can be reduced to the neighborhood of 0.01 pF which is sufficiently low for satisfactory performance at 200 GHz. However, the optimum value for the inductance of the connecting strap may be smaller than can be achieved [10]. Standoffs

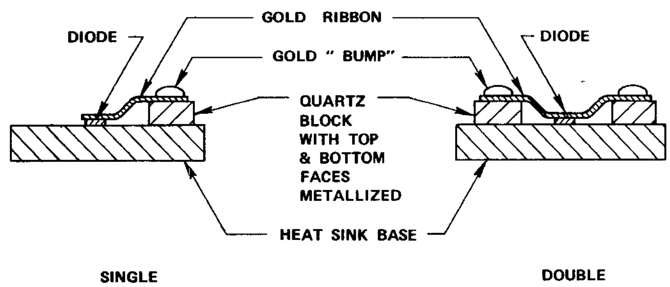

Fig. 4. Millimeter-wave diodes with standoffs.

have also been used for paramp varactors that are pumped at millimeter frequencies [11].

Diamond, with low impurity content, has a thermal conductivity value several times larger than that of copper, making it useful as a diode heat-sink material [34]. Encapsulated millimeter-wave IMPATT diodes with integral diamond heat sinks are now capable of producing roughly twice the power and efficiency of similar IMPATT diodes with copper heat sinks when operated at the same junction temperature [35]. The cost of material and added complexity in package construction will limit the use of diamond heat sinks, but it is a proven technique with a clear performance advantage.

Whisker Contacts

Whisker-contacted diodes have been used throughout the history of microwaves and millimeter waves. The whisker contact offers the best possible geometry for minimum fringing capacitance. For this reason it is widely used for millimeter-wave diodes that are not required to dissipate much power. Its principal drawback is the mechanical difficulty involved in assembling such a diode into an RF circuit. Sharpless [2] devised a wafer mount which provides easy diode interchangeability and thereby removed the principal disadvantage of the whiskered diode. Today, the wafer-type mount is used extensively for mixer and detector diodes designed for operation at the higher

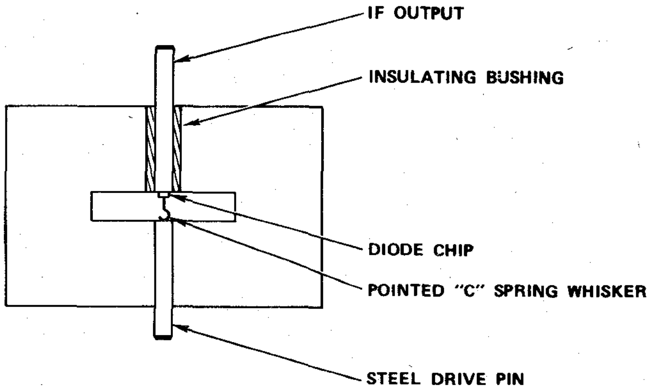

Fig. 5. Wafer package.

millimeter-wave frequencies. All types of wafer packages take the form of a reduced height waveguide section as depicted in Fig. 5. Usually, two posts are inserted from opposite sides, one has the pointed whisker attached, the other has the diode chip bonded to it. Instead of a simple post, often a filter structure is used on one side and provides the IF output connection. Coaxial [30] and stripline [31] filter structures have been used successfully.

The principal problem associated with the Sharpless wafer scheme remains the whisker-contacting procedure. For many applications, such as satellite-borne radiometers, a high degree of certainty must be established that a mechanically sound contact has been made. Precision contacting can be done using a scanning electron microscope (SEM) [36]. The wafer is mounted in a micrometer-controlled three-dimensional stage that can also be tilted. A fine wire probe that has an XYZ positioning control is used to center the whisker point over the nearest honeycomb diode window [32] after the point is brought forward to nearly touch the wafer surface. The whisker pin is then advanced to firmly seat the whisker point in the metallized window area. Since the whisker was positioned over the nearest window after bringing it to the surface of the chip, a minimum sideways deflecting force results. A sequence of SEM photographs showing this procedure is contained in Fig. 6.

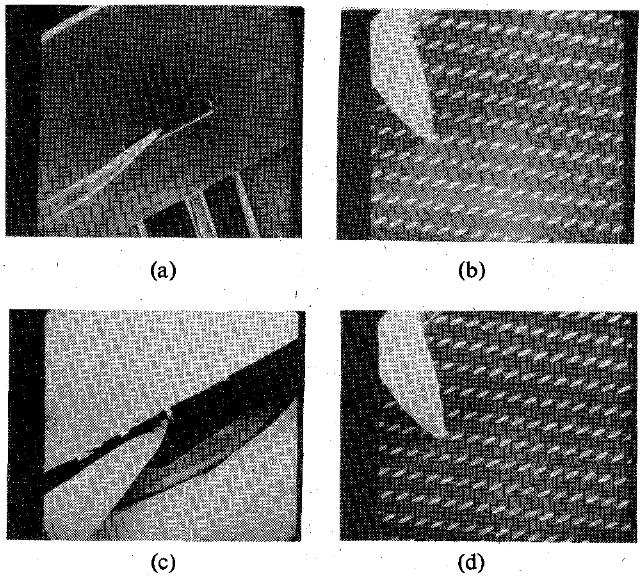

Fig. 6. Whisker contacting a honeycomb diode using a micropositioner and a three-dimensional stage mounted in SEM. (a) Positioning probe entering wafer waveguide opening. (b) Whisker in position prior to seating. (c) Magnified view of positioning probe entering wafer waveguide opening. (d) Whisker seated.

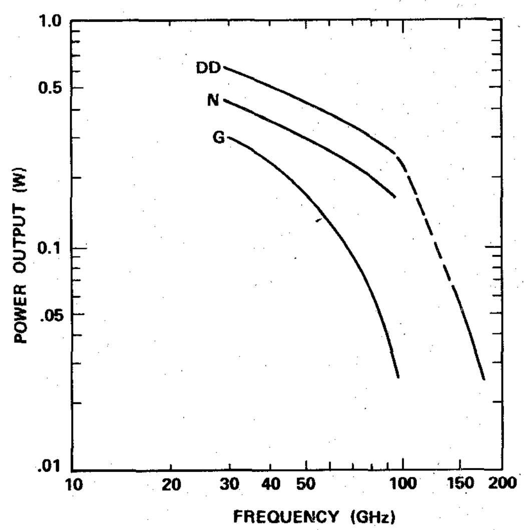

Fig. 7. Power output capability of Gunn diodes (G), n-type silicon IMPATT's (N), and double-drift silicon IMPATT's (DD).

Active Devices

Gunn and IMPATT diodes are commonly used for fundamental frequency power generation above 30 GHz. CW operation of GaAs IMPATT's has been obtained up to 74 GHz, Gunn diodes up to 95 GHz, and silicon IMPATT's up to 170 GHz.

Power and Efficiency

Temperature rise due to dc power dissipation is a limitation that must be considered in any power device. In a semiconductor device there are chemical rate processes associated with the semiconductor material and applied metallizations that are accelerated at elevated temperatures and ultimately cause failure [12]. For this reason it is appropriate to compare power generation capability on the basis of a fixed temperature rise. Figs. 7 and 8 contain a

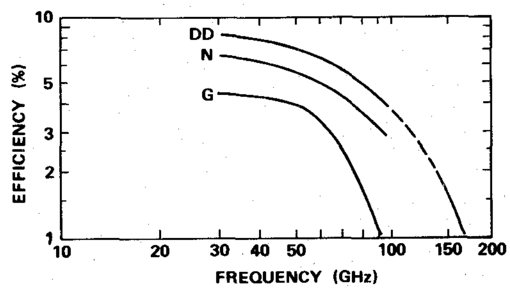

Fig. 8. Efficiency of Gunn diodes (G), n-type silicon IMPATT's (N), and double-drift silicon IMPATT's (DD).

power and efficiency comparison for Gunn diodes, and double-drift (DD) and n-type silicon IMPATT's at a temperature rise not exceeding 225°C. This comparison is based on data obtained at Hughes for silicon IMPATT's and 25–40-GHz Gunn diodes, and data from the literature for higher frequency Gunn diodes [6], [7]. It should be noted that Gunn diodes normally exhibit a maximum in output power as dc input power is increased. For the size of diodes normally used, the power maximum usually occurs at a temperature rise of less than 225°C. Thus a power/efficiency comparison of Gunn and IMPATT diodes at equal temperatures would be more favorable for Gunn diodes than is indicated by Figs. 7 and 8.

The demonstration of the performance potential of DD silicon diodes for millimeter power generation by Seidel and Scharfetter [13] in 1970 stimulated the development of this device for frequencies from 8 to 170 GHz. Schottky-barrier and n-type GaAs IMPATT's [14], [15] and p-type silicon IMPATT's [16] also perform well at millimeter wavelengths. At *Ka* band the power of these devices is slightly below the DD silicon curve of Fig. 7 and the efficiency is as good as the DD curve of Fig. 8. No data are available to make a comparison above 60 GHz.

The relation between the area of a diode and its power and efficiency can be characterized as follows. Structures with thick active regions, i.e., Gunn and DD diodes, have higher impedance per unit area, in some cases by a factor of 2 or more. With higher diode impedance, circulating currents in the cavity walls can be decreased which results in lower I^2R losses. Conversely, a larger Gunn or DD IMPATT diode can be employed with the same penalty in cavity losses. The larger diode will produce more power but not directly in proportion to its area because of increased thermal impedance per unit area. Efficiency is dependent on the input power density for both Gunn and IMPATT diodes. Since larger diodes present a higher thermal impedance per unit area, efficiency tends to decrease with increasing diode area.

Reliability

Estimates of the operating life of millimeter-wave Gunn [17] and IMPATT [18]–[20] diodes have been obtained from life testing. Due to the rise of IMPATT power and efficiency with dc input power, it is desirable, in most cases, to operate IMPATT diodes at the maximum junction temperature consistent with operating life requirements. For this reason accelerated life testing has been employed for IMPATT diodes. The result of accelerated life testing allows a quantitative tradeoff between power/efficiency and operating life. For an n-type silicon IMPATT diode with an As doped substrate and Cr–Pt–Au metallization on both sides of the chip, the median-time-to-failure is given by an Arrhenius relationship.

$$\tau = \tau_0 \exp \frac{Ea}{kT}$$

with $\tau_0 = 1.6 \times 10^{-11}$ h and activation energy $Ea = 1.6$ eV. This equation predicts an operating life of approximately 2×10^6 h at 200°C.

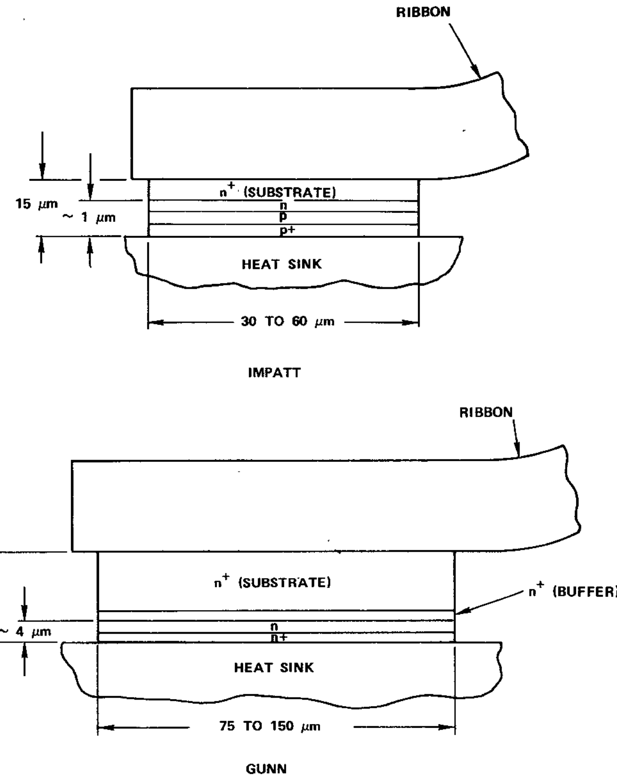

Fig. 9. Typical millimeter-wave IMPATT and Gunn diode chips showing mounting configuration.

Active Device Impedance

The comparable power generation capability of Gunn and IMPATT diodes at moderate junction temperatures can be attributed to the higher impedance of the Gunn device. A Gunn diode with several times the area of an IMPATT diode is conveniently used in a simple cavity resonator for operation in the same frequency band. Fig. 9 shows typical millimeter-wave Gunn and IMPATT chip geometries for power oscillators.

In order to understand active diode impedance quantitatively, equivalent circuits have been devised that are based on simple physical models as well as on detailed large-signal computer simulations. Most of the theoretical studies have been appropriate to the physical parameters and response times of diodes operating at 10 GHz or below. For both Gunn and IMPATT diodes, the derived equivalent circuit in the frequency band where highest power output and efficiency is available is a negative conductance shunted by a capacitive susceptance that is several times larger. This equivalent circuit is a practical representation for millimeter-wave IMPATT diodes but does not appear to be so for Gunn diodes. Swept frequency impedance measurements made on millimeter Gunn diodes usually correspond to a series *RLC* circuit characteristic [17], [21], [37]. The diode can be operated near the *LC* resonance by tailoring the mount inductance; the impedance is nearly a pure negative resistance with no shunt reactance. Thus the net Gunn diode impedance is large compared to that of an IMPATT diode with its large shunt capacitive susceptance. A study by Bosch and Thim [22] of Gunn diodes operated at millimeter frequencies shows this type of impedance

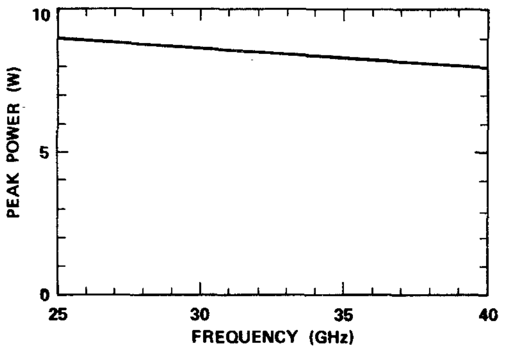

Fig. 10. Peak power output of silicon DD diodes in *Ka* band. Pulsewidth = 100 ns, PRF = 100 kHz, pulsed bias current = 4 A.

behavior for over-long diodes with a cathode doping notch. Large negative conductance is available over a frequency band where the susceptance is near zero. Overlong diodes are commonly used for oscillators at the higher millimeter frequencies [6], [7].

At millimeter wavelengths higher impedance per unit area and series *RLC* circuit behavior of the Gunn diode are beneficial to oscillator circuit design for noise control and for such applications as varactor and YIG tuning. Amplifier design is also benefited by the relatively low *Q* of the Gunn device.

Pulsed Sources

Millimeter wavelengths offer a solution to the problem of building small radars that can resolve small targets of varying angular aspect in a dense clutter environment. For this purpose it is desirable to use a radar pulse of about 100-ns duration with a frequency chirp during the pulse on the order of 1 GHz. Fortuitously, a pulsed IMPATT oscillator matches these requirements quite well. As shown in Fig. 10, peak power levels an order of magnitude higher than CW levels can be achieved since the pulsewidth is a small fraction of the semiconductor thermal time constant. Frequency chirp occurs as a natural consequence of heating during the pulse and can to some extent be controlled by shaping the bias current pulse. The design of a pulsed diode is somewhat different than a CW diode to accommodate the higher current densities and resulting space charge widening. The frequency chirp behavior of a pulsed IMPATT oscillator is indicated in Fig. 11 as a function of the bias current pulse shape.

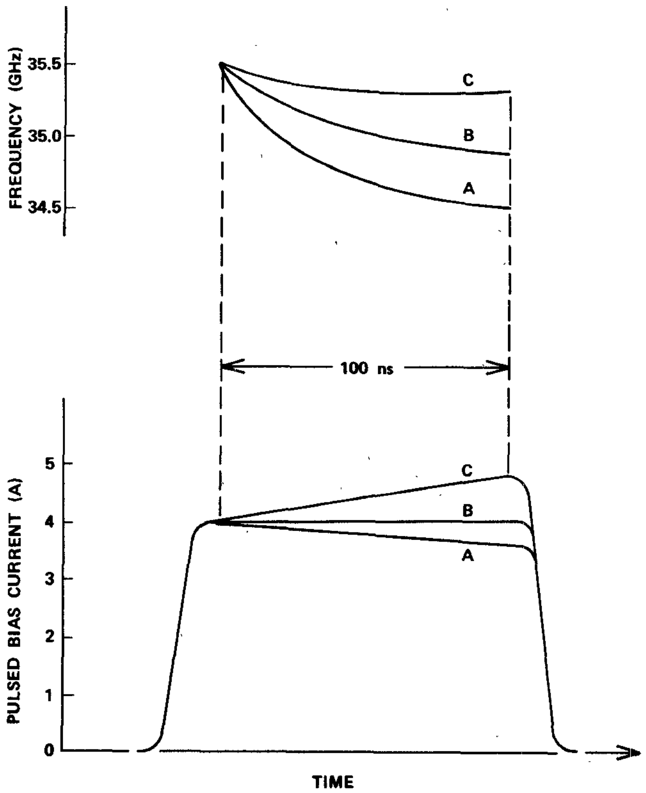

Fig. 11. Frequency chirp characteristics of pulsed *Ka*-band DD silicon IMPATT oscillator. Amount of chirp can be controlled by the bias-current pulse shape as indicated by A, B, and C.

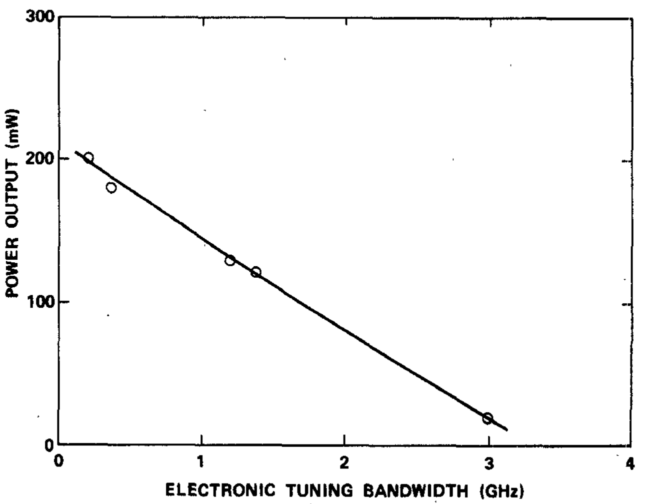

Fig. 12. Power output of 35-GHz Gunn VCO as a function of tuning bandwidth.

Tunable Oscillators

Increased use of millimeter wavelengths is heavily dependent on electronically tunable solid-state oscillator technology. Tuning is presently accomplished by several methods. The YIG resonator is a useful technique but is slow and will probably be limited to the low end of the millimeter spectrum due to the large magnetic fields required. Varactor-controlled Gunn and IMPATT oscillators can provide high power over narrow tuning ranges and local oscillator power levels over much wider tuning ranges. Fig. 12 shows the varactor tuning capability of a cavity Gunn oscillator in *Ka* band. It is possible to maintain power output relatively constant over wide frequency bands with varactor tuning [23].

Monotonic tuning of an IMPATT oscillator can be achieved by sweeping the diode bias current. This effect was predicted by Gilden and Hines [24] and has been particularly useful at the higher millimeter frequencies for multipurpose laboratory sweepers. Fig. 13 shows sweep bandwidth as a function of center frequency for single-diode bias-current tuned IMPATT oscillators. In general, as bias current is increased, power output increases as well as frequency (see Fig. 14). Circuit adjustment can often provide

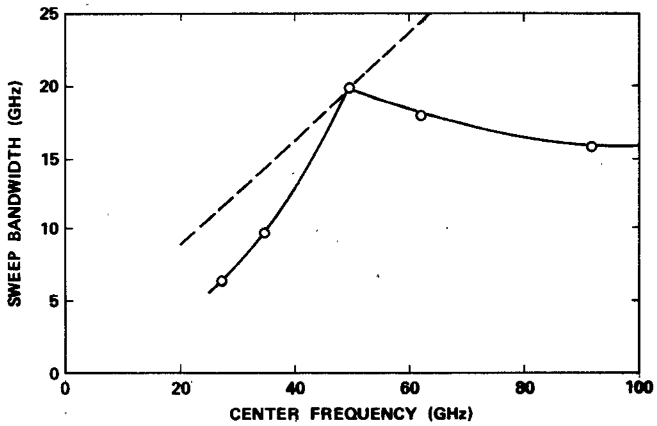

Fig. 13. Sweep bandwidth capability of bias-current tuned IMPATT oscillators. Sweep bandwidth for 1-mW minimum output is shown. Dashed line corresponds to full waveguide bandwidth.

TABLE I
OSCILLATOR NOISE PERFORMANCE

Diode Type	DSB AM Noise-to-Carrier Ratio (dB/100 Hz)	FM Noise Measure (dB)
Gunn Diode	-156 [26]	33 [6]
GaAs IMPATT	-135 [14]	33 [14]
Silicon IMPATT		
n type	-140 [27]	41 [28]
p type	-136 [16]	35 [16]

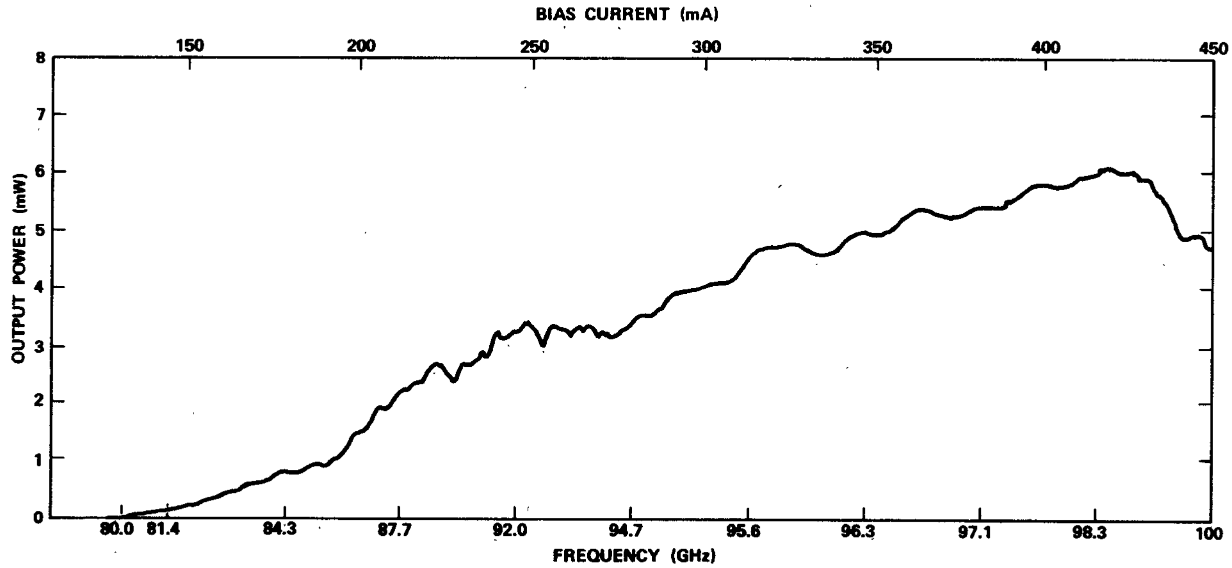

Fig. 14. Tuning characteristic of *W*-band IMPATT sweeper.

a wider sweep bandwidth with a decreasing power characteristic at the high band edge [25]. This type of behavior is shown in Fig. 15. The simplicity of construction and wide-band capability of bias-current tuned IMPATT oscillators provides an incentive to learn how to control RF circuit impedance in order to reduce noise fluctuations during tuning.

Noise

The RF noise power generated in a negative resistance semiconductor device is dependent on many factors. Detailed analysis of diode doping profile parameters, bias conditions, RF signal level, and parametric interactions shows that significant improvements in noise performance can be expected with alterations in the diode doping profile and its operating conditions. The impedance relationship between the oscillator or amplifier circuit and the diode also strongly affects noise output. Not a great deal of flexibility for noise optimization exists because of the difficulty in making subtle doping profile and circuit impedance changes at millimeter frequencies. Therefore, with a given type of diode it is commonly observed that samples from different wafers when placed in a simple waveguide or coaxial cavity resonator will produce about the same noise-to-carrier ratio when tuned for minimum noise at a specified power output level.

Table I contains a comparison of some of the best data reported for Gunn and IMPATT diodes for "far from the carrier" noise. All of the results listed in Table I are for millimeter-wave oscillators except for the Gunn diode AM noise. FM noise measure is dependent on signal level. Therefore, the FM noise measures given in Table I are for an output power level of 200 mW at *Ka* band. The noise measure for n-type silicon IMPATT's was estimated from the data of Okamoto [28] which indicates that the n-type silicon IMPATT is approximately 8 dB noisier than a GaAs IMPATT at the same output power level.

Resistive termination of the bias circuit is important to prevent amplification of low frequency noise which will appear as noise sidebands about the carrier due to upconversion in the nonlinearity of the active device [25], [28].

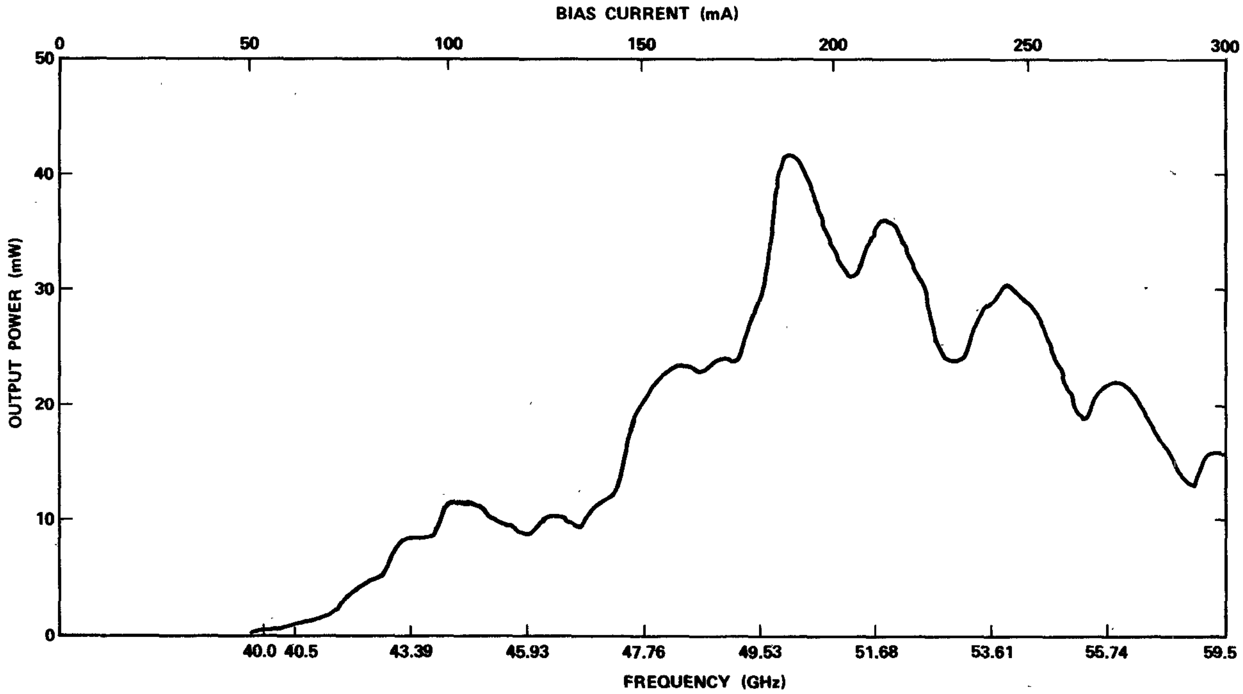

Fig. 15. Tuning characteristic of U-band IMPATT sweeper.

With proper bias-circuit design a diode can usually be tuned to approach the noise performance indicated in Table I at a single frequency. Gunn diodes, due to their more favorable impedance characteristics, will usually have good noise performance over a wide tuning range. IMPATT diodes, besides being inherently more noisy, exhibit larger noise increases with tuning above the intrinsic noise of Table I. This can be attributed to the lower impedance and higher Q of the IMPATT which makes acute angle intersections of the device and circuit impedance loci [9] much harder to avoid in a practical cavity design.

Passive Devices

In cases where a device for signal modulation, translation, or detection is not required to dissipate much power, the whisker-contacted planar honeycomb diode is widely used. This device can be made with appreciably lower capacitance than other practical structures. An important application is the downconverting mixer. Both silicon and GaAs Schottky diodes have been used for this purpose. Measured receiver double-sideband noise figures for silicon honeycomb Schottky diodes are shown in Fig. 16. The receivers all contain balanced mixers; the measured noise figures include the loss of the folded magic tee and an IF noise figure of 1.5 dB. GaAs honeycomb diodes provide approximately 0.5–1.0 dB lower noise figure [29], [30]. The relatively small superiority of GaAs over silicon is explained by the high cutoff frequencies of both diode types, which means that in either case the diode parasitic series resistance is a relatively small contributor to conversion loss. The advantage of GaAs over silicon will be more evident at higher frequencies.

Harmonic mixers operating at moderate local-oscillator power levels can also be constructed using honeycomb Schottky diodes. Fig. 17 gives an indication of the conversion loss obtainable with harmonic mixing using silicon diodes.

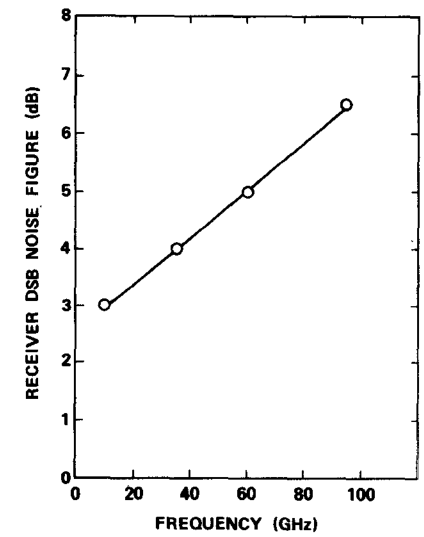

Fig. 16. Receiver double-sideband noise figures for balanced mixers/IF preamps using honeycomb silicon Schottky-barrier mixer diodes. IF noise figure = 1.5 dB.

The sensitivity of honeycomb silicon Schottky diodes used as video detectors is indicated in Fig. 18. The detector diode is usually designed to have a low barrier potential by appropriate choice of barrier metallization. This provides a low "turn-on" voltage which enables the detectors to be used without external bias to detect low level signals.

Honeycomb p-i-n diodes made by ion implantation are used for high-speed phase modulation at millimeter wavelengths [33]. Cross sections of honeycomb Schottky-barrier and junction diodes are shown in Fig. 19 to illustrate the differences in construction. The honeycomb p-i-n diode

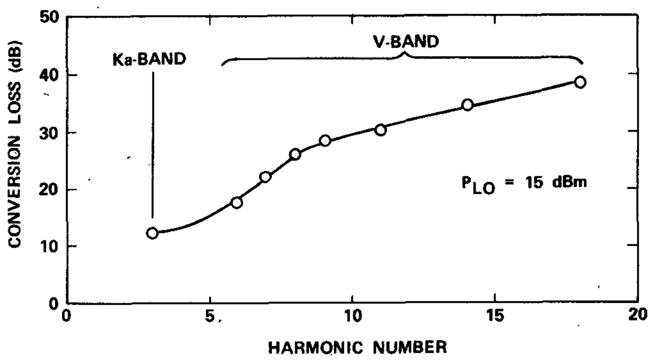

Fig. 17. Harmonic mixer conversion loss. Data are for a *Ka*-band mixer (26.5 GHz < f_{RF} < 40 GHz) and for a *V*-band mixer (50 < f_{RF} < 75 GHz).

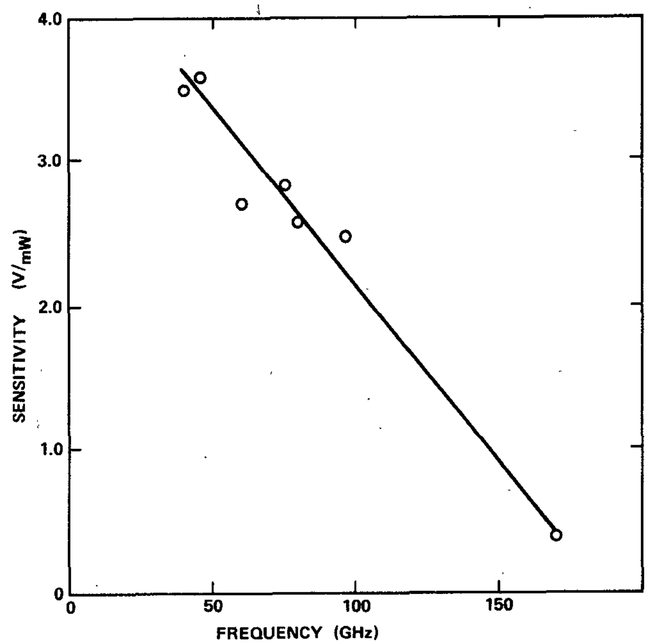

Fig. 18. Sensitivity of detectors employing honeycomb titanium-silicon Schottky-barrier diodes.

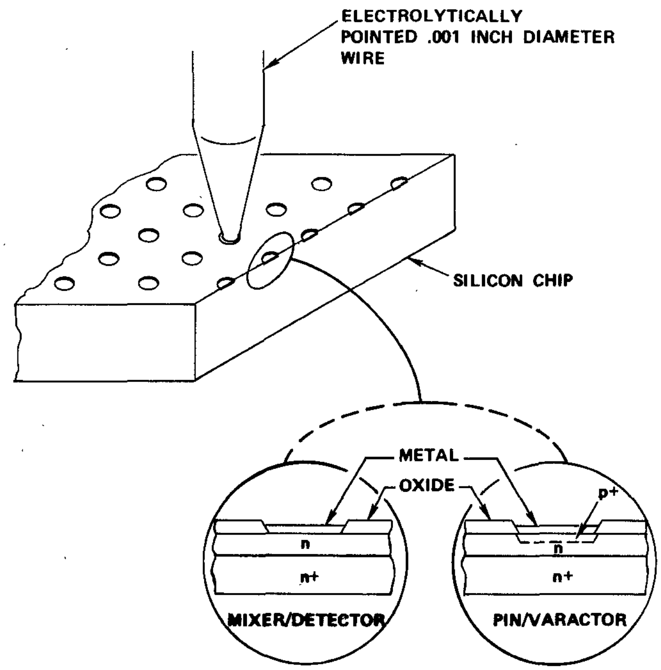

Fig. 19. Honeycomb diodes.

is useful for applications requiring subnanosecond switching times at low RF power levels. This device, with a higher doping level in the epitaxial layer, becomes a p-n junction varactor that is useful for low-power multipliers and upconverters.

In other applications passive devices are required to operate at higher power levels: varactors for parametric amplifiers, harmonic generators and oscillator tuning; p-i-n diodes for amplitude and phase modulators, duplexers and other switching applications. These devices are fabricated using the same techniques that are used for IMPATT and Gunn diodes. The same packaging principles apply.

Conclusions

Advancements in semiconductor diode design and in diode packaging technology have resulted in an increased scope of millimeter-wave applications. Most significant has been the advent of practical fundamental frequency solid-state power sources capable of producing useful amounts of power with good efficiency. New materials such as InP for Gunn diodes and more sophisticated structures such as Read diodes may provide even more millimeter power and efficiency in the future. Work to reduce noise and to better understand the circuit behavior of power generating diodes for CW and pulsed operation must continue in order for applications to grow rapidly. Also important are passive semiconductor diodes. Small-area Schottky-barrier and p-n junction honeycomb diodes provide low loss performance in signal modulation and detection applications. Efforts in small-area diode technology should be aimed at simplifying packaging and circuit mounting. Good-quality beam-lead-type diodes would be one possible solution to this problem.

Acknowledgment

The author wishes to thank C. Chao, K. P. Weller, Y. Chang, H. J. Kuno, J. W. Tully, J. W. Dozier, and F. J. Bernues for helpful discussions.

References

[1] A. R. Kerr, "Low-noise room-temperature and cryogenic mixers for 80–120 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 781–787, Oct. 1975.
[2] W. M. Sharpless, "Wafer-type millimeter-wave rectifiers," *Bell Syst. Tech. J.*, vol. 35, pp. 1385–1402, Nov. 1956.
[3] H. J. Kuno and D. L. English, "Nonlinear and large-signal characteristics of millimeter-wave IMPATT amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 703–706, Nov. 1973.
[4] J. W. Tully, private communication.
[5] F. B. Frank and G. F. Day, "High CW power *K*-band Gunn oscillators," *Proc. IEEE*, vol. 57, pp. 339–340, Mar. 1969.
[6] T. G. Ruttan, "High frequency Gunn oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 142–144, Feb. 1974.
[7] T. G. Ruttan, "Gunn-diode oscillator at 95 GHz," *Electronics Letters*, vol. 11, pp. 293–294, July 10, 1975.
[8] C. B. Swan, T. Misawa, and L. Marinaccio, "Composite avalanche diode structures for increased power capability," *IEEE Trans. Electron Devices*, vol. ED-14, pp. 584–589, Sept. 1967.

[9] K. Kurokawa, "Some basic characteristics of broadband negative resistance oscillator circuits," *Bell Syst. Tech. J.*, vol. 48, pp. 1937–1955, July/Aug. 1969.
[10] K. P. Weller, R. S. Ying, and D. K. Lee, "Pumps and local oscillators," Technical Report AFAL-TR-75-177 Air Force Avionics Laboratory, Sept. 1975.
[11] H. C. Okean and L. J. Steffek, "94 GHz parametric amplifier," Technical Report AFAL-TR-74-246 Air Force Avionics Laboratory, Dec. 1974.
[12] D. S. Peck, "Reliability predictions from accelerated testing," *9th Annual Proc. Reliability Physics Symposium*, Las Vegas, 1971.
[13] T. E. Seidel and D. L. Scharfetter, "High-power millimeter wave IMPATT oscillators with both hole and electron drift spaces made by ion implantation," *Proc. IEEE*, vol. 58, pp. 1135–1136, July 1970.
[14] K. P. Weller, A. B. Dreeben, H. L. Davis, and W. M. Anderson, "Fabrication and performance of GaAs p+n, junction and Schottky barrier millimeter IMPATT's," *IEEE Trans. Electron Devices*, vol. ED-21, pp. 25–31, Jan. 1974.
[15] K. Nawata, M. Ikeda, and Y. Ishii, "Millimeter-wave GaAs Schottky-barrier IMPATT diodes," *IEEE Trans. Electron Devices*, vol. ED-21, pp. 128–130, Jan. 1974.
[16] G. A. Swartz, Y. Chiang, C. P. Wen, and A. Gonzalez, "Performance of P-type epitaxial silicon millimeter-wave IMPATT diodes," *IEEE Trans. Electron Devices*, vol. ED-21, pp. 165–171, Feb. 1974.
[17] R. E. Goldwasser and J. F. Caldwell, "Millimeter wave Gunn devices," presented at WESCON, Los Angeles, Sept. 1974.
[18] P. Staecker, "*Ka*-band IMPATT diode reliability," presented at the International Conf. Electron Devices, Washington, DC, Dec. 1973.
[19] N. B. Kramer, "Millimeter IMPATT diode progress," presented at IEEE INTERCON, New York, March 1974.
[20] N. B. Kramer, "Millimeter IMPATT devices," presented at WESCON, Los Angeles, Sept. 1974.
[21] D. S. Matthews, private communication.
[22] R. Bosch and H. W. Thim, "Computer simulation of transferred electron devices using the displaced Maxwellian approach," *IEEE Trans. Electron Devices*, vol. ED-21, pp. 16–25, Jan. 1974.
[23] E. J. Denlinger, J. Rosen, E. Mykietyn, and E. C. McDermott, Jr., "Microstrip varactor-tuned millimeter-wave IMPATT diode oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 953–958, Dec. 1975.
[24] M. Gilden and M. E. Hines, "Electronic tuning effects in the Read microwave avalanche diode," *IEEE Trans. Electron Devices*, vol. ED-13, pp. 169–175, Jan. 1966.
[25] C. Chao, unpublished work.
[26] M. Ohtomo, "Experimental evaluation of noise parameters in Gunn and avalanche oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 425–437, July 1972.
[27] K. P. Weller, unpublished work.
[28] H. Okamoto, "Noise characteristics of GaAs and Si IMPATT diodes for 50-GHz range operation," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 558–565, Aug. 1975.
[29] W. V. T. Rusch and C. A. Burrus, "Planar millimeter-wave epitaxial silicon Schottky-barrier converter diodes," *Solid State, Electronics*, vol. 11, pp. 517–525, 1968.
[30] H. M. Leedy, H. L. Stover, H. G. Morehead, R. P. Bryan, and H. L. Garvin, "Advanced millimeter-wave mixer diodes, GaAs and silicon, and a broadband low-noise mixer," presented at the Conf. High Frequency Generation and Amplification, Cornell Univ., Ithaca, NY, August 1971.
[31] G. T. Wrixon, "Low-noise diodes and mixers for the 1–2 mm wavelength region," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1159–1165, Dec. 1974.
[32] D. T. Young and J. C. Irvin, "Millimeter frequency conversion using N-type GaAs Schottky-barrier epitaxial diodes with a novel contacting technique," *Proc. IEEE*, vol. 53, pp. 2130–2131, Dec. 1965.
[33] Y. Chang, H. J. Kuno, and D. L. English, "High data-rate millimeter-wave transmitter module," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 470–477, June 1975.
[34] C. B. Swan, "Improved performance of silicon avalanche oscillators mounted on diamond heat sinks," *Proc. IEEE*, vol. 55, pp. 1617–1618, Sept. 1967.
[35] R. S. Ying and D. L. English, unpublished work.
[36] This procedure was developed by H. H. Luckey.
[37] D. Rubin, "Wide-bandwidth millimeter-wave Gunn amplifier in reduced-height waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 833–834, Oct. 1975.

Highly Reliable High-Power 86-GHz Components and Transmitter–Receiver Modules

MASAMI AKAIKE, MEMBER, IEEE, HARUHIKO KATO, AND NOBORU KANMURI, MEMBER, IEEE

***Abstract*—The reliability of semiconductor active devices is related to the junction temperature of diodes used. This paper describes the reliability design and performance of 86-GHz active components and transmitter–receiver modules for a guided millimeter-wave transmission system. The components are IMPATT oscillators, IMPATT amplifiers, varactor frequency multipliers, and Schottky-barrier diode upconverters. The maximum output powers of these active devices are calculated for a given mean time between failure (MTBF). Active components and transmitter–receiver modules for 86-GHz operation were manufactured based upon the design with considerations for reliability as well as RF performance.**

Manuscript received February 3, 1976; revised May 5, 1976.
The authors are with the Yokosuka Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Yokosuka-shi, Kanagawa-ken, Japan.

I. Introduction

IN RECENT YEARS guided millimeter-wave transmission systems have been intensively investigated in various countries in the world for the purpose of meeting growing demands in communications in the near future. There have been publications concerned with the system design, repeaters, and overall transmission tests [1]–[7].

There are basically two means of getting the millimeter-wave modulated carrier power; an upconverter [3], [4], [6], [7] and a millimeter-wave modulator [2], [3], [5], both of which have their own merits with respect to the circuit construction, output power and system design. The guided millimeter-wave transmission system in Japan,