# Schottky-Diode Realization for Low-Noise Mixing at Millimeter Wavelengths

GERARD T. WRIXON, MEMBER, IEEE

***Abstract*—A short review of the current theory and technology of low-noise Schottky-barrier diodes for use at millimeter wavelengths is presented. Recent advances in fabrication technology are discussed which have yielded photolithographically produced GaAs diodes with a cutoff frequency in excess of 3000 GHz together with improved noise performance due to reduced contamination of the contact. Noise producing mechanisms in diodes are outlined and the limitations of noise reduction by cooling are considered. Finally, methods for overcoming the high-frequency limitations of conventional GaAs Schottky diodes are assessed.**

## I. INTRODUCTION

AT millimeter wavelengths, the lack of suitable pump sources for parametric amplifiers has resulted in much effort being invested in the development of low-noise front-end mixers. These mixers normally use ultralow capacitance gallium arsenide Schottky-barrier diodes as the nonlinear element. As has been demonstrated theoretically and experimentally [1]–[3], significant reductions in diode noise can be obtained by cryogenic cooling. There is, at present, considerable interest in extending the range of these cooled mixer receivers to the wavelength region less than 1 mm. In order to maintain the low conversion loss low-noise properties of the diodes at these very short wavelengths, however, limitations of the cooling mechanism and of the actual diode fabrication process must be recognized. In addition, the difficulty of obtaining local oscillator power at short wavelengths [4] must also be taken into account when assessing the relative merits of alternative diode configurations.

In this paper, following a brief review of conduction mechanisms in diodes, some important aspects of low-noise diode fabrication are discussed in the light of recent advances in solid-state processing technology. Noise considerations and the limitation of diode cooling in this respect are discussed, and, finally, factors pertinent to the realization of diodes for use at frequencies > 300 GHz are presented.

## II. CONDUCTION MECHANISMS IN DIODES

In general, conduction in Schottky-barrier diodes is due to a combination of two different types of electronic processes, namely, thermionic emission and field emission. The former consists of electrons with sufficient thermal energy to cross the barrier, while the latter consists of electrons which tunnel through the barrier. The relative proportion of electrons engaged in these two processes depends on the physical temperature of the diode ($T$), the doping density of the semiconductor ($N$), and the effective mass of the majority carriers ($m^*$). In general, a high $T$ will increase the proportion of electrons with energy sufficient to overcome the barrier. On the other hand, as shown in Fig. 1, image force lowering *and narrowing* of the potential barrier increases as the ratio of $N/m^*$. Initially, the barrier becomes thin enough that thermally excited carriers can tunnel through near the top of the barrier. This temperature-dependent mode of current transport is called thermionic–field emission or thermally assisted tunneling. As the impurity concentration is further increased, the barrier becomes so thin that significant numbers of carriers can tunnel through even at the base of the barrier. This is field emission tunneling and is temperature independent [5].

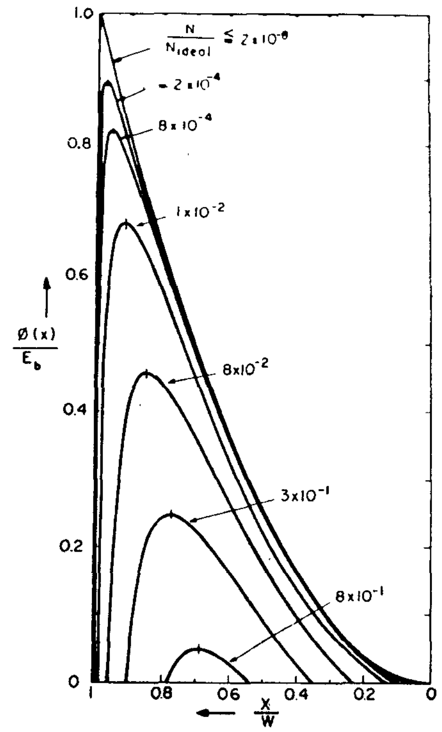


Fig. 1. The effect of image force on the shape of the potential barrier $\phi(x)$ at a metal–semiconductor interface. $N_{\mathrm{ideal}}$ is the semiconductor doping density which would result in lowering of the barrier height to zero. For n-type GaAs, $N_{\mathrm{ideal}} = 3 \times 10^{22}/\mathrm{cm}^3$, well in excess of the solubility limit. $w$ is the width of the depletion layer. As $N$ is increased, barrier narrowing ($w \propto N^{-1/2}$) proceeds more rapidly than barrier lowering ($\Delta\phi \propto N^{1/4}$). From [5].

For $I \gg I_s$ the $I$–$V$ characteristic of a Schottky diode may be written

$$I = I_s \exp\left(\frac{V}{V_0}\right). \qquad (1)$$

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The author is with the Department of Electrical Engineering, University College, Cork, Ireland.

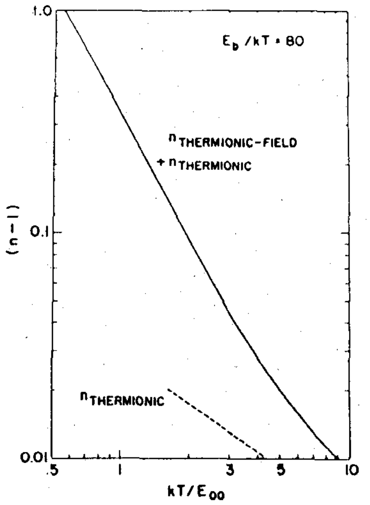


Fig. 2. The predicted deviation of the diode $n$ value from unity due to the onset of thermionic–field emission versus the parameter $kT/E_{00}$. From [5].

Padovani and Stratton [1] have shown that

$$V_0 = (E_{00}/q) \coth (E_{00}/kT) \tag{2}$$

where

$$E_{00} = q\hbar \left(\frac{N}{4 \epsilon m^*}\right)^{1/2}. \tag{3}$$

For the field emission case, i.e., high $N$, and/or low $T$, $\coth (E_{00}/kT) \to 1$ and

$$V_0 = \frac{E_{00}}{q} \tag{4}$$

which is temperature independent.

For the thermionic emission case, i.e., high $T$ and/or low $N$,

$$\coth \frac{E_{00}}{kT} \to \frac{kT}{E_{00}}$$

and

$$V_0 = \frac{kT}{q}. \tag{5}$$

Often, the diode $I$–$V$ characteristic is written ($I \gg I_s$)

$$I = I_s \exp \left(\frac{qV}{nkT}\right). \tag{6}$$

For pure thermionic emission $n = 1$ and the deviation of the $n$ value from unity may be used as a measure of the relative contribution of tunneling to conduction (see Fig. 2). This measure must be cautiously applied, however, as imperfections in diode processing, especially difficult to eliminate given the small size of millimeter diodes, may lead to the presence of an interfacial layer or impurity diffusion both of which also tend to increase $n$.

One additional factor which influences the mode of electron transport in Schottky barriers and which has been neglected in the aforementioned analysis is the presence of a dc bias voltage on the diode. This will lower the barrier potential and will cause the dominant conduction mechanism to change from thermionic–field to thermionic emission at a specific bias voltage. The value of this bias voltage depends on $N$ and will increase with decreasing $T$. For example, in a GaAs Schottky diode at room temperature with $N \approx 5 \times 10^{17}/\text{cm}^3$, forward biases of up to 0.75 V are allowed within the thermionic–field transport scheme. This number increases to 0.95 V as $T$ decreases to 15 K.

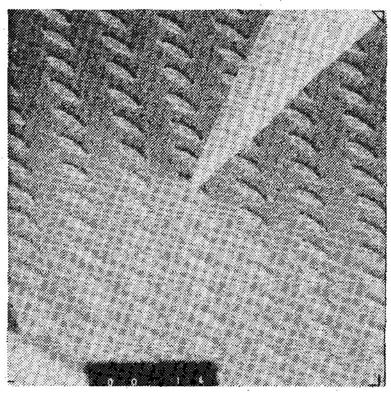

Fig. 3. Micrograph of a typical diode array, one diode of which is being contacted by means of an etched wire.

## III. Fabrication Techniques

Although it is a relatively straightforward procedure, fabrication of GaAs Schottky diodes suitable for use at millimeter wavelengths demands great care if low-noise performance is to be obtained. The presence of an interfacial oxide layer of as little as 10-Å thickness between the metal and the semiconductor will add appreciably to the diode's $n$ factor and thereby limit its noise performance. The elimination of such an oxide layer, however, can be a major problem given the extremely small diode diameter ($< 3$ $\mu$m for use at frequencies $> 90$ GHz) and the rapidity with which native oxides can grow on an exposed GaAs surface. In addition, since conventional photolithographic techniques are used to open up the array of "diode" holes (see Fig. 3) in a passivating $SiO_2$ layer on the GaAs, use of a proprietary brand photoresist stripper is normally entailed. The residue from such strippers is often extremely difficult to remove completely from the GaAs surface and it may form an additional interfacial layer component.

The application of plasma chemistry techniques [6] to millimeter diode fabrication, however, contributes in a number of ways to the solution of the aforementioned problems. For example, use of a $CF_4$ plasma in an RF discharge at a pressure of 0.3–0.5 torr to etch through the $SiO_2$ passivating layer gives etched walls which are almost perfectly vertical. This eliminates undercutting of the photoresist layer and the formation of a thin wedge-shaped ring of $SiO_2$ surrounding the exposed GaAs surface (another potential interfacial layer), both of which occur when a buffered HF solution is used as an etchant. Photoresist undercutting is a particularly serious problem for millimeter diode processing because the diodes are usually

TABLE I
PROPERTIES OF GaAs MATERIAL USED TO MAKE DIODES DESCRIBED IN TEXT

| | | |
|---|---|---|
| Epilayer thickness | : | 0.19 $\mu$m |
| Epilayer doping | : | $4 \times 10^{17}/\text{cm}^3$ |
| Epilayer dopant | : | S |
| Substrate doping | : | $2 \times 10^{18}/\text{cm}^3$ |
| Substrate dopant | : | Si |

clustered as close together as possible to allow for subsequent ease of contacting without damage to the finely etched contacting whisker (Fig. 3). When using $CF_4$ plasma etching, allowance must be made for the fact that the photoresist layer is gradually eroded by the $CF_4$ and thus a thicker layer of photoresist must be used to eliminate thinning of the $SiO_2$. After the holes have been etched, complete removal of the photoresist can be effected using an $O_2$ plasma at a pressure of 0.5–1 torr. A chlorine containing plasma (e.g., freon 12, $CCl_2F_2$ at 0.3–0.5 torr) will etch the native oxides growing on the GaAs surface; however, this step must be monitored very closely to prevent extensive etching of the gallium arsenide itself by the plasma.

In general, it is a good idea to substitute, wherever possible, processing steps where liquid solvents or etchants are used by RF plasma cleaning or etching procedures as this will decrease the possibility of epilayer contamination due to impurities in the liquids as well as inhibiting growth of native oxides on the GaAs surface.

Diodes were fabricated using these techniques on Plessey epitaxial GaAs material with properties given in Table I. 2-$\mu$m-diam holes were opened in a 0.3-$\mu$m-thick RF-sputtered $SiO_2$ passivating layer, and platinum anodes followed by gold were plated on to the epilayer. This resulted in diodes with a spreading resistance ($R_s$) of 7 $\Omega$ and a zero-bias capacitance ($C_0$) of 0.007 pF, giving a cutoff frequency $f_c$ ($= 1/2\pi R_s C_0$) of 3248 GHz. The value of $n$ due to residual interfacial effects was 1.07 when that portion due to the thermionic–field nature of the conduction process (see Fig. 2) had been subtracted.

It is sometimes overlooked that the ohmic back contact on a Schottky diode is itself a Schottky junction, the semiconductor region in contact with the metal being very highly doped so that field-emission-dominated conduction occurs and the potential barrier appears almost transparent to current flow. The usual method of forming the contact is by in-diffusion of a dopant contained in the contact metal (e.g., Au-Ge or Au-Sn for n-type GaAs). It is therefore important that the same precautions be taken against the formation of an interfacial layer when the back contact is being formed as are taken when forming the main Schottky barrier.

## IV. DIODE NOISE AND LIMITATION OF COOLING

Under most conditions, the principal source of noise from a dc-biased Schottky barrier is shot noise. In that case the available noise power

$$P = \tfrac{1}{2} q I R_x B \tag{7}$$

where $R_x$ is the variable diode resistance. From (1) we have

$$R_x \equiv \left(\frac{dI}{dV}\right)^{-1} = \frac{V_0}{I}. \tag{8}$$

Thus the equivalent noise temperature of the diode

$$T_{eq} \equiv \frac{P}{kB} = \frac{qV_0}{2k}. \tag{9}$$

Equations (2)–(5) and (9) show that for a given doping $N$, the equivalent noise temperature of the diode will decrease as the physical temperature is reduced, but only until the onset of mainly field emission when $V_0$ becomes temperature independent. It would seem logical, then, to choose the doping so that smallest $T_{eq}$ will result. Equations (3) and (4) show that this means choosing $N$ as low as possible. Other considerations, however, also influence the choice of $N$. For lowest conversion loss, for instance, the $R_s C_0$ product should be minimized, with a reasonable upper limit on $R_s$ [4] to reduce its thermal noise relative to the shot noise of $R_x$ [2], [7]. Another factor to be borne in mind which also influences $N$ is the possibility of carrier freeze-out occurring as the diode's physical temperature is reduced. If this should happen it would result in a drastic reduction in the number of mobile carriers and a large increase in $R_s$. This is particularly important for relatively "deep" but often used donor impurities such as Ge and S, which have donor levels of 0.006–0.007 eV ($= kT$ at 70–80 K). Cooling to temperatures of $\sim 15$ K would certainly cause some carrier freeze-out to occur with these donors unless the doping were sufficiently high to cause impurity band broadening with a consequent lowering of the effective ionization energy. The minimum donor density necessary to avoid carrier freeze-out of these deep donors at 15 K in n-type GaAs may be calculated from Sze [8] to be $\sim 2 \times 10^{17}/\text{cm}^3$. With this doping, the terminal value of $T_{eq}$ upon cooling [(4) and (9)] is $\sim 67$ K.

It has been pointed out [7] that in a hard-pumped diode thermal noise from $R_s$ should be the only noise present, as shot noise from $R_x$ will not be coupled out to the external circuit since the value of $R_x$ will either be very large or very small. Thus cooling a pumped diode mixer should result in a linear reduction of noise power with temperature. Such has not proved to be the case, a reduction in noise power of $\sim 2.5$ being obtained for a reduction in temperature from 290 to 18 K [13]. Significantly, no reduction in noise was observed in cooling from 77 to 18 K. This suggests that the mixer diode was shot-noise rather than thermal-noise limited, its equivalent noise temperature $T_{eq}$ reaching its terminal value, given by (4) and (9), at the onset of mainly field emission.

In order to reduce the limiting value of $T_{eq}$ which occurs at the onset of field emission in regular Schottky diodes, McColl *et al.* [9] have investigated a superconducting metal–semiconductor junction, the super-Schottky diode. This diode makes use of the small (1 mV for lead) energy gap that appears in superconductors. Over a restricted range of biases, this gives rise to a highly nonlinear $I$–$V$ characteristic. At higher bias voltages the superconducting energy gap is quenched and the device behaves as a normal diode. By operating in the restricted bias range, values of $V_0$ as low as 0.1 mV can be obtained. This compares with the limiting $V_0$ of $\sim$ 12 mV obtainable with a regular GaAs diode with $N = 3 \times 10^{17}/\text{cm}^2$. Thus extremely low values of $T_{eq}$ (1.6 K) are obtainable for diodes whose physical temperature is $\sim$ 1 K. Because of such a low $V_0$, the device has a very low $R_x$ which cannot be adjusted, as it can in a normal Schottky, by changing the bias voltage. Therefore, in order to achieve practical impedance levels, very heavily doped ($3 \times 10^{19}/\text{cm}^3$) p-type GaAs must be used. This increases the junction capacitance and contributes to a rather high conversion loss (9 dB) at $x$ band. As it is unlikely that a significant reduction in the conversion loss of the super Schottky can be achieved, and since device parasitics would be an even more serious problem at higher frequencies, it does not currently seem possible that the low-noise properties of this device can be utilized at millimeter wavelengths.

## V. High-Frequency Considerations

As the diameter ($d$) of a Schottky diode is decreased, the cutoff frequency $f_c$ increases as $d^{-n}$, where $1 < n < 1.5$ depending on the thickness of the epilayer and the diameter of the diode [4]. Assuming a GaAs epilayer of doping density $\sim 2 \times 10^{17}/\text{cm}^3$ and thickness 0.2 $\mu$m, a series resistance $R_s$ of 10–12 $\Omega$ and a zero-bias capacitance $C_0$ of $\sim$ 0.006 pF is reached as the diameter is decreased to 1.5 $\mu$m. For the diode to be useful at millimeter wavelengths, an upper limit of $\sim$ 10 $\Omega$ has been proposed for $R_s$ [4]. With the aforementioned parameters, $f_c$ lies in the general region of 3000 GHz and, in order not to be conversion-loss limited, this restricts the use of such diodes to frequencies below 300 GHz. In order to obtain diodes with a higher $f_c$, one could 1) decrease the epilayer thickness, 2) use electron lithographic techniques, or 3) use a higher mobility material such as InSb.

*1) Decrease Epilayer Thickness:* For a varistor, since the undepleted portion of the epilayer contributes only to $R_s$, there is theoretically no reason why the epilayer thickness should be greater than the depletion width at zero bias (typically $\sim$ 0.1 $\mu$m). Until now, however, growth of a uniform 0.1-$\mu$m epilayer of the required doping density has not proved to be technically feasible.

*2) Electron Lithographic Techniques:* These can be used to either a) define submicron diameter dots on heavily doped bulk semiconductor material, or b) increase the perimeter to area ratio of diodes on epitaxial material in order to reduce current bunching and therefore decrease $R_s$.

a) This method does not lead to a higher cutoff frequency diode as the use of bulk material cancels any decrease in $C_0$ which might have been expected due to the smaller area. A significantly lower back-breakdown voltage is also obtained.

b) Wrixon and Pease [10] have used this method to make diodes shaped as crossed stripes of submicron width. The shaping of the diodes resulted in a 30-percent reduction in spreading resistance over that of photolithographically formed circular diodes with approximately the same junction area and capacitance. Thus an increase in $f_c$ of at least 43 percent can be obtained using this technique.

*3) Use of InSb as a Diode Material:* Use of a higher mobility material such as InSb introduces the possibility of obtaining extremely high-frequency cutoff diodes by conventional photolithographic means. For instance, bulk n-type InSb with a carrier concentration of $\sim 10^{16}/\text{cm}^3$ has approximately the same resistivity (at 77 K) as has bulk GaAs, doped to a few times $10^{18}/\text{cm}^3$, currently used as the substrate material for epitaxial GaAs. In fact, when compared with a similar sized diode made using epitaxial GaAs of doping $2 \times 10^{17}/\text{cm}^3$, a diode made on $10^{16}/\text{cm}^3$ InSb would theoretically be expected to have $R_s$ lower by a factor of 10 and $C_0$ lower by a factor of 2 (at zero bias), giving a potential increase in $f_c$ of a factor of 20. In addition, the use of electron beam lithography to produce submicron sized diodes (as in 2)a) above) would be perfectly permissible on this low resistivity material and would lead to even higher cutoff frequencies.

InSb presents a number of formidable technical difficulties, however, among its many problems being high surface leakage currents, very rapid surface oxide growth, and extremely low barrier height. This latter difficulty precludes the use of the material at room temperature and, indeed, the barrier height at 77 K has been measured [11], [12] at only 50–76 mV (i.e., 8–11 kT) for an Au-InSb contact.

Korwin-Powlowski and Heasell [11] and McColl and Millea [12] have both made good ($n = 1$) Schottky contacts on InSb, although both have noted the deleterious effect of high leakage currents and anomalously high series resistances. It appears possible, however, using vacuum processing techniques, to fabricate devices in which the effect of these imperfections can be minimized. In that case, the limiting value of $V_0$ [see (4)], given a doping density of $10^{16}/\text{cm}^3$, would lie in the range 2–4 mV leading to a limiting $T_{eq}$ of 20 K, compared to a limiting $T_{eq}$ of 67 K using $2 \times 10^{17}/\text{cm}^3$ GaAs. Additionally, from (9), the current $I$ needed to bias an InSb diode to a certain impedance level is reduced over that required for a GaAs diode. Therefore, since $dR_x/dV = -(1/I)$, less local oscillator power is needed in the case of the InSb diode to switch over the same impedance range. Thus, apart from achieving higher frequency cutoff diodes, successful use of InSb would also lead to a lower asymptotic level of shot noise upon cooling, as well as lower local oscillator power requirements.

## VI. Summary

In this paper the limitations that noise and high-frequency operation place on the performance of GaAs Schottky-barrier diodes have been examined. It appears that use of InSb may enhance both noise and high-frequency diode performance as well as reducing local oscillator power requirements. There are severe processing difficulties to be overcome but the evolution of diode fabrication techniques toward a series of completely dry (vacuum) processes will enable tighter control to be achieved during InSb diode formation and should allow the potential of this material to be realized.

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# A Low-Noise 47-GHz Mixer Using a Permanent Josephson Junction

JOCHEN EDRICH, MEMBER, IEEE

*Abstract*—**A new method to produce permanent Josephson junctions for millimeter-wave mixers is reported. In contrast to conventional point contacts which are mechanically unstable and require adjustments after each cooldown, these point contact junctions are set at room temperature, stay mechanically stable, and can be temperature cycled without readjustments. Using these junctions in a modified Sharpless wafer mixer mount, a single-sideband noise temperature of 71 K was measured at 47 GHz. Based on these results, system noise temperatures of less than 100 K are predicted for practical broad-band radiometers, radar, and communications receivers up to at least 100 GHz.**

## I. Introduction

JOSEPHSON effect devices are known to exhibit excellent sensitivity as microwave and millimeter-wave detectors and mixers [1], [2]. However, at frequencies above a few gigahertz permanent thin-film junctions or constriction-type junctions are yielding poor conversion characteristics because of their relatively low impedance or their excessive shunt capacitance [3]. A third type of junction employs adjustable point contacts and is free of these defects; it has been used in several laboratories for mixing up to 300 GHz and it is capable of achieving a single-sideband noise temperature of less than 50 K [2], [4]. However, up to now this type could not be used in practical communications applications because of its mechanical instability and the need for a critical point adjustment after each cooldown. In this report a new type of point contact is described which is packaged in a Sharpless wafer and yields mechanically rugged and permanent Josephson devices with good mixing characteristics.

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The author is with the Denver Research Institute, University of Denver, Denver, CO 80210.

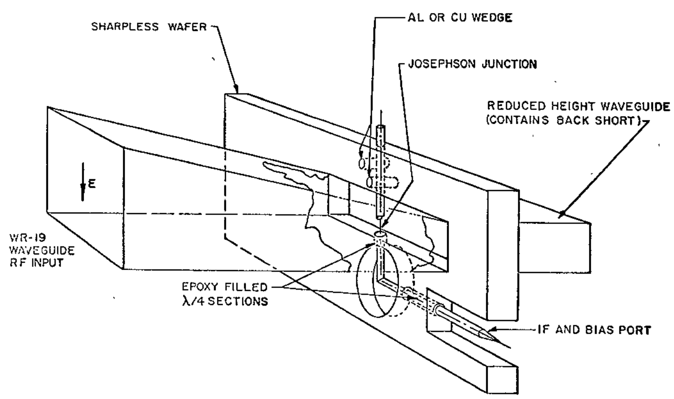


Fig. 1. Details of permanent Josephson junction in Sharpless wafer.

## II. Permanent Josephson Junction in Sharpless Wafer

Fig. 1 shows the Sharpless wafer with an attached input waveguide taper and a back short. The point contact is