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# Conversion Losses in Schottky-Barrier Diode Mixers in the Submillimeter Region

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*Abstract*—**Conversion losses, both intrinsic and parasitic, are calculated for Schottky diode mixers in the submillimeter region, and optimum mixer performance is shown to depend strongly upon operating frequency and upon diode diameter. The implications for high-frequency diode fabrication are discussed, and a comparison is made of the expected performance of GaAs, Si, and InSb Schottky diodes at frequencies up to 5 THz.**

## I. Introduction

RECENT interest in the development of sensitive low-noise heterodyne spectrometers in the submillimeter region of the spectrum has created a need for nonlinear mixing elements which will perform efficiently at wavelengths shorter than a millimeter. The role of mixing element at millimeter wavelengths is normally filled by Schottky-barrier diodes made on epitaxial GaAs, and in this paper we wish to consider quantitatively, how these diodes may be expected to perform at frequencies over 300 GHz.

The conversion loss $L$ of a mixer is the ratio of the available power from the RF source to the power absorbed in the IF load. A large fraction of this conversion loss occurs in the diode, arising from two separate processes, the intrinsic conversion loss $L_0$ and the parasitic conversion loss $L_p$, with $L=L'L_0L_p$. $L_0$ is the result of losses arising from the conversion process within the nonlinear resistance of the diode and for a broadband mixer has a theoretical minimum of 3 dB. $L_p$ is the loss associated with the parasitic elements of the diode, namely, the junction capacitance $C_0$ and the series resistance $R_s$. Finally, $L'$ is the total loss from other sources in the mixer, e.g., ohmic losses in the RF and IF circuits, mismatch losses, etc.

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The parasitic and intrinsic conversion losses $L_p$ and $L_0$ will be discussed in detail below. The figure of merit which is normally used in evaluating the high-frequency performance potential of a Schottky-barrier diode is the cutoff frequency $f_c = 1/2\pi R_s C_0$. In view of the fact that $R_s$ is frequency dependent [1] and $f_c$, as thus defined, can actually be multivalued, cutoff frequency is not a useful performance criterion at short wavelengths. Instead we examine in detail the behavior of $L_p$ and $L_0$, which can be calculated if $R_s$ and $C_0$ are known. The determination of $R_s$ as a function of operating frequency is included in Section II below, followed by the calculation of parasitic loss $L_p$ in Section III. In Section IV, intrinsic conversion loss $L_0$ is examined. Finally, in Section V, total conversion losses are calculated as a function of diode size for various frequencies. The results indicate that for a given operating frequency there is an optimum diode size which minimizes losses, irrespective of $f_c$. This conversion-loss minimum increases in value with frequency. Based upon our results we predict the performance which may be expected of state-of-the-art diodes in the submillimeter region, and discuss their implications for future diode fabrication.

## II. Series Resistance

Fig. 1(a) shows the cross-sectional details of a typical $n/n^+$ Schottky-barrier diode as used at millimeter wavelengths. The chip is fabricated by growing a thin ($\approx$0.2-$\mu$m) epitaxial layer of carrier concentration $\sim 2\times10^{17}$ $cm^{-3}$ on to a low resistivity $n^+$ substrate ($n^+ > 2\times10^{18}$ $cm^{-3}$) typically, 100 $\mu$m thick. The bottom of the substrate has an alloyed ohmic contact [2] while the front surface is covered with an $SiO_2$ passivation layer. Circular holes are opened in the $SiO_2$ photolithographically, and the Schottky barrier is formed by depositing Pt followed by Au through the holes onto the GaAs epilayer.

A simple equivalent circuit for this diode is shown in Fig. 1(b) consisting of the nonlinear barrier resistance $R_0$

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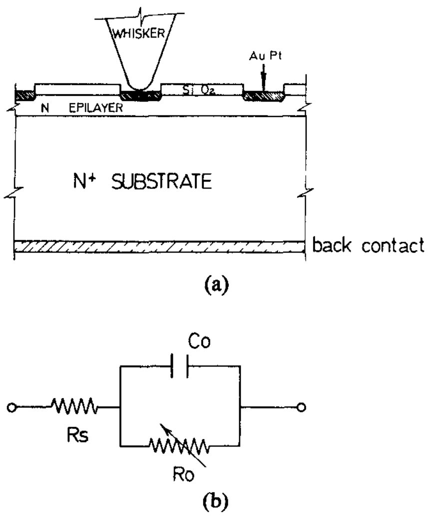


Fig. 1. (a) Cross section of a typical Schottky-barrier diode, including the contacting whisker. (b) Simple equivalent circuit for this diode.

in parallel with the depletion capacitance $C_0$, and the resistance $R_s$ in series with the junction. This series resistance consists of the sum of the spreading resistance, in both the epilayer and substrate, and the back contact resistance. The back contact resistance can generally be ignored, since contact resistivities of the order of $10^{-5}$ $\Omega \cdot cm^2$ are typical for $n^+$ GaAs, so for a normal chip size ($< 10^{-3}$ $cm^2$) this makes a negligible contribution [2]. The depletion layer capacitance per unit area at zero bias is given by

$$C_0 = \left(\frac{\epsilon q n}{2\phi_B}\right)^{1/2} \tag{1}$$

where $\epsilon$ is the dielectric constant, $q$ the electronic charge, $n$ the carrier concentration in the epilayer, and $\phi_B$ the Schottky-barrier height. The low-frequency values of spreading resistance for the undepleted epilayer ($R_{epi}$) and of the substrate ($R_{sub}$) are given by [3]

$$R_{epi} = \frac{t}{\sigma' \pi a^2} \tag{2}$$

and

$$R_{sub} = \frac{1}{2\pi\sigma a} \arctan\left(\frac{b}{a}\right). \tag{3}$$

In these expressions $a$ is the diode radius, assumed to be much larger than the undepleted epilayer thickness $t$, $\sigma'$ and $\sigma$ are the conductivities of the epilayer and substrate, and one assumes a cylindrical chip of radius $b$. The $R_s$ of a diode is normally measured from its dc current–voltage characteristics, and will consist of the sum of $R_{sub}$ and $R_{epi}$ described above, reduced by about 25 percent. This reduction has been explained by Held [4] who pointed out that a dc measurement at high currents (10 mA), which allows carriers to reach thermal equilibrium, increases diode temperature sufficiently to cause this underestimation in the size of $R_s$.

It has been known for some time [5] that as frequency is increased, $R_s$ will become larger due to the restriction of current to a thin surface layer of the order of the skin depth $d_s$, given by

$$d_s = (2/\omega\mu_0\sigma)^{1/2}. \tag{4}$$

In this expression $\mu_0$ is the semiconductor's magnetic permeability. The inverse dependence of $d_s$ upon frequency ensures that this effect will be important at short wavelengths, and it will be greater for high-conductivity materials like GaAs and InSb. The size of the skin effect for a 2.5-$\mu$m diameter GaAs diode has been measured by Held and Kerr [6] to add 2 $\Omega$ at 115 GHz. The extra series impedance due to the skin effect $Z'$ is given by [7]

$$Z' = \frac{(1+j)}{2\pi\sigma d_s} \ln(b/a). \tag{5}$$

In this expression, for an *epitaxial* configuration, the conductivity $\sigma$ is that of the substrate, not the epilayer. This approximation is used since the high-conductivity substrate will short circuit skin currents in the low-conductivity epilayer up to frequencies ($\gg 10$ THz), at which $d_s$ is of the order of the epilayer thickness.

It has been pointed out by Champlin and Eisenstein [7], [8] that the above treatment of series resistance ignores two potentially important high-frequency effects. First, above the dielectric relaxation frequency $\omega_d$, where

$$\omega_d = \sigma/\epsilon \tag{6}$$

an appreciable fraction of total current is displacement current. Second, carrier inertia becomes important above the scattering frequency $\omega_s$ given by

$$\omega_s = \frac{q}{m^* \mu} \tag{7}$$

where $m^*$ and $\mu$ are the carrier effective mass and mobility, respectively. Both of these effects together lead to carrier plasma oscillations which produce a considerable increase in the series impedance at frequencies close to the plasma frequency $\omega_p$, where

$$\omega_p = (\omega_s \omega_d)^{1/2} = (nq^2/m^*\epsilon)^{1/2}. \tag{8}$$

Champlin and Eisenstein discuss these phenomena in detail for Schottky-barrier diodes made on bulk material, and show that they have a pronounced effect upon series resistance and cutoff frequency in the neighborhood of $\omega_p$. Because of the $n^{1/2}$ dependence of $\omega_p$ upon carrier concentration, the plasma effect for epitaxial diodes will be noticed in the submillimeter region (e.g., diodes [9] with an epilayer concentration of $3 \times 10^{16}$ $cm^{-3}$ would have an $f_p (= \omega_p/2\pi)$ of approximately 1500 GHz). There has been some confusion in the literature about the magnitude of $f_p$ in GaAs. This arises from the experimental technique used in measuring $f_p$, which is based upon the detection of changes in the infrared reflectivity of the sample due to the contributions of the free carriers to the electrical susceptibility and conductivity [10]. The reflectivity exhibits a minimum at a frequency $f_{min}$ which is a function of carrier concentration, and enables the technique to be applied to the measurement of diffused surface carrier

TABLE I
$R_s$ CONSTITUENTS FOR A GaAs SCHOTTKY-BARRIER DIODE AT 300, 1500, AND 4100 GHz; GaAs DIODE* SERIES RESISTANCE (OHMS)

| Frequency | Re ($Z_{epi}$) (undepleted epilayer resistance) | Re ($Z_{sub}$) (substrate spreading resistance) | Re ($Z'$) (skin effect) | $R_s$ (Total) |
|---|---|---|---|---|
| 300 GHz | 3.8 | 3.0 | 3.3 | 10.1 |
| 1500 GHz | 4.9 | 3.0 | 8.7 | 16.6 |
| 4100 GHz ($\simeq f_p$) | 64.0 | 3.5 | 15.4 | 82.9 |

* Diode diameter: 2 $\mu$m
Epilayer: $n=2\times10^{17}\mathrm{cm}^{-3}$ $\rho=9.5\times10^{-3}\Omega\cdot$cm
$t=0.125$ $\mu$m
Substrate: $n^+=2\times10^{18}$ cm$^{-3}$ $\rho=1.2\times10^{-3}\Omega\cdot$cm
Temperature: 295 K

The dc *measured* $R_s$ of this diode would be $\sim$5 Ω.

concentration in semiconductors [11]. The position of this minimum in GaAs only coincides with $f_p$ for heavily doped material ($n>10^{18}$ cm$^{-3}$), and at low carrier concentrations there is considerable divergence between $f_{\min}$ and $f_p$. For example, GaAs with $n=10^{17}$ cm$^{-3}$ has a measured reflectivity minimum at 8.6 THz. However, it has been shown [12] that the Drude free-electron model fits the carrier behavior in GaAs at all IR frequencies, consequently $f_p$ is determined from (8), and is $\sim$3 THz.

To include these relatively low-frequency epilayer resonances, Champlin and Eisenstein's model for bulk diodes has been extended to epitaxial diodes by Kelly and Wrixon [1], [13]. The total complex series impedance of the diode $Z$ can be written as

$$Z=Z_{\mathrm{epi}}+Z_{\mathrm{sub}}+Z'. \tag{9}$$

Here, $Z_{\mathrm{sub}}$ and $Z'$ are the substrate spreading resistance and the skin effect impedance discussed by Champlin and Eisenstein, and are written as follows:

$$Z_{\mathrm{sub}}=\frac{1}{2\pi\sigma a}\arctan\left(\frac{b}{a}\right)\left\{\frac{1}{1+j(\omega/\omega_s)}+j(\omega/\omega_d)\right\}^{-1} \tag{10}$$

$$Z'=\left(\frac{\ln(b/a)}{2\pi}\right)\left(\frac{j\omega\mu_0}{\sigma}\right)^{1/2}\left\{\frac{1}{1+j(\omega/\omega_s)}+j(\omega/\omega_d)\right\}^{-1/2}. \tag{11}$$

Note that in the low-frequency limit $Z_{\mathrm{sub}}$ reduces to the expression in (2). The term $Z_{\mathrm{epi}}$ in (9) is the contribution of the undepleted epilayer, and it may be written, in the thin epilayer approximation ($t\ll a$), as follows:

$$Z_{\mathrm{epi}}=\frac{t}{\sigma'\pi a^2}\left\{\frac{1}{1+j(\omega/\omega_s')}+j(\omega/\omega_d')\right\}^{-1}. \tag{12}$$

This is essentially the dc epilayer resistance $t/\sigma'\pi a^2$ modified by the epilayer plasma-resonance term which increases strongly in the vicinity of $f_p'$. It is assumed that at any given operating frequency the imaginary parts of $Z$ may be matched by careful imbedding circuit design, so that the diode parasitic conversion loss will be characterized by the real component of $Z$, i.e., Re ($Z$). This will provide a theoretical *minimum* value for conversion loss which may be considerably higher if appreciable mismatch exists. The total series resistance is then given by

$$R_s=\mathrm{Re}\,(Z_{\mathrm{epi}})+\mathrm{Re}\,(Z_{\mathrm{sub}})+\mathrm{Re}\,(Z'). \tag{13}$$

By means of (10)–(13) it is possible to calculate $R_s$ at any operating frequency. Table I gives an indication of the changes in $R_s$ which might be expected for a typical millimeter diode at representative operating frequencies in the far IR. There is a steady increase in Re ($Z'$) due to the skin effect which is proportional (approximately) to $\omega^{1/2}$. However, in the neighborhood of the epilayer $f_p'$, Re ($Z_{\mathrm{epi}}$) becomes dominant. There will be a similar effect in Re ($Z_{\mathrm{sub}}$) at the higher resonance frequency of the substrate. In view of these large increases in $R_s$, it is clear that parasitic conversion loss will be frequency dependent, and this is examined in the next section.

## III. PARASITIC CONVERSION LOSS

The parasitic conversion loss of a Schottky diode is given by [14]

$$L_p=\frac{R_s}{R_m}\left(1+\frac{2R_s}{R_m}\right)\left(1+\frac{R_m}{R_s}+\omega^2C_0^2R_m^2\right). \tag{14}$$

In this expression $(1+2R_s/R_m)$ is the IF parasitic loss, while the remainder represents the RF parasitic losses. $R_m$ is the barrier nonlinear resistance at the RF frequency and it is assumed [15] that for a broad-band mixer it is related to the IF resistance $R_{\mathrm{IF}}$ by

$$2R_{\mathrm{IF}}=R_m. \tag{15}$$

The parasitic conversion loss can be seen from (14) to become larger both for small radii, where $R_s$ increases, and for large radii when the $C_0^2$ term increases. Thus $L_p$ is expected to be a strong function of diode size which minimizes for some optimum radii. $L_p$ was discussed by Bernues *et al.* [15] and it was pointed out that 1) for values of $f_c/f_{\mathrm{sig}}$ greater than 10, cutoff frequency has little effect upon parasitic conversion losses, and 2) $R_{\mathrm{IF}}/R_s$ is very important and should be greater than 10 to keep parasitic conversion loss below 1 dB. These conclusions are unfortunately not entirely relevant in the submillimeter region where $f_c/f_{\mathrm{sig}}$ may be 3 or less, and $R_{\mathrm{IF}}/R_s$ may be less than 1. Under these conditions more useful information will be obtained by examining the variation in conversion loss as a function of diode diameter. To do this, (10)-(13) are used to determine $R_s$; $C_0$ is assumed independent of frequency and given by (1),[1] and these values are then substituted into (14). The results are shown in Fig. 2.

[1]We have chosen $n^+=2\times10^{18}$ cm$^{-3}$, which is reasonably easy to obtain. However, good epitaxial layers have recently been reported [16] on substrates with over $5\times10^{18}$ cm$^{-3}$ concentration.

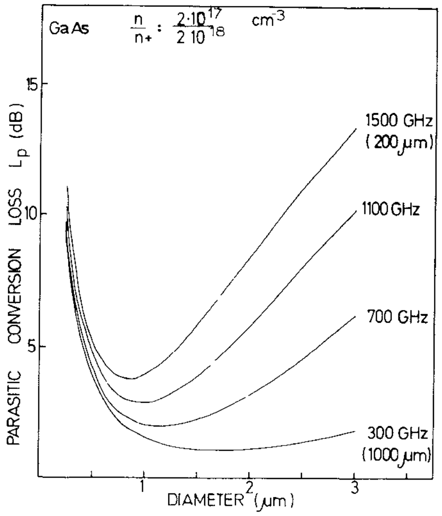


Fig. 2. The parasitic conversion loss $L_p$ of a mixer as a function of diode diameter at various operating frequencies for an $n/n^+$ epitaxial GaAs diode with undepleted epilayer thickness $t=0.125$ $\mu$m, $n=2\times 10^{17}$ cm$^{-3}$, $n^+=2\times 10^{18}$ cm$^{-3}$, and $R_{IF}=100$ $\Omega$.

As expected, at a given frequency $L_p$ has a minimum, this minimum becoming sharper at shorter wavelengths. Thus at 300 GHz the smallest conversion losses are obtained with a diode of diameter 2 $\mu$m, which fortuitously is about the limit obtainable with photolithographic techniques and is the size normally used for existing millimeter mixers. At the higher frequencies the value of the minimum conversion loss is higher, and corresponds to slightly smaller diameters so that, for example, at 1500 GHz $L_p$ has a 3.8-dB minimum at a diode diameter of 0.8 $\mu$m. It has been predicted that for high-frequency operation Schottky diodes will be capacitance limited [17], and this concept is seen to correspond to the region where $L_p$ is dominated by $\omega^2 C_0^2 R_m R_s$ (cf. (14)). For a given frequency the capacitance does dominate the parasitic losses for the larger diameters but when the diameter decreases below the optimum, $R_s$ losses begin to dominate and $L_p$ rises again. In addition, the steepness of the curve on the low-diameter side shows that it is better to have a diode whose diameter is greater than optimum, rather than smaller. This is important since it indicates that it is not sufficient to simply reduce diode diameter, e.g., by using electron beam lithography (EBL), to obtain enhanced high-frequency performance.

It should be emphasized that there are three separate effects adding together to give the results of Fig. 2.

1) At any frequency, if diameter is made small enough, $L_p$ increases steeply due to the $R_s/R_m$ terms of (14).

2) There is a steady increase in the minimum $L_p$ as frequency increases, due to the skin effect. From Table I it is clear that for the diode configuration chosen, this is responsible for most of the increase at 1500 GHz.

3) Within the plasma resonance bandwidth, $L_p$ increases even more steeply.

## IV. Intrinsic Conversion Loss

The type of broad-band mixer which should be used at millimeter frequencies has been a subject of discussion for some time. Two models which might be useful are the $Y$-mixer, in which all the out-of-band frequencies are short circuited and the $Z$-mixer, in which all the out-of-band frequencies are open circuited. Saleh [18] has compared the relative advantages of these, and shows that in theory one needs infinite pump power and/or dc bias to optimize the performance of a $Y$-mixer while the $Z$-mixer can be optimized with finite pump power and dc bias. In practice, however, it will be very difficult to obtain an ideal $Z$-mixer since the diode capacitance will tend to short circuit the high-order out-of-band frequencies, which should be open circuited. In addition, the theoretical optimization of mixer performance sometimes demands very low dc bias and diode impedances which are far too high to be successfully matched in the imbedding network. Because of these and similar considerations, Saleh concluded that no general statement could be made as to which type is better. In this section we look at the intrinsic conversion losses $L_0$ of a $Y$-mixer, which have been analyzed by McColl [14] in a recent paper.

When the diameter of a diode is decreased, intrinsic conversion losses increase steeply due to the impedance requirements which the circuit places upon the device. In order for the diode to couple effectively to a circuit with a specific impedance it must pass approximately the same current, independent of junction size ($R_0 \propto 1/I$). Consequently, a physically smaller diode requires larger current densities, and hence the dc bias voltage $V_0$ must be increased. This results in a limitation on the useful amplitude of the local oscillator voltage $V_1$, because the junction $I-V$ characteristic in the forward direction is only nonlinear for applied voltages less than the barrier height potential $V_B$, of the metal–semiconductor interface. Since $V_0 + V_1 < V_{B'}$, decreasing the area serves to limit $V_1$ and consequently will increase $L_0$.

McColl showed that the lower limit for intrinsic conversion loss $L_0$ for given values of $V_0$ and $V_1$ is obtained when a thermionic-emitting diode is optimally coupled in its imbedding circuit. This lower limit $L_{0o}$ is given by[2]

$$L_{0o} = \frac{2}{\eta}\left(1+\sqrt{1-\eta}\,\right)^2 \tag{16}$$

where

$$\eta = 2I_1^2 / \left\{ I_0^2 (1 + I_2/I_0) \right\} \tag{17}$$

and $I_0$, $I_1$, and $I_2$ are modified Bessel functions of the first kind, with argument $(qV_1/kT)$. For a given diode size, the value of LO voltage $V_1$ to be used is obtained by numerically solving

$$\frac{d}{d_m} = \left\{ (I_0 + I_2)\sqrt{1-\eta}\, \right\}^{-1/2} \exp\left(\frac{qV_1}{2kT}\right) \tag{18}$$

where $d_m$ is the smallest possible diameter for which the impedance matching condition can be met.

[2]McColl shows that by keeping the circuit impedances fixed and varying $V_0$ and $V_1$, it is sometimes possible to reduce $L_0$ somewhat below $L_{0o}$. For simplicity this is not included here.

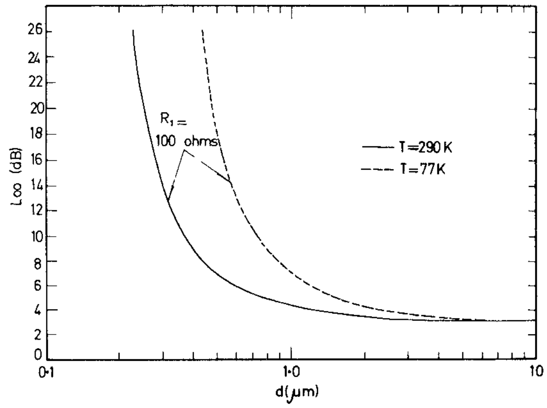


Fig. 3. Optimum intrinsic conversion loss $L_{0o}$ versus diameter for a thermionic emitting n-type GaAs Schottky-barrier diode at 290 K with an $R_m$ of 100 Ω at 290 K.

$$d_m = (\pi q R_m A^* T/4k)^{-1/2} \tag{19}$$

where $A^*$ is the Richardson constant. The calculated $L_{0o}$ for a room temperature GaAs diode is shown in Fig. 3 for a 100-Ω RF source impedance. Clearly, $L_{0o}$ increases strongly as $a$ is reduced towards $d_m$, so that materials with a large Richardson constant have a distinct advantage, in that intrinsic conversion loss will not become significantly larger than 3 dB until the value of $a$ nears that of $d_m$, which with $R_m = 100$ Ω at 290 K is ∼0.2 μm for GaAs and ∼0.04 μm for Si. In addition, cooling to 77 K causes a significant increase in $d_m$, thus increasing losses even more for small diameter diodes.

## V. Discussion and Results

The complete minimum conversion loss $L_p L_{0o}$ can now be calculated for any diode from its diameter and epilayer geometry, knowing the doping concentration of epilayer and substrate. Thus in Fig. 4, we show $L_p L_{0o}$ for the same diode configuration as was used for Fig. 2. Comparing Figs. 4 and 2, $L_{0o}$, as expected, has added about 3 dB to the 300-GHz minimum, and about 4 dB to the 1500-GHz minimum. This is what we would expect, since $L_{0o}$ should be close to 3 dB, but will rise somewhat at higher frequencies where the smaller optimum diode diameters are closer to $d_m$.

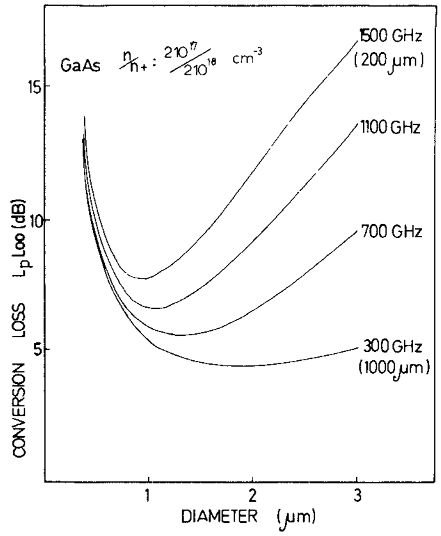


Fig. 4. Total conversion losses $L_{0o}L_p$ as a function of diode diameter for various operating frequencies. Diode characteristics identical to those used for Fig. 2.

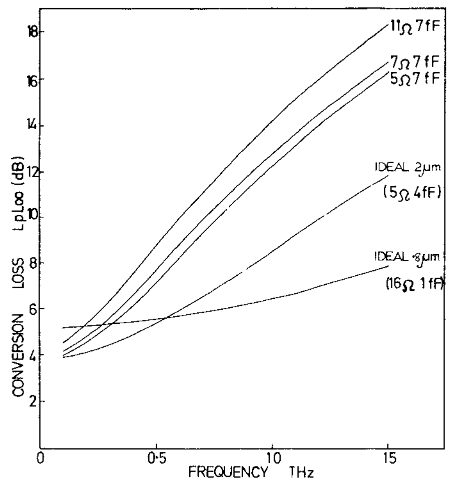


Fig. 5. Total conversion loss $L_{0o}L_p$ for some Schottky-barrier diodes discussed in the text, from 1000 to 200 μm.

Fig. 5 shows the calculated conversion loss $L_{0o}L_p$ (remember, this is a lower limit), as a function of frequency up to 1500 THz (so that in this graph $f_p$ plays a very minor role) for the following GaAs epitaxial diodes.

1) 2-μm diameter diodes with measured $R_s$ of 11 Ω and $C_0$ of 0.007 pF.[3] These diodes are included since measured data for them are available [19], indicating a 2-dB increase in conversion loss between 200 and 361 GHz and 10 dB between 200 and 671 GHz. Our model gives 1.7 and 5.3 dB as lower limits for the increases expected at these frequencies. However, in the case of the 671-GHz measurement, additional loss may have been caused by the fact that at this frequency the mixer was operating in an LO starved condition.

2) 2-μm diodes with measured characteristics of 7 Ω and 0.007 pF.[4]

3) 2-μm diodes with characteristics of 5 Ω and 0.007 pF. These are assumed to have been produced on the same GaAs chip as diode 2) by the EBL techniques of Wrixon and Pease [20], so that $R_s$ has been reduced by 30 percent from 7 to 5 Ω.

4) An "ideal" 2-μm diode with capacitance, calculated from (1), of 0.004 pF, and an assumed undepleted epilayer thickness of 0.125 μm giving a "measured" $R_s$ of about 5 Ω.

5) A diode optimized for operation at 1500 GHz with a 0.8-μm diameter which would have measured dc characteristics of 23 Ω and ≲0.001 pF.

[3] Calculated from our model by fixing $C_0$ and adjusting epilayer thickness until the dc calculated $R_s$ ($R_{epi} + R_{sub}$ corrected for thermal equilibrium effect) matches the measured $R_s$.

[4] These diodes have been produced at the European Millimeter Diode Laboratory, University College, Cork, Ireland.

Figs. 4 and 5 together contain some important information. First, one sees from Fig. 4 that although losses at 300 GHz are relatively constant for diameters between 1 and 3 $\mu$m, there is a large variation in the 1500-GHz losses for these diameters. Thus for wide bandwidth operations, the diode should be optimized for the high-frequency limit. Second, the higher the operating frequency, the sharper, the minimum, and the tighter the tolerances required of the diode geometry. Thus at 300 GHz, losses are within 1 dB of optimum for $2 \pm 1$ $\mu$m, but at 1500 GHz the same 1-dB limit requires $0.9 \pm {0.5 \atop 0.3}$ $\mu$m. Fig. 5 shows that with a 0.8-$\mu$m diameter diode it should be theoretically possible to operate between 300 and 1500 GHz with conversion loss staying between 5 and 7 dB. The numbers will, of course, be somewhat higher due to other sources of loss and to the difficulty of tuning out all of the reactive part of $R_s$. However, the lower limit of 2 dB extra diode-related conversion loss between 300 and 1500 GHz is encouraging. Comparing with the ideal 2-$\mu$m diode curve of Fig. 5 shows the importance of high-frequency size optimization. However, the 2-$\mu$m diodes being fabricated at present have both $R_s$ and $C_0$ higher than they theoretically should be, and it is thus important to master the technique of fabricating these relatively large 2-$\mu$m diodes, to approach their predicted performance.

Recent calculations by Kerr [29] and measurements by Held [4] indicate that a parasitic capacitance of the order of 1 fF may exist between the semiconductor and the diode contacting whisker. This additional capacitance has not been included in our model since in effect it is in parallel with the chip, and its reactance can to a large extent be tuned out by adjustment of the backshort. The effect of any remaining capacitance would be to increase the minimum conversion loss plotted in Fig. 4, and to make high-frequency optimum diode diamters slightly larger.

There are some data published [21] for a 5-$\mu$m and 1 1/2-$\mu$m diode operating at 1760 GHz in the same mixer, which show that the 5-$\mu$m diode, although having a larger $f_c$ than the 1 1/2-$\mu$m diode (1193 GHz compared with 601 GHz), had a signal/noise ratio only one-twentieth as large. This result is now quite understandable, since from Fig. 4 we would expect a 5-$\mu$m diode to be extremely bad at 1760 GHz. An ideal 1 1/2-$\mu$m diode at 1760 GHz can be shown to have a 13.5-dB conversion loss advantage over a 5-$\mu$m diode.

Apart from careful choice of diode size, the three measures which are probably most important in reducing conversion losses are 1) keeping the undepleted epilayer thickness to a minimum to reduce the epilayer series resistance, 2) using material with a sharp epilayer/substrate interface to keep $R_{sub}$ low and back-breakdown voltage high, and 3) metallizing the sides and front surface of the chip to reduce the skin-effect resistance, as suggested by Calviello and Wallace [22]. With large diameters, where spreading resistance is low, then skin effect is a major part of $R_s$, and its reduction by metallization will produce substantial improvement. With diodes of diameter 2 $\mu$m or less, however, the major part of $R_s$ is from epilayer and substrate, and not as much improvement can be expected. This is shown in Fig. 6. At 500 GHz metallizing the epilayer to within 15 $\mu$m of the diode will give a 2-dB improvement for a 6-$\mu$m diode but only 0.3 dB for 2 $\mu$m. This theoretical calculation does not include increases in RF diode resistance from sources such as 1) surface roughness, and 2) subsurface imperfection induced during the chip-cutting process. Surface roughness will increase the effective path length for the skin-effect calculation, and will cause resistance increases when the roughness is comparable to the skin depth in the material. This effect should be small for reasonably smooth material, since the effect is proportional to the logarithm of the path length, as in (11). However, the decrease in mobility due to surface damage during sawing may be an important effect at high frequencies when the current passes through the damaged layer only. Thus metallizing the sides of chips is probably more important than front-surface metallization, and will help to improve the RF behavior.

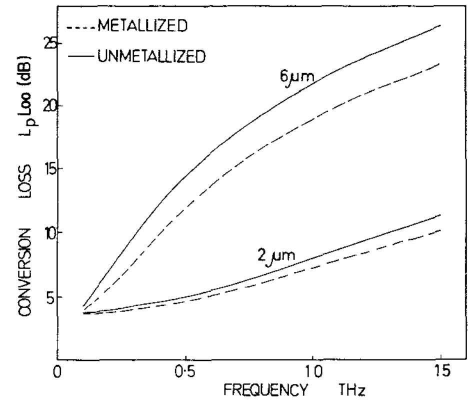


Fig. 6. Optimum conversion loss for an n/n$^+$ GaAs diode with a metallized front surface to reduce skin effect impedance. The metallization symmetrically surrounds the diode with a 15-$\mu$m separation.

We next consider what the model predicts for *optimum* conversion loss at higher frequencies, up to 5 THz, by plotting the minimum $L_pL_{0_o}$ against frequency. Fig. 7 shows the difference which intrinsic loss makes, adding about 3 dB at low frequencies, but increasing somewhat at higher frequencies where the optimum diameter approaches closer to $d_m$. It is interesting that even at 5 THz, optimum diode diameter is still no smaller than 0.5 $\mu$m. The dominant feature of Fig. 7 is the huge increase in conversion loss at the epilayer resonant frequency, when $R_s$ becomes very large.

Curves 3 and 4 of Fig. 8 show what might be expected of Si material for which substrate doping densities of $10^{20}$ cm$^{-3}$ are possible [15] using As as a dopant. The predicted optimum performance of these diodes is not as good as that of GaAs, curve 1, with the same undepleted epilayer thickness of 0.125 $\mu$m. This thickness was used because it is approximately that already achieved in good 2-$\mu$m Schottky diodes. Diodes with no undepleted epilayer remaining at zero bias have characteristics approaching those of Mott diodes—such diodes have re-

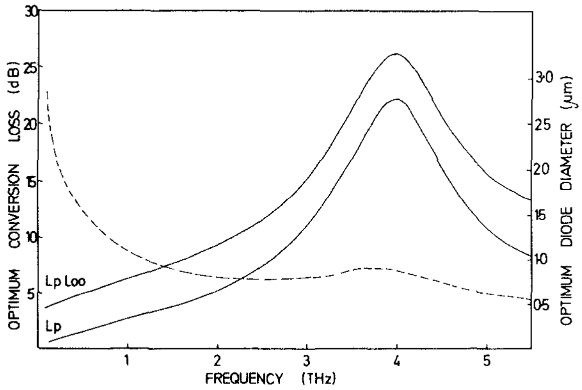


Fig. 7. Optimum conversion loss (solid curves) and the corresponding diode diameter (broken curve) plotted against frequency for a GaAs n/n$^+$ diode, with $n/n^+ = 2\times10^{17}/2\times10^{18}$ cm$^{-3}$, and $t=0.125$ $\mu$m.

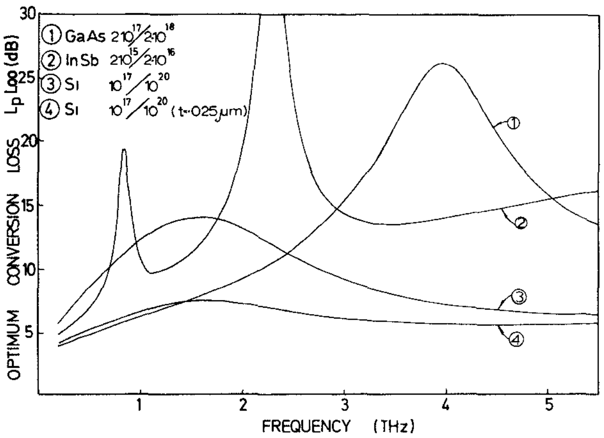


Fig. 8. Optimum $L_pL_{0_0}$ data against frequency, for various diode configurations. In each case diode RF impedance is assumed to be 100 Ω and temperature 290 K, except for InSb which is assumed to be at 77 K.

cently been successfully fabricated [23], and initial results are very promising. For reference we have added an Si curve with $t=0.025$ $\mu$m, since it has been claimed that much sharper interfaces can be produced on Si epitaxy. However, the performance of this improved Si diode is not significantly better than the GaAs with $t=0.125$ $\mu$m.

InSb is included since this material has been of interest for some time [24], [25], due to the possibility of making Schottky-barrier diodes from it which can use lower carrier concentrations due to its extremely high mobility. Padovani and Stratton [26] have shown that when a Schottky diode is cooled sufficiently, the current is mainly via field emission, in which case it reaches its limiting noise temperature $T_{eq}$ given by [28]

$$T_{eq} = \frac{qn}{2k}\left(\frac{n}{4\epsilon m^*}\right)^{1/2}. \tag{20}$$

For an n/n$^+$-InSb diode with $n \sim 2\times10^{15}$ cm$^{-3}$, the $n^{1/2}$ term in this equation gives a shot-noise improvement of a factor of more than 5, over a GaAs diode. This possibility of improved shot-noise behavior has encouraged attempts to make InSb Schottky-barrier diodes. These efforts, however, have run into problems with high series resistance and leakage currents. It can be seen from curve 2 of Fig. 8 that another disadvantage of using low $n$ material is the correspondingly low plasma-resonance frequencies.

The InSb n/n$^+$ concentrations for this curve were chosen to give a diode with approximately the same epilayer and substrate resistivities as GaAs. By changing the concentrations, the position of $f_p$ may be varied, and for InSb the substrate resonance frequency can be made much higher, but the epilayer $f_p$ will be in the 1000-GHz region. Attempts to circumvent this problem by using bulk InSb diodes necessitate using the lowest possible concentration consistent with keeping $R_s$ small, and will have $f_p$ in the 2–3-THz region.

Si looks quite promising for frequencies above 2.5 THz since the higher conductivity substrates possible on it mean that there will be a broad gap between $f_p$ epilayer and $f_p$ substrate, giving a flat region where operation would be better than GaAs. In particular, if it were possible to get $t \sim 0.025$ $\mu$m then it would keep optimum losses $<8$ dB up to 5 THz. It should be mentioned that the model discussed here does not include transit time effects in the epilayer space-charge region which, as discussed by van der Ziel [27], will degrade diode response even further at frequencies above $f_p$.

## VI. Conclusions

The series resistance $R_s$ of a Schottky-barrier diode is strongly frequency dependent due to skin effect and carrier plasma resonance. A model has been considered which allows the calculation of $R_s$, and based upon this, the determination of optimum-mixer conversion losses, both parasitic and intrinsic, for a diode of given diameter.

The results show that considerable optimization of conversion losses is possible. In summary, the steps necessary for optimization of the submillimeter performance of Schottky-barrier diodes are listed.

1) The diode should be fabricated upon GaAs epitaxial material in order to minimize the shot-noise contribution, and eliminate avalanche noise.

2) It is important to aim at having an epilayer thickness equal to the zero-bias depletion width, in which case epilayer resistance would only appear during forward LO excursions and effective undepleted epilayer thickness would be very small.

3) Diode-fabrication techniques need improvement so that the $C_0$ and $R_s$ of diodes $<2$-$\mu$m diameter are close to their theoretical values.

4) Since electron beam lithography will be necessary for precisely optimizing diode diameters, it should simultaneously be availed of to increase perimeter/area ratios, and reduce $R_s$.

5) Finally, the diameter should be chosen to optimize losses at the high-frequency end of the mixer bandwidth.

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