I-3. ULTIMATE NOISE FIGURE AND CONVERSION LOSS OF THE SCHOTTKY BARRIER MIXER DIODE

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Considerable interest has recently been shown in the use of the epitaxial Schottky barrier (ESBAR) diode as a microwave frequency down-converter. For the first time it has become possible to surpass the performance of the redoubtable point-contact diodes, through the use of photoresist techniques to achieve small areas and epitaxial material to achieve low series resistance. The new diodes are also more reproducible, have much lower reverse current leakage, lower 1/f noise, and can be designed for much higher dynamic range. Herein we calculate that they should exhibit overall calculated noise figures as low as 3 dB at X-band when the image is short-circuited and the following i-f amplifier has a 2 dB noise figure.

Mixer Noise and Gain Formulae. The theory for calculating mixer gain has been established for a number of years and has been applied to mixers using point-contact diodes by Herold et al[1] and others. The gain and impedance formulae used in this paper are identical to those used by Herold but this paper differs in that he did not develop the noise theory, nor did he consider an exponential I-V characteristic.

The basic noise theory for diode mixers has been developed by Strutt[2] and summarized by Kim[3]. This theory neglects thermal noise generated in the diode series resistance and expresses the results in terms of ratios of the Fourier coefficients of conductance (g) and equivalent shot noise current (I_{eq}) where these quantities are time varying due to the application of some arbitrary local oscillator voltage waveform across the diode.

$$g = g_o + 2g_{c1} \cos \omega_{\ell o} t$$

$$I_{eq} = I_{eo} + 2I_{e1} \cos \omega_{\ell o} t$$

The theory also neglects the effect of diode parasitic reactances, transit time phenomena, and conversion from frequencies near the higher harmonics of the local oscillator. The comparatively simple formulae presented below for minimum noise figure and conversion loss are for the case of the short-circuited image; more complicated formulae are available for cases where the image conductance is either zero or equal to the signal source. The short-circuited image gives noise and loss figures approximately half a dB higher than those obtainable with an open circuit.

Application to the Schottky Barrier Diode. The equation relating current and voltage in the Schottky Barrier diode is:

$$i = i_o(e^{\alpha V} - 1)$$

hence, $$g = \alpha i_o e^{\alpha V} \cong \alpha i \tag{1}$$

Also, the mean square shot noise current is given by:

$$\overline{i_{sh}^2} = 2qI_{eq}\Delta f$$

where

$$I_{eq} = (i+2i_o) \cong i \tag{2}$$

Throughout this paper it will be assumed that the forward current (i) greatly exceeds the reverse saturation current (i_o) and that the current vs voltage characteristic is purely exponential. Figure 2 shows that this will lead to errors in the noise calculations when the peak diode voltage is smaller than 0.1 volts but this case is of little interest because of the high noise figure.

Since g and I_{eq} are simply related through the constant (α), it is easy to show

$$\frac{g_{c1}}{g_o} = \frac{I_{e1}}{I_{eo}} \tag{3}$$

If a sinusoidal oscillator voltage is assumed, it is possible to express V as:

$$V = V_o + V_1 \cos \omega t \tag{4}$$

where V_o is the DC bias voltage. Substitution in Eq. (1) then gives:

$$\begin{aligned} g &= \alpha i_o e^{\alpha V_o} \cdot e^{\alpha V_1 \cos \omega t} \\ &= \alpha i_o e^{\alpha V_o}[I_o(\alpha V_1) + 2I_1(\alpha V_1)\cos \omega t + \dots] \end{aligned} \tag{5}$$

where I_o, I_1, etc. are modified Bessel functions with argument (αV_1). Hence from (3) and (5)

$$\frac{g_{c1}}{g_o} = \frac{I_{e1}}{I_{eo}} = \frac{I_1(\alpha V_1)}{I_o(\alpha V_1)} \tag{6}$$

Applying the results of Eq. (6) to the mixer gain and noise formulae, it is possible to show

$$G_{av(\text{min noise})} = 1/L = (I_1/I_o)^2\left(1 + \sqrt{1 - (I_1/I_o)^2}\right)^{-2} \tag{7}$$

$$F_{min} = (L+1)/2 \tag{8}$$

$$g^2(\text{optimum source}) = g^2_{out} = g^2_o - g^2_{c1} \tag{9}$$

Hence the noise ratio is given by

$$N_R = F \cdot G_{av} = \frac{1}{2} + \frac{1}{2L} \tag{10}$$

Note that the gain and noise figure are functions of (αV_1) only and are independent of bias V_o and reverse current i_o. The mixer loss, noise figure and noise ratio are plotted as functions of peak local oscillator voltage in Figure 1. As the local oscillator voltage increases, the available gain, noise figure and noise ratio all approach unity.

Figure 3 shows the optimum source conductance and absorbed power for the case where the peak instantaneous current is 10 milliamperes.

Effect of Spreading Resistance and Large L.O. Voltages. When the diode has finite series resistance r_s, then both the forward and also the reverse impedance at microwave frequencies are affected.

In the forward direction, increasing voltage lowers the junction resistance until it is finally limited by the series resistance. Beyond this point further drive only widens the effective relative conduction interval t/T (Fig. 4), which reduces the relative conversion conductance g_{c1}/g_o.

If the forward excursion is limited to the point where the diode resistance becomes comparable to r_s ($\cong$ 10 mA for the GaAs ESBAR diode in Fig. 2), the only way to reduce the loss and noise figure with increased sinusoidal pumping is to use reverse bias. It should be emphasized, however, that the loss will also increase rapidly if the voltage swings too far in the negative direction; in particular, the series resistance leads to a residual diode conductance $r_s \omega^2 c_j^2$ which should be one or two orders of magnitude smaller than g_o if this effect is to be avoided, i.e.,

$$\frac{I_o(\alpha V_1)}{e^{\alpha V_1}} > 100\left(\frac{f}{f_{co}}\right)^2 .$$

Typically for a diode with a 500 GHz cutoff frequency operating with a peak current of 10 mA at 10 GHz, the maximum peak local oscillator swing calculated from this equation is found to be about one volt and from Fig. 1 the noise figure should be 3 dB overall, including a 2 dB i-f amplifier.

Note that large voltage excursions require the largest possible ratio of reverse to forward diode resistance (f_{co}/f). In general at microwave frequencies, this switching ratio is far lower than the low frequency switching ratio $(r_{reverse}/r_s)$ and it is mainly for this reason that the capacitance of mixer diodes has always been kept very low. From this point of view mixer diodes should have very high cutoff frequencies; values in excess of 500 GHz have been obtained in the best GaAs varactors made by J. C. Irvin.

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References. (1) Herold, E.W., Bush, R.R., Ferris, W.R., "Conversion Loss of Diode Mixers Having Image-Frequency Impedance," Proc. IRE, 33, pp. 603-609, September 1945.

(2) Strutt, M.J.O., "Noise Figure Reduction in Mixer Stages," Proc. IRE, 34, pp. 942-950, December 1946.

(3) Kim, C.S., "Tunnel Diode Converter Analysis", IRE Trans. ED-8, pp. 394-405, September 1961.

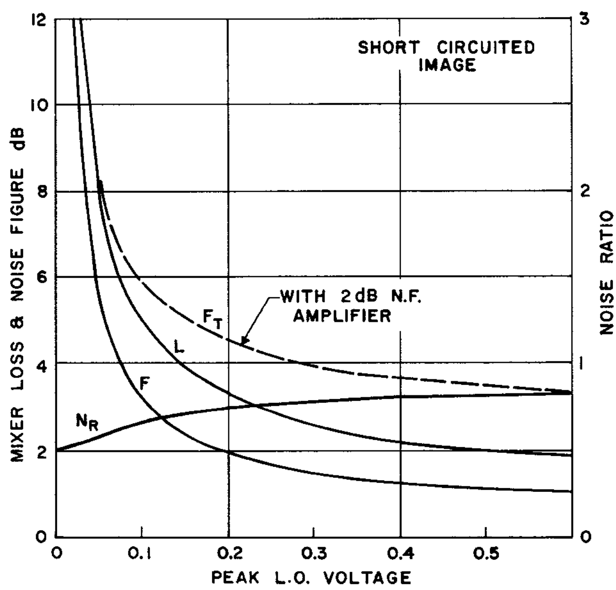

Figure 1. Schottky Mixer Performance Applicable to Diodes with No Series Resistance

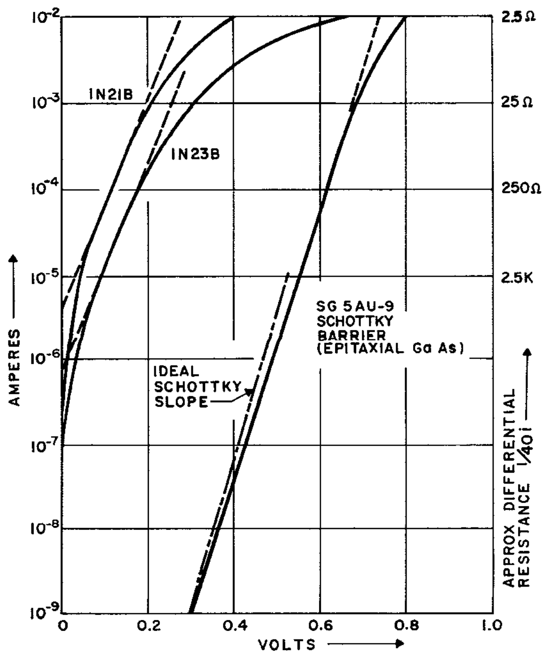

Figure 2. Point Contact and Schottky Barrier I-V Characteristics

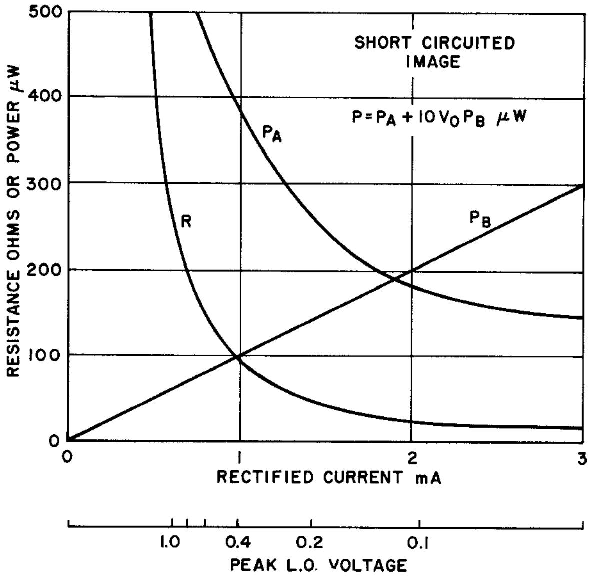

Figure 3. Mixer Optimum Input-Output Resistance and Absorbed Power for Fixed I_{max} = 10 mA

$$\text{MAX. AVAIL GAIN} = \frac{\left(\frac{g_{c1}}{g_0}\right)^2}{\left(1+\sqrt{1-\left(\frac{g_{c1}}{g_0}\right)^2}\right)^2} = 0\,\text{dB IF } \frac{g_{c1}}{g_0} = 1$$

$$\text{WHERE } g = g_0 + 2g_{c1}\cos\omega t + \ldots\ldots\ldots.$$

$$\text{AND } g_{OUT} = g_{SOURCE} = \sqrt{g_0^2 - g_{c1}^2}$$

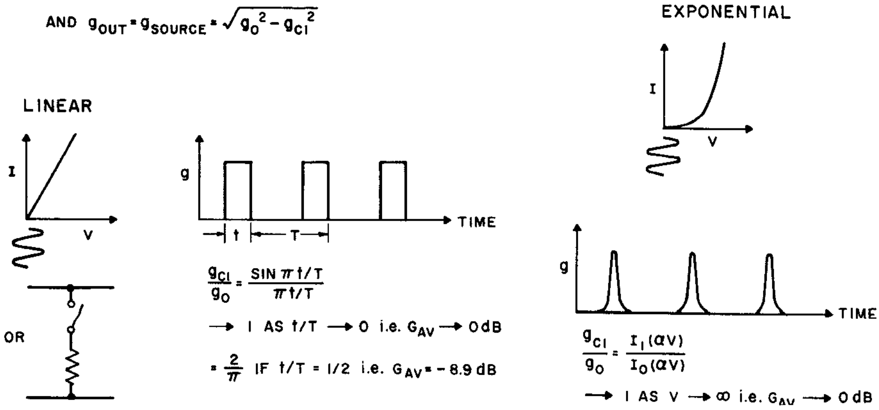

Figure 4. Linear and Exponential Mixer Gain Characteristics

I-4. SOME SELECTED TOPICS IN BRITISH SOLID-STATE RESEARCH

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