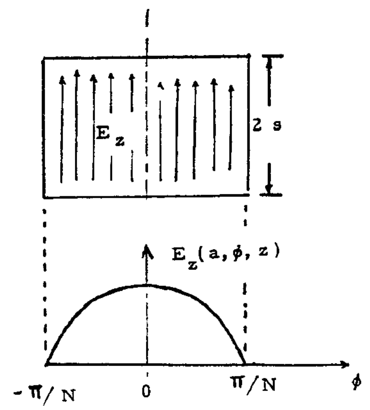

Fig. 2. Rectangular aperture and the vertical electric field distribution assumed in the analysis

and

$$-C_m^n u_n^2 I_m(u_n a) = f_{m,n}. \tag{34}$$

Again we choose a rectangular aperture with a cosinusoidal variation in the electric field such as given by the right-hand side of (20). But here, if the nonzero field E_z is constant within the aperture ($|z| < s$), we must insist that $l > s$; otherwise, (25) would be an improper representation.

Equation (26) is now reduced to

$$f_{m,n} = \frac{2\hat{\epsilon}_m}{\pi l} \int_0^l \int_0^{\pi} E_0 \cos\left(\frac{N}{2}\phi\right) \cos m\phi \cos\left(\frac{2n+1}{2l}\pi z\right) dz\, d\phi \tag{35}$$

which is evaluated to give

$$f_{m,n} = \frac{2\hat{\epsilon}_m E_0}{\left(n+\frac{1}{2}\right)\pi^2} \sin\left(\frac{2n+1}{2l}\pi s\right) \cdot \begin{cases} \dfrac{1}{2}\dfrac{N}{(N/2)^2 - m^2}\cos\dfrac{m\pi}{N} \\ \text{or } \dfrac{\pi}{2N} \text{ if } m = \dfrac{N}{2}. \end{cases} \tag{36}$$

This result is similar to (22). However, in the present case, we must keep $s < l$ to avoid a contradiction on the electric field at the ends of the cylinder. Of course, aperture conditions can be made to permit the E_z field at $\rho = a$ to vanish at $|z| = l$.

V. Concluding Remarks

The analytical results given here provide a means to calculate the internal fields in the cylinder for any assumed aperture distribution. The total power density P is then computed from

$$P = \sigma\left[|E_\rho|^2 + |E_\phi|^2 + |E_z|^2\right]/2 \tag{37}$$

in watts per meter^3. Of course, the results will depend on which model is used. If the cylinder is fully encased in a metal cast, except for the aperture, the first model considered above is indeed appropriate and the derived expressions for the fields are formally exact. The case where the metal only encloses the curved surfaces of the cylindrical target is really a much more complicated situation because the electromagnetic fields emanate to the external region. However, it is a good approximation to ignore these external fields insofar as making estimates of power deposition at points within the cylinder.

Finally, we should mention that the present analysis can be easily extended to any number of similar rectangular apertures arrayed around the periphery of the cylinder. As in the two-dimensional models [5], [6], we need merely to superimpose the results for a single aperture with due regard to angular location and individual excitation. Concentrically layered models pose no additional difficulty except for the increased complexity.

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Noise Reduction in GaAs Schottky Barrier Mixer Diodes

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***Abstract*—The sensitivity of heterodyne receivers operating at millimeter and submillimeter wavelengths is limited by the noise produced in the mixer element. In this paper we investigate the presence of excess noise in GaAs Schottky barrier mixer diodes. Comparison of the measured noise data with that predicted from noise models indicates that these devices typically exhibit excess noise. An additional fabrication step, which removes several hundred angstroms from the GaAs surface before the anode contact is formed, greatly reduces this excess noise. This additional step is outlined, and experimental evidence is presented.**

I. Introduction

The sensitivity of heterodyne receivers operating at millimeter and submillimeter wavelengths is limited by the noise produced in the mixer element [1], [2], typically a GaAs Schottky barrier mixer diode. These devices are commonly cooled to cryogenic temperatures (of order 20 K) to minimize their contribution to the receiver noise. Thus, it is very important that all sources of excess noise in these devices be identified and eliminated. Schneider [3] has recently reported an anomalous peak occurring in the noise temperature versus forward current characteristic of small diameter (< 2 μm) Schottky barrier diodes. This excess noise has recently been linked to edge effects, possibly caused by stress at the GaAs/SiO_2 interface [4].

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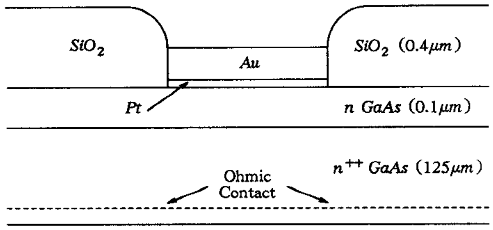

Fig. 1. Cross-sectional view of a typical GaAs Schottky barrier mixer diode.

In this paper we report on the presence of excess noise in large diameter (> 2 μm) Schottky barrier diodes. These larger devices are less susceptible to edge effects due to their increased surface-area-to-periphery ratio, and do not typically exhibit the noise peak discussed in [3] and [4]. Comparison of measured noise characteristics of these devices with those predicted by current noise theories, however, indicates that excess noise is indeed present. An additional step in the device fabrication process, by which several hundred angstroms of GaAs is etched from the wafer surface just prior to anode contact formation, has been found to greatly reduce this excess noise. In fact, the noise characteristics of these devices are very close to the minimum noise predicted by theoretical models. This effect is additional evidence of the importance of the quality of the metal–semiconductor interface to the performance of Schottky diodes.

II. The Schottky Diode

The cross section of a typical GaAs Schottky barrier mixer diode is depicted in Fig. 1. The active GaAs layer is typically doped in the 10^{16}–10^{17} range to reduce the tunneling current at low temperatures and is grown by molecular beam epitaxy on a highly conductive GaAs substrate to reduce the series resistance. The SiO_2 passivation layer is formed by chemical vapor deposition at 350°C by reaction of silane and oxygen gases, and is typically 4200 Å thick. Circular anode windows are defined in the oxide by contact photolithography and a wet chemical etch. Immediately after the oxide windows are opened, the exposed GaAs surface is electroplated to form the anode contact. However, we have found that the device performance is enhanced if a layer of GaAs several hundred angstroms thick is removed from the surface just prior to the contact formation. This is accomplished by an anodic oxidation of the exposed GaAs.

The anodization process, described by Hasegawa and Hartnagel [5], is electrochemical and involves the growth of a native oxide, Ga_2O_3, in a glycol–water solution which is 3 percent tartaric acid and pH-adjusted with NH_4OH. The oxidation apparatus is depicted in Fig. 2. The constant-current, voltage-limiting power supply controls the thickness of the oxide layer and hence limits the amount of GaAs consumed in the formation of the Ga_2O_3. The oxide is etched away in dilute HCl just prior to anode plating. The complete process of etching the GaAs through the SiO_2 windows has been described in detail by Siegel [6].

The diode's current–voltage characteristic, which is directly related to its noise performance, can be described over the current range of interest by [7]

$$I = I_{sat} \exp\left\{\frac{V - IR_s}{V_0}\right\} \tag{1}$$

where I_{sat}, R_s, and V_0 are the saturation current, the series resistance, and the diode's inverse slope parameter, respectively. The inverse slope parameter is often expressed as $\eta kT/q$, where

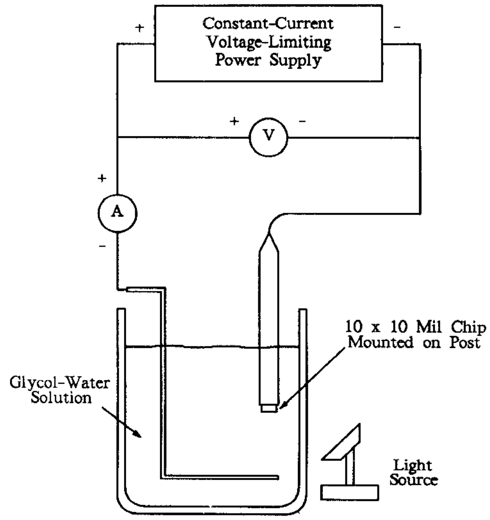

Fig. 2. Anodic oxidation apparatus (not to scale). The post is coated with wax so that it is electrically isolated from the solution.

the ideality factor η is equal to unity for ideal thermionic emission.

The equivalent noise temperature of a Schottky barrier diode is given by [8]–[10]

$$T_d = \frac{qV_0}{2k}\frac{r_j}{r_j + R_s} + T_e\frac{R_s}{r_j + R_s} \tag{2}$$

where r_j is the nonlinear junction resistance and k is Boltzmann's constant. The first term represents the junction shot noise, and the second represents the thermal noise in the series resistance. T_e is the equivalent noise temperature of the series resistance and can be approximated by [8]–[10]

$$T_e = T + KI^2 \tag{3}$$

where

$$K = \frac{2\tau_E}{3kq\mu n^2 S^2}. \tag{4}$$

Here, S is the diode's surface area, n is the free electron concentration, μ is the electron mobility, and τ_E is the average energy relaxation time for the electrons. The I^2-dependent term accounts for the heating of the electron distribution due to the electric field in the series resistance.

III. Diode Noise

The diode noise measurements for this study were made at 1.4 GHz with a bandwidth of 50 MHz using a noise reflectometer. This technique allows measurement of the reflection coefficient at the impedance mismatch between the diode and the 50-Ω measurement system, as well as the noise power output from the diode into the measurement system. Thus, the available noise power from the diode, and hence the diode's noise temperature, can be calculated as a function of the dc current. An excellent review of noise-measurement techniques has recently been presented by Faber and Archer [11].

Graphs of the equivalent noise temperature of cryogenically cooled Schottky diodes from three separate batches as a function of forward dc current are shown in Fig. 3. In each case data for both standard devices (●) and devices that were anodically thinned prior to anode plating (□) are given. The error bars indicate the uncertainty in the noise measurement, and the solid lines represent the result predicted by the noise theory (2) when

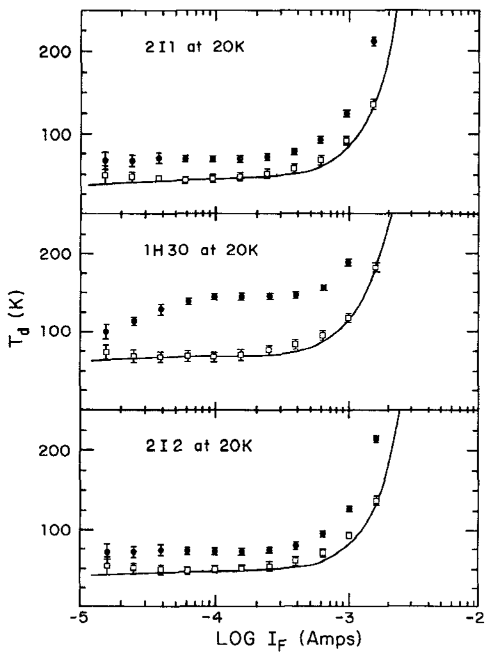

Fig. 3. The measured dc-biased equivalent noise temperature of three typical diodes from different diode batches at 20 K. Data for thinned (□) and unthinned (●) diodes are presented. The solid curves represent the noise temperature predicted by (2).

measured diode parameters and $\tau_E = 1$ ps [12] are assumed. In all three cases the extra processing step has significantly reduced the noise temperature, and, in fact, the noise of the thinned diodes very nearly approximates the minimum value predicted by the noise theory.

For all diodes investigated in this study, the measured noise for the thinned devices slightly exceeds the predicted noise at the current where the noise begins to increase sharply due to hot-electron effects. At this current, the diode's junction resistance and series resistance are of the same magnitude, and the noise of the series resistance is beginning to dominate. This slight discrepancy may be due to an excess noise source that is not affected by thinning, or to an inaccuracy of the noise model.

The removal of several hundred angstroms of GaAs by anodic oxidation prior to anode formation has been found to reduce the equivalent noise temperature of Schottky diodes by up to 50 K. This is in agreement with the work of Sherrill [4]. However, in this study the excess noise is shown to occur even in large-diameter diodes that do not exhibit the noise peaks discussed in [4]. In addition, the noise of the thinned devices has been shown to match very closely the minimum noise predicted by theory.

Previous research has shown that anodic oxidation is also beneficial to the reverse current–voltage characteristics of Schottky diodes [4], [13]. In particular, the reverse breakdown becomes much sharper. This is another indication that preparation of the GaAs surface prior to anode contact formation is very important.

The physical cause of the excess noise is not clear. Since it occurs in large devices with increased area-to-periphery ratios, it is probably not entirely due to edge effects. Surface contamination and/or crystal damage due to the oxide deposition process are likely causal candidates. It is also possible that the anodization process may act simply as a cleaning step that yields a more nearly ideal GaAs surface, which then promotes more nearly ideal anode formation.

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