Interfacial Stress and Excess Noise in Schottky-Barrier Mixer Diodes

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Abstract —**This paper presents evidence linking excess noise in submillimeter-wave Schottky-barrier mixer diodes to stress at the devices' GaAs–SiO_2 interface. At the periphery of the Schottky anodes, the SiO_2 film is discontinuous and the stress surpasses the GaAs yield stress, resulting in damage to the surrounding material. By modifying the device structure in three independent manners, the stress and damage at the diode periphery were either increased or decreased; in each case, the noise temperature increased or decreased accordingly.**

I. Introduction

LOW-NOISE, high-frequency Schottky-barrier mixer diodes are extremely important for radio astronomy and other applications requiring receivers operating at millimeter and submillimeter wavelengths. As devices are fabricated with smaller areas (diameter < 2 μm) to reduce device capacitance and allow operation at higher frequencies, an undesirable peak in the diode noise temperature (T_d) versus forward current (I_f) characteristic begins to appear. In this paper, we present evidence linking the excess noise to stress and crystal damage at the periphery of each diode.

A schematic of a typical back contact Schottky mixer diode chip is shown in Fig. 1. The SiO_2 layer is produced via chemical vapor deposition, using SiH_4 and O_2 as reactants at 350°C. An ohmic contact is formed on the back of the wafer, and circular anode windows are defined in the oxide using standard photolithographic techniques. Finally, anode contacts are formed by electroplating Pt and then Au onto the GaAs exposed by the anode windows.

Such diodes are predicted to exhibit a T_d versus I_f characteristic at cryogenic temperatures as shown by the dashed curve in Fig. 2. The low-level noise temperature below 1 mA is due to shot noise, while the sharp increase above 1 mA is due to excess heating of the electron distribution at higher current densities. For forward current below 1 mA, larger diameter diodes exhibit a T_d which is relatively independent of I_f and near its predicted value. However, in the smaller (diameter < 2 μm) devices required for submillimeter wavelength operation, an anomalous peak in T_d (the solid curve in Fig. 2) is often seen [1], [2]. Such noise peaks occur within the operating current range of cryogenically cooled devices, making them unsuitable for use as low-noise mixer elements.

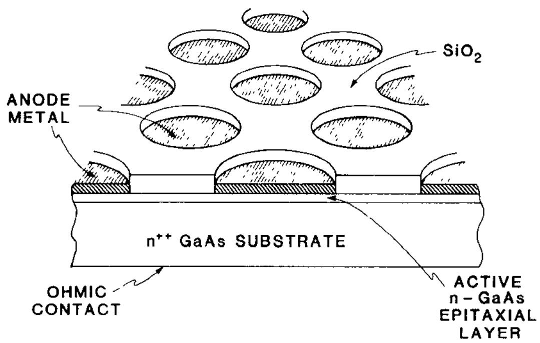

Fig. 1. Schematic of back contact Schottky-diode chip. The anode contact is made with a pointed metal whisker.

II. Interfacial Stress

Until recently, it was impossible to predict which devices might exhibit the excess noise peaks, or to explain why such noise has been more prevalent in smaller devices. Recently, though, strong evidence has been found indicating that the presence of this excess noise is due to interfacial stress at the SiO_2–GaAS interface. Because the thermal expansion coefficients of SiO_2 and GaAs differ by an order of magnitude, significant stress is created at their interface as the structure cools from the oxide deposition temperature. This interfacial stress is calculated to be on the order of 10^7 dyne/cm^2 for a uniform film [3], a value lower than the yield stress of GaAs [4]. When discontinuities (anode windows) are formed in the oxide, though, the interfacial stress at those discontinuities theoretically approaches infinity [5], but practically is held to the GaAs yield stress value via mechanical damage of the material. Thus, at the periphery of each anode, one expects the GaAs to be both stressed and damaged.

Previous work [3] has shown that the interfacial stress has a pronounced effect on the reverse current–voltage ($I-V$) characteristic of Schottky-barrier diodes, particularly on the sharpness of the reverse breakdown. Fig. 3 shows typical reverse $I-V$ characteristics for a standard Schottky diode, after removal of the oxide film, and after

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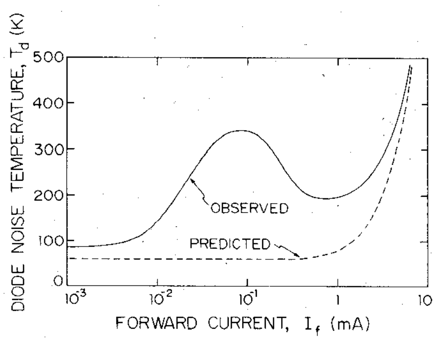

Fig. 2. Predicted and observed diode noise temperature versus forward current characteristics.

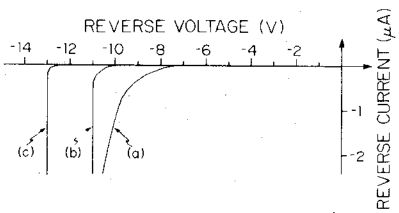

Fig. 3. Reverse current versus voltage characteristics for a Schottky diode (a) as fabricated, (b) after etching away SiO_2, and (c) after etching a mesa in the GaAs around the anode.

etching a mesa structure around the anode. The premature breakdown current is decreased and the breakdown voltage is increased, first as the interfacial stress is removed (by removing the SiO_2), and then as the damaged GaAs is etched away from the anode periphery. It is important to note that, if the GaAs etch proceeds more than a few thousand angstroms into the GaAs, the etch proceeds laterally beneath the anode at a rate such that the anode metal is completely lifted off (a lateral etch of several ten-thousand angstroms). On the other hand, similar devices with anodes defined by a low-stress photoresist layer rather than SiO_2 exhibit no enhanced lateral etching under the anodes during such processing. This indicates that the high lateral etch rate is due to the presence of damaged (and more rapidly etched) GaAs, rather than to any electrochemical reaction between the etchant and the metal–semiconductor interface.

III. Effects of Stress on T_d

The first indication that such stress and crystal damage might also effect diode noise characteristics was that devices fabricated by etching away a few hundred angstroms of GaAs through the anode windows, and then plating the anode metal, tended to exhibit no noise peak features in their T_d versus I_f characteristics. Thining the active layer even a few hundred angstroms through the anode windows removes significant amounts of the more rapidly etched, damaged GaAs at the anode periphery. Therefore, the ratio of damaged to undamaged GaAs exposed beneath the anode windows is decreased.

To study the effect of damaged material on noise characteristics, two adjacent squares from a GaAs wafer were

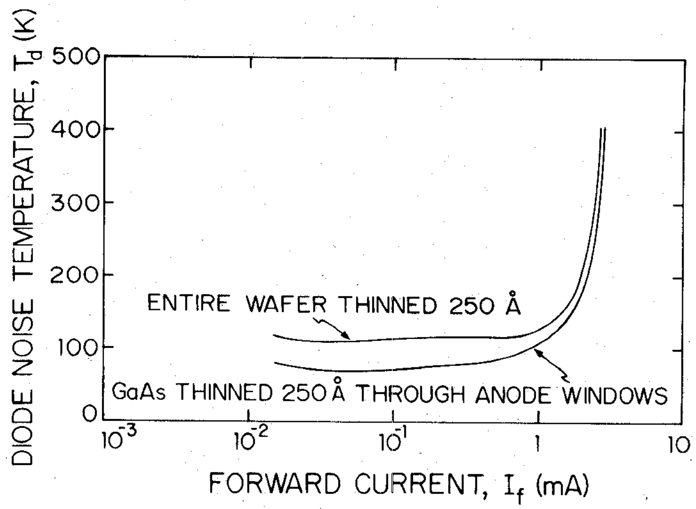

Fig. 4. T_d versus I_f characteristics for devices fabricated on GaAs (a) thinned uniformly before device fabrication and (b) thinned through the anode windows. All noise measurements were taken with the mixer cooled to 20 K, at a frequency of 1.4 GHz with a bandwidth <100 MHz, using the system described by Faber and Archer [7].

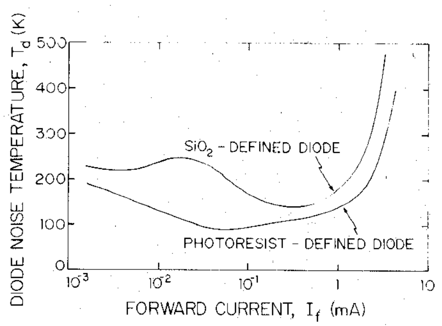

Fig. 5. T_d versus I_f characteristics for a standard device, defined with SiO_2, and for a device defined with a lower stress photoresist layer.

processed identically to produce diodes, with only one variation: one wafer was anodically thinned [6] by an amount of 250 Å over its entire surface before processing; the other's active layer was thinned 250 Å through the anode windows prior to anode formation. Both sets of devices thus had the same final active layer thickness, doping, and anode diameter, but in one set the GaAs was etched after deposition and patterning of the SiO_2, removing a portion of the damaged crystal at the anode periphery. T_d versus I_f data for both sets of devices are shown in Fig. 4.

In this particular case, neither set of devices exhibited an excess noise peak, but the devices which had their active layer thinned through the anode windows exhibited significantly lower T_d. This decrease in T_d may be attributed to one of two factors, either a lower ratio of the damaged to undamaged Schottky contact area, or some effect due to the small change in the anode geometry produced by thinning through the windows.

In order to rule out the effects of slightly different anode geometries, devices having SiO_2-defined anodes were compared with devices having anodes defined by a lower stress

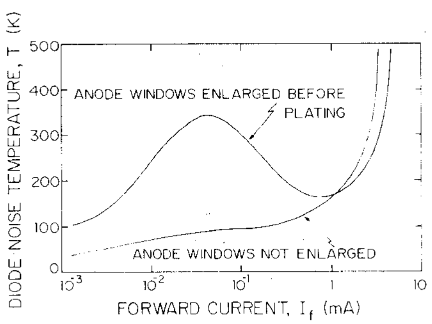

Fig. 6. T_d versus I_f characteristics for a standard device and for a device whose anode window was enlarged ~13 percent before plating.

photoresist layer. Such processing produced 2-μm-diam devices with the same geometry and active layer characteristics, differing only in the amount of stress at the anode periphery. T_d versus I_f data for the devices are shown in Fig. 5. There is no noise peak in the low-stress photoresist-defined devices, while the SiO_2-defined devices exhibit a definite noise peak. While not excessive, the presence of any such noise with these larger diameter anodes is significant, since the ratio of the damaged and stressed area (proportional to the anode circumference) to the total device area decreases as the anode diameter increases.

If the excess noise observed is in fact due to stressed and damaged crystal at the anode periphery, as the previous evidence suggests, then intentionally increasing the ratio of the damaged device area to the total device area should produce devices with increased excess noise. To test this hypothesis, devices were fabricated in the standard fashion on a GaAs wafer. Before the anodes were electroplated, the anode window diameter on several chips was enlarged ~13 percent by etching the SiO_2 with buffered HF. As the windows were enlarged, the oxide edge moved across the GaAs surface, so that the entire anode area between the original and final anode periphery had been in contact with an oxide discontinuity, and was probably damaged. Thus, the ratio of damaged area to undamaged area should be much greater for the enlarged anode devices. After the anode metals were electroplated, noise data were taken and are shown in Fig. 6. While the standard diodes exhibited no noise peak in this case, devices from the same wafer, but with windows slightly enlarged before plating, had a very pronounced noise peak in their T_d versus I_f characteristic.

IV. Conclusion

Interfacial stress has been shown to affect the reverse characteristics of high-frequency Schottky diodes, and is now linked to excess noise exhibited by forward-biased mixer devices. The amount of stress and crystal damage was varied in three independent ways. In each case, the devices with greater stress or crystal damage exhibited greater excess noise, and in two cases exhibited noise peaks, while the diodes fabricated with less stress and damage exhibited nearly ideal noise characteristics at cryogenic temperatures. (In all cases, stresses due to both the electroplated anode metal and the contacting whisker remained constant while excess noise was removed or produced, indicating that such stresses are not associated with the noise peak. The results here are thus applicable to whiskerless (beam-lead) devices and any other structure with SiO_2-defined anodes.) In conclusion, the interfacial stress inherent in SiO_2-defined high-frequency Schottky-barrier mixer diodes is seen to adversely affect their noise characteristics at cryogenic temperatures, and appears to be the primary cause of the undesirable excess noise peaks.

Acknowledgment

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