METAL-BARRIER-METAL JUNCTIONS FOR ROOM TEMPERATURE MILLIMETER-WAVE MIXING AND DETECTION*

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In the past, metal-barrier-metal (MBM) point-contact diodes have been used at room temperature as coherent detectors from microwave to optical frequencies. For the first time, the millimeter-wave mixing and detection characteristics of stable thin-film Ni-NiO-Ni junctions fabricated by photolithographic means will be reported.

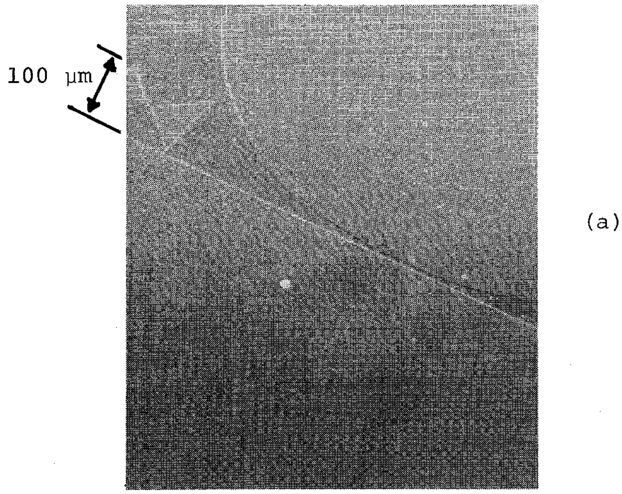
INTRODUCTION

Millimeter-wave mixing and detection have been observed for the first time using stable thin-film metal-barrier-metal (MBM) junctions. The sensitivities obtained are higher than previously reported results using point-contact MBM devices. The diodes tested were fabricated in a coplanar geometry on the surface of an insulating glass substrate. Video detection measurements at 36 GHz yielded open circuit sensitivities as high as 7 mV/μW. In the heterodyne detection mode, mixer noise temperatures were typically three times the ambient temperature (i.e. $T_m \simeq 1000^oK$), and conversion losses were large (~20 dB) due to the symmetric current-voltage (I-V) relationship of the Ni-NiO-Ni diodes. However, initial non-optimized harmonic mixing experiments between 36 GHz and 72 GHz sources have lead to more promising results.

Because electronic tunneling times are very short[1] and the use of two metal electrodes minimizes series resistance problems, MBM junctions are believed to be capable of operating at frequencies higher than semiconducting or superconducting devices. In fact, point-contact MBM diodes have been operated from microwave to optical frequencies as detectors,[2] mixers,[3] and harmonic generators.[4] Thin-film coplanar MBM devices offer a practical alternative to mechanically fragile point-contact junctions because the thin-film diodes 1) can be produced in quantity using conventional photolithographic techniques, 2) are mechanically rugged, and 3) can ultimately be integrated into semiconductor circuits. In the present work, we have chosen to operate in the millimeter-wave region (i.e. 36 GHz) to take advantage of well known matching techniques.

FABRICATION

The two Ni electrodes of the MBM devices were patterned using standard integrated circuit photoresist and wet chemical etch steps. Fabrication of the barrier was accomplished using a simultaneous sputter-etch and oxidation process described by Greiner.[5] Junction areas ranged from 1 to 4 μm^2 depending on the electrode overlap. Figure 1 shows a scanning electron microscope photograph of a junction. The diodes fabricated and tested had (zero bias) dynamic resistances ranging from 200 Ω to 10 kΩ, depending on junction area and oxide thickness. Figure 2 shows the non-linear I-V characteristic due to electrons tunneling through the thin (<<100 Å) oxide. Typical non-linearities were found to be S ~ 6 V^{-1} compared to 38 V^{-1} for an ideal Schottky diode, where $S \equiv (\partial^2 I/\partial V^2)/(\partial I/\partial V)$.



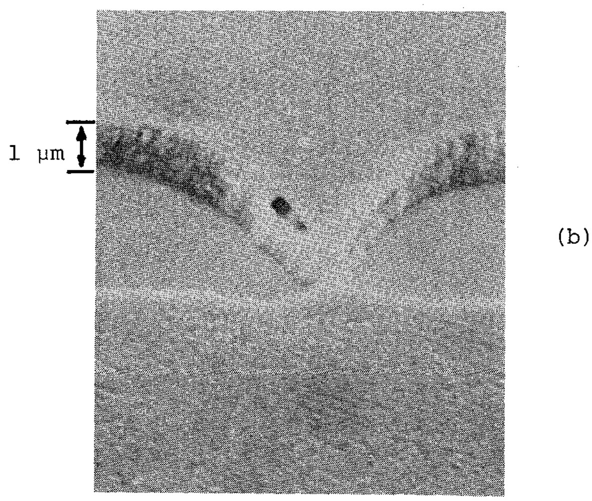


FIGURE 1. Scanning electron microscope photograph of a Ni-NiO-Ni junction on an insulating glass substrate under low (a) and high magnification (b). The upper pattern is the first electrode and is contacted to the waveguide antenna. Both electrodes are ~1 μm thick to reduce series resistance losses.

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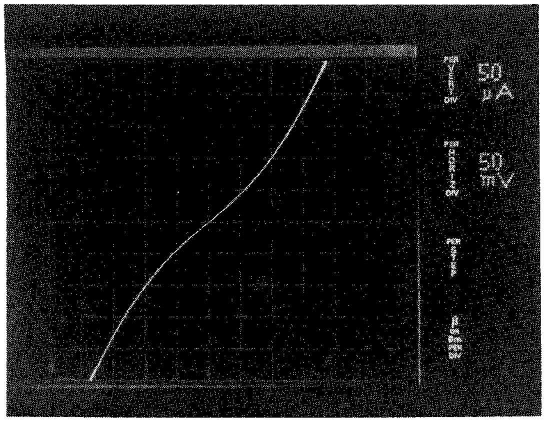

FIGURE 2. Non-linear I-V characteristic of a 1 kΩ Ni-NiO-Ni junction.

NOISE

The zero bias noise of the Ni-NiO-Ni junctions was found to be equal to the Johnson (i.e. thermal) noise of a resistor of equal impedance. Under bias, the junctions displayed a 1/f behavior up to 100 kHz, indicating a high density of surface states at the metal-oxide interface. The RMS noise current was proportional to the bias current, characteristic of the 1/f noise behavior.[6]

VIDEO DETECTION

The video and heterodyne detection characteristics were measured at 36 GHz with the junction mounted in a rectangular copper cavity of the same cross section as the WR 28 waveguide dimensions. An adjustable stub 3/4 λ_g in front of the junction and a multi-section shorting plunger behind the junction were used as tuneable matching elements. The rectangular second electrode was connected to the cavity by a tab of In. The video signal was coupled off the circular first electrode by a copper wire that acted as a waveguide antenna and was inserted through the top of the cavity. Figure 3 shows the measured and calculated voltage sensitivity γ of a 5.4 kΩ device as a function of bias. Assuming a series resistance R_s and a shunt capacitance C_j, the theoretical sensitivity is

$$\gamma_{theory} = -\tfrac{1}{2} S R_{dyn} \left[\frac{\alpha}{1 + \frac{R_s}{R_{dyn}} + \omega^2 R_s R_{dyn} C_j^2} \right] \qquad (1)$$

where $R_{dyn} \equiv (\partial I/\partial V)^{-1}$ and α is the fraction of available RF power coupled to the diode.

HETERODYNE DETECTION

The heterodyne detection experiments at 36 GHz indicate that the symmetric I-V characteristics of the Ni-NiO-Ni junctions are not well suited for fundamental mixing. Figure 4 shows the mixer noise temperature and conversion loss as a function of bias at a local oscillator (LO) power of -10 dBm. The mixer noise temperature is defined as

$$T_m = P_n / (kB) \qquad (2)$$

where P_n is the total noise power available from the mixer intermediate frequency (IF) port in a bandwidth B and $k = 1.38 \cdot 10^{-23}$ J/°K. The mixer conversion loss is defined as

$$L_m = P_{RF} / P_{IF} \qquad (3)$$

where P_{RF} is the available RF power and P_{IF} is the available IF power. No image rejection designs were used, so the devices operated in the double sideband mode. At zero bias, the conversion loss is infinite

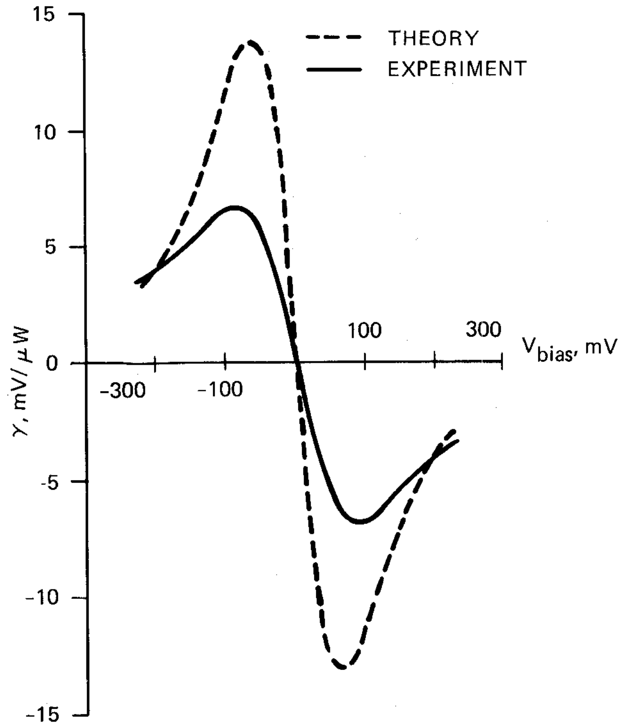

FIGURE 3. 36 GHz video detection sensitivity as a function of bias. The theoretical sensitivity was calculated from Equation (1) using the DC I-V characteristics and assuming perfect matching with no device parasitics.

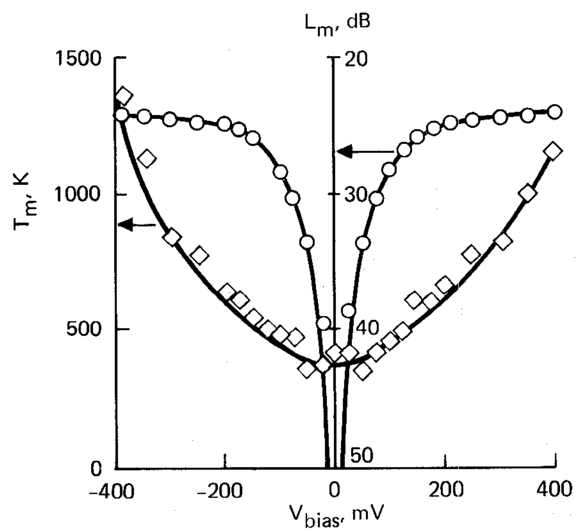

FIGURE 4. Mixer performance as a function of bias. The LO power is -10 dBm at 35.7 GHz and the signal frequency is 35.75 GHz. The zero bias impedance is 4.75 kΩ.

because the LO drive causes the diode to conduct in both the forward and reverse directions. The device performance can be improved by using a bias. Figure 5 shows conversion loss and noise temperature as a function of LO drive when a 200 mV bias is used. Beyond an LO drive of -3 dBm, the conversion loss increases because the negative swing of the LO voltage is greater than the offset of the bias.

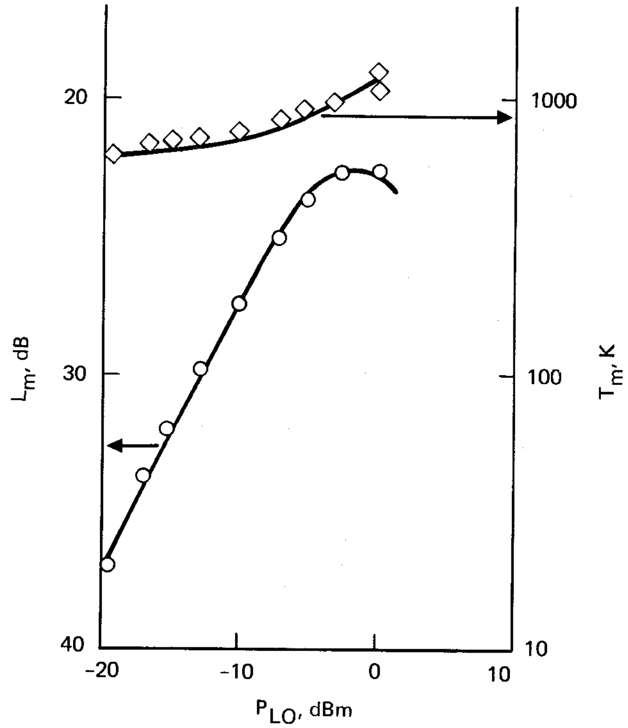

FIGURE 5. Mixer performance as a function of LO power. The zero bias impedance is 1.35 kΩ and the bias is 200 mV.

HARMONIC MIXING

The double switching characteristic of the Ni-NiO-Ni junctions can be used for harmonic mixing. Figure 6 shows that the conversion loss is a minimum at zero bias for a 36 GHz LO and a 72 GHz signal. The symmetry of the I-V characteristic (Figure 2) appears similar to the anti-parallel Schottky diode pairs used for subharmonically pumped mixers.[7] A conversion loss of 30 dB and a mixer noise temperature of 1000°K was obtained for an LO level of +10 dBm. A signifigant part of the conversion loss was due to the fact that the cavity was only designed for 36 GHz and was highly over-moded at 72 GHz. In spite of this, the performance appears comparable to the fundamental mixing results. This indicates that with an optimized cavity design, the MBM diodes can be exploited as subharmonically pumped mixers.

CONCLUSIONS

Suggestions for improved MBM devices in terms of various geometries, metal electrode combinations and barrier materials will be presented. Ultimate device performance characteristics, such as frequency response, non-linearity and noise will be discussed in comparison to semiconducting and superconducting junctions.

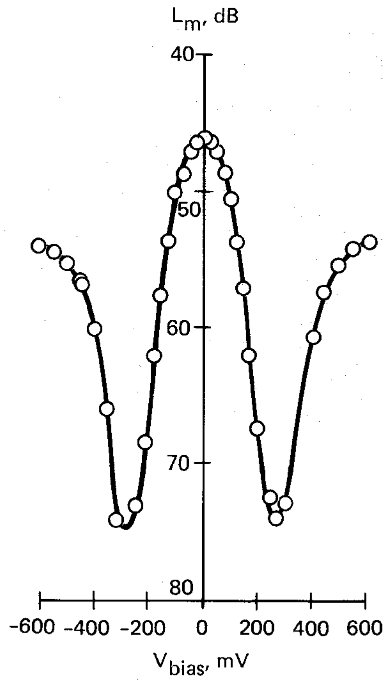

FIGURE 6. Subharmonically pumped mixer conversion loss as a function of bias voltage for a 3.75 kΩ junction. The LO power is -10 dBm at 36.46 GHz and the signal power is -20 dBm at 72.97 GHz.

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