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Coupling to an "edge metal-oxide-metal" junction via an evaporated long antenna

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The observation of planar long-antenna coupling to a metal-oxide-metal (edge configuration) has been demonstrated at $\lambda = 118$ μm. The two major lobes of an 11λ antenna are coupled to via a superstrate prism. Insufficient data is presently available to identify with certainty the mechanism of detection.

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In the present letter we report the observation of coherent coupling to a planar linear traveling-wave antenna, terminated with a photolithographically fabricated "edge metal-oxide-metal" junction ("edge MOM").

Lobe structure for an antenna on top of a sapphire substrate has been reported for the 300-μm regime,[1] but patterns were not shown explicitly. In our earlier work at 10.6 μm, patterns were either not observed[2] or exhibited poor directivity and gain.[3] For the 10.6-μm region, lossless insulating substrates are not plentiful, structural roughness starts to play an important role in scattering, and most metals absorb about 10% of the incoming power. Rutledge *et al.*[4] recently pointed out that a "sandwich" structure, in which a superstrate is placed over the antenna, would be helpful in obtaining predictable antenna patterns.[5]

We have chosen to work at a 118-μm wavelength in the present work since the major losses mentioned above for 10.6 μm are negligible at the longer wavelength.

A single-crystal quartz substrate was used ($n_0 = 2.11$, $n_e = 2.16$, and $\alpha = 0.5$ cm^{-1} at $\lambda = 118$ μm; see Ref. 6). Figure 1 illustrates the structure of the device. A thin nickel layer (~ 150 Å thick) is sandwiched between the bottom quartz substrate and a top SiO_2 buffer layer (~ 2500 Å thick), in the form of a rectangular-shaped "island" (7.5×6 μm^2). The edges of the thin nickel film are oxidized. Nickel electrodes are then overlaid in the form of long antennae terminated at two of the edges of the central island as two "edge MOM's", each with an effective area of tunneling $\sim 10^{-9}$ cm^2. The detailed fabrication process is provided in Refs. 2 and 7. The resultant structure is indicated in Figs. 1(a) and 1(b). As one can see, the junctions present minimum geometrical scattering for waves propagating along the an-

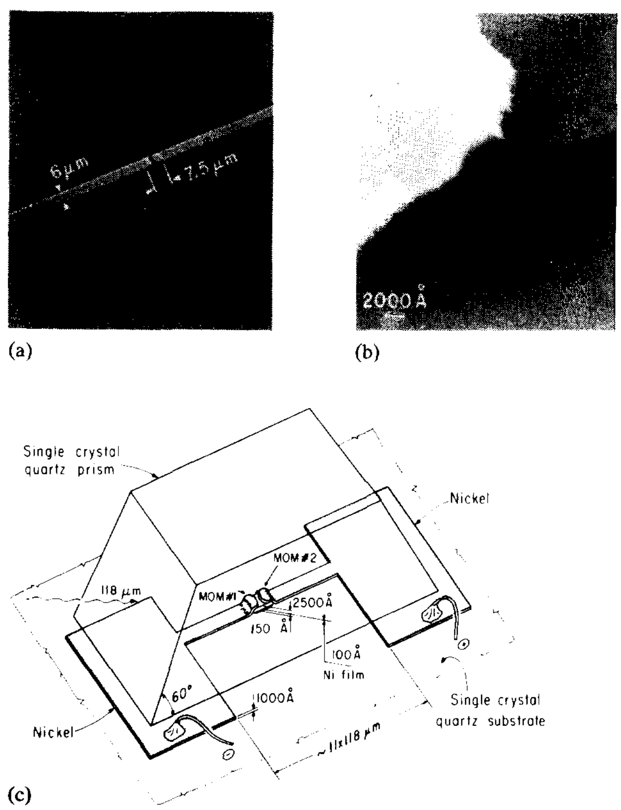

FIG. 1. MOM device coupled to via a long wire antenna: (a) Electron micrograph of the MOM device. The junctions are located on the two edges of the central 7.5-μm island. (b) Enlargement showing one of the edge MOM's. The second electrode is the 100-Å Ni layer seen as a light plane imbedded in the island shown to the right of the photograph. (c) Schematic drawing showing the prism coupler.

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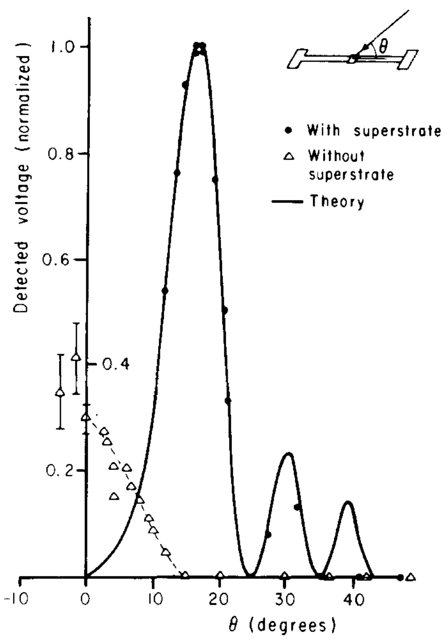

FIG. 2. Detected voltage versus angle θ, the angle of incidence of the radiation field. For the superstrate data, the angle is that within the superstrate ($V_0 = 150$ mV).

tenna, and the roughness is negligible on a wavelength order of magnitude. The total antenna length is about 11λ in terms of waves propagating with the phase velocity of the substrate.

Biasing the structure through the two ends of the antenna [Fig. 1(c)] resulted in an I-V characteristic with a dynamic resistivity at zero bias of ~ 1.5 kΩ and lead resistance of $\sim 90\,\Omega$.

If one wishes to couple efficiently to the major lobe of a long wire antenna, a match of the propagation constant of the incoming wave with that of the traveling wave along the antenna has to occur. Coming from air at an angle θ with respect to the substrate leads to a phase mismatch $k_0(\beta - \cos\theta)x$, where k_0 is the propagation constant in air, β is the effective index of the wave associated with the antenna which presumably has a value close to $n_{\rm quartz} \simeq 2.1$,[8] and x is the coordinate linear dimension along the antenna. The above factor can be minimized if the incoming wave is directed from the substrate side. Then, $k_0(\beta - n_{\rm substrate}\cos\theta)x$ can be minimized provided θ can be made arbitraily close to zero. This can be achieved if the substrate edge is polished at some angle. An alternative approach is the utilization of a superstrate on top of the antenna with an air gap much less than a wavelength between the superstrate and substrate as noted above.[4] For convenience we chose the latter configuration, in the form of a prism, as shown in Fig. 1(c).

Since the expected detector signals are a maximum near $V_b = 100$ mV, the junction was biased to that value. Initial experiments were performed with a water-vapor laser as the 118-μm source, but due to the weak power output (0.3-mW average power across the junction when the beam was polarized) no detected signals were observed. The measure junction noise was about 1 μV at a bandwidth of 100 Hz around a 1-kHz chopping frequency for phase-sensitive detection. Replacement of the source by a CH_3OH laser pumped by a CO_2 laser, line 9 P(36), led to a 4-mW average power at the junction with a polarization perpendicular to that of the CO_2 polarization.[8-10] The focal spot at the prism surface was ~ 2 mm in diameter. Plots of the detected signal versus angle of incidence on the antenna, θ, are shown in Fig. 2. For the results employing the prism superstrate, $\theta = 0°$ corresponds to grazing incidence on the antenna and 90°, perpendicular incidence for the wave impingent from within the superstrate. With the superstrate removed or for coupling from the substrate, since the faces were not polished, we have simply used the angle of incidence in air. One unit on the vertical scale corresponds to 4.7 μV. Since we were most interested in studying the superstrate coupling, the bottom surface of the substrate (which is 1.2 mm thick) was actually roughened to minimize reflection. Since the roughness was on the order of the optical wavelength, specular reflection might occur, but because of the small angle of incidence the reflected beam would not couple into the antenna.

Detected signals with the superstrate on the top follow closely the shape of the predicted pattern of a long wire antenna with total length $2.1 \times 5\lambda$. The theoretical pattern which is plotted in Fig. 2 (the amplitude of the peak of the major lobe was matched to the experimental values) is calculated from the following expression[11]:

$$P(\theta) \propto \sin^2\theta\,(a^2 + b^2 + 2ab\cos 2\phi), \qquad (1)$$

where $\phi = \frac{1}{2}kl\cos\theta$, $a = (1 - \cos\theta)^{-1}\sin(\frac{1}{2}kl - \phi)$, and $b = (1 + \cos\theta)^{-1}\sin(\frac{1}{2}kl + \phi)$. These results are applicable for a traveling current wave along the antenna of the form

$$\begin{aligned} I(x) &= I_0 \exp(inkx), \quad -l < x < 0, \\ &= I_0 \exp(-inkx), \quad 0 < x < l, \end{aligned} \qquad (2)$$

where we choose $n = 2.1$ and I_0, the peak amplitude.

The polarization of the electric field is in the plane of incidence. When the polarization is changed by 90° the signal disappears completely. When the superstrate was removed

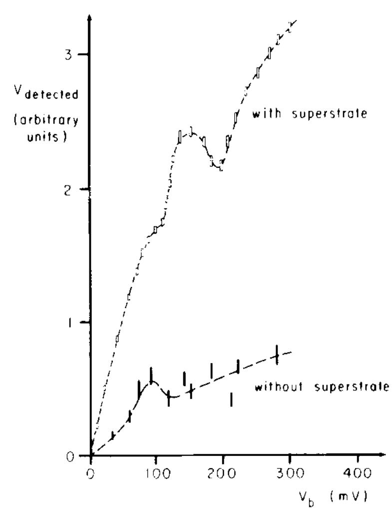

FIG. 3. Plot of the detected voltage versus bias voltage for the optimum angle θ.

the signal dropped down considerably, and its angular dependence is plotted in Fig. 2. The signal shows a strong dependence on the angle with signs of one major lobe very close to $\theta = 0°$. Near these shallow angles results are not certain since part of the beam couples into the antenna via the substrate, through the rather rough edge of the substrate. The shift in the major lobe suggests that a slow wave propagates along the antenna. This signal disappears, too, for perpendicular polarization.

Fixing the angle of incidence at the location of the major lobe, detected signals versus biasing voltage were plotted as shown in Fig. 3. As one sees, there are differences in the overall shape for the case with a superstrate present and that for no superstrate. The peak is expected near 100 mV since the detected signal by a tunneling mechanism is proportional to $-I''/I'$ $[(\partial I/\partial V^2)(\partial I/\partial V)^{-1}]$.[2] This peak is reproduced in the "superstrate" case. A narrow peak occurs near 150 mV in the latter case. Unfortunately, I' of this particular device was not measured before it failed, and it is unknown whether one junction or two exist in it. Two junctions in series can lead to a peak near 150 mV in the detected signal (the two junctions have nearly the same resistance). It is quite possible that the peak near the 150-mV bias is a result of two junctions in series, and that near 100 mV without a superstrate is due to a single junction (the other junction having been shorted when the superstrate was removed). The overall rise of the signal with bias (which does not exist at $\theta > 30$ for any polarization) may suggest a few possibilities: (a) a thermally induced signal which results from the antenna-induced optical voltage across the junction (V^2/R-type losses), (b) bias-dependent reflections from the load, due to the change of dV/dI with bias, which enhances the optical voltage across the junction for high biasing voltages, or (c) a combination of (a) and (b).

Due to the lack of a sufficient number of devices and the small detected signals, we presently cannot determine conclusively the mechanism of detection. However, we have estimated the expected signal due to antenna coupling from the measured I''/I' and dynamic resistivity, assuming the effective capacitance to be negligible. This estimate is of the order of 300 μV, compared with the observed 4.7 μV of Fig. 2. The two-orders-of-magnitude difference between the observed and calculated values are at least partly accounted for by reflection losses (the area of the focused beam was much larger than the superstrate face through which it was coupled to the junction), losses in the superstrate, and in the antenna.

It is expected that the detection sensitivity can be increased by coupling through an angled edge of the substrate. The gain is expected to be enhanced by a suppression of the free-space lobes. MOM's are also amenable to coherent arrays at this and shorter wavelengths.

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