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DIRECT MIXING AT 311 μM IN POINT CONTACT DIODES*

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Abstract

The detection characteristics of several point contact Schottky barrier submillimeter wave detectors were studied as a function of bias voltage. Both the video response of the detector, as well as a 2 GHz IF signal derived from mixing the output from two submillimeter wave lasers were compared with the low frequency I-V characteristics of the devices. Some discrepancies between the high frequency detector characteristics, and prediction made from the I-V curve were observed.

Introduction

Several investigators have studied the performance of point contact Schottky barrier submillimeter detectors. Among these were Becklake, Payne, and Prewer(1) who investigated point contacts on GaAs, Ge and Si. They observed a variety of low frequency I-V characteristics among their devices, but similar performance insofar as submillimeter detection was concerned. Zuidberg and Dymanus(2) studied mixing at 337 μm between lines from an HCN laser and the harmonics of a 3 mm wave klystron. They studied gallium arsenide, germanium, and silicon as detector materials. Using tungsten points about 1 μm in diameter, they measured conversion losses of about -65 dB for Si and Ge, and about -48 dB for GaAs. In their work however, they did not study the effect of applying a DC bias voltage to the diode on its performance. Tsang and Schwartz (3) studied detection at 10.6 μm of 1000 angstrom diameter tungsten point contacts on n-Ge, n-Si and n-GaAs. They were unable to observe any significant response with the gallium arsenide device. Germanium and silicon performed very well in comparison with a tungsten-nickel MOM detector. The germanium detector was about twice as responsive as the silicon device. Tsang and Schwartz studied the detection characteristics of their devices as a function of bias voltage, and found good agreement between the observed behavior and calculated response based on Schottky diode theory and the low frequency I-V characteristics of the junction. In the present work, measurements were made of the video and submillimeter mixing characteristics of a variety of point contact Schottky barrier detectors as a function of DC bias level. These results were compared to conventional Schottky barrier mixer theory.

The Experiment

The Schottky barrier diodes were fabricated from samples of various semiconductor materials. The materials were lapped, polished, and chemically etched to provide a damage-free surface. The samples were mounted in an open structure which provided access for two submillimeter laser beams. The point contacts were fabricated from 25 μm diameter tungsten wire, which was electrochemically etched down to about a 1000 angstrom diameter point. The wire was attached to a double micrometer drive which permitted good control of the point contact pressure of the semiconductor surface. With careful run-in procedures, and some respect for the diode mount, a well-behaved diode would last for several hours, or even overnight with little change in its characteristics. The diode mount was arranged so that two laser beams were incident along the main lobe of the antenna pattern of the cat's whisker. This was done either by making the antenna 1-1/4 wavelengths long, in which case the antenna lobe was at 45° with respect to the ground plane, allowing a 90° seperation between the laser beams, or by using a long length, high gain antenna pattern at about 75° from the ground plane. In this case, the two laser beams were combined with a silicon wafer beam combiner. The two laser signals were derived from an HCN discharge laser and an HCOOH optically pumped laser. The HCN laser was operating on its 311 μm (964.31 GHz) line, with about 4 mW of output power. The HCOOH laser was pumped with about 30 watts of power from a CO_2 laser operating on its 10R22 line. The submillimeter laser frequency was 962.25 GHz, and it had an output power of 0.4 mW.

The electrical signals from the detector were separated with a monitor T into two pathways. A low frequency port permitted I-V characterization of the device, as well as video detection of the submillimeter radiation. An rf port allowed observation of the 2 GHz difference frequency between the two lasers. The rf output from the detector was coupled to a wide band GaAs FET amplifier by a double stub matching network. The output from the amplifier was sent through a microwave isolator to a spectrum analyser. Independent frequency and power sensitivity measurements permitted absolute calibration of the spectrum analyser. A block diagram of the entire system is shown in Figure 1.

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Detector Results

A variety of materials were tested for their far-infrared Schottky barrier detector performance. These included n-type indium antimonide, n-type and p-type germanium with several different doping densities, n-type silicon, and p-type gallium arsenide. All the devices tested showed some degree of responsivity. The smallest video responsivity observed was for GaAs and silicon, which ranged around 0.01 V/W. The largest responsivity measured was for lightly doped ($6 \times 10^{17}/cm^3$) germanium, and was around 2.5 V/W. Only the indium antimonide (doped at $1 \times 10^{16}/cm^3$) and the p-type and n-type germanium doped at around $10^{18}/cm^3$ showed any mixing response. The mixer conversion loss (defined at the ratio of the output IF power to the input submillimeter power) was uniformly about -80 dB for all of the devices tested. A tungsten on nickel MOM tunneling detector also showed about the same mixing loss when used in the same experimental set-up. In these experiments, the minimum detectable power was about 1×10^{-11} watts/Hz. This figure was limited by noise in the microwave detection system, and not by noise from the diodes. Removal of the Schottky barrier diode from the circuit did not change the noise characteristics as seen on the microwave spectrum analyser. The IF signal power measured on the spectrum analyser was linear with an increase in either the HCN signal level, or the HCOOH laser signal level. This means that the diode was not being driven hard enough by the local oscillator to achieve the minimum conversion loss that would be possible.

By accessing the Schottky barrier diode through the low frequency port of the monitor T it was possible to make a DC I-V curve of the device. A typical example , for tungsten on n-type indium antimonide, is shown in Figure 2. The soft non-linearity, and slight asymmetry was typical of most of the devices studied. One exception was for tungsten:n-type germanium, which was somewhat more asymmetric, and showed a more "diode-like" I-V curve. It should be noted that for this I-V curve, the second derivative of I with respect to V (d^2I/dV^2) is positive for V positive (voltage polarity is referenced with respect to the semiconductor) zero at the origin, and negative for V less than zero. For the same device (and indeed for the same contact) it was also possible to measure the video and 2 GHz mixer response. These results are shown in Figure 3.

With no DC bias voltage across the device, a negative video (or rectified DC) signal is observed. At the same bias point, a mixer conversion loss of about -97 dB is measured. As the bias voltage across the diode is made more negative, the rectified signal goes to zero, changes sign, and then increases as a positive voltage. A saturated signal level of about 650 μ V is reached around - 0.3 V bias. At the same time, the mixer signal decreases to zero at the same voltage at which the rectified signal changes sign, and then increases again, reaching a saturation value of about -93 dB for a somewhat more strongly negative voltage. For positive bias, a rapid increase in diode noise prevents determination of the video response. However, other contacts, and other devices, behavior similar to that seen for negative bias is observed. For positive bias the mixer output signal increases, going to about -85 dB mixer loss before the limit of bias voltage is reached.

Although this behavior agrees in a rough qualitative fashion with the prediction which one would make from the low frequency I-V curve, there are discrepancies which are difficult to explain. Non-linear Schottky barrier diode theory (3) says that the video response should be proportional to $-[(dI/dV)/(d^2I/dv^2)]$ and hence the output should be negative for a bias voltage greater than zero, and positive for a bias voltage less than zero. As Figure 3 shows, the zero crossing for this device is shifted towards the negative bias region. This results in a significant (negative) video responsivity at zero bias, and a significant mixer response as well. It should be noted that the microwave mixer response closely follows the video behavior. This is a strong indication that the same detection mechanism is responable in both cases. Even more divergent behavior was observed for some of the other devices. In Figure 4, the mixer response for p-type germanium is shown as a function of DC bias. The multiple zeros of this curve are more suggestive of tunneling behavior, where third order terms often become important (4).

Discussion and Conclusion

For all of the devices which were investigated in this study, irrespective of the shape of the I-V curve, a zero bias response was observed. Most of the time the rectified signal had a negative polarity, but there were instances (such as with some of the n-type germanium contacts) where a positive zero bias response was seen. As mentioned above, some devices exhibited a multiple zero behavior, with several changes in polarity. One is tempted to try to invoke a combination of Schottky and tunneling behavior (there is of course, some oxide formed on the surface of the semiconductor. However, tunnel diodes should have zero response at zero bias as well. (4) For these devices the agreement between high-frequency detector response, and low-frequency I-V characteristics is not good. Some modification of the I-V curve at high frequency must be made in order to bring things into agreement. The simplest choice which would explain the data is a shift of the "knee" of the i-V curve towards the negative voltage side of its characteristic. What kind of frequency dependent mechanism could bring this about however, is hard to imagine. The behavior of point-contact Schottky barrier detectors in the submillimeter region is more complicated than at first supposed, and one should not infer far-infrared behavior on the basis of the low frequency I-V characteristics.

References

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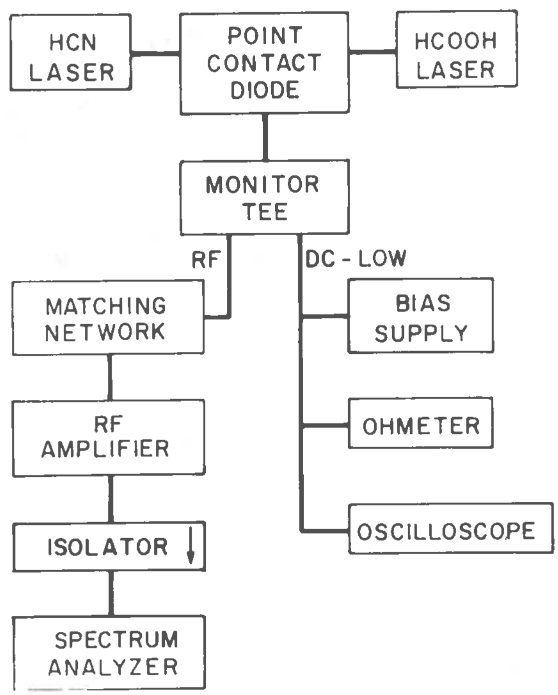

Fig. 1. Block diagram of the experimental set-up

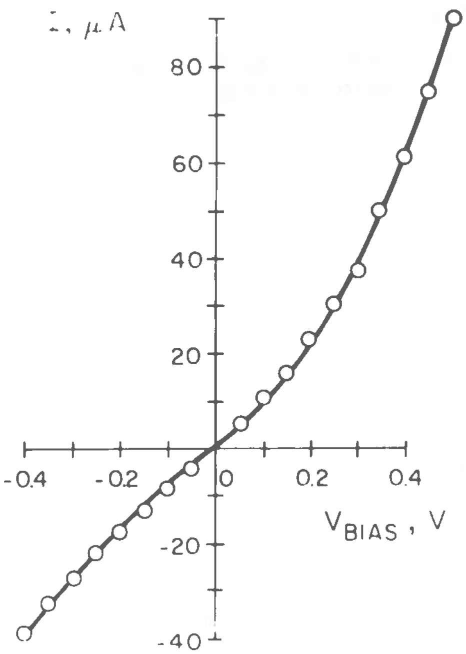

Fig. 2. I-V Characteristic for tungsten on n-type Indium Antimonide diode.

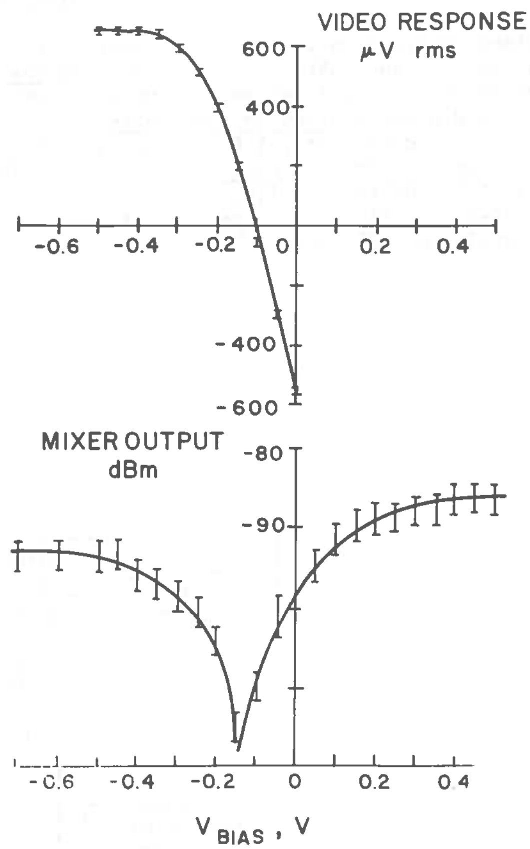

Fig. 3. Video and mixer response for tungsten on n-type indium antimonide diode vrs. bias voltage.

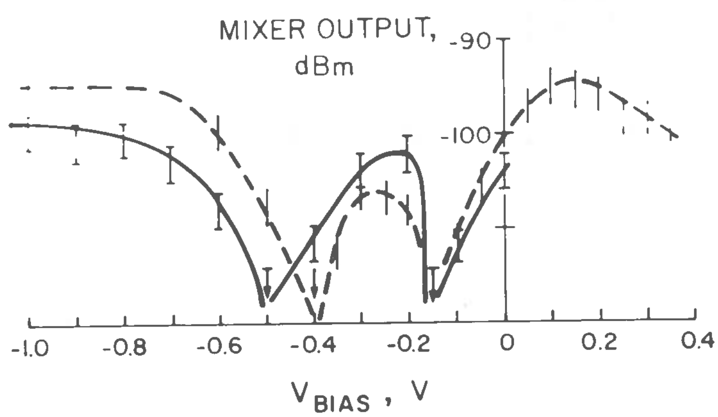

Fig. 3. Mixer response for tungsten on p-type germanium vrs. bias voltage.