Infrared Physics Vol. 19, pp. 335 to 340
© Pergamon Press Ltd 1979. Printed in Great Britain
0020-0891/79/0801-0335$02.00/0

MIXING OF SUBMILLIMETER WAVE RADIATION IN METAL–METAL AND METAL–SEMICONDUCTOR POINT CONTACT DIODES*

P. J. EPTON,† W. L. WILSON Jr, F. K. TITTEL and T. A. RABSON
Rice University, Department of Electrical Engineering, Houston, TX 77001, U.S.A.

Abstract—Point contact diodes of tungsten on metal and tungsten on semiconductors were used as direct mixers of two submillimeter lasers. Their performance as both mixers and video detectors was studied and compared to their low-frequency *I–V* characteristics. The observed behavior was in some respects inconsistent with the mechanisms usually advanced to explain the operation of such diodes.

INTRODUCTION

Point contact diodes have been extensively utilized as video detectors and mixers in the submillimeter and infrared regions of the spectrum. Previous experiments have focused on mixer sensitivity[1] as well as harmonic generation and high order mixing for making accurate measurements of submillimeter and infrared laser frequencies.[2,3] The detection mechanism of metal–metal point contact diodes has been investigated and many results suggest tunneling through an intermediate oxide barrier as the primary conduction process.[4,5] Tsang and Schwarz have presented a case for Schottky barrier behavior in some metal–semiconductor point contacts,[6] while Aukerman and Erler[7] have shown that other materials exhibit detection as a result of thermoelectric heating of the electrons in the semiconductor.

In the present study, a selection of tungsten–semiconductor point contact diodes have been investigated and compared to the more common tungsten–nickel diode.[3] The experimental work involved direct observation of a 2 GHz beat frequency between two submillimeter lasers, as well as video detection of a modulated laser signal. *I–V* characteristics of the diodes were also studied. Parameters of the experiment included submillimeter laser power, zero-bias contact resistance, and the level of applied d.c. bias. The nonlinearity in the *I–V* characteristic of each diode was measured and related to the bias dependence for both the video and beat signals. The results reported below raise some questions concerning the predominant detection mechanism in point contact diodes.

EXPERIMENTAL

The experimental apparatus is shown in Fig. 1. An optically pumped HCOOH laser, excited by a grating-tuned CO_2 laser, was used as one of the submillimeter sources. The CO_2 pump power was approximately 30 W at the 10R22 pump line required for exciting an HCOOH 311 μm line. The submillimeter waveguide laser, based on a design by Hodges *et al.*[8] consisted of a 2 m long × 38 mm i.d. pyrex tube with the end mirrors mounted in vacuum boxes. The pump power was coupled into the submillimeter laser through a 4 mm dia. hole in a copper mirror located at one end of the laser. This mirror had a 4 m radius of curvature, which reduced the number of low-loss transverse waveguide modes, and facilitated tuning of the submillimeter laser. The submillimeter signal was coupled out of the laser through a hybrid mirror which consisted of a silicon substrate coated with a dielectric stack of ZnSe/Ge with high reflectivity at 10.6 μm. An additional gold overcoat with a 3–13 mm dia. hole provided submillimeter wave feedback as well as output coupling. The best power obtained from the 311 μm line was 0.4 mW. The second submillimeter source was a discharge pumped HCN laser which served as the local oscillator. It consisted of a 3 m long × 9 cm dia. tube, and had a Michelson interferometer output coupler. With proper adjustment of the output coupler, 5 mW could be obtained from the 311 μm HCN line.

The point contact whiskers were fabricated from 25 μm dia. tungsten wire by the usual electro-etching process.[9] Tip diameters from 1000 Å were achieved. The tungsten wire was bent at 90°, with an additional

* Work supported by a grant from the National Science Foundation.
† Presently with the Electronics Department, General Motors Research Labs, GM Technical Center, Warren, MI 48090, U.S.A.

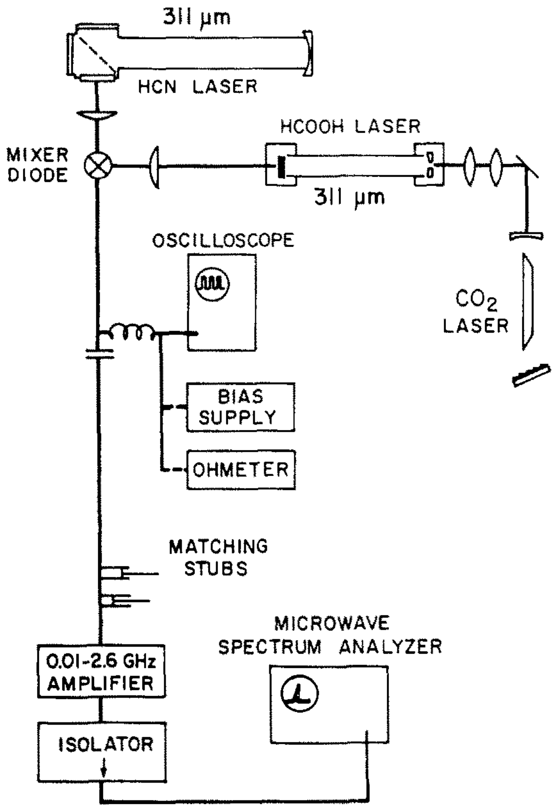

Fig. 1. Diagram of the experimental apparatus, showing the two lasers and the electrical connections to the diode.

small loop to provide both a spring loading on the point and an inductance that defined the electrical length of the antenna.[10] The whisker was placed in a diode mount consisting of a whisker holder attached to an OSM r.f. connector, and a substrate mount which could be moved and brought into contact with the whisker (see Fig. 2). The diode substrate material (either nickel or one of the semiconductors studied) was polished to an optically shiny finish, and attached to the mount. The substrate was brought into contact with the diode, and the resistance of the junction was monitored with a special low current, low capacitance circuit. Although some of the semiconductor surfaces were lightly etched prior to mounting, no special effort to either inhibit or encourage the growth of an oxide layer on any of the surfaces was made. The electrical characteristics of the substrates were stable over several months time.

The two laser beams were focused independently on the diode with approximately $f/7$ polyethylene lenses (focal lengths 27.6 and 30.2 cm). Initially, the tungsten whiskers used were 1-1/4 wavelengths long, which placed the principal antenna lobes at about 45° from the axis of the whisker. The two lasers were focused on the diode from two opposite sides of this conical antenna pattern (see Fig. 3a). Later experiments used a silicon wafer as a simple beam combiner, so that the two submillimeter laser beams were collinear at the diode (Fig. 3b). A long whisker, with a high antenna gain and a beamwidth more nearly matched to the focused laser beam width could be used with this arrangement. With a 7–3/4λ antenna, an improvement of 4 dB was obtained for the conversion loss, despite a 6 dB decrease in the local oscillator power due to reflection and aperture effects at the beam combiner.

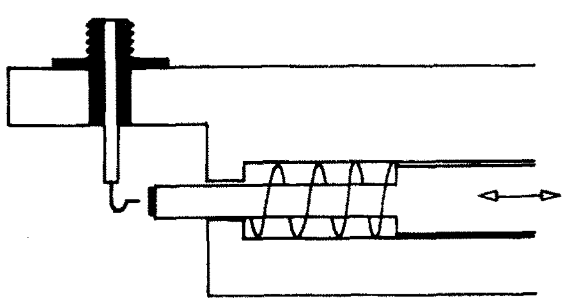

Fig. 2. Detail of the whisker diode, and the diode mount.

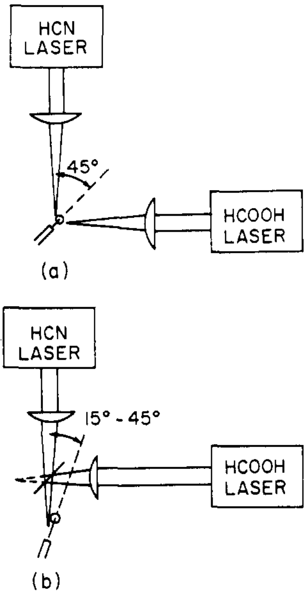

Fig. 3. Duplexing schemes for illuminating the diode with both laser signals. (a) Right-angle coupling resulting from 45° beam direction on a 1–1/4λ antenna. (b) Beam-splitter combiner, using high gain 7–3/4λ long antenna.

The i.r. signal from the diode was matched to a broadband GaAs FET amplifier (Avantek SD8-0601 N) with a double stub tuner. The amplifier output was detected by a microwave spectrum analyzer with a sensitivity of -92 dBm in a 10 kHz bandwidth. A monitor-tee, placed between the diode and the double stub tuner, allowed d.c. bias to be applied to the diode during mixing without affecting the i.r. match. In addition, video detection of one laser signal and I–V characterization of the diode could be obtained for the same contact that the mixing experiments were performed on.

RESULTS

Table 1 summarizes the video and mixer sensitivities of the various materials studied. As described below, the diode response was a sensitive function of applied d.c. bias. The values quoted here are for optimum bias.

The lowest conversion loss observed with these detectors was still quite large (Table 1). This was due in part to difficulties in matching the submillimeter signal to the diode structure. For all the diodes studied, the magnitude of the output signal was

Table 1. Summary of characteristic and performance of the diodes studied

Material	Antenna length (wavelengths)	Video responsivity (V/W)	Mixing conversion loss* (dB)	Video NEP (W/Hz$^{1/2}$)	Mixing MDP (W/Hz)
Ni	7–3/4	0.4 ± 0.2	—	2.7×10^{-8}	—
	1–1/4	—	82 ± 4	—	13×10^{-12}
	7–3/4	—	75 ± 4	—	2.5 ± 10^{-12}
n-InSb	7–3/4	1.6 ± 0.3	—	300×10^{-8}†	—
	1–1/4	—	81 ± 4	—	10×10^{-12}
	7–3/4	—	77 ± 4	—	4×10^{-12}
p-Ge	7–3/4	4 ± 2	—	1×10^{-8}	—
	1–1/4	—	79 ± 7	—	6.3 ± 10^{-12}
	7–3/4	—	75 ± 5	—	2.5×10^{-12}
n-Ge	7–3/4	17 ± 4	—	0.65×10^{-8}	—
	1–1/4	—	81 ± 4	—	10×10^{-12}
	7–3/4	—	78 ± 5	—	5×10^{-12}

* +2 dBm of LO for 1–1/4λ antenna; -4 dBm of LO for 7–3/4λ antenna.
† Noise was unusually high and may have been instrumental, not detector-limited.

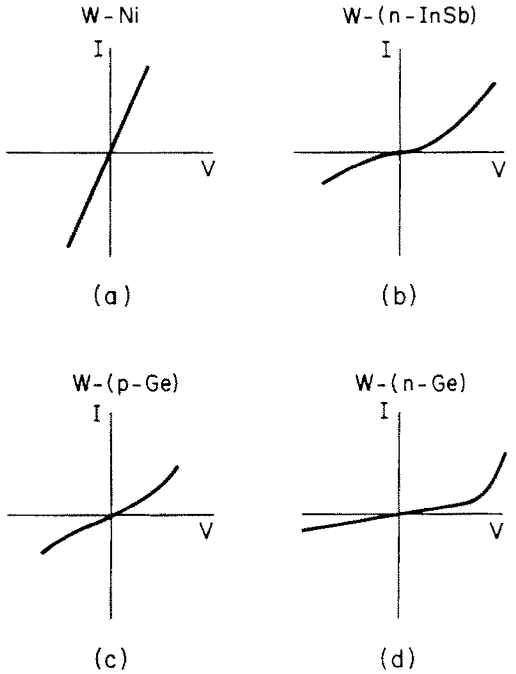

Fig. 4. I–V characteristics of the 4 diodes studied. All curves are drawn to the same scale.

a linear function of the LO power, implying that the devices were far from being saturated[11] and thus large conversion losses could be expected. In the only other available study of conversion loss in point contact semiconductor mixers[12] 65 dB of conversion loss were observed with tens of milliwatts of klystron LO power. In this work, no real attempt was made to achieve minimum conversion loss. Rather the data were used to elucidate some of the operational characteristics of these diodes.

Figure 4 shows typical I–V curves for the different diodes. The low current resistance could be varied by several orders of magnitude with the diode mechanical adjustment, and the overall I–V curve varied correspondingly. In addition, qualitative changes occurred coincidently with discrete changes in the submillimeter video and mixing characteristics. For diodes displaying "good" response, tungsten–nickel was linear on the scale observed while n-type indium antimonide and p-type germanium showed nearly symmetric nonlinearities and higher zero-bias resistances. The n-type germanium displayed an exponential forward characteristic, and a linear reverse behavior. For all

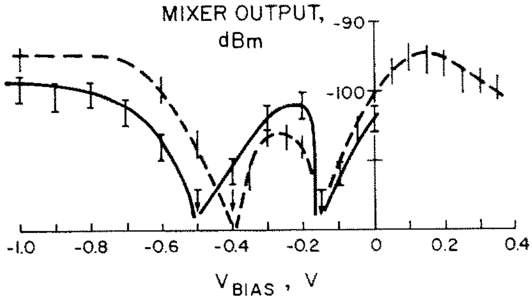

Fig. 5. Rectified signal (video response) and mixer signal output as a function of average d.c. voltage across an n-InSb diode. The continuous and dashed curves represent two different contacts.

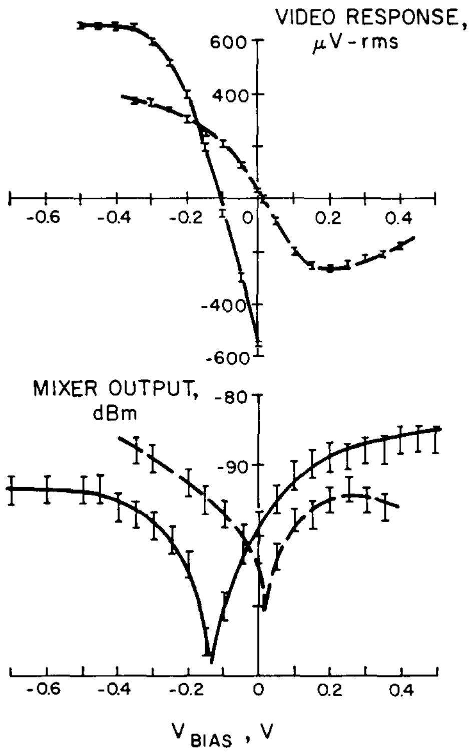

Fig. 6. Mixer output power as a function of bias voltage for a tungsten p-Ge diode. Broken and continuous lines represent two different contacts.

of the detectors, good mixing required the points to be run in harder than the initial contact, with associated lower resistances and smaller nonlinearities.

The mixer and video response of n-InSb, p-Ge, n-Ge and Ni all showed similar behavior. Diodes of n-silicon and p-GaAs were also tested, and while they did exhibit some weak video response, any mixing was below the system detection limit. Figure 5 shows typical behavior of both mixing response and the video detection as a function of bias voltage. These particular results are for n-InSb, for two different contacts. The solid line corresponds to the I–V curve shown in Fig. 3b. Two significant conclusions can be made from these results. First of all, the video response and the mixer output correlate well with bias voltage. That is, a zero in mixer response occurs at the same bias level as the zero in video output. However, correlating this detector behavior with the low frequency I–V characteristics of the junctions, as some other workers have done[4,13–15] is quite difficult.

In the usual interpretation of response due to a non-linear I–V characteristic, the output should be proportional to $-d^2I/dV^2$, the curvature of the I–V curve.[4] Most of the present curves, therefore, imply zero response for no average d.c. voltage across the junctions, with peaks of different magnitude and opposite sign on either side of 0 V.

A comparison of the device response data and the curvature of the I–V characteristics reveals that in all cases there is no correlation between zeros in the detector performance, and zeros in d^2I/dV^2. In particular, note that p-Ge (Fig. 6) displayed two zeros in the beat signal neither of which correlated with inflection points in the I–V characteristics.

DISCUSSION

The principal detection mechanism attributed to point contact diodes as noted is rectification due to a nonlinear I–V characteristic that responds directly at the terahertz frequency of the submillimeter laser. Twu and Schwarz[13] and Faris *et al.*[4] have studied the bias dependence of MOM devices at frequencies up to the infrared and observed the proper behavior for a tunneling nonlinearity. In particular, the signal was symmetric and reversed polarity at zero bias. Yasuoka *et al.*[5] studied the temperature dependence of these diodes and also concluded that tunneling properly described their behavior. Nagasima and Tako,[14] by contrast, measured the second derivative of the I–V directly, and found that while some diodes showed rectification at 10.6 μm that was consistent with d^2I/dV^2, there was still a significant qualitative disagreement with the tunneling theory prediction of that derivative. Small *et al.*[15] noted that some diode contacts could be obtained that had zero-bias signals nearly as large as the best signal with bias. These last two results cannot be explained by tunneling as usually applied to MOM diodes. For metal–semiconductor diodes Tsang and Schwarz[6] suggest a bias enhanced Schottky barrier mechanism as being responsible for the signal detection. They observed an optimum rectification with about 0.3 V bias on n-Ge. This is in contrast to the polarity reversal near 0.35 V seen in this work.

A possible alternate detection mechanism for metal–semiconductor detectors is the thermoelectric effect involving hot electrons in the semiconductor as observed by Aukerman and Erler.[7] This effect predicts a signal at zero bias, as observed here, but signal polarity and sensitivity, for different doping levels and contact resistance, were generally inconsistent with this mechanism.

In summary, point contact diodes of tungsten on Ni, n-InSb, p-Ge and n-Ge have been studied as both video detectors and submillimeter wave mixers. The best video responsivities among the various diodes differed by a factor of 40, despite mixer conversion losses which were all within 3 dB of one another. In an attempt to determine the mechanism responsible for the detection process, we compared the I–V characteristics of the diodes and the bias dependence of the device performance. The behavior of all four diodes, MOM and metal–semiconductor, was quite similar, but not explainable by the commonly accepted mechanisms. Thus it is apparent that something other than thermoelectric effects, low frequency tunneling, or Schottky barrier characteristics are responsible for the submillimeter video rectification and harmonic mixing in these point contact diodes.

REFERENCES

1. McColl M., *Proc. Soc. Photo. opt. Instrum. Engrs* **105**, 24–34 (1977).
2. Jimenez J. J. & F. K. Peterson, *Infrared Phys.* **17**, 541–546 (1977).
3. Knight D. J. E. & P. T. Woods, *J. Phys.* E**9**, 898–916 (1976).
4. Faris S. M., T. K. Gustafson & J. C. Wiesner, *IEEE J. Quant. Elect.* QE-**9**, 737–745 (1973).
5. Yasuoka Y., T. Sakurada & T. Miyato, *Jap. J. appl. Phys.* **17**, 171–176 (1978).
6. Tsang D.-W. & S. E. Schwarz, *Appl. Phys. Lett.* **30**, 263–265 (1977).
7. Aukerman L. W. & J. W. Erler, *Opt. Lett.* **1**, 178–180 (1977).
8. Hodges D. T., F. B. Foote & R. D. Reel, *Appl. Phys. Lett.* **29**, 662–664 (1976).
9. Wentworth F. L., J. W. Duzier & J. D. Rodgers, *Microwave J.* June 69–75 (1964).
10. Matarrese L. M. & K. M. Evenson, *Appl. Phys. Lett.* **17**, 8–10 (1970).
11. Torrey H. C. & C. A. Whitmer, *Crystal Rectifiers*, *MIT Radiation Lab. Series*, Vol. 15, Chapter 5, McGraw-Hill, New York (1948).
12. Zuidberg B. F. J. & A. Dymanus, *Appl. Phys. Lett.* **29**, 643–645 (1976).
13. Twu B. L. & S. E. Schwarz, *Appl. Phys. Lett.* **25**, 595–598 (1974).
14. Nagasima A. & T. Tako, *Jap. J. Appl. Phys.* **16**, 1349–1354 (1977).
15. Small J. G., G. M. Elchinger, A. Javan, A. Sanchez, F. J. Bachner & D. L. Smythe, *Appl. Phys. Lett.* **24**, 275–279 (1974).