First MMW Characterization of ErAs/InAlGaAs/InP Semimetal-Semiconductor-Schottky Diode (S^3) Detectors for Passive Millimeter-wave and Infrared Imaging*

H.Kazemi[1], J. D. Zimmerman[2] E. R. Brown[3], A. C. Gossard[2], G. D. Boreman[3], J. B. Hacker[1], B Lail[3], C Middleton[3]

[1] **Rockwell Scientific Company, Thousand Oaks, CA**
[2] **Materials Department, University of California, Santa Barbara**
[3] **Department of Electrical and Computer Engineering, University of California Santa Barbara, CA**
[3] **College of Optics and Photonics: CREOL & FPCE, University of Central Florida, Orlando, FL**

***Abstract*–We present the first mm-wave characterization of Semimetal Semiconductor Schottky (S^3) diodes for direct detector applications from 94 GHz to 30 THz. The S^3 devices use molecular-beam epitaxy growth of binary compounds that are closely lattice-matched and crystallographically perfect across the heterointerface to reduce 1/f and burst noise while maintaining ultra-high-frequency performance. The S^3 diodes are fabricated from an InAlGaAs/InP based material system with both the Schottky layer and contact layer having n and n^+ doping levels. The semimetal Schottky contact is ErAs which is grown in-situ during the MBE growth. By varying the InAlAs percentage content in the epitaxial layer structure, the diode dc I-V characteristics and its zero bias responsivity are optimized. Diode *s*-parameter data from dc-100 GHz is used to determine the diode responsivity as a function of frequency and diode capacitance and resistance. These measurements then allow the device intrinsic and extrinsic equivalent-circuit elements to be optimized for direct detection from 94 GHz to ~30 THz.**

***Index Terms*— Schottky diodes, semimetal, zero bias detectors, millimeter-wave imaging, responsivity, low noise operation**

I. Introduction

The challenges of concealed-weapons detection, all-weather imaging, and bioparticle remote sensing provide a new system pull in the upper millimeter and THz bands, particularly for room-temperature systems that are portable. One of the most useful semiconductor devices, the Schottky diode (SD), is a cornerstone for large-signal THz applications such as mixers and frequency multipliers, but is not as common in small-signal applications such as square-law and envelope detection. In this paper the authors discuss the novel device characterization of a semimetal-based Schottky detector. These devices use a semimetal material such as ErAs instead of an evaporated metal as the Schottky contact in the InP material system to provide a lattice match and a defect-free interface. This could result in low noise performance (1/f) and still maintain the Schottky zero bias sensitivity and its scalability to higher frequencies. In this paper the first MMW characterization of the semimetal semiconductor Schottky (S^3) detectors is described.

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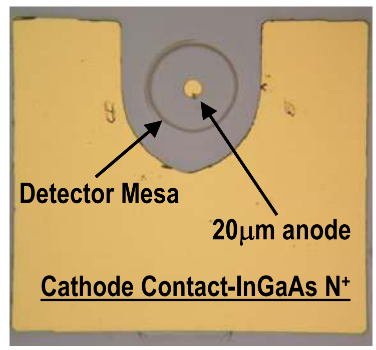

Figure 1- The S^3 detector geometry for MMW characterization

II. Detector fabrication

The S^3 detectors used for this work were designed and fabricated at the University of California at Santa Barbara as early devices for characterization and verification of this new technology [1]. The epitaxial wafers are MBE grown, Si-doped $(InGaAs)_{1-x}$ $(InAlAs)_x$ on InP substrates. The layer structure consists of a buffer layer followed by the n^+ doped InGaAs ($5x10^{18}cm^{-3}$) contact layer. The Schottky layer is a digital alloy of InGaAs and InAlAs doped at $1x10^{17}$ cm^{-3}. The digital alloy ratio can be altered to optimize performance for either biased or zero bias operation. The Schottky layer is capped by an in-situ MBE grown ErAs semimetal

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with a small lattice mismatch (2.1%). This not only allows for a dislocation-free single crystal Schottky interface, but also an interface free from oxide, which has been major issue with conventional Schottky diode performance quality at MMW frequencies.

The ErAs semimetal layer is covered in-situ with an Al layer to preserve the semimetal region during the fabrication process. The fabrication process starts by defining the anode dimension with a 20µm diameter circular metal layer of Ti/Pt/Au on the Al layer. Schottky area is defined by the ErAs semimetal layer that resides under the Al layer. These layers are subsequently etched in an Al etch solution (photoresist developer) in a self-aligned process, and some undercutting of the 20µm anode is assumed to occur during the latter process. However, by keeping the Al layer thin (750Å), the undercut is limited and controlled. The final process is the definition of the cathode contact for the lowest resistance possible. The InGaAs n^+ layer is highly doped ($5x10^{18}$ cm^{-3}) to reduce sheet resistance from the anode to the cathode before it reaches the cathode metal contact. The cathode contact is shaped in a semicircular pattern surrounding the 20 µm anode as shown in Figure 1. Following photolithographic patterning of the cathode contact, a citric-based etch is used to remove the top layer and expose the highly doped InGaAs ohmic layer. A metal stack of Pd/Ti/Pt/Au is

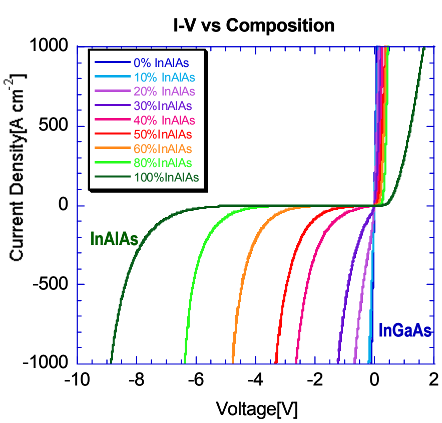

Figure 2 – Digital alloy performance control on the S^3 detectors using semimetal-semiconductor interfaces

evaporated to serve as the non-alloyed ohmic contact.

Figure 2 shows the I-V curve of the S^3 detectors fabricated with various $(InGaAs)_{1-x}$ $(InAlAs)_x$ digital-alloy compositions. Digital alloying is an advantageous growth technique using short period superlattices to create a weighted average of two compounds. The resulting effect is that the barrier potential, Φ_n can be controlled accurately by changing the bandgap, electron affinity, and effective mass to optimize the detector for zero or a non-zero operation. The detector fabrication process

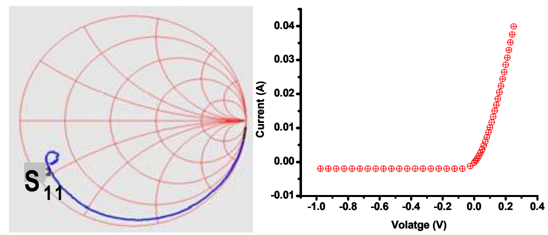

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Figure 3- Smith chart data from dc-110GHz and the I-V characteristics of the S3 detectors

and optimization of the digital alloy with reference to its DC performance have been reported in [1] and will not be covered in this paper. Specific to the work covered in this paper, the detectors are $(InGaAs)_{0.8\%}$ $(InAlAs)_{0.2\%}$ for zero bias operation, with an anode diameter of 20µm as previously described in the fabrication process. Figure 2 shows a microphotograph of a detector used with the center contact directly probed by a CPW wafer probe and with ground contacts separated by 150µm.

III. MMW CHARACTERIZATION OF S^3 DETECTORS

The MMW characterization of the detectors was carried out by probing the detectors directly using a CPW probe connected to an 8510XF Agilent vector network analyzer. A 2-port Load-Reflect-Reflect-Match (LRRM) calibration routine was performed from 500MHz to 100GHz to define the reference plane of the measurement. The detectors were then probed and the 1-port S-parameter data for the detectors were stored. Following the diode measurements the intrinsic device data was extracted by using a de-embedding routine. This accounted for the parasitic capacitance between the anode and the cathode contact and the inductance to ground, originating from the cathode geometry. Figure 3 shows the Smith chart plot of the S_{11} detector measurements, indicating the capacitive nature of the data representing the detector capacitance at zero bias. The detector resistance is also noticeable since the S_{11} data has been drawn inside the chart. The structure shown in Figure 1 is not ideal for W-band characterization, since direct probing of the anode introduces errors in determining the exact position of

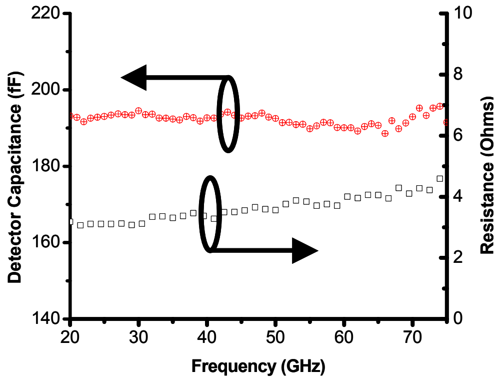

Figure 4- Device capacitance and resistance as a function of frequency for the 20um Semimetal Semiconductor Schottky Detector

the probe, resulting in increase in the parasitic components of the de-embedding model. This effect is shown by the presence of the resonance on the Smith chart data in Figure 3 and is represented by a tight loop at the highest frequency region.

The intrinsic detector data was extracted by accounting for and deembedding all the parasitic components. The accuracy of this procedure is shown in the plot of detector capacitance as a function of frequency, resulting in no variation across the measured frequency for the junction capacitance of 192 fF as shown in Figure 4. The extracted diode resistance 3.8 Ω results in a cut-off frequency of greater than 200 GHz for the 20μm S^3 detector. The resistance is thought to be due to the excess sheet resistance from the 70 μm separation between the anode and cathode contact. In the future, a planar airbridged device will replace the existing structure to allow the contacts to be made to the contact pads of the detector. A low resistance metal airbridge will connect the anode to the contact pads. This allows not only for more accurate device characterization but also the capability of measuring smaller anode geometries in the submicron range.

IV. MMW S^3 Detector Performance

The figure of merit for a detector is its responsivity (sensitivity) defined as the dc rectified amplitude as a function of RF input power to the detector, and has the units of mV or mA per Watt. The higher the recorded value of the dc component and the lower the input power level, the more sensitive the detector is to rf radiation. At MMW frequencies factors such as the input impedance match to the detector and the device intrinsic cut-off frequency are also important and are discussed later.

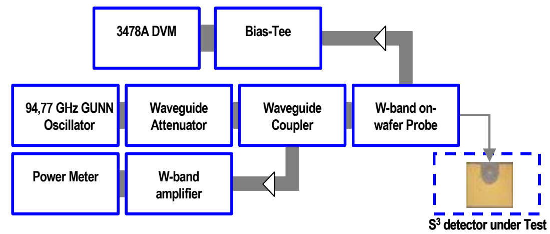

Figure 5- W-band Reflectometer setup for responsivity measurements of the S^3 detector

In order to establish the S^3 detector responsivity at MMW frequencies, two independent frequency points at 94GHz and 77GHz in the W-band frequency range were measured. Figure 5 shows the block diagram of a single frequency W-band reflectometer setup assembled in WR10 waveguide.

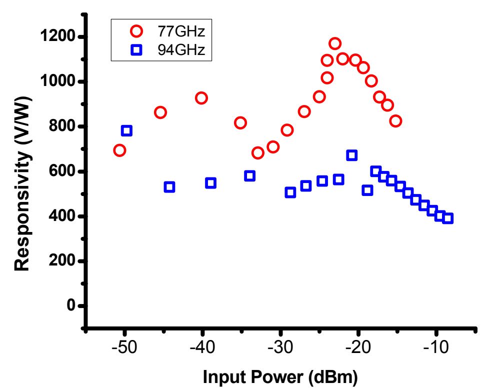

Figure 6- S3 Detector Responsivity as a function of detector input power at 94 and 77GHz

The Gunn oscillators at both frequency points are used as a power source, fed into an attenuator to reduce and control the input power to the device. A 20dB coupler samples the reflected power into a W-band amplifier before it is measured with a power meter. A waveguide-to-CPW probe is used to on-wafer probe the devices shown in Figure 2. A bias tee and a DVM measure the millivolt level signals generated by the detector. The measurement system was calibrated by characterizing each component for insertion loss at W-band. In addition, for each attenuator setting, an on-wafer short-circuit standard was used to calibrate the power meter and coupler assembly. The scalar measurement performed by this represent a relative measurement between the reflected power from the short-circuit standard and the diode detector, and hence measurement accuracy is limited.

Figure 6 shows the measured responsivity (V/W) plot as a function of the power absorbed by the detector. The responsivity measurements are taken at 94GHz and 77GHz using Gunn oscillators tuned to each frequency after calibration. The measured responsivity data shows less input power is required to register the same responsivity at 77GHz than 94GHz. The closer the frequency of operation is to the cut-off frequency of the device, the less nonlinearity is experienced by the device, therefore, less responsivity is measured.

Figure 6 and 7 show the data extracted at 77 and 94 GHz from the reflectometer. Figure 7 shows the detector square law behavior is maintained up to –20 dBm input power, beyond which is the start of the

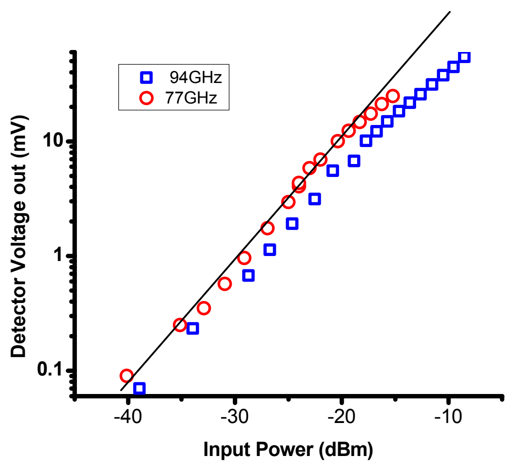

Figure 7- S3 Detector output voltage as a function of detector power input

linear region. The responsivity data in Figure 6 also show peaks at –20dBm both at 94 and 77 GHz with the 77 GHz responsivity being higher than at 94 GHz. The peak in responsivity at –20dBm shows that the detector is not truly a zero bias detector experiencing the highest responsivity at higher input power. This results in the RF signal self biasing the detector at –20dBm. By varying the digital alloy composition in the epitaxial layer, for example reducing the InAlAs percentage to 10%, this effect could be mitigated.

The responsivity data measured is comparable to the published data [2,3] at W-band frequencies. Further improvements to devices cut-off frequency would expect to lead to increased responsivity at zero bias. The main advantage of the S^3 detectors is their low noise performance due to the in-situ, deposited defect-free interface. The authors will be measuring the noise response of the devices in the near future.

V. CONCLUSION

The first MMW characterization of semimetal semiconductor Schottky detectors is presented based on s-parameter measurements from dc-110GHz. The de-embedded device data show a capacitance of 192fF with a resistance of 3.8Ω. The corresponding responsivity measurements show 800-1000 V/W at 77GHz and 500-600 V/W at 94 GHz. In the near future, detector capacitance and resistance will be reduced, thereby increasing the cut-off frequency of the detectors to the THz range. This will in turn ensure nonlinearity of the detectors is preserved at W-band, and responsivity is increased.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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