Ultra sensitive ErAs/InAlGaAs direct detectors for millimeter wave and THz imaging applications

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***Abstract*–A new class of zero bias, room temperature ultra sensitive detectors have been introduced for detection of millimeter wave radiation. The detectors have been scaled to micron level and have shown record responsivity in three forms. A W-band waveguide detector was designed and measured to have 4500 V/W voltage responsivity. A planar antenna coupled detector was also evaluated with and measured a responsivity 16100 V-mm^2/W from 75-110 GHz. Following a resonant impedance matching technique an on-wafer characterization have shown voltage responsivity to exceed 20,000 V/W. The result does not include the reflected power from the detector and have shown that these detectors could provide noise equivalent power (NEP) values in the 4x10^{-13} W/ √Hz level.**

***Index Terms*— Millimeter wave imager, direct detection, Schottky diode, ErAs, InGaAs, rectifier diode, responsivity, sensitivity, W-band**

I. INTRODUCTION

Direct detection from millimeter wave to DC in an in-coherent imaging system allows a tremendous simplification of the focal plane array architecture by eliminating expensive and complicated components such as power sources and pre-signal amplification of each pixel.

In prior attempts to develop direct detectors for millimeter wave imagers, many device technologies have been tried and optimized to increase the sensitivity and lower the generated noise level. These include GaAs planar doped barrier diodes [1], resonant interband tunneling diodes [2], and InGaAs Schottky diodes [1], all of which have shown high sensitivity in the millimeter and sub-millimeter wave frequency range through optimization of the epitaxial layer structure and the device interface technology.

In this paper, we discuss the millimeter wave performance of a new detector technology based on an in-situ formed Schottky contact. This technique provides a zero biased operation with high intrinsic short circuit responsivity, low capacitance per unit area and low dynamic resistance. The detector is very scalable and can be designed for the sub-millimeter wave region. This is achieved by reducing both the junction area size and minimizing the parasitic elements of the circuit to reach cutoff frequencies as high as 10 THz. The discussion includes a novel fabrication process for high cut-off frequency detectors a W-band waveguide detector is built to characterize the performance of the fabricated detectors and how the detectors were integrated into a planar antenna and characterized in a quasi-optical setup. Finally, on-wafer coplanar-waveguide measurements on various detector diodes showing their potential, with the highest responsivity numbers to date are described.

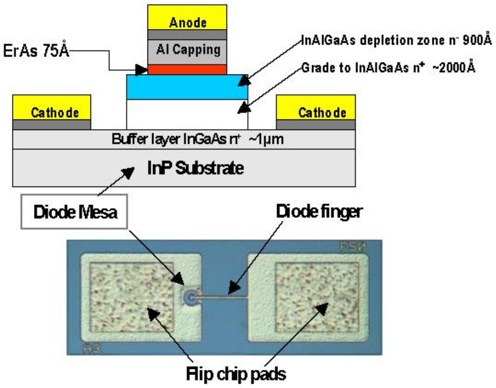

Figure 1- Epitaxial layer structure of the ErAs detector scaled to micron size in a planer flip chip structure

II. RECTIFIER DESIGN AND FABRICATION

The ErAs detector is based on a semimetal semiconductor interface where the Schottky contact is made in-situ during the molecular beam epitaxy growth. This allows for a robust, defect free, and stable Schottky interface resulting in a very low noise performance and zero bias operation. The semimetal used is an ErAs film grown on Si-doped $(In_{0.53}Ga_{0.47}As)_{1-x}(In_{0.52}Al_{0.48}As)_x$ on InP substrates. The lattice mismatch between the ErAs and InAlGaAs is only 2.1% resulting in a dislocation free interface. The performance of the ErAs detector can be varied by controlling the Al percentage in the InAlGaAs Schottky layer. This results in the modification of the Schottky barrier height from approximately –0.05eV to 0.45eV in a highly controlled manner. Other control features are the doping density concentration and the interface type described in an earlier paper [3]. The work carried out in this paper uses the same doping density of 2x10^{17} cm^3 and 20% Al composition used in the InAlGaAs Schottky layer [3,4]. Previously we have described the fabrication of large area ErAs detectors for evaluation and grading of the epitaxial

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[1] Manuscript submitted November 30, 2006. This Work is supported by DARPA MTO under MicroArray Antenna, Technology and Applications (MIATA) Program and Army Research Laboratory under the contract W911QX-04-C-0125

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growth [3,4]. In order to improve the detector performance efforts were made to increase the cut-off frequency from a previously reported 200 GHz [4]. This requires the reduction in the Schottky anode size accompanied by a low series resistance. A unique planar-bridged fabrication process was devised by which the anode contact was Au electroplated on the Aluminum capped ErAs layer with a Ti/Pt layer separating the Au from the Aluminum contact. A non-alloyed ohmic contact was made to the n^+ InGaAs region using a Ti/Pt/Au metal stack. Ohmic to anode separation was kept to a minimum to reduce sheet resistance contributions to the total series resistance. The detectors were then mesa isolated from each other through a wet etch process combining citric and phosphoric chemistry. Anode sizes were 2, 3, 4, 5 and 6 um in diameter and connected to the planar anode pad by an electroplated finger. The width and length of this finger is a design parameter and provides the internal impedance matching inductance to the diode capacitance. The finger lengths were varied from 25um to 200um in 25um steps. The proximity of the finger inductance to the diode junction capacitance ensures the creation of the resonance at the design frequency. Figure 1 shows the epitaxial wafer layer structure and a flip chip ErAs detector with a 100um finger length.

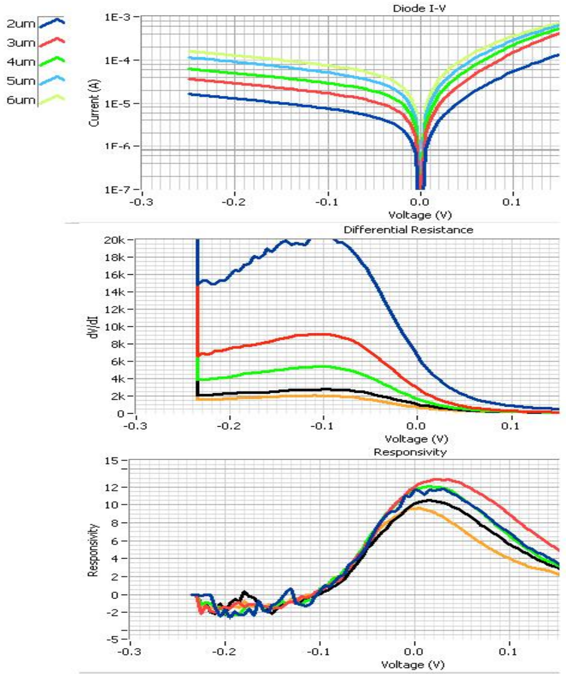

Figure 2- DC parameters of micron scale ErAs detectors with I-V data; zero bias resistance and short circuit responsivity

III. DC CHARACTERIZATION

Following the fabrication of various sized micron scale planar ErAs detectors, their I-V curve was measured. A numerical calculation based on the derivative of the I-V data, resulted in the responsivity value in terms of A/W units. The short circuit responsivity in A/W is derived from the Taylor expansion of the Schottky diode equation. By applying a coherent signal of $V\cos(\omega t)$ the average power of the coherent signal can be defined in terms of current (I) derivatives. The short circuit responsivity is defined as the down converted current in Amps due to the incoming signal in Watts [3] and is defined as:

$$\Re = \frac{\frac{\partial^2 I}{\partial V^2}}{2\frac{\partial I}{\partial V}}$$

Where I and V are current and voltage measured. Figure 2 represents the measured current, differential resistance and the short circuit responsivity against applied voltage for 2, 3, 4, 5 and 6um diameter planar ErAs detectors. The measured current scales with detector size and shows a current density of 12.5-20(μA/μm^2) at the applied forward voltage of 0.1V. The zero bias differential resistance values of 6.4 KΩ for the smallest diode size of 2um and 690 Ω for the largest size of 6um diameter detectors are shown. This represents a dynamic resistance per unit area of 20,000 $\Omega.\mu$m^2. The responsivity plots for each detector size shows no change with the area size. This is appropriate since the short circuit responsivity is only related to the ideality factor and is independent of the diode area. In fact, by using the exponential I-V equation for a Schottky diode and extracting the short circuit responsivity, the equation above will simplify to 19.2/n, where n is the ideality of the Schottky diode. The value of 10-12 A/W is strongly dependent on the epitaxial design of the layer structure with mainly the Aluminum content of the InAlGaAs digital alloy layer playing a crucial role. This is explained further in an earlier paper [3].

Diam.(um)	R0 (Kohm)	Resp.(A/W)	J (uA/um2) @0.1V	Cap (fF)
2	6.50	11.69	17	5.5
3	2.90	12.03	20	12
4	1.60	11.73	17	22
5	1.00	10.11	15	35.7
6	0.69	9.60	12.5	49.5

Table1- Summary of DC and capacitance characterization data for the ErAs detectors

The capacitance of the planar rectifier diodes was also measured using a single ended coplanar waveguide structure fabricated on wafer. The diodes were characterized from 1-110 GHz using an 8510XF network analyzer with minimum power level settings to reduce uncertainty in extraction of the zero bias capacitance of the diodes. Each structure was carefully de-embedded [4] and the capacitance at zero bias was extracted. Table 1 captures the DC and capacitance values of the planar detectors showing a capacitance of 1.75 fF/μm^2, linearly scaled with device area. It is also important to mention that the combination of low capacitance and resistance per unit area compared to other detector technologies is the key figure of merit for these detectors. Having a low capacitance reduces the shunting of millimeter wave current to ground and allows for coupling across the dynamic resistance (R0) and hence results in higher measured voltage responsivity at W-band frequencies and beyond.

IV. W-BAND WAVEGUIDE DETECTOR

The above described the short circuit responsivity of the ErAs detectors in A/W units. This number is tabulated and acts only as a qualitative value for the diode detector. The most important criterion is the voltage responsivity measured directly in a millimeter wave setup. This is a ratio of the DC voltage measured in Volts to the incident millimeter wave power in Watts. The highest value ultimately possible from the detector is the product of its short circuit responsivity and its zero bias resistance. In practice it may not be possible to reach this number mainly due to the requirement of optimum impedance match to both the source and the load. To investigate this further and access the millimeter wave responsivity of these novel detectors, the voltage responsivity was measured in three forms. These forms are a W-band waveguide detector, an antenna coupled detector and finally an on-wafer detector setup.

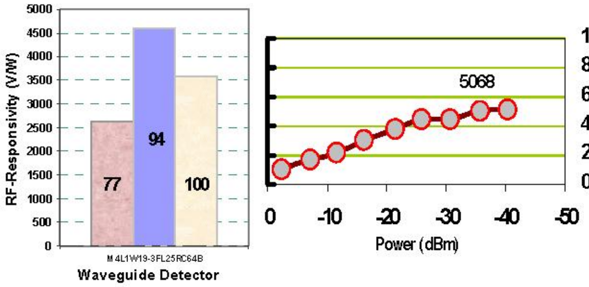

Figure 3- W-band waveguide detector responsivity (a) shown at 77, 94 and 100GHz (b) As a function of input power at 94 GHz

A W-band waveguide (WR10) detector was designed with an E-plane feed circuit to operate from 75-110GHz. The circuit was made from 4mil quartz and was designed to optimally couple to the waveguide. The simulated insertion loss across the W-band was 0.2dB. A slot was made in the waveguide to transition from the waveguide to microstrip and designed to be cut-off to the W-band radiation. The planar detector was flipchip mounted on the circuit with a radial stub presenting an RF short so the DC voltage could be optimally extracted. The circuit was mounted in the waveguide and measured using the W-band setup described in [3]. Calibrated power from Gunn diodes through a variable attenuator was measured at the waveguide detector port at 77, 94 and 100 GHz. The DC voltage was measured as the power level was varied from –50dBm to more than –10dBm. The voltage responsivity was measured at each power level increment and averaged for values from –50dBm to –30dBm. The results are shown graphically in figure 3 where the average responsivity at 94 GHz shown to be 4500 V/W for a 2um ErAs detector with a 25um finger length. With responsivity values of 2500 V/W at 77GHz and 3500 V/W at 100 GHz, the waveguide detector has shown to be one of the most sensitive room temperature W-band detectors to date.

V. ANTENNA COUPLED DETECTORS

To be able to use the novel ErAs detectors in a focal plane array of an imaging system, it is important to evaluate its sensitivity in a quasi-optical W-band system. A log periodic antenna was therefore designed and fabricated on GaAs semi-insulating wafers. The planar antenna had a port impedance of 85 ohms and designed to cover 75-110GHz. The log periodic antenna is known for its large bandwidth and it was therefore chosen to cover the entire 35GHz bandwidth of the W-band region. A 4um planar ErAs detector was flip chip mounted at the port of the antenna and tested at DC for continuity. A 4mm wide silicon hyper-hemisphere lens was used to provide high unidirectional gaussian coupling efficiency by eliminating substrate mode energy losses. The DC component was extracted through the outer periphery of the antenna where only the DC component is present. A Gunn diode coupled to a horn antenna provided a plane wave at the aperture of the planar antenna. Calibrated power density arriving at the plane of the silicon lens was obtained by separately measuring the response of a calibrated power meter coupled to the plane wave through a scalar feedhorn of known (previously measured) effective area. The ratio of diode response, measured on a lockin amplifier, to the power meter response, all multiplied by the reference horn's effective area, gives the product of the diode's responsivity and planar antenna's effective area. This "specific responsivity" is shown in Fig. 4 for both plane wave polarizations, along with an antenna layout. The plot shows considerable variation as a function of frequency that can be attributed both to variation in the resonant impedance matching (antenna to diode) and to frequency dependence in the antenna's effective area. Separate 2-dimensional antenna pattern measurements were performed (not shown) at several frequencies within the band, and indicate effective areas of 4 – 8 mm^2, though with significant frequency variations and measurement uncertainty within this range. Thus, the responsivities obtained in the substrate lens-coupled configuration are in good agreement with those from the waveguide test configuration.

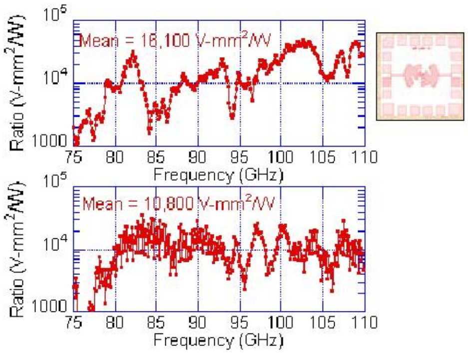

Figure 4 - Diode response to plane wave input. For the upper plot, E is normal to the leads (see layout in inset); for the lower, E is parallel to the leads.

VI. ON-WAFER DETECTOR

Both the waveguide and the antenna-coupled measurements have shown very high responsivity at room temperature. However, in order to improve the value of the voltage responsivity even further, an attempt was made to investigate the impedance matching to the ErAs detector. Since the dynamic resistance of the diode is in $K\Omega$ range and the source impedance of the antenna or the waveguide circuit is in the 70-100Ω range, there exist a considerable mismatch. This can be circumvented by resonating the capacitance of the diode with an inductance, which could be provided by the optimized length of the diode finger as described in section II.

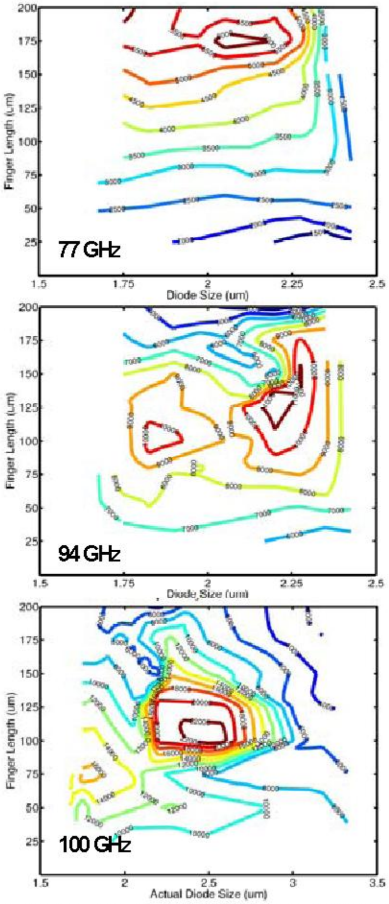

Figure 5- Contour plots of measured responsivity as a function of diode size and finger inductance for three W-band frequency points

To investigate this further, various detector sizes were fabricated on wafer with different finger lengths. These were designed, simulated and measured to provide inductance of 1pH per μm of length. The resonance created by the inductance and diode capacitance allows the efficient delivery of the incident millimeter wave power to the dynamic resistance of the detector. This results in a considerable increase in the responsivity value. The resonant impedance match is however a strong function of the capacitance values of the detector and the finger inductance and as a result, a narrowband solution. The detectors where coupled to a CPW probe and each detector size and finger length were measured through a similar setup as described in the waveguide detector characterization. Figure 5 shows three contour plots of voltage responsivity for 77, 94 and 100 GHz as a function of finger length and diode size. By varying the finger length (inductance) and the diode size (capacitance), areas of very high voltage responsivity are observed. This is the direct result of improved impedance matching and coupling of the incident power across the dynamic resistance of the rectifier diode. Record voltage responsivity of

- 6000 V/W is measured at 77GHz for a 2um diode with 175um finger length
- 10,000 V/W is measured at 94GHz for a 1.8um diode with 100um finger length
- 22,000 V/W is measured at 110GHz for a 2.25um diode with a 100um finger length

The short circuit responsivity of all detectors was greater than 9 A/W for above measurements. The main reason behind this record responsivity is not only the efficient coupling of the power to the dynamic resistance but also the low junction capacitance of these detectors. Reducing this capacitance per unit area and maintaining the zero bias responsivity has been the two principle contributions to achieving such sensitive millimeter wave detectors.

VII. CONCLUSION

A new class of room temperature, zero bias ErAs detectors has been scaled to millimeter wave frequencies. They exhibit low capacitance per unit area, high short circuit dc responsivity and have been evaluated in three forms at millimeter wave frequencies. The W-band waveguide detector has shown a responsivity of 4500V/W, while an antenna coupled detector measured 16,100 and 10800 V-mm^2/W for horizontal and vertical polarizations respectively. The on-wafer probed data following a resonant matching scheme has shown that an optimized ErAs planar detector can achieve over 20,000 V/W at 100 GHz. It is also important to mention that since the detectors are operating at zero bias, the only source of noise is Johnson noise, which is related to their zero bias resistance. The emerging noise equivalent power (NEP) for these detectors at W-band could reach $4x10^{-13}$ watts/$\sqrt{\text{Hz}}$ level with measured responsivity values stated.

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