Long Wave Infrared Detection Using Dipole Antenna-Coupled Metal-Oxide-Metal Diodes

Jeffrey A. Bean, Badri Tiwari, Gergő Szakmány, Gary H. Bernstein, Patrick Fay, and Wolfgang Porod
Center for NanoScience and Technology, Department of Electrical Engineering,
University of Notre Dame, Notre Dame, IN 46556 USA

***Abstract*—This work focuses upon dipole antenna-coupled metal-oxide-metal diodes, which detect long wave infrared radiation. These detectors offer CMOS compatible fabrication in a small pixel footprint, high speed and frequency selective detection, and full functionality at room temperature. These devices can be fabricated by either of two methods, both of which provide for the aforementioned device characteristics. In addition, the detection characteristics can be tailored to provide for multi-spectral imaging in specific applications by modifying device geometries.**

I. Introduction And Background

The long wave infrared (LWIR) band is a frequency range for which developing detectors capable of functioning at room temperature is of special interest. The reason is twofold; humans emit radiation most strongly in this range and absorption is relatively low in the atmospheric window between 8 and 12 µm. These facts provide motivation to develop detectors for use in this frequency range, which could be used for target detection, tracking, and navigation in autonomous vehicles. One such device that has been developed for LWIR sensing is the antenna-coupled metal-oxide-metal diode (ACMOMD) detector [1, 2].

In this paper, we report on the fabrication and detection characteristics of ACMOMD infrared detectors. The devices consist of two main components: a dipole antenna and a metal-oxide-metal (MOM) diode. An ACMOMD functions by the rectification of antenna currents by a nonlinear junction, which in this case is the MOM tunnel diode. These detectors can be fabricated using either of two methods, both of which employ electron beam lithography (EBL).

The first fabrication method utilizes a single EBL step followed by a double angle, or shadow, metal evaporation. By utilizing shadow evaporation and an intermediate oxidation step, the need to align multiple EBL steps is negated. Shadow evaporation through an electron beam resist was first utilized in the fabrication of nano-scale tunnel junctions [3] and later in single electron transistors [4], but this research is the first to exploit this technology for detector fabrication.

The second fabrication method involves two electron beam lithography steps, each followed by a metal evaporation. A Kaufman ion source is used to remove the native oxide of first deposited layer of metal, so that a controlled layer may be grown before the second metal deposition through the patterned electron resist [5]. This provides for control over the oxide barrier in the MOM diode, just as in the case of the shadow evaporation fabrication method. The structures fabricated by both methods are shown in Fig. 1, where the dipole antenna length is 3.1µm and the MOM overlap area is approximately 50 nm x 80 nm.

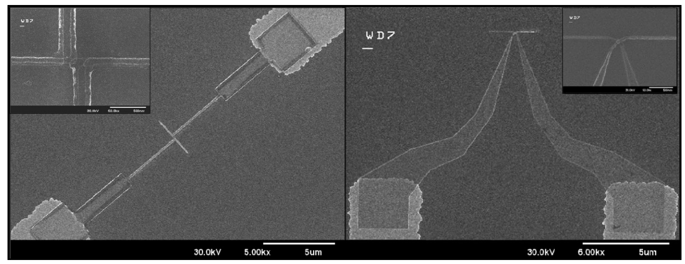

Fig. 1: $Al/Al_2O_3/Pt$ ACMOMDs fabricated by shadow evaporation (left) and two-lithography (right) processes. The inset micrographs show the overlap area where the MOM diodes are formed.

II. Results

The output of these detectors, due to incident radiation, is the rectified current from the nonlinear junction. This current is a function of detector sensitivity, found by dividing the negative of the second derivative of the I-V characteristic by the first derivative [6]. The current-voltage characteristic of these devices can be tailored by material selection; devices of various material combinations, such as $Al/Al_2O_3/Al$, $Al/Al_2O_3/Ni$, and $Al/Al_2O_3/Pt$, have been fabricated utilizing both ambient air oxidation and controlled low-pressure oxidation of the first metal layer. By controlling the fabrication conditions, the oxide layer can be tailored to obtain the desired zero-bias resistance and sensitivity. These controlled conditions also provide a high level of precision between devices and fabrication runs. Fig. 2 shows zero-bias resistance, zero-bias sensitivity, and peak sensitivity as a function of oxygen exposure for $Al/Al_2O_3/Pt$ devices.

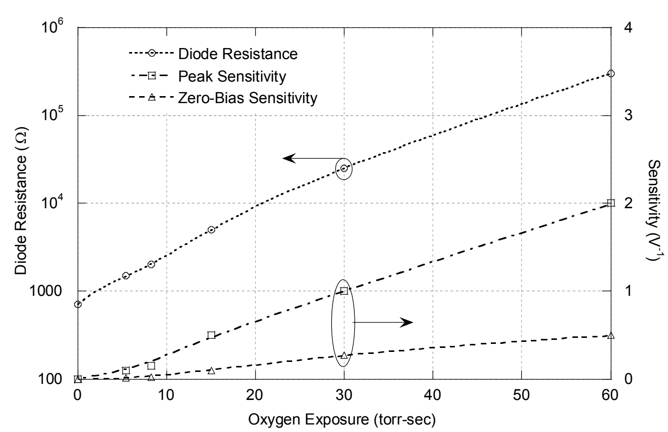

Fig. 2: Zero-bias resistance, zero-bias sensitivity, and peak sensitivity as a function of oxygen exposure during barrier layer formation for $Al/Al_2O_3/Pt$ ACMOMD detectors.

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The polarization dependence of these detectors was measured using a rotational sample stage and is shown in Fig. 3. The response of these devices can be represented by the sum of a constant, thermally-generated polarization independent response, plus a cosine-squared polarization dependent signal. The maximum signal is obtained when the electric field of the incident infrared radiation is parallel to the antenna, while the minimum is measured with the polarization perpendicular to the antenna. The response of an $Al/Al_2O_3/Ni$ ACMOMD fabricated by the shadow evaporation procedure is shown in Fig. 3. In agreement with antenna theory, these devices follow this cosine-squared dependence, denoted by the dotted line. This proves that the detection mechanism in these devices is due to radiation-induced longitudinal currents propagating along the dipole antenna. The polarization ratio, which is the ratio between the maximum and minimum signal, is around 15, which is equal to the highest previously reported value [7].

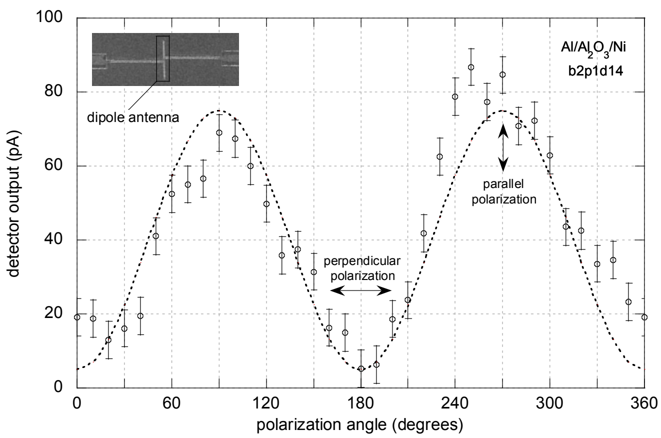

Fig. 3: Polarization response a $Al/Al_2O_3/Ni$ ACMOMD. Deviations from this response are due to mode hopping of the CO_2 laser used for testing, and are denoted by the error bars.

The response of a typical $Al/Al_2O_3/Pt$ ACMOMD fabricated by the two-lithography, two-evaporation method is shown in Fig 4. These devices also show a cosine-squared dependence with respect to the polarization angle of the incident radiation. In this case, the polarization ratio is around 5.

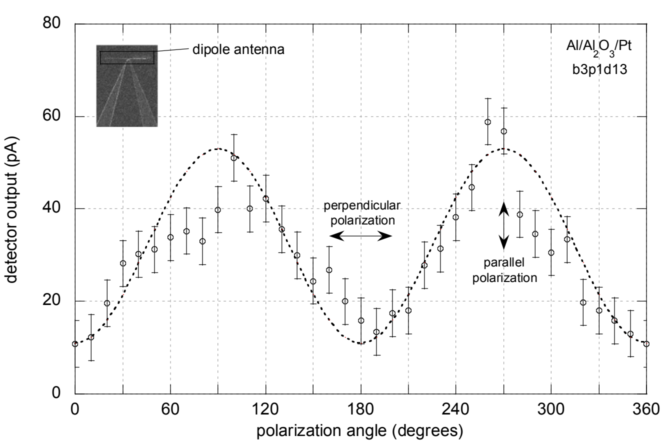

Fig. 4: Polarization response a $Al/Al_2O_3/Pt$ ACMOMD.

Specific detectivity (D*) is used as a figure of merit to compare optical and infrared detectors [8]. Using a 10.6 µm CO_2 laser, D* has been measured for ambient oxidation $Al/Al_2O_3/Pt$ devices fabricated with shadow evaporation and is shown in Table 1. This D* value is higher than any other reported MOM-based infrared detector. D* has also been measured for controlled oxidation $Al/Al_2O_3/Pt$ devices fabricated with the two lithography method. For each fabrication method, D* is expected to increase for reduced resistance controlled-oxidation devices. Noise equivalent power (NEP), the amount of radiant power collected by a detector that will produce a signal-to-noise ratio (SNR) of 1, was measured for both fabrication methods of $Al/Al_2O_3/Pt$ devices and is also shown below in Table 1. The signal to noise (SNR) values listed below correspond to an input infrared irradiance of 166 mW/cm^2.

TABLE 1
ACMOMD FIGURES OF MERIT

ACMOMD Materials	Fab. Method	Responsivity [mA/W]	SNR [dB]	NEP [nW]	D* [$cmHz^{1/2}W^{-1}$]
$Al/Al_2O_3/Ni$	shadow	1.137	30	1.53	2.15×10^6
$Al/Al_2O_3/Pt$	2-litho.	0.947	14.2	3.87	2.13×10^6

III. CONCLUSION

We have fabricated ACMOMDs which, when fully developed, promise frequency selectivity, high speed detection, and full functionality at room temperature without cooling. Measured data proves that the functionality of these detectors is based upon radiation-induced antenna currents which are rectified by the MOM diode. These types of detectors could be easily implemented in portable devices due to their small geometry, ability to function without biasing, and CMOS compatible fabrication. Further, detector geometries could be modified to provide for detection of different frequencies, providing for multi-spectral imaging. This technology could also be extended to provide for on-chip RF interconnects.

REFERENCES

[1] J. Miller, *Principles of Infrared Technology*. New York: Van Nostrand Reinhold, 1992.

[2] P. Esfandiari, G. Bernstein, P. Fay, W. Porod, B. Rakos, A. Zarandy, B. Berland, L. Boloni, G. Boreman, B Lail, B. Monacelli, and A. Weeks, "Tunable Antenna-Coupled Metal-Oxide (MOM) Uncooled IR Detector," Proc. *SPIE Defense and Security Symposium 2005, Infrared Technology and Applications Conference,* vol. 5783 (2), 470-482 (2005).

[3] G. J. Dolan, "Offset Masks for Lift-off Photoprocessing", *Appl. Phys. Lett.*, vol. 31, pp. 337-339, 1977.

[4] I. Amlani, A. O. Orlov, R. Kummamuru, G. H. Bernstein, C. S. Lent, and G. L. Snider, "Experimental Demonstration of a Leadless Quantum-dot Cellular Automata Cell," *Appl. Phys. Lett.*, vol. 77, pp. 738-740, 2000.

[5] B. Tiwari et. al, "Fabrication of Antenna-Coupled MOM Diodes for Thermal Infrared Detection", *manuscript in preparation*.

[6] B. M. Kale, " Electron Tunneling Devices in Optics," *Opt. Eng.*, vol. 24, pp. 267-274, 1985.

[7] C. Fumeaux, M. A. Gritz, I. Codreanu, W. L. Schaich, F. J. Gonzalez, and G. D. Boreman, " *Infrared Phys. & Techn.*, vol. 41, pp. 271-281, 2000.

[8] D Dereniak, E.L. and G.D. Boreman, *Infrared Detectors and Systems*. New York: John Wiley & Sons, Inc., 1996.