Antenna-coupled metal-oxide-metal diodes for dual-band detection at 92.5 GHz and 28 THz

M.R. Abdel-Rahman, F.J. González and G.D. Boreman

An antenna-coupled metal-oxide-metal diode for dual-band infrared millimetre-wave detection is presented. Electron-beam lithography and conventional sputtering methods were used to fabricate an Ni–NiO–Ni diode coupled to a $\lambda/2$ resonant dipole antenna at 28 THz and a $\lambda/2$ resonant mmW slot antenna at 92.5 GHz; simultaneous dual-band detection was tested and verified.

Introduction: Antenna-coupled metal-oxide-metal (MOM) diodes have been used in the past for detection and mixing in the infrared (IR) [1] and millimetre-wave (mmW) [2, 3] portions of the spectrum. Owing to the nonlinear relationship between the tunnelling current and the applied bias voltage of an MOM junction, antenna-coupled AC voltage, V_{ac}, developed across the junction will be rectified resulting in a DC signal described by [4]:

$$V_{rect} = -\frac{1}{4}\frac{I''(V_{bias})}{I'(V_{bias})}V_{ac}^2 \tag{1}$$

where I' and I'' represent the first and second derivatives evaluated at V_{bias} of the I–V characteristic curve of the junction [4].

Sensitivity is a parameter used to characterise the performance of an MOM diode; it is proportional to the current responsivity of an MOM diode and is defined by [4]:

$$S = \frac{-I''(V_{bias})}{I'(V_{bias})} \tag{2}$$

An MOM diode with low enough junction capacitance to rectify IR radiation will also rectify mmW radiation. The cutoff frequency of an MOM diode junction is described by [5]:

$$f_c = \frac{1}{2\pi R_A C_D} \tag{3}$$

where R_A represents the resistance of the antenna, and C_D is the capacitance of the diode which is described by

$$C_D = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{4}$$

where ε_r is the relative permittivity of the oxide, A is the contact area between the two metal electrodes and d is the thickness of the oxide layer.

Here, we are using an antenna-coupled MOM diode for dual-band detection at 28 THz and 92.5 GHz. The ratio between the two required frequencies of operation is roughly 300:1. Several detector designs can be used to accommodate the required dual-band performance. One possible design is a frequency-independent antenna structure with a small enough feed to allow for operation at the high frequency limit; the diode is then to be located at the feed. Another approach, which we implemented, is to integrate the diode with two resonant antenna structures at the two required frequencies of operation. We report on an Ni–NiO–Ni diode coupled to a dipole antenna for 28 THz response and a slot antenna for 92.5 GHz response.

Sensor fabrication: The device is fabricated on an Si substrate coated with a 1 µm layer of SiO_2 for electrical isolation. Fabrication was performed using electron-beam lithography and conventional liftoff methods. First, the bottom electrode and an IR dipole antenna arm are defined along with the bond pad; an Ni layer of 140 nm was then deposited using DC magnetron sputtering. Secondly, the top electrode along with the other IR antenna arm and the bond pad were patterned. An NiO layer of 3.5 nm was then deposited using RF diode sputtering followed by another 140 nm Ni layer deposited using DC magnetron sputtering. As shown in Fig. 1*a*, the L-shaped structures are the bond pads. The vertical separation between the bond pads defines the mmW slot antenna; while the two horizontal separations are defined to allow for detector bias [6]. The MOM diode is located at the centre of the slot antenna and is connected to an IR dipole antenna as shown in Fig. 1*b* and Fig. 2. The diode contact area is 0.075 µm^2. The length of the mmW slot is 644 µm, its width is 15 µm and it is designed for $\lambda/2$ resonant operation at 92.5 GHz. The IR dipole was also designed for $\lambda/2$ resonant operation at 28 THz; its total arm length is 3 µm and its cross-arm width is 0.25 µm.

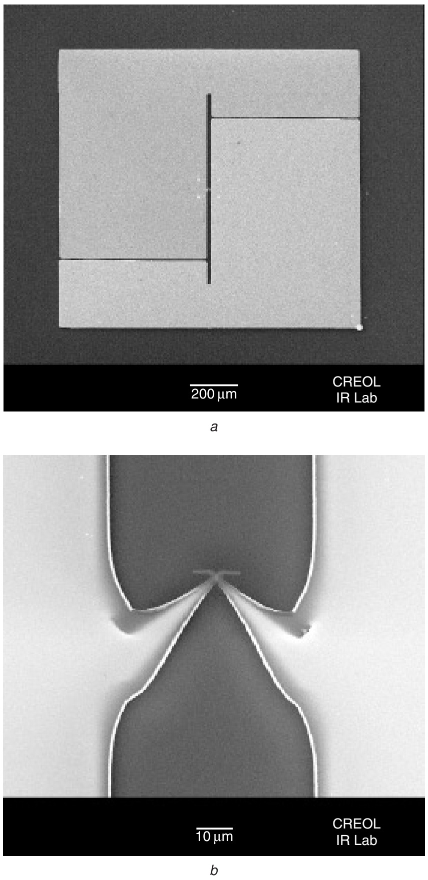

Fig. 1 *SEM images of mmW slot antenna and bond pads, and of connection between MOM diode and bond pads*

a mmW slot antenna and bond pads
b connection between MOM diode and bond pads

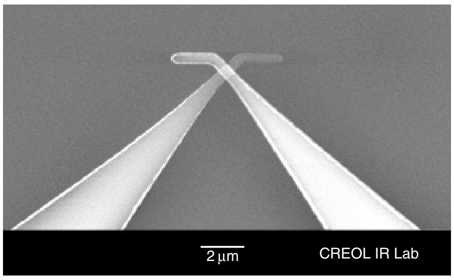

Fig. 2 *SEM image of MOM diode coupled to IR dipole antenna*

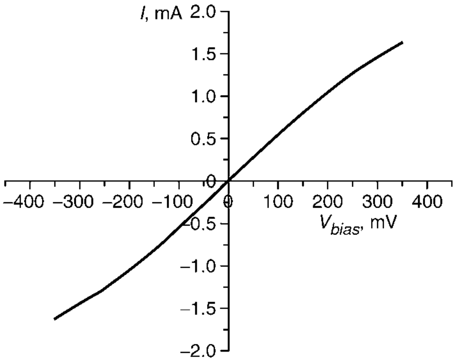

Fig. 3 *I–V characteristic plot of MOM diode*

Experimental results: *I*–*V* plots for the device were measured using an HP4145B parameter analyser. A typical plot is shown in Fig. 3.

The plot shows the typical nonlinear relation between the tunnelling current and the bias voltage of the diode. The device shown in the plot has a zero-bias resistance of 179.8 Ω and a maximum sensitivity (S) of 1.65 V^{-1} at 300 mV of bias.

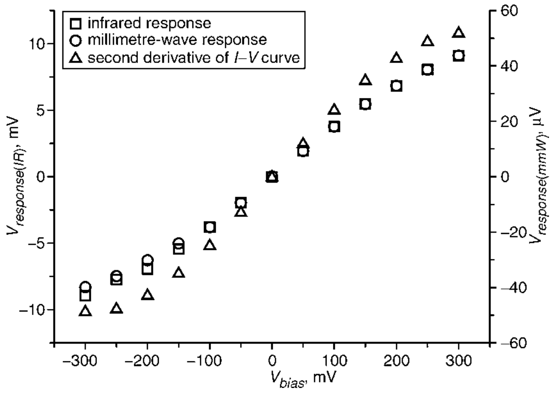

Fig. 4 *IR, mmW response and second derivative of I–V characteristic curve (a.u.) against diode bias*

For testing THz response, the detector was irradiated by a CO_2 laser at 10.6 µm. The laser radiation is attenuated by a neutral density filter and further by a linear polariser. An afocal system is used to expand and collimate the beam; and a final F/1 lens is used to focus the beam into a diffraction limited spot onto the device. The device response was optimised by accurately positioning it in the focus of the laser beam by mounting it on a three-axis micro-positioning stage. A mechanical chopper was used to modulate the laser beam at a frequency of 2.6 kHz. For testing in the GHz region, radiation from a 92.5 GHz Gunn oscillator at 25 mW of output power was input into a *pin* diode switch that is modulated at 3 kHz using a function generator and finally a horn antenna (2.7 × 2.3 cm) was used to irradiate the device. The modulated detector response signals were amplified and then captured using a lock-in amplifier. Fig. 4 shows a plot for the IR, mmW response and the second derivative of the *I–V* characteristic curve against bias voltage of the diode. The response at both frequencies shows a good fit to the second derivative of the *I–V* characteristic curve of the junction which indicates that electron tunnelling is the dominant detection mechanism [7]. The sensor was measured to have a detectivity (D^*) of 1×10^6 $cmHz^{0.5}/W$ and 1×10^7 $cmHz^{0.5}/W$ in the IR and mmW, respectively, at the above-mentioned modulation frequencies. For simultaneous response verification, IR and mmW radiation were modulated at 2.6 and 3 kHz, respectively, and made simultaneously incident on the device. An image of the spectrum analyser output, Fig. 5, verifies simultaneous dual-band operation of the device.

Conclusions: The simultaneous response to 92.5 GHz and 28 THz radiation using a dual-band antenna coupled MOM diode was verified. IR and mmW responses can be further improved by better matching the impedance of the diode and the antennas. IR response can be further improved by decreasing the junction which will decrease the junction capacitance and therefore increase the cutoff frequency of the device.

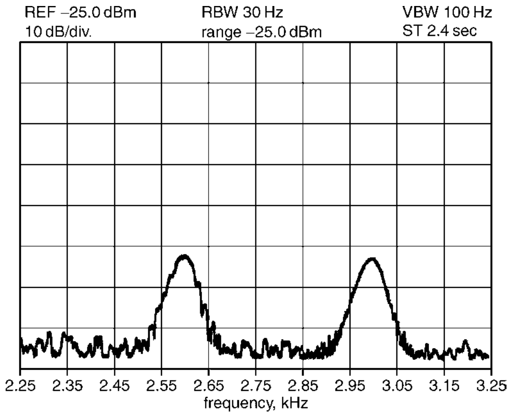

Fig. 5 *Spectrum analyser output showing simultaneous response for 92.5 GHz and 28 THz*

Acknowledgment: This work was supported by DARPA under contract DAAD190210232.

1 December 2003
Electronics Letters online no: 20040105
doi: 10.1049/el:20040105

M.R. Abdel-Rahman, F.J. González and G.D. Boreman (*School of Optics/CREOL, University of Central Florida, Orlando, FL 32816, USA*)

References

1 Fumeaux, C., *et al.*: ‘Nanometer thin-film Ni–NiO–Ni diodes for detection and mixing of 30 THz radiation’, *Infrared Phys. Technol.*, 1998, **39**, pp. 123–183

2 Marchetti, S., Sandi, P., and Simili, R.: ‘Theoretical and experimental responsivity of FIR antenna coupled metal-insulator-metal detectors’, *Int. J. Infrared Millim. Waves*, 1997, **18**, pp. 2161–2175

3 Dees, J.W.: ‘Detection and harmonic generation in the sub-millimeter wavelength region’, *Microw. J.*, 1966, **9**, pp. 48–55

4 Kale, B.M.: ‘Electron tunneling devices in optics’, *Opt. Eng.*, 1985, **24**, pp. 267–274

5 Sanchez, A., *et al.*: ‘The MOM tunneling diode: theoretical estimate of its performance at microwave and infrared frequencies’, *J. Appl. Phys.*, 1978, **49**, pp. 5270–5277

6 Yasuoka, Y., Shimizu, T., and Gamo, K.: ‘Fabrication of slot antenna coupled warm carrier detectors for millimeter wave radiation’, *Microelectron. Eng.*, 1998, **41/42**, pp. 445–448

7 Gustafson, T.K., Schmidt, R.V., and Perucca, J.R.: ‘Optical detection in thin-film metal-oxide-metal diodes’, *Appl. Phys. Lett.*, 1974, **12**, pp. 620–622