Temperature-Dependent Microwave Performance of Sb-Heterostructure Backward Diodes for Millimeter-Wave Detection

N. Su[1], Z. Zhang[1], H. P. Moyer[2], R. D. Rajavel[2], J. N. Schulman[2] and P. Fay[1*]

[1] Department of Electrical Engineering, University of Notre Dame,
Notre Dame, IN 46556 Tel: (574)-631-5693, Email: pfay@nd.edu
[2] HRL Laboratories LLC, 3011 Malibu Canyon Rd, Malibu, CA 90265

Direct detection using unbiased Sb-heterostructure backward diodes has been demonstrated with excellent sensitivity and bandwidth through W-band for passive imagers and radiometers [1-3]. We report the first direct experimental investigation of the temperature-dependent millimeter-wave performance of Sb-heterostructure backward diode detectors. The observed temperature-dependent RF performance is consistent with previous dc temperature studies [3,4]. However, the RF performance provides new insight into device operation and allows a physical model of the phenomenon to be obtained.

The device heterostructure [3] and band diagram are shown in Fig. 1. The performance of the diodes was assessed through dc I-V and on-wafer s-parameter measurement from 1 to 110 GHz, as well as direct microwave detection testing from 4K to 333K. The measured and modeled s-parameters for a 4 μm^2 device are shown in Fig. 2. The junction capacitance (C_j) extracted from the equivalent circuit model decreases from 18 fF at 298K to 11 fF at 77K, consistent with 1 MHz zero-bias capacitance measurements (Fig. 3). The intrinsic cut-off frequency, $f_c=1/(2\pi C_j R_s)$, increases 48% from 740 GHz at 298K to 1.1 THz at 77K. I-V measurements indicate that the curvature, $\gamma = \left(\partial^2 I/\partial V^2\right)\Big/\partial I/\partial V$, is constant from room temperature (36 V^{-1}) down to 150K, below which it rises to 74 V^{-1} (Fig. 4). The junction resistance, $R_j = 1/\left(\partial I/\partial V\right)$, depends only weakly on temperature as expected for tunneling, with R_j changing from 13.9 kΩ at 298K to 10.2 kΩ at 4K; thus the temperature dependence of γ arises from an increase in $\partial^2 I/\partial V^2$, rather than a decrease in $\partial I/\partial V$. Measured voltage sensitivities (β_v) at 50 GHz (frequency limited by the test fixture) of 3650 V/W and 7190 V/W were obtained at 298K and 8.9K, respectively (Fig. 5). The increased β_v with deceasing temperature is consistent with the expected $\beta_v=2Z_0\gamma$ dependence. A 1 dB compression point of 18.5 μW and 7.2 μW at 298K and 8.9K, respectively, was measured (Fig. 6).

Analysis based on Poisson-Schrodinger equation solutions are consistent with the measured results; a 30% decrease in C_j is calculated from 333K to 77K, compared to a 37% decrease in the measured capacitance. The change in C_j arises from redistribution of the charge carriers due to a combination of the temperature dependence of the band gap and occupation statistics. This charge carrier redistribution favors backward tunneling compared to forward tunneling, resulting in an increasingly nonlinear current-voltage characteristic as the temperature is lowered. These observations suggest that further increases in room-temperature curvature may be obtained through tailoring of the carrier concentration profile within the device, as well as the possibility of further desensitizing the device to ambient temperature.

Reference:
[1] J. N. Schulman et al., *IEEE Microwave and Wireless Components Lett.*, vol. 14, no. 7, 2004.
[2] P. Fay et al., *IEEE Electron Device Lett.*, vol. 23, no. 10, pp. 585-587, 2002.
[3] R. G. Meyers et al., *IEEE Electron Device Lett.*, vol. 25, no.1, pp. 4-6, 2004.
[4] J. N. Schulman et al., *Electronics Lett.*, vol. 38, no. 2, pp. 94-95, 2002.

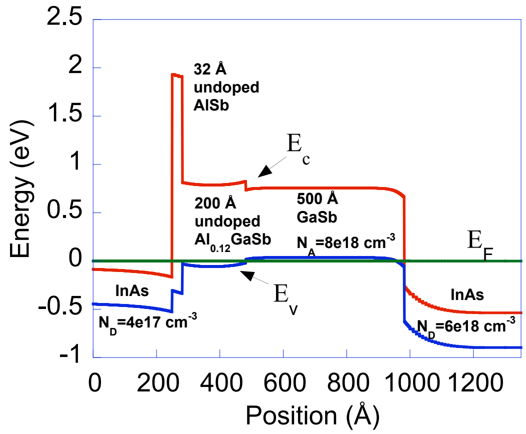

Figure 1: Calculated band diagram for Sb-based heterostructure backward diode.

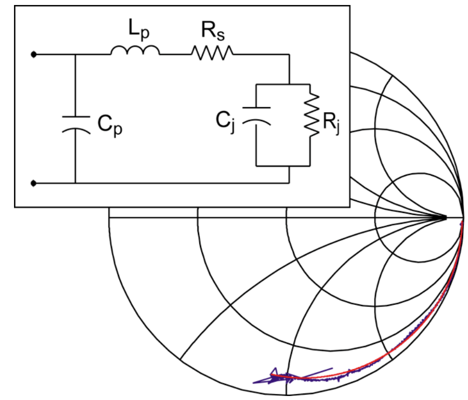

Figure 2: Measured and modeled s-parameters for a 4 μm^2 device from 1 to 110 GHz. Inset is the equivalent circuit model used in the modeling.

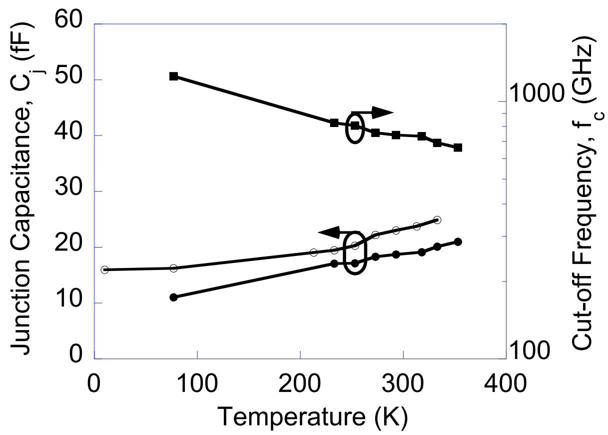

Figure 3: Junction capacitance and calculated cut-off frequency vs. temperature. Data points (●) and (■) represent the extracted C_j and calculated f_c based on measured s-parameters. Data points (○) are taken from zero-bias C-V measurement.

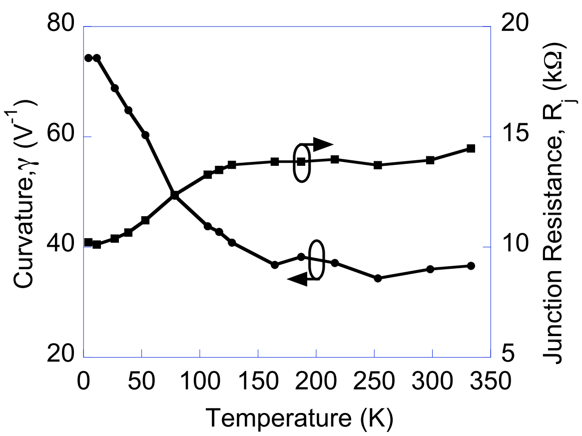

Figure 4: Measured dc curvature (γ) and junction resistance (R_j) vs. temperature.

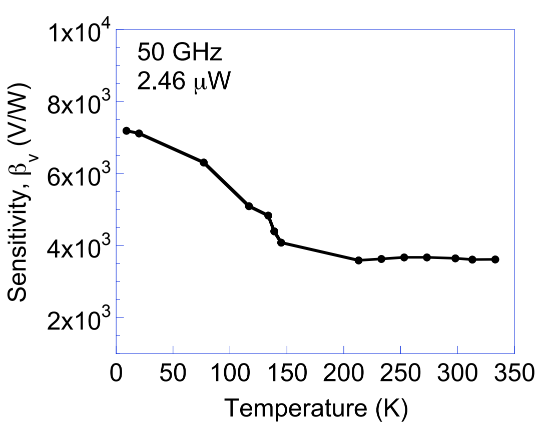

Figure 5: Measured voltage sensitivity vs. temperature at 50 GHz with incident RF power of 2.46 μW.

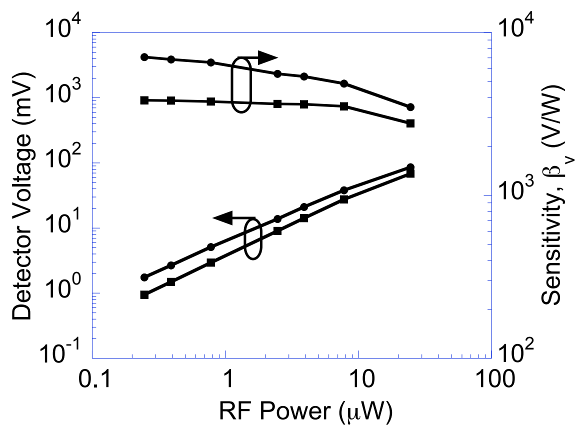

Figure 6: Measured detector voltage and sensitivity vs. incident RF power at 50 GHz. Data points (●) and (■) are taken at 8.9 K and 298 K, respectively.