

Vertical Tunnel Diodes on High Resistivity Silicon

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Silicon tunnel diodes operating at below 1 GHz have applications in micropower circuits for radio frequency identification (RFID), sensors and sensor networks, and low power RF communications. Here we demonstrate for the first time, vertical tunnel diodes formed by rapid thermal diffusion using spin-on diffusants [1,2] on high resistivity (100) Si substrates, 1000-5000 Ω cm, 100 mm, allowing the extraction of an RF device model. The simple process flow is compatible with techniques found in any commercial front end. The device model is extracted from dc, microwave frequency S-parameter, and RF impedance measurements. The tunnel diode characteristics are well described by the Schulman-Broekaert [3,4] analytic model developed for the resonant tunneling diode and therefore fit readily into SPICE and ADS modeling environments.

The microwave frequency S-parameters of these diodes were measured from 45 MHz to 30 GHz, using an Agilent 8510XF vector network analyzer with a port power of -33 dBm. A two-port LRM (line-reflect-match) calibration was performed using a Cascade Microtech 104-783 Impedance standard substrate. The measured S-parameters were de-embedded from the probe pads using a π -equivalent circuit model. Excellent agreement between the measured S-parameter S_{11} and simulated S_{11} based on the equivalent circuit model at zero bias is shown.

When biased in the negative resistance region of the I - V characteristic, a tunnel diode oscillates. By biasing the tunnel diode at 0.275 V using a 4155 semiconductor parameter analyzer, with a Tektronix oscilloscope attached to the two terminals of the tunnel diode, we observed the oscillation with frequency of approximately 190 kHz. The estimated response frequency, $f = I_p / (2C_D \Delta V) \approx 450$ MHz, is lowered by the parasitic capacitance of our measurement configuration. The intrinsic speed index of this tunnel diode is estimated to be 0.23 mV/ps is within the speed range of interest for micropower circuits.

We have also taken the RF impedance measurements on these diodes from 0.5 MHz to 100 MHz, using an Agilent 4294A precision impedance analyzer. Differential conductance of the tunnel diode extracted from the impedance measurement and the derivative of the dc current-voltage curve shows good agreement between RF model extraction and dc measurement.

- [1] J. Wang et al., IEEE Electron Device Lett. 24, 93-95 (2003).
- [2] L.-E. Wernersson et al., Electronics Lett., 40, 83-85 (2004).
- [3] J. N. Schulman et al., IEEE Electron Dev. Lett. 17, 220-222 (1996).
- [4] T. P. E. Broekaert et al., IEEE J. Solid State Circ. 33, 1342-1349 (1998).

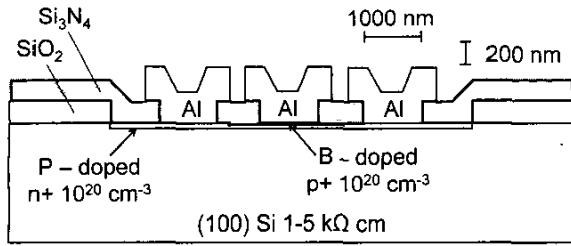


Fig. 1. Schematic cross section of vertical Si tunnel diode formed by rapid thermal diffusion on a high resistivity substrate.

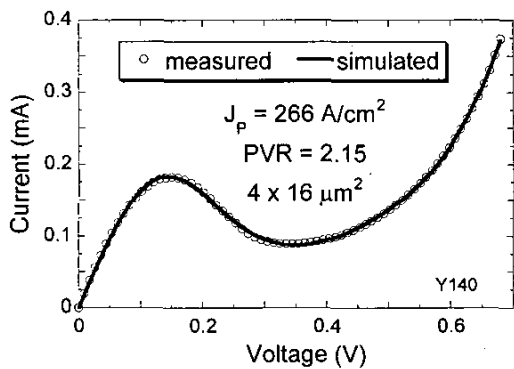


Fig. 2. Comparison of measured current-voltage characteristic and SPICE model fit using the Schulman-Broekaert model.

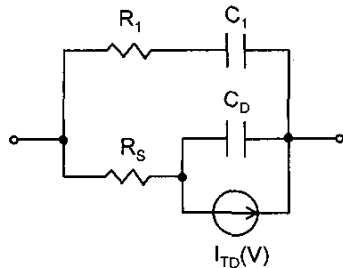


Fig. 3. Equivalent circuit model for the Si tunnel diode, where R_s is the series resistance, C_D is the junction capacitance and $I_{TD}(V)$ represents the tunnel diode current-voltage characteristic. C_1 and R_1 represent the parasitic resistance and capacitance respectively, due to the Si/SiO₂ interface under the bonding pads.

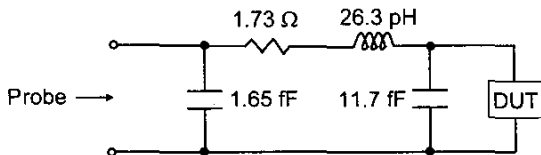


Fig. 4. One-port microwave test pad equivalent circuit. An open-circuited and a short-circuited test structure were measured to extract the pad parasitics.

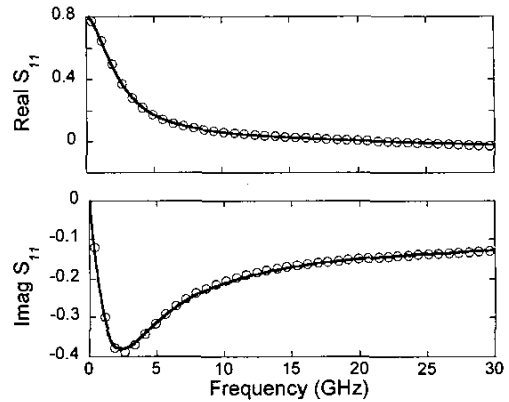


Fig. 5. Comparison of measured (circles) and simulated (line) S-parameter shows excellent agreement of the model. The equivalent circuit model, shown in Fig. 3, is used in the simulation. 5% of the 801 measured data of points are shown for clarity.

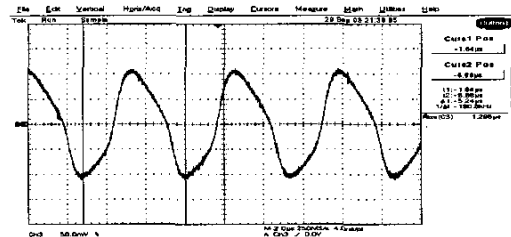


Fig. 6. Silicon tunnel diode oscillator on-wafer biased at 0.275 V and exhibiting a characteristic frequency of 190 kHz.

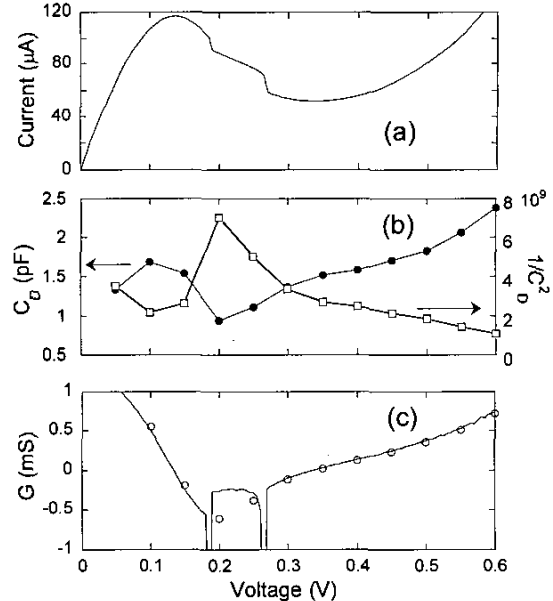


Fig. 7. (a) Measured I-V characteristics, (b) extracted junction capacitance C_D and $1/C_D^2$, (c) comparison between the extracted conductance (circle) from our model in Fig. 3 and that from the direct derivative of dI/dV (line).