

## New Physical Understanding of the Resonant Tunneling Diode Small-Signal Equivalent Circuit

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The resonant tunneling diode (RTD) stands as the highest speed, large-signal semiconductor switching device with measured slew rates as high as 300 mV/ps [1]; the RTD continues to be explored for use in triggers, quantizers, oscillators, and memory [e.g. 2]. Circuit designs using tunnel diodes require an accurate small-signal equivalent circuit model and two simple equivalent circuits are commonly used: a series-inductance model [3] and a parallel-inductance model [4]. The inductance which arises in the latter model is due to the charging of the quantum well [4-7]. These published models all assume the quantum inductance only exists when the RTD is biased in the negative differential resistance region, and the capacitance only comes from the geometrical capacitance. We report in this paper that the above two assumptions are incorrect. We have derived an analytic expression for the quantum inductance and capacitance which is bias dependent and easily implemented into SPICE.

Our derivation parameterizes the sequential tunneling process between emitter and quantum well, and quantum well and collector in terms of the quantum well and emitter charges and the tunneling time constants. We show that it is possible to account for the charge build-up in the well through the entire bias range of the device. We find that the quantum inductance is given by  $L = \tau / g$ , where  $\tau$  is the electron lifetime in the quantum well, and  $g$  is the differential conductance of the RTD. The change in the quantum well electron density also induces a change in the image charge density in the collector that results in an additional quantum capacitance which adds to the geometrical capacitance. The quantum capacitance is derived to be  $C_Q = -g/v$ , where  $v$  is the electron escape rate ( $s^{-1}$ ) from the quantum well to the collector. There is a sign difference between our quantum capacitance model and the Broekaert model [2].

Both S-parameter measurement and DC current-voltage ( $I$ - $V$ ) measurement were made on  $1.6 \times 1.6 \mu\text{m}^2$  AlAs/InGaAs/AlAs RTDs. S-parameters were measured from 45 MHz to 30 GHz using an Agilent 8510XF vector network analyzer with a source power of  $-33$  dBm. The inductance and capacitance values in the equivalent circuit were extracted from fitting the measurement data. The differential conductance values of the RTD are also extracted from S-parameter measurements and agree closely to that of the derivatives of the DC  $I$ - $V$  curve. The RF and DC characterization support the model theory.

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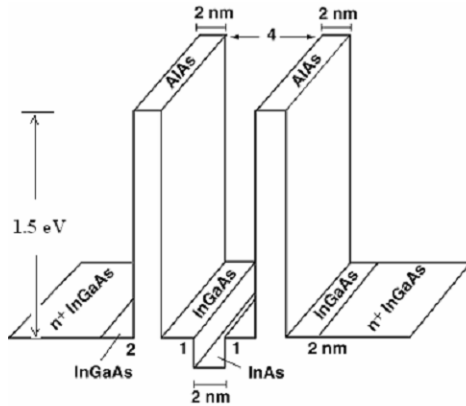


Fig. 1. Resonant tunneling diode structure.

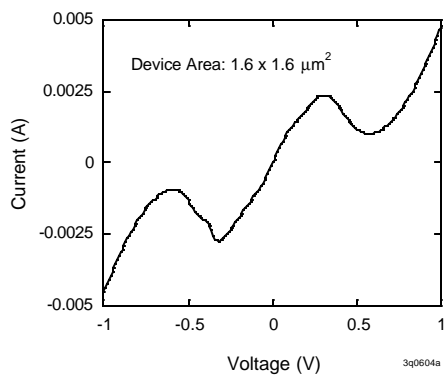


Fig. 2. RTD current-voltage characteristic.

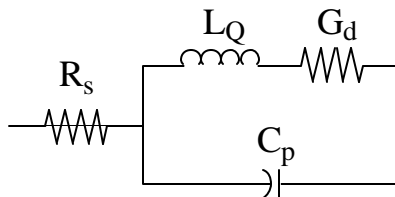


Fig. 3. Parallel-inductance RTD equivalent circuit model.

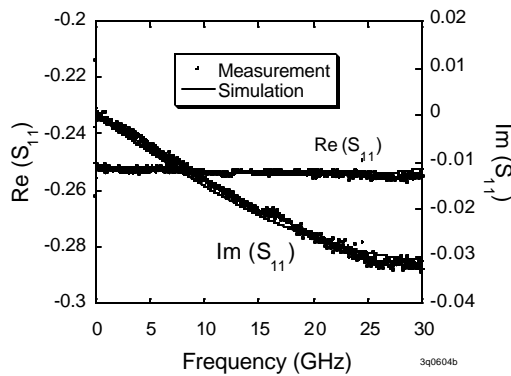


Fig. 4. Measured and simulated  $S_{11}$  at a bias voltage of  $V = 0.45$  V (biased near the center of the NDR region).

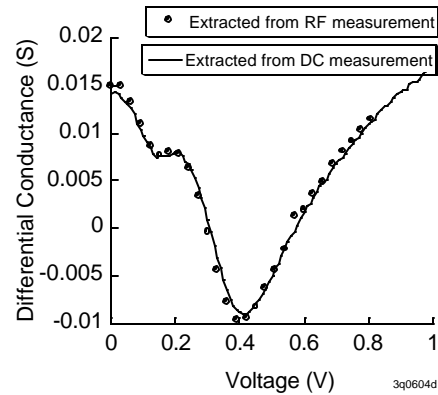


Fig. 5. Differential conductance vs. bias showing good agreement between DC and RF measurements.

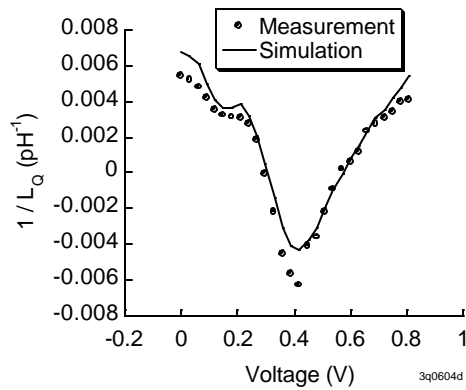


Fig. 6. The reciprocal of the inductance vs. bias showing good agreement of model with measurement over bias.

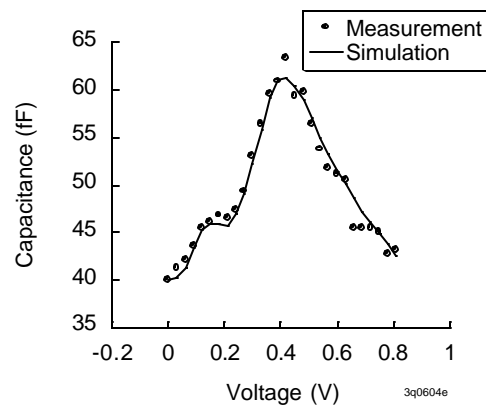


Fig. 7. Total capacitance vs. bias also showing close agreement of model with measurement over bias.