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Input Power Dependence of Large-Signal Microwave Characteristics of Resonant-Tunneling High Electron Mobility Transistors

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1. Introduction

The negative differential resistance (NDR) of resonant-tunneling transistors (RTTs) and their potential for high-speed operation suggest the possibility of using them to construct high-performance microwave circuits. One type of RTT is the resonant-tunneling high electron mobility transistor (RTHEMT), which exhibits both pronounced NDR and negative transconductance at room temperature [1, 2]. Furthermore, a nearly flat current has been obtained in the drain current versus drain voltage (V_{DS}) characteristics beyond the valley voltage (V_v), which results in a large operating margin in V_{DS} to utilize the negative transconductance. These features make the RTHEMT highly attractive for use in microwave circuits such as frequency multipliers [2], mixers, and oscillators.

In this paper, we report the input power dependence of the large-signal, microwave characteristics of RTHEMTs by both experiments and simulations. We experimentally observed a large number of harmonics with a significant output level, caused by the inherent strong nonlinearity of RTHEMTs; this demonstrates their promise for use in high-performance microwave devices. We also found that the operating point swinging across the negative transconductance region is essential for producing high harmonics. This model will provide useful guidelines for designing RTHEMT-based high-performance microwave circuits.

2. Experimental Setup and Results

An InP-based RTHEMT incorporates a pseudomorphic InGaAs/AlAs/InAs resonant-tunneling diode (RTD) into the source of a non-alloyed ohmic contact InAlAs/InGaAs high electron mobility transistor (HEMT). The RTHEMT we used had a two-finger configuration. The area of the RTD was $3 \times 5\ \mu m^2 \times 2$, and the gate length and width of the HEMT were 0.7 μm and 50 μm × 2, respectively. The device structure, fabrication procedure, DC characteristics, and mechanism for producing an NDR with a nearly flat current beyond V_v and a negative transconductance have been given in detail in [1].

The large-signal, microwave characteristics of RTHEMTs were obtained in the common-source configuration. An input signal of 2-GHz sine wave was applied from a synthesizer via a bias-tee to the gate, and the output signal from the drain was measured by a spectrum analyzer also via a bias-tee. No matching circuits were provided for the input and output. The gate voltage (V_{GS}) was set at 0.4 V, near the negative transconductance region, and V_{DS} was fixed at 1.5 V.

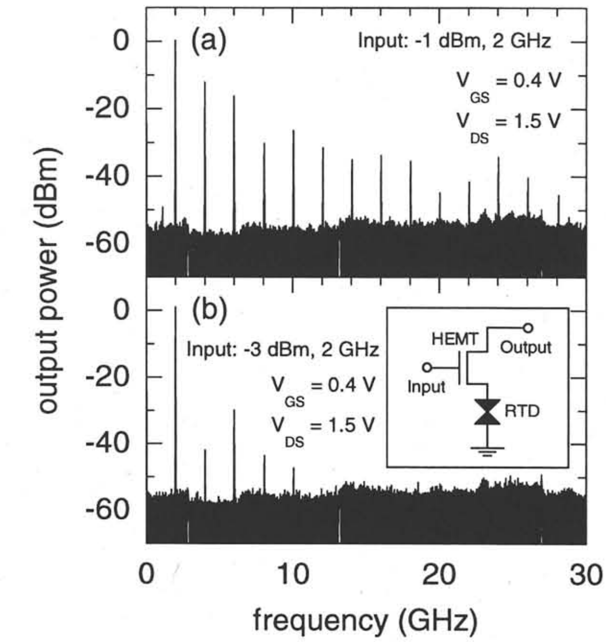

Fig. 1. Output power spectrum of the RTHEMT for input power of (a) -1 dBm and (b) -3 dBm. The inset illustrates the measurement configuration for an RTHEMT.

The output power spectrum of the RTHEMT for an input power level of -1 dBm is shown in Fig. 1 (a). The most important feature is that many of the harmonics up to the fourteenth, which is the upper limit of the experimental setup, were observed even with the small input power level of -1 dBm and without matching circuits. The extremely high harmonics with a significant output level that the RTHEMTs provide will allow us to construct novel high-performance microwave circuits. This feature can be ascribed to the operating point of the RTHEMT swinging over the negative transconductance region. Moreover, from the input power dependence of the output power spectrum, we found the critical value needed for the input power level to produce the high harmonics. At input power levels higher than -1 dBm, we observed similar output power spectrums, although there were small relative variations among the various harmonics. On the other hand, at a lower input power level of -3 dBm, the clear harmonics were observed only up to the fifth and higher harmonics vanished, as shown in Fig. 1 (b). This discontinuous change can be explained in terms of the hysteresis associated with the negative transconductance in the transfer characteristics, described in the next section.

3. Simulation Results and Discussion

For the device simulation, we regarded the RTHEMT as a serial connection of an RTD and a HEMT. For simplicity, the parasitic series resistance to the RTD and HEMT was neglected. The RTD was treated as a parallel connection of a current source and a capacitor. The current source was defined by the RTD current-voltage (I-V) model proposed by Schulman [3], in which the parameters were fitted to reproduce the I-V characteristics of the isolated RTD on the same wafer. The capacitor was defined using the Schottky diode model, in which parameters were determined from the size of the RTD structure. A nonlinear HEMT model was derived from the DC characteristics and S-parameters of the isolated HEMT fabricated on the same wafer.

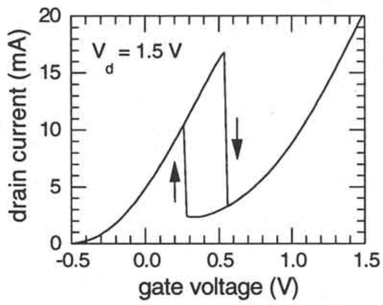

Fig. 2. Transfer characteristics simulated for the RTHEMT.

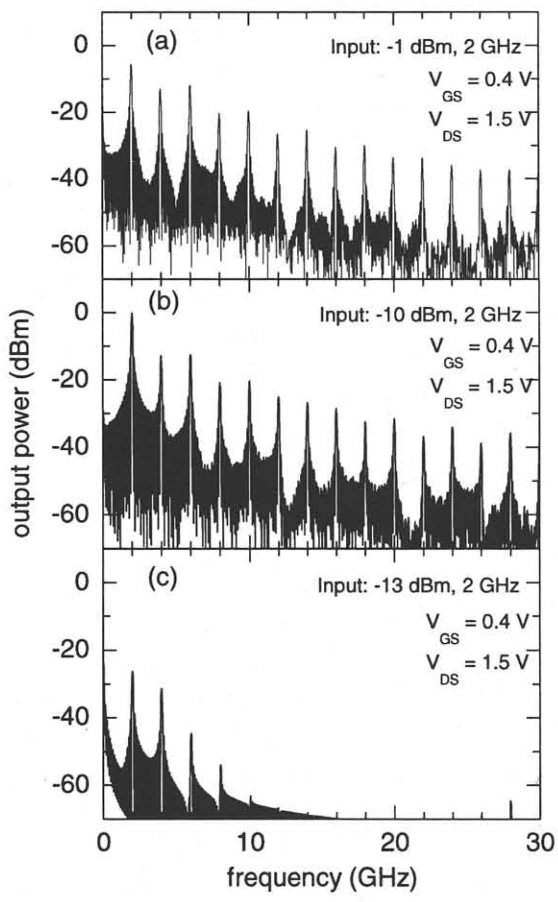

Fig. 3. Simulated output power spectrum of the RTHEMT for input power of (a) -1 dBm, (b) -10 dBm, and (c) -13 dBm.

The transfer characteristics derived by the simulation clearly demonstrate the existence of the hysteresis associated with negative transconductance (see Fig. 2). This hysteresis appears because the absolute value of the negative differential conductance of the RTD is larger than the sum of the drain conductance and the transconductance of the HEMT. The simulation results of the output power spectrum are shown in Fig. 3. Many of the harmonics were observed at input power levels between -1 dBm and -10 dBm, but higher harmonics discontinuously disappeared at -13 dBm. These features are in good agreement with those obtained experimentally, including the discontinuous change below a certain critical point of the input power level, despite a quantitative difference in the critical values.

The high harmonics appear due to the discontinuous change in the drain current between the two branches in the transfer characteristics when the RF input signal oscillates across the whole hysteresis. This hysteresis accounts for the existence of the critical input power level. Below the critical level, the amplitude of the input signal centered at V_{GS} is too small to drive the RTHEMT across the whole hysteresis region and hence to cause the discontinuous change in the drain current at the branch ends. The discrepancy in the critical input powers between the experiment and the simulation can be ascribed to the fact that the parasitic series resistance was neglected in the simulations.

4. Conclusion

The input power dependence of the large-signal, microwave characteristics of RTHEMTs was investigated by both experiments and simulations. We experimentally observed a large number of harmonics with a significant output power level, caused by the inherent strong nonlinearity of the RTHEMTs; this demonstrates their promise for use in high-performance microwave circuits. We found that the operating point swinging across the negative transconductance region is essential for obtaining high harmonics. This model will provide useful guidelines for designing RTHEMT-based high-performance microwave circuits.

Acknowledgments

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