MILLIMETER-WAVE SIMULATION OF A SERIES-INTEGRATED RESONANT TUNNELING DIODE INCLUDING TRANSIT TIME EFFECT

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ABSTRACT

An oscillator scheme that substantially increases the millimeter-wave power generation capabilities of the quantum-well resonant tunneling diode (RTD) by a device-level series integration is analyzed. A series-integrated RTD including transit time effect has been simulated in great detail at millimeter-wave frequencies. Using the available experimental characteristics of a GaAs/AlAs quantum-well RTD, our simulation shows that, for example, 120 mW output power with 10% dc-to-RF conversion efficiency at a 5-Ω load can be obtained at 100 GHz, when ten such RTD's are integrated in series.

INTRODUCTION

The negative conductance possessed by a double-barrier quantum-well resonant tunneling diode (RTD) is very attractive for power generation at millimeter-wave frequencies. Millimeter-wave RTD oscillators have been demonstrated by Kesan et al. [1] and Gronqvist et al. [2]. More recently, oscillations up to 712 GHz in InAs/AlSb RTD were reported [3]. For frequencies above 90 GHz, all reported output power from a single RTD has been below 0.1 mW. However, it is feasible to substantially increase the output power by a device-level integration, which stacks a number of RTD's in series. In this paper, a series-integrated GaAs/AlAs RTD (GaAs quantum well and drift layers, AlAs barriers) including transit time effect has been simulated at millimeter-wave frequencies. For instance, an output power of 120 mW with 10% dc-to-RF conversion efficiency at a 5-Ω load is obtained at 100 GHz by integrating ten identical RTD's in series. This power is more than one thousand times larger than the power from a single RTD.

OSCILLATION SCHEME

Vorontsov et al. had analyzed and experimentally verified the oscillatory process in circuits with several series-connected tunnel diodes [4]. They had shown that if an applied dc bias voltage can be turned on fast enough (as in a voltage shock wave) so that the capacitive current dominates, the initial distribution of the total voltage among the individual tunnel diodes will not be determined by static analysis. It is possible then to bias every diode in the negative differential resistance (NDR) regime of its I-V characteristics. Self-oscillation can thus be initiated. The oscillation can be maintained by the appropriate circuit design as long as the oscillation voltage amplitude is large enough to cover part of the positive differential resistance (PDR) regimes of the I-V curve [4]. Such an oscillator with as many as ten tunnel diodes connected in series had been demonstrated [4].

The RTD has a much higher cutoff frequency than the tunnel diode due to the fact that the capacitance of the RTD can be reduced by an added depletion region adjacent to the double-barrier quantum well. In order to utilize the oscillation scheme in [4], the transit time effect in the depletion region of the RTD has to be carefully examined. We have carried out a detailed analysis that includes transit time effect for RTD's in the series-integrated device-level configuration. On the other hand, in order to initiate a millimeter-wave frequency oscillation of the series-integrated RTD device, an extremely fast switch to turn on a dc power supply in a picosecond range is needed. This can be accomplished by an optical switch, which is very expensive. An alternative is to use the recently developed nonlinear transmission line (NLTL), which can generate picosecond voltage shock waves due to its extremely fast transition time [5]. Thus, the oscillation scheme described in [4] is achievable at millimeter-wave frequencies.

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TRANSIT TIME EFFECT

The total current (I_{tot}) of each diode in the series-integrated RTD device is composed of a displacement current due to junction capacitance and a conduction current (I_c), i.e.,

$$I_{tot}(t) = C\frac{dV(t)}{dt} + I_c(V(t)) \qquad (1)$$

where $C = C(V)$ is the junction capacitance from the depletion approximation. Without transit time effect I_c is obtained from the diode dc current-voltage (I-V) characteristics as was done in [4]. When transit time effect is included, I_c in (1) should become the induced current (I^{ind}), which is given by [6]

$$I^{ind}(t) = \frac{L}{L+W} I^{inj}(t) + \frac{1}{L+W}\int_0^W \int_0^\infty v(\tau)\, g(x,\tau)\, I^{inj}(t-\tau)\, d\tau\, dx \qquad (2)$$

where I^{inj} is the conduction current of the injector (i.e., intrinsic RTD) of length L, W is the drift region length, v(t) is the average carrier transient velocity after injection, and g(x,t) is the Gaussian profile function describing the carrier diffusion and drift motion after injection [6].

The induced current in (2) is a functional of the terminal voltage (V). In other words, $I^{ind}(t)$ depends on the previous history of V(t). Indeed, $I^{ind}(t)$ is a weighted average of $I^{inj}(t)$ over the transit time of the carriers. Thus, transit time effect usually smears out some negative differential resistance observed in dc I-V characteristics.

SIMULATION RESULTS

Using (1) and (2), we have simulated the power generation capabilities of a ten-RTD device including transit time effect at microwave and millimeter-wave frequencies. The parameters for diffusion and velocity overshoot used in [6] are adopted here. The injector I-V curve is deduced from a measured GaAs/AlAs quantum-well RTD I-V curve obtained from wafer 3 in [7]. The drift region of each RTD is 700 Å doped with 2×10^{17} cm^{-3}. We assume that each individual RTD is grown epitaxially with a 500-Å-thick GaAs spacer layer doped to 2×10^{18} cm^{-3}. Wolak et al. [8] has reported that quantum interference between adjacent RTD's is negligible such that each RTD can be considered as an independent circuit element. The series resistance due to the spacer layer ($\sim 8 \times 10^{-9}$ Ω-cm^2) is very small in this case. The specific contact resistance of 10^{-6} Ω-cm^2 is used in the simulation. The total device area is determined by matching to a 5-Ω load.

Shown in Fig. 1 is the simulated negative conductance density of the ten-RTD device versus frequency. Below 30 GHz, the negative conductance is almost a constant, indicating that transit time effect is not very significant at microwave frequencies. On the other hand, the negative conductance decays quickly as frequency approaches 100 GHz and beyond, where transit time effect becomes very critical to the device RF performances. Based on simulation results, it is found that the negative conductance density is approximately inversely proportional to frequency square root at frequencies beyond 100 GHz. This leads to a fast power generation rolloff against frequency. The total output power generated by the ten-RTD device at different frequencies is presented in Fig. 2, where the corresponding total device area required to match the 5-Ω load is also shown. The dc-to-RF conversion efficiency versus frequency is plotted in Fig. 1. If the total RF voltage amplitude across the device is not large enough, instabilities are observed in our simulation as described in [9]. The results shown in Figs. 1 and 2 are simulated from the stable RF regime, assuming that the integrated RTD's are identical. For example, the output power of 120 mW with the associated dc-to-RF conversion efficiency of 10% can be obtained at 100 GHz from the ten-RTD device, where the total device area is 570 μm^2. The poor performances at 300 GHz are primarily due to the fact that the device structure is not optimized for operation at such high frequency.

In our simulations, the RF voltage waveform is sinusoidal, and the dc bias is located near the center voltage point of NDR regime. As an illustration, a voltage waveform as well as the corresponding current density across the injector and the RTD device over one oscillation period at 100 GHz are shown in Fig. 3(a) and Fig. 3(b), respectively. The RF voltage amplitude in Fig. 3 is chosen in such a way that for any RF voltage amplitude smaller than that in Fig. 3, no stable sinusoidal solution could be found in our simulation. The dips shown in the current curves of Fig. 3 indicate that the voltage waveforms do swing into PDR regimes in order to maintain a stable oscillation mode. Notice that the second peak in the induced current is slightly higher than the first one. This is due to some remaining carriers injected by the first peak of I^{inj}.

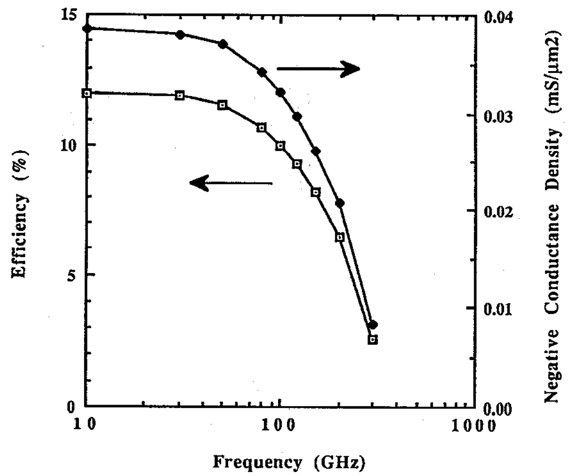


Fig. 1. Negative conductance density and dc-to-RF conversion efficiency of a ten-RTD device versus frequency.

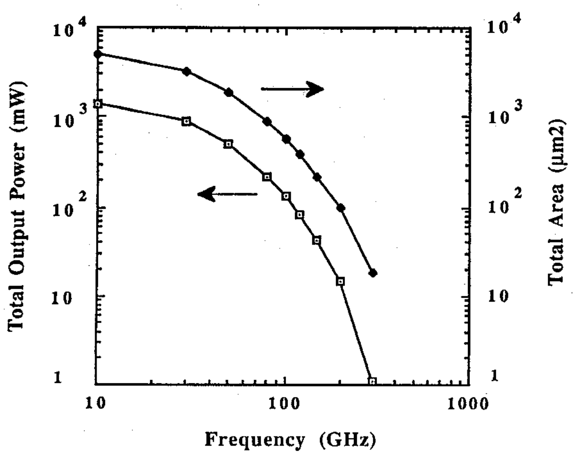
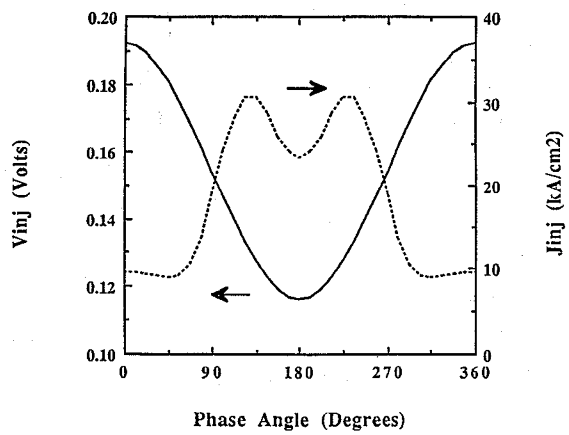
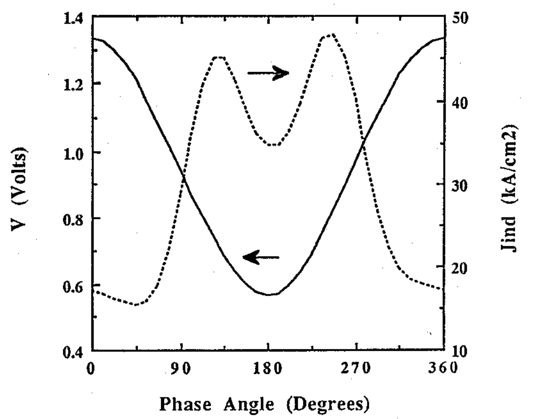


Fig. 2. Simulated total output power and the corresponding total device area of a ten-RTD device matched to a 5-Ω load at various frequencies.



(a)



(b)

Fig. 3. (a) The waveform of the injection voltage (V_{inj}) and the corresponding injection current density (J_{inj}) across the injector, and (b) the waveform of the terminal voltage (V) and the corresponding induced current density (J_{ind}) across the RTD device over one oscillation period at 100 GHz.

DISCUSSIONS

In the experiment with series-connected tunnel diodes, the oscillator was excited by turning on the power supply with a simple tumbler [4]. In order to initiate a millimeter-wave frequency oscillation of the series-integrated RTD, an extremely fast switch to turn on a dc power supply in a picosecond range is required. This is achievable by the NLTL because of its extremely fast transition time [5]. However, the details of the oscillator circuitry design need further investigations. The ultimate limitation for power generation will be determined by the uniformity of the integrated RTD's and thermal effect. Although the IMPATT diode can generate significant power at millimeter-wave frequencies and be integrated in series at the device level as well, the RTD device has a superior noise performance because of the relatively quiet tunneling process [10].

ACKNOWLEDGEMENT

This work at UCLA was supported by the Air Force Office of Scientific Research under contract F49620-92-C-0055.

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