Bias Stabilization for Resonant Tunnel Diode Oscillators

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***Abstract*—While Resonant tunnel diodes (RTD's) are useful as submillimeter-wave oscillators, circuit design constraints imposed to suppress parasitic bias circuit oscillations have limited output powers to well below 1 mW. We report a 7-GHz RTD oscillator with a shunt regulator for bias circuit stabilization. With regulation, oscillator power is not limited by stability constraints. Regulation elements are readily integrated with RTD's to construct monolithic RTD oscillator arrays.**

I. Introduction

Resonant tunnel diode (RTD) oscillators have been demonstrated at frequencies as high as 712 GHz [1]. Because of design constraints imposed to prevent parasitic oscillations in the bias circuit at frequencies below the desired frequency of oscillation ω_{osc} and also due to the frequency dependence of the output power, RTD oscillator output powers at ω_{osc} have been very small. Increasing the RTD junction area proportionally increases the RTD current, hence the maximum oscillator output power. As a function of the bias circuit's frequency-dependent output impedance, there is a maximum RTD junction area beyond which parasitic oscillations or dc bistability in the bias circuit will arise. The RTD output power is thereby limited [2].

Proposed methods for suppression of parasitic oscillations or bias circuit bistability include RTD mulitivibrator oscillators [3] or RF excitation [4], both requiring a drive signal to initiate oscillation at the desired frequency. If, for any reason, the oscillation is interrupted, the drive signal must be reapplied to ensure oscillation in the desired mode. Here we demonstrate an RTD oscillator with a shunt regulator element which suppresses both bias circuit oscillations and bistability. Constraints on the RTD junction area are eliminated, and RTD oscillators can thus be designed for increased output power. The bias regulation element can be fabricated on a common integrated circuit substrate with the RTD, permitting monolithic integration of single-element or array [5], [6] RTD oscillators with increased output power.

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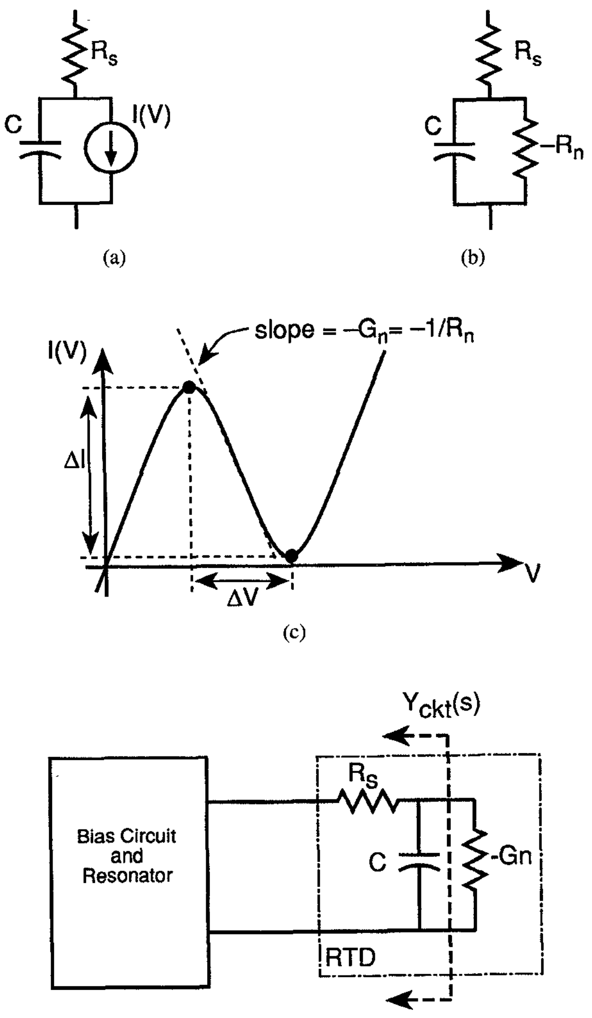

Fig. 1. Resonant tunnel diode. (a) Large-signal model. (b) Small-signal model. (c) *I-V* characteristics. (d) General oscillator configuration.

The RTD negative differential resistance extends from dc to the RTD maximum frequency of oscillation $\omega_{\max}$. If the RTD is to oscillate only at a single desired frequency of oscillation ω_{osc}, the combination of the RTD and its embedding circuit must be stable at all frequencies except ω_{osc}. Neglecting the space-charge and quantum-well transit times, the RTD is modeled as voltage-dependent current source $I(V)$ with parasitic capacitance C and series resistance R_s [Fig. 1(a)] and $\omega_{\max} \cong G_n^{1/2} R_s^{-1/2} C^{-1}$. The current $I(V)$ is replaced by the negative resistance $R_n = 1/G_n$ in the small-signal model

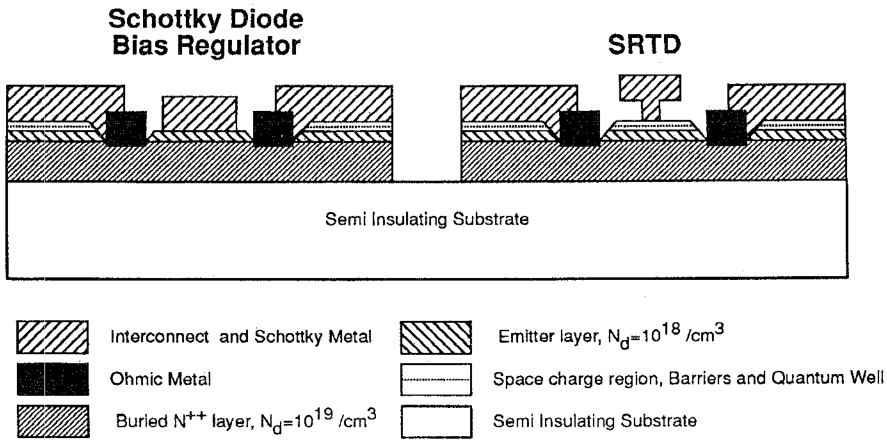

Fig. 2. Schematic cross-sections showing monolithic integration of a stabilizing Schottky diode and a Schottky-collector RTD.

[Fig. 1(b)]; $I(V)$ shows a negative differential resistance region (NDR) of extent ΔV in voltage and ΔI in current with a peak negative conductance of magnitude $Gn \equiv |(dI/dV)_{\min}|$ [Fig. 1(c)].

A general RTD oscillator [Fig. 1(d)] consists of the RTD, a circuit resonant at ω_{osc}, and a bias network. These present an admittance $Y_{ckt}(s)$ to the RTD conductance $-G_n$. Defining the complex frequencies $s_i = \sigma_i + j\omega_i$ at which the $Y_{ckt}(s) = G_n$, the necessary and sufficient condition for instability at the frequency ω_i is $\sigma_i > 0$ [7]. A sufficient condition for stability is $\mathrm{Re}\,[Y_{ckt}(j\omega)] = G_{ckt}(j\omega) > G_n$, that the circuit present a low impedance to the device at all frequencies except at ω_{osc}.

Approximating $I(V)$ with a cubic polynomial in V, the maximum oscillator output power at ω_{osc} is (3/16)($\Delta I \Delta V$) ($1 - \omega_{osc}^2/\omega_{\max}^2$) [7], while $G_n = 3\ \Delta I/2\Delta$V. When biased with a voltage source or regulator of output resistance R_{bias}, the RTD will be stable at dc only if $1/R_{bias} > G_n$. The maximum oscillator output power is thus limited to $P_{\max} = (\Delta V^2/8R_{bias})\ (1 - \omega_{osc}^2/\omega_{\max}^2)$.

Consider the leads connecting the bias stabilizer to the RTD. Modeling the connecting leads as a transmission line Z_0, unless $R_{bias} \geq Z_0$, the impedance presented to the RTD will be greater than $Z_0$when the line is odd multiples of $\lambda/4$ in length. Lines having $Z_0 < 20\,\Omega$ are hard to realize at mm-wave frequencies. To avoid resonances below the intended frequency of oscillation, we must either set $R_{bias} = Z_0$, or the lead length must be less than λ/4. Since setting $R_{bias} = Z_0$ results in a very small maximum power $P_{\max} = \Delta V^2/8Z_0$, the bias regulator must instead be placed within one-quarter-wavelength distance from the RTD. For sub-mmwave RTD oscillators λ_{osc}/4 is on the order of 100 μm, hence the shunt regulator must be fabricated on the RTD wafer.

For bias regulation, we use a forward-biased Schottky diode because of ease in on-wafer integration with Schottky-collector RTD's (SRTD's) [8]. The Schottky diodes are fabricated on an SRTD wafer by etching through the barriers and quantum well prior to depositing Schottky metal (Ti/Pt/Au) onto the SRTD emitter layer (N-doping = 10^{18} cm^{-3}) (Fig. 2). With M series diodes, the bias circuit impedance is $R_{stab} = MkT/qI_{stab}$, where I_{stab} is the bias regulator dc current. For bias stability I_{stab}, is selected such that $1/R_{stab}$ is greater than G_n. The

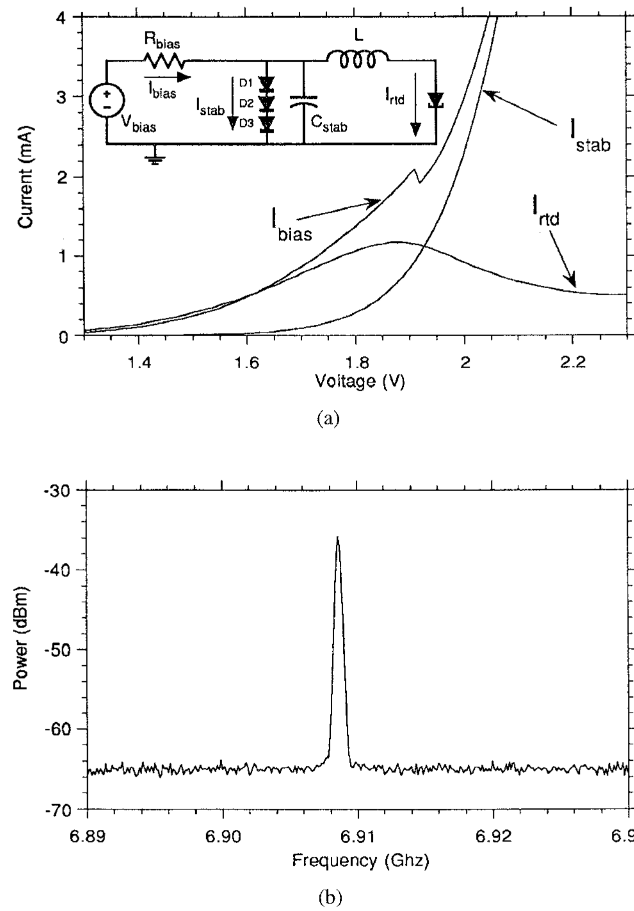

Fig. 3. (a) I-V characteristics of the RTD and its stabilizer showing dc stability in the bias circuit. (b) Oscillation spectrum at 6.9 GHz for the hybrid realization of bias stabilized RTD oscillator [inset of Fig. 3(a)].

regulator diode junction areas are then chosen such that the forward voltage of the M series-connected diodes falls within the RTD negative-resistance region [Fig. 3 (a)].

To complete the oscillator [inset of Fig. 3(a)], the bias regulator is given a low ac impedance by the shunt capacitor C_{stab}. The regulator is decoupled from the RTD with either a series inductor L or a series line section of $\approx\lambda_{ocs}$/4 length (not shown), either of which forms a resonator with the RTD capacitance at ω_{osc}. The bias regulator degrades the oscillator dc-to-RF conversion efficiency in proportion to the ratio $I_{rtd}/(I_{rtd} + I_{stab})$.

To demonstrate feasibility, we have fabricated an SRTD oscillator with the components (Schottky diodes and RTD) assembled in a hybrid form by ribbon bonding. The regulator element is connected to the SRTD [9] with a 5 mm ribbon bond having $L \approx$ 6-nH inductance [inset of Fig. 3(a)]. Given the hybrid assembly, the RTD is shunted with 35-fF bond-pad capacitance, and the RTD oscillates $f_{osc} = (2\pi)^{-1}[L(C_{bond}+C_{rtd})]^{-1/2} \approx 10$ GHz. The output is coupled to a spectrum analyzer through a small capacitance. The parallel combination of the RTD and the diodes ($I_{bias} \approx I_{rtd} + I_{stab}$) is dc stable, exhibiting only a very small net negative-resistance region [Fig. 3(a)] and the RTD can be biased within the NDR without bias circuit instability. I_{rtd} is the I–V curve of a 1×2 μm^2 SRTD. Oscillation was observed only at $f_{osc} \approx 6.9$ GHz [Fig. 3(b)]. Bias regulation can be extended to sub-mm-wave quasioptical oscillator arrays [5], [6]. This requires integration of RTD's, Schottky diodes and monolithic antennas. The antenna serves as both the circuit resonator and the output power coupler for the RTD oscillator.

Monolithic integration of a low impedance bias regulator close to the RTD is proposed for achieving bias stabilization in a RTD oscillator, and a hybrid implementation is demonstrated. Bias regulation is important both for single-element RTD oscillators and in RTD array oscillators [5], [6]. Sub-mm wave array oscillators incorporating on wafer Schottky diode bias regulators and GaAs/AlAs SRTD's [9] are currently under fabrication.

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