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The Resonant Tunneling Diode characterization for high frequency communication systems

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ABSTRACT

In this paper, a detailed derivation process is proposed to characterize the Resonant Tunneling Diode (RTD) for high frequency regime. The proposed model is used to design and analyze a simple microwave oscillator based on the RTD using the commercial circuit simulation software, ADS from Agilent Technologies. The simulation is carried out using different equivalent circuit models; the proposed model, the original constant RC model, and the series/parallel double RC model, which is an alternative to the quantum-inductance RLC model. This is performed in terms of oscillation frequency and output power against resonant circuit elements, considering the CPU time. A comparison between the simulation results of the three models indicates that the proposed model is simple, accurate, and appropriate to investigate the behavior of the RTD at high frequency without any singularity and convergence problems. Also, its complexity (CPU time) is less than that of the series/parallel double RC model and higher than that of constant RC model. However, the constant RC model is inaccurate, especially in high frequency regime. In addition, the proposed technique can be easily incorporated into computer aided circuit design software, such as SPICE and ADS software, to simulate circuits containing RTD in high frequency regime. In brief, this work adds important contributions to the accurate characterization and modeling of RTDs and analyzes its based circuits in high frequency regime by addressing the problems of the current RTD equivalent circuit models.

1. Introduction

Oscillation is among the simplest of dynamic behaviors that has been used to study a wide variety of physical phenomena. In theoretical physics, the word oscillator refers to a physical object or quantity oscillating sinusoidally, or at least periodically, for a long time, ideally forever, without losing its initial energy [1–4].

An important type of oscillator widely used today is the electronic oscillator that converts direct current (DC) power into radio frequency (RF). It consists of an active device and a resonant circuit that determines the frequency of oscillation. The active device can be either a negative differential resistance (NDR) device to compensate for the losses of the resonator such as Gunn diode, RTD, and so on, or a transistor with appropriate feedback to cause instability [3]. The two approaches are identical, but the negative-differential resistance is the most famous used approach in microwave oscillators.

RTDs are different from other active devices in that they exhibit their NDR from DC up to the highest operating frequencies. Some researches [2,3] exploited RTDs using different material types resulting in an oscillation frequency in the range of THz but with a severe limitation in the output power. Nonetheless, the published spectra of free-running RTD oscillators are much broader than those of, for example, free-running Gunn oscillators [5].

Since the work of L. L. Chang et al. [6], an increasing interest has been given to study the characterization of RTD behavior for high frequency operation. This is considered through three different approaches, as follows.

i. Computationally complicated quantum simulator approach [7–12], where the small and large signal responses of RTD have been obtained numerically by solving Poisson and Schrodinger equations self consistently using a harmonic balance technique.
ii. RF measurements approach [13–16].
iii. Equivalent circuit approach [14,17–19].

The current researches [20–26] of RTD for high frequency applications show that a significant growth of frequency has been achieved and the RTD is a candidate for THz sources. In Refs. [20,21], the experiment

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and theory of sub-THz and THz oscillators are described with RTDs integrated on planar circuits and harmonic oscillation up to 1.02 THz were obtained at room temperature. In Refs. [22,23], the oscillation frequency is further increased up to 1.42 THz using thin barriers and quantum wells and by optimizing the thickness of the collector spacer. In Ref. [24], the oscillation frequency is extended up to 1.55 THz by reducing the length of the antenna integrated with the RTD. However, the conduction loss around the antenna increases with decreasing antenna length [25]. In Ref. [26], by reduced conduction loss together with an optimum RTD structure, a fundamental oscillation of up to 1.92 THz is obtained, which is the highest fundamental oscillation frequency of room-temperature to date [26].

Despite the tremendous progress in fabrication process of the RTDs which improves their structures for obtaining higher frequency and output power and increasing its use for THz sources, there is still lack of modeling of the RTD, particularly at high frequency. This is considered the main motivation of this work to propose a model that has competitive advantages over the current models and to be characterized by higher accuracy. Also, it recommended to have the ability to be implemented into a computer aided circuit design software, such as SPICE and ADS software, to simulate circuits containing RTD in high frequency regime without any singularity or convergence problems.

In this paper, an RTD model has been proposed as an alternative for the well-kwon and well verified quantum-inductance RLC model, which provides a better understanding of the mechanisms that limit the transient behavior of the RTD. This model overcomes the disadvantages of the quantum-inductance RLC model, which suffers from a singularity and the ambiguity of the negative quantum inductance at NDR that gives rise to convergence problems and makes it useless when used in circuit simulators. Also, a simple microwave oscillator based on an RTD device is designed and simulated using the ADS simulator [27]. For the sake of simplicity, the RTD frequency dependent circuit elements are realized exploiting Symbolically Defined Devices (SDD) components [27].

The simulation is carried out using different equivalent circuit models, original constant RC model, series/parallel double RC model which is alternative to the quantum-inductance RLC model and the proposed model. This is performed to address the problems with the current RTD equivalent circuit models.

The rest of the paper is organized as follows. In Section 2, an overview of nonlinear equivalent circuit models is introduced. In Section 3, high frequency characterization parameters are defined to describe the dependency of these circuit elements on the frequency. Section 4 characterizes the RTD device under test. Analysis of the RTD based oscillator is introduced in Section 5. The RTD oscillator circuit simulation results are presented and discussed in Section 6. Section 7 is devoted for the main conclusions of this work. An appendix is added to describe the ADS Simulation.

2. Nonlinear equivalent circuit model for high frequency characterization of RTD

An overview of the equivalent circuits for RTD published so far indicates that most of them have been applied for characterizing the RTD in the small-signal regime [8,9,14,17,28,29]. Also, their equivalent circuit elements extraction approaches are based on fitting the equivalent circuit model with measured S-parameter data over the frequency under restricted bias conditions in the three regions of RTD current – voltage characteristics or using numerical analysis.

The simplest equivalent circuit model introduced to represent a double barrier quantum well (DBQW) RTD was early proposed by Ref. [30]. This was used to describe Esaki tunnel diodes using a parallel combination of conductance and capacitance as illustrated in Fig. 1.

The shortcomings of the simple model have been overcome in Ref. [17] to modify the simple equivalent circuit of Fig. 1 by introducing an inductance in series with the RTD conductance. This model is called parallel inductance equivalent circuit model. But, it suffers from a singularity that gives rise to convergence problems and makes it useless when used in circuit simulators.

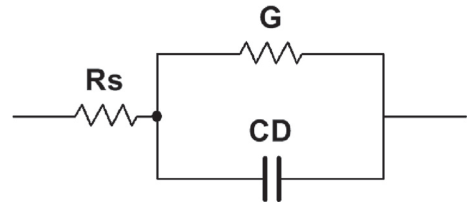

Fig. 1. RC small signal equivalent RTD model [30].

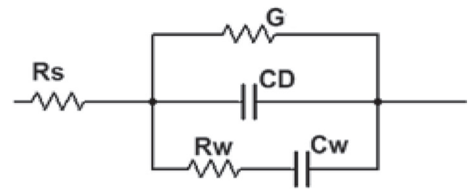

Fig. 2. Series/parallel double RC network [31].

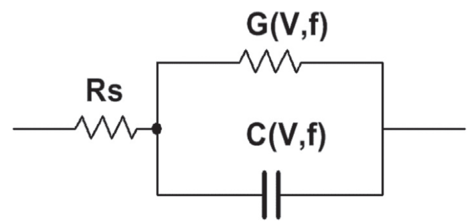

Fig. 3. The large signal and equivalent circuit model [32].

The small-signal series/parallel double-RC equivalent circuit (SPDRC), shown in Fig. 2 [31] has been optimized as a full mutual alternative for the RTD quantum-inductance equivalent circuit model to overcome the mentioned shortcomings of the parallel inductance equivalent circuit model.

Actually, it has been shown experimentally that the real and imaginary parts of RTD admittances change with frequency, instead of having a constant value. So, this simple model is not applicable for RTD at high frequencies [13]. Therefore, we need to modify the values of the simple (G-C) equivalent circuit, shown in Fig. 1, to change with the frequency instead of having a constant value.

The large signal and nonlinear equivalent circuit model proposed by Ref. [32] is shown in Fig. 3. The aim of this model is to modify the values of the simple (G-C) equivalent circuit, shown in Fig. 1, to change with the frequency instead of having a constant value.

3. High frequency characterization parameters

In this section, a simplification of the analytical expressions of the proposed equivalent circuit elements is introduced through new parameters to describe the dependency of these elements on the frequency.

At first, we define two parameters that determine the relation between the simple equivalent circuit model elements G(V) and C(V) and the proposed equivalent circuit model elements $G_{eq}(V,f)$ and $C_{eq}(V,f)$. This is carried out using the new parameters α(f) and β (f) that are assumed as

$$\alpha(f) = \frac{G_{eq}(V,f)}{G(V)}, \quad \beta(f) = \frac{C_{eq}(V,f)}{C(V)} \tag{1}$$

where G_{eq} (V, f) is given by

$$G_{eq}(V,f) = \frac{R_D}{(R_D)^2 + (\omega L_Q)^2} = \frac{G(V)}{1 + (\omega\tau)^2} \tag{2}$$