Bursting and Excitability in Neuromorphic Resonant Tunneling Diodes

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Summary. We study in this paper the dynamics of quantum nanoelectronic resonant tunneling diodes (RTDs) as excitable neuromorphic spike generators. We disclose the mechanisms by which the RTD creates excitable all-or-nothing spikes and we identify a regime of bursting in which the RTD emits a random number of closely packed spikes. The control of the latter is paramount for applications in event-activated neuromorphic sensing and computing. Finally, we discuss a regime of multi-stability in which the RTD behaves as a memory.

Introduction

Spike information processing and transmission in the form of events that occur at continuous times has numerous advantages over digital encoding and signaling [1]. It is a key mechanism in the dynamics of neurons and the brain, which suggests its value in the development of biologically-inspired artificial intelligence. Neurons are *excitable systems*; they respond to an external stimulus by realizing a large amplitude response, typically in the millisecond and millivolt range, before returning to their rest state, provided that said stimulus is larger than a certain threshold. Several neuromorphic circuits have been proposed which attempt to emulate the transmission of information in the brain and the nervous systems [2,3,4], including the IBM TrueNorth chip and the Intel Quark SE chi. These approaches are still based on adapting the conventional Complementary Metal Oxide Semiconductor architecture, and have some drawbacks, such as low frequency (kHz) and much higher power consumption than the brain.

Results

In this work, we provide a detailed analysis on the performance of quantum nanoelectronic resonant tunneling diodes (RTDs) as neuromorphic spike generators. Resonant tunneling diodes are promising candidates and are the fastest electronic oscillators up to date, reaching frequencies in the order of the hundreds of GHz, with a world record of 1.98 THz. Double barrier quantum well RTDs exhibit a nonlinear current-votage characteristic with regions of negative differential conductance (NDC) [1] (fig. 1). This property is key for the potential configuration of RTDs as excitable spike generators [5]. Excitable systems respond to an above-threshold stimulus by realizing a large amplitude response, typically in the millisecond and milivolt range, before returning to their rest state. For the duration of the response, known as lethargic time, the system is unable to respond to any other stimulus, irrespective of its amplitude [6]. Here, a theoretical model is proposed following the first-principle calculations of [5] accounting for an RTD with a single NDC connected to a DC voltage source (see fig. 1 inset).

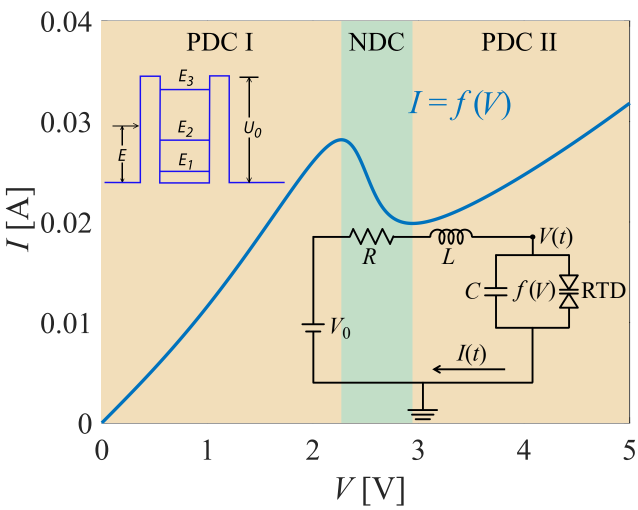

Figure 1: DBQW RTD connected to DC voltage.

The system of two first-order differential equations for the current and voltage derived from Kirchoff laws reads

$$\mu\dot{V} = I - f(V), \quad (1)$$
$$\mu^{-1}\dot{I} = V_0 - V - RI. \quad (2)$$

Here, $V(t)$ is the voltage across the RTD and $I(t)$ is the total current. V_0 is the bias DC voltage, R is the circuit intrinsic resistance and the parameter μ is the stiffness coefficient defined as $\mu = \sqrt{\frac{C}{L}}$, where L and C are the equivalent inductance and capacitance, respectively, which sets the circuit's natural frequency. The system's response depends on three parameters: the bias voltage, the circuit's resistance and a parameter accounting for the stiffness of the dynamics. Provided that this stiffness coefficient is sufficiently small, the system exhibits an adiabatic limit cycle with stages of slow and fast dynamics when biased in the NDC region and a stable fixed point when biased elsewhere (fig. 2.b). If the bias is set in the proximity to the NDC region and the system is perturbed with a perturbation above a certain threshold, it responds with a spike reminescent of the slow-fast limit cycle. If the system is subjected to noise instead of a single perturbation, it randomly generates spikes depending on the noise intensity. If the bias is set in the proximity to the I-V curve valley, the spikes appear agglomerated in bursts (fig. 2.c), which has already been observed in experiments [5].

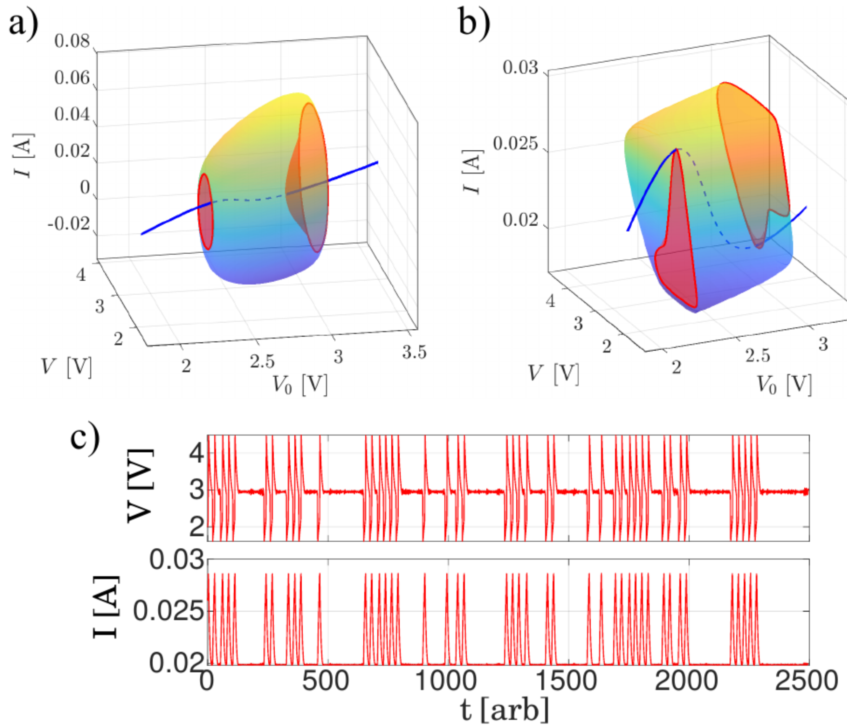

Figure 2: a,b) RTD response as a function of the bias voltage. Limit cycles are smooth (a) or stiff (b) depending on the stiffness coefficient. c) RTD response to external noise in the form of bursts of spikes.

An extensive study on the system's responses in terms of the parameters mentioned above is performed. Depending on the I-V characterisic, there may be narrow ranges of bias voltage at each side of the NDC region where the system is bistable. A critical value for the resistance is also found, above which the system exhibits a rich variety of multistabilies, with multiple fixed points and homoclinic curves. The bistability ranges and the lethargic time are measured as functions of the stiffness coefficient and the resistance, and they are found to be mainly dependent on the former, with little influence by the latter. In particular, the lethargic time is found to be inversely proportional to the circuit's inductance.

Conclusions

A Liénard-type nonlinear oscillator was proposed to model the dynamics of a double barrier quantum well resonant tunneling diode (DBQW RTD) connected to an electrical DC input.The configurations where the circuit behaves as an excitable spike generator were disclosed in a perspective to design and fabricate optoelectronic, nanoscale devices able of transmission, reception and storage of spike-coded information. The RTD oscillator may exhibit one or more equilibrium solutions in the form of a fixed point or a limit cycle. In particular, the stiffness coefficients determines whether or not the system behaves as a smooth oscillator or a spike generator.

References

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