A Design Theory for a Terahertz-Frequency Quantum Oscillator that Operates in the Positive Differential Resistance Region

Dwight Woolard
US Army Research Lab., ARO, Research Triangle Park, NC, USA

Peiji Zhao
Department of Electrical and Computer Engineering, NCSU, Raleigh, NC 27696 USA

H. L. Cui
Department of Physics and Engineering Physics, Stevens Institute of Tech
Hoboken, NJ 07030 USA

Abstract

The traditional implementation of resonant tunneling diodes (RTD) as high-frequency power sources always requires the utilization of negative-differential resistance (NDR). However, there are inherent problems associated with effectively utilizing the two-terminal NDR gain to achieve significant levels of output power. This paper will present a new design methodology where resonant tunneling structures (RTS) are engineered to exhibit electronic instabilities within the positive-differential-resistance (PDR) region. As will be demonstrated, this approach utilizes a microscopic instability that alleviates the need to reduce device area (and therefore output power) in an effort to achieve low-frequency stabilization.

Terahertz frequency systems have previously found applications in radio astronomy, atmospheric monitoring, plasma diagnostics, imaging and surveillance, etc. Though terahertz technology already has potential importance for some civilian and military applications, this region of the electromagnetic spectrum has not reached maturity for commercial exploitation. The main reason for this is the general absence of reliable, low-cost, miniaturized solid-state power sources. To date, most of the two-terminal devices can only provide significant power for applications at the very lower limit of the terahertz electromagnetic spectrum.

The RTD, when implemented in the traditional manner, have been shown capable of reaching frequencies up to 712 GHz with output power of ~0.3 μW. However, the conventional RTD oscillators have some inherit drawbacks. In the traditional implementation, a RTD is utilized as the gain component in a traditional two-terminal oscillator configuration. Here, the RTD is biased in its negative differential resistance (NDR) region. This leads to several problems that severally influence the output power performance. First, any noise fluctuations will be amplified when the RTD and its inherit charge storage capacitance resonates in an unstable manner with some external charge-storage element (e. g., inductance of the contact lead). This effect will finally drive the balance point of the oscillation to the edge of the NDR region. Second, since a RTD acts as an unstable gain mechanism, the oscillation can only be produced through an energy exchange with an external element. Hence, the energy associated with the oscillation must pass through a physical contact, which will always possess some loss. Third, the NDR of a RTD will encourage oscillation in the bias circuitry down to zero frequency. Therefore, one must design the circuit coupled to the RTD-based oscillator so that it is low-frequency stable to prevent energy losses to lower frequency modes. This requires the designer to reduce the RTD capacitance thereby the cross-sectional area of the RTD. This reduction in RTD device area significantly limits the available output power of the oscillator at high frequencies.

In previous numerical experiments, intrinsic current oscillations at terahertz frequency in a double barrier quantum well (DBQW) system have been observed [1]. However, the bias voltage window in which the current oscillates for the device structure studied earlier occurs in the NDR region. This situation occurs because the oscillation criteria are satisfied when an emitter quantum well (EQW) is being created by the interference between the injected and the reflected electron waves just as the bias voltage passes the resonance bias voltage (i.e., when the energy level in the main quantum well is passing the Fermi level in the emitter). As stated earlier, current oscillations that arise within the NDR region will be severally limited in power since the area of the cross-section of the device has to be made small to reduce the capacitance of the device. This work will consider an emitter engineering technique that induces microscopic instabilities within resonant tunneling structures (RTSs). An artificial shallow well is "induced" in front of the emitter barrier. This shallow well enhances the formation of the EQW (and subsequent the instability mechanisms), so that the criteria for the creation of the intrinsic current oscillation in the RTS system can be realized at bias voltages outside of the NDR region. Therefore, bias voltage windows for intrinsic oscillations can be created in the positive differential resistance (PDR) region as long as the underlying oscillation criteria can be satisfied.

To illustrate the potential design of a new quantum oscillator in the PDR region, we have performed Wigner-Poisson based numerical simulation studies. The device structure used in the simulation is based on that used in our previous research [1]. An emitter-engineering method is used to modify the device structure so that the oscillation can be obtained in the PDR region. Specifically, a small pre-well is built in front of the emitter barrier as shown by Fig. 1. The depth of the pre-well is 0.05eV. The length of the pre-well is 200Å. Grading of the Al in the well is used to achieve potential dip.

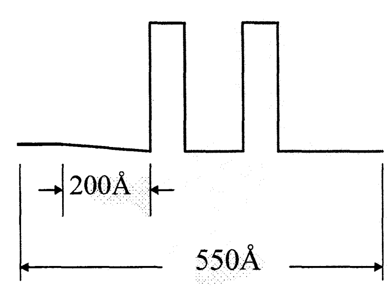

Fig.1 Band structure of the double barrier quantum well structure.

In order to analyze the device, the one-dimensional Wigner-Poisson model has been applied. This model was used to derive the potential profiles, electron distributions and current density. The simulation results are given in Figs. 2 and 3. Fig. 2 shows the average I-V characteristics and demonstrates that there are two bias voltage windows (BVWs). Fig. 3 shows the current oscillatory behavior at select bias voltages. In the lowest BVW, the oscillations are damped. In the higher BVW, the oscillations are significant. Most importantly, the oscillations are located in a PDR region. These studies demonstrate intrinsic current oscillations in the PDR region of a tunneling diode for the first time. Fig. 2 and Fig. 3 show the salient features of the suggested terahertz power source. These features can be outlined as follows. First, the BVW for current instabilities can be located in the PDR region. This feature of the oscillation can be used to overcome the bias-point-shift problem in the engineering design of two-terminal oscillators. Furthermore, there is no broadband gain since the mechanism is not related to negative resistance. This will allow *the area of the cross-section of the device to remain large.* Finally, the operation temperature of the oscillator is in the temperature region of liquid nitrogen. In contrast, QC lasers can provide terahertz power output on the order of pico-watts only at very low temperature, such as $5\,K^0$.

In conclusion, we have presented a new design method for two-terminal high frequency power sources. Since the gain mechanism is not related to negative resistance and the oscillations are designed in positive resistance region, the oscillators based on this design method should lead to enhanced levels of output power.

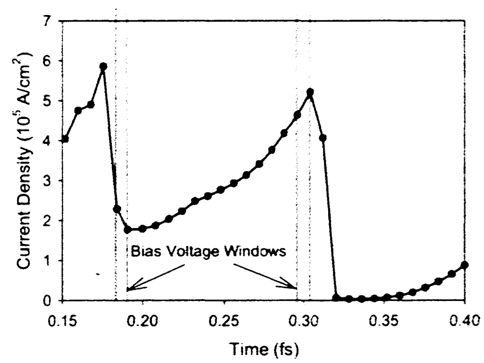

Fig. 2. The I-V characteristics of the new device structure. In the denoted bias voltage windows, the current density oscillates. The values of the current density in the bias voltage window in this figure are the time-average of the time-dependent current density.

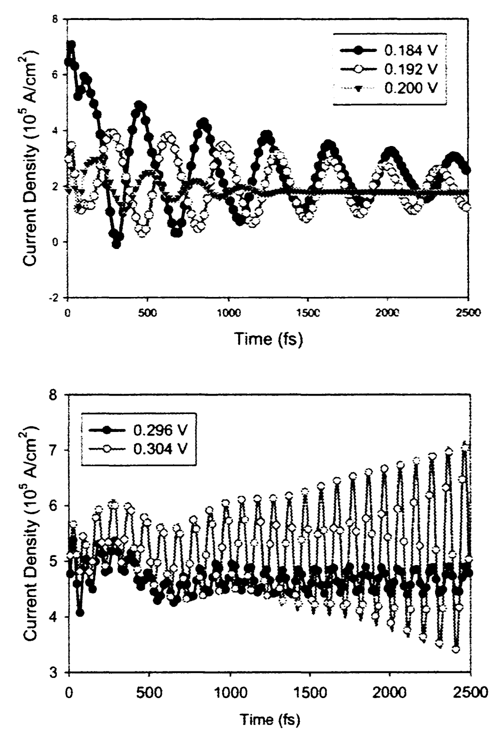

Fig.3. The time-dependent current density in the bias voltage windows. For the oscillation in positive differential resistance region, the oscillation frequency is 16.7 THz.

Reference:

[1] Peiji Zhao, H. L. Cui and D. Woolard, Physical Review B63, 75302(2001); Peiji Zhao, D. Woolard, and H. L. Cui, Phys. Rev. B67, 085312(2003).