A MULTI-SUBBAND THEORETICAL CRITERION FOR THE DESIGN OF A TERAHERTZ-FREQUENCY QUANTUM-WELL OSCILLATOR

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SUMMARY

The search for compact solid-state based, high-frequency power sources have been an important research subject for many years. Since the end of 1980's, resonant tunneling diodes (RTD) have been treated as possible high frequency power sources. However, as it is well known, the traditional implementation of a RTD has not been successful as a power source at terahertz (THz) frequency. Indeed, the output power of a RTD is on the order of μwatts at operation frequencies near 1 THz. This failing is due to the extrinsic design manner of the oscillator that utilizes external circuit elements to induce the oscillation. This failing of the "traditional" RTD-based oscillator is tied directly to the physical principles associated with its implementations. In fact, the f^2 law points out it is impossible to get higher output power at tearahertz frequencies for a single device utilized in an extrinsic design manner.

In contrast to the extrinsic design of RTD oscillators, the intrinsic design of RTD oscillators makes use of the microscope instability of RTDs directly. This type of an approach will avoid the drawbacks associated with the extrinsic implementation of RTD's. It is believed that if the dynamics surrounding the intrinsic oscillation can be understand and controlled, RTD sources based on the self-oscillation process should yield milliwatt levels of power in the THz regime. However, the exact origin of the intrinsic high-frequency current oscillation has not yet been fully established. The transport dynamics in RTD's is governed by the quantum mechanical tunneling process that occurs through a quantum-well that is formed by a double-barrier heterostructure. The lack of knowledge related to the origin of the intrinsic instabilities in double-barrier quantum-well structures (DBQWSs) directly hampers realizing an optimal design (device and circuit) of a RTD-based oscillator. Thus, it is extremely important to understand the creation mechanism of the intrinsic instability in DBQWSs.

Previously, a new theory was presented by our group that provided a basic idea for the origin of the intrinsic oscillation in a DBQWSs. This theory revealed that the current oscillation, hysteresis and plateau-like structure in I-V curve are closely related to the quantum mechanical wave/particle duality nature of the electrons. In addition, these effects were shown to be a direct consequences of the development and evolution of a dynamical emitter quantum well (EQW), and the ensuing coupling of the quasi-discrete energy levels that are shared between the EQW and the main quantum-well (MQW) formed by the DBQWS. Through this new understanding of the dynamical behavior of the RTD, it was possible to qualitatively predict the existence of an oscillation. However, while this initial description was able to self-consistently explain all the physical phenomena related to the intrinsic oscillation it could not provide quantitative design rules.

This research will extend the earlier theory through the application of basic quantum mechanical model. According to the fundamental theory of quantum mechanics, there is two equivalent methods for determining the energy levels of a coupled system if the system can be viewed as the combination of several sub-systems. The first method treats the subsystems separately initially and then models the interaction between the subsystems to get the combined energy-level structure of the entire system. The second deals with the system as a whole and obtains the energy-level structure by direction solution of Schrodinger's equation. The advantage of the later is that it can give an exact description of the system's energy subbands without the development of models for the sub-systems. This paper will develop multi-subband model for the describing the electron dynamics in DBQWSs. The multi-subband based theory will provide a relationship between the oscillation frequency and the energy-level structure of the system. A method for calculating the energy levels for an open quantum system is also presented. This subband model is then combined with time-dependent Wigner-Poisson simulation results to provide; (1) a quantitative explanation for the origin of the intrinsic oscillations in RTD's, and (2) a detailed design methodology for a future implementation and optimization of DBQWS-based THz oscillators.

Hence, a completely new theoretical criterion for the origin of high frequency current oscillations in a double-barrier quantum-well structures (DBQWSs) is presented. The origin of the current oscillations (as dipicted in

Figure 1) is traced to the development of a dynamic emitter quantum well (EQW) and the coupling of that EQW to the main quantum well (MQW) which is defined by the double-barrier quantum-well system. The relationship between the oscillation frequency and the energy level structure of the system is demonstrated to be a simple relation (i.e., $\nu = \Delta E_0 / \hbar$, where is the average subband energy difference). Insight into DBQWSs as potential devices for very high frequency oscillators is facilitated through two simulation studies. First, a self-consistent, time-dependent Wigner-Poisson numerical investigation is used to reveal sustained current oscillations in an isolated DBQWS-based device. Furthermore, these terahertz-frequency oscillations are shown to be intrinsic and that they can be enhanced using emitter engineering procedures. Second a multi-subband based procedure for calculating, ΔE_0, which is the energy separation of the quantum states in the system that are responsible for the instablity mechanism, is also presented. An example of the results for the subband calculations is given in Figure 2. Together, these studies establish the fundamental principals and basic design criterion for the future development and implementation of DBQW-based oscillators. Furthermore, this paper provides physical interpretations of the instability mechanisms and explicit guidance for defining new structures that will admit enhanced oscillation characteristics. These physics-based models and design criterion will be used in the future to facilitate the design of a realistic oscillator where a tunneling structure integrated and optimized within a high-frequency embedding circuit. This effort is actively being pursued under a collaboration with the ARL-ARO managed DURINT program on “Nanoscale & Molecular Electronics Modeling and Simulation.”

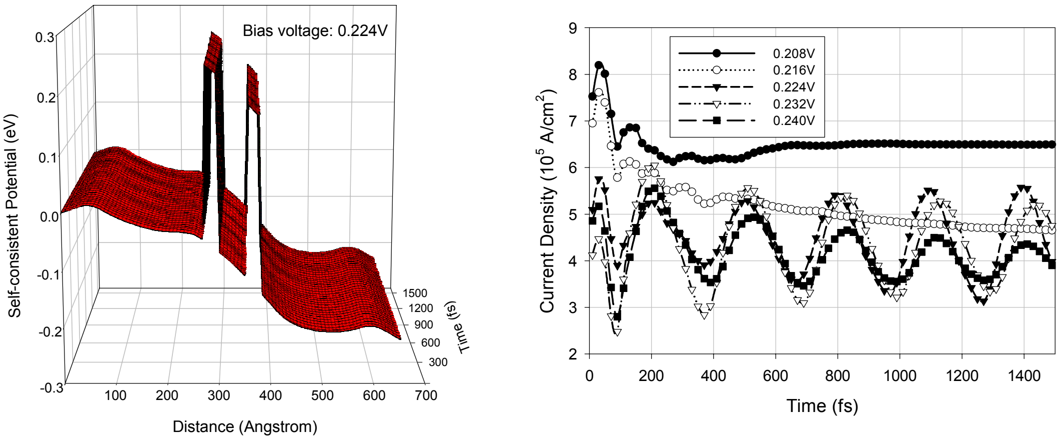

Figure 1. The double-barrier quantum-well structure and associated intrinsic oscillation behavior.

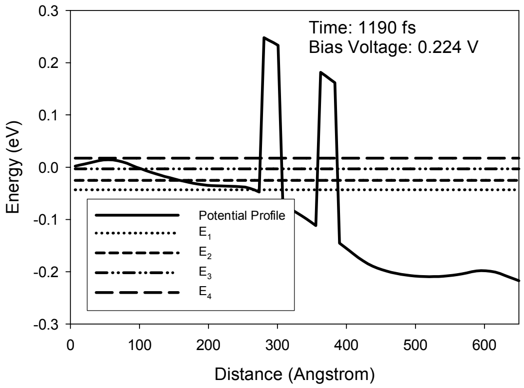

Figure 2. The quantum subband structure that is used to reveal the underlying source of the oscillations.