Experimental demonstration of resonant-tunneling-diode operation beyond quasibound-state-lifetime limit

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Abstract. We show, first, that the charge relaxation (response) time of resonant-tunneling diode (RTD) can be significantly shorter or longer than the resonant-state lifetime, depending on RTD operating point and RTD parameters. Coulomb interaction of electrons is responsible for the effect. Second, we demonstrate that the operating frequencies of RTDs are limited neither by resonant-state lifetime, nor by relaxation time; particularly in the RTDs with heavily doped collector, the differential conductance can stay negative at the frequencies far beyond the limits imposed by both time constants. We provide experimental evidences for both effects.

Introduction
Resonant-tunneling diodes (RTDs, see Fig. 1) are the most simple structures with resonant tunneling. Such structures were intensively studied in the last several decades, they are used for studies of fundamental aspects of tunneling and they are also attractive for practical applications. E.g., RTDs belong to the fastest [1] operating devices nowadays and their negative differential conductance (NDC) is useful for high-frequency oscillators [2, 3]. The question that arises in connection with any electronic device: what is limiting its response time and its operating frequencies? The response of RTD is connected to population and depopulation of the resonant states in the quantum well (QW) of the diode. Therefore, it is typically accepted [4, 5] that the inherent response-time limitation of such structures should be determined by the resonant-state lifetime ($\tau$). Also it is intuitively expectable [5] that the current and conductance of the structure should tend to zero, when $\omega \tau \gg 1$.

One of us has shown theoretically previously that the intuitive picture is not generally correct [6, 7, 8]. The objective of the present work is to demonstrate that experimentally. We show that the response time or, equivalently, the time constant of charge-relaxation processes ($\tau_{rel}$) can be significantly shorter than $\tau$. Such behavior is the consequence of the Coulomb interaction between the charge carriers in the structures [6, 7]. We also show that, under certain conditions, the Coulomb interaction can lead to the opposite effect, when $\tau_{rel}$ becomes longer than $\tau$. Additionally, we demonstrate that, as predicted [8], the resonant-tunneling conductance can
stay large and it can stay even negative in RTDs, when \( \omega \tau \gg 1 \) and \( \omega \tau_{rel} \gg 1 \). Such effects have not been observed till recently [9].

![Figure 1](image.png)

**Figure 1.** a. Schematic band diagram of the fabricated RTD. Panel b shows measured (dots) and simulated (solid line) room-temperature I-V curves of 3 × 15 \( \mu \)m\(^2\) RTD with the following layer sequence: QW with 1.4 nm \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) / 3.0 nm \( \text{In}_{0.68}\text{Ga}_{0.32}\text{As} \) / 1.4 nm \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) layers is sandwiched between \( \approx 3.5 \) nm (nominal value) Al\( \text{As} \) barriers and \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) emitter and collector regions n-doped at the level of \( 10^{18} \) cm\(^{-3}\) with 1.5 nm spacers close to the barriers.

c. The photograph of fabricated RTDs with connecting circuitry for microwave-probe measurements.

### 1. Experimental

For the experimental demonstration of the above effects, we were studying InGaAs/Al\( \text{As} \) RTDs with heavily doped collector specially designed (see subscript to Fig. 1) to have approximately equal effective thicknesses (including the screening and depletion lengths) of the emitter (\( d \)) and collector (\( l \)) barriers. \( l \approx d \) is a necessary condition to achieve NDC when \( \omega \tau_{rel} \gg 1 \) and \( \omega \tau \gg 1 \) [9]. Without loss of generality of the obtained results and for the sake of ease of measurements only, the barriers of RTDs were made thick (\( \approx 3.5 \) nm), so that the value of \( \tau \) is \( \approx 100 \) ps. For such diodes, the conditions \( \omega \tau \gg 1 \) and \( \omega \tau_{rel} \gg 1 \) are already well satisfied at the frequencies below 10 GHz and the effects we are looking for could be demonstrated with standard microwave measurement techniques.

The layout of the fabricated RTD structures is shown in Fig. 1c. RTD is connected via air bridges and other metal lines to the contact pads for the standard microwave-probe measurements. The admittance of RTD with the surrounding parasitic circuitry has been measured with a conventional vector network analyzer. To determine the contribution of the parasitic circuitry, the additional short and open structures were fabricated and measured, where RTD is replaced by a short (for the measurement of the inductive contribution) or open (for the capacitive contribution) circuits. The parasitic parameters measured in such a way are supported by simulation results (with CST Microwave Studio). When the parasitic contributions to the measured admittance are excluded, we get the resultant "pure" RTD admittance, see Fig. 2. The plots of conductance in the NDC region clearly show that RTD conductance stay negative in the whole measurement range of 12 GHz, where the conditions \( \omega \tau_{rel} \gg 1 \) and \( \omega \tau \gg 1 \) are satisfied.

Further, we simulate the static and dynamic characteristics of RTDs. The sequential-tunneling approximation is used in our self-consistent static simulations, we take into account the nonparabolicity in the barriers, finite (room) temperature, thermionic emission over the barriers, tunneling through the second subband in QW. The simulated curves are in very good agreement with the measured ones, they describe well the peak and valley regions of the I-V curves both
Figure 2. The plots of measured (solid lines) and simulated (dashed lines) RTD conductances ($Re(G)$) and excess susceptances ($Im(G) - \omega C_{RTD}$) for forward (0.34 V and 0.56 V) and reverse (−0.3 V and −0.46 V) biases, $C_{RTD}$ is the geometrical RTD capacitance. The biases of 0.34 V and −0.3 V are in the PDC region of the I-V curve (see Fig. 1b) and those of 0.56 V and −0.46 V are in NDC region. The RTD was designed in such a way that the values of $1/2\pi\tau$ and $1/2\pi\tau_{rel}$ in NDC region are close to 1 GHz. The plots of RTD conductance at 0.56 V and −0.46 V show that the conductance stays negative, even when $\omega \tau_{rel} \gg 1$ and $\omega \tau \gg 1$: $\omega \tau_{rel} \approx 12$ and $\omega \tau \approx 8$ at 12 GHz.

for the forward and reverse biases applied to RTD (see Fig. 1b). The RTD parameters used in the simulations (the barrier thicknesses are 3.3 nm and 3.2 nm) are in good agreement with the nominal MBE growth parameters and the parameters of the layers determined by X-ray diffraction on the calibration test structures (the barriers were 3.6 nm and 3.5 nm). Further, the AC characteristics of RTD have been calculated relying on our previously developed theory [7, 8]. The simulated and measured AC admittances are in good agreement with each other both in the positive differential conductance (PDC) and NDC regions and also for the forward and reverse biases, see Fig. 2.

Knowing the RTD parameters from the simulations and comparison with experimental data above, we calculate $\tau$ and $\tau_{rel}$ for our diodes, Fig. 3. The values of $\tau_{rel}$ can be also determined from the admittance plots (Fig. 2). As it has been shown by one of us theoretically [7, 8], the characteristic conductance roll-off frequency and the peak in the excess susceptance (see Fig. 2) correspond to the condition $\omega \tau_{rel} = 1$. The experimental values of $\tau_{rel}$ determined in such a way are also plotted in Fig. 3. The figure shows that $\tau_{rel}$ determines the roll-off of the AC characteristics of RTD, while $\tau$ has even qualitatively different behavior. The value of $\tau$ is decreasing with bias as a consequence of the decrease of the collector-barrier height, whereas
$$\tau_{rel}$$ is increasing, as a consequence of the Coulomb-interaction effects [6, 7], when one goes from PDC to NDC region of the I-V curve. The experimental and theoretical values of $$\tau_{rel}$$ are in quantitative agreement with each other. Both the simulations and measurements do indeed show that $$\tau_{rel}$$ is by a factor of $$\approx 2$$ shorter (longer) than $$\tau$$ in the PDC (NDC) regions.

Although the measurements presented here are done at relatively low frequencies, the same effects should be observable also at much higher frequencies. E.g., the same RTDs with 1.5 nm barriers would have $$\tau \approx 0.5$$ ps and $$1/2\pi\tau \approx 300$$ GHz. One of the practical consequences of the presented results is that the frequency range, where the differential conductance of RTD stays negative and realization of RTD oscillators is possible, should be limited neither by $$\tau$$ nor by $$\tau_{rel}$$ in RTDs with heavily doped collectors. Such diodes should allow one to overcome the upper frequency of $$\approx 0.7$$ THz achieved [2, 3] with RTD oscillators till now. Additionally, although we present in this work the data on the most simple resonant-tunneling structure and at relatively low frequencies, the observed effects (Coulomb shortening of the relaxation time and conductance beyond the resonant-state-lifetime limit) are also expected in the more complicated structures (multi-barrier structures, single-electron-transistor-like structures, quantum-cascade lasers, etc.) and at the frequencies much higher than those covered in the present work and even in the THz frequency range.

The financial support of DFG and the Alexander von Humboldt Foundation are gratefully acknowledged.

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