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Transient Behavior of Germanium Quantum-dot Resonant Tunneling Diode

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1. Introduction

The study of quantum transport in mesoscopic systems has received considerable attention in the past decade, not only originating from the scientific interest on the fundamental physics, but also for its great potential as the new generation of electronic and photonic devices. The transport properties of single-electron devices studied so far have been mainly related to steady-state processes. Recently, time-dependent transport phenomena have begun to attract more and more attention. In general, the external time-dependent perturbation affects the phase coherent differently in different parts of the system and a multitude of new effects have been observed, for example, photon-electron pumping, sideband effect, turnstile, ac response in resonant-tunneling devices, and so on.

A resonant tunneling diode (RTD), consisting of a double or multi-barrier system, is the structural heart for quantum transport. In this work, we consider a RTD with a Ge quantum-dot (QD) coupled to two leads through SiO_2 barriers and study the time-varying characteristics of the tunneling current through such a system in which the time-dependent external fields are applied to the leads. We found that the transient response current of a Ge-QD RTD is composed of an oscillation current, called ringing current, and an exponential decay/rise current in response to the rising/falling edge of the voltage pulse. The symmetry of tunneling barriers and voltage pulse bias/amplitude strongly affect the transient response of a Ge-QD RTD, such as the amplitude of ringing current and time constant.

2. Experimental works

The fabrication of a Ge-QD RTD started from a silicon-on-insulator wafer with a top silicon layer and a buried oxide layer thickness of 35 nm and 380 nm, respectively. A trilayer of a 10 nm Si buffer layer/an 8 nm strained $Si_{0.95}Ge_{0.05}$/a topmost 2 nm Si cap layer was grown by ultrahigh vacuum chemical vapor deposition at 550 ^{o}C. Then, SiGe/Si nanowires connecting source/drain (S/D) electrodes was patterned using electron beam lithography and SF_6/C_4F_8 plasma etching. Figure 1(a) shows the scanning electron microscopy (SEM) image of the channel of a RTD with a typical length and width of 50 nm and 25 nm, respectively. Subsequently, thermal oxidation was performed in H_2/O_2 ambient at 900 ^{o}C to completely oxidize the SiGe/Si nanowires not only from the top plane but also from sidewalls to form a Ge QD weakly coupled to leads via oxide barriers. In previous work, we have verified that only single Ge QD would be produced in the core of a nanowire with a length less than 150nm and self-aligned to the leads by SiO_2 tunneling barriers as shown in Fig. 1(b). Since the nanowire's width is less than its thickness, the required oxidation time for completely oxidizing the SiGe/Si nanowire is determined by the former. While only a small portion of SiGe/Si layer in the electrodes would be consumed once the nanowire is completely oxidized. The QD diameter is about 10 nm. After thermal oxidation, S/D electrodes were implanted with 5×10^{15} cm^{-3} arsenic ions and then activated at 900 ^{o}C for 20 seconds. Finally passivation, contact, metallization, and sintering processes were performed to complete device fabrication.

The direct-current (dc) transport properties and transient response of a Ge-QD RTD were characterized by Keithley 4200-SCS with Pulse I-V system. The rise-time and fall-time of the voltage pulse was set to 2 ns during transient measurement. All the measurement was performed in darkness and at room temperature.

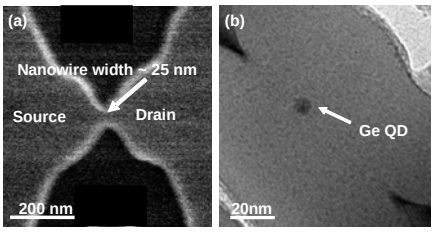

Fig. 1 (a) Plane-view SEM of the channel of a RTD. (b) Transmission electron microscopy image of Ge QDs formed by thermal oxidation of SiGe/Si-on-insulator nanaowires.

3. Results and discussion

The dc current-voltage (I-V) characteristic of a Ge-QD RTD is plotted in Fig. 2. The tunneling current displays a quasi-oscillatory behavior with a nearly periodic voltage separation of 0.14 V and negative differential conductance (NDC). The presence of NDC implies that the fine structure at 1.18 V and the first oscillatory current peak at 1.56V correspond to the ground state (E_0) and the first excited state (E_1) of a Ge QD, respectively.

Figure 3 shows the transient current response (solid lines) of a Ge-QD RTD after a voltage pulse rises from low state to high state. It is noted that the response current features with clear overshoot on the rising edge rather than gradual increasing to steady-state current. In addition, the transient response current of a Ge-QD RTD composes of an oscillation current (or ringing current) due to the coherently resonant tunneling between electrodes and the QD as well as an exponential rise/decay response (with a time constant τ on μs scale) originating from displacement current as

shown by the dash lines in Fig. 3. The effects of symmetry of tunneling barriers and pulse bias height/amplitude on the transient response of a Ge-QD RTD are investigated below:

(a) Symmetry of tunneling barrier:

The left and right electrodes are regarded as "source" and "drain" in the case of Fig. 3(a, b, e, f), while they are interchanged in the case of Fig. 3(c, d). The amplitude of ringing current and time constant in the case of Fig. 3(a)/(b) are quite different from those in Fig.3(c)/(d) even though the same pulse bias (V_{ds}) is applied between electrodes (0→1.56V or 1.18V). Such asymmetric current response might come from asymmetric tunneling barriers in this device. Theoretical calculation has predicted that the tunneling rate ratio of an asymmetric double barrier system would play a considerable role on the transient current behavior. Consider a system with a QD closer to the left electrode relative to the right electrode as sketched in Fig. 4(a). If a positive V_{ds} is applied as shown in Fig 4(b), an electron in the source electrode would tunnel into a QD through a thinner barrier and then passes through a thicker barrier to drain. This will lead to a net charge accumulation and an increased Coulomb potential within the QD, which will induce weak coherently resonant tunneling and hence weak ringing current response due to $\Gamma_{in} > \Gamma_{out}$. On the other hand, if the electrodes are interchanged ($\Gamma_{in} < \Gamma_{out}$) as shown in Fig. 4(c), electrons would sequentially tunnel from the source electrode through the QD to the drain electrode (no charge accumulation), leading to strong coherently resonant tunneling and hence enhanced transient current response. The observed transient current evolution implies that our measured Ge-QD RTD has an asymmetrical tunneling barriers system with the QD closer to the right electrode.

(b) Voltage bias of a pulse:

Both the amplitude of ringing current and time constant in the case of Fig. 3(a)/(c) (V_{ds} = 1.56V corresponding to E_1) are larger than those in Fig. 3(b)/(d) (V_{ds} = 1.18V corresponding to E_0). As V_{ds} is biased at 1.56V, electrons in source electrode would possibly get resonance with E_1 and E_0 simultaneously, leading to more densities of state allowed for electrons tunneling relative to the case of V_{ds} = 1.18V. Meanwhile, once electrons pass through the QD via the first excited state (E_1), the effective potential barrier for electrons tunneling is smaller than that through the ground state (E_0), leading to a higher tunneling rate. Due to more available densities of state and smaller effective potential barrier, the transient resonant tunneling current response at V_{ds} = 1.56V would be stronger than that at V_{ds} = 1.18V. Furthermore, when V_{ds} is applied at 1.56V, the intralevel interaction between E_0 or E_1 of tunneling electrons might get enhanced due to the electron wavefunction's interference. This will lead to a longer time constant for the system (current) to reach steady state. On the other hand, only E_0 is available for electrons tunneling at V_{ds} = 1.18V and hence a shorter time constant would be observed due to more localized electron wavefunction.

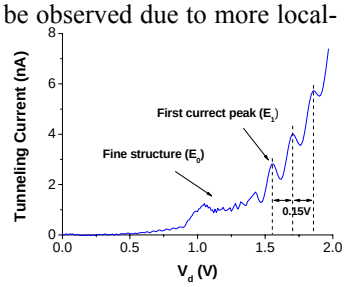

Fig. 2 DC I-V characteristic of a Ge-QD RTD

(c) Voltage amplitude of a pulse:

The voltage amplitude of the pulse is reduced to 0.1V for each bias level to further investigate the transient current behavior of electrons tunneling through a given energy level as shown in Fig. 3(e) and (f). As V_{ds} is biased at 1.46V (the low state of the pulse) in Fig 3(e), electrons in source electrode would only possibly get resonance with E_0 and then achieve steady state. As V_{ds} is raised from 1.46V to 1.56V, electrons would begin to get resonance with E_1 in a very short time and induce ringing current response. This will lead that the transient current (or ringing current) is weaker than that as V_{ds} is changed from 0V to 1.56V in Fig. 3(a). Moreover, when V_{ds} is biased at 1.08V or 1.46V, electrons in source electrode might get chance to be resonant with E_0 or E_1 due to thermal fluctuation. Hence, transient current response and time constant would be smaller than that in the case of Fig. 3(a/b) as V_{ds} changes from 0V to 1.18V/1.56V.

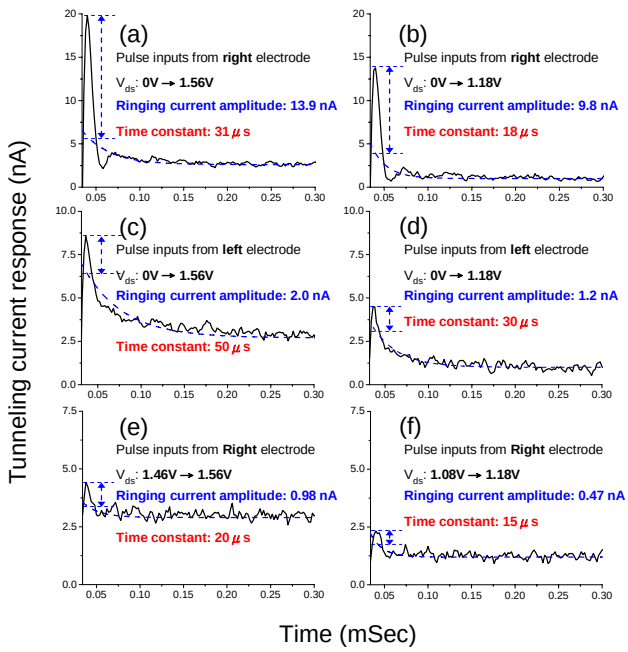

Fig.3 The transient current response (solid line) and the exponential decay fitting curve (dash line).

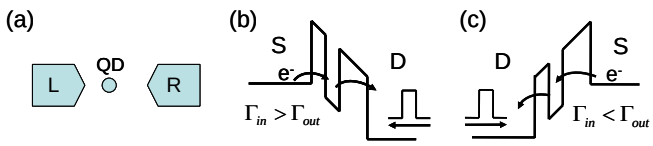

Fig. 4 Sketch for electron tunneling through an asymmetrical double barrier system.

4. Conclusions

The transient behavior of a Ge-QD RTD is reported. The current response is composed of a ringing current and an exponential rise/decay current. The possible factors to affect the transient current in response to the external voltage bias are discussed.

Acknowledgements

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