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Donor-location-dependent RTS Observed by Trapping and Detrapping of a Photoexcited Electron by a Single Donor

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1. Introduction

An individual dopant has the unique property of two electronic states (neutral and ionized), which makes dopants promising for novel electronic and photonic devices. Some prospective applications of individual dopants, such as dopant quantum computing [1,2], single-dopant single-electron transistors (SETs) [3], dopant-based memory [4], and dopant-based photon detection [5], have been proposed and studied. In this background, it is attractive to develop dopant-based nanophotonics. In this work, we study the mechanism of photoexcited-electron trapping and detrapping by a single donor in nanoscale silicon-on-insulator field-effect transistors (SOI-FETs). As a result, it was found that photon-induced random telegraph signal (RTS) in FET tunneling current occurs and contains information of trap-donor location in the channel. This finding would be useful in charging state control of individual donors.

2. Trapping and detrapping of photoexcited electron by single donor

We fabricated nanowire SOI-FETs, as shown in **Fig. 1(a)**. The channel, source, and drain are doped with phosphorus ($N_D \approx 1 \times 10^{18}$ cm^{-3}, i.e., an average inter-dopant distance of ~10 nm) and is covered by 10 nm-thick SiO_2 layer without overlying top gate. The p-Si substrate, doped with boron ($N_A \approx 1 \times 10^{15}$ cm^{-3}), is used as the back gate.

We measure I_{ds}-V_{bg} characteristics at ~15 K. V_{ds} is kept constant at 10 mV. **Figure 2** shows typical I_{ds}-V_{bg} characteristics under light illumination onto the device. Current peaks are ascribed to single-electron tunneling through individual donors, as schematically illustrated in **Fig. 1(b)** [2]. By keeping V_{bg} fixed at the first observable peak (4.9 V), we measure I_{ds}-*time* characteristics. In dark, I_{ds} is almost constant with time, while, under light illumination, I_{ds} exhibits RTS with two distinct current levels [**Fig. 2** (inset)], indicating that photon absorption in the channel induces single-charge trapping. Next, we vary the incident photon flux, ϕ_{inc}. We found that the number of upward current jumps in the RTS (N_{RTS}) monotonically increases with ϕ_{inc}, suggesting that RTS is triggered by photons.

Since RTS is formed by trapping and detrapping of single-charge, we clarify the event which is mostly affected by photons. For that, we decompose the average time of empty (τ_{emp}) and occupied (τ_{occ}) states of the trap as a function of ϕ_{inc}. **Figure 4** shows that τ_{emp} is strongly influenced by ϕ_{inc}, suggesting that trapping is induced by the absorption of a photon. τ_{occ} is independent of ϕ_{inc}, indicating that detrapping is governed by a different mechanism.

Generally, the RTS observed for different devices has different characteristics, which can be most likely due to different donor arrangements. The trap-donor location can be examined by taking the data sets of RTS at different V_{bg} values along the first peak. This is because current on the left and right sides of the peak is dominated by tunneling conductance of the source-side barrier and the drain-side barrier, respectively. When the location of the trap donor is deviated from the current-path donor to the source-side barrier, the RTS should be observed only on the left side of the current peak, since the trapped electron will raise only the source-side barrier potential. In this case, the RTS should be almost absent on the right side, as schematically illustrated in **Fig. 5**. In **Fig. 6**, I_{ds}-*time* characteristics are shown around the first peak for a different nanowire SOI-FET. The I_{ds}-*time* characteristics measured on the left side (V_{bg} = 16.2 and 16.25 V) show a clear two-level RTS, while, on the right side (V_{bg} = 16.75 and 16.85 V), only a single current level is observed with several noise spikes. Although the origin of the spikes is not known, I_{ds}-*time* characteristics are clearly different on the left and on the right sides of the peak. Therefore, this result indicates that the trap donor is located close to the source-side tunnel barrier.

These results indicate the potential for controlling the charge state of a donor by light. In the future, control over the location of the active donor can be achieved by assistance of biases. This controllability is essential for further development of donor-based nanophotonics devices.

3. Conclusions

We demonstrated trapping and detrapping of a photoelectron by a donor in phosphorous-doped SOI-FETs. We show that the relative position of the trap-donor can be estimated from the RTS behavior around the first current peak.

References

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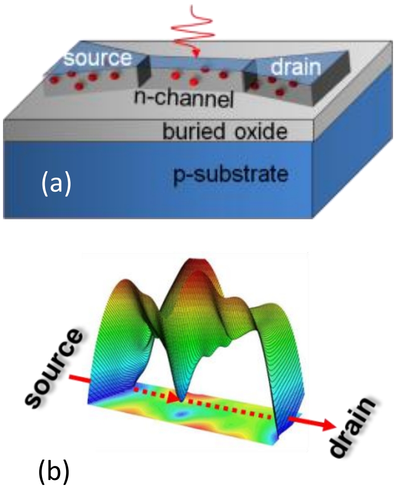

Fig. 1. (a) Schematic SOI-FET device structure. **(b)** Single-electron transport through a single donor.

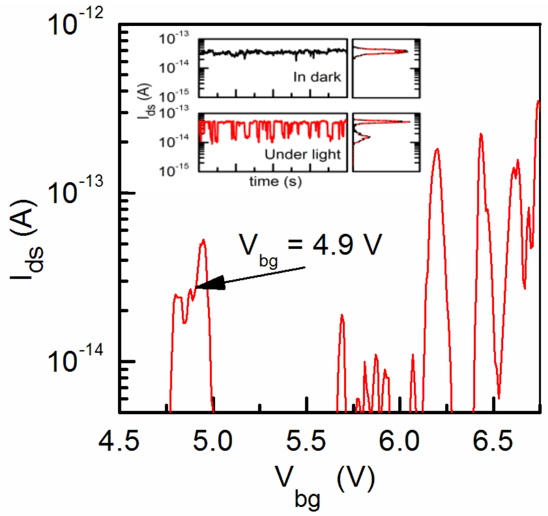

Fig. 2. Typical I_{ds}-V_{bg} characteristics under light, showing current oscillation due to Coulomb blockade effect. (**Inset**) I_{ds}-*time* characteristics in dark and under light. Under light, current switches between two levels due to trapping of a photoelectron by a donor and subsequent detrapping.

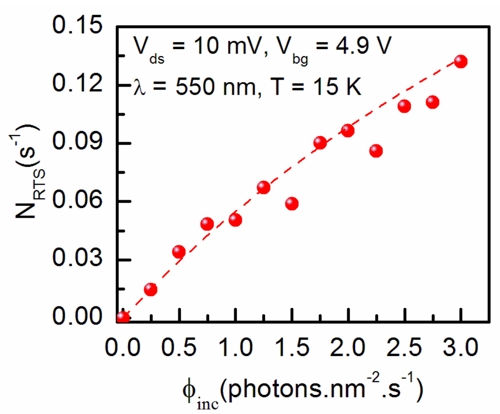

Fig. 3. Number of RTS versus incident photon flux (ϕ_{inc}), showing an increasing dependence, indicating that RTS is triggered by photons.

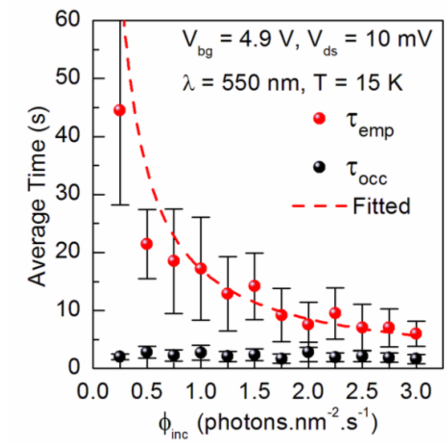

Fig. 4. Average time of empty (τ_{emp}) and occupied (τ_{occ}) states of the trap versus incident photon flux (ϕ_{inc}).

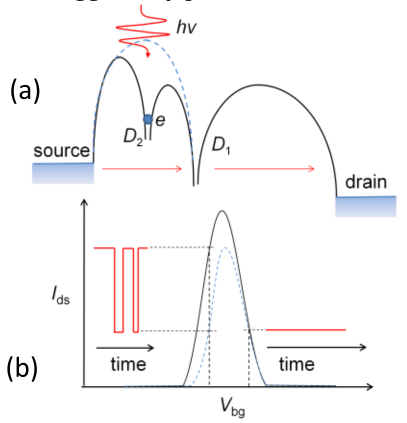

Fig. 5. (a) Illustration of the barrier height modulation due to trapping of a photoexcited electron by a trap donor (D_2) sensed by single-electron tunneling via D_1. **(b)** Corresponding I_{ds}-V_{bg} characteristics and RTS behavior for different V_{bg}.

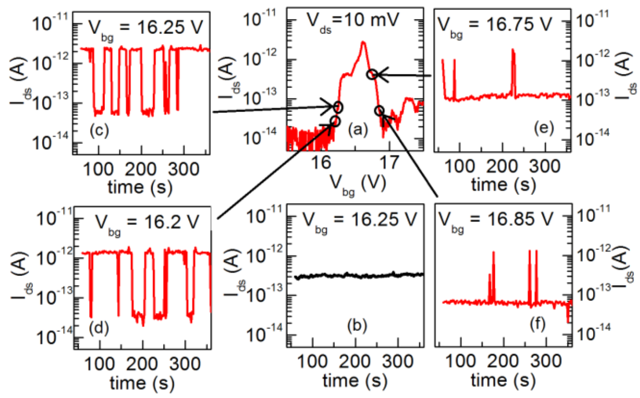

Fig. 6. (a) First peak of I_{ds}-V_{bg} characteristics. **(b)** I_{ds}-*time* characteristics in dark. **(c)-(f)** I_{ds}-*time* characteristics under light for V_{bg} on the left side of peak [**(c)** and **(d)**] and on the right side [**(e)** and **(f)**].