Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp945-946

Photoexcited-Electron Trapping by Individual Donor in Lateral Nanowire *pn* Junction

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1. Introduction

Interest in single-photon detection (SPD) has significantly increased during the last decade. This trend has been driven by high demands for new applications in quantum information technology [1,2]. Related to SPD, we previously reported photon-induced random telegraph signals (RTS) in Si multi-dots field-effect transistors (FETs) [3] and, thereafter, we observed single-dopant based single-photon detection [4,5].

The *pn* junction device has been utilized for photon detection based on avalanche multiplication [6]. However, interaction between single photon and individual dopant in nanoscale *pn* junctions has not been reported. The observation of light illumination effects in such systems, containing both donors and acceptors in the same region, can provide useful information for dopant-based photonics.

In this work, we study interaction between photon and individual dopant in lateral nanowire *pn* junction. In these devices, a photogenerated electron can be trapped in an ionized donor in the depletion region. The electron trapped in the donor changes the local electrostatic potential, causing current fluctuations, which we observed as RTS.

2. Device structure of *pn* and *pin* junction

We fabricated nanowire silicon-on-insulator (SOI) *pn* junctions, with structure schematically shown in Fig. 1(a). Nanowires were patterned on the SOI layer by an electron beam (EB) lithography technique. Then, a selective doping technique was used to create the *n*-type (phosphorus-doped) and *p*-type (boron-doped) regions. Doping concentration was estimated to be $N_D \approx 1.0 \times 10^{18}$ cm^{-3} (phosphorus) and $N_A \approx 1.5 \times 10^{18}$ cm^{-3} (boron). The nanowire length, width, and thickness are designed as 1000 nm, 75 nm, and 10 nm, respectively. Aluminum contact pads were formed for electrodes.

We fabricated both *pn* junctions and *pin* junctions. *pn* junctions contain a co-doped region, in which both boron (B) and phosphorus (P) atoms co-exist, as illustrated in Fig. 1(b). Due to higher B concentration than P concentration, it is expected that individual P donors are surrounded by several B acceptors, which should effectively raise the donor's potential. Therefore, the probability of photogenerated electron trapping should be increased. For the *pin* device, *i*-region was maintained un-doped.

3. Photogenerated electron trapping by single donor

We focus on the effects related to trapping and detrapping of single photogenerated electrons in nanoscale *pn* junctions. For that, we measured current versus applied bias (*I-V*) characteristics at low temperature (T = 20 K) in dark and under monochromatic light (λ = 410 nm). In the *pin* junctions, *I-V* characteristics exhibit no noise features that could be related to charge trapping [Fig. 2(a)]. On the other hand, the *pn* junction characteristics, shown in Fig. 2(b), exhibit current fluctuations under light. This suggests that current fluctuations are promoted in *pn* junctions, most likely due to co-existence of B and P dopants.

Figure 3 shows the potential profile around the depletion region for *pn* junction. As described above, individual P donors are likely to be surrounded by several B acceptors. Within such dopant cluster, the potential of the ionized donor is raised compared to the case of an isolated P donor and the P donor works as a trap for photogenerated electrons. When forward bias is applied to the device, diffusion current flowing through the lowest-potential region can sense changes in the electrostatic potential in the channel [Fig. 3(a)]. When a photon is absorbed in the depletion region, photogenerated electron and hole are separated by electric field. The photogenerated electron has sufficient energy to be captured by the ionized P donor with raised potential. Due to electron trapping in the donor, the local electrostatic potential in the depletion region is increased [Fig. 3(b)] and current is reduced. The trapped electron will eventually escape and, as a result, the depletion layer potential and current return to the initial condition. Current modifications caused by trapping and de-trapping are observed as RTS [as indicated in Fig. 3(c)], where the high current level is ascribed to the empty state of the donor and the low level to the occupied state.

We investigated the time dependence of the current at fixed applied bias (V = 5.6 V) as a function of photon flux, as shown in Fig. 4. In dark, current is almost constant, while, under light illumination, current switches between mainly two distinct levels as RTS. Additional spike-like current jumps observed at higher flux are most likely due to other donor traps. The number of RTS jumps increases by increasing light intensity, as also shown in Fig. 5, confirming that RTS is induced by photons. It can be seen that RTS can only be observed above a certain threshold flux. This may be related to the photovoltaic effect due to which the potential barrier in the depletion layer is lowered at higher flux. For low flux, potential barrier and electric field in the depletion layer remains large, which hinder the observation of electron trapping.

The average times of empty and occupied states are plotted in Fig. 6 as a function of photon flux (Φ). It is seen that only the empty time is affected by Φ, while the occupied time is Φ-independent. This suggests that the de-trapping mechanism is not related to photons, but most likely field-assisted thermal escape [7].

Conclusions

We demonstrated electron trapping by individual donor in the co-doped region of lateral nanowire *pn* junctions. Photons absorbed in the depletion layer induce electron trapping in P donors with potential modified by surrounding B acceptors. These results may contribute to the development of applications based on interaction between single photons and single dopants.

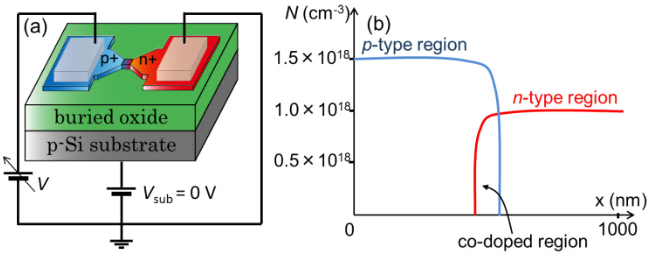

Fig. 1. (a) SOI *pn* junction structure and bias configuration. (b) Doping concentration for B (in the *p*-type region) and P (in the *n*-type region). In the co-doped region, B concentration is higher than P concentration.

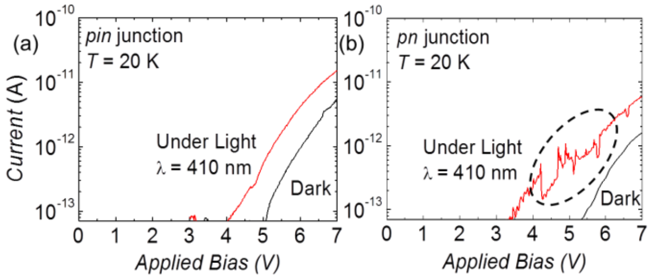

Fig. 2. *I-V* characteristics at low temperature (T = 20 K) in dark and under light illumination (λ = 410 nm) for: (a) *pin* junctions and (b) *pn* junctions. For *pn* junctions, current fluctuations are observed under light (marked by dashed circle).

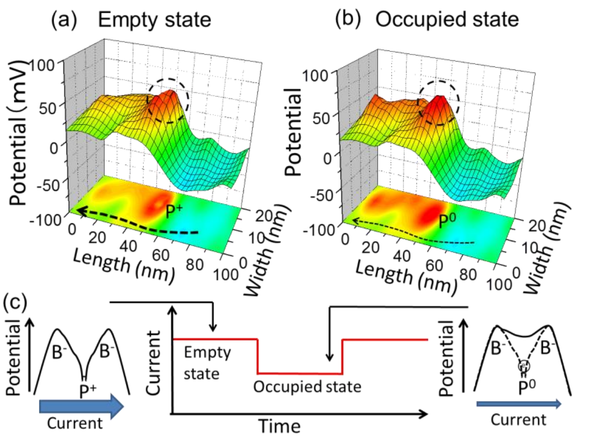

Fig. 3. Potential landscape in the *pn* junction's depletion region before [(a)] and after the capture of a photogenerated electron in a P donor with higher potential [(b)]. Dashed line indicates electron diffusion current. (c) RTS with current levels related to the states of a P donor surrounded by B atoms.

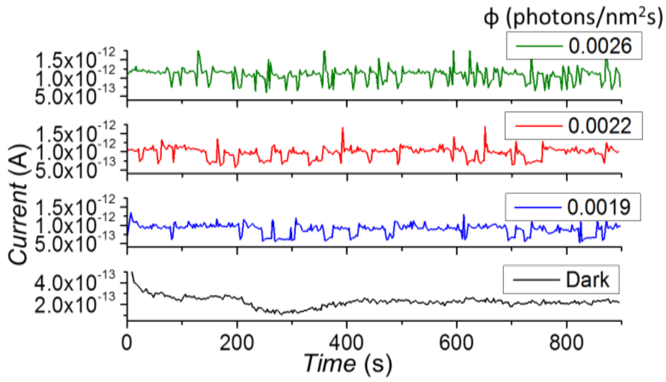

Fig. 4. Current-time characteristics at fixed bias (V = 5.6 V) in dark (bottom panel) and under light illumination (λ = 410 nm) for different photon flux values (upper panels). RTS can be observed under light illumination as signature of charge trapping and de-trapping in the depletion layer.

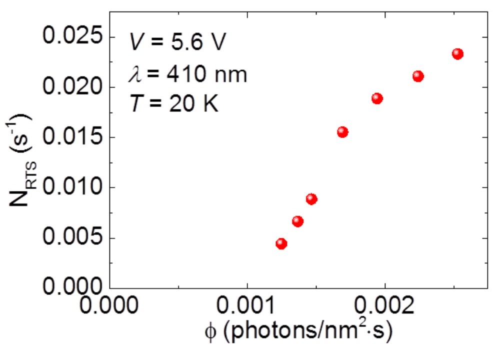

Fig. 5. Number of RTS jumps (s^{-1}) as a function of photon flux. Above a certain threshold flux, N_{RTS} increases with increasing photon flux, suggesting that RTS is induced by photon absorption.

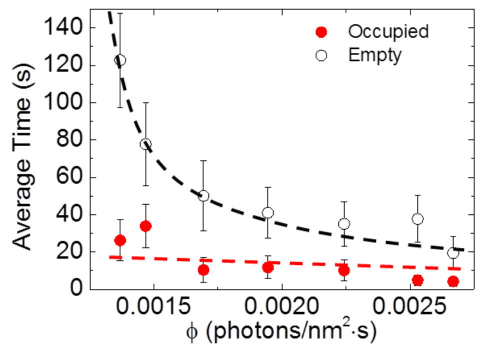

Fig. 6. Average times of the trap's occupied time (lower level of the RTS) and empty time (higher level of the RTS) as a function of photon flux. Only occupied time is affected by photon flux.

References

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