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Single-Photon Detection by Individual Dopants and the Effect of Channel Shape in SOI-FET

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1. Introduction

Interest in single-photon detection (SPD) has dramatically increased during the last decade. This trend has been driven by high demands on new applications in quantum information technology [1,2]. So far, photomultiplier tubes [3] and Si avalanche photodiodes [4] are the most widely employed devices to detect single-photon. Lately, quantum dots (QDs) [5,6] have become attractive alternatives to detect single photon, since they are less susceptible to afterpulsing. In QD-SPD, the detection principle relies on the sensing of electrostatic charge of photo-generated carrier trapped in the dot.

Recently, it also has been reported that discrete dopant can be employed as QD [7-9]. These structures allow us to control single-electron transport from source to drain through individual dopants. This may open a new design of atomic devices with low power consumption, high density, and even simpler in terms of fabrication process.

In this work, we demonstrate for the first time single-photon detection by individual dopants. Under continuous illumination, we observed trapping of single electrons in individual dopants. The trapped electron in the dopant leads to electrostatic potential modulation causing current fluctuation [Fig. 1]. We also demonstrate that increasing internal electric field by utilizing channel pattern shape allows us to enhance the detection sensitivity.

2. Single-photon detection in dopant-induced QDs

We fabricated two different channel shape silicon-on-insulator field-effect-transistors, nanowire and disk channel shapes. The channel was doped with phosphorus dopants ($N_d \approx 1\times10^{18}$ cm^{-3}) and covered with 10 nm-thick SiO_2 layer to allow light irradiation. Schematic device structure, bias configuration, and SEM images are shown in Fig. 2.

Typical device source-drain current versus backgate voltage (I_{ds}-V_{bg}) characteristics in dark and under light are shown in Fig. 3. Current oscillation in dark is caused by Coulomb blockade effect, while sudden jumps of the current under light (marked by dot circle) are due to trapping and detrapping of carriers in the channel.

In nanowire device, superimposition of individual dopant potentials creates a global and local minimum potential along the channel. They will act as conduction path and carrier trap, respectively. Since dopants are relatively uniformly distributed, only a weak internal electric field is created [Fig. 2(a)].

Under light exposure, a few incident photons are absorbed in the channel and generate electron-hole pairs. Since electric field is relatively weak, most of the photo-generated electrons and holes will quickly recombine with each other. Only few electrons are likely to be trapped in the vicinity of conduction path. This leads to local electrostatic potential modulation causing I_{ds} fluctuation [Fig. 3(b)].

In order to understand the stability of current fluctuation, we investigated time dependence of the current at fixed V_{bg} as a function of incident photon flux. We observed random-telegraph-signal (RTS) with two or three levels. Two-level RTS corresponds to trapping and detrapping in a dopant, since a dopant can exist either in an ionized state or in a neutral state. The number of RTS is proportional to the number of photons absorbed in the channel [Fig. 4], indicating that trapping events are triggered by photons. This is the first direct observation of interaction between single photon and single dopant.

3. Sensitivity enhancement by channel shape effect

Next, we studied disk-shaped channel device [Fig. 2(b)]. The dopant distribution inside relatively isolated nano pattern leads to the formation of a deeper global minimum potential close to the center of disk. As a result, a larger internal electric field is formed. Based on the calculation, it is few times stronger than in nanowire device. When light is exposed, this allows separation of photo-generated electron-hole pairs. Some electrons are trapped in dopant nearby conduction path, leading to current fluctuation. We observed time dependence of the current at fixed V_{bg} for several photon fluxes [Fig. 5]. The number of current jump events increases proportionally to the photon flux.

Figure 6 is the plot of number of jump events as function of number of photons absorbed in channel for both nanowire and disk-shaped channel devices. This plot shows that disk-shaped channel exhibits higher number of jump events, around 4 times more frequent than in the nanowire.

4. Conclusions

We have demonstrated single-photon detection based on trapping of single photo-generated electrons in individual dopants. We show that detection sensitivity can be controlled by channel shape. This finding may be used to build new electro-photonic application based on the interaction of elementary quanta of charge, light and atomic impurities.

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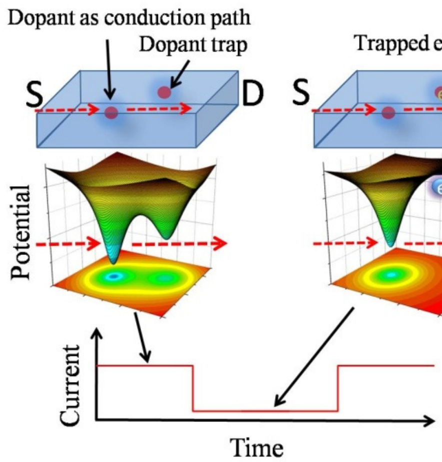

Fig. 1. Schematic view of QD-SPD. Single electrons tunnel through conduction path from source (S) to drain (D). Trapped electron in the dopant trap modulates channel potential causing current fluctuation.

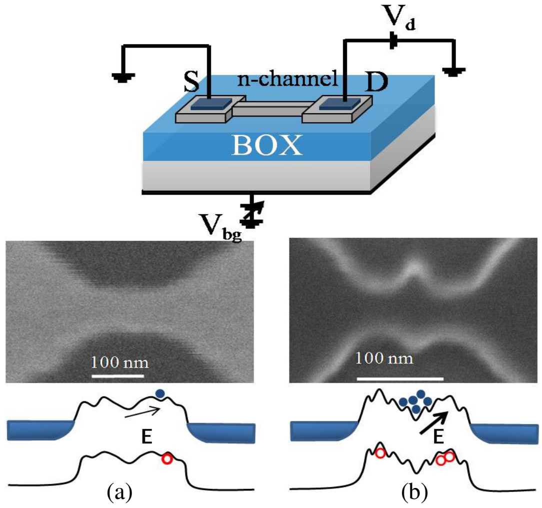

Fig. 2. Schematic device structure and bias configuration. SEM images and potential profiles of (a) nanowire and (b) disk-shaped channel.

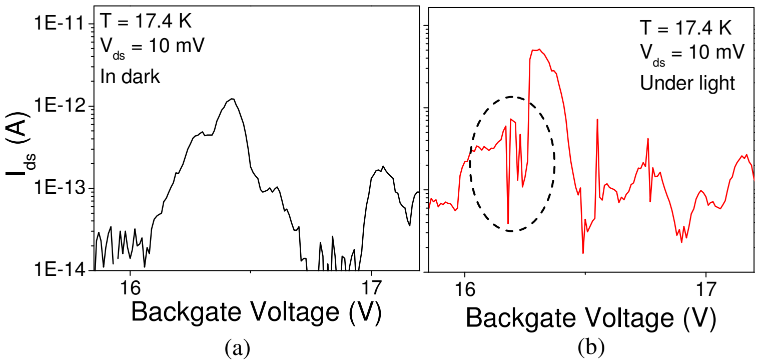

Fig. 3. Typical I_{ds}-V_{bg} characteristics: (a) in dark and (b) under light. Current fluctuation indicates trapping and detrapping.

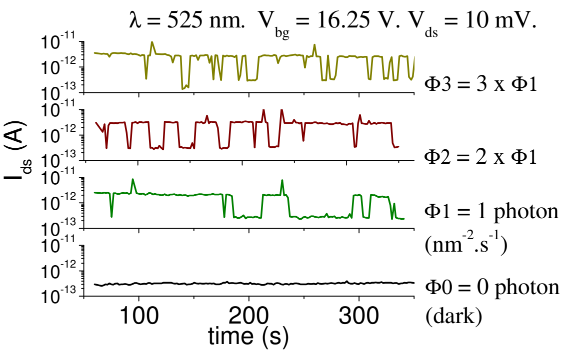

Fig. 4. I_{ds}-time in dark and under light illumination for several photon flux values (photons/nm^2·s), increasing from bottom to top. (Nanowire device).

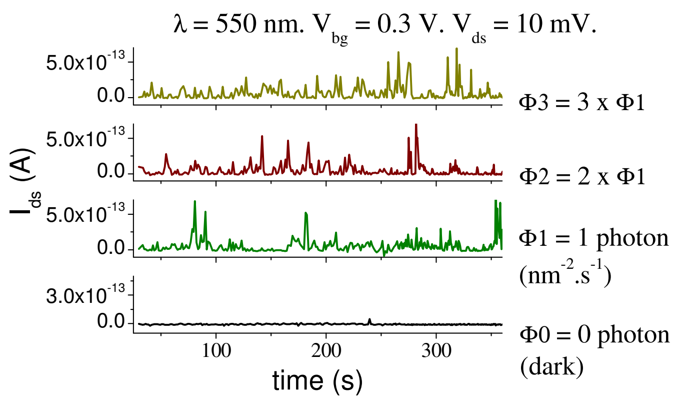

Fig. 5. I_{ds}-time in dark and under light illumination for several photon flux values (photons/nm^2·s), increasing from bottom to top. (Disk-shaped device).

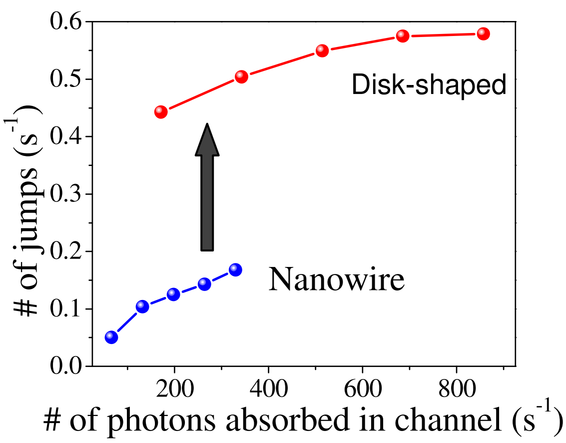

Fig. 6. Number of jump events as function of number of photons absorbed in channel. Disk-shaped devices are more sensitive than nanowire devices.