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Effect of electric field on single-electron tunneling transport in dopant-atom transistors

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Introduction

In the past decade, several experiments have reported access to single dopants in nanoscale transistors [1-4]. However, control of the donor electron under an electric field, in interaction with nearby interfaces, has not been extensively studied experimentally. Here, we report single-electron tunneling via donor-induced quantum dots (QDs) in ultrathin nanoscale SOI-FETs in the presence of varying electric field.

Dopant-atom based SOI-FETs

A schematic bird's eye view of a nano-channel SOI-FET is shown in Fig. 1(a). The channel is uniformly doped with phosphorous (P) ($N_D \approx 1\times10^{18}$ cm^{-3}). Smallest devices, such as shown by SEM image in Fig. 1(b) with a possible dopant distribution, have channel width of ~20 nm and length of ~50 nm. The channel is ultrathin (~2 nm), as seen from the cross-sectional TEM image in Fig. 1(c). An Al front gate is formed on top of a ~14-nm-thick thermally grown SiO_2 layer, while the *p*-type Si susbtrate is used as a back gate.

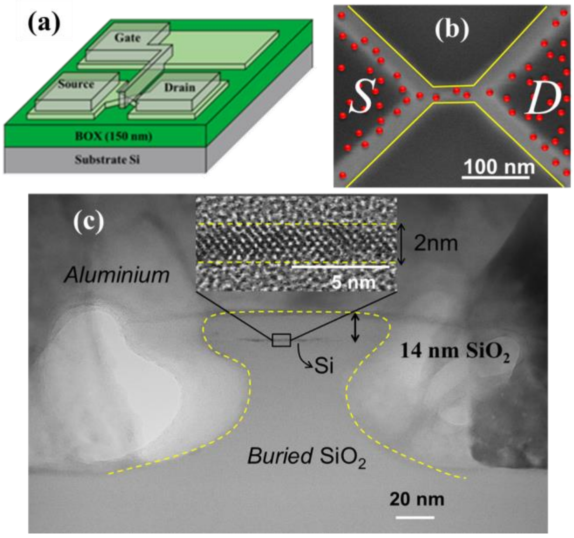

Fig. 1. (a) Bird's eye view of an SOI-FET. **(b)** Scanning electron microscope (SEM) image, with a possible distribution of the P donors. **(c)** Cross-sectional TEM image, showing the ultrathin (~2 nm) Si channel, embedded between thermally grown SiO_2 and buried oxide layers.

Electric field effect on I-V characteristics

Figure 2 shows the contour plot of I_{DS} versus V_{FG} and V_{BG} at low temperature (5.5 K) and small V_{DS} (5 mV). Several current peaks (bright traces) can be observed, starting with lowest V_{FG}. These are due to single-electron tunneling via donor-induced QDs [3,4]. It is most likely that the donors responsible for transport are located in the side edges of the channel, due to the stronger dielectric confinement effect which deepens their ground-state energy levels [4].

We can characterize the effect of electric field on the donor electrons in the V_{FG} - V_{BG} plane. For negative V_{BG}, the electron wavefunction if pushed toward the front SiO_2 interface, and transport through donors (D-states) located there can be observed. For positive V_{BG}, the electron wave function is pulled toward the buried oxide interface, and tunneling transport takes place through a QD formed at this interface (I). This change of the location of the electron wave function is seen as the modification of the slope of the current peak traces (around $V_{BG} \cong 5$ V). This is similar, in principle, to the manipulation of electron wave function in conventional FET channels, observed as a change of the capacitive coupling to the gates [5].

In addition, in the positive V_{BG} region, sudden shifts of V_{FG} (marked by the circle) are identified. These shifts are ascribed to the change of the charge state of a nearby trap site. The trap site can be either an oxide trap or another donor, but more analysis is needed to clarify this point.

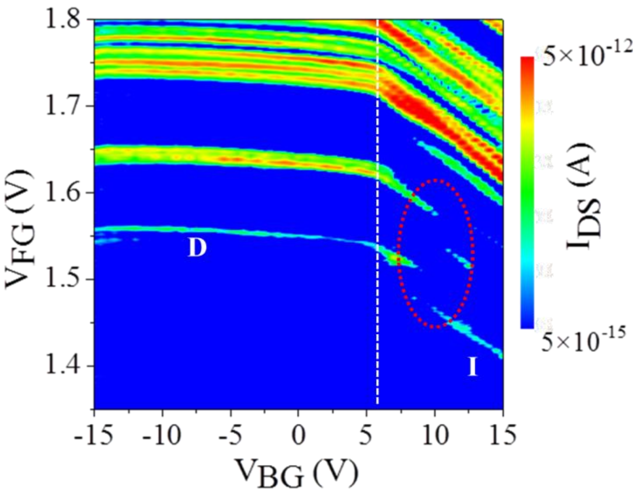

Fig. 2. Drain current (I_{DS}) as a function of V_{BG} and V_{FG} at a source/drain bias (V_{DS}) of 5 mV and T = 5.5 K. Bright traces correspond to SET transport through donor-induced QDs. Sudden shifts of V_{FG} for positive V_{BG} are marked.

References: [1]H. Sellier *et al.*, Phys. Rev. Lett. **97,** 206805 (2006). [2]M. Pierre *et al.*, Nature Nanotechnol. **5,** 133 (2010). [3]M. Tabe *et al.*, Phys. Rev. Lett. **105,** 016803 (2010). [4]E. Hamid *et al.*, Phys. Rev. B **87**, 085420 (2013). [5]S. Horiguchi *et al.*, Jpn. J. Appl. Phys. **43**, 2036 (2004).