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) \(N_D = 1 \times 10^{18} \text{ cm}^{-3}\). 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 substrate is used as a back gate.

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 \(V_{BG} \equiv 5\) 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.