Correlation between single-electron tunneling characteristics and potential landscapes in dopant-atom transistors

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Introduction

In dopant-atom transistors, low-temperature I-V characteristics reveal single-electron tunneling (SET) via QDs induced by individual or clustered dopant-atoms [1-3]. However, so far, there has been no direct correlation between I-V characteristics and dopant-induced potential landscapes. Here, we clarify this correlation between SET transport and potential maps measured by Kelvin probe force microscopy (KPFM).

I-V characteristics at low temperatures

We study SOI-FETs with nanoscale channels doped with phosphorus (P) with different $N_D$ ($\sim 1 \times 10^{10}$ cm$^{-3}$ and $\sim 1 \times 10^{19}$ cm$^{-3}$) [Figs. 1(a) and 1(b)]. Figures 1(c)-(d) show typical I-V characteristics at low temperature ($< 15$ K) for low and high $N_D$, respectively. For low $N_D$, isolated current peaks with irregular distribution are ascribed to SET transport via individual P-donors. On the other hand, for high $N_D$, current envelopes with some periodicity are ascribed to SET transport via a cluster of P-donors as a dominant QD [3].

Potential landscapes by KPFM and simulations

Potential landscapes were measured by KPFM for devices without a top gate [Fig. 2(a)]. Figures 2(b)-(c) show 100×100 nm$^2$ images measured for channels with low and high $N_D$, respectively. For high-$N_D$, we used a selective doping technique to form a local dopant-induced QD between two barriers. In the potential landscapes, potential minima (marked) can be identified as induced by either discrete P-donors (low $N_D$) or by a large number of P-donors (>10) as a cluster (high $N_D$) [4].

Figures 2(d)-(e) show simulated successive potential minima obtained by adding one electron into the QD. Such potential minima work as transport QDs for successive current peaks. For low $N_D$, the minimum changes position for different current peaks. However, for the high-$N_D$ case, the minimum remains stable in position even for increased electron occupation of the QD, due to a macroscopic U-shaped potential background induced by the combination of high-$N_D$ and selective-doping.

This study provides a first-level correlation between electrical characteristics and potential landscapes in dopant-atom transistors. This correlation can offer a pathway to design dopant-atom devices with better control for more practical applications.