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 (~1×10^{18} cm^{-3} and ~1×10^{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].

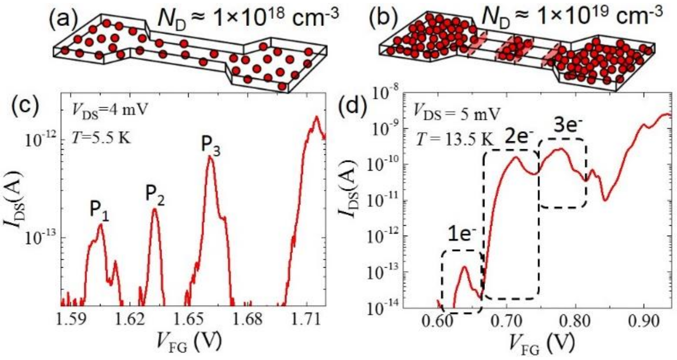

Fig. 1. (a)-(b) Illustrations of SOI-FET channels doped with different N_D, in low and high concentration regimes. (c)-(d) I_D-V_G characteristics measured at low temperature, representative for the two types of devices investigated.

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].

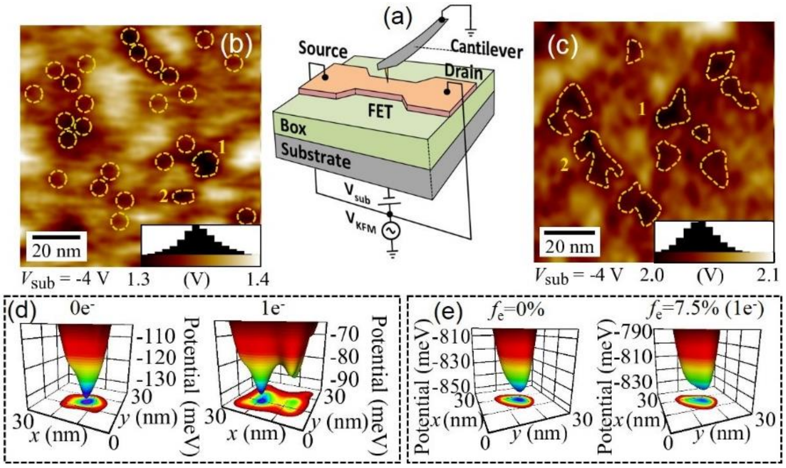

Fig. 2. (a) KPFM measurement setup. (b)-(c) Room-temperature KPFM measurements (100×100 nm^2) for channels with low and high N_D. Dominant minima are labeled in order of depth among many dopant-induced QDs (marked). (d)-(e) Simulated deepest-potential QDs with one electron addition.

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.

References [1] H. Sellier *et al.*, Phys. Rev. Lett. **97**, 206805 (2006). [2] M. Tabe *et al.*, Phys. Rev. Lett. **105**, 016803 (2010). [3] D. Moraru *et al.*, Sci. Rep. **4**, 6219 (2014). [4] K. Tyszka *et al.*, J. Appl. Phys. (to be published).