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KPFM Observation of Quantum Dots Induced by Clustered Donors in Selectively-Doped SOI-FETs

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Abstract
Dopant-atom-based tunnel transistors have been recently studied as a breakthrough beyond miniaturization limit. We challenge the formation of dopant-induced quantum dots (QDs) by CMOS compatible selective doping technique, rather than by single-dopant control. In this work, we investigate the potential profiles of selectively-doped areas in silicon-on-insulator (SOI) transistor channel by Kelvin probe force microscopy (KPFM) as a function of substrate bias. The formation of QD potential induced by local fluctuation of donor concentration inside the selectively-doped region is observed. Result is consistent with I-V characteristics analysis showing transport via cluster-donor QDs, recently reported by our group.

1. Introduction

Devices with single dopants working as QDs based on tunneling-transport have been already widely investigated [1-3]. However, precise control of single dopant-atom position is still under research [4,5] and far from industrial implementation. Our approach is to challenge the fabrication of localized dopant-induced QDs by more conventional technique, i.e., selective doping via ultra-small windows opened in a doping-mask oxide layer. With such process, the QD is formed by several coupled donors, not by single donors, which may favor high-temperature operation.

In order to directly observe QD potential formation, selectively-doped channel was scanned by KPFM under different bias applied to the substrate (V_{sub}). As main results, we found that: (i) phosphorous (P)-doped region becomes deeper above a critical V_{sub} because of electron depletion; (ii) clustered-donor region, due to fluctuations of P-donor distribution, becomes visible at depleting biases. These findings provide useful information about the formation of QDs by our conventional selective doping technique.

2. Selectively-doped SOI-FETs

We fabricate SOI-FETs with the channel selectively-doped with phosphorus ($N_D \approx 5\times10^{18}$ cm^{-3}). Doping was done by thermal diffusion through slits (Fig. 1(a)) opened in an oxide layer by EB lithography. Within the narrow slit, it is likely that clusters containing a few P-donors are dominant [6] inducing the potential profile like in Fig. 1(b). By electrical characterization of devices with a single doped-slit at low temperatures (T<15 K), it is found that tunneling occurs through a unique QD, which can be seen as consecutive current-peak envelopes in the I_D-V_G characteristics [7]. For KPFM measurements, larger-scale SOI-FETs are fabricated with ultra-thin top oxide layer (~2 nm) and substrate-Si working as back gate (V_{sub}). Channel has thickness, length, and width of 20, 1000, and 500 nm, respectively, and contains 250-nm-wide doped slits.

3. Results of KPFM measurements

KPFM measurements [8], due to ability to resolve individual dopants [9], can image the potential inside selectively-doped areas. Our KPFM system (Fig. 2) allows measurement of devices under different bias conditions. For all measurements, source and drain electrodes were virtually grounded, while back gate bias was varied. So far, the measurements were performed at room temperature (T = 300 K) under high-vacuum conditions ($p \cong 10^{-7}$ Torr).

First measurements were focused around one slit. Different bias was applied to substrate (0, -2.5, -4 V, as shown in Figs. 3(b-d)) in order to control the electron distribution in the channel. As expected, contrast is small for 0 V bias condition since dopants are screened by the electrons in the channel. Potential modulation comes from work-function difference between doped (darker) and non-doped (brighter) regions.

For -2.5 V (Fig. 3(c)) bias, contrast is slightly changed, due to partial depletion of the channel. For -4.0 V (Fig. 3(d)), the contrast is significantly increased. To confirm channel depletion, further measurements, under different biases (from 0 to -6 V), were done. Line profiles along the channel were measured to highlight how potential depth (barrier height) changes with applying bias. In Fig. 3(e), step-like change of potential depth after -3 V can be seen, suggesting that depletion of the slit is achieved above this bias.

Under present conditions of KPFM measurement, it is possible to observe mainly potential modulations due to non-uniform distribution of donors. When the slit is depleted of electrons, it is possible to see also local deeper-potential area (as marked in Fig. 4(a)), which can be ascribed to a large dopant-cluster. This is surrounded by flatter-potential region, due to more uniformly-distributed dopants (as schematically shown in Fig. 4(b)). This model is supported by further analysis of KPFM line profiles along the doped slit (as shown in Fig. 4(c)), with two levels ascribed to the potential within the dopant-cluster QD and, respectively, in the area with uniformly-distributed dopants.

3. Conclusions

KPFM measurements of selectively-doped FETs show the modulation of potential due to non-uniform distribution of dopants. Features due to multiple-donor cluster-QDs can also be seen for depleting gate biases. This observation confirms the formation of QDs induced by dopant clusters in result of selective-doping.

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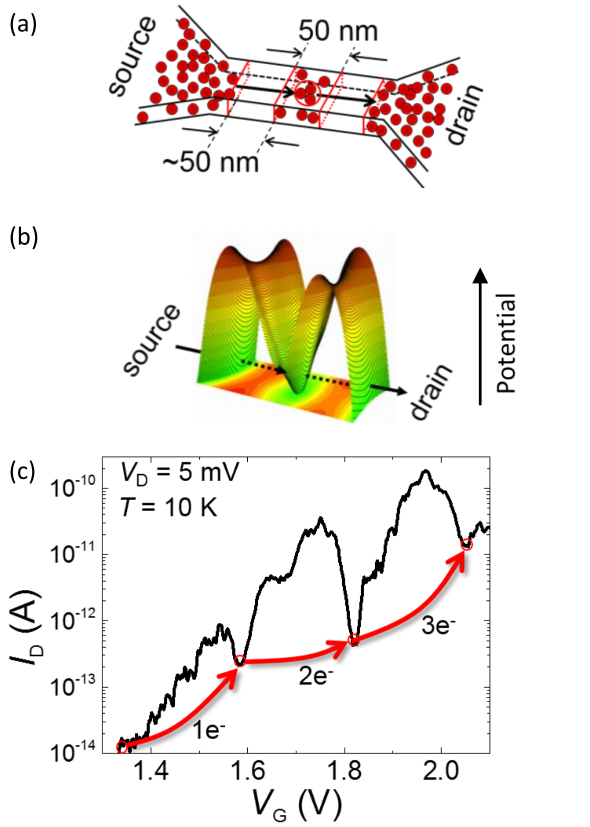

Fig. 1 (a) Single-slit channel with the QD formed by few clustered P-donors. (b) Example of potential landscape induced in the channel by selective doping.(c) Low-temperature I_D-V_G characteristics showing multiple-electron occupancy of the QD.

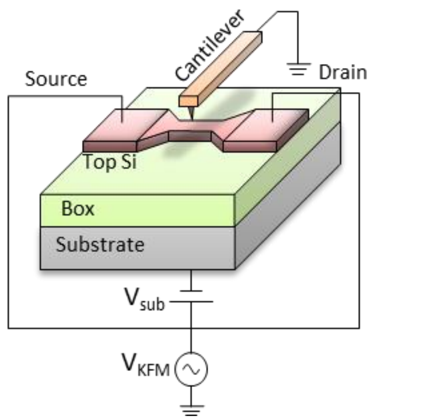

Fig. 2 KPFM measurement setup for slit-doped SOI-FETs, with the substrate-Si working as back-gate (V_{sub}) and source and drain electrodes grounded.

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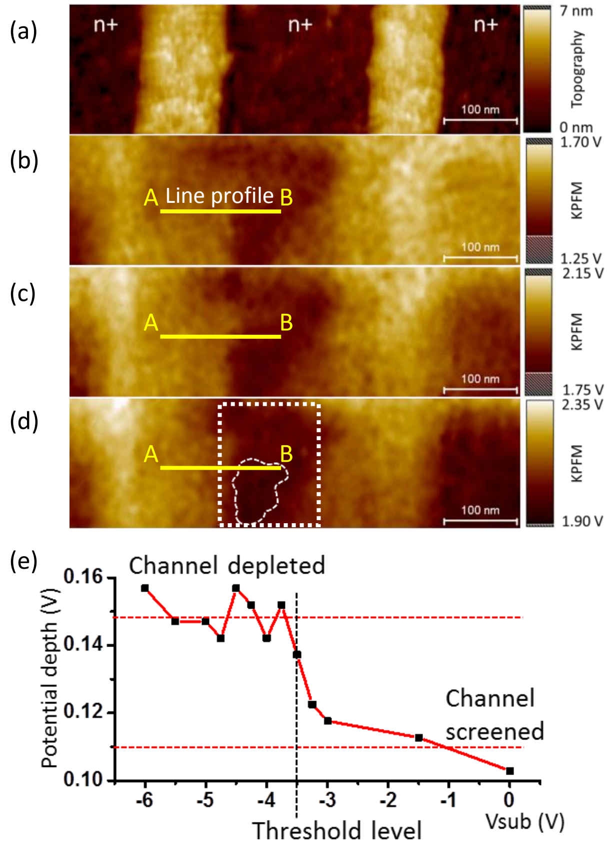

Fig. 3 (a) Topography image and (b)-(d) KPFM images of selectively doped channel taken under different V_{sub} conditions: (b) 0 V, (c) -2.5 V, and (d) -4 V. The outlined area is shown in Fig. 6. (e) Potential depth of the doped area A relative to the non-doped area B (along yellow line (b-d)) as a function of V_{sub}.

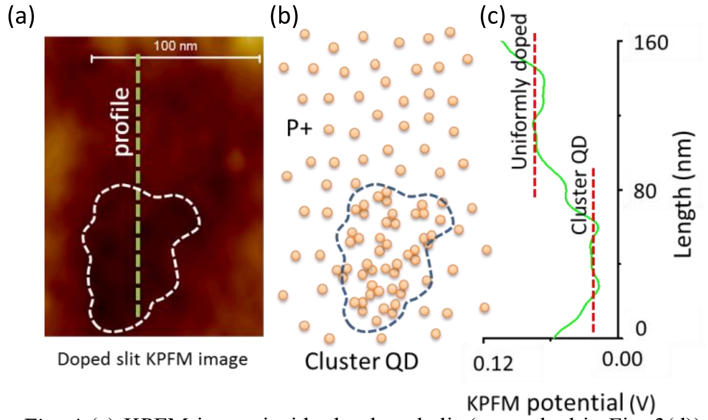

Fig. 4 (a) KPFM image inside the doped slit (as marked in Fig. 3(d)), with outlined deeper-potential region ascribed to a large donor “cluster”. (b) Possible arrangement of dopants inside the slit. (c) Potential profile taken along the slit (dashed line shown in (a)).