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Tunneling transport spectroscopy of interacting donors in silicon nano-transistors

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Introduction

Most studies on *dopant-based devices* [1-5] characterize tunneling transport through a few randomly-located dopant atoms in transistor channels. Only recently, state-of-the-art technologies were used for controlling number and location of a few dopants [6,7]. However, simpler controlled-doping techniques are desirable for further development of practical dopant-based applications.

Device design and characteristics

We have recently showed that nanoscale selective doping of nano-channel FETs can be realized with conventional CMOS processes [8]. The technique involves the opening of a fine (~30 nm-wide) doping window by electron-beam (EB) lithography processes. Then, doping with phosphorus (P) donors is performed as thermal-diffusion doping. Doping concentration is relatively high ($N_D \cong 5 \times 10^{18}$ cm^{-3}), which ensures, with high probability, the formation of multiple-P-donor "clusters", inside which interactions among neighbor P donors are strong (Fig. 1).

We found that low-temperature I-V characteristics are consistent with the properties of quantum dots (QDs) created by several interacting P donors (not by individual P donors). This was observed as repeated current peak envelopes, indicating multiple-electron occupancy of a QD. Here, we analyze the energy spectrum of multiple-donor QD, from tunneling transport spectroscopy measurements, supported by first-principles simulations.

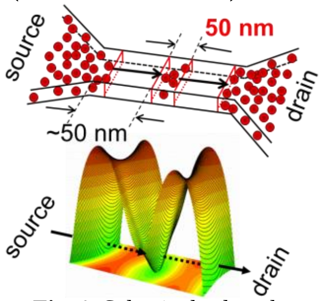

Fig. 1. Selectively-doped nanoscale channel and possible potential landscape.

Tunneling transport spectroscopy of multiple-donor QDs

We compared low-temperature I-V characteristics for several types of SOI-FETs, with different doping conditions of the channel. We find that only selectively-doped SOI-FETs exhibit the specific features consistent with the model of a multiple-donor QD, dominating low-temperature transport.

Figure 2(a) shows one representative set of I-V characteristics, with individual peak envelopes zoomed-out for comparison in (b)-(d). Fine features appear inside each peak envelope, partly preserved on consecutive peak envelopes, i.e., by changing the electron occupancy of the QD. Simple model diagrams are shown in the lower panels. We find, as supported by first-principles simulations, that the number of fine features (3-5) is reflecting the number of interacting donors. This is because the ground state splits into a number of levels practically equal to the number of closely-spaced atoms.

Further optimization, aiming for high-temperature tunneling operation, can be done by controlling the tunnel barrier width, which was also used as a variable parameter.

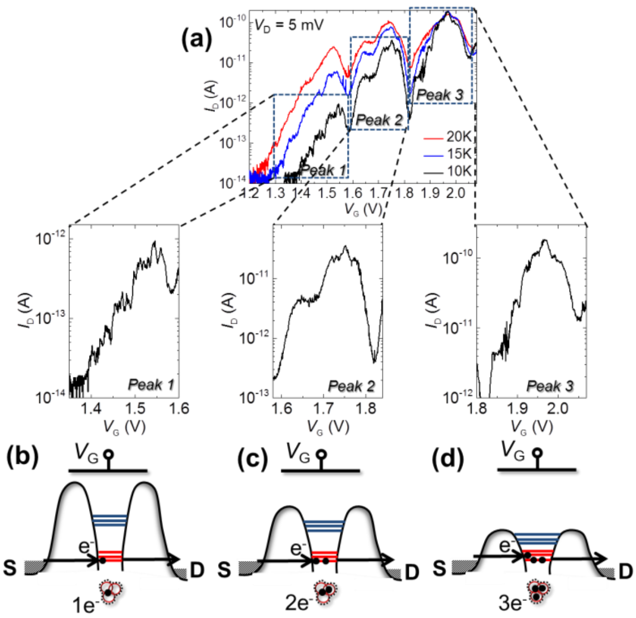

Fig. 2. (a) Representative low-temperature I-V characteristics for a selectively-doped SOI-FET. (b)-(d) Each peak envelope, zoomed out for clarity, with corresponding model.

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