Study of single-electron tunneling in Si nano-transistors in different doping concentration regimes for room-temperature operation

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In recent years, Si nanoscale transistors in which single-electron tunneling (SET) occurs via dopants as quantum dots (QDs) have received attention for low-power applications [1]. However, SET operation temperature is typically <20 K, a temperature range in which thermally-activated transport above the barriers of the dopants can be significantly suppressed. It was previously demonstrated that SET via a P-donor can be observed even at >100 K due to the increase of the barrier height as result of dielectric confinement effect in nano-patterned stub-shaped silicon-on-insulator (SOI) channels [2]. Furthermore, it was also reported that coupling of a few P-donors, introduced by a selective-doping technique [3] at intermediate doping concentrations, can allow formation of QDs with deeper potentials (larger barrier height) and SET at elevated temperatures (~150 K) could be observed [4].

Control of nano-patterning and of the nanoscale selective-doping is, however, challenging due to side diffusion of dopants and complex electron-beam techniques. Here, we present a study of nanoscale SOI field-effect transistors (FETs) with no specific patterns and no selective doping (channel and source/drain are doped simultaneously, as junctionless transistors), but in different regimes of doping concentrations. We aim to provide an overview of the possibility of formation of donor "clusters" (isolated QDs formed by several P-donors) that may sustain SET operation at room temperature.

From a statistical analysis of dopant distributions in different regimes, below and above the metal-insulator transition (N_{MIT}≈3.8×10^{18} cm^{-3}), typical QD distributions are obtained in nanoscale channels. At low concentration (1×10^{18} cm^{-3}), single-donor QDs or, at most, double-donor QDs dominate the transport and only low-intermediate temperature (~100 K) can be expected for SET operation. As concentration is increased (~5×10^{19} cm^{-3}), "clusters" of several P-donors become dominant, while at highest concentrations, connected paths between source and drain are formed. Therefore, at intermediate concentrations, suitable conditions for SET operation at high temperatures are expected. Results are shown in **Fig. 1**, for low concentration [**(a)**] and higher concentration [**(b)**] in terms of number of donor-induced QDs, decomposed by the number of P-donors in each QD (n).

Experimental results on nanoscale SOI-FETs support the possibility of room-temperature operation in high-concentration channels, as long as dimensionality is maintained in nanoscale. **Fig. 2** shows an example of I_D-V_G characteristics measured for a nanoscale SOI-FET with final dimensions in nanoscale (channel thickness, width and length all below 30 nm). Clear signatures of SET operation can be observed and are ascribed to a QD with a radius of 3.0±0.4 nm in a parallel-plate capacitor model.

These results provide basic guidelines for the statistical formation of multiple-donor "clusters" in uniformly-doped nano-transistors, aiming for room-temperature SET operation.

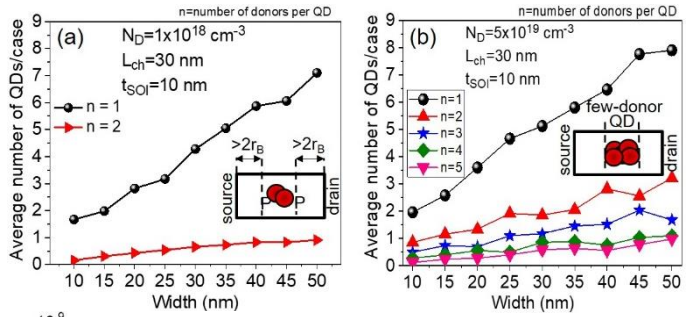

Fig. 1 Statistical analysis (50 cases) of P-donor distributions in nanoscale Si channels as a function of width. Average number of QDs is decomposed by the number of P-donors in each QD for: **(a)** low concentration (1×10^{18} cm^{-3}); **(b)** high concentration (5×10^{19} cm^{-3}). Insets show schematically QDs formed by two P-donors (at most) at low concentration of by multiple P-donors at high concentration.

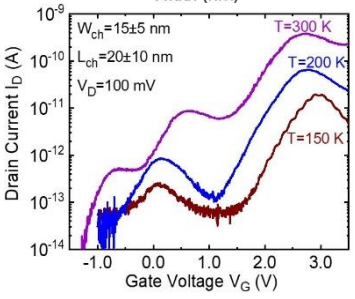

Fig. 2 I_D-V_G characteristics for a nanoscale SOI-FETs (SOI thickness ~10 nm) with high N_D, at elevated temperatures (150-300 K). Current peaks ascribed to SET operation are observed even at room temperature.

References: [1] M. Pierre *et al.,* Nature Nanotechnol. **5**, 133 (2010). [2] E. Hamid *et al.,* Phys. Rev. B **87**, 085420 (2013). [3] D. Moraru *et al.,* Sci. Rep. **4**, 6219 (2014). [4] A. Samanta *et al.,* Appl. Phys. Lett. **110**, 093107 (2017).

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