Effect of coupling of a few donor-atoms as a quantum dot for single-electron tunneling operation at room temperature

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Introduction

Dopant-atom transistors offer the ability to control carrier transport to the level of single atoms and single electrons. However, typical dopants in Si (such as P) have small barrier height and cannot sustain tunneling operation at practical temperatures. Here, we discuss an alternative of using strongly-coupled a few donors to form quantum dots (QDs) with larger barriers, allowing tunneling operation at room temperature.

Single- and coupled-donor QDs

Fig. 1 gives an overview of our approach. For single-electron tunneling (SET) operation, barrier height (E_B) and charging energy (E_{ch}) are essential. Many reports for single-donor transistors [1-6] have a limited temperature range (<100 K), even when dielectric confinement increases ionization energy [5,6].

To reach SET operation at 300 K, it is practical to couple donor-atoms as a QD (insets). The central graph shows how the energy changes with inter-donor distance (based on [7]), suggesting that we can reach $E_B > 10\times k_BT$ at 300 K (~25 meV).

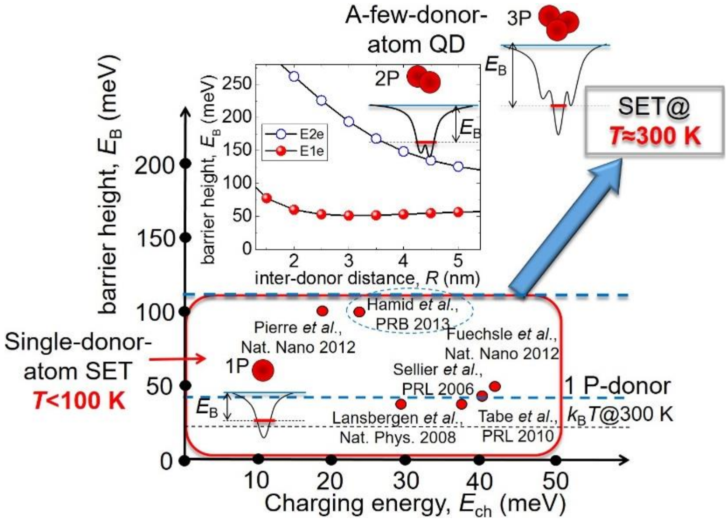

Fig. 1. An overview of reports on single-donor SETs (limited to T<100 K) and our approach to use a few coupled P-donors as QD (insets) for SET at 300 K. Calculations are shown for 2-donors QD (doubly-ionized, i.e., 2e, and singly-ionized, i.e., 1e).

SET operation via a-few-donor-QDs in nano-FETs

An implementation of the above concept is illustrated in Fig. 2(a), as a nanowire-channel (W, t~10 nm) SOI-FET containing a small number of P-donors. P-donors are doped by a selective doping technique to high concentration [8]. Figure 2(b) shows the temperature evolution in the range approaching room temperature. Clear signatures of SET behavior, also seen as Coulomb diamonds in Fig. 2(c) at 150 K, remain visible up to room temperature [9]. This behavior is due to a cluster of a few donors strongly controlling tunneling transport in such device.

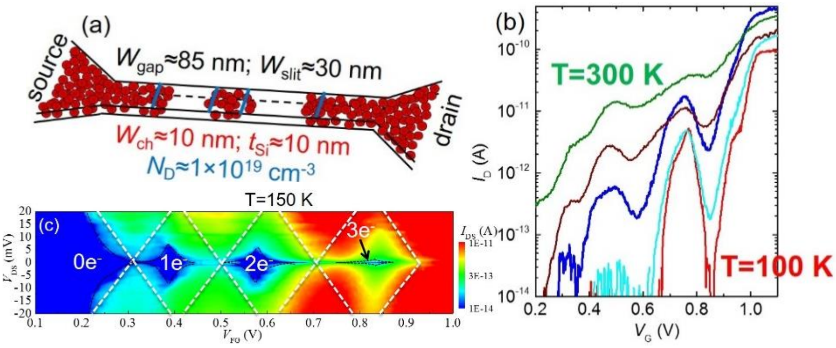

Fig. 2. SET operation at high temperatures via a-few-donor-QD. (a) Nano-FET channel with selectively-doped central cluster. (b) I_D-V_G characteristics as a function of T at elevated temperature; (c) Stability diagrams at T=150 K.

The above approach and preliminary results are encouraging for designing future dopant-based devices using a few coupled donors. The basic trend discussed here can be further enhanced by the effect of nano-structuring the Si channel, providing new guidelines for *dopant-atom electronics*.

References [1] H. Sellier *et al*., Phys. Rev. Lett. **97**, 206805 (2006). [2] G. P. Lansbergen *et al*., Nat. Phys. **4**, 656 (2008). [3] M. Tabe *et al*., Phys. Rev. Lett. **105**, 016803 (2010). [4] M. Fuechsle *et al*., Nat. Nanotechnol. **7**, 242 (2012). [5] E. Hamid *et al*., Phys. Rev. B **87**, 085420 (2013). [6] M. Pierre *et al*., Nat. Nanotechnol. **5**, 133 (2009). [7] A. L. Saraiva *et al*., J. Phys.: Cond. Mat. **27**, 1 (2015). [8] D. Moraru *et al*., Sci. Rep. **4**, 6219 (2014). [9] A. Samanta, D. Moraru *et al*., Proc. Si Nanoelectronics Workshop, Honolulu (2016).