Possible Non-equilibrium Kondo Effect in a Nanocrystalline Silicon Point-Contact Transistor

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1. Introduction

Nanocrystalline silicon (nc-Si) devices are promising candidates for the development of quantum-dot (QD) and single-electron transistors compatible with large-scale integration processes [1]. These devices use nanocrystalline silicon materials where nanometre-scale crystalline silicon grains 'naturally' form large numbers of silicon QDs, isolated by tunnel barriers formed at thin amorphous silicon or silicon oxide grain boundaries. The small grain size leads to large electron-confinement and single-electron charging energies [2].

This paper reports on the observation of non-equilibrium Kondo effect [3, 4, 5] in the characteristics of the electron transport in a 30 nm × 30 nm nanocrystalline silicon point-contact (PC) transistor at a temperature of 4.2 K where a nc-Si QD, acts like a magnetic impurity, couples asymmetrically to source-drain contact regions with semi-free electrons.

2. Device structure

The PC transistors (schematic and SEM, Fig. 1) are fabricated using high resolution electron beam lithography on PMMA resist on 40 nm thick nc-Si film (n-type heavily doped) deposited by LPCVD on 150 nm thick buried SiO_2. This is followed by a reactive ion etching to trench isolate the double side gates from the PC channel. The channel is 30 nm × 30 nm in size and contains a few nc-Si QDs coupled through thin grain boundary layers. We oxidised the devices in dry O_2 gas for 30 minutes at 750°C. This process is used to modify and improve the potential at the grain boundaries [6]. We used the Arhenius plot for one of the PC devices to estimate the average height of the potentials at the grain boundaries as ≈ 20 meV. This low barrier height allows for the strong interaction between the semi-free electrons (e.g. spin ↓ electron in the source, Fig. 2a), in the heavily doped source-drain contact regions, and the localised electrons in a nc-Si QD (e.g. a nc-Si QD with spin imbalance state |↓>, Fig. 1a) in the PC channel, leading to the Kondo effect in nc-Si QD system (Kondo resonance: enhanced density of state at the Fermi level, red line, Fig. 2a).

3. Results and discussion

Figure 2b shows the 3D colour plot of a PC transistor characteristics of the source-drain conductance, dI_{ds}/dV_{ds}, as a function of the source-drain voltage, V_{ds}, and gate 1 voltage, V_{g1}, at gate 2 voltage, $V_{g2} = -3$ V, and at a temperature of 4.2 K. The corresponding 3D line plot is shown in Fig. 3a. Conductance resonances are observed within the Coulomb blockade region (blue region, Fig. 2b). These resonances shift along a diagonal line (dashed white line, Fig. 2b) in the negative V_{ds} range. The inset, Fig. 3a, shows the resonance (black circles) at $V_{g1} = 0$ V and near $V_{ds} = 0$ V, which fits well to a Lorentzian line (red line).

We associate the resonances observed within the Coulomb gap in Fig. 2b and 3a with conductance through non-equilibrium Kondo resonance (e.g. red resonance, Fig. 2a) formed at a nc-Si QD coupled strongly to the biased source contact and less strongly to the grounded drain contact i.e. asymmetrically coupled to the contacts. According to Semmel *et al* [4] and Krawiec *et al* [5], this asymmetric coupling may result in pinning of the Kondo resonance to the source contact, leading to their observed diagonal shift (dashed white line, Fig. 2b) across the Coulomb gap in the negative V_{ds} range. The Kondo temperature, $T_{Kondo} > 45$ K, is estimated from the width at half maxima of the Lorentzian fit (red line, inset, Fig. 3a).

The effect of the asymmetric coupling can also be seen in the I_{ds} v.s. V_{ds} characteristics of the device at temperatures below 4.2 K (Fig. 3b). Here we observe asymmetric current steps and negative differential conductance (NDC) associated with asymmetric coupling of a nc-Si QD to a metallic-like source and semiconductor-like drain. This is further shown in Fig. 3c by the simplified schematic energy band diagram of a single QD with single level and rectangular tunnel barriers.

We notice that, at lower temperatures (< 1 K), all the interesting quantum effects (e.g. NDC and Kondo effects) disappear, and we only observe classical Coulomb blockade characteristics with wider Coulomb gap. This is associated with that when the temperature is lowered, multiple nc-Si QD at the source and drain contacts act as Coulomb blockade charging islands, leading to the domination of single electron charging effects over quantum effects. The effect of the multiple charging nc-Si QD is expected to create difficulties in observing clear temperature dependence of the Kondo resonance (inset Fig. 3a).

4. Conclusion

Resonance peaks are observed at 4.2 K within the Coulomb gap region in the electron transport characteristics of a nanocrsyatlline silicon point-contact transistor. These resonances shift diagonally in the negative range of the source-drain bias, suggesting a non-equilibrium Kondo effect arising from a strong asymmetric interaction between the free electron spins at the contacts and the spin of the localised electrons in a nc-

Si QD. This asymmetric coupling may be manifested by the asymmetric current steps and NDC observed in the characteristics of the current v.s source-drain bias at lower temperatures. The Kondo temperature estimated from the Lorentzian fit of a Kondo resonance is larger than 45 K.

References

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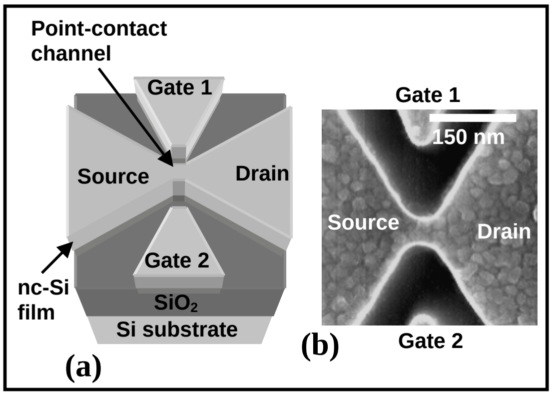

Fig.1 Nanocrystalline silicon (nc-Si) point contact transistor (a) schematic diagram (b) Scanning Electron Micrograph (SEM).

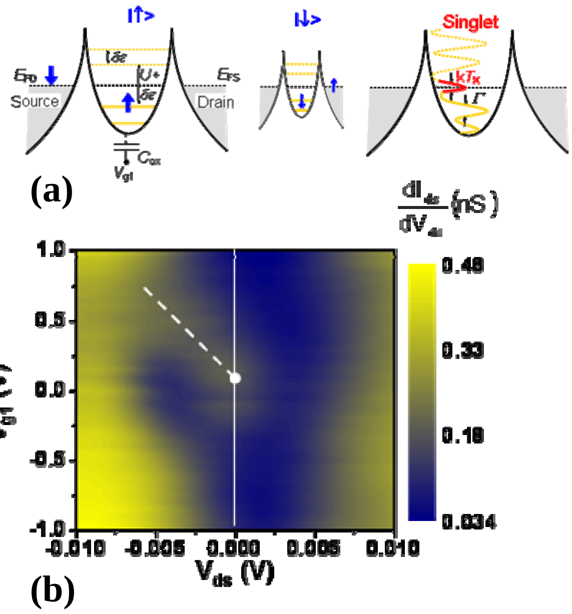

Fig.2 (a) Kondo resonance (red line, singlet state) in a nc-Si QD with parabolic potential (b) A 3D colour plot of a point contact transistor conductance dI_{ds}/dV_{ds} v.s V_{ds} and V_{g1} at V_{g2} = – 3 V and 4.2 K.

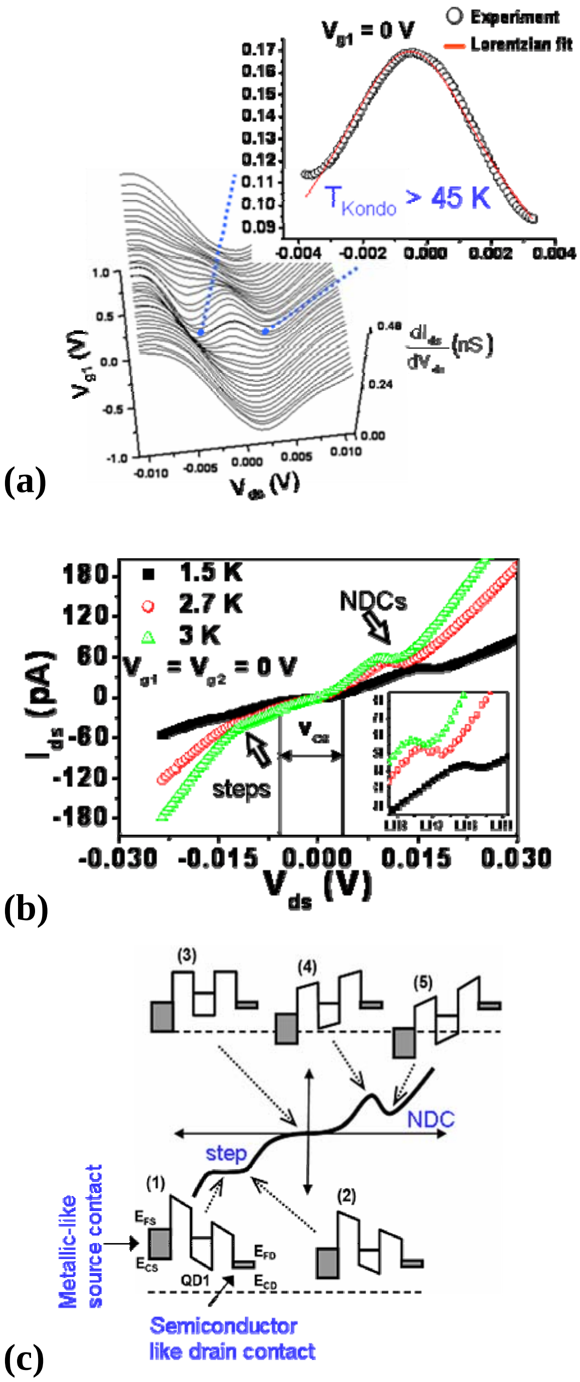

Fig.3 (a) The corresponding 3D line plot of Fig. 2(b). Inset: Lorentzian fit (red line) to the experimental data at $V_{g1} \approx 0$ V. (b) Asymmetric negative differential conductance and current steps in I_{ds} v.s. V_{ds} characteristics at $V_{g1} = V_{g2} = 0$ V. (c) A schematic energy band diagram of a single level QD model coupled asymmetrically to a metallic-like source electrode and a semiconductor like drain electrode. This coupling leads to asymmetric NDC and current step about V_{ds} = 0 V.