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Single-electron transport through a Germanium-Nanowire Quantum Dot

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1. Introduction

In the recent years, mass production of Germanium nanowires (GeNWs) with a diameter of sub-100 nanometers becomes possible by metal-catalyst assisted chemical-vapor deposition (CVD) methods [1]. Ge of the 4th group has, therefore, attracted renewed attentions in better electrical performances of transistor applications due to much higher carrier mobility than that of silicon [2-5]. GeNWs could provide longer electron-spin coherence time than that of III-V group compound [6] because of smaller spin-orbit interactions and even smaller hyperfine interactions. These quasi- one-dimensional GeNWs are further proposed as a leading building block for electron-spin freedom based quantum information processing technology. Moreover, well established semiconductor technologies can be helpful and useful too. Manipulation of an elementary electron-spin can be realized in a single-electron transistor (SET). In this work, we study the development and realization processes of an n-type GeNW SET, which has not received enough attentions, and explore single-electron transport characteristics.

2. Experimental

n-type GeNWs with diameters of 10-50 nm and lengths more than 1 μm were synthesized by the gold catalyst-assisted CVD method. Subsequently, the as-grown GeNWs were suspended in ethanol solution and transferred onto a surface oxidized Si substrate. A GeNW with a diameter of 40 nm was selected to build a transistor. Electron-beam lithography methods following with metal evaporation and lift-off techniques were used to make contacts with the GeNW. The source and drain electrodes (70 nm Ti followed by 30 nm Au) were separated by 200 nm. Prior to the metal evaporation process, the surface of the GeNW was treated by 5 % HCl for 5 min to remove oxide films on the surface as well as to form chloride terminations, which could keep the surface from re-oxidation during exposure to the air [7]. The sample was moved to the next evaporation process right after the surface treatment to avoid unintended re-oxidation. The metal/semiconductor contacts give rise to

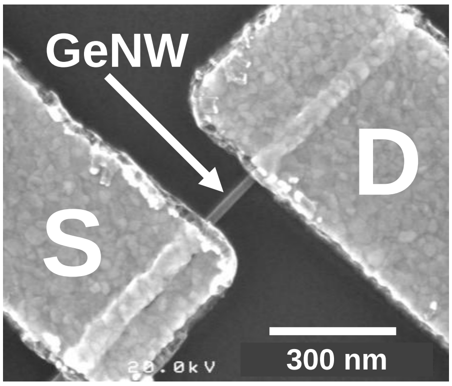

Fig. 1. Scanning electron microscpe (SEM) image of the n-type GeNW single-electron transistor (SET).

Schokkty barriers on the GeNW. The double barriers leave the rest of GeNW as a dot. A scanning electron microscope (SEM) image of a typical device is shown in Fig. 1. The characteristics of single-electron transport across the GeNW were probed by measuring channel current (I_{ds}) as functions of source-drain voltage (V_{ds}) and back-gate voltage (V_g) at milli-Kelvin temperatures.

3. Results and Discussion

The electron transport characteristics were investigated in a linear response region at a mixing chamber temperature of 22 mK. Successive Coulomb oscillation peaks were observed when the V_g was biased from -10 to 10 V. Fig. 2 shows an exampled region from -4.2 to -3.4 V. The result indicates that the GeNW dot was occupied by a lot of electrons. The oscillations feature in equidistant spacing in V_g, and largely varied peak heights in I_{ds}. The average peak spacing (ΔV_g) is 17 mV. The equidistant spacing is similar to that of metallic SETs [8, 9]. On the contrary, the largely varied peak heights are usually observed in a small semiconductor quantum dot (QD) [10], where each peak height varies very much due to the different coupling strength of separated quantum confined energy levels with the source/drain.

A charge stability diagram in the V_g region from -4.29 to -4.13 V is shown in Fig. 3(a). The I_{ds} is suppressed at

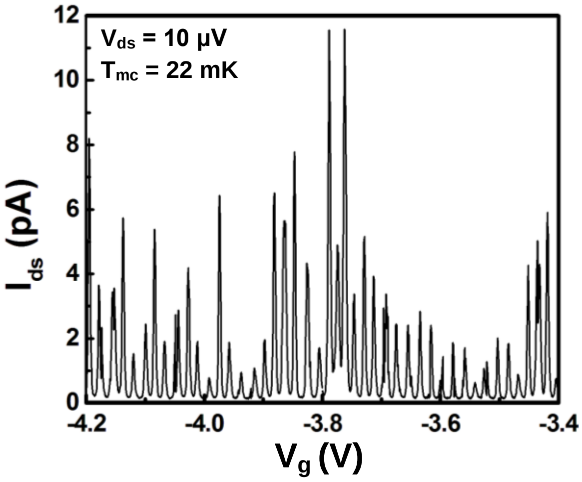

Fig. 2. Coulomb oscillations with back-gate voltages from -4.2 to -3.4 V.

diamond-shaped white regions so called Coulomb diamonds. The V_g locations of coulomb peaks in Fig. 3(b) are accord with meeting points of two adjacent diamonds in Fig. 3(a). From the dimensions of the Coulomb diamonds, the charging energy $E_c=e^2/C_\Sigma$ can be obtained to be 100 μeV, where e is the elementary charge and C_Σ is the total capacitance of the GeNW dot with outside circumstance. The C_Σ is, therefore, calculated to be 1.6 fF. A gate capacitance $C_g=e/\Delta V_g$ can be obtained by 9.4 aF. A gate conversion factor $\alpha \equiv C_g/C_\Sigma$ is calculated to be 5.9×10^{-3}. Source and drain capacitances (C_s and C_d) are obtained to be 1.2 fF and 0.47 fF, respectively, by calculating the slopes of Coulomb-diamond boundaries.

The dimensions of the Coulomb diamonds turns out to be identical, while the coulomb peak heights are largely varied. The characteristics manifest not only classical natures in terms of the equidistant spacing in V_g and the uniform shapes of Coulomb diamonds, but quantum natures in terms of fluctuated amplitude of I_{ds} peaks. In some certain regions, even-odd effects of electron numbers can be observed. To observe much clearer quantum effects so that to control electron-spin freedom, one may need a smaller diameter of GeNWs than 40 nm.

4. Conclusions

A SET using an n-type GeNW with a diameter of 40 nm was fabricated, and electrical characteristics of single-electron transport were probed at milli-Kelvin temperatures. Pronounced Coulomb peaks with the equidistant spacing in V_g were observed. While the Coulomb peak heights were varied very much, the dimensions of Coulomb diamonds were identical. Not only classical natures, but quantum natures are observed in the present device. Further work is desired to scale the GeNW diameter down to allow quantum effects dominate the device performance.

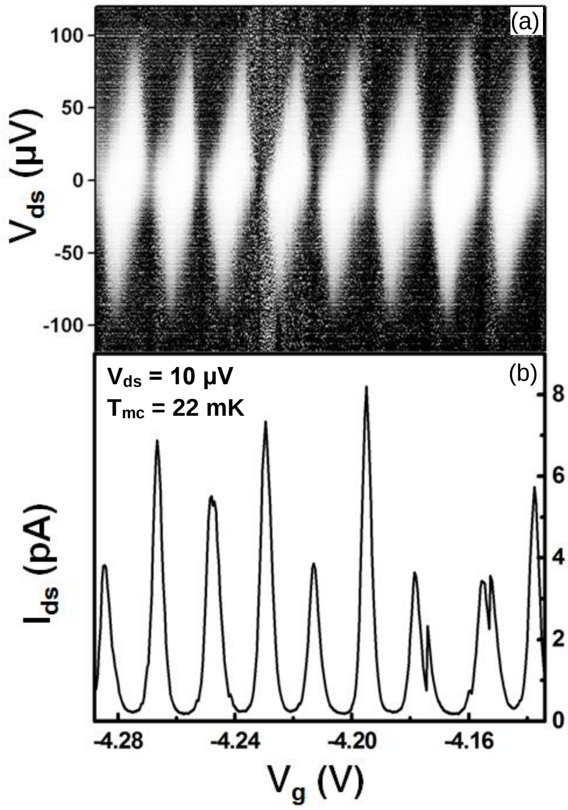

Fig. 3. (a) Charge stability diagram and (b) Coulomb oscillation peaks of the n-type GeNW SET with back-gate voltages from -4.29 to -4.13 V.

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