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Highly Tunable Multiple Quantum Dots Made in InAs Nanowires by Local Finger Gates

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Abstract

We have fabricated locally gated quantum dot devices using single-crystal pure-phase InAs nanowires and investigated their low-temperature transport characteristics. The nanowires are grown by molecular beam epitaxy and the devices are made by placing the grown nanowires with a diameter of 50 nm on top of predefined arrays of Ti/Au finger gates with a period of 80 nm and a line width of 30 nm. Using these finger gates, a single or a multiple quantum dot can be defined in the InAs nanowires. The fabricated devices are characterized by low-temperature transport measurements in a dilution refrigerator. The measurements show that not only the tunneling barriers and the electrical potentials of the dots, but also the coupling strengths between the quantum dots can be tuned flexibly.

1. Introduction

One-dimensional semiconductor InAs nanowires are promising candidates to build quantum dot devices for applications in quantum computation due to their small effective electron mass and large Lander g-factors [1, 2]. The quantum dots can be simply defined in the nanowires by the Schottky barriers induced on the nanowire surfaces by source and drain electrodes or by the tunneling barriers grown in axial InAs/InP heterostructures [3, 4]. However, the height of these tunneling barriers is constant and tunneling processes cannot be manipulated in a wide range to allow these quantum dots to work at desired coupling conditions. Alternatively, underneath finger gate arrays generate strong local electric field to induce local potential barriers in the above nanowire so that offer better controllability [5, 6]. Consequently, high crystal-quality InAs nanowires are desired to ensure reliable homogeneity [7, 8]. In this work, we have successfully fabricated locally gated multiple quantum dot devices based on single-crystal pure-phase InAs nanowires. Single and double quantum dots were demonstrated and corresponding transport characteristics have been investigated.

2. Experiments and Discussions

The InAs nanowires, grown by molecular beam epitaxy (MBE) method, are about 3 to 5 μm long with a diameter of 10~50 nm [7]. Fig. 1(a) shows a representative high resolution tunneling electron microscopy (HRTEM) image of pure-wurtzite-phase InAs nanowires. The InAs nanowires grown along the [0001] direction with a diameter less than ~48 nm are single wurtzite crystals, free from stacking

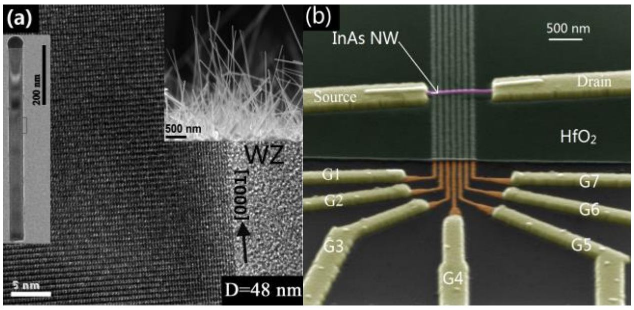

Fig. 1. (a) The HRTEM image of a single-crystal pure-wurtzite-phase InAs nanowire, with a diameter of 48 nm grown on [0001] direction. Insets show SEM image of the InAs nanowires. (b) The SEM image of locally gated InAs nanowire quantum device.

faults and twin defects. The inset shows the scanning electron microscopy (SEM) image of the InAs nanowires grown on the Si (111) substrate. The device fabrication processes relies on standard nanofabrication techniques as followings. (a) Electron beam lithography (EBL) and electron beam evaporation (EBE) are used to obtain Ti/Au finger gate arrays with thickness of 5/15 nm on a Si/SiO_2 substrate. The narrowest width of the finger gate can be down to 25 nm, which ensures us to generate sharp local potential in the nanowires. (b) Windows are opened with EBL on the gate array regions only. (c) A layer of HfO_2 with thickness of 10 nm is deposited by atomic layer deposition method at 90 ^{o}C. (d) Subsequently, an InAs nanowire is transferred onto the opened window region. (e) EBL is used to open source/drain windows at two sides of the nanowire. (f) In order to obtain ohmic contact between metal and nanowire interfaces, the exposed areas are etched in a diluted $(NH_4)S_x$ solution. (g) 5 nm Ti and 90 nm Au are deposited sequently with EBE. A representative SEM image of the final locally gated InAs nanowire device is shown as in Fig. 1(b).

As shown in Fig. 2(a), associating with three left finger gates, we obtain the stability diagram of left single quantum dot at V_{g2} = -1.78 V and V_{g4} = -1.73 V, as shown in Fig. 2(b). The charging energy Ec = 7 meV, total capacitance C_Σ = 22 aF, plunger gate capacitance C_{g3} = 6.6 aF and conversion factor α = 0.3 can be extracted accordingly. Moreover, the excited states marked by the dark dashed lines can be seen going parallel with the diamond boundary. Therefore, a small quantum dot is generated between finger gate G2 and G4 with strong coupling from center plunger gate G3. Both the tunneling barriers and the chemical potential can be tuned intentionally. Indeed, with any three neighboring

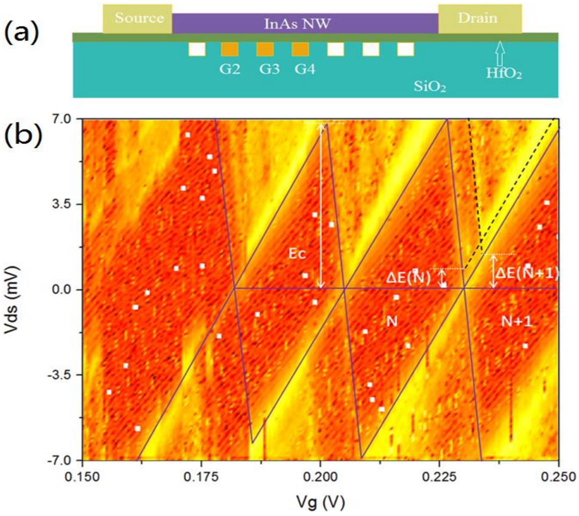

Fig. 2 (a) Left single quantum-dot defined by three finger gates (G2, G3, and G4 in dark yellow color). (b) Stability diagram of the left single quantum dot.

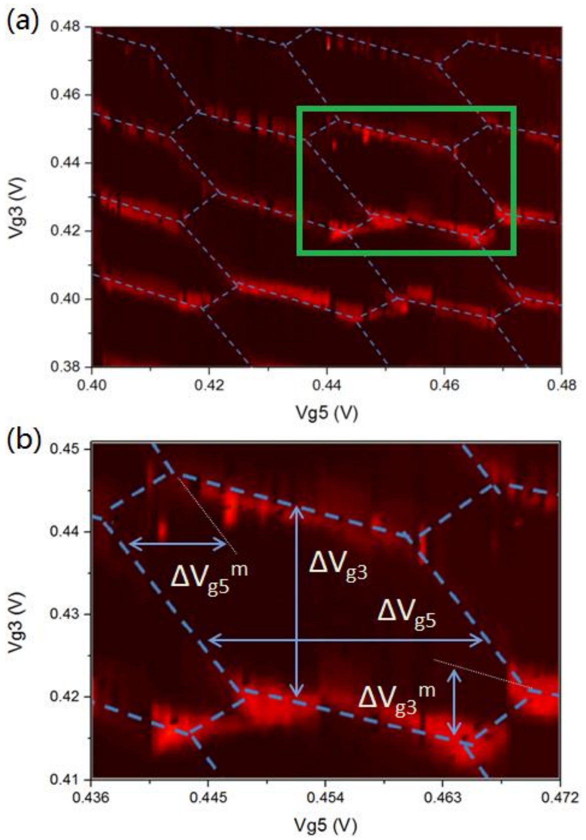

Fig. 3 Double quantum-dots defined by five finger gates (a) Stability diagram with regards to plunger gates of G3 and G5 shows honeycombed regions. (b) Selected honeycomb cell from the green rectangle of (a).

finger gates, we can realize one single quantum dot wherever along the nanowire, indicating satisfied homogeneity of InAs nanowires and flexible controllability of the device. For an example, associating with the finger gates of G4 ~ G6, we realize the right single quantum dot at V_{g4} = -1.3 V and V_{g6} = -1.78 V. The quantum dot shows almost identical charging energy and conversion factor.

The capability of realizing complete controlled quantum dots allows us to generate double quantum dots with five finger gates (G2 to G6). With constant V_{g2} = -1.3 V, V_{g4} = -0.9 V, and V_{g6} = -1.73 V, the stability diagram with regards to plunger gates of G3 and G5 can be obtained, as shown in Fig. 3(a). Clearly, we can identify continuous honeycombed regions, which indicate the coupling between the neighboring quantum dots [9]. From the selected region, as shown in Fig. 3(b), we can extract the mutual capacitance of C_{g3}=7.0 aF, C_{g5}=7.0 aF, C_3=23.3 aF, C_5=23.3 aF, C_m=12 aF, indicating a moderate coupling between two quantum dots. Moreover, it is clear to see that the triple points have grown into triangles with finite bias of 2 mV. Further efforts are dedicated to verify desired flexible controllability of the device by tuning each gate accordingly to allow the series multiple quantum dots to work at certain coupling conditions.

3. Conclusions

We have successfully fabricated locally gated quantum dot devices along single-crystal pure-phase InAs nanowires. Low temperature transport characteristics show that almost identical single quantum dot can be generated in any position of InAs nanowire by tuning underneath finger gates accordingly. Moreover, double-quantum-dots can also be formed along the nanowire with five neighboring finger gates and work on desired tunneling transparency and coupling strength.

Acknowledgements

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References

[1] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89** (2001) 11
[2] M. T. Bjork, A. Fuhrer, A. E. Hanse, M. W. Larsson, L. Samuelson, Phys. Rev. B **72** (2005) 201307
[3] S. Csonka, L. Hofstetter, F. Freitag, S. Oberholzer, C. Schonenberger, T. S. Jespersen, M. Aagesen, and J. Nygard, Nano Lett. 8 (2008) 3932-3935
[4] R. Lorenzo, R. Stefano, P. Alessandro, E. Daniele, S. Lucia, and B. Fabio, Nano Lett. **12** (2012) 4490-4494
[5] K. D. Petersson,C. Fasth, A. Fuhrer, M. T. Bjork, and L. Samuelson, Nano Lett. **5** (2005) 1487-1490
[6] J.W. G. van den Berg, S. Nadj-Perge, V. S. Pribiag, S. R. Plissard, E. P. A. M. Bakkers, S. M. Frolov, and L. P. Kouwenhoven, Phys. Rev. Lett. **110** (2013) 066806
[7] D. Pan, M.-Q. Fu, X.-Z Yu, X.-L. Wang, L.-J. Zhu, S.-H. Nie, S.-L Wang, Q. Chen, P. Xiong, S. von Molnar, and J.-H. Zhao, Nano Lett. **14** (2014) 1214-1220
[8] Q. Li, S.-Y. Huang, D. Pan, J.-Y. Wang, J.-H. Zhao, H. Q. Xu, Appl. Phys. Lett. **105** (2014) 113106
[9] W. G van der Wiel, S. De Franceschi, J. M. Elzerman, T. Fujisawa, S. Tarucha, L. P. Kouwenhoven, Rev. Mod. Phys. **75** (2003) 1