Functional Nano-spin Research Team

Team Leader : Koji Ishibashi

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Spin bottleneck in double quantum dots with different Zeeman splittings

S. M. Huang, et al. Phys. Rev. Lett. In press (2010).

. leEElecron g-factors in III-V semiconductor heterostructures can be tuned by changing its alloy ratio and thickness of quantum well layer. We discuss a novel behavior of a single electron spin in a g-factor-tuned double dot with greatly different Zeeman splittings, giμBB, for each dot in a magnetic field B, where gi (i = 1, 2) is the g-factor of each dot, and μB is Bohr magneton. We investigate this system in a simple, well-defined regime where the total electron number in the double dot is set to exactly zero or one due to Coulomb blockade and single electron tunneling. Accompanying the theoretical calculation, we reveal that the resonant tunneling via two Zeeman-split levels is suppressed even if one pair of Zeeman-split levels is aligned.

The demonstrated g-factor tuning can be powerful tool for coherent manipulation of the electron spins for possible future devices for spin-based quantum information in semiconductor nanostructures, spatially quantum dot. This can be a novel candidate for future spintronic device that works even in a single electron level.

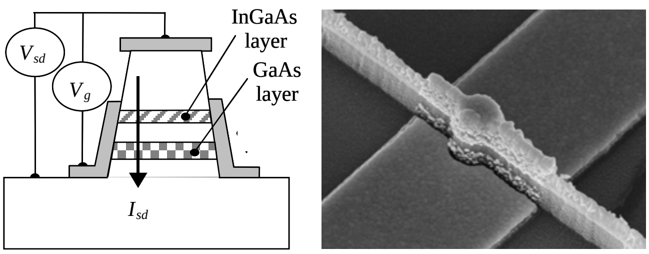


Figure 1: Schematic and SEM image of the device. The g-factor is –0.89 for InGaAs dot, and –0.33 for GaAs dot.

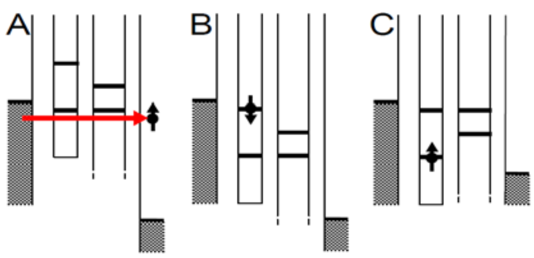


Figure 2: Characteristic potential land-scapes A-C for double dot with different Zeeman splitting. A; the aligned levels for up-spin for both dots is in the transport window and the resonant tunneling current is carried out by up-spin electrons. B; although the up-spin states are aligned and the resonant tunneling channel exists, the resonant tunneling is Coulomb-blocked once the down-spin state in the left dot is occupied. C; the occupation of the up-spin in the left dot prohibits the subsequent tunneling even though the aligned down-spin channel exists.

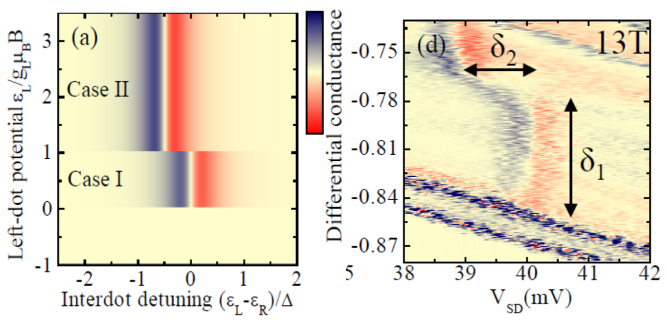


Figure 3: Result of numerical simulation (left) and (Rght) Experimental result; Showing dierential conductance, as a function of VSD and VG under several dierent magneticelds, showing a kink structure characterized by δ1 and δ2..

Microwave-induced zero-resistance states in 2D electrons on helium

D. Konstantinov, K. Kono, Phys. Rev. Lett. 103 (2009) 266808.

We study classical electrons on liquid helium, the cleanest 2D system with the highest electron mobility known in nature. In our experiments, we observe that when electrons are placed in the magnetic field applied normal to the 2D-plane and irradiated with resonant sub-teraherz (~0.1 THz) microwaves [Fig. 1], they exhibit giant oscillations of electrical resistivity [Fig. 2]. Remarkably, these oscillations are accompanied by states with vanishing resistance, which are reminiscent of zero-resistance states observed in the Quantum Hall Effect in the degenerate 2D electron gas (2DEG). We elucidate that the giant oscillations originate from the scattering-assisted transitions of the microwave-excited electrons into the states with a periodic structure caused by the Landau quantization of the electron energy [Fig. 3]. States with vanishing resistance are possibly related to the radiation-induced zero-resistance states observed recently in GaAs/AlGaAs heterostructures.

Our finding provides a unique opportunity to study the phenomena of zero-resistance states in a classical compliment of quantum-degenerate 2DEG in semiconductors. Our studies are also motivated by the potential applications of electrons on helium for quantum information processing and quantum simulation.

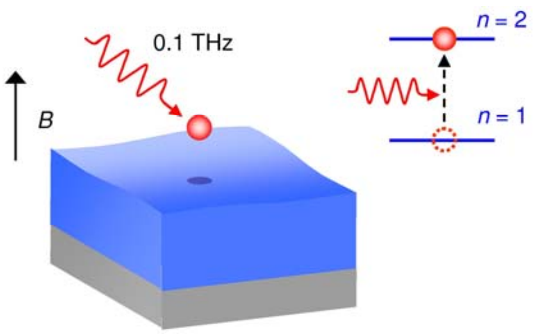


Figure 1: Microwave excitation of electron bound states (index *n*) on liquid helium.

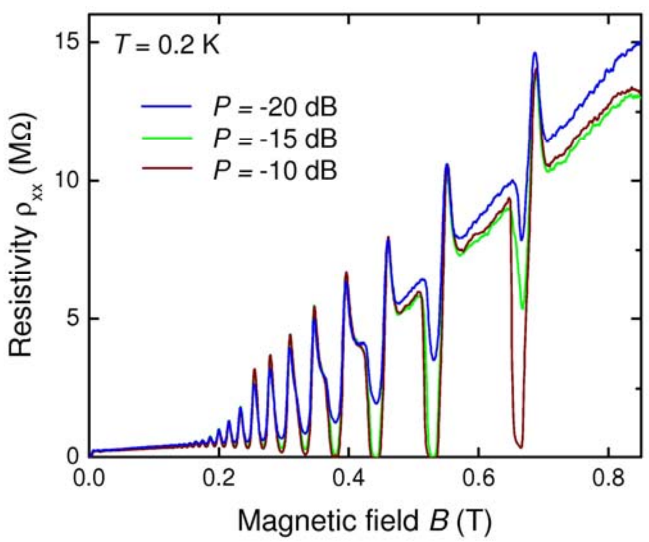


Figure 2: Microwave-induced giant oscillations and zero-resistance states at *T*= 0.2 K and for several values of the radiation power.

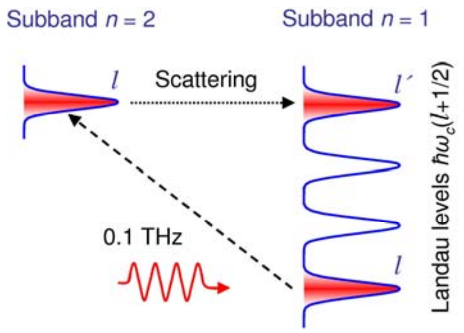


Figure 3: Scattering-assisted decay of microwave-excited electrons into Landau levels of n=1 subband.

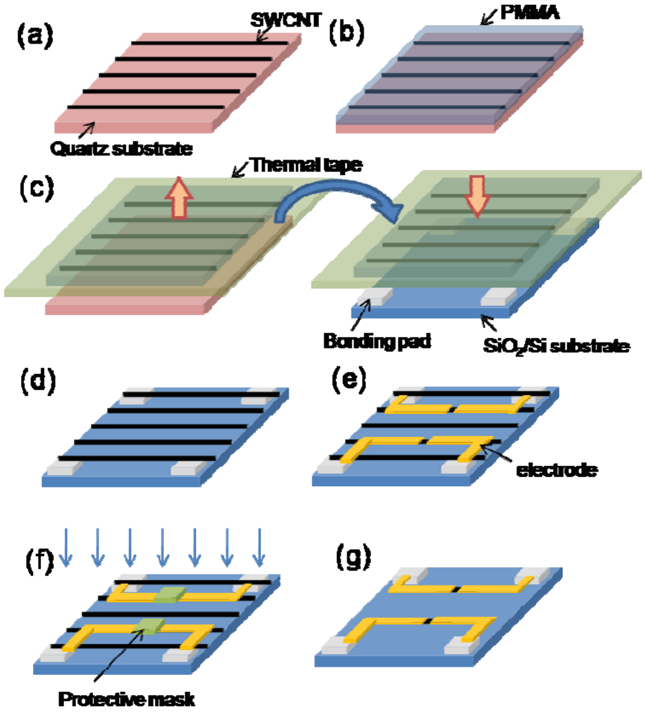
Aligned carbon nanotube growth and transfer-printed technique for integrated nanodevices

H. Tabata et al. Appl. Phys. Lett. 113107, 2009

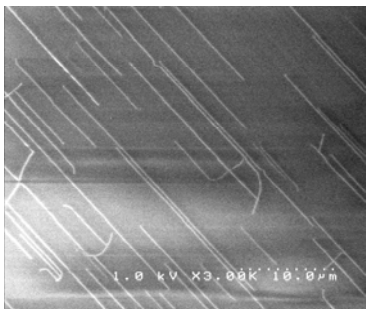
Single-wall carbon nanotubes (SWCNTs) are ideal building blocks of extremely small nanodevices because of their small diameter (~1nm). But, the chirality control and the integration technique are to be developed for practical use of integrated nanodevices. In this work, we have developed the aligned growth technique of SWCNTs that can be transferred to a useful substrate for the electron device fabrication. We have confirmed that the process does not produce serious damages to the SWCNTs, and in fact, succeeded in fabricating single electron transistors from the transferred SWCNTs.

The aligned growth of SWCNTs and their transfer technique will make the simple integrated nanodevice fabrication possible, and we are trying to fabricate the single electron memory that are composed of multi-tunnel junctions, a single electron box that is capacitively coupled to the single electron transistor.

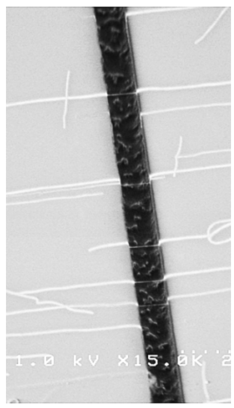
SWCNT transfer process



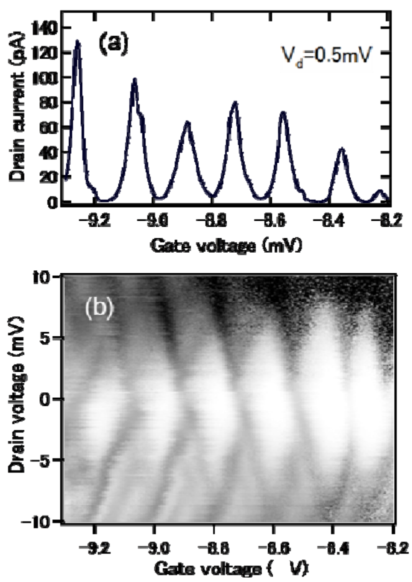
Aligned SWCNTs are grown in the CH4 CVD on a quarz substrate using ferritin as a catalyst. The aligned CNTs are peeled off with PMMA, and transferred to the useful substrate for electrical device fabrication.



Aligned SWCNTs grown on a quarz substrate



transferred SWCNTs to the SiO_2/Si substrate with a groove



Single electron transistor performance at 1.5K fabricated in the transferred SWCNT
(a) Coulomb oscillations
(b) Coulomb diamonds

Si and Ge nanowires as building blocks of quantum dots

Collaboration with NIMS

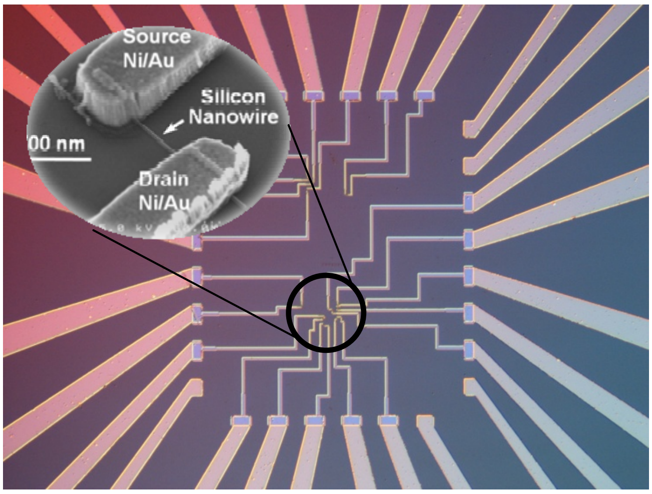
S.Y. Huang, et al. Appl. Phys. Lett. 92, 213110 (2008)

Si and Ge quantum dots are attractive for spin-based quantum nanodevices because of the possible spin coherence. For quantum level to be important, the size of the dot has to be extremely small. To meet the requirement, we have used the self-assembly (VLS) grown nanowires as building blocks of the quantum dots. The quantum dot is formed simply by depositing metallic contacts. The Schottky barriers formed between the semiconductor nanowire and the metal contact serve as tunnel barrier to confine electrons. For the Si, an indication of the quantum nature, the non-uniform peak height distribution, was observed for the diameter of 30nm. The dot did not show the clear indication of the quantum levels in the Coulomb diamonds. For this to occur, the wire width has to be less than 10nm. Our preliminary wires of this width were not conductive, and the device process needs to be improved. On the contrary, the Ge nanowire-dot showed the similar quantum nature for the width of 40nm probably because of the smaller effective mass. Interestingly, the alternating peak distances were observed in some gate voltage range, suggesting the even-odd effect. To confirm the effect, the magnetic field dependence of the peak positions need to be measured.

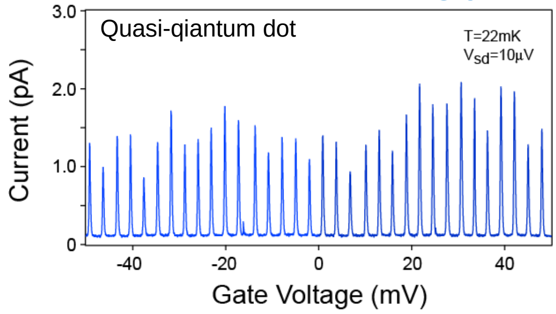
Si and Ge nanowires have proved to be useful for the spin-based quantum-dot devices, such as a spin qubit. The one-dimensional nature of the structure would make the shell structures simple, indicating the realization of the single spin in the quantum dots with many electrons. The reproducibility of the fabrication process is much higher than that of carbon nanoube, an ideal one-dimensional material. But, the wire width of ~10nm is required.

Si Nanowire quantum dots

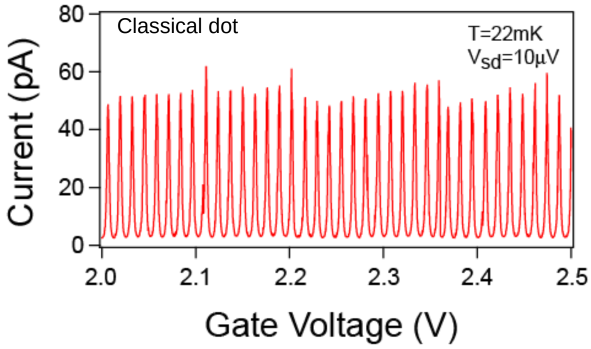
Si Nanowire: Coulomb oscillations for the dot with a wire width of 70nm show the uniform peak height, suggesting the classical nature, while those for the 30nm diameter wire-dot shows non-uniform peak height distribution, suggesting the quasi-quantum nature.



30nm



70nm



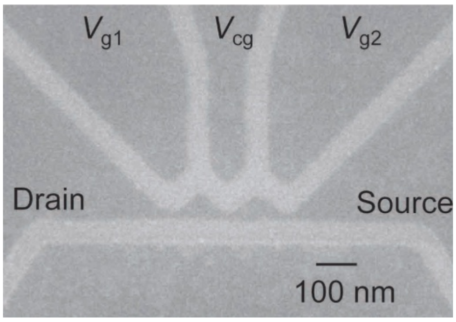
Graphene coupled quantum dots

Collaboration with NIMS

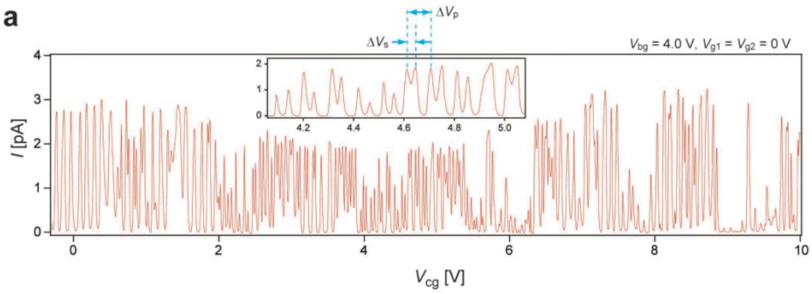
S. Moriyama et al. Nano. Lett. 9, 2891, 2009

Graphene is a sheet of graphite, and can be prepared recently. This material has a high mobility at room temperature, and its band structure is very unique in that it is a zero gap semiconductor with a linear dispersion near the Fermi energy. To use the material for quantum nanodevices is a natural extension of the conventional quantum dot research with semiconductor materials. It is especially attractive for the spin-based nanodevices, such as spin qubit, because a spin is stable in the material due to the fact that the host carbon does not have nuclear spins and the spin-orbit interaction is small. In the present work, in collaboration with Dr. Moriyama et al. of NIMS, we have, for the first time, succeeded in demonstrating the formation coupled quantum dots that are basic structures for the spin and charge qubit. The measured coupled dots are fabricated with a triple-layer of graphene that appears to have a band gap. The data show that the each dot is controlled by the adjacent gate voltage and the coupling between the dots are controlled by the center gate that separates the two dots.

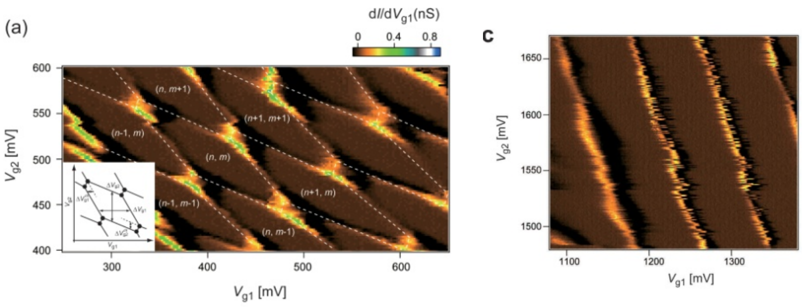
The present results indicate a feasibility of the graphene for the dot-based devices. Unfortunately, the clear indication of the effect of confined levels has not been observed. The techniques developed in the work are useful also for graphene based nanotransistor as well as quantum nanodeivces.



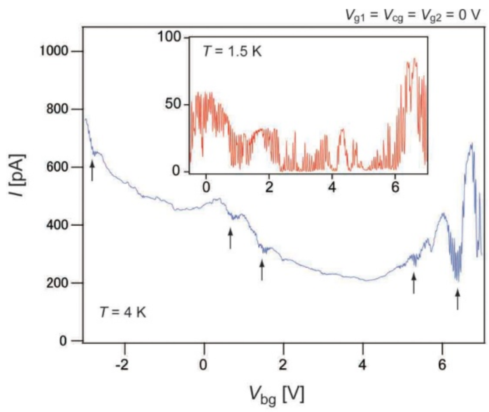
SEM image of the coupled dots: Coupled dots are fabricated by etching



Center gate voltage dependence of the current. Coulomb oscillations are observed. Inset: In the specific gate voltage range, the peak pairs are observed, suggesting the coupling between the two dots.



Current as function of left and right gate voltages (V_{g1} and V_{g2}) The strength of the coupling is controlled by the center gate voltage (left) coupled condition (right) two dots are merged into single dot.



Gate voltage dependence of the current at liquid He temperature. Ambipolar characteristic indicating the band gap is observed