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Detection of nuclear spin signals from a quantum dot under Kondo effect regime

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1. Introduction

Electron spins in GaAs-based semiconductor devices can interact with their nuclear spin environment via the hyperfine interaction. The hyperfine interaction allows building a dynamic nuclear spin polarization when the population of electron spins is driven out of equilibrium [1]. The resultant change in the nuclear spin polarization can be detected through the electron transport measurements under special conditions of the electronic systems, such as spin-phase transition points in fractional quantum Hall systems [2], breakdown regimes of odd-integer quantum Hall systems [3], or spin-blockade regimes in coupled quantum dot systems [4]. Combination of the dynamic nuclear spin polarization and the resistive detection technique of nuclear spin signals has made it possible to detect nuclear magnetic resonance (NMR) signals from the small amount of nuclear spins involved in semiconductor nano-scale devices. Recently, these techniques are used to determine non-trivial spin configuration arising from electron correlation in fractional quantum Hall systems [5].

Quantum dot (QD) systems have also provided experimental platforms for the studies of many-body effects, for example the Kondo effect [6-8]. NMR studies have a potential to reveal magnetic properties arising from the many-body effects in an individual QD. However, the small number of nuclear spins involved in a single QD makes it difficult to detect NMR signals from a single QD.

In this paper, we report that the differential conductance spectra of a single QD under the Kondo effect regime can be employed to detect nuclear spin signals from the QD. We find that the differential conductance spectra exhibit remarkable hysteresis loops under magnetic fields due to the dynamic nuclear spin polarization. The involvement of nuclear spins to the hysteresis is unambiguously confirmed by the detection of NMR signals by monitoring the differential conductance.

2. Methods

The Kondo effect in a QD appears as enhanced conductance through the QD [6-8]. The application of a bias voltage V_{sd} between the source and drain electrodes suppresses the differential conductance, forming a sharp differential conductance peak at $V_{sd} = 0$. When an external magnetic field B is applied, the differential conductance spectrum splits into two peaks with a voltage gap $V_{p\text{-}p}=2g^*\mu_B B$, where g* is the effective g-factor for electron spins and μ_B is the Bohr magneton.

In the presence of non-zero average nuclear spin polarization, the hyperfine interaction produces an effective magnetic field B_N for electron spins. The effective magnetic field modifies the voltage gap between the differential conductance peaks $V_{p\text{-}p}=2g^*\mu_B(B+B_N)$. The change in the voltage gap is reflected in differential conductance measurements under a fixed working bias voltage on the slope of the differential conductance peaks, where a small change in the Zeeman energy induces a large variation in the differential conductance. We use this technique to detect nuclear spin signals from a single QD.

We prepared QDs using split-gate devices following the strategy in Ref [9]; QDs form occasionally in split-gate devices near the pinch-off conditions in the presence of disorder. The devices were fabricated on a wafer of GaAs/$Al_{0.3}Ga_{0.7}As$ single heterostructure with a two-dimensional electron gas at the interface. The carrier density and the mobility of the wafer are 2.3 x 10^{15} m^{-2} and 17 m^2/Vs, respectively. The Ti/Au split-gate electrodes were defined using the electron-beam lithography. The devices were cooled using a dilution refrigerator. Magnetic fields were applied parallel to the plane of two-dimensional electron gas. The differential conductance measurement was conducted using a standard lock-in technique with an excitation voltage and a frequency of 10 μV and 18 Hz, respectively.

3. Results and discussion

One of the devices exhibits behaviors typical to the Kondo effect in a QD [6-8]. An increase in the conductance with decreasing temperature and a pronounced zero-bias conductance peak are observed at B = 0.00 T. When a magnetic field B is applied, the differential conductance peak is suppressed and splits above B = 1 T. The voltage gap $V_{p\text{-}p}$ between the spilt conductance peaks almost agrees with the theoretically expected values of $2g^*\mu_B B$ [10].

As shown in Fig. 1, the differential conductance spectrum exhibits a remarkable hysteresis loop in each magnetic field except for B = 0.00 T when the bias voltage was scanned positively and negatively at a rate of 5μV/s. The presence of hysteresis in the transport coefficient suggests that the nuclear spins are dynamically polarized during the scan of V_{sd} [2-4]. The hysteresis loops appear in a particular range of V_{sd} and V_g between the differential conductance peaks and in the Coulomb valley where the Kondo effect

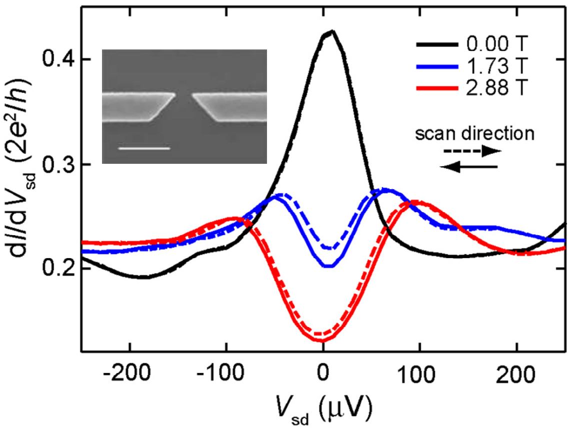

Fig. 1 Dependence of the differential conductance dI/dV_{sd} on V_{sd} at V_g = -0.66 V under magnetic fields B = 0.00 T, 1.73 T, and 2.88 T. The dI/dV_{sd}-V_{sd} curves are obtained by scanning V_{sd} in the positive (dashed curves) and negative (solid curves) directions at a rate of 5 μV/s at temperature T = 30 mK. The inset shows a micrograph of the split-gate device. Scale bar defines 1 μm.

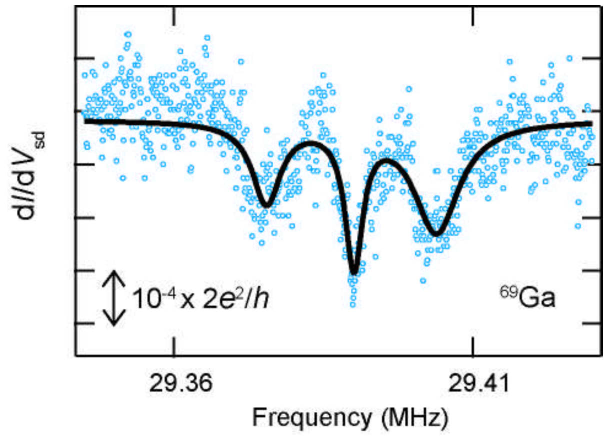

Fig. 2 Dependence of dI/dV_{sd} on the frequency of the radio-frequency magnetic field obtained at (V_g, V_{sd}) = (-0.65 V, -40 μV) and B = 2.88 T. The black curve is the Lorentzian fitting result. The value of dI/dV_{sd} decreases at the NMR frequency of ^{69}Ga (gyromagnetic ratio γ = 64.21 MHz rad/T). The splitting of the spectrum is attributed to the quadrupole interaction of the nuclei.

occurs. The integrated intensity of the hysteresis increases with increasing B and becomes saturated above B = 2 T. With increasing temperature T, the integrated intensity of the hysteresis decreases and almost disappears at around T = 360 mK.

When the gate and bias voltages are rapidly changed under B = 2.88 T from the pinch-off condition to the differential conductance peak at (V_g, V_{sd}) = (-0.65 V, -40 μV), the value of the differential conductance keeps increasing over 150 s. The characteristic time for the slow increase in dI/dV_{sd} is in the same order as that for the dynamic nuclear spin polarization reported in GaAs-based devices [2, 3]. The slow increase in dI/dV_{sd} also suggests the occurrence of the dynamic nuclear spin polarization in the QD.

Relevance of nuclear spins to the hysteretic dI/dV_{sd} spectra is unambiguously confirmed by the following NMR measurement. Continuous waves of radio-frequency (rf) magnetic field are applied using a single-turn coil wound around the device. With scanning the frequency of the rf-field, the value of dI/dV_{sd} decreases at the NMR frequency of ^{69}Ga, as shown in Fig. 2. The NMR spectra of ^{75}As and ^{71}Ga are also obtained by monitoring dI/dV_{sd}. The observation of the NMR spectra indicates that the hysteresis and the slow increase in dI/dV_{sd} originate from the dynamic nuclear spin polarization in the QD. These results show that the differential conductance under the Kondo effect regime is sensitive to the change in the nuclear spin polarization.

4. Conclusions

We find the hysteresis loops in the dI/dV_{sd} spectra and the slow increase in dI/dV_{sd} in the single QD under the Kondo effect regime. The relevance of nuclear spins to the hysteresis is confirmed by the detection of NMR signals via the differential conductance measurement. Our observations indicate that the differential conductance of the Kondo effect can be employed for the resistive detection of nuclear spin signals. We believe that this newly developed technique of resistively-detected NMR has a potential to uncover non-trivial spin properties arising from the Kondo effect in a single QD.

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