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# Electrically Driven Dynamic Nuclear Spin Polarization in Single Quantum Dot

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**Abstract**

**Electrically driven dynamic nuclear spin polarization is studied in a single quantum dot (QD) under magnetic fields. Nuclear spins in the QD are dynamically polarized by transmitting an electric current through the QD. The resultant nuclear spin magnetic field is measured by monitoring the differential conductance of the QD. Examining the bias and gate voltage conditions to polarize nuclear spins, we find that the co-tunneling process of electron transport through the QD is relevant to the nuclear spin polarization.**

## 1. Introduction

Nuclear magnetic resonance (NMR) is a widely used technique to study spin-related phenomena in condensed matter physics[1]. Hyperfine interaction between electron spins and nuclear spins makes it possible to study static and dynamic aspects of electron spins by means of the NMR measurements. However, because of poor sensitivity of the standard NMR technique, it was difficult to study spin properties of semiconductor nano-scale devices by the NMR measurements.

Recently developed techniques of resistively-detected NMR (RDNMR) are so sensitive to the changes in nuclear spin polarization that they have opened a way to study spin properties in semiconductor nano-scale devices[2-6]. For example, electron spin polarizations are determined in quantum Hall systems from the Knight shift of NMR spectra[5]. The RDNMR is demonstrated recently in a single quantum dot (QD) under the Kondo effect regime[6] and is anticipated to uncover spin properties in a single QD. One of the key techniques to realize RDNMR is electrically-driven dynamic nuclear spin polarization (DNSP), which drives population of the nuclear spins out of thermal equilibrium by transmitting electric current through the QD. However, the mechanism or the required conditions for the DNSP is still elusive.

In this paper, we report the electrically-driven dynamic nuclear spin polarization in a single QD. The bias and gate voltage dependence of the nuclear spin magnetic field $B_N$ created by the DNSP is studied systematically. The value of the differential conductance $dI/dV_{sd}$ of the QD changes as the DNSP develops. The change gives a measure of $B_N$. By investigating the source-drain voltage $V_{sd}$ and gate voltage $V_g$ conditions to create DNSP, we obtain a map of $B_N$ as a function of $V_{sd}$ and $V_g$. We find that the nuclear spins are polarized effectively in the co-tunneling regimes of Coulomb blockade with an odd number of electrons in the QD.

## 2. Experimental

Quantum dots were prepared using a wafer of $GaAs/Al_{0.3}Ga_{0.7}As$ single hetero structure with a two-dimensional electron system (2DES) at the interface. The carrier density and mobility of the 2DES are $n = 2.3 \times 10^{15}$ $m^{-2}$ and $\mu = 17$ $m^2/Vs$, respectively. The QDs were formed using split-gate devices, following the approach in Ref. [7]. Because of disorder in the wafer, QDs were formed accidentally at the constriction part as the gate voltage approaches the pinch-off conditions. The devices were cooled down to 30 mK using a dilution refrigerator and magnetic fields $B$ were applied parallel to the 2DES plane using a superconducting solenoid. A standard lock-in technique was employed to measure the differential conductance under application of the source-drain voltages. Typical excitation voltage and the frequency were 10 μV and 18 Hz, respectively. The data presented in this paper are from the same split-gate device used in the previous study [6] but from a different cool down.

## 3. Results and Discussion

Figure 1(a) shows dependence of $dI/dV_{sd}$ on $V_{sd}$ at $B = 3$ T and $V_g = -0.490$ V obtained by scanning $V_{sd}$ at a rate of 5 μV/s in the positive and negative directions. Remarkable hysteresis is seen in the $V_{sd}$ range of $-100$ μV $< V_{sd} < +100$ μV. Similar hysteresis is seen at other gate voltages. The region where the hysteresis appears is summarized in Fig. 1(b) which plots the amplitude of the hysteresis $\Delta(dI/dV_{sd})$ defined as a difference in $dI/dV_{sd}$ between the positive and negative scans of $V_{sd}$. The hysteresis is remarkable in the $V_g$ range of $-0.495$ V $< V_g < -0.465$ V, where Kondo effect is seen at $B = 0$ T. The value of $dI/dV_{sd}$ increases gradually over a period of 100 s when $V_g$ is changed instantaneously from the pinch-off condition to $V_g = -0.475$ V where the hysteresis appears. Under irradiation of radio-frequency magnetic field $B_{rf}$, the value of $dI/dV_{sd}$ decreases when the frequency of $B_{rf}$ matches the nuclear magnetic resonance frequencies of $^{69}Ga$. Therefore the origin of the hysteresis and the slow increase in $dI/dV_{sd}$ is attributed to the DNSP in the QD[6].

The hysteresis shown in Fig. 1(b) is affected not only by the nuclear spin magnetic field $B_N$ but also by other factors such as the sensitivity of $dI/dV_{sd}$ to the change in $B_N$, the decay rate of nuclear spin polarization, and the scan rate

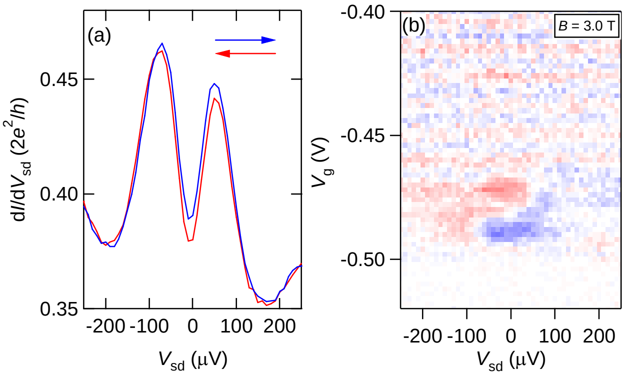


Fig. 1 (a) Dependence of d$I$/d$V_{sd}$ on $V_{sd}$ under a magnetic field $B$ = 3 T and $V_g$ = -0.490 V obtained by scanning $V_{sd}$ at a rate of 5 μV/s in the positive and negative directions. (b) Color-scale plot of the hysteresis Δ(d$I$/d$V_{sd}$) plotted as a function of $V_{sd}$ and $V_g$. The hysteresis Δ(d$I$/d$V_{sd}$) is defined as the difference in d$I$/d$V_{sd}$ between the positive and negative scans of $V_{sd}$.

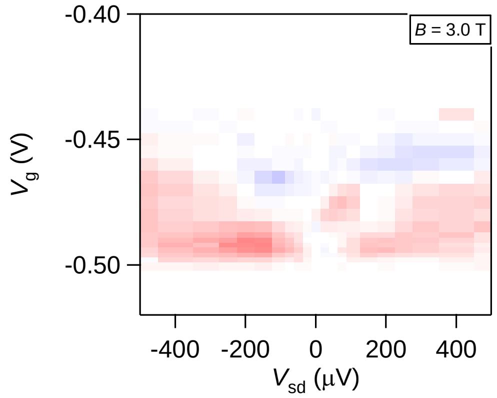


Fig. 2 (a) Color-scale plot of the relative amplitude of $B_N$ measured by the pump and probe measurement described in the main text. The data were taken at $B$ = 3.0 T. The red (blue) color represents negative (positive) $B_N$.

of $V_{sd}$. Therefore, to understand the mechanism for the DNSP, it is necessary to investigate the dependence of $B_N$ on $V_{sd}$ and $V_g$. To obtain such a dependence of $B_N$, we perform a pump and probe measurement as described below. First, nuclear spin polarization is relaxed by waiting for 900 s under the pinch-off condition. Then, the voltages are changed instantaneously to a set of voltages ($V_{sd,\ pump}$, $V_{g,\ pump}$) and wait there for 600 s to polarize nuclear spins. Finally, measure the value of d$I$/d$V_{sd}$ at ($V_{sd,\ read}$ =0 μV, $V_{g,\ read}$ = -0.482 V). The difference between the values of d$I$/d$V_{sd}$ with and without the nuclear spin polarization gives a measure of $B_N$. Because the value of d$I$/d$V_{sd}$ decreases with increasing $B$, the decrease (increase) in d$I$/d$V_{sd}$ correspond to positive (negative) $B_N$.

Figure 2 shows the result of the pump-probe measurement at $B$ = 3.0 T. The red- and blue-colored regions correspond to negative and positive $B_N$, respectively. The amplitude of $B_N$ is large in the gate voltage range of -0.500 V < $V_g$ < -0.450 V where the number of electrons in the QD is odd, while the amplitude of $B_N$ is negligibly small at the gate voltages $V_g$ > -0.450 V where the number of electron in the QD is even. Although the positive $B_N$ are seen under certain conditions, the negative $B_N$ is dominant as a whole.

At the gate voltages -0.500 V < $V_g$ < -0.48 V, the amplitude of $B_N$ is small in the range of -50 μV < $V_{sd}$ < +50 μV, suggesting that there is a threshold of the source-drain voltage for the DNSP. The energy range of the DNSP suppression region is close to the twice the Zeeman energy assuming a bulk g-factor of GaAs g = -0.44. The DNSP suppressed region around $V_{sd}$ = 0 μV becomes narrow with decreasing magnetic field $B$. When the energy difference between the source and drain electrodes is smaller than the Zeeman energy, the electron transport via co-tunneling process is suppressed. But the co-tunneling process becomes allowed when the bias voltage exceeds the Zeeman energy. Our observation suggests that the electron co-tunneling process through a spin-polarized QD is relevant to the DNSP in the QD.


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