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Gate voltage dependence of nuclear spin relaxation in an impurity-doped semiconductor quantum well

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We investigated the gate voltage dependence of the nuclear spin relaxation in a Schottky-gated $n$-GaAs/AlGaAs (110) quantum well by the time-resolved Kerr rotation measurement combined with the nuclear magnetic resonance technique. The Fermi contact hyperfine interaction is enhanced by decreasing the background electron density, as the electrons become localized at impurity site. The energy relaxation time $T_1$ and the decay time of the Rabi oscillation $T_{2\text{Rabi}}$ can be controlled by more than a factor of 10 and a factor of $\sim 2$, respectively. © 2010 American Institute of Physics. [doi:10.1063/1.3309687]

Nuclear spin dynamics in semiconductors have recently been studied with the use of nuclear magnetic resonance (NMR) techniques which have higher sensitivity and spatial resolution compared with the conventional NMR technique by utilizing optical and electrical detection and manipulation. For the study of local nuclear spin dynamics, semiconductor devices have an advantage of gate-controllability of the density and distribution of electrons. In our previous work, we demonstrated a gate-control of dynamic nuclear polarization (DNP), which is drastically enhanced when the background two-dimensional electron (2DE) density $n$ is reduced from the metallic to the insulating phase. In this work, we studied the $n$-dependence of energy relaxation time ($T_1$) and the decay time of the Rabi oscillation ($T_{2\text{Rabi}}$) of nuclear spins in a gated $n$-GaAs/AlGaAs (110) quantum well (QW) structure. We found that the relaxation of nuclear spins is rather enhanced by reducing $n$ in the $n$-doped QW, which is different from the case of high-mobility 2DE system reported in Ref. 12, possibly due to the enhanced Fermi contact hyperfine interaction between nuclear spins and electron spins localized in the impurity-doped QW.

The sample we studied here was a 10 nm $n$-GaAs/Al$_{0.4}$Ga$_{0.6}$As (110) single QW doped with $5 \times 10^{10}$ cm$^{-2}$ Si. We made InSn-alloyed ohmic contacts and a semitransparent Au Schottky gate to apply gate voltage $V_g$ between the top and 2DE. $n$ was examined by the Hall measurement. Figure 1 shows the $V_g$-dependence of $n$ measured at 77 K after the irradiation of light as follows: the electrons in the QW are completely depleted at $V_g \sim -4$ V. The sample was set in a cryostat with a superconducting magnet. The energy relaxation time $T_1$ and the decay time of the Rabi oscillation $T_{2\text{Rabi}}$ can be controlled by more than a factor of 10 and a factor of $\sim 2$, respectively. © 2010 American Institute of Physics. [doi:10.1063/1.3309687]

\begin{align}
\theta_K = C \exp(-\Delta t/T_{2e})\cos(2\pi\nu_L\Delta t),
\end{align}

where $C$ is the constant. $\nu_L$ can be approximated by $g\mu_B(B_0+B_g)/\hbar$, where $g$ is the electron g-factor, $\mu_B$ is the Bohr magneton, $B_0$ is the nuclear magnetic field, and $\hbar$ is the Planck’s constant. We first measured the $V_g$-dependence of $\theta_K$ with and without DNP to examine the degree of the hyperfine interaction. Figure 2(b) shows the $V_g$-dependence of $\nu_L$ measured by using circularly polarized pump beam ($\nu_{1\text{circ}}$) and alternating left- and right-circularly polarized pump beam through a photo elastic modulator ($\nu_{1\text{PEM}}$). The difference between $\nu_{1\text{circ}}$ and $\nu_{1\text{PEM}}$ reflects the magnitude of DNP ($B_0$). When $V_g < -3$ V ($n < 1 \times 10^{11}$ cm$^{-2}$), $B_0$ is increased, indicating that DNP is enhanced by reducing $n$. When $V_g$ is further decreased from $-4$ to $-5$ V, $\nu_L$ turns out to be saturated.

In Fig. 2(c), $T_{2e}$ is shown as a function of $V_g$. $T_{2e}$ has a maximum value at $V_g = -2.2$ V. When further negative $V_g$ is

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applied, $T_{2e}^*\text{c}$ becomes shorter mainly due to the enhanced hyperfine interaction. When $n$ is decreased, the electrons are localized in a disordered potential with donor impurities, resulting in the enhancement of the hyperfine interaction as described below. When $V_g > -2.2$ V, on the other hand, $T_{2e}^*\text{c}$ becomes shorter as the electron spin relaxation due to the D'yakonov–Perel' mechanism is enhanced with the increase in their kinetic energy.\(^\text{11}\)

Next, we studied the nuclear spin relaxation time as a function of $V_g$. Figure 3(a) shows schematically the method to measure $T_1$ by TRKR detection. First, we pump spin-polarized electrons with circularly polarized light for a time enough to saturate the nuclear polarization with applying $B_0$ at $V_g = -5$ V (at which DNP is most enhanced). Then, a mechanical shutter placed on the paths of both pump and probe beams is closed at a fixed $V_g$. Then, we open the shutter again after an interval $t_{close}$ and detect the change of the Kerr

rotation angle $\Delta \theta_K$, which changes linearly to a good approximation with the degree of the depolarized nuclear spins by setting $\Delta t$ appropriately. In Fig. 3(b), we show $\Delta \theta_K$ measured at $V_g = -3$ V as a function of $t_{close}$. These curves can be fitted by a single exponential decay function, from which we evaluated $T_1$. In Fig. 3(c), $T_1$ is shown as a function of $V_g$. When $V_g$ is decreased from 1 to $-4$ V, $T_1$ becomes shorter by more than a factor of 10. This indicates that when $n$ is decreased from the metallic to the insulating phase, the nuclear spin relaxation due to the hyperfine interaction with localized electrons becomes enhanced.\(^\text{11}\) When $V_g$ is further decreased from $-4$ to $-5$ V, however, $T_1$ slightly recovers. This reveals the reduction in the effect of the hyperfine interaction due to full depletion of the electrons.

Now we estimate the minimum $T_1$ on the assumption that the fluctuation field of electron spins governs the nuclear spin relaxation.\(^\text{11,13}\) When the electrons are localized at a donor impurity potential, we can estimate $T_1$ from

$$\frac{1}{T_1(\tau)} \equiv \frac{\Gamma}{2}[\gamma b_e(0)]^2 \tau_c \exp(-4r/a_0) \tag{2}$$

with $r \equiv a_0$, where $\Gamma$ is the degree of electron occupation of the donor site, $\gamma$ is the nuclear gyromagnetic ratio, $\tau_c$ is the correlation time, $r$ is the distance from impurity, $a_0$ is the Bohr radius, and $b_e(0)S$ ($S$ is the electron spin) represents the electron magnetic field at an impurity center.\(^\text{13}\) Assuming that the electrons are completely localized at $V_g \sim -3.5$ V from Fig. 3(c), $\Gamma = 0.1$ from Fig. 1, and $a_0 \equiv 10$ nm (Ref. 13). The electron spin relaxation time $T_1$ is typically nanosecond order; then, $\tau_c$ is nanosecond order here. We employed the following \(^\text{13}\) As parameters because all species of nuclei have the same order of $\gamma b_e(0)$ as follows: $\gamma = 45.81$ Mrad/T s (Ref. 1) and $b_e(0) \equiv 0.022$ T (Ref. 13). Calculated $T_1$ is of the order of 10 s in good agreement with the experiment. With increasing $n$, the wave functions of electrons extend and be delocalized, resulting in longer $T_1$.

Finally, we discuss the $n$-dependence of $T_{2Rabi}$ obtained by employing TRKR detection of pulse NMR\(^2\) at $T = 3.5$ K. In the present work, we investigated quadrupolar-split \(^\text{12}\) As as a target nucleus. Figure 4(a) shows the TRKR-detected cw-NMR spectrum of \(^\text{12}\) As at $V_g = -5$ V. The data was taken by measuring $\theta_K$ with changing the frequency of the rf magnetic field $B_{1\text{f}}$ at fixed $\Delta t$ and constant $B_0 = 0.734$ T. $B_{1\text{f}}$ was applied to the [110] direction of the sample by a split-coil. By setting the frequency of $B_{1\text{f}}$ at the center of three resonance lines (5.370 MHz), we obtained Rabi oscillations by detecting $\Delta \theta_K$ after application of a $B_{1\text{f}}$ pulse with pulse duration $t_{p\text{ulse}}$. Then, we set $V_g = -5$ V during initialization, and changed $V_g$ to an arbitrary value during the application of the $B_{1\text{f}}$ pulse with the shutter closed. In Fig. 4(b), the Rabi oscillation is shown by the change of $\theta_K$ at $V_g = -3$ V. We obtained the $T_{2Rabi}$ for the single-photon resonance by

$$\Delta \theta_K = A[1 - \exp(-t_{p\text{ulse}}/T_{2Rabi}) \cos(2\pi v_t/pulse)] \tag{3}$$

where $A$ is the constant, and $v_{\text{Rabi}}$ is the frequency of the Rabi oscillation. $T_{2Rabi}$ provides an indication of the effective coherence time of nuclear spins $T_{2e}^*$.\(^\text{2}\)

In Fig. 4(c), $T_{2Rabi}$ is shown as a function of $V_g$. $T_{2Rabi}$ has almost the same $V_g$-dependence as $T_1$. $T_{2Rabi}$ takes the minimum value at $V_g = -4$ V and recovers in the range $-5 < V_g < -4$ V, revealing that the hyperfine interaction

![FIG. 2. (Color online) (a) The TRKR signal $\theta_K$ measured at $T = 3.5$ K, $B_0 = 0.734$ T and $V_g = -3$ V is shown as a function of the pump-and-probe delay $\Delta t$. (b) Gate voltage $V_g$ dependence of the Larmor frequency of photoexcited electron spins $\nu_1$ with and without the nuclear magnetic field $B_0$. (c) $V_g$ dependence of the effective coherence time of photoexcited electron spins $T_{2e}^*$.](https://aplu.aip.org/about/rights_and_permissions)
works most effectively with the electrons localized, and gets weaker as the electrons are fully depleted. However, $T_{2\text{Rabi}}$ has a different dependence from $T_1$ at $-2\,V \leq V_g \leq 1\,V$. We can qualitatively explain this dependence in terms of the dipole-dipole interaction among nuclear spins in the following way. The nuclear spins feel different local fields from each other. They precess either faster or slower than the average by different local $B_n$, which results in the dephasing of the ensemble spins. When the hyperfine interaction is suppressed and $T_1$ become longer at $-2\,V \leq V_g \leq 1\,V$, the nuclear spins feel nuclear magnetic fields longer as $T_1$, which in turn reduces $T_{2\text{Rabi}}$ by the dipole-dipole coupling among nuclear spins.

In conclusion, we have investigated the effect of background conduction electrons on the nuclear spin relaxation in the $n$-doped GaAs/AlGaAs (110) QW by optical TRKR measurements combined with NMR. We have shown that $T_1$ decreases with decreasing $n$ into the insulating phase, indicating that the hyperfine interaction is enhanced by the localization of the electrons. $T_{2\text{Rabi}}$ also shows the $V_g$-dependence similar to $T_1$ qualitatively, but we found a different $V_g$-dependence at higher $V_g$ (larger $n$), suggesting that the dipole-dipole interaction limits the maximum $T_{2\text{Rabi}}$ for the weak interaction with the electron spins. The data shown in this work reveal that we can control $T_1$ and $T_{2\text{Rabi}}$ by more than a factor of 10 and a factor of $\sim 2$, respectively, which opens a way to effectively switch the hyperfine interaction for initialization and storage by changing $V_g$ in a gated device.

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