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著者	Ono M., Kobayashi H., Matsuzaka S., Ohno Y., Ohno H.
journal or publication title	Applied Physics Letters
volume	96
number	7
page range	071907
year	2010
URL	http://hdl.handle.net/10097/51779

doi: 10.1063/1.3309687

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

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(Received 20 October 2009; accepted 15 January 2010; published online 17 February 2010)

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 ~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[1–8] and electrical[9,10] 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.[5,11] 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.[11] 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 5×10^{17} cm^{-3} 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 in the Voigt geometry; the static magnetic field B_0 was along the [001] direction of the sample. From that geometry, we tilted the sample slightly by an angle $\alpha=6°$ from the direction of B_0 in order to enhance DNP.[3] Under the application of B_0, the Larmor precession of photoexcited electron spins was detected by the time-resolved Kerr rotation (TRKR) technique as a measure of a local nuclear magnetic field acting on electron spins.[2–5,7] We set the pump- and probe-beam powers at 7.6 and 0.38 mW, respectively, and the diameter of the spot size was ~30 μm on the sample. Here, 5×10^{10} cm^{-2} spin-polarized electrons are excited per one pump pulse.

Figure 2(a) shows the trace of the Kerr rotation angle θ_K as a function of the time delay between pump and probe pulses Δt measured at $T=3.5$ K, $B_0=0.734$ T, and $V_g=-3$ V. When α is small, the effective coherence time T_{2e}^* and the Larmor frequency ν_L of photoexcited electron spins are given by

$$\theta_K = C\exp(-\Delta t/T_{2e}^*)\cos(2\pi\nu_L\Delta t), \qquad (1)$$

where C is the constant. ν_L can be approximated by $g\mu_B(B_0+B_n)/h$, where g is the electron g-factor, μ_B is the Bohr magneton, B_n is the nuclear magnetic field, and h is the Planck's constant. We first measured the V_g-dependence of θ_K with and without DNP to examine the degree of the hyperfine interaction. Figure 2(b) shows the V_g-dependence of ν_L measured by using circularly polarized pump beam (ν_L^{circ}) and alternating left- and right-circularly polarized pump beam through a photo elastic modulator (ν_L^{PEM}). The difference between ν_L^{circ} and ν_L^{PEM} reflects the magnitude of DNP (B_n). When $V_g<-3$ V ($n<1\times10^{11}$ cm^{-2}), B_n is increased, indicating that DNP is enhanced by reducing n. When V_g is further decreased from -4 to -5 V, ν_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

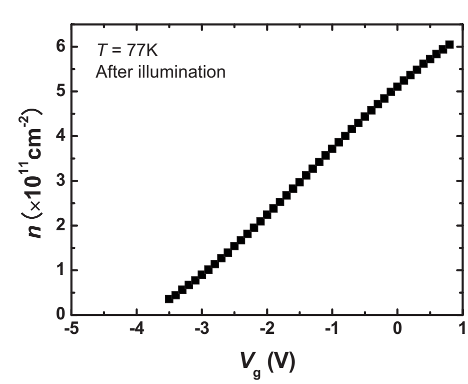

FIG. 1. Gate voltage V_g dependence of the electron density n obtained by the Hall measurement at $T=77$ K.

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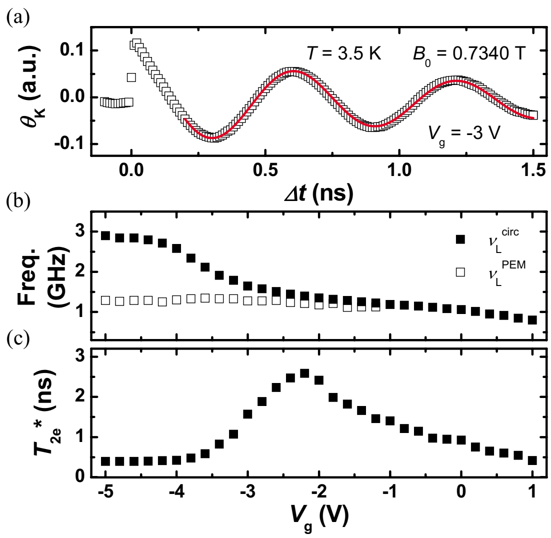

FIG. 2. (Color online) (a) The TRKR signal θ_K measured at T=3.5 K, B_0=0.734 T and V_g=−3 V is shown as a function of the pump-and-probe delay Δt. (b) Gate voltage V_g dependence of the Larmor frequency of photoexcited electron spins ν_L with and without the nuclear magnetic field B_n. (c) V_g-dependence of the effective coherence time of photoexcited electron spins T_{2e}^*.

applied, T_{2e}^* 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}^* becomes shorter as the electron spin relaxation due to the D'yakonov–Perel' mechanism is enhanced with the increase in their kinetic energy.[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 Δt appropriately.[7] 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.[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.

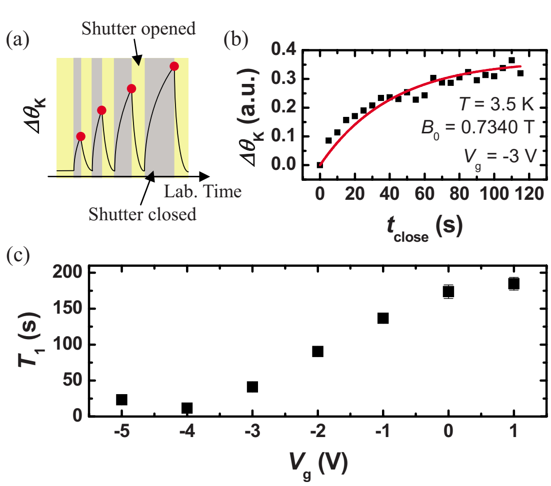

FIG. 3. (Color online) (a) Shutter-control sequence for the energy relaxation time T_1 of nuclear spins. (b) The Changes of the Kerr rotation signal $\Delta\theta_K$, corresponding to the depolarized nuclear spins, are plotted as a function of shutter-closing time t_{close} at T=3.5 K, B_0=0.734 T, and V_g=−3 V. (c) V_g-dependence of T_1 evaluated from the fitting.

Now we estimate the minimum T_1 on the assumption that the fluctuation field of electron spins governs the nuclear spin relaxation.[1,13] When the electrons are localized at a donor impurity potential, we can estimate T_1 from

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

with $r \cong a_0$, where Γ_t is the degree of electron occupation of the donor site, γ is the nuclear gyromagnetic ratio, τ_c is the correlation time, r is the distance from impurity, a_0 is the Bohr radius, and $b_e(0)\boldsymbol{S}$ ($\boldsymbol{S}$ is the electron spin) represents the electron magnetic field at an impurity center.[13] Assuming that the electrons are completely localized at $V_g \sim -3.5$ V from Fig. 3(c), $\Gamma_t \cong 0.1$ from Fig. 1, and $a_0 \cong 10$ nm (Ref. 13). The electron spin relaxation time T_{1e} is typically nanosecond order; then, τ_c is nanosecond order here. We employed the following ^{75}As parameters because all species of nuclei have the same order of $\gamma b_e(0)$ as follows: γ =45.81 Mrad/T s (Ref. 1) and $b_e(0) \cong -0.022$ 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[7] at T=3.5 K. In the present work, we investigated quadrupolar-split ^{75}As as a target nucleus. Figure 4(a) shows the TRKR-detected cw-NMR spectrum of ^{75}As at V_g=−5 V. The data was taken by measuring θ_K with changing the frequency of the rf magnetic field B_{rf} at fixed Δt and constant B_0 =0.734 T. B_{rf} was applied to the $[1\bar{1}0]$ direction of the sample by a split-coil. By setting the frequency of B_{rf} at the center of three resonance lines (5.370 MHz), we obtained Rabi oscillations by detecting $\Delta\theta_K$ after application of a B_{rf} pulse with pulse duration t_{pulse}. Then, we set V_g=−5 V during initialization, and changed V_g to an arbitrary value during the application of the B_{rf} pulse with the shutter closed. In Fig. 4(b), the Rabi oscillation is shown by the change of θ_K at V_g=−3 V. We obtained the T_{2Rabi} for the single-photon resonance by

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

where A is the constant, and ν_{Rabi} is the frequency of the Rabi oscillation. T_{2Rabi} provides an indication of the effective coherence time of nuclear spins T_2^*.[7]

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 $< V_g <$ −4 V, revealing that the hyperfine interaction

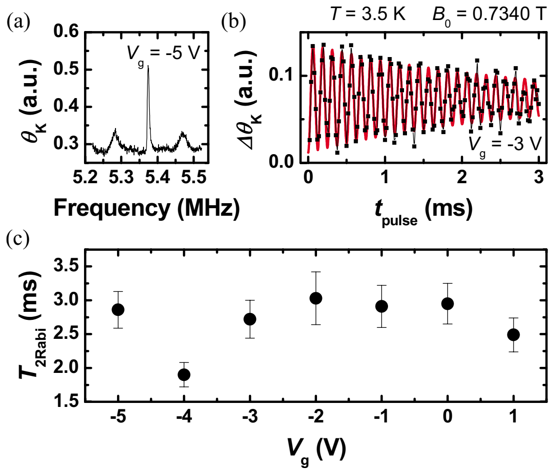

FIG. 4. (Color online) (a) TRKR-detected NMR spectrum for ^{75}As at $T=3.5$ K, $B_0=0.734$ T, and $V_g=-5$ V. The quadrupolar splitting is 95 kHz, and the line widths of the center peak and the side peaks are 6 and 25 kHz, respectively. (b) The Rabi oscillation taken by a single pulse NMR at the center of the three resonance lines are plotted as a function of the rf pulse width t_{pulse} at $V_g=-3$ V. (c) V_g-dependence of T_{2Rabi} evaluated from the fitting.

works most effectively with the electrons localized, and gets weaker as the electrons are fully depleted. However, T_{2Rabi} has a different dependence from T_1 at $-2\ \text{V} \le V_g \le 1\ \text{V}$. 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 $-2\ \text{V} \le V_g \le 1\ \text{V}$, the nuclear spins feel nuclear magnetic fields longer as T_1, which in turn reduces T_{2Rabi} 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_{2Rabi} 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_{2Rabi} for the weak interaction with the electron spins. The data shown in this work reveal that we can control T_1 and T_{2Rabi} by more than a factor of 10 and a factor of ~ 2, respectively, which opens a way to effectively switch the hyperfine interaction for initialization and storage by changing V_g in a gated device.

This work was partly supported by the Grant-in-Aid for JSPS Fellows and Scientific Research (Grant Nos. 17686001, 19048007, and 19048008 in Priority Area "Creation and control of spin current") from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), and the Global COE Program Center of Education and Research for Information Electronics Systems at Tohoku University.

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