Optically Pumped NMR in Semiconductor InP

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Abstract

We have performed optically pumped NMR measurements on iron doped InP. A circularly polarized laser light pumps up the polarizations of electron spins, which are transferred to the nuclear spins via hyperfine couplings resulting in a significantly enhanced NMR signal. The enhancement of ^{31}P NMR signal strongly depends on the temperature and the helicity of the laser light.

Key words: optical pumping; NMR; InP; quantum computer

NMR is a promising candidate for a practical quantum computer (QC)[1]. A 7 quantum-bit (qubit) QC was realized by a solution NMR[2]. On the other hand, no solid-state NMR-QC has been realized even for 2 qubits. However, a solid-state NMR-QC is desired for a practical QC, because the number of qubits in a solution NMR-QC is believed to be limited up to about 10 qubits.

NMR-QC has the great advantages of a long decoherence time of the system and the well-matured spin manipulation technique. However, NMR-QC has the difficulties in the initialization and read-out processes due to the extremely low nuclear spin polarization at thermal equilibrium. One way for improving the low polarization is the optically pumped (OP) NMR technique. In the OP-NMR, a circularly polarized laser light pumps up the polarizations of electron spins, which are transferred to the nuclear spins via hyperfine couplings, resulting in a significantly enhanced NMR signal. The OP-NMR technique is applicable to the system with relatively long lifetime for the spin-triplet excited states such as semiconductors[3], which are the potential candidate for a solid-state NMR-QC. Moreover, they could be used as *qubit initializers*[4], where the nuclear polarizations created by the optical pumping are transferred to the nuclei in other non-OP materials that serve as QCs.

So far, many III-V group semiconductors have been reported to be capable of optical pumping[3]. Among them, phosphides such as InP have favorable characteristics for a solid-state NMR-QC, because ^{31}P has I=1/2 and 100 % abundance. However, the optimized condition for the OP-NMR in InP has not yet been clarified. In this study we have developed the OP-NMR system for InP and performed OP-NMR measurements.

Figure 1 shows the experimental setup used in the present study. A Ti:Sapphire tunable laser pumped by a diode-pumped Nd:YVO_4 cw green laser is used to produce a linearly polarized light with the wavelength of 950 $\sim$ 1050 nm. The light is delivered to the bottom of the NMR probe in a cryostat installed in a 6.347 T superconducting magnet by a polarization-maintaining optical fiber. A quarter wavelength plate is attached to the bottom of the NMR probe, which converts the polarity of the light to the circular one. The helicity of the light ($\sigma^{\pm}$) can be changed by the half wavelength plate placed on the optical table before the light is introduced into the optical fiber.

The sample used in the experiments is a commercially available iron doped InP wafer. It is a compen-

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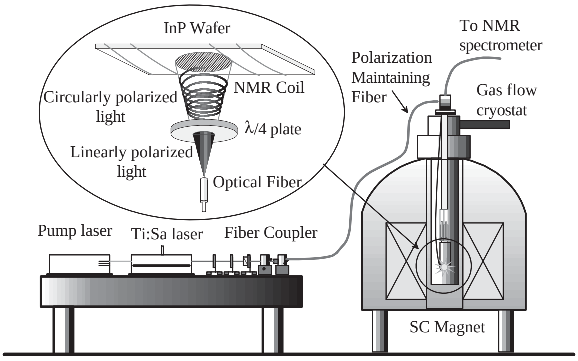

Fig. 1. Schematic illustration of the experimental setup for the OP-NMR experiments.

sated semi-insulator whose carrier concentration is extremely small ($\sim 7.0 \times 10^7$ cm^{-3}). The wafer of 350 μm in thickness was cut into a 5 × 8 mm rectangular shape and mounted on the NMR probe with its surface [100] normal to the magnetic field. The sample was loosely wound by a copper wire, which served as an NMR detection coil. The circularly polarized light was irradiated to the sample through the aperture of the coil. The diameter of the irradiated spot is about 5 mm. The ^{31}P NMR signals were detected by a pulsed NMR spectrometer with the pulse sequence of comb(64 $\times\pi/2$-pulses)-τ_L-$\pi/2$ pulse-FID. Here, the first 64 comb pulses extinguish the nuclear magnetization, and the magnetization built up by the laser light during the exposure time of τ_L is detected by a free induction decay signal. The *dark* experiment was performed with the same pulse sequence but without laser irradiation, where τ (instead of τ_L) corresponds to the long delay time in the saturation recovery experiments.

In Fig. 2, the ^{31}P NMR spectra for the cases of σ^+ and σ^- light irradiations with the power density of 430 mW/cm^{-2} and $\tau_L = 600$ s are shown together with that in the dark case with $\tau = 600$ s. The intensity of the spectrum is enhanced in either helicity, but the phase of the signal for σ^+ is shifted by 180° (negative) from the dark case. This is a clear signature of the occurrence of the optical pumping effect. For σ^+, the electron spins are polarized parallel to the magnetic field, which polarize the nuclear spins antiparallel to the electron spins. Figure 3 shows the temperature dependence of the ^{31}P NMR intensities for the cases of σ^+ and σ^- light irradiations with the power density of 89 mW/cm^{-2} and $\tau_L = 600$ s together with that in the dark case with $\tau = 600$ s. The intensities for the cases of σ^+ and σ^- light irradiations increase with decreasing temperature. It is clear that the OP-NMR is more effective at lower temperature. The intensity for the dark case has a peak around 10 K, because the spin-lattice relaxation time T_1 becomes longer than 600 s below 10 K.

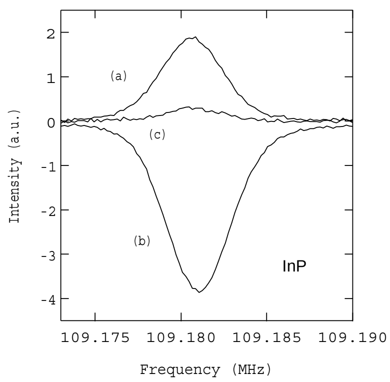

Fig. 2. ^{31}P NMR spectra taken under the laser irradiation of 430mW/cm^{-2} with τ_L=600 s at T = 4.2 K and H_0 = 6.347 T. (a) σ^- at λ = 1.420 eV, (b) σ^+ and at λ = 1.416 eV. (c) The spectrum for the dark case with τ = 600 s.

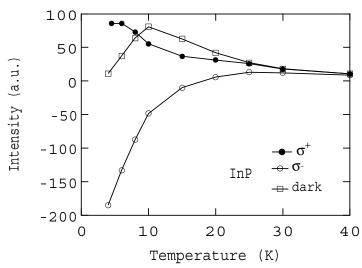

Fig. 3. Temperature dependence of the ^{31}P NMR signal under the laser irradiation of 89 mW/cm^{-2} with τ_L = 600 s at H_0 = 6.347 T. λ=1.420 eV and 1.416 eV for σ^- and σ^+, respectively. The temperature dependence of the intensity for the dark case with τ = 600 s is also shown.

In summary, we have developed OP-NMR system for iron doped InP and performed the measurements. By measuring the temperature dependence of the intensity under laser irradiation, it is clear that the OP-NMR is more effective at lower temperatures. More detailed studies are necessary to clarify the optimized conditions for the OP-NMR.

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