Temperature dependence of the optical nuclear orientation in InP

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Abstract. We report on the temperature dependence of the optical orientation of $^{31}\text{P}$ in semi-insulating iron-doped indium phosphide. The nuclear spin orientation manifests itself as an enhanced NMR signal under the irradiation of circularly polarized infrared light. We find that the temperature dependence of the enhancement is strongly photon-energy ($\hbar\nu$) dependent. At 10 K, the enhancement is observed in a wide range of $\hbar\nu$ between 1.26 and 1.43 eV, but most of them disappear above 20 K. The only exception is that at $\hbar\nu=1.407$ eV (slightly below the band gap $\sim 1.42$ eV), where the enhancement survives up to 50 K. This difference may originate from that in the spin relaxation times of photo-excited electrons trapped at donor centers.

1. Introduction

Optical pumping NMR is a method of creating highly polarized nuclear spins in a material using electron spin polarizations created by light. For semiconductors with direct band gaps, this is achieved with circularly polarized light with a photon energy close to the band gap.[1] This scheme is quite effective, but it works only at low temperatures below a few tens of Kelvins, [2, 3, 4] which limits potential applications of the scheme. For this reason, we have been exploiting schemes for optical nuclear orientation at higher temperatures. In this paper, we report on the temperature dependence of the nuclear spin orientation in indium phosphide. Possible strategies for the realization of the schemes are also presented.

2. Experimental method

The measurements were performed with the optical-pumping double-resonance NMR system developed by the authors.[5] A semi-insulating iron-doped InP wafer with a thickness of 350 $\mu$m and a [100] crystal orientation was set in the probe and inserted in a magnetic field of 6.347 T with the sample surface normal to the field. The pulse sequence used for this study was ‘combs-$\tau_L$-(\pi/2)-FID’. At the beginning of the sequence, comb pulses $[8 \times (\pi/2)$ pulses with 1 ms intervals] were applied to both the nuclei ($^{31}\text{P}$ and $^{115}\text{In}$) to set their initial polarizations to zero. Then, a light with a $\sigma^+$ helicity, an intensity of $\sim 200$ mW and a spot size at the sample surface of $\sim \phi 4$ was applied to the sample for an effective duration of $\tau_L= 120$ s. The nuclear spin polarization created by the light irradiation was detected as a free induction decay (FID) signal of $^{31}\text{P}$ induced by a (\pi/2)-pulse.

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3. Results

Figure 1 shows the photon energy dependences of the $^{31}$P signal intensity measured at five temperatures between 10 K and 50 K. One finds that the signal intensities are negative for all the photon energies, implying that the nuclear spins are polarized in the opposite direction to that in the thermal equilibrium state. At 10 K, large signal enhancements are observed at two distinct regions below the band gap ($\sim 1.42$ eV), i.e., the region around 1.407 eV ($\equiv \hbar \nu_1$) and that below 1.398 eV with a (negative) peak at 1.382 eV ($\equiv \hbar \nu_2$). The peak intensities at $\hbar \nu_1$ and $\hbar \nu_2$ having similar values at 10 K show quite different temperature dependences, as seen in Fig. 2. The intensity at $\hbar \nu_2$ disappears rather abruptly between 10 K and 20 K, whereas that at $\hbar \nu_1$ decreases rather slowly with increasing temperature, and survives even at 50 K.

4. Discussion

Primarily, the nuclear spin polarization in the optical pumping is determined by the net spin polarization of the photo-excited electrons ($S$) given by,$^{[6]}$

$$S = \frac{S_0}{1 + \tau/\tau_s},$$

where $S_0$ is the electron spin polarization at the instant of photo-excitation, and $\tau$ and $\tau_s$ are the lifetime and the electron spin relaxation time of the photo-excited electrons. Among these parameters, $\tau_s$ is the most strongly dependent upon temperature; it changes by a few orders of magnitude in the temperature range between 4.2 K and 300 K. The dominant origin of this temperature dependence is the D’yakonov-Perel’ (DP) mechanism,$^{[7]}$ which depends on the state of the photo-excited electrons, and thus, on the photon energy of the light applied to the sample.

The DP mechanism originates from the effective internal magnetic fields felt by the electrons with $k \neq 0$ caused by spin splittings due to the lack of inversion center in the zincblende structure. Hence, in principle, it can be suppressed by reducing the average momentum of the electrons. For shallow donor electrons, the translational motions are quenched, resulting in the suppression of the DP mechanism. Similar effect is expected for electrons in a magnetic field ($H_0$), where the
motions of the electrons with \( \mathbf{k} \perp H_0 \) are suppressed due to the cyclotron motions. Note that the DP mechanism is ineffective for the electrons with \( \mathbf{k} \parallel [100] \), i.e., for those moving parallel to \( H_0 \).

5. Conclusion
We report on the effect of temperature on the optical nuclear orientation in InP doped with iron. The enhanced signal intensity of \(^{31}\text{P} \) at 1.407 eV survives even at 50 K, indicating that shallow donors may be effective for the optical nuclear orientation at high temperatures.

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