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Electron Spin Lifetime in pnpn-Structured GaAs

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1. Introduction

Recently, electron and nuclear spin in semiconductor have been investigated for quantum information technologies and expected to be a candidate of quantum bit (qubit). However, electron spin relaxation time is not enough long in conventional semiconductors to control spin degree of freedom for the qubit. Three mechanisms of electron spin relaxation in semiconductor have been studied: band mixing of conduction and valence band (the Eliott-Yafet process) [1], electron spin splitting in noncentrosymmetric media (the Dyakonov-Perel' process) [2], and electron-hole exchange interaction (the Bir-Aronov-Pikus process) [3]. In present study, we investigate effect of electron-hole exchange interaction on spin lifetime in pnpn structure [4], in which optically excited electrons and holes are spatially separated.

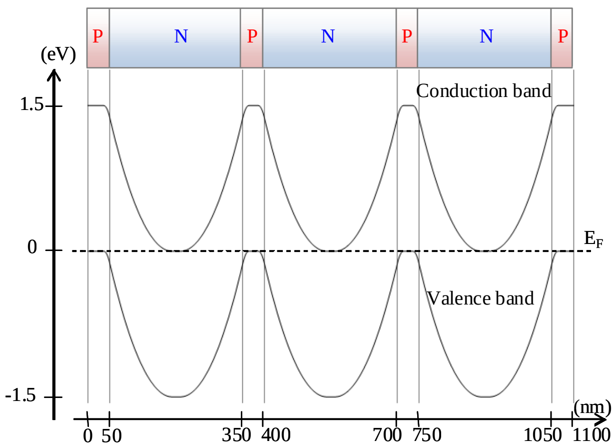

Fig. 1 Calculated band structure of pnpn structure in real space. Origins of horizontal and vertical axis mean sample surface and Fermi level, respectively. Curves above and under the Fermi level indicate conduction and valence band, respectively. Band gap energy of GaAs used in this calculation was 1.5 eV. Corresponding sample structure is illustrated in upper side.

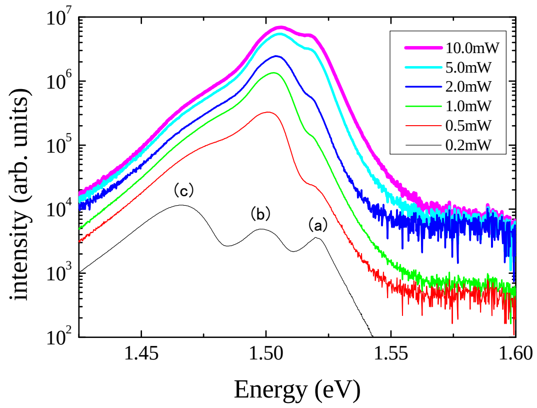

Fig. 2 PL spectra of pnpn structure with excitation powers of 10 to 0.2 mW from up to bottom.

2. Experimental

Sample used in our experiments is GaAs based stacking structure consists of 4 layers of C doped p-type GaAs with a doping density of 10^{18} and 3 layers of Si doped n-type GaAs with a doping density of 10^{17} (pnpn structure). Widths of the p- and n-layers are 50 and 300 nm, respectively. Schematic illustration of the pnpn structure is shown in upper side of Fig. 1. In this study, we designed the sample satisfying that (1) energy modulation depth at the depletion layer is the same as band gap energy, and (2) almost all the regions in the structure are depleted, assuming that (1) Fermi level of p- and n-type semiconductor lies at upper edge of valence band and lower edge of conduction band, respectively, and (2) band-gap energy of GaAs is 1.5 eV. Calculated result of band simulation in real space is shown in Fig. 1.

Circularly-polarized laser pulses were irradiated on the surface of the pnpn structure to generate spin polarized electrons. Excitation power dependence of degree of spin polarization was measured by detecting circularly-polarized photoluminescence (PL) components using computer controlled polarization-resolved measurement system. Figure 2 shows PL spectra excited by right-handed circularly-polarized light with excitation powers of 0.2 to 10 mW. Excited electron density in n-layer at the excitation power of 10 mW is estimated to be 3×10^{17} cm^{-3} from spectral width measurement using bulk-GaAs sample.

A few peaks are observed in each excitation power conditions; especially we can see three clear emission peaks in excitation power condition of 0.2 mW. We defined these three peaks as peak (a), (b), and (c) from higher energy as shown in Fig. 2. The emission peak (a) is an emission of interband transition. This emission is occurred by recombination emission of electrons and holes before being spatially separated by electric field in depletion layer. The peak (b) is a recombination emission of spatially separated electrons and holes by tunneling effect. The peak (c) is donor-accepter (DA) emission by carriers trapped in impurity level in n-type GaAs layers. The DA emission becomes weak comparing to other emission peaks with increasing the excitation power, since the carrier number trapped in the impurity is limited.

3. Results and Discussion

To investigate characteristics of recombination emission caused by spatially separated electrons and holes, we focused on the emission peak (b) around 1.5 eV. Figure 3 shows excitation power dependence of degree of spin polarization. The degree of spin polarization in bulk-GaAs sample is also plotted for a reference. The degree of spin polarization decreased with increasing the excitation power as shown in Fig. 3.

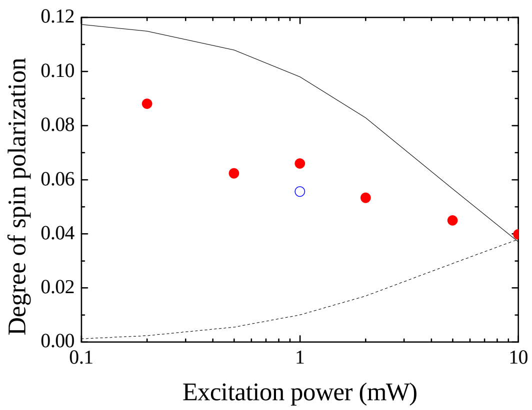

Fig. 3 Excitation power dependence of degree of spin polarization. Solid and open circles are obtained from peak (b) of pnpn structure and bulk-GaAs sample, respectively. Solid and dotted curves indicate fitting results with and without considering excitation power dependence of spin lifetime, respectively.

When the excitation power is strong, the degree of spin polarization should be large because a large amount of spin polarized "excited electrons" are generated in conduction band. However, observed degree of spin polarization was smaller than expected. It is concerned that the spin polarization of the electron is reduced by strong electron-hole exchange interaction among a large amount of excited carriers. The exchange interaction may affect to the electron before electrons and holes are spatially separated by internal electric field in pnpn structure. Moreover, reduction of the spatial separation between electrons and holes caused by band modulation under strong excitation condition results in a strong exchange interaction to electrons. These mechanisms may increase spin relaxation in strong excitation condition.

When the excitation power is weak, spin polarized "excited electrons" is much smaller than "accumulated electrons" in conduction band and main contribution to PL polarization is spin polarization of "accumulated electrons". The measured degree of spin polarization of pnpn structure at the excitation power of 0.2 mW was higher than that of bulk-GaAs sample. This result assumes that the spin polarization of "accumulated electrons" is kept longer than period of excitation pulse.

To clarify the relation between excitation power and spin lifetime, we performed simple calculation using a fitting function

$$(poralization) = c\tau_s \frac{N_P}{N_B + N_P} \qquad (1) \quad .$$

Here τ_s is spin lifetime, N_B is number of "accumulated electron", N_P is number of "excited electron", and c is a constant. The calculated results assuming that the spin lifetime is inversely proportional to hole concentration well describe the trend of experimental results as shown solid curve in Fig. 3. Even when the optically excited electron density becomes much lower than the doping density of the n-layer, relatively high spin polarization is obtained. It infers that spin lifetime is prolonged in the pnpn structure especially when optical excitation power is weak and the density of the excited electrons is low.

4. Conclusions

Excitation power dependence of degree of spin polarization in pnpn structure was evaluated by polarization-resolved PL measurements. It is found that the degree of spin polarization increases with decreasing the excitation power. From the experimental results it is inferred that the spin lifetime in pnpn structure is markedly prolonged. The prolongation of the spin lifetime is attributable to the reduction of electron-hole exchange interaction in pnpn structure.

References

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