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Fabrication of *p*-doped quantum dot spin-polarized light-emitting diodes

Kouhei Etou, Satoshi Hiura, Junichi Takayama, and Akihiro Murayama

Faculty of Information Science and Technology, Hokkaido Univ.
Kita 14, Nishi 9, Kita-ku, Sapporo 060-0814, Japan
Phone: +81-11-706-6482 E-mail: eto02166910@eis.hokudai.ac.jp

Abstract

We have studied III-V semiconductor quantum dot (QD) spin-polarized light-emitting diode (spin-LED) that can directly convert electron-spin property into circularly polarized light. *P*-doping of QDs are well known to increase their luminescence intensity and to suppress the electron-spin relaxation during light emission. In this study, we have fabricated a spin-LED having the ferromagnetic Fe electrode as a spin injector and the optimized $In_{0.5}Ga_{0.5}As$/GaAs QDs with *p*-doped capping barrier as an optically active layer. We observed a dominant electroluminescence of QD ground state, showing the net circular polarization degree of 10%, which corresponds to the spin-injection efficiency of 25%, considering that the spin polarization of Fe is 40%.

1. Introduction

In recent years, spintronics has attracted much attention due to its potential applications in information technology as well as revealing fundamental physics of electron spin in condensed matter [1]. In particular, optical transfer of spin information of carriers in solid state circuits will be important for optical interconnection in future opto-spintronics integration in information processing. Spin-functional optical devices, such as a spin-polarized light-emitting diode (spin-LED), have been extensively studied by employing III-V compound semiconductor quantum wells (QWs) [2] and quantum dots (QDs) [3, 4] as active layers. Circularly polarized light reflecting spin states of carriers injected from spin injectors can be emitted according to the optical-transition selection rule in the semiconductor active layers. However, the spin polarization of carriers electrically injected into the semiconductor quantum structures can be largely affected by electron-spin relaxation in them. Time-resolved optical spin orientation measurements in $In_{0.5}Ga_{0.5}As$/GaAs QDs revealed that the thermal reinjection of depolarized electron spins from the barrier to QDs accelerate the spin relaxation in QDs at high temperatures [5]. We have recently demonstrated that the spin relaxation in QDs can be suppressed using *p*-doped capping barrier due to the suppressed relaxation of electron spins reinjected from the capping barrier, where the D'yakonov-Perel' spin relaxation, which was dominant at high temperatures, was potentially weakened by impurity scattering [6].

In this study, we have fabricated a spin-LED that uses $In_{0.5}Ga_{0.5}As$/GaAs QDs with *p*-doped capping barrier as an optically active layer. Circularly polarized electroluminescence (EL) properties were investigated as functions of injection current, magnetic field, and temperature.

2. Experimental

Sample growth and device fabrication

Figure 1 shows a schematic of the sample structure. The spin-LED structures were grown by molecular beam epitaxy for the semiconductor part while the tunnel barrier and the ferromagnetic electrode were grown using electron beam (EB) deposition. The *p-i-n* LED device has the following sequence: *p*-GaAs:Zn (100) substrate ($p = 1 \times 10^{19}$ cm^{-3})/350 nm *p*-GaAs:Be ($p = 1 \times 10^{18}$ cm^{-3})/50 nm *p*-$Al_{0.15}Ga_{0.85}$As:Be ($p = 1 \times 10^{18}$ cm^{-3})/40 nm undoped GaAs/QD active layer/50 nm *n*-$Al_{0.1}Ga_{0.9}$As:Si ($n = 2 \times 10^{17}$ cm^{-3})/5 nm *n*-GaAs:Si ($n = 2 \times 10^{17}$ cm^{-3}). The QD active layer consists of three layers of 7.5-ML-thick $In_{0.5}Ga_{0.5}$As QDs grown at 520℃ with 10-nm-thick *p*-doped capping barrier ($p = 6 \times 10^{17}$ cm^{-3}) and the further 30-nm-thick undoped GaAs barrier. After the growth of the semiconductor part, the sample was transferred to the EB chamber without an air exposure to grow 3-nm-thick MgO tunnel barrier at 300℃. Then, the sample was transferred in air into another EB chamber to grow 10-nm-thick Fe electrode. Before the growth of the Fe electrode, the MgO surface was cleaned by annealing at 300℃ for 30 min in an oxygen atmosphere of 7×10^{-5} Pa while monitoring reflection high energy electron diffraction patterns. Finally, standard photolithography and chemical etching processes were carried out to fabricate a spin-LED with a trench structure, and then no noticeable leakage currents were detected.

Circularly polarized EL measurement

The EL intensity and its circular polarization characteristics of the spin-LED were measured at 15–298 K by mounting the device in a superconducting magnet cryostat with a maximum magnetic field of 5 T normal to the sample plane. The magnetic field was changed from −5 to +5 T. In this paper,

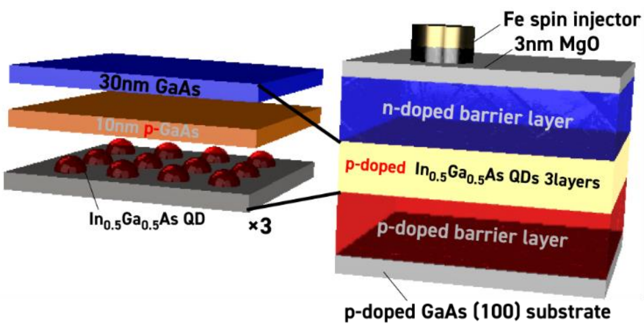

Fig. 1 Schematic illustration of *p-i-n* spin-LED device having Fe/MgO spin injector and active layer of three layers of *p*-doped $In_{0.5}Ga_{0.5}$As/GaAs QDs.

the data obtained at 15 K under a magnetic field of +5 T are only shown. An injection current was changed from 0.3 to 10 mA. The EL signal was detected by an InGaAs detector in the Faraday geometry. The EL circular polarization degree (CPD) was analyzed through a combination of quarter-wave plate with a linear polarizer, which was defined as CPD = $(I_{\sigma+} - I_{\sigma-})/(I_{\sigma+} + I_{\sigma-})$ where $I_{\sigma\pm}$ is the circularly polarized EL intensity. The CPD measured in QDs directly reflects the electron-spin polarization at QD emissive states, because hole spins are rapidly depolarized before injection into QDs.

3. Results and Discussion

Figure 2 shows the typical circularly polarized EL spectra and the corresponding CPD measured at an injection current of 0.3 mA. Here, the contributions of Zeeman splitting to the CPD values were removed from the magnetic-field dependence of the CPD. We observed a dominant EL signal from the QD ground state (GS) (1.25 eV), showing the CPD values of approximately 10%. Considering that the spin polarization of the used Fe electrode is 40%, spin-injection efficiency from the ferromagnetic electrode to the optically active layer was estimated as 25%. Another EL peak can be seen at the higher energy of 1.32 eV. This peak is likely due to the contribution of the first excited state of QDs or the GS of the smaller-sized QD ensembles. More quantitative measurements, such as an exploration of radiative lifetime, are needed for the understanding of the origin of this EL peak.

Next, we discuss the injection-current dependence of the CPD properties of the QD-GS. Figure 3 shows the averaged CPD values of the QD-GS as a function of the injection current. Here, the averaged CPD of the QD-GS is defined as a simple average value of the data points between 1.22 eV and

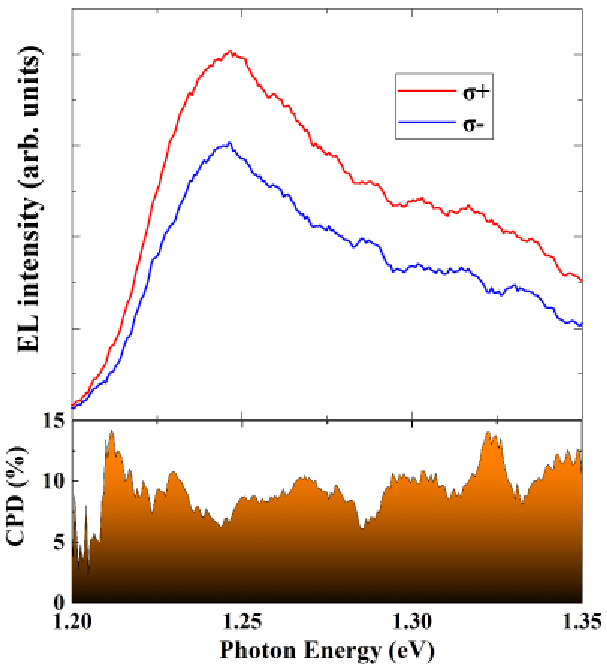

Fig. 2 Typical circularly polarized EL spectra and corresponding CPD measured at an injection current of 0.3 mA under a temperature of 15 K and a magnetic field of +5 T.

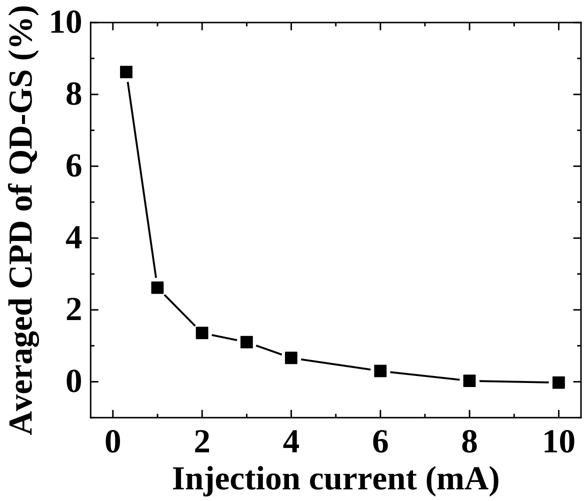

Fig. 3 Injection-current dependence of averaged CPD of QD-GS measured at 15 K under a magnetic field of +5 T.

1.27 eV in the CPD spectrum. The highest CPD value of ~9% was obtained at the lowest injection current of 0.3 mA. We observed a gradual decrease of the CPD with increasing injection current. Generally, the number of electrons injected into the QDs increases as the injection current increases. In this case, spin-state filling effect in QDs largely reduces the electron-spin polarization at QD emissive states, leading to a large decrease of the CPD value, as reported in time-resolved optical spin orientation studies [7, 8]. Therefore, we anticipate that the CPD properties of the QD-GS observed at the injection current above 1 mA can be largely affected by a strong spin-state filling effect in QDs.

4. Conclusions

In conclusion, we have fabricated a spin-LED device having the ferromagnetic Fe electrode as a spin injector and the self-assembled $In_{0.5}Ga_{0.5}As$/GaAs QDs with *p*-doped capping barrier as an optically active layer. We observed a dominant EL from the QD-GS with a net CPD value of ~10%. Considering that the spin polarization of Fe is 40%, we have achieved the conversion efficiency of 25% of the electron spin information created by the ferromagnetic Fe electrode into circularly polarized light information.

Acknowledgements

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