Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp436-437

Temperature Dependences of Spin-injection Dynamics and Spin-polarized Electroluminescence in InGaAs Quantum Dots

Y. Nomura[1], Y. Akei[1], J. Takayama[1], T. Kiba[2], A. Subagyo[1], T. Yamamura[1], D. Yamazaki[1], K. Sueoka[1], and A. Murayama[1]

[1] Hokkaido Univ.
Kita 14, Nishi 9, Kita-ku, Sapporo 0600814, Japan
Phone: +81-11-706-6519 E-mail: yuzuru_nomura@ist.hokudai.ac.jp
[2] Kitami Inst. of Tech.
165 Koen-cho, Kitami, Hokkaido 090-8507, Japan

Abstract

Temperature dependence of spin-injection dynamics has been studied in InGaAs self-assembled quantum dots (QDs). Spin-polarization of electroluminescence in the QDs is also studied as a function of temperature, where current injection of electron spins is performed from Fe-based ferromagnetic electrodes into the QDs. The spin-injection efficiency increases with temperature, originating from suppression of Pauli spin blocking.

1. Introduction

Quantum dots (QDs) of III-V compound semiconductors are attractive electron and photonic device materials. Barrier potentials around the QD can strongly confine carriers and therefore the density of the carrier states in the QD becomes completely discrete, which is beneficial to realizing photonic devices with superior performances such as ultra-low-energy consumption lasing. Moreover, freezing of carrier momentum in the QD can significantly enhance the stability of spin states. Therefore, employing the QDs in optically active layers enables one to develop photonic devices exhibiting spin functionalities, such as, spin-polarized light-emitting diodes (LEDs) and lasing.

However, electron-spin injection, which is injection of spin-polarized electrons, into the QD has not been sufficiently established because of unavoidable relaxation of the spin states in spin transport across semiconductor barrier layers and potential steps prior to the injection, in addition to spin relaxation arising from energy relaxation inside the QD. These spin relaxation processes are well known to be sensitive to temperature. Therefore, we have studied the temperature dependence of the spin-injection dynamics in a pico-second time region from GaAs barriers into self-assembled QDs of InGaAs, by using circularly polarized time-resolved photoluminescence (PL) after optical excitation of spin-polarized electron-hole pairs in barriers [1]. Spin-polarization of electroluminescence (EL) in QD-based LEDs is also studied as a function of temperature, where current injection of electron spins is performed from Fe-based ferromagnetic electron-spin electrodes to the QD active layers. Then, we will discuss about the efficiency of electron-spin injection into the QDs from these temperature dependences of the spin-injection dynamics and spin-polarized EL in the QDs.

2. Experimental procedure

Sample preparation

Self-assembled QDs of InGaAs were grown by molecular beam epitaxy with GaAs buffer and barrier layers on GaAs (100) substrates. LEDs with active layers composed of the InGaAs QDs were fabricated by standard photolithography. Metallic ferromagnetic thin films of Fe or FeCo with a thickness of 10 nm were deposited on the top as electron-spin electrodes. Single crystal Fe or FeCo layers were grown on MgO tunneling barriers with a thickness of 3 nm, which were directly grown on surfaces of AlGaAs or GaAs barrier layers under ultra-high vacuum. Optical windows were fabricated at the top of the LED samples.

Time-resolved PL measurement

The temperature dependence of the spin-injection dynamics into InGaAs QDs was measured by circularly polarized time-resolved PL after pulsed optical excitation of spin-polarized electron-hole pairs in barriers. The maximum spin polarization of excited electrons in barriers is 50 % due to the optical selection rule. The degree of circular polarization (CPD) of PL or EL was defined using circularly polarized PL or EL intensities: $I(\sigma^{\pm})$, as follows;

$$\rho = \frac{I(\sigma^{+}) - I(\sigma^{-})}{I(\sigma^{+}) + I(\sigma^{-})} . \qquad (1)$$

This CPD value reflects time integration of time-dependent spin polarization of the electron at emissive states in the QDs. The circularly polarized PL at the excited states in the QDs was detected using a streak camera, where these states were situated energetically slightly below the barrier, and thus enabled one to detect the spin states and dynamics immediately after the spin injection from the barrier.

3. Results and discussion

Temperature dependence of spin-injection dynamics

A CPD value in the QD PL is constant to be 10 % below 100 K and monotonically increases from 10 to 25 % with increasing temperature from 100 to 225 K. There are 3 important parameters dominating the spin-injection dynamics, such as, a spin-injection time, a spin-conservation factor during injection, and a state-filing parameter for the spin-split state in the QD. The first spin-injection time is almost constant to be about 10 ps for temperature. This ultrafast injection can sustain smooth and efficient spin injection before spin relaxation from the barrier into the QDs. The second spin-conservation factor is constant to be 80 % below 150 K. Beyond 150 K, this factor decreases down to 70 %. The third state-filing parameter shows similar temperature dependence to that of the CPD. The filling parameter is constant below 100 K, where the spin-split states of the majority spin in the QDs are largely occupied after the spin injection. However, above 100 K, this state filling effect is gradually resolved with increasing temperature because of thermal redistribution of spin-polarized electrons among the excited states in the QDs and the barrier level, which is responsible for the CPD increase with increasing temperature. Therefore, spin blocking due to the Pauli exclusion principle in the QD is a major factor to prevent efficient spin injection into the QDs.

Temperature dependence of spin-polarization in electroluminescence

We have observed bright EL from QD LEDs with Fe or FeCo electrodes. Circular polarization proprieties were also observed when external magnetic fields were applied perpendicular to the film plane, where perpendicular magnetizations in Fe or FeCo thin films were induced by the magnetic field and thus the direction of electron spin injected to the semiconductor layers became parallel to the direction of EL emission observed (in Faraday geometry).

Figure 1(a) shows circularly polarized EL spectra and corresponding CPD values as a function of photon energy at 200 K. The CPD values up to 5 % are seen, which indicates electron-spin injection from the FeCo electrode across AlGaAs and GaAs barriers with the total thickness of 120 nm into the InGaAs-QD active layer. The magnetic-field dependence of the CPD value indicates saturation behavior due to saturation of the perpendicular magnetization in the FeCo thin film, where contribution of the Zeeman effects is deduced to be less than 1 %. Therefore, efficient electron-spin injection is concluded with electron-spin polarization of 15 % of that initially generated in the FeCo electrode. Figure 1(b) shows circularly polarized EL spectra and CPD values at 100 K. As can be seen, the CPD values are strongly suppressed. We attribute this suppression at low temperatures to the filling effect for the spin-split states in the QDs, which is elucidated and discussed by the time-resolved PL measurements in the previous section.

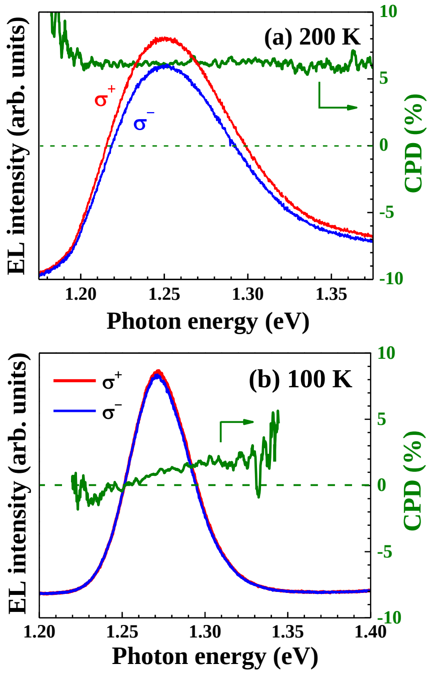

Fig. 1 Circularly polarized EL spectra and the corresponding CPD values as a function of photon energy at 200 K (a) and 100 K (b) with the perpendicular magnetic field of 5 T, in the LEDs with InGaAs QD active layers and FeCo electron-spin electrodes.

4. Conclusions

We have studied temperature dependences of the optical spin-injection dynamics and spin-polarized EL in InGaAs self-assembled QDs. Pauli blocking of spins in the QDs is elucidated to be the major factor to prevent smooth and efficient spin injection. This spin blocking can be resolved at high temperatures, because of thermal redistribution of electron spins among excited states in the QDs and the barrier level.

Acknowledgements

This work is supported by Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (S) No. 22221007 and Bilateral Joint Research Project.

References

[1] T. Kiba, X.J. Yang, T. Yamamura, Y. Kuno, A. Subagyo, K. Sueoka, and A. Murayama, Appl. Phys. Lett. **103** (2013) 082405.