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Observation of Out-of-Plane Spin Injection from MnSb/GaAs spin-LED

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1. Introduction

When spin-polarized carriers are electrically injected in a light emitting diode (LED), light emission is accompanied by circular polarization. This novel functionality was named spin-LED [1,2], and has been used primarily for optical detection of carrier spins. The spin-LED would have great potential as a novel light source for other applications for which the state of optical polarization is important. Works of Refs.1 and 2 were succeeded by spin-LEDs with ferromagnetic metals, Fe [3,4] and CoFe [5]. These materials have in-plane magnetization, and one needs to apply high magnetic fields normal to the device surface in order to force magnetization and injected carrier spins parallel to the direction of light emission. This is unfavorable in view of surface emitting devices, because circular polarization is not available at zero or small external magnetic fields. Therefore, a ferromagnetic metal electrode having perpendicular magnetization is desirable.

Epilayers of MnSb on GaAs (001) are known as an in-plane ferromagnet [6,7]. We report here that spin injection characteristics obtained from MnSb/GaAs-based LED show spin injection due to out-of-plane magnetization. Our results suggest that remanent circular polarization is possible with a spin injector of perpendicular magnetization, which is important for the development of spin-LED.

2. Experiment

MnSb/GaAs-based LED were prepared by molecular beam epitaxy (MBE). GaAs-LED was first grown with an arsenic cap layer in the first MBE chamber. It is then transferred, via air atmosphere, into the second MBE chamber in which n^+-GaAs and MnSb epilayers were grown. Substrate temperature during the growth of MnSb was 250 °C. Growth rate of MnSb was 80nm/hr. The sample structure was, from the top, 80-nm MnSb/ 30-nm n^+-GaAs (1×10^{19}cm^{-3})/ 300-nm n-$Al_{0.1}Ga_{0.9}As$ (1×10^{17}cm^{-3})/ 20-nm i-$Al_{0.1}Ga_{0.9}As$/ 50-nm i-GaAs/ 20-nm i-$Al_{0.2}Ga_{0.8}As$/ 200-nm p-$Al_{0.2}Ga_{0.8}As$ (1×10^{18}cm^{-3})/ 500-nm p-GaAs buffer (1×10^{18}cm^{-3})/ p^+-GaAs(001) substrate.

Circular Au electrodes of 1-mm diameter were then fabricated on top of a MnSb layer by photolithography and wet etching. Light emitted from the front surface around mesas were collected and analyzed. An external magnetic field was applied normal to the sample surface. Circular polarization was measured by using photo-elastic modulation technique. Magnetization of LED samples was examined for both in-plane and out-of-plane by magnetic susceptibility measurements with SQUID.

3. Results and Discussion

θ-2θ x-ray diffraction data of MnSb/GaAs LED structure are shown in Fig. 1. In addition to reflections from GaAs(002) and (004) planes, peaks at 29.4° and 60.9 ° are observed, which are the reflections from MnSb (10-11) and (20-22) planes, respectively. The observed crystallographic relation is typical for MnSb/GaAs(001) system [6,7]. No other macroscopic second phases were detected.

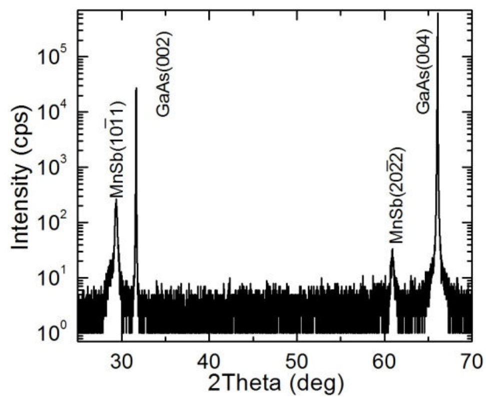

Fig.1. XRD measurement of MnSb/GaAs-based spin-LED

Figure 2 shows electroluminescence (EL) spectrum obtained at the forward bias voltage of 2.1V at 4 K without an external magnetic field. The inset shows *I-V* characteristics, indicating good rectification. EL spectrum consists of two emission bands: the primary band peaking at 1.514eV, and the secondary band at 1.48 eV. The former is attributed to the near band edge emission of electrons and holes from the *i*-GaAs active layer, whereas the later may be due to donor-acceptor pair recombination in the vicinity of the *i*-GaAs layer. We analyzed the magnitude of circular polarization $P_{EL} = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$ of the primary emis-

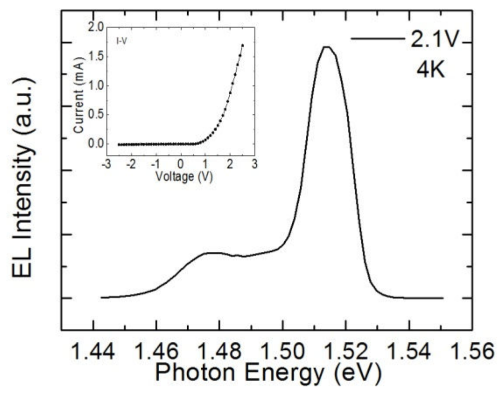

Fig.2. EL spectrum at 4 K without an external magnetic field. Inset shows current-voltage characteristics of spin-LED at 4 K.

sion band, and found that EL obtained from the front surface was accompanied by circular polarization of $P_{EL} \sim$ 3 % under the external field of $\mu_0 H = 0.5$ T.

Figure 3 shows magnetic field dependences of P_{EL} in the EL obtained from the front surface and magnetization curves of a MnSb/GaAs-based LED. Magnetic field was applied normal to the MnSb surface for EL experiments. Forward bias of $V = 2.1$ V was applied to the diode. P_{EL} increases non-linearly with increasing the field, approaches to the saturation of $P_{EL} \sim 3$ % at around 0.5 T, beyond which it is nearly constant. In detail, a narrow hysteresis is noticeable, with remanent polarization of $P_{EL} \sim 0.5$ %. These results indicate the radiative recombination involving the electrons whose spin axis is normal to the sample surface. In other words, the presence of perpendicular magnetization component in a MnSb spin injector is suggested. Note that magnetization easy axis is in the sample plane for a MnSb epilayer, as discussed in the next paragraph.

Solid and dashed lines in Fig.3 are magnetization curves $M_\perp$ and $M_{//}$ obtained under external magnetic fields applied normal and parallel to the sample surface, respectively. The $M_{//}$ curve exhibits well defined square hysteresis, being typical for a ferromagnetic layer with the easy axis in the plane. It is obvious that the overall shape of $M_\perp$ is close to the P_{EL} profile, including a good matching of hysteretic region which is ± 0.4T in the $M_\perp$ curve. This fact suggests that some perpendicular component in a MnSb layer is responsible for the observed circularly polarized light emission. Ferrimagnetic Mn_2Sb may be one of such candidates that is responsible for the perpendicular component [8]. If this is the case, it must exist at least at the MnSb/GaAs interface.

Figure 4 show temperature dependence of remanent P_{EL}. P_{EL} decreases with increasing temperature up to 40 K, beyond which the reduction becomes very moderate. Finite value of circular polarization ($P_{EL} \sim 0.3$ %) was still detectable, which was limited by the intensity of the EL itself. Further improving the quality of the spin-LED would push the limitation of detection toward higher temperatures.

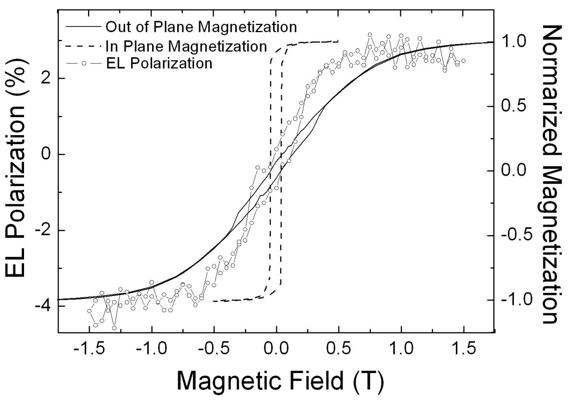

Fig.3. Magnetic field dependences of circularly polarized light and magnetization for MnSb/GaAs-based spin-LED.

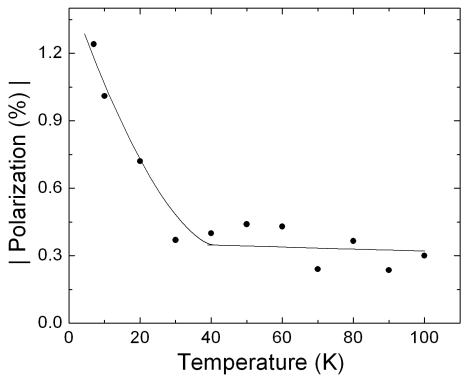

Fig.4. Temperature dependence of circularly polarized light without an external magnetic field.

4. Conclusion

MnSb/GaAs-based spin-LEDs were prepared by molecular beam epitaxy and tested in view of light emitters with circular polarization. Spin injection characteristics show spin injection due to out-of-plane magnetization component. At the point of writing this abstract, the magnitude of circular polarization is small, and the origin of the out-of-plane magnetization is unknown. However, we found remanent circular-polarization-emission at relatively high temperature, which is probably a very important feature for the development of spin-LED.

Acknowledgements

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Reference

[1] Y. Ohno *et al* Nature **402**, 790 (1999)
[2] R. Fielderling *et al*., Nature **402**, 787(1999)
[3] A. T. Hanbicki *et al.*, Appl. Phys. Lett. **80**, 1240 (2002)
[4] H. J. Zhu *et al*., Phys. Rev. Lett. **87**, 016601 (2001)
[5] X. Jiang *et al.*, Phys. Rev. Lett. **94**, 056601 (2005).
[6] S. Miyanishi *et al*., Appl. Phys. Lett. **68**, 2890 (1996)
[7] Y. Ogawa *et al*., International Symposium Compound Semiconductors (Oct. 15, 2007, Kyoto), abstract booklet p187
[8] S. Miyanishi *et al*., Appl. Phys. Lett. **70**, 2046 (1997)