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Fabrication of Ge-based light-emitting diodes with a ferromagnetic electrode

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Abstract

We successfully fabricated light-emitting diodes (LEDs) having an Fe/n^+-Ge/p^+-Si structure. Clear electroluminescence (EL) from the direct band gap of the Ge layer was observed at room temperature. Our result is an important step toward developing a Ge-based spin-polarized LED.

1. Introduction

Electrical injection of spin-polarized carriers from a ferromagnetic electrode into a semiconductor is key to developing semiconductor-based spintronic devices [1]. In this perspective, the ability to evaluate the degree of spin polarization (P) of the injected carriers is important because the performance of the spintronic devices critically depends on P.

Spin-polarized electron detection based on injection luminescence is one of the most powerful tools available exclusively to semiconductors such as GaAs [2-4], Si [5,6] and SiGe [7]. This technique enables us to directly estimate the P values, using the light-emitting diode (LED) geometry, from the degree of circular polarization of the direct-gap electroluminescence (EL) through the selection rules of optical transition [2-4].

Ge has attracted much attention for use as the core of such semiconductor-based spintronic devices as spin field-effect transistor. In fact, there have been attempts of electrical spin injection to Ge using a ferromagnetic metal contact so far [8-15]. However, extracting an accurate value of P is not trivial when the detection of the injected spin-polarized carriers is done by electrical means.

Ge has long been considered to be only poorly light-emitting because of its indirect band gap (that is, optical transition is dipole-forbidden between the conduction band minimum at the L-point and the valence band maximum at the Γ-point). However, the energy difference between the L and Γ conduction minima is relatively small (~ 0.14 eV), which allows direct-gap emission (transition between the zone-center conduction and valence band) when the quasi-Fermi level in the conduction band is high enough [16]. Sun *et al*. recently demonstrated a direct-gap EL from n^+-Si/n^+-Ge/p^+-Si LED at room temperature (RT) [16]. Yasutake *et al*. reported circularly polarized direct-gap photoluminescence (PL) from a Ge film grown on Si at RT, where the spin-polarized electrons were created by optical means [17]. These results suggest that Ge has a great potential for developing spin-LEDs.

In this report, we demonstrate the direct-gap EL from a Ge-based LED having a ferromagnetic metal (Fe) electrode.

2. Sample preparations

We used a custom Ge-on-Si epitaxial wafer grown by chemical vapor deposition (IQE plc). The wafer consists of a 1-μm-thick n^+-Ge epilayer doped with P to a concentration of 6×10^{18} cm^{-3} grown on top of a B-doped p^+-Si(001) substrate with a doping concentration of 1×10^{19} cm^{-3}. The wafer was first etched by buffered HF (HF : H_2O in 50 : 1 ratio) for 10 min, and was placed in deionized (DI) water (30 sec), H_2O_2 (30 sec), DI water (30 sec), and buffered HF (30 sec), followed by a rinse in DI water. This process was repeated 5 times to realize a clean and smooth Ge surface [18]. The wafer was then installed into the ultra-high-vacuum growth chamber and maintained at 700°C for 10 min to remove the surface oxide. Reflection high-energy electron diffraction (RHEED) showed a streaky (2×1) pattern, indicating the clean, atomically flat surface. A Au (10 nm)/Fe (5 nm) bilayer was grown at RT using electron beam evaporation. The film was processed into mesa structures with the active area (A) ranging from 50 × 100 up to 300 × 600 μm^2 using standard micro-fabrication including photolithography, Ar-ion milling, reactive ion etching and SiO_2 sputtering.

3. Results and discussion

Figure 1 shows the X-ray diffraction (XRD) pattern of

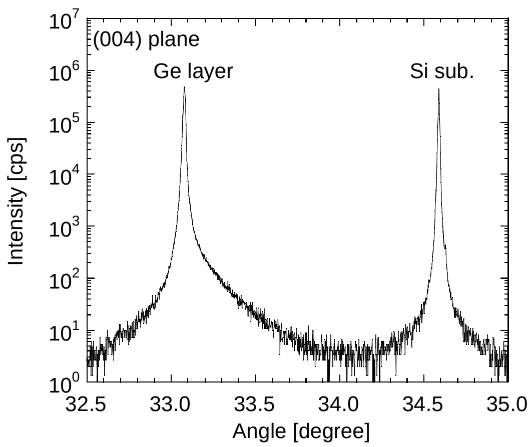

Fig. 1 XRD pattern of the Ge on Si epiwafer.

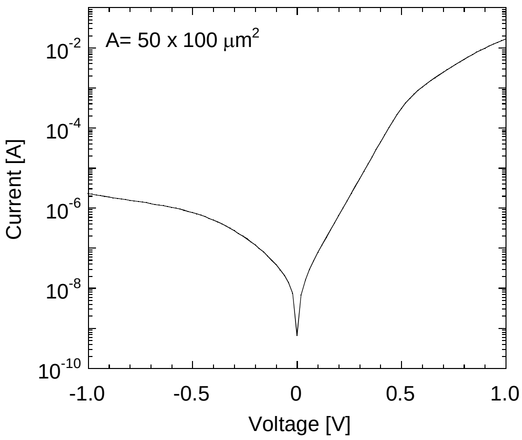

Fig. 2 *I-V* characteristics of the Fe/*n*-Ge/*p*-Si device at RT.

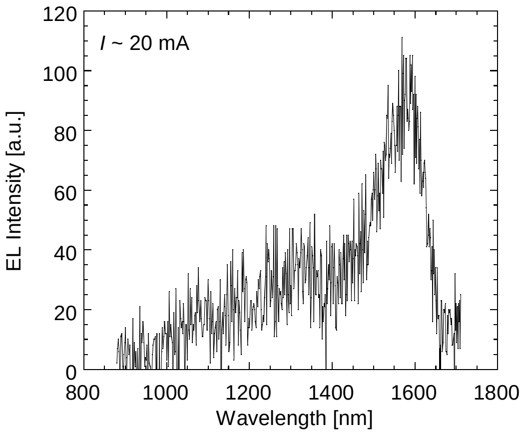

Fig. 3 EL spectrum of the Fe/*n*-Ge/*p*-Si device at RT.

the wafer. The angle of the (004) reflection of the Ge layer 33.055° corresponds to the lattice constant of 5.649 Å in the growth direction. Note that this is smaller than that of the bulk Ge, 5.657 Å. This means that a tensile strain has been unintentionally induced in Ge although Si has a smaller lattice constant (5.431 Å) than that of the bulk Ge. Such tensile strain presumably came from the difference of thermal expansion coefficient between Ge and Si [16]. Nevertheless, it is favorable for LED application because the direct-gap EL could be enhanced thereby [16].

The current-voltage (*I-V*) characteristics of our device measured at RT are presented in Fig. 2. The typical diode behavior is clearly visible. Also, a linear regime in the ln(*I*)-*V* plot is observed in the forward-bias direction, which is expected for a normal *p-n* junction [19]. These results indicate that a high-quality *n*-Ge/*p*-Si junction was obtained.

We successfully observed EL from our LED at RT as shown in Fig. 3. A peak appeared at the energy of the direct-gap of Ge, 1590 nm (0.78 eV). On the other hand, the indirect-gap EL which should be peaked around 1800 nm was not detected, which is consistent with the previous studies [16,17]. The absence of the indirect-gap EL is expected to turn useful in determining the otherwise diminishing *P* values of the injected electrons [17]. Moreover, the optical selection rules are established only for the direct-gap transitions and little is known for the indirect-gap EL.

4. Conclusions

We demonstrated Ge-based LEDs with ferromagnetic electrodes and investigated their electrical and optical properties. Our LED showed clear rectification behavior, indicating a high-quality *p-n* junction. We successfully observed a clear direct-gap EL at RT without a trace of indirect-gap EL. These results are an important step toward the development of the Ge-based spin-LED, a superior method to directly estimate the *P* values of the injected electrons.

Acknowledgment

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