C-1-1 (Invited)

Si-Based Infrared Light Emitters Using Semiconducting Iron Disilicide

Takashi Suemasu, Shigemitsu Murase, Yuta Ugajin and Mitsushi Suzuno

University of Tsukuba, Institute of Applied Physics Tsukuba, Ibaraki 305-8573, Japan Phone: +81-29-853-5111 E-mail: suemasu@bk.tsukuba.ac.jp

1. Introduction

Semiconducting iron disilicide (β -FeSi₂) has been attracting significant interest as a Si-based light emitter since the demonstration of EL from β -FeSi₂ precipitates embedded in Si pn diodes on Si(001) substrates [1,2]. The emission wavelength of 1.6 µm at RT corresponds to a low loss window of the Si/SiO2 photonic wire waveguide. We therefore think that β -FeSi₂ is a promising material as a light emitter for optical interconnect in Si integrated circuits. There have been several reports to date on the EL of β -FeSi₂ at RT. Further efforts have been paid to enhance the luminescence intensity of β -FeSi₂. One way to enhance the luminescence intensity of β-FeSi₂ is to increase the volume of β -FeSi₂ particles in Si without introducing defects. Two- and three-layered β-FeSi₂-particles/Si structures with β-FeSi₂ size kept constant enhanced the luminescence intensity of β -FeSi₂. Another way is to embed a β -FeSi₂ continuous film in Si instead of β-FeSi₂ particles, and to form Si/β-FeSi₂/Si (SFS) double heterostructures (DH). Recently, a SFS DH was realized on Si(111) substrates in spite of the larger lattice mismatch of approximately 5%, and the EL of β-FeSi₂ at RT was also realized. However, it has been no report on the formation of SFS DH on Si(001). This is probably because the epitaxial β -FeSi₂ film on Si(001) easily agglomerates into isolated islands when it was annealed or embedded in Si by MBE at high temperatures for improving the crystallinity of β-FeSi₂. Very recently, Sunohara et al. succeeded the formation of SFS DH on Si(001) for the first time and obtained intense 1.54 β m PL at 77 K [3].

In this paper, we discuss the difference in PL and EL properties between SFS DH with β -FeSi₂-particles active region and β -FeSi₂-film active region.

2. Experimental

SFS structures with β -FeSi₂-particles active region were fabricated on Si(001) as follows. First, 10-nm-thick [100]-oriented β -FeSi epilayers were grown on n^+ -Si(001) substrates by reactive deposition epitaxy (RDE) at 470°C. The sample was then annealed *in situ* at 850°C for 1 h to improve the crystal quality of the β -FeSi₂. The β -FeSi film agglomerates into islands during this process. Consequently, a 0.3-µm-thick undoped *p*-Si layer was grown by MBE at 500°C. Samples were finally annealed at 900°C for 14 h in Ar atmosphere, resulting in β -FeSi₂ particles embedded in the Si matrix. Fabrication of an SFS DH on Si(001) is as follows. [100]-oriented 8-nm-thick β -FeSi₂ films were grown on n^+ -Si(001) substrates by RDE at 470°C. Next, a 0.3-µm-thick undoped *p*-Si layer was grown by MBE at 500°C. Steady-state PL measurements and time-resolved PL were performed.

3. Results and discussion

 θ -2 θ XRD patterns of these samples were shown in Fig. 1. In both samples only [100]-oriented diffraction peaks of β -FeSi₂ were observed, indicating that the epitaxial relationship between β -FeSi₂ and Si was preserved even after the agglomeration and MBE-Si overgrowth. The high-temperature annealing enhanced the XRD intensity much more in sample A compared to that in sample B.

Figures 2(a) and 1(b) show SEM cross sections of samples A and B, respectively. The white parts in these figures are β -FeSi₂ particles. We can see that the β -FeSi₂ particles are embedded in Si for sample A, while the β -FeSi₂ continuous film was embedded in Si for sample B.



Fig.1 0-20 XRD patterns of samples A and B.



Fig.2 SEM cross sections of (a) sample A and (b) sample B.

Figure 3(a) shows normalized PL spectra of samples A and B at 8 K. Distinct PL was obtained even in sample B, which was not annealed at a high temperature. All the samples have a peak wavelength of approximately 1.54 μ m. For detailed investigation of the 1.54 μ m PL, time-resolved PL was performed, first, at around 80 K. The wavelength resolution was limited by the slit opening of the monochromator, and was approximately 15 nm. The time resolution of the system was approximately 1 ns. The PL decay curves of the 1.54 μ m PL from samples A and B are shown in Fig. 3(b). The decay curve obtained from sample A, SFS with β -FeSi₂ particles, could be explained well, as shown by the solid white line in Fig. 3(b), by one exponential decay curve with a decay time of 15 ns. In contrast, the decay curves obtained from sample B, SFS DH can be fitted assuming that it is composed of the sum of two exponentials as eq.(1),

$$I(t) = I_1 \exp(-\frac{t}{\tau_1}) + I_2 \exp(-\frac{t}{\tau_2})$$
(1)

When the τ_1 and τ_2 are 15 ns and 97 ns, respectively, the experimental curve of sample B is reproduced well. We cannot rule out other components with different decay times, but it can at least be stated that the two components are dominant.

In order to investigate temperature dependence of decay times, time-resolved PL measurements were performed from 8 K to around 150 K. PL decay curves for sample B can be described well by two discrete decay times over the entire temperature range. Figure 4 shows the obtained PL decay times versus temperature plots. As seen in the figure, the PL emission of sample B exhibited two different decay times over a wide temperature range. The short decay times were of the same order as those obtained from sample A, and they are less dependent on the temperature. The origin of these short decay times is considered to be recombination in β -FeSi₂. On the other hand, the long decay time obtained for sample B is considered to be due to the D1 luminescence. This is because the D1 line is another origin of the 1.54 µm PL. In addition, the long decay time obtained was comparable to the reported D1 decay times [4]. On the basis of these results, 1.54µm PL originated from at least two sources for sample B.



Fig. 3(a) Normalized PL spectra at 8 K and (b) time-resolved PL decay curves measured at 80 K.



Fig. 4 Temperature dependence of PL decay times.

Figure 5(a) shows the EL spectra at RT obtained from sample B, SFS DH. This is the first realization of EL at RT in SFS DH on Si(001). The current density, J, required for 1.6 µm EL (~20 A/cm²) is significantly supcompared pressed to sample A. LEDs with β -FeSi₂-particles active region, as shown in Fig. 5(b). On the basis of these results, we can say that SFS DH LEDs grown on Si(001) is much better than those SFS LEDs with β-FeSi₂ particles in terms of process simplicity and EL intensity. However, the EL intensity still increases super linearly with J. This means that numerous defect levels acting as nonradiative recombination centers exist in the LEDs. When the current flowing through the defect levels saturates, the bias current begins to contribute to radiative recombination and a reasonable EL output is obtained. By reducing these nonradiative centers, practical Si-based LEDs will be obtained in the near future.



Fig.5 (a) RT EL spectra of sample B, (b) current density necessary for EL output at RT.

4. Conclusions

We have formed SFS LEDs with β -FeSi₂ particles and β -FeSi₂ film active regions on Si(001) substrates. The current density necessary for EL output at RT was significantly suppressed in SFS DH LEDs compared to that in SFS LEDs with β -FeSi₂ particles.

References

- [1] Leong et al., Nature 387 (1997) 686.
- [2] Suemasu et al., Jpn. J. Appl. Phys. 39 (2000) L1013.
- [3] Sunohara et al., Thin Solid Films 508 (2006) 371.
- [4] Fukatsu et al., Appl. Phys. Lett. 68 (1996) 1889.