Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp216-217

Enhanced Room-Temperature 1.6 μm Electroluminescence from Si-Based Double Heterostructures Light-Emitting Diodes Using Iron Disilicide

M. Suzuno, T. Koizumi, H. Kawakami and T. Suemasu

Institute of Applied Physics, University of Tsukuba,
1-1-1, Tennoudai, Tsukuba, Ibaraki 305-8573, Japan
Phone: +81-29-853-5111 E-mail: bk200201424@s.bk.tsukuba.ac.jp

1. Introduction

Semiconducting iron disilicide (β-$FeSi_2$) has been attracting recent interest as a Si-based light emitter ever since the first demonstration of electroluminescence (EL) from β-$FeSi_2$ precipitates embedded in Si *pn* diodes [1]. There have been several reports to date on the EL of β-$FeSi_2$ fabricated on Si substrate at RT [2-5]. However, the EL intensity has been very weak, and thus the emission power and quantum efficiency of this material have yet to be reported. These two figures of merit are indispensable when comparing the EL properties of various silicon-based light emitters. The purpose of the present work is to improve EL intensity by reducing nonradiative recombination at the β-$FeSi_2$/Si heterointerfaces. The lattice mismatch is estimated to be approximately 5.5% and 2% for β-$FeSi_2$ on Si(111) and Si(001), respectively [5]. These values are high enough to result in a relatively high density of defects at the heterointerfaces. To suppress nonradiative recombination there, we attempted two methods. First, we investigated the dependence of β-$FeSi_2$ thickness on EL intensity in *p*-Si/β-$FeSi_2$/*n*-Si(111) (SFS) double heterostructures (DH) LEDs fabricated by molecular beam epitaxy (MBE). With increasing a β-$FeSi_2$ thickness up to 1 μm, the EL intensity was increased, and a 1.6 μm EL emission of over 0.4 mW was achieved at RT. Next, we employed lattice-matched $Si_{0.7}Ge_{0.3}$ layers and fabricated *p*-SiGe/β-$FeSi_2$/*n*-SiGe (S_GFS_G) DH LEDs on Si(001) by MBE. The current density necessary for EL output decreased significantly down to around 1 A/cm^2, the smalles value ever reported.

2. Experimental

The growth procedure employed for the preparation of SFS DH LEDs on *n*-Si(111) is the same as that adopted previously [6]. Briefly, a 20-nm-thick highly [110]/[101]-oriented β-$FeSi_2$ epitaxial template was formed at 650 °C by RDE of iron onto a hot *n*-Si(111) substrate. Si and Fe were then coevaporated by MBE onto the template at 750 °C to form a continuous β-$FeSi_2$ film. The total thickness of the β-$FeSi_2$ film was varied among samples in a range from 80 nm to 1 μm. A 1-μm-thick undoped *p*-Si layer was then grown on the β-$FeSi_2$ by MBE at 500 °C, followed by B-doped p^+-Si at 700 °C. Finally, the wafers were annealed at 800 °C in N_2 for 14 h.

The growth procedure employed for the preparation of β-$FeSi_2$ on lattice-matched Si(001) surfaces using $Si_{0.7}Ge_{0.3}$ layers is the same as that adopted previously [7]. A 20-nm-thick strained-Si layer was epitaxially grown at 650 °C on a 0.75-μm-thick relaxed $Si_{0.7}Ge_{0.3}$ layer. The lattice mismatch between the two materials is reduced to approximately one-third of the original value using the strained-Si layer. Approximately 220-nm-thick [100]-oriented β-$FeSi_2$ films were grown by RDE and MBE. Next, an approximately 300-nm-thick undoped $Si_{0.7}Ge_{0.3}$ layer was grown by MBE at 550 °C, followed by an approximately 200-nm-thick Sb-doped n^+-Si capping layer at 500 °C.

The crystal quality of the grown layers was characterized by x-ray diffraction (XRD). Luminescence was detected phase sensitively by a liquid nitrogen cooled InP/InGaAs photomultiplier (Hamamatsu Photonics R5509-72). Emission power of LEDs was measured in a face-to-face configuration using an optical power meter (Newport1815-C).

3. Results and Discussion

Figure 1 shows θ–2θ XRD patterns of SFS DH LED with a 1-μm-thick β-$FeSi_2$ layer and S_GFS_G DH LED. Highly [110]/[101] and [100]-oriented β-$FeSi_2$ film was epitaxially grown on Si(111) and lattice-matched Si(001), respectively. Similar results were obtained for other LEDs.

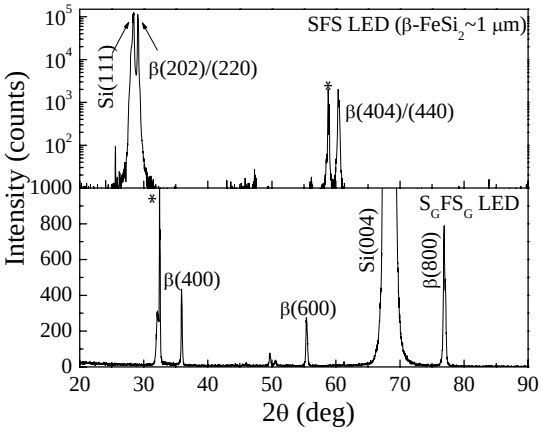

Fig. 1 θ-2θ XRD patterns of LEDs.

Figure 2 shows the EL emission power with respect to injection current I for SFS LEDs with different β-$FeSi_2$ thicknesses of 80 nm, 200 nm, and 1 μm operating at RT. Inset shows a RT EL spectrum for the LED with a 200-nm-thick β-$FeSi_2$ layer at I=400 mA. The asymmetric spectrum is attributed to the fact that the quantum efficiency of the detector decreased for wavelengths beyond 1.6 μm. With increasing β-$FeSi_2$ thickness, the emission power increased and the injection current necessary for EL output decreased. Emission power of 0.4 mW was achieved for the LED with a 1 μm-thick β-$FeSi_2$ layer, at an injection current of 460 mA (current density, 20 A/cm^2). This emission power is the highest reported for any silicon-based light emitter, and corresponds to an external quantum efficiency, η, of 0.11%. On the basis of these result, we conclude that the separation of injected carriers in β-$FeSi_2$ from the defective Si/β-$FeSi_2$ heterointerfaces improved the luminescence intensity in β-$FeSi_2$ as the thickness of the β-$FeSi_2$ layer increased. The influence of defective heterointerfaces on the luminescence has already been reported in GaAlAs/GaAs/GaAlAs heterointerfaces [8]. However, the J value necessary for EL output (~5 A/cm^2) is still larger. Figure 3 shows a RT EL spectrum for the S_GFS_G DH LED. The J value necessary for EL output decreased drastically to approximately 1 A/cm^2, which is the smallest J ever reported for β-$FeSi_2$. This result shows that the influence of nonradiative recombination due to defects at the β-$FeSi_2$/Si heterointerfaces was suppressed by using lattice-matched Si surface. Figure 4 shows thermal quenching of the normalized integrated EL intensity of S_GFS_G DH LED when the injection J was 1.8 A/cm^2. The internal η value was estimated to approach a value as large as approximately 1% at RT assuming that it approaches 100% at the lowest temperature.

3. Conclusion

We have fabricated Si/β-$FeSi_2$/Si (SFS) DH LEDs on Si(111) substrates with β-$FeSi_2$ thickness ranging from 80 nm to 1 μm, and SiGe/β-$FeSi_2$(220 nm)/SiGe (S_GFS_G) DH LEDs on lattice-matched Si(001) surface using $Si_{0.7}Ge_{0.3}$ layer by MBE. As the thickness of the β-$FeSi_2$ layer increased in SFS DH LEDs, the EL output increased for a given J. The emission power of over 0.4 mW and external η of approximately 0.1% was demonstrated for 1 μm β-$FeSi_2$. The smallest current density necessary for EL, that is approximately 1 A/cm^2, was achieved for S_GFS_G DH LEDs.

[1] D. Leong, M. Harry, K. J. Reeson, and K. P. Homewood, Nature (London) **387**, 686 (1997).
[2] T. Suemasu, Y. Negishi, K. Takakura, and F. Hasegawa: Jpn. J. Appl. Phys. **39**, L1013 (2000).
[3] L. Martinelli, E. Grilli, M. Guzzi, and M. G. Grimaldi: Appl. Phys. Lett. **83**, 794 (2003).
[4] S. Chu, T. Hirohada, H. Kan, and T. Hiruma: Jpn. J. Appl. Phys. **43**, L154 (2004).
[5] J. E. Mahan, V. L. Thanh, J. Chevrier, I. Berbezier, J. Derrien, and R. G. Long, J. Appl. Phys. **74**, 1747 (1993).
[6] M. Suzuno, S. Murase, T. Koizumi, and T. Suemasu, Appl. Phys. Express **1**, 021403 (2008).
[7] T. Saito, T. Suemasu, K. Yamaguchi, K. Mizushima, and F. Hasegawa: Jpn. J. Appl. Phys. **43** , L957 (2004).
[8] R. J. Nelson and R. G. Sobers, Appl. Phys. Lett. **32**, 761 (1978).

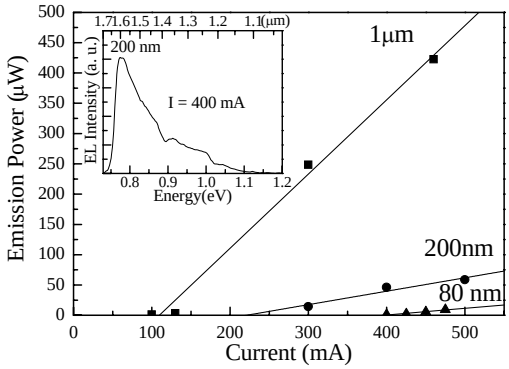

Fig. 2 EL emission power with respect to injection current measured at RT for SFS DH LEDs with β-$FeSi_2$ layer thicknesses of 80 nm, 200 nm, and 1 μm. (Inset) RT EL spectrum for LED with a 200 nm-thick β-$FeSi_2$ layer at 400 mA.

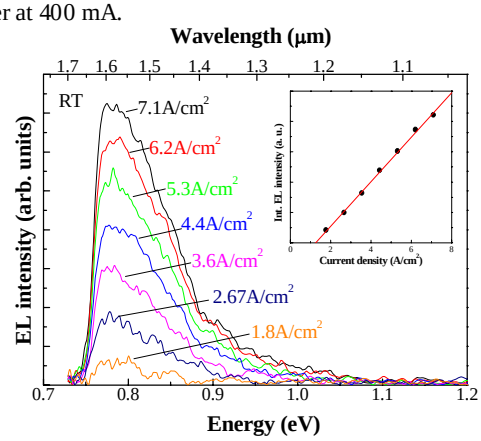

Fig. 3 EL spectra of S_GFS_G DH LED measured at RT. The dependence of integrated EL intensity on J was inserted.

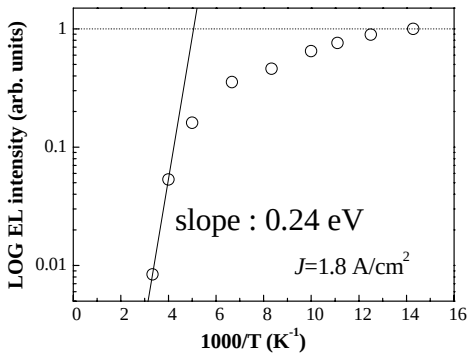

Fig. 4 Normalized integrated EL intensity versus inverse temperature for S_GFS_G DH LED at J=1. 8 A/cm^2.