High-Power Infrared Silicon Light-emitting Diodes Fabricated and Operated using Dressed Photons

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Abstract
Mesh-electrode type and flip-chip type silicon light-emitting diodes were fabricated by using dressed photons. Their emission spectral profiles showed several peaks originating from phonons in a dressed-photon–phonon, from which the existence of a photon breeding phenomenon was confirmed. The highest optical output power emitted from these devices was 2 W at a substrate temperature of 77 K. The highest optical power density from the flip-chip type was as high as eight-times that from the mesh-electrode type.

1 Introduction

There is a long-held belief in optical science and technology that crystalline silicon (Si) is not suitable for use in light-emitting devices. The reason for this is that it is an indirect-transition type semiconductor, in which the momentum of an electron at the bottom of the conduction band and that of a hole at the top of the valence band are different from each other. Therefore, for electron–hole recombination, a phonon is required to satisfy the momentum conservation law. However, the probability of the electron–phonon interaction is low, resulting in a low interband transition probability.

In order to realize light-emitting devices using Si, porous Si [1], a super-lattice structure of Si and SiO_2 [2,3], Si nanoprecipitates in SiO_2 [4], Er-doped Si [5], and Si-Ge [6] have been employed. However, in these examples, the optical output powers were very low since the Si still worked as an indirect-transition type semiconductor.

In contrast to these examples, the authors have previously realized novel light-emitting diodes (LEDs), lasers, and related light-emitting and -detecting devices by using Si bulk crystal and dressed photons (DPs) [7]. A DP is a novel quantum field created as a result of the interaction between a photon and an electron–hole pair in a nanometric space. A dressed-photon–phonon (DDP), created as a result of the interaction between the DP and a phonon, has also been used [8]. The DPP was created in an Si crystal, resulting in efficient light emission by the momentum exchange between a multi-mode coherent phonon in the DPP and an electron in the conduction band of the Si.

In the present study, we improved on a previously fabricated infrared Si-LED (wavelength: 1.3 μm) [9] to achieve higher current injection and more efficient heat dissipation. This paper reports the fabrication method and light-emission characteristics of the improved high-power Si-LEDs.

2 Fabrication

The first part of this section reviews the principles of fabrication based on a novel DPP-assisted annealing method. The second part is devoted to the procedures for fabricating devices of a mesh-electrode type and a flip-chip type for allowing higher current injection and more efficient heat dissipation.

2.1 Principles

To fabricate an LED, as the first step, the surface of an n-type Si crystal is doped with boron (B) atoms to transform it to a p-type layer, thereby forming a pn-homojunction. As the second step, the crystal is annealed using a novel method named DPP-assisted annealing [7]. In this method, by means of current injection, the Si crystal is heated by Joule energy to diffuse the B atoms. During this heating, the Si crystal surface is irradiated with light to create DPPs at the B atoms. The electrons injected into the conduction band exchange momenta with the phonons in the created DPPs, thus recombining with positive holes and emitting light. This emission process is stimulated emission because it is triggered by light irradiation. The emitted light propagates outside the Si crystal, which means that a part of the Joule energy for heating is dissipated out in the form of optical energy. As a result, the diffusion rate of the B atoms decreases locally. By a balance between heating by the Joule energy and cooling by the optical energy dissipation, the spatial distribution of B atoms varies autonomously and reaches a stationary state.

Such a stationary distribution of B atoms can be the optimum distribution for spontaneous emission because its probability is proportional to the probability of the stimulated emission above. From high-resolution analysis of the B atom distribution, it was confirmed that two B atoms formed a pair whose length was three-times the crystal lattice constant of Si. It was also confirmed that the pair was oriented perpendicular to the propagation direction and to the polarization direction of the irradiated light [10].

2.2 Procedures

Sb-doped n-type Si crystal was used. In order to transform its surface to an n-type layer, the Si crystal was doped with B atoms by a two-step ion implantation method, where the doping energies were 700 keV and 10 keV.

2.2.1 Mesh-electrode type LED

Figure 1 shows a photographic profile of the fabricated device: A homogeneously flat film of Cr/Al/Au (thicknesses: 30/200/300 nm) was coated on the n-type surface of the Si crystal described above to serve as a cathode. A mesh film of Cr/Au (thicknesses: 30/300 nm) was coated on the p-type surface to serve as an anode. The crystal was diced to form devices with areal sizes of 1 mm × 1 mm, and these devices were bonded on a PCB substrate made of high-thermal-conductivity AlN. The diameters of eight electric wires were increased from the previously employed 25 μm [9] to 45 μm to avoid damage to the electric wires and electrodes during high current injection.

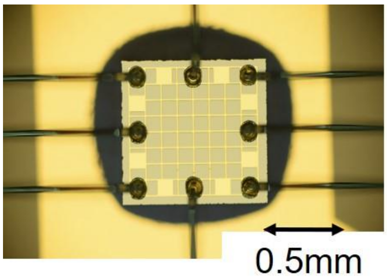

Fig. 1 Photographic profile of the fabricated mesh-electrode type LED.

The conditions for the DPP-assisted annealing were: (1) A substrate temperature, of 285 K; (2) irradiation light with a wavelength of 1342 nm and a power of 2.0 W; (3) injected current having a triangular waveform (50 s period) and a peak current of 1.3 A (current density 1.3 A/mm^2); and (4) an annealing time of 2 hours.

Figure 2 shows the relation between the applied voltage and injected current in the fabricated Si-LED. A drastic decrease in the electrical resistance can be seen after the DPP-assisted annealing, which is evidence of successful annealing.

2.2.2 Flip-chip type LED

To achieve higher injected current density than that of the mesh-electrode type, a flip-chip type LED was fabricated. First, its areal size was decreased. Second, a larger-diameter electric wire was used. Third, the flip-chip structure was employed, in which the p-type layer was contacted to the PCB substrate for efficient heat dissipation.

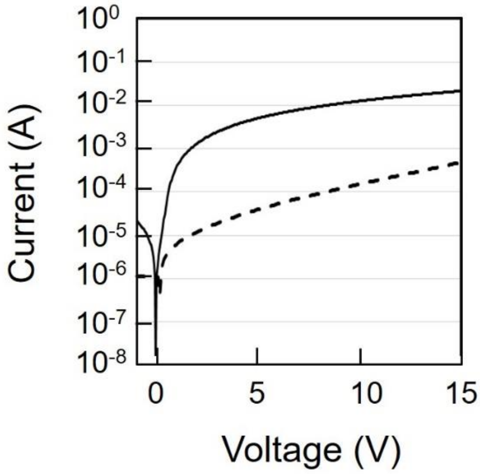

Fig. 2 Relation between the applied voltage and injected current.
Broken and solid curves are the results acquired before and after the DPP-assisted annealing, respectively.

Figure 3 shows a photographic profile of the fabricated device: A homogeneously flat film of Cr/Au/Ti/Pt/Au (thicknesses: 3/300/100/300/500 nm) was coated on the p-type surface of the Si crystal to serve as an anode. A patterned film of Cr/Au (thicknesses: 10/500 nm) was coated on the n-type surface as a cathode. The crystal was diced to form devices with areal sizes of 0.35 mm×0.35 mm, which was smaller than that of the mesh-electrode type described in Subsection 2.2.1. This is equivalent to the size of commercially available devices made by using a conventional direct-transition type semiconductor. The diced device was bonded on a PCB substrate made of AlN. A single electric wire with a diameter as large as 60 μm was used to realize high-density current injection without any electrical damage.

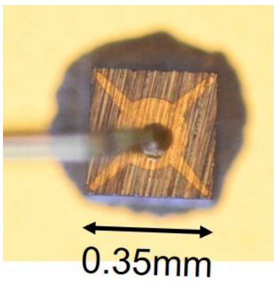

Fig. 3 Photographic profile of the fabricated flip-chip type LED.

The conditions for the DPP-assisted annealing were: (1) A substrate temperature of 289 K; (2) irradiation light with a wavelength of 1342 nm and a power of 0.24 W (areal power density: 1.9 W/mm^2); (3) injected current with a triangular waveform (10 s period) and a peak current of 0.16 A (current density: 1.3 A/mm²); and (4) an annealing time of 7.2 hours.

3 Light emission characteristics

With conventional current injection, the fabricated device worked as a Si-LED: The electrons injected into the conduction band exchanged momenta with phonons even though the probability of this exchange was extremely low. As a result, they recombined with a positive hole, resulting in spontaneous light emission. Since this light created DPPs at the B atoms, phonons in the DPP could exchange momenta with other electrons, resulting in further light emission. By repeating this process, the emitted light intensity increased and reached a stationary state to establish steady LED operation.

3.1 Mesh-electrode type LED

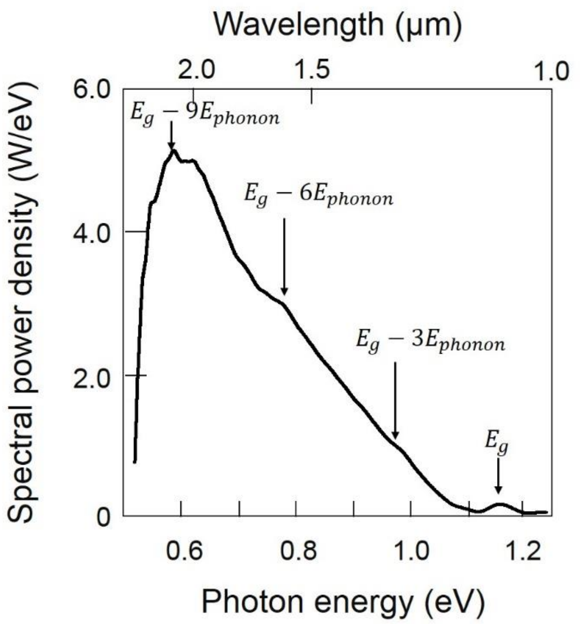

Fig. 4 Spectral profile of the emitted light at substrate temperature of 77 K.

Figure 4 shows the spectral profile of the emitted light, which was acquired by cooling the substrate to 77 K and injecting a current of 2.0 A. In this figure, E_g represents the bandgap energy of the Si crystal at 77 K. This figure shows that the spectral profile has several peaks at $E_g - nE_{phonon}$, where n is an integer and E_{phonon} is the phonon energy.

The spectral peak at $E_g - 3E_{phonon}$ corresponds to the photon energy of the light irradiated during the DPP-assisted annealing [10]. This correspondence has been named photon breeding [11], which originates from the autonomous formation of pairs of B atoms by DPP-assisted annealing, as was described in Subsection 2.1. Three phonons contribute to the light emission at $E_g - 3E_{phonon}$, because the length of the B atom pair is three-times the crystal lattice constant of Si. This figure also shows the higher harmonics of the phonon contributions, i.e., $E_g - 6E_{phonon}$ and $E_g - 9E_{phonon}$.

Figure 5 shows relations between the injected current (I) and the optical output power (P) of the upward-emitted light from the upper surface of the Si-LED, which were acquired at several substrate temperatures. It shows that P is proportional to I^2 in the lower current region, whereas it is proportional to I^4 in the higher current region. The origin of the I^2-relation has been identified as Auger scattering [9]. The I^4-relation originated in amplification by the stimulated emission.

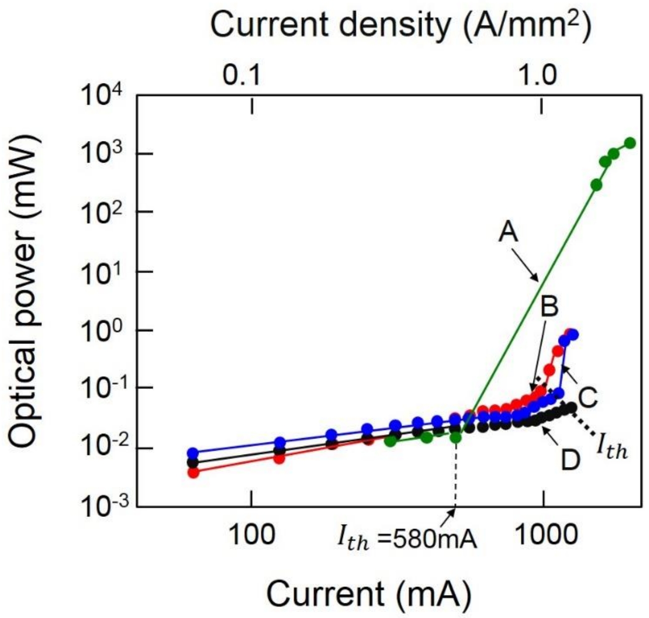

Fig. 5 Relations between the injection current and the optical output power. Substrate temperatures were 77 K (A), 273 K (B), 290 K (C), and 293 K (D).

By defining the current at the boundary between the region of the I^2- and I^4-relations as the threshold I_{th}, it is found that its value was lower at lower substrate temperatures. For example, it was 580 mA at 77 K. This means that the threshold current density was 0.58 A/mm², which is close to the threshold current density (0.20–0.35

A/mm^2) of the Si-laser fabricated by the DPP-assisted annealing [12]. The highest optical output power in Fig. 5 was 2 W with an injection current of 2 A and a substrate temperature of 77 K. This value is as high as 10^3-times that of a commercially available LED*.

The image A in Fig.6 shows the photograph of the light spot emitted from the presently fabricated Si-LED. The image B is from the commercially available LED above*. By comparing these images, a very high optical output power of the present Si-LED can be recognized.

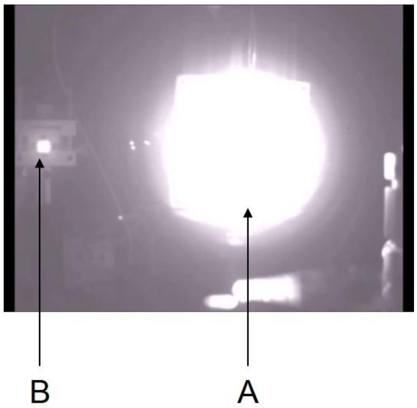

Fig. 6 Photographs of light spots.

A and B are the spots emitted from the Si-LED fabricated in the present study and from a commercially available LED, respectively.

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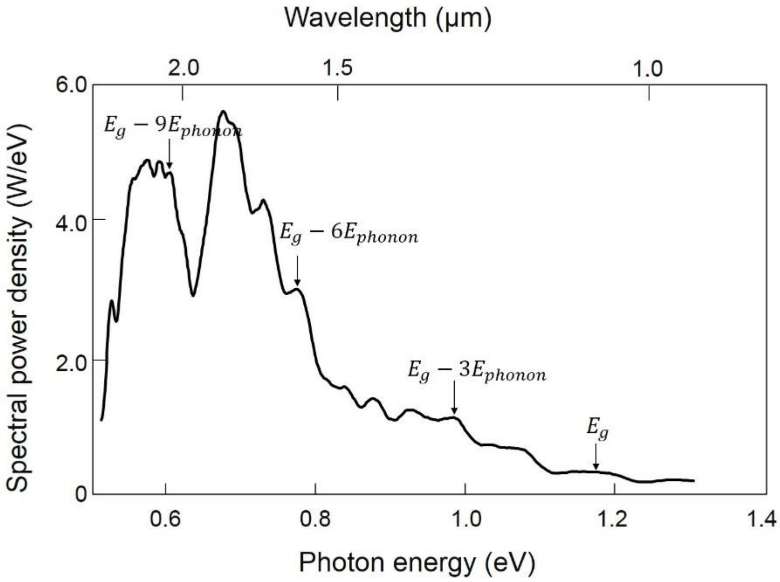
*For example, the optical output power of a Hamamatsu Photonics model L12509-0155K, which is made of a direct-transition type semiconductor (InGaAs), is 2 mW. The peak emission wavelength is 1.55 μm.

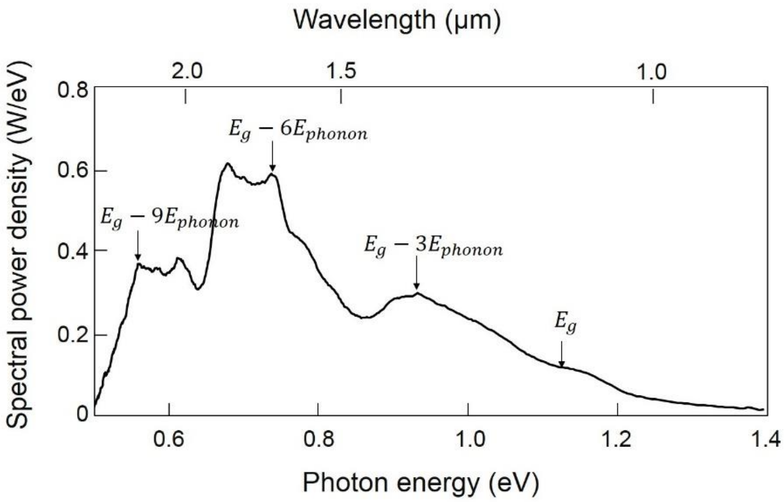
3.2 Flip-chip type LED

Figure 7(a) shows the spectral profile of the light emitted from the flip-chip type LED, which was acquired by cooling the substrate to 77 K and by injecting a current of 3.21 A. Figure 7(b) shows the profile at a substrate temperature of 283 K and an injection current of 2.45 A. These figures also clearly demonstrate spectral peaks at $E_g - 3E_{phonon}$, $E_g - 6E_{phonon}$, and $E_g - 9E_{phonon}$, as was the case in Fig. 4.

Figure 8 shows relations between I and P of the upward-emitted light from the upper surface of the Si-LED, which were acquired at several substrate temperatures. The highest optical output power in this figure was as high as 2 W at 3 A-injection current and at a 77 K-substrate temperature. This demonstrates an extremely high optical output power density was achieved, as high as eight-times that of the mesh-electrode type LED described in Subsection 3.1.



(a)



(b)

Fig. 7 Spectral profile of the light emitted from the flip-chip type LED.
(a),(b) The substrate temperatures were 77 K and 283 K, respectively.

It can be seen that the relations between I and P showed more complicated profiles than those in Fig. 5: In the low-current region [a], P increased slowly with increasing I, whereas it increased rapidly in the high-current region [c]. The unique feature is that P decreased with increasing I in the intermediate region [b]. Figures

9(a)-(c) show photographs of the upward-emitted light spots in the regions [a]-[c], respectively. Among them, Fig. 9(b) shows that the light was emitted not only in the upward direction but also in the side direction of the device. This side-emission was attributed to the decrease in the acquired value of P in region [b]. It should be noted that this side-emission was due to stimulated emission, which suggests the possibility of super-luminescent diode and laser operation.

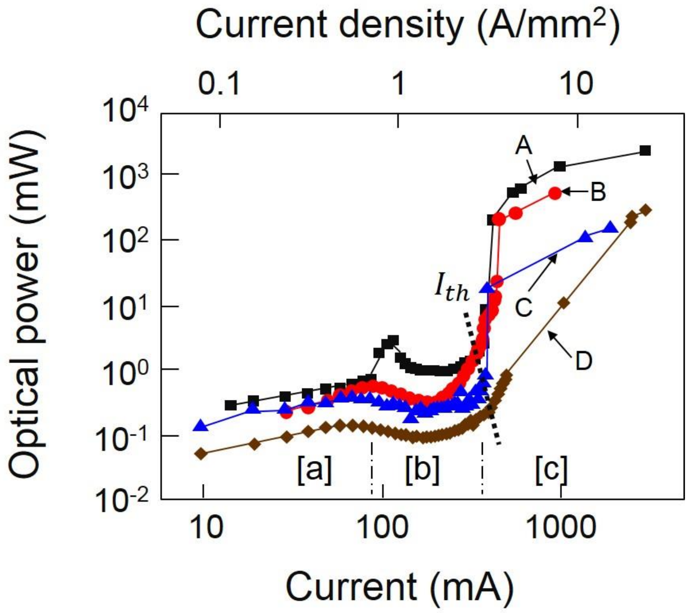


Fig.8 Relations between the injection current and the optical output power of the upward-emitted light from the surface of the Si-LED.

Substrate temperatures were 77 K (A), 195 K (B), 255 K (C), and 283 K (D).

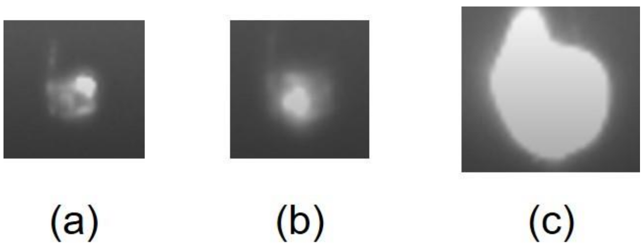


Fig.9 Photographs of the upward-emitted light spots.

(a), (b), (c) are images obtained in regions [a], [b], and [c] in Fig. 8, respectively.

As was the case in Fig. 5, the threshold I_{th} can be defined as the current at the boundary between regions [b] and [c]. Figure 10 shows its dependence on the substrate temperature T. The solid line, fitted to the experimental results of the closed circles, was expressed as $I_{th} = I_0 \exp(T / T_0)$. The characteristic temperature T_0 in this expression was 63 K, which corresponded to the energy $3E_{phonon}$ of three phonons in the DPP. This means that the electron–hole pair was confined in the potential well formed by three phonons. This value of T_0 was as high as that of a conventional laser fabricated by a direct-transition type semiconductor (InGaAsP), lasing at a wavelength of 1.3 μm [13], which suggests that future progress in the present study can realize highly reliable light-emitting devices using crystalline Si.

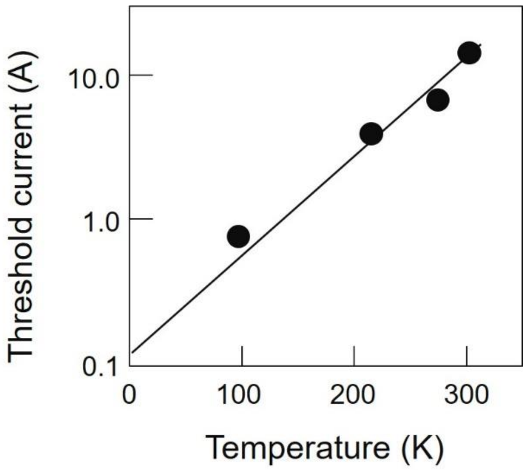


Fig. 10 Relation between the substrate temperature and the threshold current.

4 Summary

Mesh-electrode type and flip-chip type Si-LEDs were fabricated to realize higher-density current injection and more efficient heat dissipation. Their emission spectral profiles showed several peaks that originated from phonons in the DPP, by which a photon breeding phenomenon was confirmed. Their highest optical output powers were 2 W at injection currents of 2 A and 3 A, respectively, and a substrate temperature of 77 K. The highest optical power density from the flip-chip type was as high as eight-times that from the mesh-electrode type. In the case of the flip-chip type, the characteristic temperature of the threshold current for the rapid increase in the optical output power was 65 K, which corresponded to the energy of three phonons in the DPP.

Acknowledgements

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