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Stimulated Emission in Silicon Fin Light-Emitting Diode

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1. Introduction

Si based light source is the only missing component for Si photonics to achieve the convergence of electronics and photonics on a chip [1-4]. The nature of the indirect band gap can be overcome by the quantum mechanical confinement effects [5]. However, the severe trade-off between the confinement and carrier injections in low dimensional nanostructures limited practical applications.

In order to solve the problem, we previously proposed a device structure, where the ultra-thin Si quantum well (QW) is directly connected to the thick Si electrodes [6]. The device was fabricated by the local oxidation of the silicon-on-insulator (SOI) wafer with its uniformity controlled in an atomic level, and the electro-luminescence was observed by lateral carrier injections into the Si QW [6]. Moreover, the stimulated emissions have been observed by embedding the Si QW in a free standing resonant cavity with distributed-feedback structures made of Si_3N_4 and SiO_2 [7].

The next requirement towards a practical Si laser diode is to enhance the effective gain due to the evanescent coupling between the guided optical mode and Si QW. The obvious approach is to increase the number of QWs from the single QW (SQW) to multiple QWs (MQWs). However, it is not easy to make Si MQWs whose surface was covered with amorphous SiO_2 by epitaxial growth. Unlike compound semiconductor technologies, it is difficult to make vertical stacks of MQWs or the vertical-cavity surface-emitting laser (VCSEL) [8] in Si processes. Instead, we propose planar MQWs structures suitable to Si technologies.

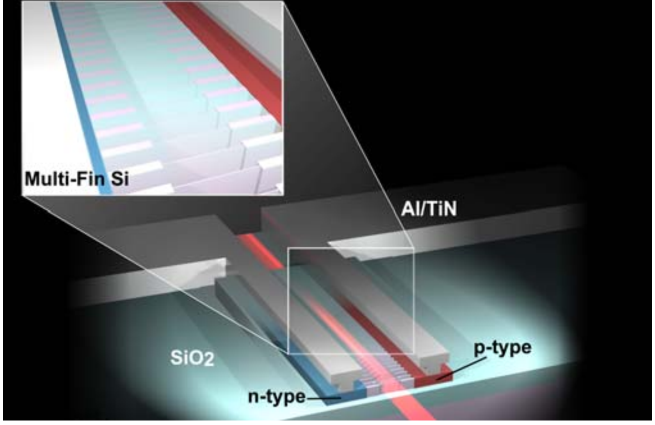

Fig. 1 Silicon multi-fin light-emitting diode.

2. Device Structure and Fabrication

The proposed Si fin light-emitting diode (FinLED) is schematically shown in Fig. 1. Instead of a lateral SQW, MQWs are formed along the vertical direction to the substrate. Each side of MQWs is connected with a heavily doped Si electrode, forming a lateral *pin* diode. In this FinLED, thousands of QWs can be integrated by simple lithography and etching processes.

The similar multi-fin device structure known as FinFET was proposed by one of the author for the final version of the double gate field-effect-transistor (FET) at the end of the scaling [9]. The differences between FinLED and FinFET are impurity profiles and absence/presence of gate processes. Therefore, it is possible to integrate both devices solely from the small modification of process steps. The practical challenge for the FinLED is that the width of the fin should be sufficiently small to expect the efficient light emission by quantum confinements, while for the FinFET the width should be larger to avoid the threshold voltage shift.

The fabricated multi-fin Si by dry etching is shown in Fig. 2. By using Si_3N_4 as a hard mask, the fin with the width of 20 nm and the height of 50 nm was formed. The width of the fin was further reduced by the oxidation processes. After the formation of multi-fins, the heavily doped electrodes are formed by ion implantations and the activation. Then, the Si_3N_4 film with the thickness of 250 nm was deposited and patterned to become a core of a waveguide located at the center of Si fins. After the metallization of Al/TiN, the H_2 annealing is performed to passivate the interface traps.

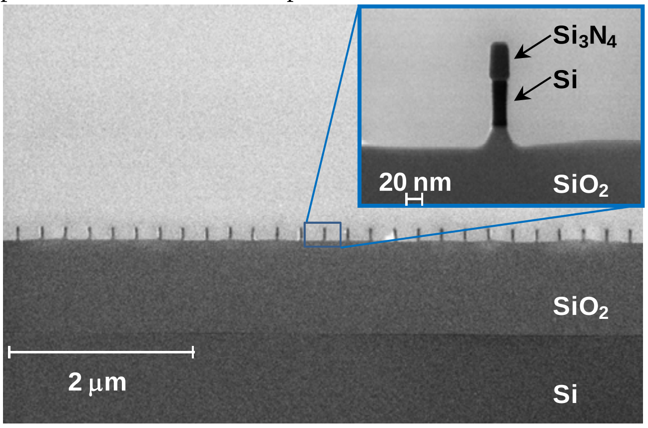

Fig. 2 Transmission-electron-microscope images of multi-fin Si.

3. Results and Discussions

The current-voltage characteristics of the Si FinLED are shown in Fig. 3. Under the application of the reverse bias, the dark current was less than 0.1 pA, confirming the formation of the lateral *pin* junction and excellent crystalline quality of fins. The small sub-threshold slope of 92 mV/decade also shows the low trap density at the Si fin/SiO_2 interface. The threshold voltage of 1.76 V in the present Si FinLED is larger than the typical value of 0.8 V in the bulk. The increase of the threshold voltage is consistent with the widening of the band gap by the quantum confinements.

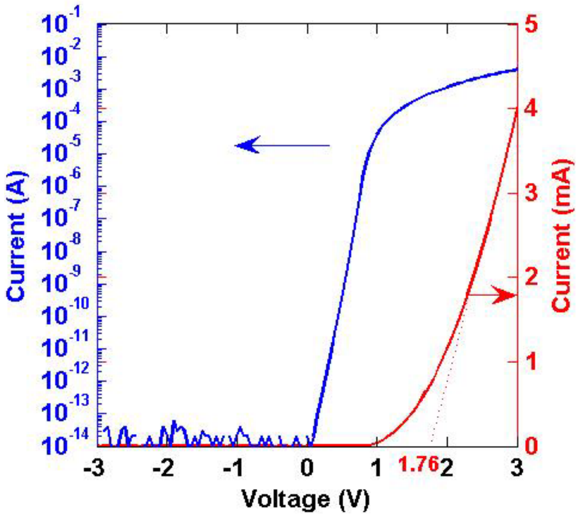

Fig. 3 Current-voltage characteristics of Si FinLED.

The electro-luminescence spectrum from the Si FinLED is shown in Fig. 4. Two peaks at 802.4 nm and 734.4 nm developed significantly with increased currents. These wavelengths correspond to emissions from Si fins with widths of around 1.0 nm according to our theoretical calculations [5]. The integrated intensity increased super-linearly with injected currents, as shown in the inset of Fig. 4, which indicates stimulated emissions.

In order to understand these spectral peaks, we observed near field images at the edge of the waveguide as shown in Fig. 5 (a). The image shows that the beam spreads vertically to the substrate, although the horizontal width of the waveguide (600 nm) is much larger than the thickness (250 nm). Therefore, the lowest cavity mode with the higher effective index n_{eff} was not dominated. Instead, the higher modes mainly propagating along the buried-oxide (BOX) layer would be responsible. The calculated mode profiles are similar to the experimental one, as shown in Fig. 5 (b) and Fig. 5 (c). For these modes, Si Fins work as index and gain coupled distributed-feedback (DFB) structures and stimulated emissions are expected at the stop band edge near the Bragg wavelength of $2n_{eff}\Lambda$, where Λ (300 nm) is the pitch of Si Fins. The calculated stimulated wavelengths almost agreed with experimental ones.

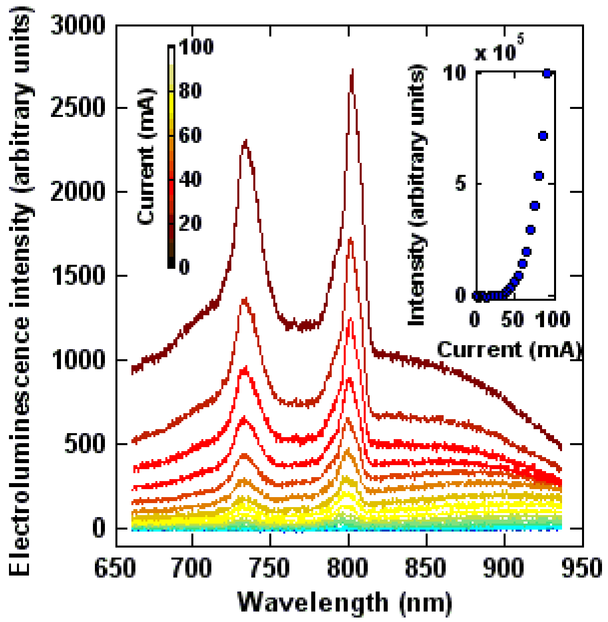

Fig. 4 Electro-luminescence spectra from Si FinLED under constant currents at room temperatures. The inset shows the integrated intensity.

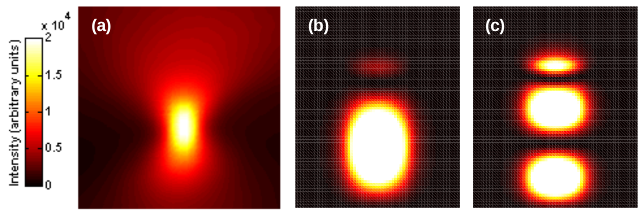

Fig. 5 Near field images of edge emissions from Si FinLED. (a) Experimental images under constant currents of 85 mA. Calculated mode profiles for stimulated emissions designed at the wavelengths of (b) 800.9 nm (n_{eff}=1.333) and (c) 752.5 nm (n_{eff}=1.250).

4. Conclusions

We have proposed a Si fin light-emitting diode to realize multiple quantum wells fabricated by Si technologies. The experimental results demonstrate the excellent transport characteristics and efficient electroluminescence in the infrared regime. Si based light emitters should open up a new opportunity for the convergence of photonics and electronics on a Si chip.

Acknowledgements
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