Silicon Quantum Well Light-Emitter for Optical Interconnections

S. Saito[1], Y. Suwa[2], H. Arimoto[3], D. Hisamoto[1], T. Mine[3], K. Takeda[3], T. Sugawara[3], and M. Aoki[1]

[1]*Central Research Laboratory, Hitachi, Ltd., and SORST, Japan Science and Technology, Kokubunji, Tokyo 185-8601, Japan.*
Tel: +81-42-323-1111, Fax: +81-42-327-7673, E-mail Address: shinichi.saito.qt@hitachi.com
[2]*Advanced Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185-8601, Japan.*
[3]*Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185-8601, Japan.*

Abstract: We have developed all-silicon based light-emitter for optical interconnections. The relatively short florescent lifetime of 4.2 ns in a silicon quantum well makes direct modulations at 10 Mbps accessible for low-end high-volume consumer applications.

OCIS codes: (230.5590) Quantum-well, -wire and -dot devices; (230.3670) Light-emitting diodes(140.3948); Microcavity devices

1. Introduction

One of the main issues to solve the interconnect bottleneck by silicon photonics is the lack of practical all-silicon laser diodes (LDs), since the indirect band gap character of bulk silicon impedes the stimulated emissions. Major achievements for developing silicon based lasers include photoluminescence [1] and electroluminescence (EL) [2] from porous Si and optical gain in Si nanocrystals [3]. While Raman [4, 5] and hybrid [6, 7] silicon lasers were successfully demonstrated, all of these require light sources made of non-silicon based materials. Therefore, all-silicon based light sources are still preferable options in silicon photonics.

We previously proposed the lateral carrier injection scheme, where the ultra-thin Si (100) quantum well (QW) is directly connected to the thick Si electrodes [8, 9]. Next prerequisite towards all-Si LDs was to realize the positive optical gain [10, 11]. One way to make an LD by small gain medium is to reduce the optical loss as much as possible. A vertical cavity surface emitting laser (VCSEL) [12] was a possible candidate to be made. However, it is difficult to make efficient distributed Bragg reflector (DBR) mirrors by stacking thick insulating films of the order of *100* pairs of films with different reflective index for high reflectance, for example ~*99.99* %. Instead, we propose to make a planar structure suitable for Si technologies and examine the possibility to apply it for the low-end high-volume consumer applications, such as mobile phones and lap top PCs.

2. Device structures and electron-luminescence characteristics

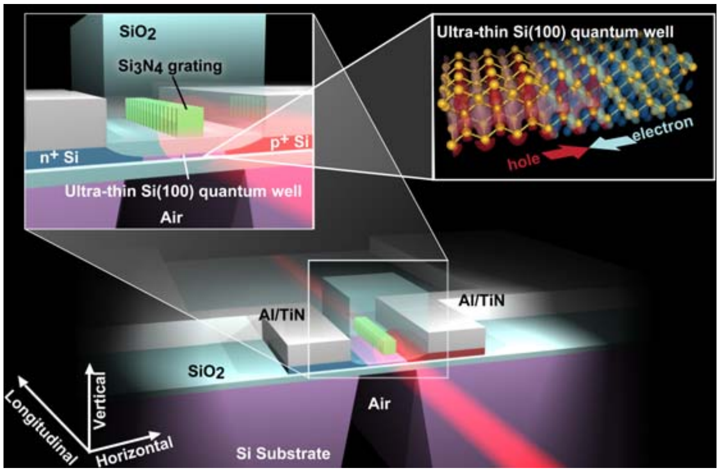

Fig.1 Schematic structure of Si quantum well (QW) light-emitter. The device consists of the lateral *pin* diode embedded in the distributed-feedback (DFB) resonant cavity. The grating is made of Si_3N_4 on the top of the thin SiO_2 layer. The part of the Si substrate is locally removed to enhance the optical confinement. The *evanescent* coupling to the cavity mode with the Si QW induces the stimulated emissions. Insets shows the enlarged view and wavefunctions of electrons and holes.

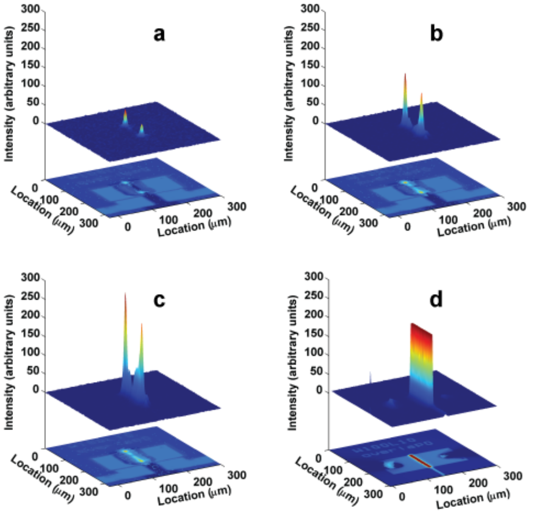

Fig.2 Electroluminescence (EL) from Si QW. Images were obtained constant DC current operations with integration time of *5* s. (a)-(c), EL images from LD with resonant cavity taken at *0.1*, *0.3*, and *0.5* mA. Most EL emissions are observed from edge of resonant cavity, which proves effective optical confinement in cavity. (d), EL images from reference device without resonant cavity taken at *3* mA. EL emissions are observed from entire Si QW.

Figure 1 shows the Si quantum well light-emitter fabricated by using the standard Si processes [8, 9, 11]. The Si (100) QW was made by local oxidation of Si-on-insulator (SOI) substrate. The Si_3N_4 grating was located just above the Si QW to ensure the evanescent coupling. The high difference of the reflective index between Si_3N_4 and SiO_2 is responsible for the strong optical feedback inside the distributed-feedback (DFB) resonant cavity. The part of the supporting Si substrate is removed by the alkali wet etching to prevent the optical loss to the substrate.

The EL images obtained from the vertical direction is shown in Fig. 2. We observed the EL emissions exclusively from the edge of the DFB cavity, which proves the effective optical confinements inside the Si3N4 core. On the other hand, in the reference device without the cavity, the EL emissions were observed from the entire Si QW. By increasing the currents, the emissions from the edge increases further, indicating stimulated emissions similar to our previous device with the DBR reflector [11].

Next, we examined the EL spectra, as shown in Fig. 3. In this experiment, we applied the forward voltage pulse with the pulse width of 100 ns and the period of 1 μs. In the device with the DFB cavity, we observed several peaks from the cavity modes, which were assigned to be the emissions from the stop band edge. No such modes observed in the reference device without the cavity. The integrated intensity also shows the amplified emissions at higher currents in the DFB device.

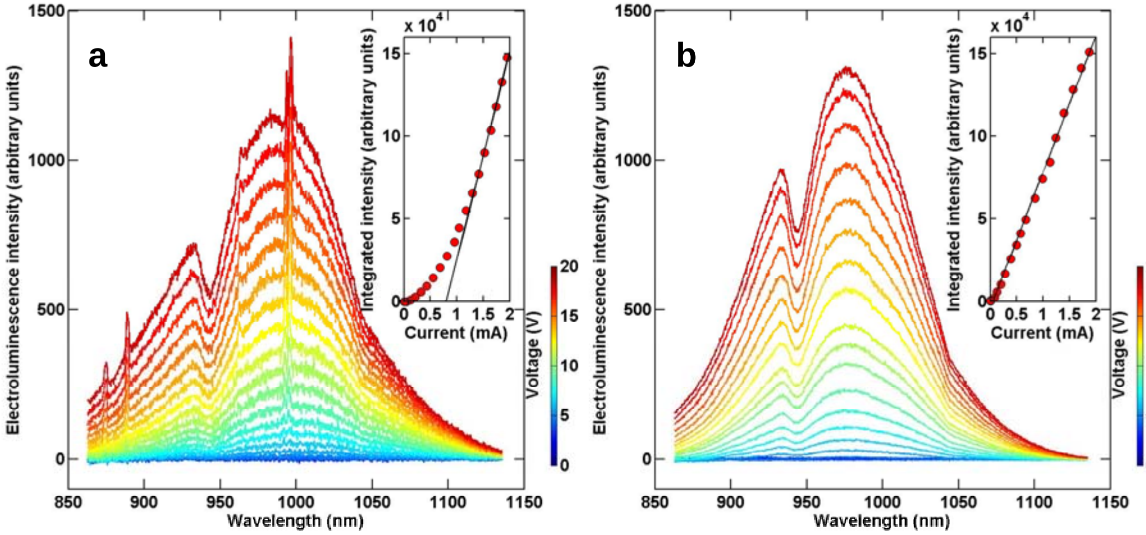

Fig. 3 Spectroscopic analysis of Si QW. (a), Stimulated emission spectra from LD with resonant cavity operated under application of voltage pulse. EL spectra obtained with integration time of *60* s are shown with applied voltage of *0* to *20* V with *1*-V steps. Inset shows amplified emissions at larger currents. (b), Spontaneous emissions spectra from reference device without resonant cavity operated under the same pulsed operation. No resonant peak observed. Inset shows no amplification. Dips around *940* nm originate from optical loss due to fiber and not device.

3. Direct modulation characteristics

The typical radiative recombination lifetime known so far in the low-dimensional Si nano-structure is of the order of 10 μs [3]. Such a large lifetime is not preferable to any practical low-end applications without using optical modulators. Therefore, we have examined modulation characteristics of the present device.

The experimental setup is schematically shown in Fig. 4 (a). We have characterized the recombination dynamics by a wafer level testing system. The observed decay time 4.2 ns was extremely small, but the decay dynamics might be limited by non-radiative recombinations at impurities or Auger effects. Then, we applied voltage pulses with a reduced width of 50 ns and a period of 100 ns, and we observed the clear modulation signals of emissions, as shown in Fig. 4 (b). Below a pulse period of 100 ns, the current was reduced due to the parasitic resistive-capacitive (RC) delay of the device. Therefore, the radiative lifetime is at least smaller than 100 ns, which is still small compared with similar systems. We think that the short radiative lifetime suggests that the mechanism of radiative recombinations were attributed to direct band gap behaviors by the conduction band valley projection to the Γ point in the Si (100) QW [10]. If our recombination mechanism is valid, we can reduce the radiative lifetime further, since our Si QW is not completely optimized [10]. Concerning with mechanisms, however, we cannot rule out the possible contributions from the interface states on the optical gain, whose importance was established in Si nanocrystals [3]. It is our future problem to explain the recombination dynamics completely in our Si QW systems.

No matter what the exact recombination mechanism is, the relatively fast direct modulation of 10 Mbps may well open up a possibility of using our Si QW light-emitters for low-end high-volume practical applications. The fabrication processes of the device can be fully compatible to the standard complementary-metal-oxide-semiconductor (CMOS) processes, therefore, there is no obstacle for the monolithic integration with Si QW light-emitters and CMOS logic/memory devices. Another advantages of using all-Si based light emitters is large-scale integration of light sources. By simply tuning up the width and spacing of the DFB grating, arrays of wavelength-division-multiplexing (WDM) light sources would be integrated with driver integrated-circuits (ICs).

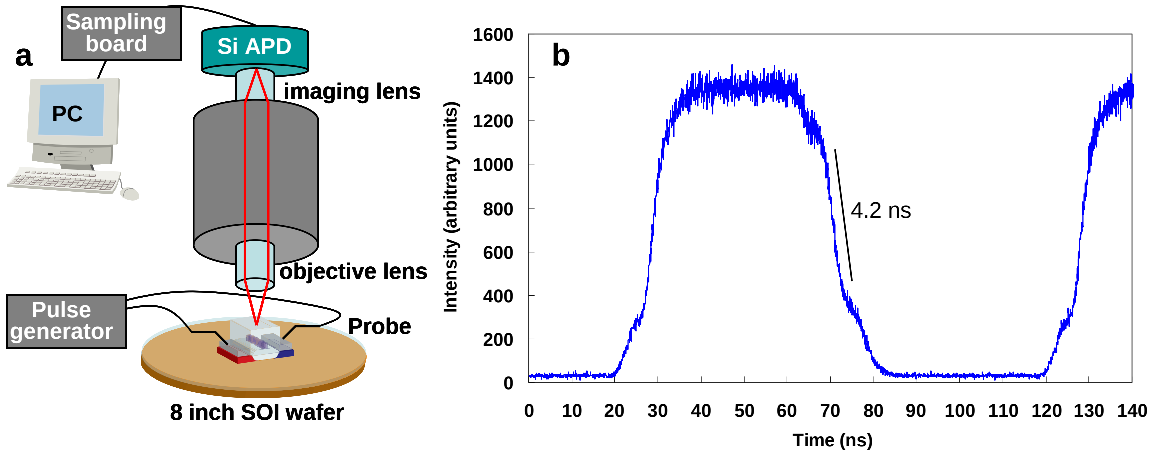

Fig.4 (a) Schematic experimental setup to examine the direct modulation characteristics of Si QW light-emitter. The electrical pulse is directly applied to the device on the 8 inch substrate. The EL emissions are collected by an objective lens located above the probe station and detected by the Si avalanche photo-diode (APD) module controlled by PC through an imaging lens.
(b) Modulation signal from Si QW light-emitter detected by Si APD module. The voltage pulse with the 20-V height, 50-ns width, and 100-ns period was applied directly to the Si QW light emitter. The florescent decay time was 4.2 ns.

4. Summary

We have developed Si QW light-emitters with the DFB structure for optical interconnections. We confirmed efficient optical confinement within the cavity of the suspended membrane. The EL spectra shows the resonant cavity modes, and the integrated intensity indicates the amplification at higher injection currents. By the direct modulation characteristics, we have found the relatively short florescent lifetime of 4.2 ns in the Si QW. The device might be applicable to the low-end applications operated around 10 Mbps.

5. References

[1] L. T. Canham, “Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers.”, Appl. Phys. Lett. **57**, 1046–1048 (1990).
[2] N. Koshida and H. Koyama, “Visible electroluminescence from porous silicon.”, Appl. Phys. Lett. **60**, 347–349 (1991).
[3] L. Pavesi, *et. al.*, “Optical gain in silicon nanocrystals.”, *Nature* **408**, 440-444 (2000).
[4] O. Boyraz and B. Jalali, “Demonstration of a silicon raman laser.”, Opt. Express **12**, 5269 (2004).
[5] H. Rong, *et. al.*, ”An all-silicon raman laser.” *Nature* **433**, 292 (2005).
[6] H. Park, *et. al.*, ”Hybrid silicon evanescent laser fabricated with a silicon waveguide and III-V offset quantum wells.”, Opt. Express **13**, 9460 (2005).
[7] A. W. Fang, *et. al.*, “A continuous-wave hybrid AlGaInAs-silicon evanescent laser.”, IEEE Photon. Technol. Lett. **18**, 1143 (2006).
[8] S. Saito, *et. al.*, “Electro-luminescence from ultra-thin silicon.”, Jpn. J. Appl. Phys. **45**, L679 (2006).
[9] S. Saito, *et. al.*, “Silicon light-emitting transistor for on-chip optical interconnection.”, Appl. Phys. Lett. **89**, 163504 (2006).
[10] Y. Suwa and S. Saito, “Intrinsic optical gain of ultrathin silicon quantum wells from first-principles calculations”, Phys. Rev. B **79**, 233308 (2009).
[11] S. Saito, *et. al.*, “Observation of Optical Gain in Ultra-Thin Silicon Resonant Cavity Light-Emitting Diode”, IEEE international electron devices meeting (IEDM), 19.5 (2008).
[12] K. Iga, “Vertical-cavity surface-emitting laser: Its conception and evolution.”, Jpn. J. Appl. Phys. **47**, 1–10 (2008).