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Quantum Confined Ultra-Thin Silicon Light-Emitting Transistor for On-Chip Optical Interconnection

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1. Introduction

Silicon photonics [1] are considered to be promising technologies for future on-chip optical interconnection beyond the conventional Cu interconnection. However, due to its indirect band-gap character of the bulk silicon, the integration of an appropriate light source to a Si chip is one of the most difficult challenges.

Quantum confinement effects [2] are useful to change the situation in the various nano-structures (Fig. 1). By choosing the appropriate crystallographic orientation, low dimensional Si is predicted to become the direct band gap semiconductor [3, 4].

A further difficulty exists in the device architecture, since the surface of Si is easily oxidized to form highly insulating SiO_2 layer, which prevents current injections except for small tunneling currents. In this paper, we propose a device structure [4] to inject currents directly to quantum confined ultra-thin Si and discuss its possible application to the on-chip optical interconnection [5].

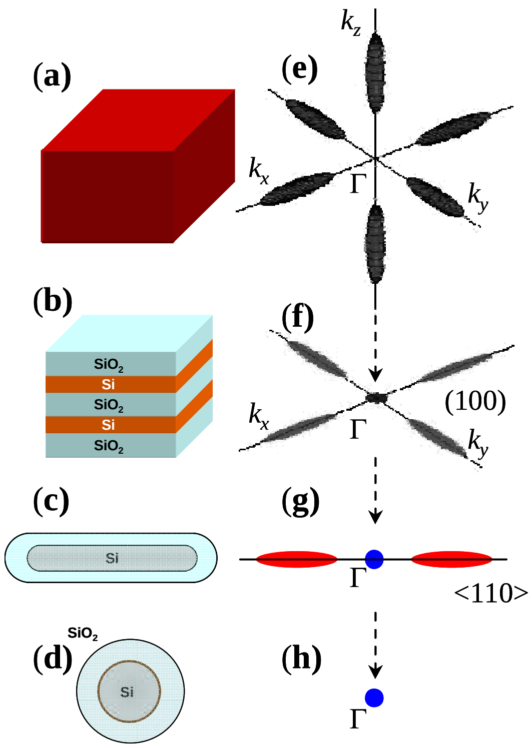

Fig. 1 Relationship between dimensional structure and electronic band structure in Si. Schematic structures like (a) bulk (3D), (b) well (2D), (c) wire (1D), and (d) dot (0D), are shown comparing with corresponding conduction band structures (e-h).

2. Device structure

Figure 2 shows our device structure [4, 5]. We used an ultra-thin Si (< 10nm) as an optically active layer, and the active is directly corrected to the electrodes made of thick highly doped Si (~26nm). Then, electrons and holes are laterally injected from both sides of the electrodes without tunneling SiO_2. Therefore, high currents (typically >100 kA/cm^2) can be injected without breaking the single crystal Si. The recombination and resulting light emission occurs along the line of the pn-junction (line emission).

The optical intensity can be controlled by biasing the substrate as a back gate, so that we call this device Si light-emitting transistor (LET). The emitted light from the LET can be detected as a photocurrent in none doped Si pads on the same chip.

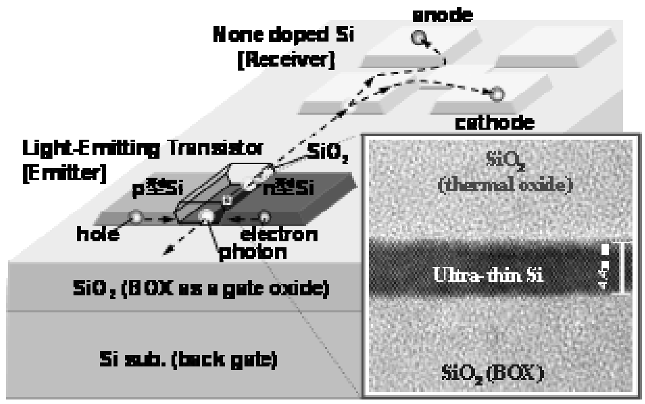

Fig. 2 Si light-emitting transistor using the ultra-thin Si quantum confined ultra-thin Si. Inset: Transmission-Electron-Microscope image of the single crystal ultra-thin Si.

3. Experimental results and discussion

Figure 3 shows the current-voltage characteristics of the LET with the channel length L=100 μm and channel width W=100 μm. The large series resistance is recognized presumably because of the large L. In fact, the order of the magnitude larger currents flowed in devices with shorter L.

The electro-luminescence (EL) intensity mapping image from this device is shown in Fig. 4. We confirmed that the enhanced EL intensity was exclusively recognized in the ultra-thin Si region, and that from the thicker electrodes was negligible. This confirms that the quantum confinement enhances the optical emission. We also confirmed that the photo-luminescence (PL) intensity increased with decreasing the thickness of Si.

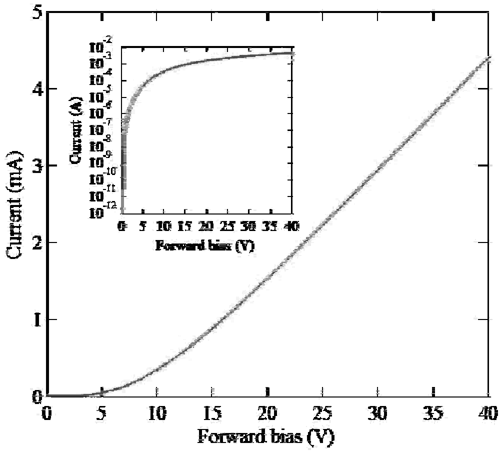

Fig. 3 The diode characteristics of light-emitting transistor. Inset: sub-threshold characteristics.

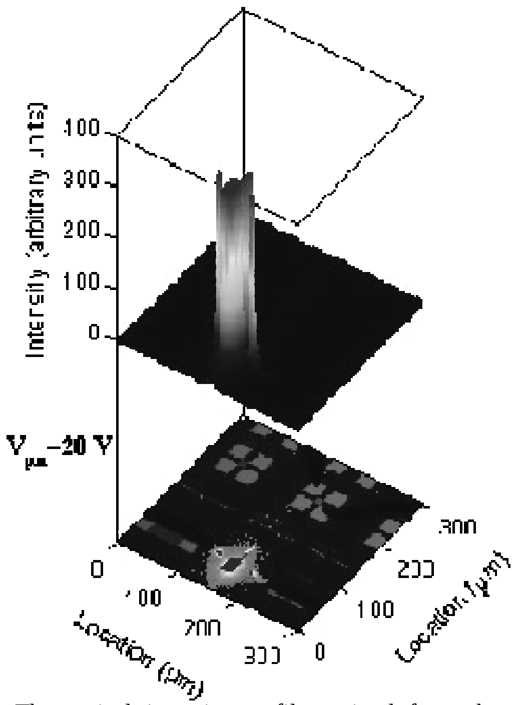

Fig. 4 The optical intensity profile emitted from the silicon light-emitting transistor obtained by a charge-coupled device (CCD) integrated for 60 s. The upper plane shows the EL intensity mappings, while the lower plane shows the same EL data superimposed onto the visible images. The enhanced intensity was exclusively recognized in the ultra-thin Si region.

Next, we examined a primitive optical interconnection by using the LET. We applied the simple input pulse voltage between the pn-junction, and observed the photocurrents in the detector of none-doped Si pads. As shown in Fig. 5, the detector slowly responded the input signal. In particular, by biasing the back gate, we can control the optical intensity and generated photocurrents. In the present device, negative back bias helps the optical emission. This would come from the reduced doping concentration of the p-type ultra-thin Si region during the oxidation, since the boron tends to dissolve to SiO_2, while the phosphorous tends to pile up at the Si/SiO_2 interface. As a result, the negative back bias helps to inject holes to the ultra-thin Si.

The extremely low responsibility would come from no waveguide in the present set-up, no appropriate design of the detector, and low absorption coefficient of Si around the wave length of 1000 nm. But, these limitations will be solved, if we integrate optimum existing optical devices in Si chips along with developed LETs.

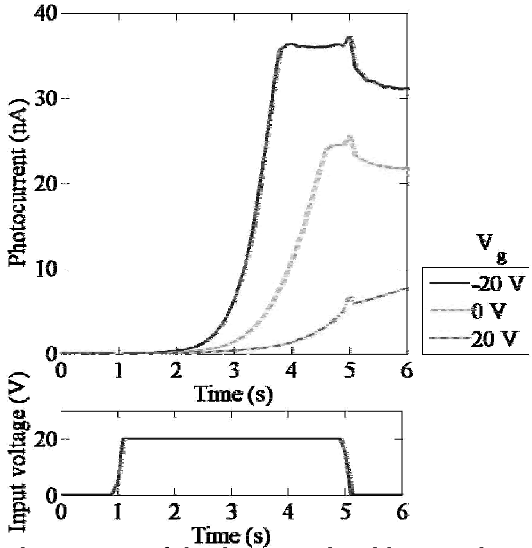

Fig. 5 Photocurrents of the detector induced by optical emission from light-emitting transistor. The input forward bias voltage was applied between the pn-junction, while the back gate voltage was set to be constant.

4. Conclusions

We have proposed the lateral carrier injection scheme to quantum confined Si, and confirmed the enhanced optical emission from the ultra-thin Si. The light-emitting transistor has a compatibility with conventional planar device architecture and might be one of the optimum device to introduce a light source to Si chips.

Acknowledgements

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