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Optical Gain in Ultra-Thin Silicon Resonant Cavity Light-Emitting Diode

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1. Introduction

Si photonics is expected to solve the global interconnect bottleneck beyond the conventional Cu/low-k interconnection. The flip-chip bonding or hybrid integration of a III-V laser diode (LD) is a practical approach to introduce a light source to a Si chip. Si based light sources have potential abilities to drastically change the architecture and are suitable for low cost, monolithic, high density integrations [1]. A challenge towards a Si LD is to overcome the fundamental in-direct band gap character.

Quantum confinement effects [2] are the most straightforward approach to make direct recombination possible in low-dimensional Si nano-structures. For example, the conduction band valleys in the ultra-thin Si (100) are projected onto the gamma point [3,4]. Efficient carrier injections to these nano-structures were demonstrated by the lateral *pin* diode. The next requirement towards an all-Si LD is to induce optical gain under population inversion conditions. However, it is not established whether the intrinsic optical gain becomes positive or not. We have examined the issue both theoretically and experimentally, and found that the experimentally accessible conditions for the optical gain in ultra-thin Si by current CMOS technologies.

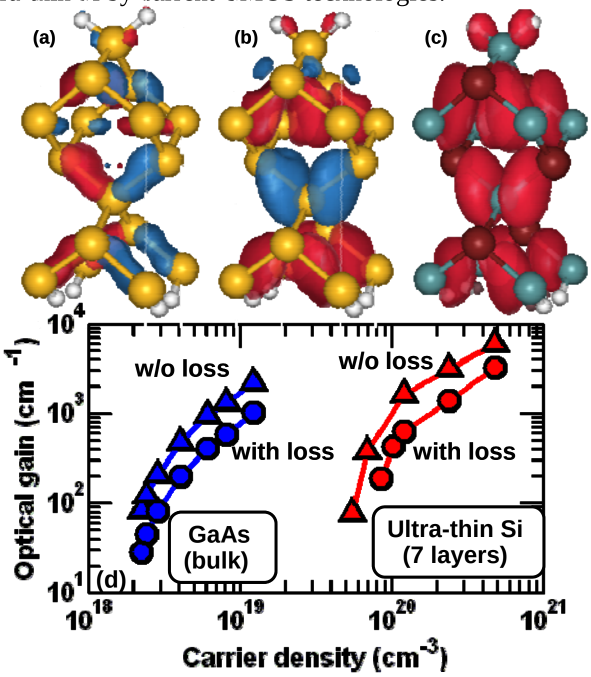

Fig. 1 Optical dipole moments of ultra-thin Si for (a) TM and (b) TE modes, compared with (c) GaAs. (d) Theoretical optical gain.

2. Theory

We have made first principle calculations based on density functional theory (Fig. 1) [5]. The optical transition matrix elements calculated in the ultra-thin Si are locally oscillating functions at atomic scales. It is almost cancelled for TM modes (Fig. 1 (a)), but it remains positive for TE modes (Fig. 1 (b)) due to the finite thickness. The optical gain expected in the ultra-thin Si is much smaller than that in GaAs under the same carrier concentrations (Fig. 1 (d)). However, we can increase the carrier density in Si orders of magnitude higher than that in GaAs, because of the higher solid solubility densities of impurities. As a result, we can expect the optical gain in Si comparable to GaAs.

3. Device structure

Figure 2 shows the device structure of the ultra-thin Si resonant cavity light-emitting diode. We have embedded the ultra-thin Si within the resonant cavity made by a Si_3N_4 core and SiO_2 clad waveguide. The strong optical feedback is expected by the distributed Bragg reflector (DBR) mirror with the high reflective index difference between Si_3N_4 and SiO_2. To enhance the vertical optical confinements, we have removed the parts of the supporting Si substrate by NEMS processes. The active device area is a suspended membrane in the air. We have confirmed that the single crystal structure of the ultra-thin Si (100) is preserved after processing.

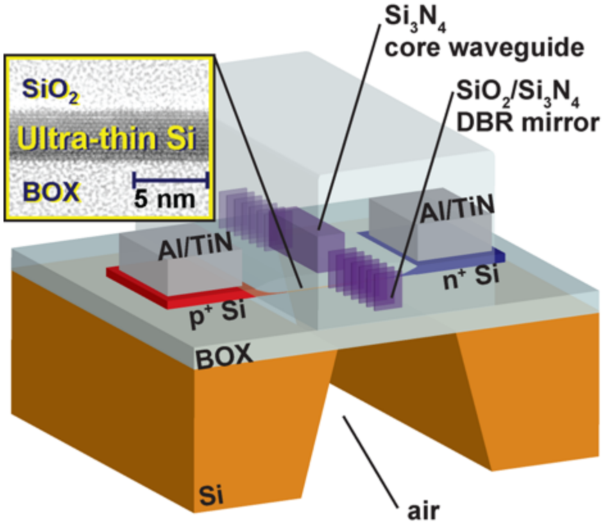

Fig. 2 Ultra-thin Si resonant cavity light-emitting diode. Inset: Transmission-Electron-Microscope image of the ultra-thin Si.

3. Experimental results and discussion

All measurements are performed at room temperatures. Figure 3 shows the electroluminescence (EL) images taken by a CCD. We examined the EL from the top since we could not dice the wafer due to its fragile structure. Nevertheless, The strong EL emissions were observed at the edge of the waveguide, and the emissions from the center of the waveguide were suppressed. Therefore, photons were effectively confined within a cavity. By increasing currents, the emission from the edge of the cavity was amplified more than the emission from the center of the cavity.

This suggests that the stimulated emissions from the cavity dominate the spontaneous emissions. By contrast, in the device without the cavity, the EL was observed from the entire Si QW and the spontaneous emissions spread in all directions [3, 4].

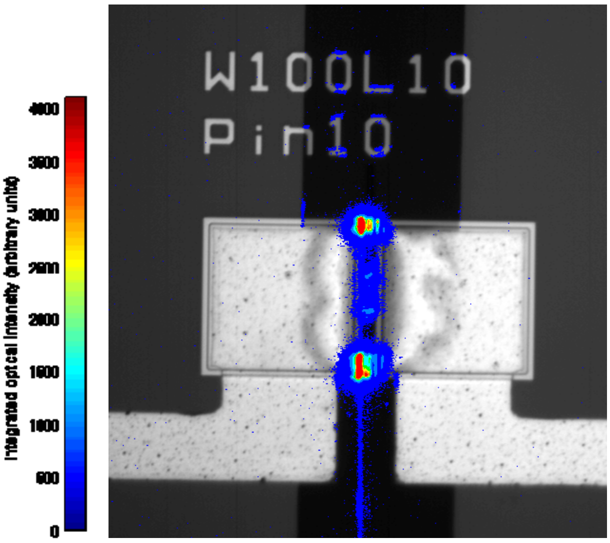

Fig. 3 Electroluminescence images in the near-infrared region under the application of the constant voltage of 20 V to ultra-thin Si resonant cavity light-emitting diode.

The integrated EL intensity increases super-linearly (Fig. 4), suggesting the positive optical gain, while no such enhancement is observed in a device without a cavity. The curves are almost independent on the channel width (cavity length) *W*, which means that the loss is independent of *W*. We can extract the optical gain assuming the DBR reflectance *R* of 99.0~99.9 %. In the EL intensity from the top view, the facet contribution is underestimated, so that the optical gain would be underestimated. Nevertheless, we have confirmed positive optical gain of 1~10 cm^{-1}.

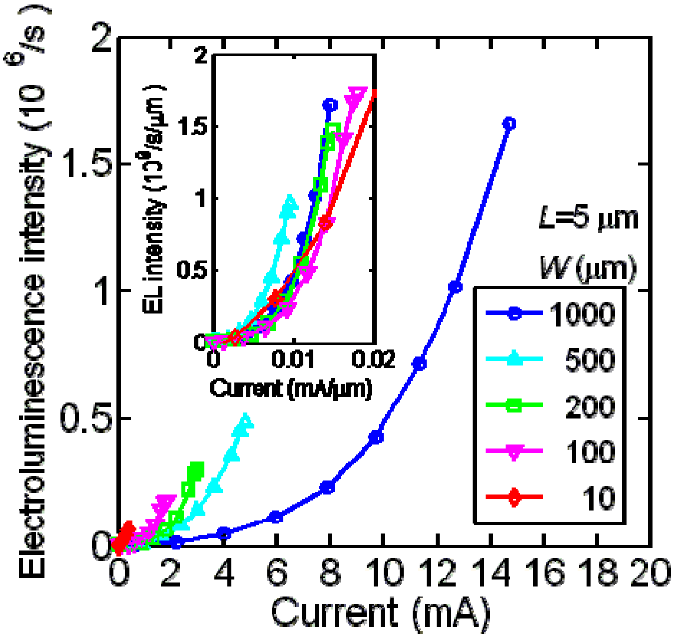

Fig. 4 Electroluminescence intensity increased with current injections.

4. Conclusions

The EL emission from the waveguide edge and the super-linear increase in the EL intensity suggest that the ultra-thin Si (100) has positive optical gain. These results show that stimulated emissions from the ultra-thin Si by current injections at room temperatures are indeed possible within experimental conditions accessible to the current Si technologies. After succeeding to improve the device performance, the Si based light emitters would be highly integrated with CMOS transistors for future on-chip optical interconnections.

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