Performance of Hybrid Laser Diodes Consisting of Silicon Slab and InP/InGaAsP Deep-Ridge Waveguides

Young Ahn Leem, Kisoo Kim, Jung-Ho Song, O-Kyun Kwon, and Gyungock Kim

The fundamental transverse mode lasing of a hybrid laser diode is a prerequisite for efficient coupling to a single-mode silicon waveguide, which is necessary for a wavelength-division multiplexing silicon interconnection. We investigate the lasing mode profile for a hybrid laser diode consisting of silicon slab and InP/InGaAsP deep ridge waveguides. When the thickness of the top silicon is 220 nm, the fundamental transverse mode is lasing in spite of the wide waveguide width of 3.7 μm. The threshold current is 40 mA, and the maximum output power is 5 mW under CW current operation. In the case of a thick top silicon layer (1 μm), the higher modes are lasing. There is no significant difference in the thermal resistance of the two devices.

Keywords: Hybrid laser diode, fundamental transverse mode.

I. Introduction

Recently, hybrid laser diodes [1]-[3] have been actively studied because the optoelectronic merits of III-V materials can be incorporated into Si-based electronics. The main advantage of this technology is that there are no tight alignment requirements compared to flip chip bonding; however, the optical power transfer to a silicon nanowire is still a technological problem because the optical confinement in a silicon waveguide is too low (less than 20%) when the cross section of the silicon waveguide is less than 300 nm high and 500 nm wide.

Because the adopted waveguide for on-chip communications is a single-mode waveguide, the lasing mode should be a fundamental transverse mode for efficient optical coupling to a single-mode waveguide. Considering a laser diode based on direct bonding, a hybrid waveguide is a combination of a silicon slab/ridge waveguide and a III-V ridge/slab waveguide. The thickness of the top silicon is the main parameter in the waveguide design because the confinement factors of the active layer and the silicon waveguide are closely related to the size of the silicon waveguide [3]. When the top silicon layer is very thin compared with the III-V layer, a waveguide structure should be formed in the III-V region for optical guiding. A ridge waveguide is preferred, considering mode size and fabrication. The mode profile does not strongly depend on the width of the silicon waveguide in this case. Since a silicon slab waveguide has an advantage in its thermal conductivity due to a large contact area [4], [5], in this work, we fabricated a hybrid laser diode in which the waveguide consists of a silicon slab and a III-V deep ridge waveguide. We vary the thickness of the top silicon in a silicon-on-insulator (SOI) wafer in order to characterize the optical and thermal characteristics.

II. Fabrication

An InP buffer, InGaAs contact layer, p-InP clad, active layer, and n-InP were grown in order on an n-InP substrate using metal-organic vapor deposition. The active structure was a strain-compensated InGaAsP/InGaAsP multi-quantum well with a two-step separated confinement structure. The thickness of the n-InP layer was set at 200 nm for efficient optical coupling. We prepared two SOI samples having 1 μm thick (SA) and 220 nm thick top silicon (SB) layers, respectively. The thickness of the buried oxide (BOX) was 1 μm. The sample size in this experiment was 1 cm × 1 cm considering thermal stress in the fabrication processes. After the SOI and

Manuscript received Aug. 31, 2009; revised Dec. 1, 2009; accepted Dec. 28, 2009.
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doi:10.4218/etrij.10.0209.0172

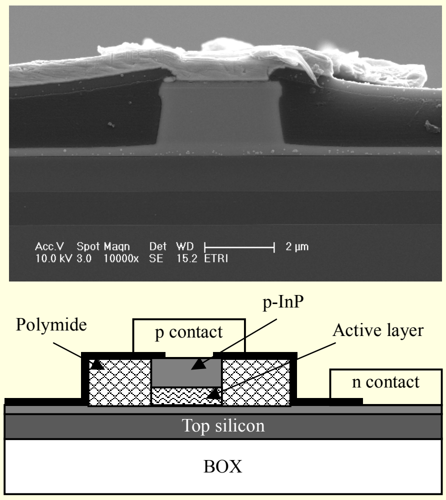

Fig. 1. SEM image of the fabricated device and a schematic diagram.

InP/InGaAsP samples were cleaned, they were bonded together via plasma bonding [6]. The fabricated laser diode structure and a schematic diagram are shown in Fig. 1. The cavity lengths are 823 µm and 515 µm for SA and SB, respectively, and the waveguide width is 3.7 µm for both devices.

III. Results and Discussion

Figure 2(a) shows the light intensity-driving current (L-I) characteristics of the laser diodes and far-field data. The threshold current densities are 2,690 A/cm^2 (SA) and 2,623 A/cm^2 (SB). The slope efficiencies at I_{th}+20 mA are 8% for both devices. The deep ridge waveguide, which is shown in Fig. 1, has merit in optical and electrical confinement; however, scattering loss due to sidewall roughness and surface recombination at the exposed active layer deteriorate the performance of the laser diode [7]-[10]. Sidewall roughness generally depends on the processing technology and causes optical loss. The contribution of this extra waveguide loss to the threshold currents was estimated to be an approximate 2% increase, which was expected from our optical gain measurement. In the case of a shallow-ridge laser diode with a similar epitaxial growth layer structure fabricated in our laboratory [11], its threshold current is 30 mA, and its slope efficiency is 13.5% for an 850 µm cavity length. Therefore, the surface recombination might be the main reason for the measured high-threshold current. Furthermore, the measured slope efficiency of 8% is lower than that of the shallow-ridge laser diode because the surface recombination reduces the internal quantum efficiency [10].

As the influence of a surface recombination strongly depends on the waveguide width [8], wide waveguide width is preferable. However, the carrier confinement worsens, and multimode lasing easily occurs. The waveguide structures of both samples have multiple transverse modes based on the measured dimension (3.7 µm) and mode calculation. Due to the thick top silicon, the SA waveguide has multiple modes in both the vertical and lateral directions, but that of SB is of a single mode in the vertical direction and multiple modes in the lateral direction based on the mode calculation. The calculated optical confinement of the fundamental mode in the InGaAsP active layer is less than 1% for SA and 12% for SB. On the other hand, the optical confinement of the higher mode in the vertical direction is 13% for SA. As shown in Fig. 2, the far-field pattern of SA has two main lobes in the vertical direction, and there is fluctuation in the planar far-field pattern. We also measured the amplified spontaneous emission (ASE) spectrum. The result of SA near the threshold provides that several modes share the gain. These facts support multimode lasing of SA. In the case of SB, the far-field pattern gives a Gaussian profile in

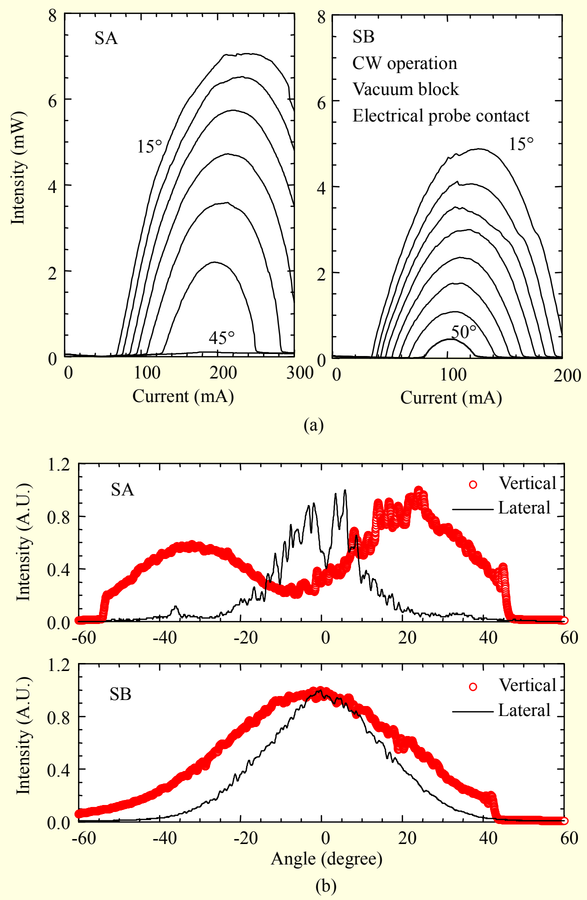

Fig. 2. (a) Measured L-I curves at various temperatures. A chipbar was attached to a vacuum block. The temperature was controlled using TEC, and the data was measured under CW current operation. The temperature steps were in increments of 5°C. (b) Measured far-field patterns.

both directions, and the ASE spectrum shows Fabry-Perot fringe originating from one mode. Thus, the lasing mode is definitely the fundamental mode. It is strange as the waveguide is a multimode waveguide due to the wide width of 3.7 μm. However, this kind of behavior was already reported in a high index contrast laser diode with an actual active stripe width of 7 μm [7]. Although the origin is not clearly defined, this implies that a wide waveguide can be a solution to reduce the surface recombination in our structure.

Thermal roll-over is clearly shown in Fig. 2(a). Considering the large series resistance (SA: 7.8 Ω, SB: 16 Ω), high current operation, and experimental setup (vacuum block/electrical probe contact), the thermal degradation is not severe. The reason is that Si-InP wafer bonding provides an advantage in thermal conduction [5]. We obtained thermal resistances of 42 K/W and 72 K/W for SA and SB, respectively [12]. Assuming the linear dependence on the inverse of the cavity length [4], [13], the values are 42 K/W and 45.5 K/W for the 823 μm-long cavity. Due to the low thermal conductivity of the BOX layer, the heat spreads over the top silicon layer, after which it flows through the BOX layer. Therefore, an effective thermal contact area determines the thermal resistance of the BOX and Si substrates. The small difference implies that the effective thermal contact area does not vary significantly with the top silicon thickness in the range of 220 nm to 1 μm. Because the entire n-InP current channel layer is bonded to the top silicon layer in our waveguide structure, the real contact area to the thermal source is already sufficiently large. Therefore, the top silicon thickness does not have a large effect on the thermal resistivity. This fact implies that the adopted waveguide structure has an advantage in its thermal conductivity. However, as the thickness of the BOX is a main factor in determining the thermal resistance, a structure such as a thermal via hole will improve the thermal conductivity.

IV. Conclusion

This study investigated hybrid laser diodes consisting of InP/InGaAsP deep ridge and silicon slab waveguides. For a thin top silicon layer, we confirmed that the fundamental transverse mode stably lases in spite of the wide waveguide width of 3.7 μm. The thermal resistance depends little on the thickness of the top silicon due to the wide bonding area. However, non-radiative recombination through the surface should be improved. A shallow-ridge laser diode or wide-stripe laser diode are possible solutions.

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