Electrically Pumped Supermode Si/InGaAsP Hybrid Lasers

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Abstract: Supermode Si/InGaAsP hybrid lasers with a varying-width Si waveguide have been fabricated and shown to be superior to those lasers with a uniform-width Si waveguide. Edge emission images demonstrate mode evolution.

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1. Introduction

Recent years have witnessed an ever-increasing pace of results in achieving a compact, high-efficiency laser source compatible with integration on the platform of Si photonic circuits [1-4]. Although different schemes have been implemented to achieve that goal, currently the most promising approach is based on a low-temperature wafer-bonding technique which brings together III–V gain material for amplification and Si for guiding and transportation [5]. Hybrid Si evanescent lasers based on this technology have been demonstrated with the III–V gain material being AlGaInAs [1] and InGaAsP [4]. Since this approach involves two waveguiding structures in close proximity, we have proposed, using supermode theory and the adiabaticity theorem, to adiabatically vary the Si waveguide width so as to control the modal profile and utilize each material optimally [6]. The modal gain is expected to be greatly enhanced, resulting in a lower lasing threshold and higher emission efficiency and, most importantly, shorter optical devices.

In this work, we demonstrate experimentally the superiority of supermode Si/InGaAsP hybrid lasers with a varying Si waveguide width along their cavities over lasers with a uniform Si waveguide width. Fabricated on the same platform, the supermode lasers have lower lasing thresholds and higher slope efficiencies. Edge emission images demonstrate mode evolution and confirm that light is predominantly emitted from the Si waveguide facet when above threshold.

2. Device design

The hybrid laser consists of a III–V waveguide in close proximity (by wafer-bonding) to a silicon-on-insulator (SOI) waveguide as illustrated in Fig. 1(a). According to the supermode theory, changing the effective index of the Si waveguide by altering its width changes the spatial distribution of the combined modes (i.e., the supermodes) of the Si/III–V waveguide system. By proper choice of the Si waveguide width, it is possible to localize the supermode mostly in the III–V waveguide or mostly in the Si waveguide [6]. The efficient mode transformation between the two states is to be realized by adiabatic tapers [7]. Therefore, as shown in Fig. 1(b), the Si waveguide is designed in the shape of a dumbbell which comprises a central region having a width of w_{ctr}, two end regions having a width of w_{end}, and two tapered regions connecting each of the two end regions with the central region. Using the structural parameters of the III–V wafer epi-layer [4] and refractive indices of Si and SiO_2, the supermode field profile is obtained by a numerical solution for the modes of the hybrid structure with different Si waveguide widths, with calculated confinement factors (Γ) in both III–V and in Si plotted in Fig. 1(c). As can be seen, at $w_0 = 0.7$ μm, the modal power is evenly distributed in the III–V and the Si waveguide.

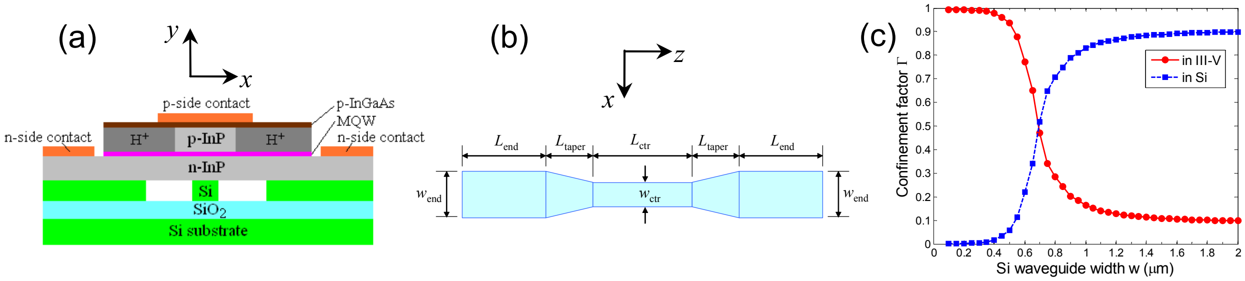

Fig. 1. (a) Illustration of the cross-sectional view of the hybrid laser. (b) Si waveguide structure dimensions. (c) Calculated confinement factors in III–V material and in Si waveguide.

We designed the lasers to have a cavity length of 1500 μm. For supermode devices, we fabricated lasers with varying-width Si waveguides: w_{end} = 1.2 or 1.4 μm, L_{end} = 350 μm, w_{ctr} = 0.6, 0.7, 0.8, or 0.9 μm, L_{ctr} = 400 μm, linear taper with L_{taper} = 200 μm. For comparison, we also fabricated lasers with uniform-width Si waveguides: $w_{\mathrm{end}} = w_{\mathrm{ctr}}$ = 1.2 or 1.4 μm, total length = 1500 μm, that are otherwise identical to the supermode devices. Our simulation predicts that a supermode device with w_{ctr} = 0.6 μm has its modal gain enhanced by a factor of 2.5 compared to uniform-Si-waveguide devices with a width of 1.2 or 1.4 μm.

3. Experimental results and discussions

The device fabrication procedure has been described in detail in [4]. The only change is that Si waveguide width is varied along the cavity during SOI lithography. All the devices were tested at room temperature under pulsed current injection with a duty cycle of 1%. The results are listed in Table 1. Due to the imperfections in the steps of wafer-bonding and electrical contact fabrication in this run, the threshold current density of all the devices are higher than those in [4]. The data reported herein are obtained from the best device of many of the same design to rule out unpredicted and uncontrollable imperfections in fabrication which can arbitrarily degrade the device performances. Since the supermode devices and uniform-width devices were tested on the same platform, direct comparison of results is meaningful. Supermode devices have substantially lower threshold (I_{th} or J_{th}) and higher slope efficiency (η_{ex}) than their uniform-width counterparts. These data reflect the effects of longitudinal variation of modal confinements in the laser cavity. It is evident that the supermode devices are superior to those uniform-width ones.

Shown in Fig. 2 are images of edge emission from a device, collected by an IR camera, from below threshold to above threshold. As clearly seen from the mode evolution, the hybrid mode gradually moves to the lower Si waveguide as the injected current increases from below to above threshold.

Table 1. Test Results of Supermode (Varying-Width) and Uniform-Width Devices on the Same Platform

Si waveguide type	w_{end} (μm)	w_{ctr} (μm)	I_{th} (mA)	J_{th} (kA·cm^{-2})	V_{th} (V)	η_{ex}
Varying-width	1.2	0.6	110	1.47	3	1.06%
Varying-width	1.2	0.7	165	2.20	4	1.88%
Varying-width	1.2	0.8	289	3.85	5	2.31%
Varying-width	1.2	0.9	876	11.7	9	1.50%
Uniform-width	1.2	1.2	891	11.9	11	0.36%
Varying-width	1.4	0.6	453	6.04	5	1.48%
Varying-width	1.4	0.7	346	4.61	6	1.45%
Varying-width	1.4	0.8	692	9.23	9	2.89%
Varying-width	1.4	0.9	3170	42.3	30	0.73%
Uniform-width	1.4	1.4	×	×	×	×

Tests were performed at room temperature under pulsed current injection with pulse duty cycle of 1%. ("×" means no lasing obtained from devices of this design.)

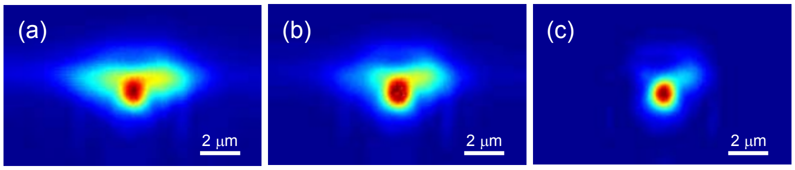

Fig. 2. Images of edge emission from a device operated (a) below threshold, (b) at threshold, and (c) above threshold.

Acknowledgments

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