Improved design of an InP-based microdisk laser heterogeneously integrated with SOI

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***Abstract*—Microdisk lasers heterogeneously integrated with SOI are promising sources for photonic integrated circuits based on silicon. The microdisk lasers are only a few micrometers in size and they allow for wafer scale fabrication. We have demonstrated a new design of an electrically injected microdisk laser bonded on SOI with a considerable improvement of the performance. We observed threshold currents as low as 350 μA and output power up to 120 μW for a 7.5 μm microdisk diameter under continuous-wave operation. Compared to previous results this comes down to a 30% reduction of the threshold current and a maximum output power which is increased by more than a factor of 10.**

I. Introduction

silicon based photonic integrated circuits (PICs) have received a lot of commercial interest because of their low cost, compactness and CMOS compatibility. Also it has become a wide believe that optical interconnects are inevitable in order to overcome the bottleneck that electrical interconnects will form as a result of the increasing data flows. Although silicon based photonics is very promising, optical sources in silicon are not trivial and therefore a lot of research is focusing on achieving stimulated light emission in silicon and heterogeneous integration of III-V material with silicon-on-insulator (SOI). In order to be used in practical applications these lasers should be driven electrically. Until now, this has only been achieved with the heterogeneous approach. Several types of lasers already have been demonstrated like a Fabry-Prot, hybrid racetrack and microdisk lasers [1]–[3]. The microdisk laser is an interesting approach because of the small dimensions and straightforward fabrication. Furthermore, the microdisk is a very flexible device with a lot of possible applications. In [4] a multiwavelength laser was demonstrated by cascading a number of microdisks with different diameter, which are all coupled to the same output waveguide. This allows for on chip wavelength division multiplexing, which will drastically increase the available bandwidth. It is also believed that microdisks can be used as optical flip-flops as is demonstrated for coupled ring lasers in [5] and for single ring lasers in [6]. Microdisk modulators have also been reported in silicon [7] and heterogeneously integrated with SOI [8].

The lowest reported threshold current of heterogeneously integrated microdisk lasers is 500 μA and the maximum output power under continuous-wave (CW) operation is 10 μW [3]. Theoretical calculations suggest that a threshold current of 150 μA and an output power of 100 μW should be possible. In this paper we report on a considerable improvement of the performance of an InP-based microdisk laser heterogeneously integrated with SOI waveguides. A threshold current of 250 μA and output power over 100 μW were measured.

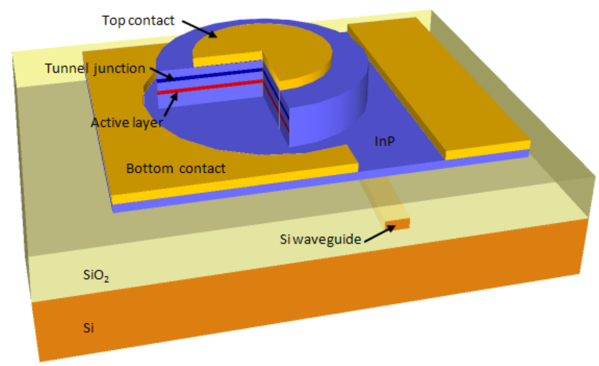

Fig. 1. Schematic representation of a heterogeneously integrated microdisk laser on SOI.

II. Design and Fabrication

The heterogeneously integrated microdisk laser is schematically shown in Fig. 1. The microdisk is etched in a thin InP-based membrane, which contains 3 compressively strained InAsP quantum wells with a thickness of 6 nm in 15 nm Q1.2 barrier layers. The InP-based membrane is bonded on top of SOI with a thin layer of Benzocyclobutene (BCB). The oxide layer contains a silicon wire waveguide with a 500 nm width and a thickness of 220 nm. The laser mode is evanescently coupled to this waveguide. Electrical injection is possible via a top metal contact in the center of the disk and a bottom contact on a 100 nm thin lateral contact layer.

An important design issue of the electrically injected microdisk laser is the composition of the epilayer heterostructure. Because the membrane is typically between 500 nm and 1 μm thick, a tradeoff has to be made between the electrical injection and the optical properties of the device. One of the difficulties

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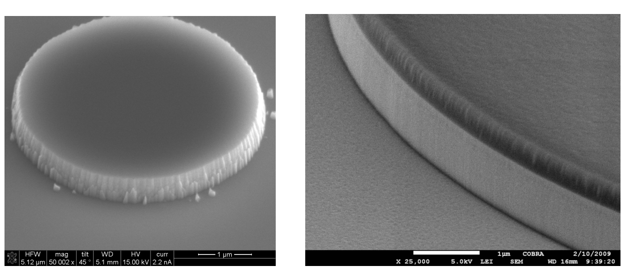
is to form an ohmic contact at the p-type layer of the junction. Normally this is done by using a heavily p-doped layer, but these layers are very absorbing and thus not suitable for thin membranes. To circumvent this we make use of a tunnel junction (TJ), which allows us to have two n-type contacts. The TJ consists of two very thin (20 nm) and highly doped ($> 10^{19} cm^{-3}$) layers and is reverse-biased. The TJ makes it possible to have low electrical resistivity and acceptable optical losses. In previous designs [3] we used a TJ below the active layer because in principle the TJ should be grown as one of the last layers in order to avoid doping diffusion in the active layer. Note that because of the bonding process this indeed results in a TJ below the active layer. However, the TJ also induces some optical losses and by placing it in between the active layer and the underlying waveguide a substantial part of the optical field will be absorbed. In the new design the TJ is above the active layer, which became possible because of optimized growth conditions. In this case the optical confinement in the TJ is less, which results in lower optical absorption.

Another important loss factor is the scattering loss due to the sidewall roughness. To estimate the scattering loss in a microdisk resonator we used a generalized closed-form expression based on the current volume method, which was derived in [9] and is given by:

$$\alpha_s = \frac{16\pi^3}{3R}\left(1 - \frac{n_0^2}{n_{eff}^2}\right)^2 \left(\frac{n_{eff}\sigma}{\lambda}\right)^2 \frac{n_{eff} L_c \Gamma_z t}{\lambda^2} \quad (1)$$

Where R is the radius and t the thickness of the microdisk resonator, n_{eff} the effective index in the disk n_0 the index of the surrounding medium σ the RMS roughness value , L_c the correlation length and Γ_z the vertical confinement factor. From this formula we found that the scattering loss is one of the major loss factors in our devices. The reduced thickness of the membrane has already a positive effect on the scattering loss and in order to reduce it further we aimed at reducing the sidewall roughness of the microdisk. A SEM picture of the previous and new device are displayed in Fig. 2. Although we have not yet been able to quantify the sidewall roughness, we can conclude from the SEM pictures that the sidewall roughness is improved considerably.



(a) Previous device (b) New device

Fig. 2. SEM pictures of the previous device (a), and the new device with reduced sidewall roughness (b).

The total thickness of the membrane is 580 nm in the new designs while the previous devices [3] had a thickness of 955 nm. This is advantageous because not only the optical mode will have a larger exponential tail in the cladding, and thus a larger overlap with the silicon waveguide, it will also lead to a better phase matching with the underlying waveguide, according to 3D FDTD simulations. Both effects have a positive influence on the coupling efficiency. As an adhesive bonding method is used, the thickness of the BCB bonding layer will also influence the coupling because, it determines the distance between the waveguide and the microdisk. For these devices we used a bonding layer thickness of 200 nm.

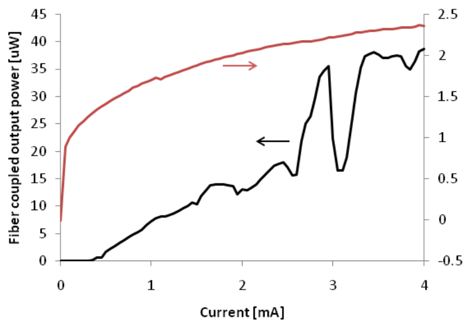
In order to lower the threshold current and increase the efficiency of the microdisk laser, the temperature should be kept low. However, since the thermal conductivity of the bonding material is low, the microdisk suffers from severe self heating. This self heating results in thermal roll-over behavior in which the output saturates and drops sharply at a certain current. In previous devices this roll-over behavior already started at 2 mA in CW operation. In the new design we included a thermal heat sink by covering the top contact with a larger area of gold. Within the new design we still observe a thermal roll-over effect, but it only starts around 4 mA.

III. Measurement results

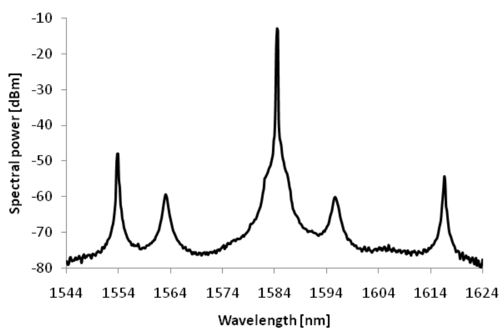
The characterization of the microdisk lasers was done by applying a DC voltage to the laser. The output power was collected at one end of the SOI waveguide by using fiber grating couplers [3]. We observed continuous-wave lasing at room temperature for microdisks with a diameter of 7.5 and 10 μm. Fig. 3(a) shows both the LI and VI curve for a microdisk with a diameter of 7.5 μm.

A threshold current of 350 μA and a maximum output power in the fiber of 38 μW is observed. The oscillations in the LI curve are due to reflections of the grating couplers which are placed at both sides of the output waveguide. In the first part of the LI curve the mode with a wavelength of 1554 nm is lasing and from 2.4 mA onwards the mode with a wavelength of 1584 nm will lase. The abrupt change in the LI curve at this point can be explained by the different efficiencies of the grating couplers at these frequencies. The grating couplers have an efficiency of 21% at 1554 nm and 30% at 1584 nm, which means the maximum power coupled into the waveguide is 120 μW. Fig. 3(b) shows the corresponding optical spectrum of this microdisk at a current of 4 mA. The lasing wavelength is 1584 nm and the fundamental mode has a FSR of 30 nm. The side mode suppression ratio (SMSR) is 35 dB and thus we can conclude that the device is in the single mode regime.

In Fig. 4(a) the LI and VI curve of the microdisks with a 10 um diameter are shown. These devices also have a threshold current of 350 μA but a slightly lower maximum output power of 25 μW coupled in the fiber. The spectrum is plotted in Fig. 4(b) and in this case we observe two competing modes at 1588 and 1595 nm, which means it is in the multimode regime. This can be explained by the size of the top metal contact, which was just too small. A microdisk supports optical modes of

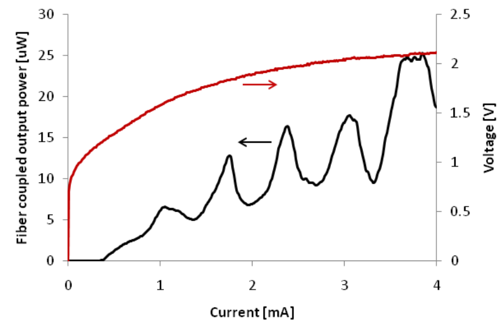


(a) LI curve

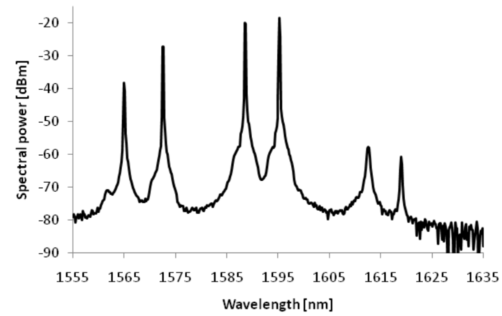


(b) Optical spectrum

Fig. 3. LI curve (a) and spectrum (b) of a 7.5 μm diameter microdisk



(a) LI curve



(b) Optical spectrum

Fig. 4. LI curve (a) and spectrum (b) of a 10 μm diameter microdisk

the whispering gallery type, the fundamental mode propagates close to the edge of the disk. Higher order radial modes can also exist which are less confined to the edge. By making the top metal contact large enough, these higher order radial modes can be suppressed as they are absorbed by the metal.

IV. Conclusion

We have demonstrated a new design of an electrically injected microdisk laser bonded on SOI with a considerable improvement of the performance. We observed threshold currents as low as 350 μA and output power up to 120 μW for a 7.5 μm microdisk diameter under CW operation. Compared to previous results this comes down to a 30% reduction of the threshold current and a maximum output power which is increased by a factor of 10.

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