Strategies to increase the modal gain in electrically pumped quantum dot based amplifiers integrated on a Silicon-On-Insulator waveguide circuit

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We propose two waveguide structures that allow for high optical confinement in the active region, low loss and electrical injection using a regular P-I-N injection scheme. To achieve these properties, we use a bonded III-V film on a Silicon-On-Insulator circuit. By deeply etching the III-V film to define the waveguide and shallowly etching trenches in the top p-InP contact layer, we can push the mode towards the active layer and away from the lossy contact layers. These waveguide structures were developed for a quantum dot active region to relieve its low confinement factor and consequently reach a higher modal gain.

Silicon-On-Insulator (SOI) is an excellent platform for the realization of passive optical functions. However, most optical functions require also active devices such as lasers and detectors. Due to silicon's indirect band gap, creating active devices on silicon remains a challenge. One approach to circumvent this problem is the heterogeneous integration of III-V epitaxial layers on the SOI waveguide circuit. This can be done by adhesive die-to-wafer bonding with DVS-BCB as a bonding agent[1]. Several single mode lasers have been designed and fabricated using this approach[2]. Now we want to do the same for a mode-locked laser, as this would open up a whole new set of applications. The stable picosecond pulses which are generated by a mode-locked laser can for instance be used in telecommunications for time division multiplexing, or in optical signal processing for all-optical clock recovery. These classes of applications typically also require complex passive circuitry, which can be realized on the SOI platform.

Early experimental results have shown that quantum dots (QDs) are ideal as gain material to achieve mode-locking, as they show both ultrafast carrier dynamics and a broad bandwidth[3], which are important for the creation of ultrashort pulses. Therefore, it would be appropriate to use a bonded quantum dot laser stack to create a mode-locked laser on SOI. This is not straightforward however. Although QDs are excellent for mode-locking, they also pose stringent demands on the waveguide structure.

In the following, we will look into the requirements for a QD gain section. Then the properties of the standard P-I-N laser structure will be discussed and two new waveguide structures will be proposed that meet the requirements set by the use of QDs.

Boundary conditions for a quantum dot gain section

Next to the advantages of QDs for mode-locking, the use of QDs as a gain material also has disadvantages. Because of the small sizes of the QDs and the relatively low density that can be achieved, the confinement of the mode in the active region is limited. Therefore, the maximal achievable gain is low and long cavity lengths are required to achieve

lasing[4]. On the other hand, the low density of QDs also leads to a low transparency carrier density, so the lasing threshold could be quite low.
Because of the fast carrier capture times that QDs show[3], the injected carriers have no time to diffuse in the active region. As a consequence, the current injection profile will be very similar to the carrier density profile in the QDs. It is thus important to have a uniform current injection profile, to be able to pump all the QDs in the active region. The reduced carrier diffusion also has an important advantage: as carriers barely diffuse towards the surfaces, surface recombination will be suppressed and one should be able to etch through the active layers without consequences.

Configuration of the standard P-I-N laser structure

The standard InP-based P-I-N laser structure of a bonded laser is shown in figure 1(a). It basically consists of a thin bottom n-InP layer, an InGaAsP active region and a thick

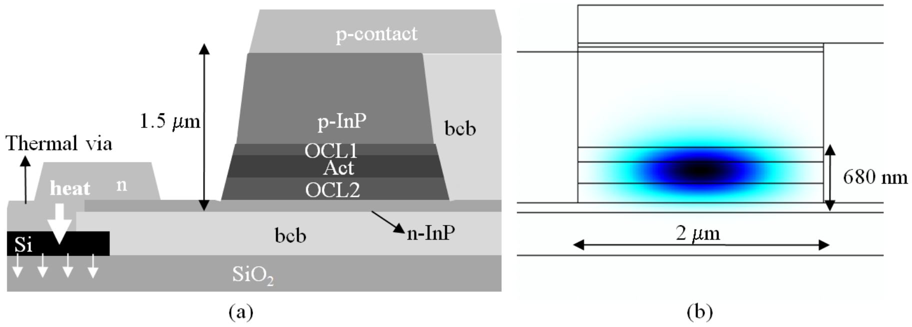

Figure 1: (a) The standard structure of a bonded InP-based P-I-N laser waveguide. (b) The corresponding mode profile.

p-InP layer which is then contacted at the top using an InGaAs-Ti-Au layer stack. To optimize the confinement in the active region and reduce mode leakage towards the top metal contacts, two high index optical confinement layers (OCL) are typically added around the active region. One of the metal contact layers is contacted to the silicon waveguide layer to act as a heat sink.
This approach has some disadvantages however. As can be seen in figure 1(b), the mode still has a significant tail in the p-InP layer, so losses due to p-type doping will be significant and the top metal contacts need to be placed at a relatively large distance to keep metal absorption negligible. Furthermore, a large part of the mode is confined in the OCLs around the active region, which does not contribute to the gain of the laser. Another disadvantage is the position of the mode in the waveguide. The point of highest intensity is far away from the interface with the BCB bonding layer. Therefore, hybrid structures that rely on evanescent coupling to an underlying silicon waveguide, will require a long interaction length and will be very intolerant to fabrication imperfections.
These disadvantages are all the consequence of the high index top cladding that is used in this waveguide structure. If one could reduce the effective index of the top p-InP contact layer, the mode would be pushed down towards the active region and away from the heavily absorbing top contact layers. This can be achieved by etching sub-wavelength trenches in the top contact layer and planarizing the resulting structure with BCB.

The gallery waveguide structure

The gallery waveguide structure for a bonded InP-based P-I-N laser is shown in figure 2. Like the previous waveguide, it consists of an InGaAsP active region, sandwiched

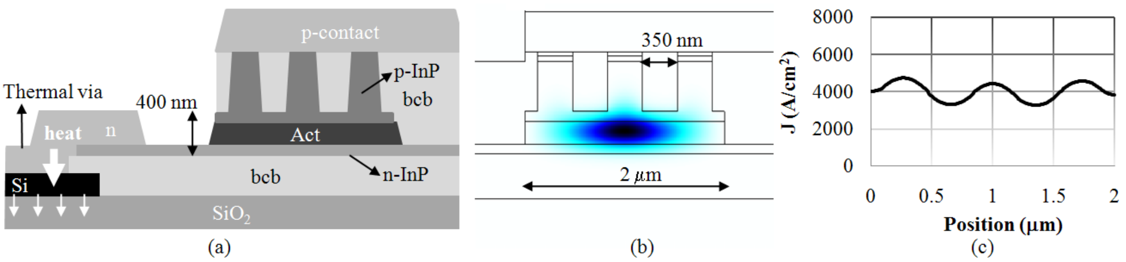

Figure 2: (a) The gallery waveguide structure of a bonded InP-based P-I-N laser. (b) The corresponding mode profile. (c) Current injection profile through the active layer.

between the n-type and p-type InP layers. Because of the trenches in the top p-InP layer however, extra OCLs are not necessary anymore, as the mode is pushed down into the active region (figure 2(b)). Furthermore, the mode tail in the top InP layer is shorter and therefore the required stack thickness is less than 1 μm. Also the point of the highest intensity is much closer to the BCB interface, so evanescent coupling to an underlying silicon waveguide will be easier and the design will be more tolerant for fabrication errors. A disadvantage of this structure, is that the top contact surface area is reduced to around 50% compared to the standard laser structure, so the electrical resistance will be higher. As the threshold current for a QD device is low however, this does not have a large impact. One can even think of tuning the position of the p-InP pillars to inject the current only at the places where the mode is the strongest. In figure 2(c) the current injection profile is shown for a three pillar gallery structure. The injection uniformity is very good if the spacing of the pillars is kept low enough.
Another disadvantage of the structure are the small features sizes required for fabrication. Lithography with a resolution of 200-400 nm is required, which is only possible using a DUV stepper or e-beam for lithography.

Viking helmet waveguide structure

As the fabrication of the gallery waveguide structure requires high-end lithography, one can opt for an alternative that can be fabricated using contact lithography, but still shows most of the advantages of the gallery. This viking helmet waveguide structure for a bonded InP-based P-I-N laser is shown in figure 3.
The biggest difference between the gallery and the viking helmet is that the distance between the current injecting pillars is much higher in the latter. To have a sufficiently uniform current injection profile, the p-InP current spreading layer below the pillars needs to be at least twice as thick (see figure 3(c)). Furthermore, the mode still has a long tail towards the contact layers at the edges of the waveguide, so the total required stack thickness will be higher (1.3 μm).
In table 1, the most important parameters are listed for the three discussed waveguide structures, for a p-type doping of $2.0 \times 10^{17}\,\mathrm{cm}^{-3}$ and n-type doping of $1.0 \times 10^{18}\,\mathrm{cm}^{-3}$.

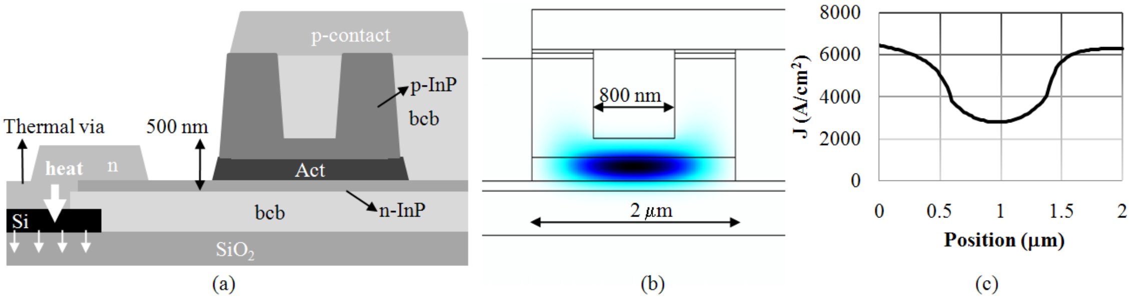

Figure 3: (a) The viking helmet waveguide structure of a bonded InP-based P-I-N laser. (b) The corresponding mode profile. (c) Current injection profile through the active layer.

	Standard	Gallery	Viking helmet
Confinement in active layer	0.44	0.72	0.61
Maximal achievable net gain estimate	$12.9\,\mathrm{cm}^{-1}$	$20.3\,\mathrm{cm}^{-1}$	$18.3\,\mathrm{cm}^{-1}$
Thickness of total stack	$1.5\,\mu m$	$1.0\,\mu m$	$1.3\,\mu m$

Table 1: The most important parameters for the discussed waveguide structures

By calculating the different confinement factors and using the data on the achieved gain in literature [4], we can calculate a maximal achievable net gain estimation for every waveguide structure. Not taking into account scattering losses, this estimate is given by $g_{net} = \Gamma_{act} g_{mat} - \alpha_{doping} - \alpha_{metals}$.

Conclusion

We have shown that by etching trenches in the top p-InP cladding layer, the confinement in the active layer can be increased by more than 60%. On the other hand, the mode is kept away from the metals more efficiently and the total laser stack can therefore be reduced in thickness. Using this waveguide structure, also shorter mode-locked lasers with higher repetition rates should be possible. Future work will focuss on the fabrication of devices using these waveguide designs.

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