Design and Simulation of a Photonic Crystal Laser in InP-based Membranes On Silicon

R. Zhang[1], J.J.G.M. van der Tol[1], P. Thijs[2], and M.K. Smit[1]
[1]COBRA Research Institute, Technische Universiteit Eindhoven Address: P.O. Box 513,5600 MB Eindhoven, The Netherlands
[2] Philips Research Eindhoven, High Tech Campus, 5656 AE Eindhoven, The Netherlands

The high vertical index contrast and the small thickness of thin InP-based membrane structures bonded with BCB on Silicon allow the realization of very small devices. In COBRA, we aim to make a direct electrically pumped photonic crystal laser in this platform. Together with submicron selective area re-growth and oxidation of AlInAs for the current confinement techniques that we developed previously, a "W1 like" photonic crystal cavity type is designed and simulations in FDTD show good performance in terms of quality factor and tolerance to the manufacturing imperfections. Simulations show that doping and oxidation of AlInAs does have a negative effect on the Q factor, yet it is acceptable. All in all, we expect to make electrically injected photonic crystal lasers with high pumping efficiency and small threshold current as well as low power consumption.

1 Introduction

The complexity of photonic integrated circuits (PICs) has been raised significantly these last few years, following Moore's law in Photonics[1]. But to satisfy the need for even more complexity, devices and waveguides have to be made smaller and less power consuming. This is especially so for using PICs in combination with Silicon and CMOS chips.

InP-based membrane bonded On Si(IMOS) technology, which has a high vertical index contrast with an ultra-thin (200nm) membrane layer (see Fig.1), allows the realization of very small devices. A wide range of passive components[2] such as MMI and ring resonators have already been realized in this platform. In COBRA, we are now moving towards making the active devices, such as lasers and amplifiers, in IMOS. Photonic Crystal (PhC) lasers, with its ultra-high Q-factor and low mode volume, has been a hot research topic for more than 30 years. Yet making a directly electrical pumped PhC laser is still quite a challenge, although it has been shown in a few papers[3,4] .

We aim at making a electrical pumped PhC laser in the IMOS platform. Together with submicron active-passive integration[5] and oxidation of AlInAs[6] for current confinement[6] developed previously, we expect to make electrically injected PhC lasers with high pumping efficiency and small threshold current and low power consumption.

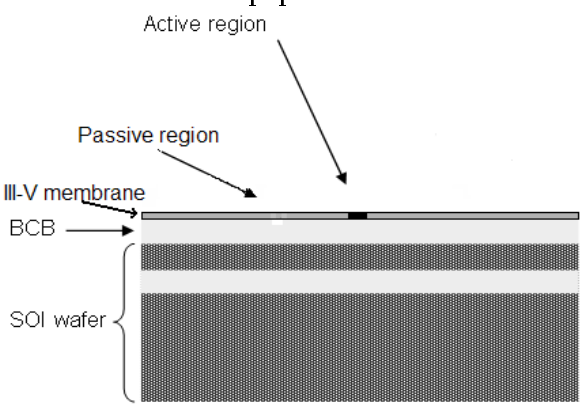

Fig.1 The layer stack of the IMOS platform

2 Photonic crystal cavity design

There is a variety of PhC cavity types. A "W1 like" cavity (see Fig.2) is chosen in our case. Light source is in the middle, black region represents the QWs. The key feature of this cavity is an extremely small(0.124 um^3) buried active region (InGaAsP based quantum wells) located in a straight line-defect waveguide in an InP photonic-crystal slab. Optical confinement is realized both by photonic crystal arrays and the refractive index difference between the active region and the passive part. This cavity has shown to have a high quality factor[7] and meanwhile keeps a good tolerance to manufacturing errors. This is essential to submicron active-passive integration which requires a nano-range alignment accuracy.

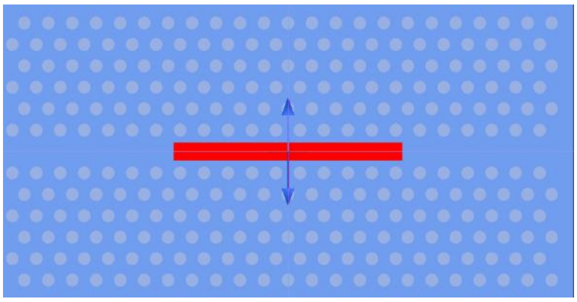

Fig.2 W1 photonic crystal cavity model

3 Simulation results

A Finite-difference time-domain (FDTD) method is used to perform the 3-D numerical calculations.

3.1 Simplified model

Firstly, a simplified model which doesn't includes doping and oxidation of AlInAs, is calculated. The spectrum of the resonance can be seen from Fig.3 and a high Q of 17000 at the wavelength of 1576 nm is obtained. The field profile of the cavity mode is shown in Fig.4. Fig.5 shows a good overlap of the buried active region with the cavity mode profile.

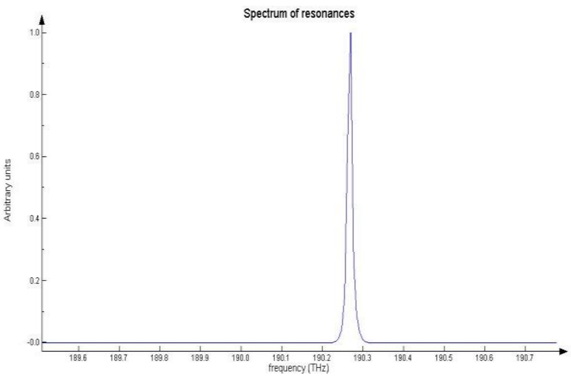

Fig.3 Resonance spectrum of simplified model

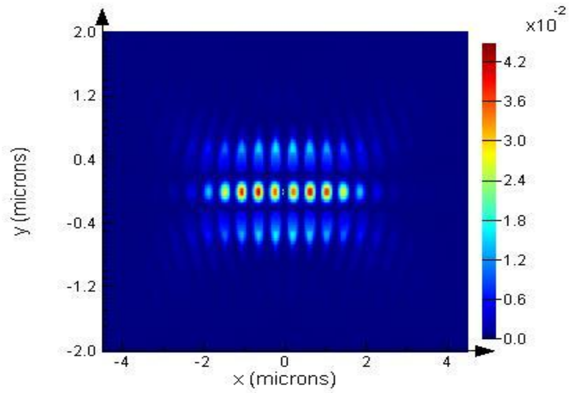

Fig.4 Mode field profile of the main resonant mode

3.2 Extended model

An extended model simulation includes two physical factors which could influence the performance of the cavity: doping and AlInAs oxidation. Fig.6 shows the simulation results in the frequency domain. A reduced, quality factor (3507) is obtained. This decreased value of quality factor is expected, first because doping, especially p-type doping, will increase the optical loss in the cavity and therefore reduce the quality factor. Secondly, oxidation of AlInAs is used to realize the current blocking function. The side-effect of this technique is that there is also a refractive index decrease with the oxidation of AlInAs which subsequently influence the Q factor negatively.

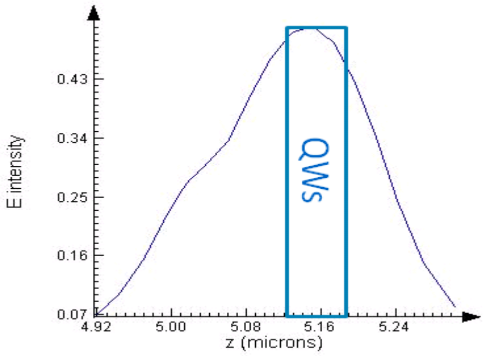

Fig.5 Mode overlap with active region (QWs)

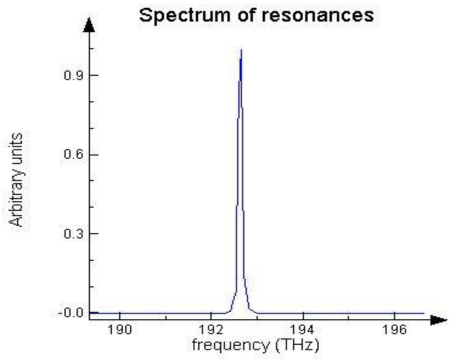

Fig.6 Resonance spectrum of physical model

3.3 Tolerance check

Manufacturing imperfections are inevitable during the fabrication process. Therefore it is necessary to check whether the cavity is tolerant to the common manufacturing errors. In our simulation, two types of manufacturing errors are considered. The first one is the misalignment of active region (see Fig.7) and the second one is the variation of the hole radius in the PhC arrays. In the first case, the active region is "misaligned" by 100nm, which is the maximum alignment error for our Electron Beam Lithography. The Q-factor of the cavity decreases to 2623. Fig.8 shows how the Q factor changes with the variation of photonic crystal hole radius. As one can see, both tolerance checks show that the cavity is tolerant to the typical manufacturing imperfections.

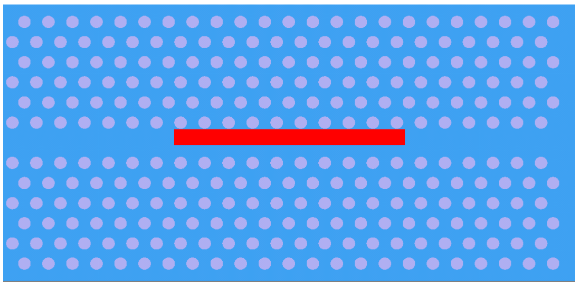

Fig.7 Misalignment of active region(100nm upwards)

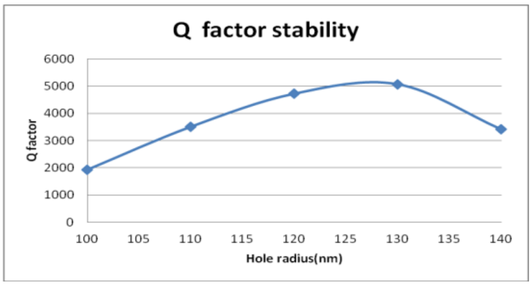

Fig.8 Quality factor vs hole radius variation

4 Conclusion

In this paper a "W1 like" photonic crystal cavity is designed and simulated. Results show that this cavity gives good performance in terms of quality factor and tolerance to manufacturing imperfections. A simulation included doping and oxidation of AlInAs shows a negative effect on the Q factor, but the negative influence is acceptable and controllable. Together with the success of two important test (Submicron active–passive integration and Oxidation of AlInAs) which we achieved in the last two years, we believe it is possible to make an electrical pumped PhC laser in the IMOS platform.

5 Acknowledgement

The authors thank EU Project HISTORIC for its financial support.

6 References

[1] R. P. Nagarajan and M.K. Smit, “Photonic integration”, IEEE LEOS Newsletter Vol 21, Nr. 3, pp. 4-10, June, 2007.
[2] J.J.G.M. van der Tol, R. Zhang, J. Pello, F. Bordas, G. Roelkens, H. Ambrosius, P. Thijs, F. Karouta and M.K. Smit, “Photonic Integration in Indium-Phosphide Membranes on Silicon” , IET optoelectronics, June, 2010.
[3] Hong-Gyu Park, Se-Heon Kim, Soon-Hong Kwon, Young-Gu Ju, Jin-Kyu Yang, Jong-Hwa Baek, Sung-Bock Kim, Yong-Hee Lee, “Electrically Driven Single-Cell Photonic Crystal Laser”, SCIENCE VOL 305, September, 2004.
[4] Bryan Ellis, Marie A. Mayer, Gary Shambat, Tomas Sarmiento, James Harris, Eugene E. Haller, and Jelena Vucˇkovic´, “Ultralow-threshold electrically pumped quantum dot photonic-crystal nanocavity laser”, NATURE PHOTONICS VOL 5, MAY, 2011.
[5] R. Zhang, F. Bordas, J.J.G.M. van der Tol, H. Ambrosius, G. Roelkens, M.A.Dundar and M.K. Smit, “Sub-micrometer Active-Passive Integration for InP-based Membranes on Silicon” Proc. ECIO 2010, Cambridge (UK), paper ThH1.
[6] R. Zhang, J.J.G.M. van der Tol , H. Ambrosius, P. Thijs, B. Smalbrugge, T. de Vries, G. Roelkens, F. Bordas, and M.K. Smit, “Oxidation of AlInAs for Current Blocking in a Photonic Crystal Laser”, Proc. COMMAD 2010, Canberra (Australia), paper105.
[7] Shinji Matsuo, Akihiko Shinya, Takaaki Kakitsuka, Kengo Nozaki, Toru Segawa, Tomonari Sato, Yoshihiro Kawaguchi and Masaya Notomi, “High-speed ultra-compact buried heterostructure photonic-crystal laser with 13 fJ of energy consumed per bit transmitted” NATURE PHOTONICS VOL 4 September, 2010