

# Performance analysis of III-V/SOI microdisk based all-optical gate for on-chip interconnects

**Citation for published version (APA):**

Kumar, R., Kumar, P., Roelkens, G., Liu, L., Regreny, P., Vries, de, T., Thourhout, Van, D., Baets, R. G. F., & Morthier, G. (2010). Performance analysis of III-V/SOI microdisk based all-optical gate for on-chip interconnects. In J. Pozo, M. Mortensen, P. Urbach, X. Leijtens, & M. Yousefi (Eds.), *Proceedings of the 15th Annual Symposium of the IEEE Photonics Benelux Chapter, 18-19 November 2010, Delft, The Netherlands* (pp. 129-132). TNO.

**Document status and date:**

Published: 01/01/2010

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

## Performance Analysis of III-V/SOI Microdisk Based All-Optical Gate for On-chip Interconnects

R.Kumar<sup>1</sup>, P.Kumar<sup>1</sup>, G. Roelkens<sup>1</sup>, L. Liu<sup>1\*</sup>, P. Regreny<sup>2</sup>, T. de Vries<sup>3</sup>, D. Van  
Thourhout<sup>1</sup>, R. Baets<sup>1</sup>, G. Morthier<sup>1</sup>

<sup>1</sup> Photonics Research Group, INTEC department, Ghent University-IMEC, Sint Pietersnieuwstraat 41,  
9000 Gent, Belgium

<sup>2</sup>INL, Site Ecole Centrale de Lyon Batiment F7, 36, Avenue Guy de Collongue, 69134 Ecully, France .

<sup>3</sup>OED Group, Department of Electrical Engineering, Technische Universiteit Eindhoven, P.O. Box 513  
5600 MB EINDHOVEN, The Netherlands

\*currently at: Institut for Fotonik, Nanophotonic Devices, Danmarks Tekniske Universitet Ørstedts  
Plads Bygning 345v, rum 1812800 Kgs. Lyngby, Denmark

*All-optical devices such as optical filters, (de)multiplexers, switches, modulators and optical buffers etc. have been demonstrated either on silicon or hybrid silicon platform. Power consumption, speed of operation, bandwidth and footprint etc. are important performance metrics for on-chip interconnects. Here we present the experimental and theoretical analysis of the performance of an all-optical gate, realized on III-V/SOI platform, for its applications in on-chip photonic interconnects.*

### Introduction

Due to the extensive research being done in the optical technology it is set to revolutionize the short-reach interconnects. This research is motivated by the fact that optical interconnects are capable of bringing several major advantages over their electrical counterparts. Most important among these are low power consumption, ultra-high speed (of the orders of tens of GHz), immunity to cross talk, precise clock distribution and system synchronization [1]. Silicon photonics is on the forefront to lead the optical technology for on-chip signal processing due to the availability of the mature and cost-effective CMOS technology. Impressive progress has been made in the past few years to experimentally realize various optical devices, e.g. switches [2-4], modulators [5,6], wavelength filters [7,8], and wavelength convertors [9,10] using CMOS technology. Research on silicon based optical devices is most likely to be continued in the coming years for the performance improvement. But for the realization of fully-functional all-optical chips we also need to realize and integrate the active photonic components and devices on a single chip. Active photonic components require the laser as a transmitter and its derivatives such as memory elements (flip-flops). This is where we need to think hard if it is ever possible to realize the fully-functional optical chips with the use of only silicon material since silicon is not a good gain medium fundamentally limited by its indirect bandgap. The answer may be yes as there have been demonstrations of lasing action in silicon [11], [12]. But for the on-chip interconnects the performance of these lasers is still far below the acceptable level of different metrics including modulation speed, optical bandwidth, footprint and power consumption to compete with the electrical counterparts. Therefore, it has become necessary to work with the hybrid solutions for optical sources by integrating III-V material on top of silicon waveguide circuits. If one hybrid component is necessarily required then other hybrid components must be, and can be, integrated on the same chip with low additional cost. At present, the III-V-on-silicon technology has the most advanced devices and most advanced photonic integrated circuits [13].

All-optical gate form an important building block for on-chip photonic interconnects. Cascaded all-optical gates can be used for realizing the multichannel (de)multiplexers. Active photonic components such as all-optical flip-flops and shift registers need all-optical gates in combination with bistable lasers [14]. In this paper, we analyze the performance of an all-optical gate realized with an InP-InGaAsP microdisk resonator heterogeneously integrated onto the SOI waveguide circuit [15].

### Transmission Characteristics

Measurement of input to through port transmission response of a 10 micron diameter disk resonator, as shown in Fig. 1(a), for TE polarized light gives an FSR of 22.68 nm which in turn gives the group index of 3.5325. The transmission characteristic of microdisks resonators can be altered using a forward or reverse bias. Fig. 1(b) illustrates the red shift in the resonance by 0.9nm with the application of a reverse bias voltage of 1 Volt. This shift corresponds to an effective index change of  $2 \cdot 10^{-3}$ . It has already been demonstrated by many other researchers [e.g. 16] that using the reverse bias reduces the carrier life time and can be used to improve the speed of all-optical gating which will be discussed in the next section.

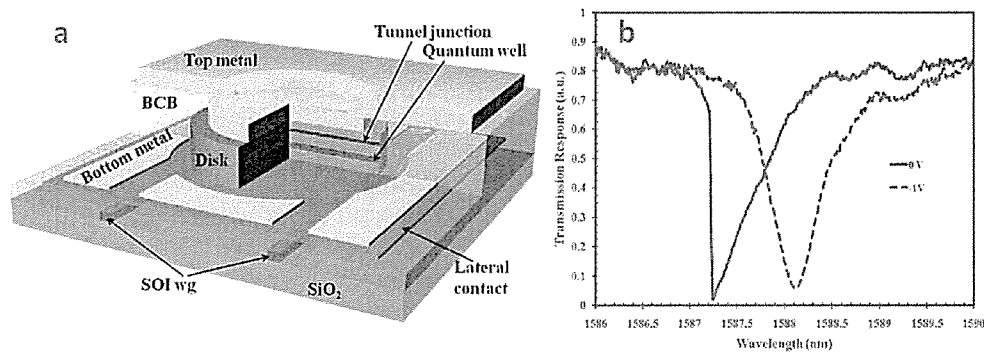


Figure 1. (a) Schematic of microdisk resonator and (b) its transmission response

### Dynamic Performance

All-optical gating is realized in a pump-probe configuration and the working principle of all-optical gating is explained in [15]. Fig. 2 (b) shows the gating response of the microdisk under the reverse bias of 1 volt to a pulse train of 10Gb/s as shown in the Fig. 2(a). Each pulse in the pulse train is of Gaussian shape with duration of 7.5 ps and has an extinction ratio of more than 20dB. The extinction ratio of the gating output is 4.5dB and is acceptable for on-chip communication. Transient details of the gating response are shown in the Fig 2(c) and (d). As can be seen from the transient responses that this device can accommodate a 20 Gb/s data stream since the rise time and fall time put together are 50 ps. The speed of the device is mainly limited by the fall time of the device which is attributed to the life time of the free carriers generated by the pump data stream. By making the carrier life time shorter the speed of the devices can be enhanced further. When a reverse bias is applied it sweeps out the carriers from the active region of the microdisk and effectively reduces the carrier life time.

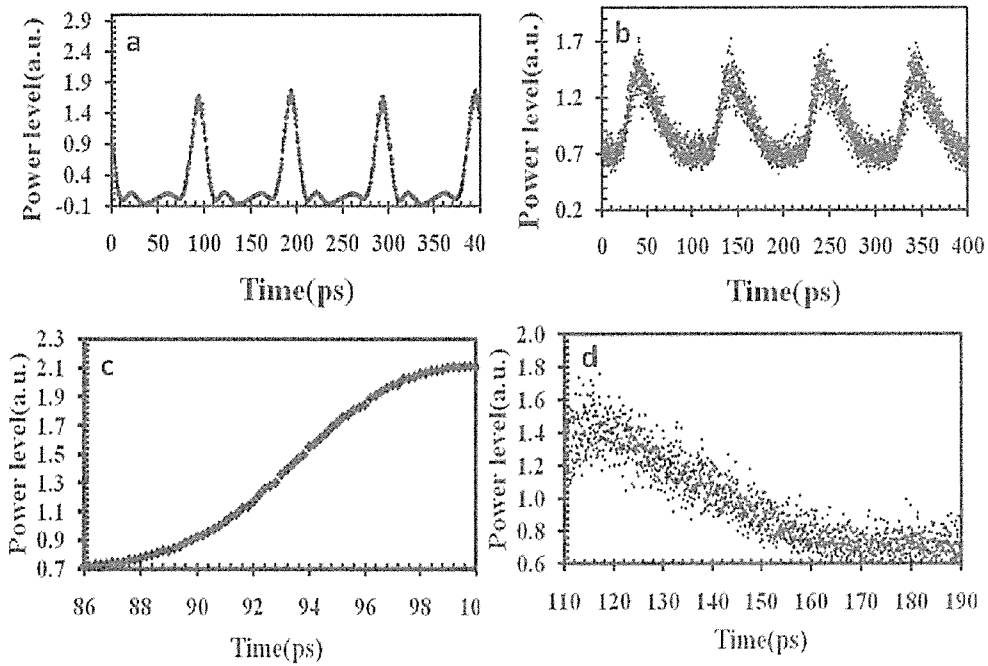


Figure 2. Dynamic performance: (a) Pulse train, (b) Gate output, (c) Rising edge transient details and (d) falling edge transient details

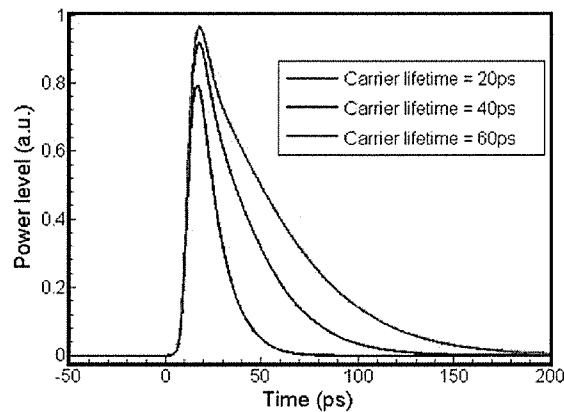


Figure 3. Dependence of fall time of gating response on carrier life time

Using a rate equation model, the gating response is simulated, with the carrier life time a variable parameter. Fig. 3 shows the dependence of the gating fall time on the carrier life time. It is obvious from this figure that the shorter the carrier life time is, the smaller is fall time and hence the faster is the recovery of the gate.

### Conclusions

As can be seen from the transmission characteristic measurements, the investigated microdisk has a low quality factor of  $\sim 4500$  and allows the relatively long wavelength

range of  $\sim 0.35\text{nm}$  for gating around the resonance. Further tuning is possible by applying forward or reverse bias. Probe power and pump power in the demonstrated device is  $170\mu\text{W}$  and  $4\text{ mW}$  respectively and can be reduced further. Speed limitation imposed by the fall time can be further improved e.g. by ion implantation in the microdisk. Based on the principle of gating, logic functions such as AND, OR and NAND can be realized using the same kind of single microdisks.

## References

- [1] D. A. B. Miller, "Rationale and challenges for optical interconnects to electronic chips", proceedings of the IEEE, vol.88, 728-749, 2005.
- [2] M. Waldow, T. Plotzing, M. Plotzing, M. Gottheil, M. Forst, J. Bolten, T. Wahlbrink, and H. Kurz, "25ps all-optical switching in oxygen implanted silicon-on-insulator microring resonator", Opt. Exp., vol.16, 7693-7702, 2008.
- [3] F. C. Ndi, J. Toulouse, T. Hodson, and D. Prather, "all-optical switching in silicon photonic crystal waveguides by use of plasma dispersion effect", Opt. Lett., Vol. 30, 2254-2256, 2005.
- [4] Y. Vlasov, W. M. J. Green, and F. Xia, "High-throughput silicon nanophotonic wavelength-insensitive switch for on-chip optical network", Nature. Phot., Vol. 2, 242-246, 2010.
- [5] Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, "Micrometer-scale silicon electro-optic modulator", Nature, Vol. 435, 325-327, 2005.
- [6] A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Cherit, N. Izhaky, and M. Paniccia, "High-speed optical modulation based on carrier depletion in silicon waveguide", Opt. Exp., Vol. 15, 660-668, 2007.
- [7] P. Koonath, T. Indukuri, and B. Jalali, "Add-drop filters utilizing vertically coupled microdisk resonators in silicon", App. Phys. Lett., Vol. 86, 1-3, 2005.
- [8] W. Bogaerts, S. Seelvaraja, P. Dumon, J. Brouckaert, K. de Vos, D. van Thourhout, and R. Baets, "Silicon-on-insulator spectral filters fabricated with CMOS technology", IEEE J. Select. Top. Quant. Elec., Vol. 16, 33-44, 2005.
- [9] Q. Xu, V. R. Almeida, and M. Lipson, "Micrometer-scale all-optical wavelength convertor on silicon", Opt. Lett. Vol. 30, 2733-2735, 2005.
- [10] R. Dekker, A. Driessen, T. Wahlbrink, C. Moorman, J. Niehussmann, and M. Forst, "Ultrafast Kerr-induced all-optical wavelength conversion in silicon waveguides using  $1.55\mu\text{m}$  femtosecond pulses", Opt. Exp., Vol. 14, 7693-7702, 2008.
- [11] O. Boyraz, and B. Jalali, "Demonstration of a silicon Raman laser," Opt. Exp., Vol. 12, 5269-5273 2004.
- [12] H. Rong, S. Xu, Y. Kuo, V. Sih, O. Cohen, O. Raday, and M. Paniccia, "Low-threshold continuous-wave Raman silicon laser", Nat. Phot., Vol.1, 725-728, 2005.
- [13] D. Lang, and J. Bowers, "Recent progress in lasers on silicon", Nature. Photon., Vol.4, 511-517, 2010.
- [14] L. Liu, R. Kumar, K. Huybrechts, T. Spuesens, G. Roelkens, E.-J. Geluk, T. de Vries, P. Regreny, D. Van Thourhout, R. Baets, and G. Morthier, "An ultra-small, low-power, all-optical flip-flop memory on a silicon chip", Nature. Photon., Vol. 4, 182-187, 2010.
- [15] R. Kumar, L. Liu, G. Roelkens, E.-J. Geluk, T. de Vries, F. Karouta, P. Regreny, D. Van Thourhout, R. Baets, and G. Morthier, "10GHz All-Optical Gate Based on a III-V/SOI Microdisk", IEEE Photon. Tech. Lett., Vol.22, 981-983, 2010.
- [16] A. C. Foster, M. A. Foster, J. S. Levy, C. B. Poitras, R. Salem, A. L. Gaeta, and M. Lipson, "Ultrashort free-carrier lifetime in low-loss silicon nanowaveguides", Opt. Exp., Vol. 18, 3582-3591, 2010.