10-GHz All-Optical Gate Based on a III–V/SOI Microdisk

Rajesh Kumar, *Member, IEEE*, Liu Liu, *Member, IEEE*, Gunther Roelkens, *Member, IEEE*, Erik-Jan Geluk, Tjibbe de Vries, Fouad Karouta, Philippe Regreny, Dries Van Thourhout, *Member, IEEE*, Roel Baets, *Fellow, IEEE*, and Geert Morthier, *Senior Member, IEEE*

***Abstract*—We demonstrate an ultrafast and low-power all-optical gate in pump–probe configuration based on free-carrier-induced refractive index modulation in a 5-μm radius InP–InGaAsP microdisk heterogeneously integrated onto a silicon-on-insulator waveguide circuit. High-speed gating is obtained by extracting the carriers from the microdisk active layer by applying a reverse bias. Measured transient responses show that this gate is capable of working up to 20 GHz.**

***Index Terms*—Microdisk, optical gate, silicon-on-insulator (SOI).**

I. Introduction

WITH the ever increasing demand of high-speed communication and computing, electronics-based devices and components are reaching their speed limit. All-optical signal processing seems to be the only way forward to meet these challenges. Various types of devices and components are needed for communication and computing. Many of these components have been realized in the optical domain using different approaches and technologies, e.g., [1] and [2]. Power consumption is becoming a serious issue and hence there is a need for low-power all-optical components and devices which are ever faster and smaller. Silicon photonics has emerged as a promising field of research, as monolithic integration of different optical components on a silicon chip offers the advantage of utilizing mature complementary metal–oxide–semiconductor (CMOS) fabrication technology. Using heterogeneous integration [3], different types of components [4]–[6] have been reported in the recent past. Disk and ring resonators are attracting a lot of attention for the realization of all-optical functionalities owing to their compact size, high quality factor, and low power consumption. Availability of compact electrical injection schemes makes disks better suited as compared to the ring resonators. In this letter, we report the fabrication and experimental results of a relatively low-power 10-GHz all-optical gate operating at telecommunication wavelengths, based on a III–V/silicon-on-insulator (SOI) microdisk. In this gate, the transmission of a low-power probe beam is controlled by a high-power pulse train which essentially behaves as a pump. The gating approach used here has the advantage of integration with other active devices such all-optical flip-flops [7], resulting in the realization of more complex photonic integrated circuits. In Section II, we give an overview of the fabrication. The gating concept is illustrated in Section III, while measurements are described in Section IV. In Section V, results are presented and the conclusions are drawn.

II. Device Fabrication

Before defining III–V microdisks, an unpatterned InP–InGaAsP epitaxial layer structure is bonded on top of an SOI waveguide circuit, containing 600-nm-wide and 220-nm-high silicon strip waveguides, using adhesive die-to-wafer bonding with the divinylsiloxane-benzocyclobutene (DVS-BCB) polymer [3]. After epitaxial layer transfer, microdisks of 10-μm diameter are defined by photolithography and transferred to the InP-based active material using reactive ion and inductively coupled plasma (RIE-ICP) etching. The total thickness of the epitaxial layers is around 580 nm, including three strained quantum wells, while the etch depth is around 500 nm. After carving out the microdisks, metal electrodes are defined for contacting. The step by step fabrication process is similar to that reported in [4]. A schematic drawing of the device is shown in Fig. 1. Focused-ion-beam (FIB) scanning electron microscope (SEM) images of the fabricated device are shown in Fig. 2. It is clear from this figure that the offsets of the two waveguides are different with respect to the microdisk edge. This is due to a small registration error in the definition of the III–V microdisk. This offset is an important parameter which determines the coupling of light from the waveguide to the microdisk and vice-versa. Ultimately

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R. Kumar, G. Roelkens, D. Van Thourhout, R. Baets and G. Morthier are with the INTEC Department, Ghent University-IMEC, 9000 Ghent, Belgium (e-mail: Rajesh.Kumar@intec.Ugent.be; Gunther.Roelkens@intec.Ugent.be; dries.vanthourhout@intec.Ugent.be; Roel.Baets@intec.Ugent.be; morthier@intec.Ugent.be).

L. Liu was with the INTEC Department, Ghent University-IMEC, 9000 Ghent, Belgium. He is now with the Institut for Fotonik Nanophotonic Devices, Danmarks Tekniske Universitet ørsteds PladsBygning 345v, rum 1812800 Kgs. Lyngby, Denmark (e-mail: Liu.Liu@intec.Ugent.be; lliu@fotonik.dtu.dk).

E.-J. Geluk and T. de Vries are with the OED Group Department of Electrical Engineering, Eindhoven University of Technology, 5600 MB, Eindhoven, The Netherlands (e-mail: e.j.geluk@tue.nl; t.d.vries@tue.nl).

F. Karouta was with the OED Group Department of Electrical Engineering, Eindhoven University of Technology, 5600 MB, Eindhoven, The Netherlands. He is now with the Australian National Fabrication Facility Research School of Physics and Engineering, Australian National University, Canberra 0200 ACT, Australia (e-mail: f.karouta@tue.nl; fjk109@physics.anu.edu.au).

P. Regreny is with the Institut des Nanotechnologies de Lyon INL-UMR5270, CNRS, Université de Lyon, Ecully F-69134, France (e-mail: philippe.regreny@ec-lyon.fr).

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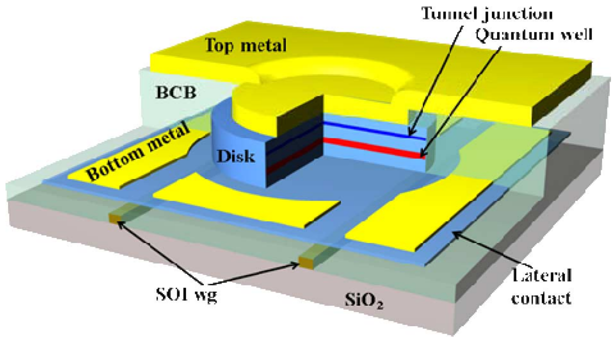

Fig. 1. Schematic view of the structure of the device.

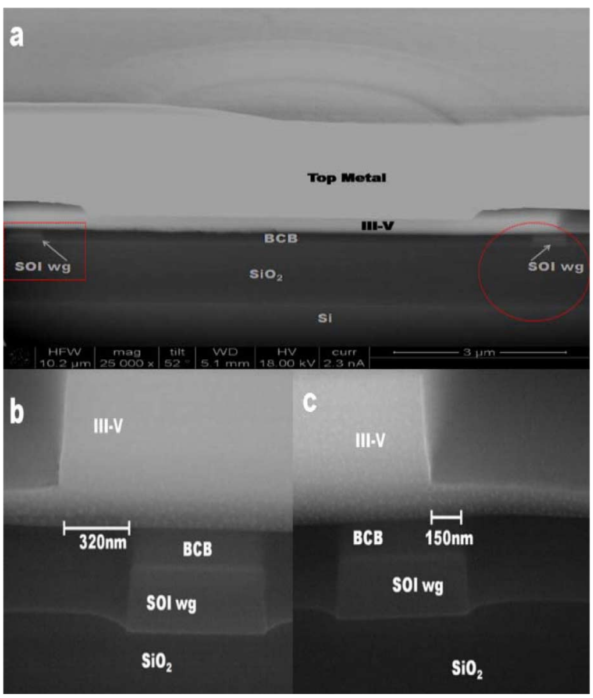

Fig. 2. FIB-SEM micrograph showing (a) cross section of the fabricated device, zoom-in-view of cross section part marked by rectangle and circle showing position of (b) drop port and (c) through port waveguide, respectively.

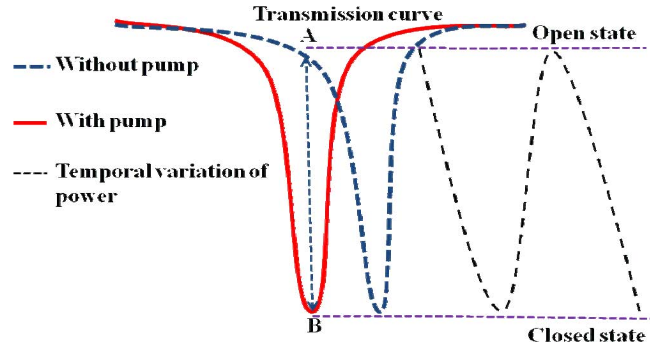

Fig. 3. Illustration of concept for all-optical gate.

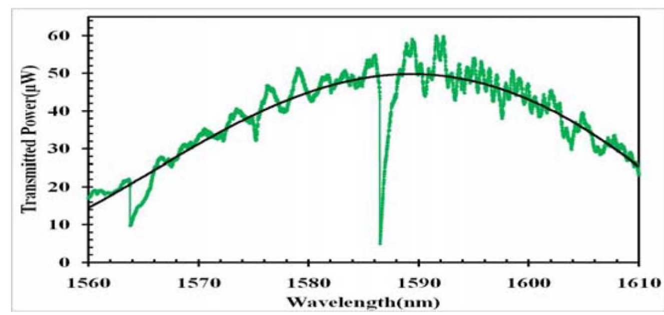

Fig. 4. Transmission spectrum (green curve) of the microdisk, and a fit (black curve) for the light coupling efficiency of the grating couplers.

this determines the performance of the device. This will be discussed further in Section IV.

III. Concept of the All-Optical Gate

Gating operation can be achieved in microdisk resonators in pump–probe configuration with the probe beam tuned at one of the resonances and the pump at another. The intensity of the probe beam is kept low to avoid carrier generation in the III–V active region. The transmission characteristic of the microdisk is altered by having the pump intensity many times higher than that of the probe beam. Fig. 3 illustrates the gating concept in a pictorial way. The dotted blue curve shows the transmission dip of the microdisk around the probe wavelength. When pump light is injected into the microdisk at another resonance of the microdisk, free carriers are generated which causes a blue shift in the transmission dip as shown by the solid red curve. Using a pulse train as a pump results in high or low output of the probe beam due to a periodic shifting of the resonance around the probe wavelength. If the probe wavelength is slightly blue tuned off the transmission dip, then in the absence of the pump pulse, the output is high and the gate is said to be in the open state. In the presence of the pump pulse, due to blue shift of the resonance, the output will be low and the gate is said to be in the closed state. In this way, the power level varies between points A and B in the time domain as represented by the dotted black line. During this whole process, the variation in the power level of the output of the gate follows the pattern of the pump pulses.

IV. Measurements

To find the microdisk resonances, the transmission spectra at the through and drop port were measured with the transverse-electric (TE) polarized light from a continuous-wave (CW) tunable laser. A good transmission characteristic is observed only at the through port, which is shown in Fig. 4 with the green curve along with a fit (black curve) for the light coupling efficiency of the grating couplers. We attribute this to the better alignment of the through port SOI waveguide with respect to the disk edge [see Fig. 2(c)]. Since the whispering gallery modes propagate along the edge of the microdisk, the light which couples into the microdisk from the input port does not couple well to the drop port due to the position of the drop port SOI waveguide away from the microdisk edge and more to the center of the disk as is clear from Fig. 2(b). Two resonances, one at 1563.9 nm and another at 1586.5 nm, are observed. We believe that ripples in the spectral response of the microdisk are due to a Fabry–Pérot resonance formed between the two grating couplers used for coupling light from the tunable laser to the waveguide through single-mode fiber, and reflections from fiber

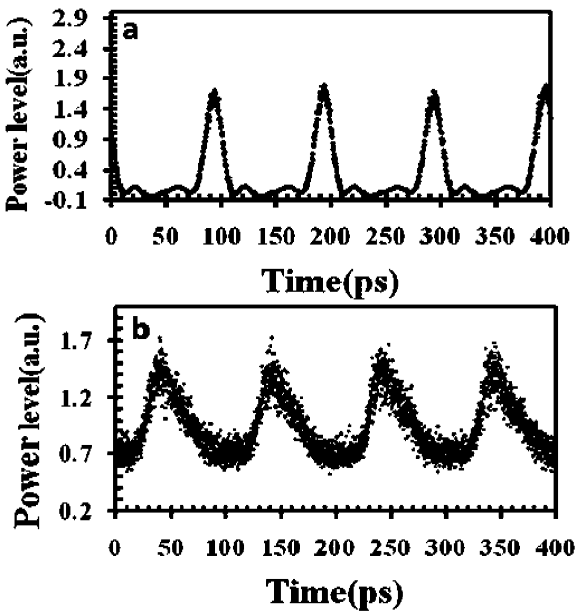

Fig. 5. (a) Pattern of the pulse train and (b) corresponding gate output.

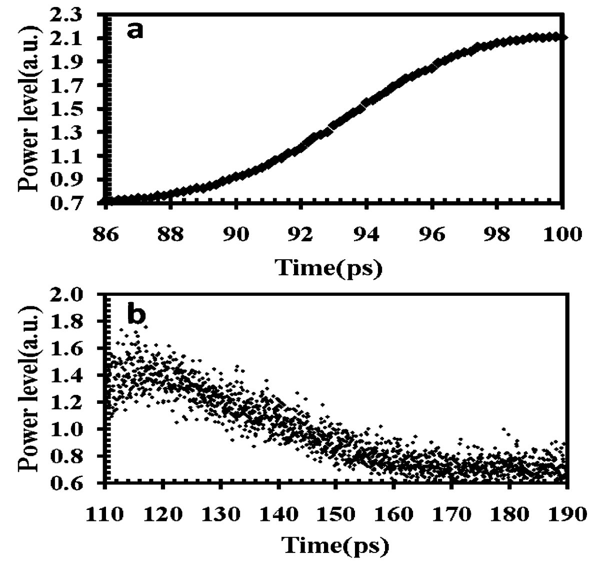

Fig. 6. Transient response of the gate output: (a) rise and (b) fall edge.

facets, connectors, etc. We see large change in the resonance behavior (extinction ratio, Q-factor) at two wavelengths due to the fact that the shorter wavelength (1563.9 nm) has higher absorption as it lies far away from the bandgap wavelength, which is ~1600 nm, while the longer wavelength (1586.5 nm) lies closer to the bandgap wavelength of the microdisk. The wavelength of the pump light injected at the through port is set at the lower resonance (1563.9 nm), while the wavelength of the probe light injected at the input port is set slightly below the longer resonance (1586.5 nm). The probe light is TE polarized CW light from a tunable laser, while the pump light is a pulse train of 10-GHz repetition rate with each pulse of 7.5-ps duration, extiction ratio of more than 20 dB, and Gaussian in shape as shown in Fig. 5(a). Probe and average pump power in the SOI waveguide is 170 μW and 4 mW, respectively. While carrying out measurements, the microdisk was kept under a reverse bias of -1 V to reduce the fall time by sweeping away the generated carriers from the active region [8].

V. Results and Discussion

The gate output corresponding to the pulse train [Fig. 5(a)] is plotted in Fig. 5(b). When the pump pulse has a high/low power level, the gate is in the closed/open state as discussed in Section III. The extinction ratio between the closed state and the open state is 4.5 dB. To estimate the gating speed of the device under investigation, transient responses are measured and plotted in Fig. 6. The rise time and fall time are 8.5 and 41.5 ps, respectively, which suggest that this device can operate up to 20 GHz.

The low extinction ratio between the closed and the open state can be attributed to the spontaneous emission noise generated in the erbium-doped fiber amplifier (EDFA) used to amplify the gate output before feeding it to the oscilloscope. We believe that the high speed of the gate is due to the surface-state recombination at the side walls of the microdisk, along with a contribution from the reverse bias. It seems that by increasing the pump power, the rise time can be reduced but it also requires increasing the reverse bias (e.g., to -2 or -3 V) to compensate the increased fall time. Under the same pump power and increasing the reverse bias to -2 V, no improvement in the fall time was seen. The bandwidth of the pump pulse used is 1 nm while the bandwidth of the transmission resonance at 1563.9 nm is 0.4 nm. This implies that the pump power can be further reduced by matching the bandwidth of the pump signal to that of the microdisk resonance.

In summary, we have demonstrated a fast all-optical gate based on a III–V microdisk heterogeneously integrated on the SOI waveguide platform, with a small footprint and a low power consumption.

References

[1] T. Sadagopan, S. J. Choi, S. J. Choi, P. D. Dapkus, and A. E. Bond, "Optical modulators based on depletion width translation in semiconductor microdisk resonator," *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 567–569, Mar. 2005.

[2] T. A. Ibrahim, K. Amarnath, L. C. Kuo, R. Grover, V. Van, and P.-T. Ho, "Photonic logic NOR gate based on two symmetric microring resonators," *Opt. Lett.*, vol. 29, no. 23, pp. 2779–2781, Dec. 2004.

[3] G. Roelkens, J. Brouckaert, D. Van Thourhout, R. Baets, R. Notzel, and M. Smit, "Adhesive bonding of InP/InGaAsP dies to processed silicon-on-insulator wafers using DVS-bis-bezocyclobutene," *J. Electrochem. Soc.*, vol. 153, no. 12, pp. G1015–G1019, Oct. 2006.

[4] J. Van Campenhout, P. R. Romeo, P. Regreny, C. Seassal, D. Van Thourhout, S. Verstuyft, L. Di Cioccio, J.-M. Fedeli, C. Lagahe, and R. Baets, "Electrically pumped InP-based microdisk lasers integrated with a nanophotonic silicon-on-insulator waveguide circuit," *Opt. Express*, vol. 15, no. 11, pp. 6744–6749, May 2007.

[5] L. Liu, J. Van Campenhout, G. Roelkens, R. A. Soref, D. Van Thourhout, P. R. Romeo, P. Regreny, C. Seassal, J.-M. Fedeli, and R. Baets, "Carrier-injection-based electro-optic modulator on silicon-on-insulator with a heterogeneously integrated III–V microdisk cavity," *Opt. Lett.*, vol. 33, no. 21, pp. 2518–2520, Nov. 2008.

[6] J. Brouckaert, G. Roelkens, D. Van Thourhout, and R. Baets, "Compact InAlAs–InGaAs metal–semiconductor–metal photodetectors integrated on silicon-on-insulator waveguides," *IEEE Photon. Technol. Lett.*, vol. 19, no. 19, pp. 1484–1486, Oct. 1, 2007.

[7] L. Liu *et al.*, "An ultra-small, low-power all-optical flip-flop memory on a silicon chip," *Nat. Photon.*, vol. 4, no. 3, pp. 182–187, Mar. 2010.

[8] S. F. Preble, Q. Xu, B. S. Schmidt, and M. Lipson, "Ultrafast all-optical modulation on a silicon chip," *Opt. Lett.*, vol. 30, no. 21, pp. 2891–2893, Nov. 2005.