

European HELIOS Project: Silicon Photonic Photodetector Integration

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Abstract:

We report recent experimental results of two kinds of photodetectors developed in the framework of the European project HELIOS: InAlAs–InGaAs metal–semiconductor–metal photodetectors and germanium photodetectors.

Keywords: microphotronics, waveguide, silicon-on-insulator, germanium, InGaAs, photodetector, integrated optics

Silicon-based photonics has generated an increasing interest in the recent year, mainly for optical telecommunications or optical interconnects in microelectronic circuits. The rationale of silicon photonics is the reduction of photonic system cost through the integration of photonic components and an electronic integrated circuit (EIC) on a common chip. At longer term, the EIC characteristics with the introduction of optics inside a high performance circuit should be enhanced.

For several years, numerous developments of silicon-based passive and active building blocks on and in silicon like waveguides [1,2], modulators [3-5], III/V source on silicon [6] and photodetectors [see table 1] have been carried out with impressive breakthroughs.

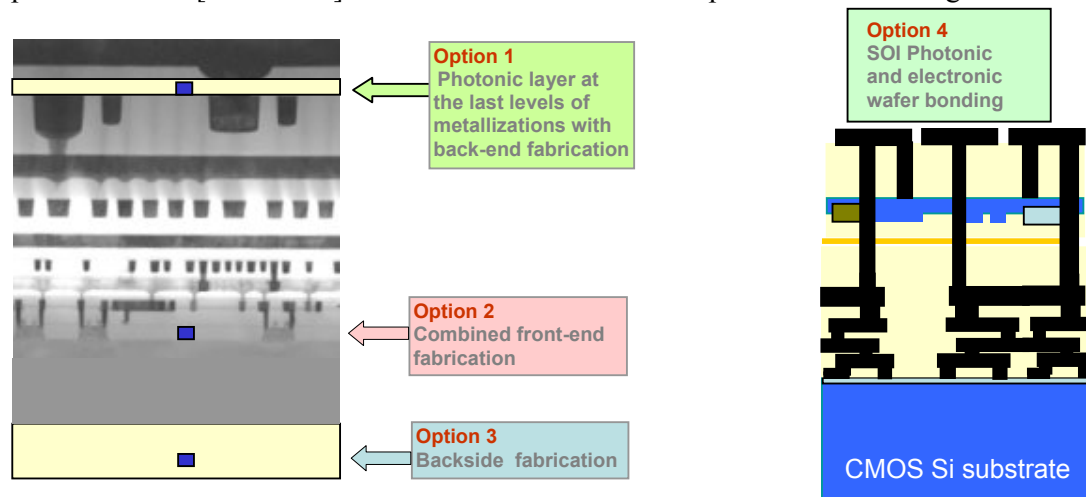


Figure 1: Possible integration routes [7]

Among all elementary components, efficient light photodetectors is one of the most important to make a high speed optical link for either optical telecommunications or interconnects. The choice of the absorbent material at telecom wavelength is directly linked to the integration

scheme we choose. Indeed, two kinds of active material can be used to detect light on silicon: germanium which is directly compatible with CMOS technology and III–V compound semiconductors which can be heterogeneously integrated. Different integration technology options are presented in figure 1.

The integration schemes presented in figure 1 require different material strategies for photonic devices, especially for active components. Indeed, in option 1 often called 3D integration or above IC integration, the photonic layer is realized at the metallization levels with back-end of the line technology (BEOL). In this case, all photonic devices are processed at low temperature and efficient III-V material will be used. In the option 2, III-V material can hardly be integrated at the level of silicon transistor. While in other options, either III-V or germanium can be used with a slight preference to consider monolithic integration using germanium instead of III-V components. In the framework of European project Helios, each option will be considered and both III-V and germanium photodetectors integrated in silicon waveguides are studied. Table 1 presents a non-exhaustive state of the art of photodetectors in/on silicon using either III-V materials bonded on Si or germanium on silicon.

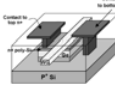

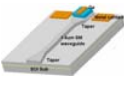
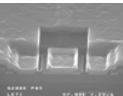
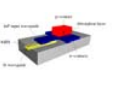
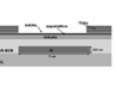
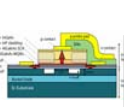

	Ge-on-Si photodetectors				III-V-on-Si photodetectors			
								
	MIT	UPS-IEF & LETI	INTEL	UPS-IEF & LETI	PICMOS	IMEC	INTEL	LETI
Year	2007	2007	2007	2008	2006	2007	2007	2007
structure	PIN	MSM	PIN	PIN	PIN	MSM	PIN	PIN
Dark current at -1V	~1 μ A	~100 μ A	~170 nA	~20 nA	~1 nA	~1 nA	~50 nA	~10 nA
Responsivity	~1.08 A/W	> 1 A/W	~0.9 A/W	~1 A/W	~0.45 A/W	~1 A/W	~0.31 A/W	~0.01 A/W
Bandwidth	7.2 GHz	25 GHz	31 GHz	42 GHz	33 GHz	-	0.5 GHz	-

Table 1: Non-exhaustive state of the art germanium and III-V photodetectors on silicon [8-16].

In the framework of the European project HELIOS, compact and efficient InAlAs–InGaAs metal–semiconductor–metal photodetectors and germanium photodetectors integrated on silicon-on-insulator (SOI) waveguides are studied and optimized to achieve data transmission up to 40Gbit/s. dark-current and responsivity at a wavelength of 1.55 μ m of both III-V and Ge waveguide photodetectors are about few nA and 1 A/W respectively.

As an example, we obtained an open eye diagram from a vertical pin Ge-on-Si diode integrated with a rib waveguide, modulated at 40Gb/s, as shown in Fig. 2.

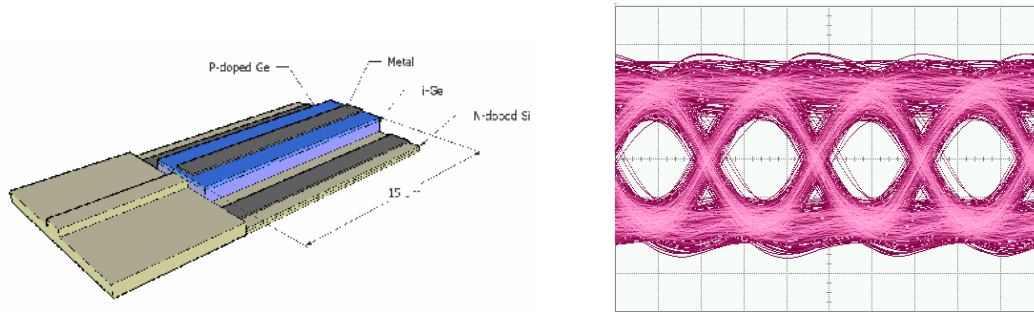


Figure 2: (a) Schematic view of vertical pin Ge-on-Si diode integrated in rib waveguide. (b) Open eye diagram at 40Gbit/s.

In conclusion, we report recent results of two kinds of photodetectors developed in the framework of the European project HELIOS: InAlAs–InGaAs metal–semiconductor–metal photodetectors and germanium photodetectors. Low dark-current and high responsivity at a wavelength of $1.55\mu\text{m}$ have been achieved with both photodetectors. Data transmission up to 40 Gbit/s for Ge photodiode has been obtained.

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- [1] S.Lardenois, D.Pascal, L.Vivien, E.Cassan, S.Laval, R.Orobtcouck, M.Heitzmann, N.Bouzaida, L.Mollard, Low-loss submicrometer silicon-on-insulator rib waveguides and corner mirrors, *Opt. Lett.* **28**, 1150-1152 (2003).
- [2] W. Bogaerts, D. Taillaert, B. Luyssaert, P. Dumon, J. Van Campenhout, P. Bienstman, D. Van Thourhout, R. Baets, V. Wiaux, and S. Beckx, "Basic structures for photonic integrated circuits in Silicon-on-insulator," *Opt. Express* **12**, 1583-1591 (2004)
- [3] Delphine Marris-Morini, Laurent Vivien, Jean Marc Fédéli, Eric Cassan, Philippe Lyan, and Suzanne Laval, "Low loss and high speed silicon optical modulator based on a lateral carrier depletion structure," *Opt. Express* **16**, 334-339 (2008)
- [4] Delphine Marris-Morini, Xavier Le Roux, Laurent Vivien, Eric Cassan, Daniel Pascal, Mathieu Halbwx, Sylvain Maine, Suzanne Laval, Jean Marc Fédéli, and Jean François Damlencourt, "Optical modulation by carrier depletion in a silicon PIN diode," *Opt. Express* **14**, 10838-10843 (2006)
- [5] L. Liao, A. Liu, et al, "40 Gbit/s silicon optical modulator for highspeed applications", *Electronics Letters*, **43**, (22) (2007).
- [6] P. Rojo Romeo, J. Van Campenhout, P. Regreny, A. Kazmierczak, C. Seassal, X. Letartre, G. Hollinger, D. Van Thourhout, R. Baets, J. M. Fedeli, and L. Di Cioccio, "Heterogeneous integration of electrically driven microdisk based laser sources for optical interconnects and photonic ICs," *Opt. Express* **14**, 3864-3871 (2006)
- [7] J.M. Fedeli, L. Di Cioccio, D. Marris-Morini, L. Vivien, R. Orobtcouck, P. Rojo-Romeo, C. Seassal AND F. Mandorlo, Development of silicon photonics devices using microelectronic tools for the integration on top of a CMOS wafer, *Advances in Optical Technologies AOT*, special issue : "Silicon Photonics", vol. 2008, Article ID 412518, 15 page,(2008)
- [8] D. Ahn, C.-yin Hong, J. Liu, W. Giziewicz, M. Beals, L. C. Kimerling, J. Michel, J. Chen and F. X. Kärtner, " High performance, waveguideintegrated Ge photodetectors," *Opt. express* **15** (7), 3916-3921 (2007).
- [9] L. Vivien, M. Rouvière, J-M. Fédéli, D. Marris-Morini, J-F. Damlencourt, J. Mangeney, P. Crozat, L. El Melhaoui, E. Cassan, X. Le Roux, D. Pascal, and S. Laval, " High speed and high responsivity germanium photodetector integrated in a Silicon-On-Insulator microwaveguide," *Opt. Express* **15** (15), 9843-9848 (2007).
- [10] T. Yin, R. Cohen, M. M. Morse, G. Sarid, Y. Chetrit, D. Rubin, and M. J. Paniccia, " 31GHz Ge n-i-p waveguide photodetectors on silicon-on-insulator sunstrate," *Opt. express* **15** (21), 13965-13971 (2007).
- [11] Laurent Vivien, Johann Osmond, Jean-Marc Fédéli, Delphine Marris-Morini, Paul Crozat, Jean-François Damlencourt, Eric Cassan, Y. Lecunff, and Suzanne Laval, "42 GHz p.i.n Germanium photodetector integrated in a silicon-on-insulator waveguide," *Opt. Express* **17**, 6252-6257 (2009)
- [12] G. Roelkens, D. Van Thourhout, R. Baets, R. Nötzel, and M. Smit, "Laser emission and photodetection in an InP/InGaAsP layer integrated on and coupled to a Silicon-on-Insulator waveguide circuit," *Opt. Express* **14**, 8154-8159 (2006)
- [13] Joost Brouckaert, Gunther Roelkens, Dries Van Thourhout, and Roel Baets, Compact InAlAs–InGaAs Metal–Semiconductor–Metal Photodetectors Integrated on Silicon-on-Insulator Waveguides, *IEEE Phot. Techn. Lett.* **19**,(2007)
- [14] Hyundai Park, Alexander W. Fang, Richard Jones, Oded Cohen, Omri Raday, Matthew N. Sysak, Mario J. Paniccia, and John E. Bowers, "A hybrid AlGaInAs-silicon evanescent waveguide photodetector," *Opt. Express* **15**, 6044-6052 (2007)
- [15] CEA/LETI – Internal report
- [13] P.R.A. Binetti, X.J.M. Leijtens, T. de Vries, Y.S. Oei, L. Di Cioccio, J.-M. Fedeli, C. Lagahe, J. Van Campenhout, D. Van Thourhout, P.J. van Veldhoven, R. Nötzel and M.K. Smit, InP/InGaAs Photodetector on SOI Circuitry, Group IV Photonics 2009.