13TH INTERNATIONAL CONFERENCE ON GROUP IV PHOTONICS

24 - 26 August 2016

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Welcome to the
13th International Conference on Group IV Photonics

24 - 26 August 2016

Grand Kempinski Hotel Shanghai
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Welcome to the 13th International Conference on Group IV Photonics at the Grand Kempinski Hotel Shanghai, Shanghai, China!

The Group IV Photonics Conference (GFP 2016), now in its 13th year, delivers insights on current and future innovations in Group IV element-based photonic materials and devices, including silicon photonics, as well as other integration and fabrication technologies. Scheduled as a single-track conference, GFP 2016 facilitates personal interaction between colleagues, including oral and poster sessions of contributed and invited papers, as well as a plenary session with overviews of important Group IV element photonics topics.

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Group IV Photonics 2016 Program at-a-Glance

TUESDAY, 23 AUGUST	WEDNESDAY, 24 AUGUST	THURSDAY, 25 AUGUST	FRIDAY, 26 AUGUST
All Sessions will be in the Suncuba Ballroom	**WA:** Welcome Remarks/Plenary I/Systems & Subsystems 8:00am-10:00am	**ThA:** Plenary II/ Passives & Couplers I 8:15am-10:00am	**FA:** Lasers & Light Sources 8:00am-10:00am
	EXHIBITS/COFFEE BREAK 10:00am-10:30am		
9:00am-1:00pm Masterclass: Designing Silicon Photonic Wavelength Filters **Sponsored by: Luceda Photonics and Ghent University**	**WB:** Modulators, Switches & Thermal Control 10:30am-12:00pm	**ThB:** Hybrid Photonics 10:30am-12:00pm	**FB:** Passives & Couplers III 10:30am-12:00pm
			Best Papers & Best Posters Award Ceremony 12:00pm-12:20pm
	LUNCH BREAK (ON OWN) 12:00pm-1:30pm		LUNCH BREAK (ON OWN) 12:20pm-1:30pm
2:00pm-6:00pm Silicon Photonics Workshop **Sponsored by: Synopsys & PhoeniX Software** Followed by a Coffee Break	**WC:** Sources & Detectors 1:30pm-3:30pm	**ThC:** Photonic Circuits 1:30pm-3:30pm	**FC:** Integration Platforms 1:30pm-3:30pm
	EXHIBITS/COFFEE BREAK 3:30pm-4:00pm		
	WD: Germanium Photonics 4:00pm-5:30pm	**ThD:** Passives & Couplers II 4:00pm-5:30pm	**FD:** Transceivers 4:00pm-5:30pm
	Welcome Reception 5:30pm-7:30pm **Havana Nights** **Sponsored by: Intel Corporation**	**ThP:** Poster Session 5:30pm-7:00pm **Havana Nights** **Sponsored by Luceda Photonics**	**Post-Deadline Session** 5:30pm-6:30pm

6:00 PM-7:00 PM Coffee Break

Wednesday, 24 August 2016

8:00 AM- 10:00 AM
Session WA: Opening Remarks/Plenary I/Systems & Subsystems
Session Chair: Lin Yang, IOSCAS, China & Zhiping (James) Zhou, Peking University, China

8:00 AM-8:05 AM Welcome address- Lin Yang, IOSCAS, China

8:05 AM-8:15 AM Technical report- Zhiping (James) Zhou, Peking University, China

8:15 AM-9:00 AM Plenary I - Introduced by Zhiping (James) Zhou, Peking University, China

9:00 AM-10:00 AM Invited talks - Chaired by Lin Yang, IOSCAS, China

WA1 8:15 AM-9:00 AM (Plenary)

Silicon Photonics and the Future of Optical Connectivity in the Data Center, A. Bjorlin, *Intel Corporation, USA*

The bandwidth challenges inside the data center and between data centers has many of the largest cloud service providers exploring new innovations in networking and optical connectivity. Silicon photonics is one such innovation area, enabling very high bandwidth with significant density and cost advantages, and is a key enabler for driving optics closer and closer to the server and switch silicon. In this talk we'll review the recent advances in silicon photonics, discuss where silicon photonics is deployed in the data center of today, and how it will be transforming the data center of the future.

WA2 9:00 AM-9:30 AM (Invited)

Dynamic Control of Silicon Photonic Switches for the Post-Moore Era, S. Namiki, National Institute of Advanced Industrial Science and Technology, Japan

WA3 9:30 AM-10:00 AM (Invited)

Silicon Photonics System and Subsystem Integration, P. O'Brien, *Tyndall National Institute, Ireland*

10:00 AM-10:30 AM Coffee Break/Exhibits: Huangpu Room and Meeting Room 2 & 3

10:30 AM- 12:00 PM
Session WB: Modulators, Switches and Thermal Control
Session Chair: Graham Reed, University of Southampton, United Kingdom

WB1 10:30 AM-10:45 AM

Ultra-Large-Scale Silicon Optical Switches, L. Qiao, W. Tang and T. Chu, *Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China*

32 × 32 electro-optic and 64 × 64 thermal-optic Mach-Zehnder interferometer (MZI)-based switches were demonstrated using a 180-nm CMOS process. To the best of our knowledge, both switches that were demonstrated were the largest-scale electro-optic and thermal-optical silicon switches available.

WB2 10:45 AM-11:00 AM

Electrostatic Discharge Sensitivity of Silicon Photonic Photodetectors and Thermo-Optic Tuning Elements, D. Celo and D. Goodwill, *Huawei Technologies Canada Co, Ltd, Ottawa, Ontario,* C. Banks and S. Trifoli, *MuAnalysis Inc, Ottawa, Ontario*, P. Dumais, J. Jiang, C. Zhang and D. Geng, *Huawei Technologies Canada Co, Ltd, Ottawa, Ontario*, E. Bernier, *All-Optics Laboratory, Huawei Technologies Co. Ltd, Shenzhen*

ESD sensitivity of silicon photonics critically affects manufacturability. We report the ESD sensitivity of monolithic silicon photonic elements, using ESDA/JEDEC tests. TiN heaters were class 1C, requiring JEDEC Basic ESD Control. Ge-photodiodes were class 0B, requiring Detailed ESD Control, unless on-chip ESD solutions are implemented.

WB3 11:00 AM-11:15 AM

Design of Integrated Capacitive Modulators for 56GBPS Operation, M. DOUIX and D. Marris-Morini, *STMicroelectronics SAS, CROLLES*, C. Baudot, *Institut d'Electronique Fondamentale, Orsay, France*

We present TCAD simulation results for the integration of capacitive modulators in a 300mm SOI platform. We show that tuning the capacitor oxide thickness improves the bandwidth and the component efficiency, leading to 860µm active length, 56Gbps data rate and low power consumption (1.2Vpp).

WB4 11:15 AM-11:30 AM

All-Silicon Thermal Independent Mach-Zehnder Interferometer with Multimode Waveguides, X. Guan and L. Frandsen, *DTU Fotonik, Kgs. Lyngby, Denmark*

A novel all-silicon thermal independent Mach-Zehnder interferometer consisting of two multimode waveguide arms having equal lengths and widths but transmitting different modes is proposed and experimentally demonstrated. The interferometer has a temperature sensitivity smaller than 8pm/°C in a wavelength range of 18nm.

WB5 11:30 AM-11:45 AM

A 2×2 Silicon Thermo-Optic Switch Based on Nanobeam Cavities with Ultra-Small Mode Volumes, H. Zhou, C. Qiu, Z. Xu, X. Jiang, Y. Yang, L. Han, Y. Zhang and Y. Su, *State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, China*

We propose and experimentally demonstrate a 2×2 thermo-optic (TO) switch implemented by dual photonic crystal nanobeam (PCN) cavities. This structure can achieve low switching power owing to the small mode volumes of the PCN cavities. Extinction ratio of ~15 dB is achieved at through port.

WB6 11:45 AM-12:00 PM

Thermal Tuning Double Ring Resonator Filters: Experimental Analysis, C. Manganelli, P. Pintus, G. Gambini, and F. Di Pasquale, Consorzio Nazionale Interuniv. Per le Telecomunicazioni, Pisa, Italy, C. Oton, *Scuola Superiore Sant'Anna, Pisa, Italy, and C. Kopp, CEA LETI, Genoble, France*

We present experimental results of thermally tunable double ring resonators with doped silicon and silicide heaters and different geometries. We study the effects of fabrication inaccuracies which affect the symmetry of the heating, and we show how spectra are recovered when asymmetry is electrically compensated.

12:00 PM-1:30PM Lunch (On Own)

1:30 PM-3:30 PM
Session WC: Sources and Detectors
Session Chair: Andy Knights, McMaster University, Canada

WC1 1:30 PM-1:45 PM

Manufacturable Hybrid Silicon Array Laser Source Using an Interposer Based Back-End- of-the-Line Integration, X. Zheng, *Networking Group, Oracle, San Diego, California, USA*

We report a silicon interposer based 1x4 external-cavity hybrid III-V/Si laser array using a manufacturable back-end-of-the-line integration. All channels are individually-tunable and wavelength-stabilized with a threshold current of 14mA, output powers of >3mW, over 35dB side mode suppression ratio and less then 46kHz linewidth.

WC2 1:45 PM-2:00 PM

Ultrahigh-Sensitivity On-Chip Power Monitor using a Resistive Microheater in a Silicon Waveguide, D. Lee, L. Zhou and J. Chen, *Shanghai Jiao Tong University, Shanghai, China*

A doped-silicon microheater is routinely used to thermally tune the optical devices. We demonstrate that such a microheater assisted with an external lock-in amplifier can also work as a non-invasive ultra-high sensitivity optical power monitor. Waveguide optical power as low as -40 dBm is detected.

WC3 2:00 PM-2:15 PM

Novel Cost Effective Butt-Coupled PIN Germanium Photodetector Integrated in a 200mm Silicon Photonic Platform, B. Szelag, l. Virot, S. Malhouitre, b. Blampey, S. Brision, J. Hartmann, P. Brianceau, J. Fedeli and C. Kopp, *CEA-LETI, Grenoble, France*

A photodiode based on a double SiGe heterojunction integrated in silicon platform with only one additional mask is presented. Advantages versus conventional devices are: cost reduction, improved responsitity and access resistance, robustness. Responsivity of 0.7-0.8 A/W with bandwidth higher than 30GHz are demonstrated at 1310nm.

WC4 2:15 PM-2:30 PM

Germanium Photodetectors on Amorphous Substrates for Electronic-Photonic Integration, B. Pearson, B. Pearson, L. Kimerling and J. Michel, *Massachusetts Institute of Technology, Cambridge, MA,USA*

A germanium photodetector is fabricated on silicon dioxide at low temperature in order to demonstrate monolithic compatibility with back-end-of-line CMOS manufacturing. Final MSM photodetectors demonstrate net gain with an internal quantum efficiency greater than 100%.

WC5 2:30 PM-2:45 PM

Design Effects on the Performance of High-Speed Ge Photo Detectors, S. Lischke, D. Knoll, C. Mai, M. Kroh, D. Schmidt, A. Peczek, J. Kreißl, *IHP, Frankfurt (Oder)* and J. Lee, *IHP, Frankfurt*, M. Kim, W. Choi and L. Zimmermann, *Department of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea*

We investigate design effects on the opto-electrical frequency response of waveguide-coupled, lateral Ge p-i-n photodiodes to estimate the sensitivity of this response to diode fabrication tolerances and, in particular, to improve our understanding how diffusion of photo carriers acts on the response behavior

WC6 2:45 PM-3:00 PM

Narrow-Linewidth Widely Tunable Hybrid External Cavity Laser Using Si3N4/SiO2 Microring Resonators, R. Oldenbeuving, R. Ji, S. Fu and L. Zeng, *Huawei Technologies Co, Ltd, Wuhan*, J. Zhao, J. Epping, M. Hoekman and R. Heideman, *LioniX B.V, Enschede*, R. Dekker, *XiO Photonics B.V, Enschede*, Y. Fan and K. Boller, *University of Twente, Enschede*

We report on the characteristics of a tunable hybrid external cavity laser using silicon nitride microring resonators. A wavelength tuning range covering from 1530nm to 1580nm is demonstrated with a side mode suppression ratio larger than 45dB. Typical linewidth values are 65kHz.

WC7 3:00 PM-3:15 PM

Ultra-High Responsivity Photodetector on the Silicon-Graphene Platform, Y. Yin and L. Yu, *Zhejiang University, Hangzhou, China*

A graphene-silicon conductive photodetector is designed and demonstrated with ultra-high responsivity (~10^7A/W) by introducing a graphene-sheet with a geometrical size designed optimally.

WC8 3:15 PM-3:30 PM

Structure and Stress Engineering for Ge-on-Si Lasers Using Silicon Nitride Stressors, J. Ke, *Department of Materials Engineering, University of British Columbia, Vancouver*, L. Chrostowski, *Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada*

Two Ge-on-Si laser designs with CMOS compatible side and top silicon nitride stressors were proposed and shown to effective ways to increase wall-plug efficiency η_{wp} and decrease I_{th}. The two structures were then optimized and a η_{wp} up to 31.5% can be achieved.

3:30 PM-4:00 PM Coffee Break/Exhibits: Huangpu Room and Meeting Room 2 & 3

4:00 PM-5:30 PM
Session WD: Germanium Photonics
Session Chair: Jurgen Michel, Massachusetts Institute of Technology, USA

WD1 4:00 PM-4:15 PM

Intersubband Absorption in p-Ge QWs on Si, K. Gallacher, R. Millar, A. Bashir, I. MacLaren and D. Paul, *University of Glasgow, Glasgow*, A. Ballabio, J. Frigerio and G. Isella, *L-NESS, Dipartimento di Fisica del Politecnico di Milano, Como,* M. Ortolani, *Center for Life Nanosciences, Istituto Italiano di Tecnologia, Rome, Italy*

Mid-infrared intersubband absorption from p-Ge quantum wells with $Si_{0.5}Ge_{0.5}$ barriers grown on a Si substrate is demonstrated from 6 to 9 µm wavelength at room temperature and can be tuned by adjusting the quantum well thickness.

WD2 4:15 PM-4:30 PM

Modeling and Fabrication of Ge-on-Si_3N_4 for Low Bend-Loss Waveguides, W. Li, *School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore*

Germanium on Silicon Nitride (Ge-on-Si_3N_4) structure is realized by the layer transfer technology to extend applications of group four photonics to Mid-IR range. Large refractive contrast between Germanium and Silicon Nitride can result in extremely low bend loss suitable for compact designs.

WD3 4:30 PM - 4:45 PM

Defect-Free GeSn Alloy Strips on Si by Sn Self-Catalyzed MBE Method, K. Yu, h. Cong, X. Zhang, Y. Zhao and B. Cheng, *State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China*

The lateral growth of GeSn strips on Si(111) has been successfully achieved by Sn self-catalyzed MBE method. The effect of Sn catalysts on morphology and the quality of the materials were studied. The high quality GeSn on Si will contribute to development of Si-based optoelectronics.

WD4 4:45 PM-5:00 PM

Mid-Infrared Supercontinuum Generation in a Low-Dispersion Ge-on-Si Waveguide Using Sub-picosecond Pulses, *M. Yang, Z. Han, K. Wada and L. Zhang, Photonic Systems Laboratory of Opto Electronic Information Technology of Ministry of Education, School of Precision Instrument and Opto-electronics Engineering, Tianjin University, Tianjin,* Y. Guo, L. Kimerling, A. Agarwa and J. Michel, *Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts,* J. Wang, *Department of Materials Engineering, University of Tokyo, Tokyo,* G. Li, *College of Optics and Photonics, CREOL and FPCE, University of Central Florida, Orlando, Florida, USA*

We present a dispersion-engineered Ge-on-Si waveguide with flat and low dispersion from 3 to 11 µm, which enables coherent supercontinuum generation from 3700 to 9240 nm using a sub-picosecond pulsed pump.

WD5 5:00 PM-5:15 PM

Direct Band Gap Germanium in High Q-Factor Cavities, M. El Kurdi, A. Elbaz, M. Prost, A. Ghrib, R. Ossikovski, G. Picardi and S. Sauvage, *IEF CNRS/Université Paris-Sud, Orsay, France*, X. Checoury and G. Beaudouin, *LPICM, CNRS/Ecole Polytechnique, Palaiseau, France*, I. Sagnes and F. Boeuf, *LPN,UPR20 CNRS, Marcoussis, France*, P. Boucaud, *STMicroelectronics, Crolles, France*

Direct band gap germanium microdisks are obtained by applying high tensile strain using external stressor layers. We performed temperature dependent photoluminescence analysis to quantify that the indirect-to-direct band gap transition occurs at 1.67% of biaxial strain and study the emission on high Q-factor strained cavities.

WD6 5:15 PM-5:30 PM

Highly Strained Direct Bandgap Germanium Cavities for a Monolithic Laser on Si, T. Zabel, E. Marin, R. Geiger and C. Bonzon, *Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, Villigen*, S. Tardif, *Institute for Quantum Electronics, ETH Zürich, Zürich*, K. Guilloy, A. Gassenq, J. Escalante, Y. Niquet, I. Duchemin and J. Rothman, *University Grenoble Alpes, CEA INAC, Grenoble*, N. Pauc, F. Rieutord, V. Reboud, V. Calvo, J. Hartmann, J. Widiez, A. Tchelnokov and J. Faist, *CEA-LETI Minatec Campus, Grenoble*, H. Sigg, *Institute for Quantum Electronics, ETH Zürich, Zürich*

Cavity enhanced photoluminescence at a wavelength as long as 5 µm is obtained in uniaxial tensile strained GeOI micro-bridges. We show, using temperature dependent photoluminescence spectroscopy, a crossover to fundamental direct bandgap and reveal from a mode analysis the free carrier induced loss increase.

5:30 PM-7:00 PM Welcome Reception: Havana Nights- Sponsored by Intel Corporation

Thursday, 25 August 2016

8:15 AM-10:00 AM
Session ThA: Plenary II/Passives & Couplers
Session Chair: Zhiping (James) Zhou, Peking University, China & Lin Yang, IOSCAS, China

8:15 AM-9:00 AM Plenary II- Introduced by Lin Yang, IOSCAS, China

9:00 AM-10:00 AM Contributed talks - Chaired by Zhiping (James) Zhou, Peking University, China

ThA1 8:15 AM-9:00 AM (Plenary)

Silicon Photonics: A University Perspective, G. Reed, *Southampton University, United Kingdom*

ThA2 9:00 AM-9:15 AM

SiGe-on-SOI Mach-Zehnder Modulators Enabling Large Mode Size Edge Coupling, X. Sun, F. Li, Z. Shao, W. Guo, Y. Huang, F. Liu and L. Jia, *LaXense, Inc., Walnut, CA, California*, N. Feng and J. Hu, *MIT, Cambridge, Massachusetts, USA*

Design Effects on the Performance of High-Speed Ge Photo Detectors

S. Lischke(1), D. Knoll(1), C. Mai(1), M. Kroh(1), D. Schmidt(1), A. Peczek(1), J. Kreißl(1),
J.-M. Lee(2), M. Kim(2), W.-Y. Choi(2), and L. Zimmermann(1)

(1) IHP, Im Technologiepark 25, 15236 Frankfurt (Oder), Germany
(2) Department of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea

ABSTRACT

We investigate design effects on the opto-electrical frequency response of waveguide-coupled, lateral Ge p-i-n photodiodes to estimate the sensitivity of this response to diode fabrication tolerances and, in particular, to improve our understanding how diffusion of photo carriers acts on the response behavior.

INTRODUCTION

Ge p-i-n photodiodes (PD), coupled to a Si waveguide (WG), are the most widely used light detecting elements for Si-based photonic or electronic-photonic integrated circuits. Meanwhile, such diodes are available with opto-electrical (OE) bandwidths beyond 60 GHz [1–4]. That "slow" photo carrier diffusion can have an essential effect on the OE frequency response of high-speed Ge-PD was discussed recently [3, 4] and taken into account for diode modelling too [5]. Here, we investigate design effects on the OE frequency response of WG-coupled Ge lateral p-i-n photodiodes, to estimate the sensitivity of this response to diode fabrication tolerances and, in particular, to improve our understanding how diffusion of photo carriers acts on the response behavior.

EXPERIMENTS

Construction and fabrication details of the diodes investigated here are described in [3] and [4]. Note also that a diode version providing > 60 GHz bandwidth is already a key component of IHP's photonic BiCMOS process [6].

Figure 1 illustrates the PD design variations investigated here. At a fixed width ("X") of the SiN pedestal, which is used for self-aligned doping and thus controls the PD depletion layer width, three basic designs were realized: 1) PDs with equally wide n^+ and p^+ doped Ge regions where each of which is ~2 times wider than "X" (left). 2) PDs with equally wide doped Ge regions where each of which is much narrower than "X" (center). Width of the doped regions ("Y") was varied here. 3) Asymmetrical diodes with either wide n^+ or wide p^+ doped Ge regions (right).

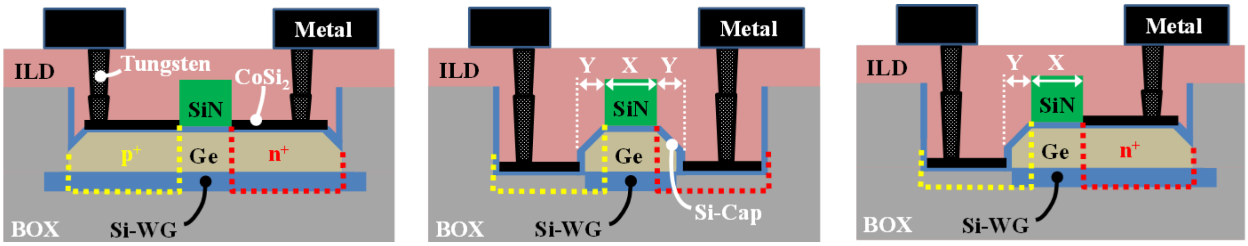

Figure 1: Schematic cross sections of lateral Ge p-i-n photodiodes differing in the width of the doped Ge regions **at a fixed depletion layer width** (controlled by the width of SiN pedestal "X"): Width of equally wide doped Ge regions is either large (left) or small, compared to "X" (center). One of the doped Ge regions is much wider than "X" (right). Cut is perpendicular to the direction of light incidence.

We focus first on the middle structure to study the effect of a stepwise increased enclosure "Y". It is, even for biggest "Y", still 2x smaller than "X". Change of "Y" by design emulates here fabrication-related variations which can result from small width variations of the SiN pedestal and the Si-WG. Figure 2 (left) shows that increasing "Y" deteriorates the OE frequency response behavior. Because 248 nm lithography is used both for defining Si-WG and SiN pedestal, variations in "Y" can well be kept under the 50 nm level where degradation of the response behavior is still weak. Diode I-V and C-V characteristics (Fig. 2, center and right) indicate that the observed "Y" dependency of the frequency response can't result from RC or photo carrier drift effects: Series resistance lowers with increasing "Y", due to increasing $CoSi_2$ coverage [3], and capacitances, i.e. depletion widths do not show any "Y" effect. We thus conclude that only photo carrier diffusion effects can be responsible for the observed response behavior.

Next, we compare the behavior of a PD with narrow doped Ge regions (Fig. 2, center, std. "Y") with that of the other designs depicted in fig. 1. Big differences in the response behavior can be seen (Fig. 3, left), which also can only result from photo carrier diffusion effects (see Fig. 3, center and right). First, we see that response degradation continues when "Y" becomes a multiple of "X" (Fig. 3, left, black vs. blue). Interesting is the behavior of the

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asymmetrical diodes, where widening of n^+ Ge regions much more degrades the response behavior than widening the p^+ side (Fig. 3, left, black vs. red and green, resp.). It indicates that holes diffusion in the n-doped Ge region has much more influence than diffusion of electrons on the other side. Also catches the eye that the asymmetrical diode with wide n^+ region behaves worse than the PD with equally wide doped Ge regions (Fig. 3, left, red vs. blue). This effect and the "Y"-dependency of frequency response can be understood when one considers that increasing "Y" or making diodes asymmetrical changes the ratio between carrier generation in high-field and non-depleted Ge regions.

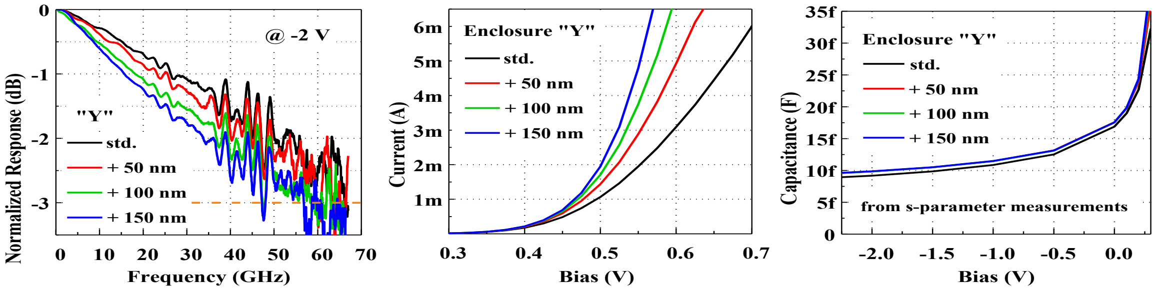

Figure 2: Normalized OE response vs. frequency (left), forward I-V (center) and C-V characteristics (right) for Ge-PD differing in "Y".

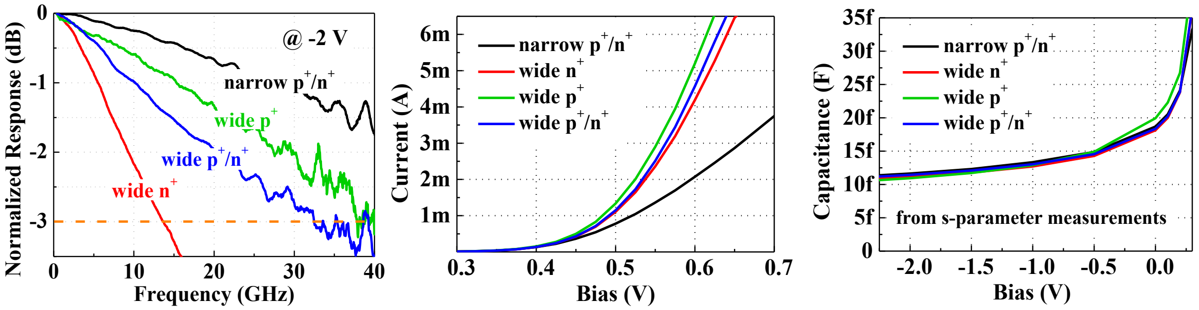

Figure 3: Normalized OE response vs. frequency (left), forward I-V (center) and C-V characteristics (right) for Ge-PD with narrow p^+ and n^+ doped Ge regions (Fig. 1, center), wide p^+ and n^+ doped Ge regions (Fig.1, left), and either wide n^+ or p^+ Ge regions (Fig. 1, right).

SUMMARY

Design effects on the OE frequency response of high speed lateral p-i-n Ge photodiode have been presented, pointing out the importance of a proper layout. Further, our results clearly indicate the importance of a separate treatment of the photo carrier diffusion contribution for both carrier types and of weighting photo carrier generation in high-field and non-depleted Ge regions in a photodiode equivalent circuit model.

ACKNOWLEDGEMENT

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[2] H. Chen et al., "−1 V bias 67 GHz bandwidth Si-contacted germanium waveguide p-i-n photodetector for optical links at 56 Gbps and beyond," *Optics Express*, vol. 24, no. 5, p. 4622, 2016.

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[4] S. Lischke et al., "High-speed, waveguide Ge PIN photodiodes for a photonic BiCMOS process," in *2014 IEEE Bipolar/BiCMOS Circuits and Technology Meeting - BCTM*, 2014, pp. 29–32.

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