

A single InP-on-SOI microdisk for high-speed half-duplex on-chip optical links

Citation for published version (APA):

Hofrichter, J., Morf, T., La Porta, A., Raz, O., Dorren, H. J. S., & Offrein, B. J. (2012). A single InP-on-SOI microdisk for high-speed half-duplex on-chip optical links. *Optics Express*, 20(26), B365-B370.
<https://doi.org/10.1364/OE.20.00B365>

DOI:

[10.1364/OE.20.00B365](https://doi.org/10.1364/OE.20.00B365)

Document status and date:

Published: 01/01/2012

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

Take down policy

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

openaccess@tue.nl

providing details and we will investigate your claim.

A single InP-on-SOI microdisk for high-speed half-duplex on-chip optical links

Jens Hofrichter,^{1*} Thomas Morf,¹ Antonio La Porta,¹ Oded Raz,² Harm J. S. Dorren,² and Bert J. Offrein¹

¹IBM Research – Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland

²COBRA Research Institute, Eindhoven University of Technology, Eindhoven, P.O. Box 513, 5600 MB, The Netherlands

*jho@zurich.ibm.com

Abstract: We demonstrate for the first time that a single compact, electrically contacted indium phosphide based microdisk heterogeneously integrated on a silicon-on-insulator waveguide can be used as both a high-speed modulator and photo detector. We demonstrate high-speed operation up to 10 Gb/s and present bit-error rate results of both operation modes.

©2012 Optical Society of America

OCIS codes: (040.5160) Photodetectors; (130.4110) Modulators; (130.3120) Integrated optics devices; (230.4110) Modulators; (230.4205) Multiple quantum well (MQW) modulators; (230.5160) Photodetectors; (250.4110) Modulators.

References and links

1. I. Christiaens, G. Roelkens, K. De Mesel, D. Van Thourhout, and R. Baets, "Thin film devices fabricated with BCB waferbonding," *J. Lightwave Technol.* **23**(2), 517–523 (2005).
2. 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 Photonic Circuitry," *IEEE Photon. Journal* **2**(3), 299–305 (2010).
3. J. Van Campenhout, P. Rojo 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* **15**(11), 6744–6749 (2007).
4. J. Hofrichter, O. Raz, L. Liu, G. Morthier, F. Horst, P. Regreny, T. de Vries, H. J. S. Dorren, and B. J. Offrein, "All-optical wavelength conversion using mode switching in InP microdisc laser," *Electron. Lett.* **47**(16), 927–929 (2011).
5. 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," *Nat. Photonics* **4**(3), 182–187 (2010).
6. L. Liu, J. Van Campenhout, G. Roelkens, R. A. Soref, D. Van Thourhout, P. Rojo-Romeo, P. Regreny, C. Seassal, J.-M. Fédéli, and R. Baets, "Carrier-injection-based electro-optic modulator on silicon-on-insulator with a heterogeneously integrated III-V microdisk cavity," *Opt. Lett.* **33**(21), 2518–2520 (2008).
7. Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, and M. Lipson, "12.5 Gbit/s carrier-injection-based silicon micro-ring silicon modulators," *Opt. Express* **15**(2), 430–436 (2007).
8. J. Liu, M. Beals, A. Pomerene, S. Bernadis, R. Sun, J. Cheng, L. C. Kimerling, and J. Michel, "Waveguide-integrated ultralow-energy GeSi electro-absorption modulators," *Nat. Photonics* **2**(7), 433–437 (2008).
9. O. Raz, L. Liu, R. Kumar, G. Morthier, P. Regreny, and H. J. S. Dorren, "A single InP membrane disc cavity for both transmission and detection of 10Gb/s signals in on chip interconnects," presented at the 36th European Conference on Optical Communication (ECOC 2010), Paper 2.12, Torino, Italy, Sept. 2010.
10. Y.-H. Kuo, H.-W. Chen, and J. E. Bowers, "High speed hybrid silicon evanescent electroabsorption modulator," *Opt. Express* **16**(13), 9936–9941 (2008).
11. J. E. Roth, O. Fidaner, R. K. Schaevitz, Y.-H. Kuo, T. I. Kamins, J. S. Harris, Jr., and D. A. B. Miller, "Optical modulator on silicon employing germanium quantum wells," *Opt. Express* **15**(9), 5851–5859 (2007).
12. B. Aslan, H. C. Liu, A. Bezinger, P. J. Poole, M. Buchanan, R. Rehm, and H. Schneider, "High responsivity, dual-band response and intraband avalanche multiplication in InGaAs/InP quantum well photodetectors," *Semicond. Sci. Technol.* **19**(3), 442–445 (2004).

1. Introduction

The heterogeneous integration platform is an attractive path to extend the capabilities of silicon photonics [1]. Photo detectors [2], lasers [3], wavelength converters [4], optical flip-flops [5] and modulators [6] have been shown in this technology. Whereas several modulator concepts are based on the free-carrier plasma-dispersion effect [7] or the Franz-Keldysh

effect in strained germanium [8], we focused on InP-based material with multiple quantum wells (MQWs), where the band gap and thus the absorption can be modulated by the quantum-confined Stark effect (QCSE). Moreover, the light intensity in the waveguide can be modulated, and also detected as a photo current [9].

In this paper, we report on the performance of indium phosphide (InP) microdisks used as modulators and photo detectors under negative bias conditions, which have been heterogeneously integrated on a SOI waveguide. We demonstrate high-speed electro-optical modulation of the device with a bit-error rate (BER) below 1×10^{-9} at data rates of 2.5 Gb/s, 5.0 Gb/s and 10 Gb/s, and compare the performance with a commercial lithium niobate modulator. The power penalties are presented and discussed. As a complimenting functionality we demonstrate that when injecting optical signals into the device it can be used as a photo detector. Eye diagrams, a small signal analysis and bit-error rates up to 10 Gb/s are presented.

2. Device description and characteristics

The InP microdisks were fabricated using heterogeneous integration. First, a silicon photonic waveguide with grating couplers on either end was fabricated on a silicon-on-insulator (SOI) wafer. Then, benzocyclobutene (BCB) was spun on top of the SOI substrate. An InP die comprising a MQW with peak photoluminescence emission at 1520 nm was bonded face-down. After removing the InP substrate, the device was structured using optical lithography, dry etching and lift-off. Figure 1(a) illustrates the final device structure and Fig. 1(b) shows a focused ion beam (FIB) cross-section through the center of the device. The diameter of the microdisk is $8 \mu\text{m}$, resulting in an active area of about $50 \mu\text{m}^2$. When injecting light into the device on resonance, it evanescently couples to the whispering gallery modes of the disk. Its absorption properties may be varied electronically such that the intensity of the light can be modulated [10], or detected as a photo current [9]. Because the change of the absorption properties by the QCSE is instantaneous, the operation speed is governed by the parasitics, lending the device to high-speed operation.

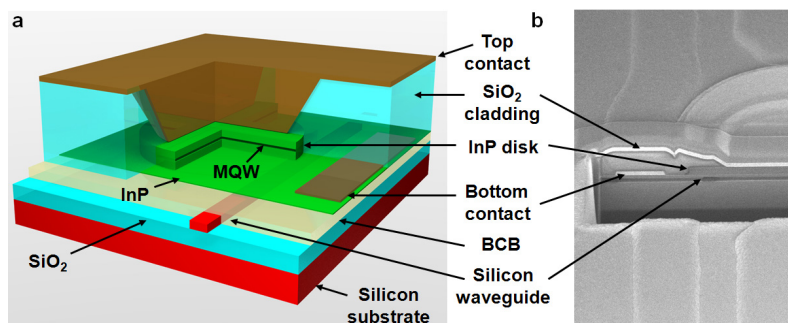


Fig. 1. Device structure of the InP microdisk heterogeneously integrated on an SOI waveguide. (a) Schematic view of the device structure. (b) FIB-cross section through the center of the device.

For electrical device characterization, the IV-curves of more than 30 devices on the same chip were acquired as shown in Fig. 2(a). Instead of lasing operation under positive biasing conditions [3], here we are interested in the negative bias regime. Leakage currents lower than $1 \mu\text{A}$ were observed for negative bias voltages up to -4 V . We chose 1555.8 nm as the operation wavelength for the experiments. This wavelength denotes a good compromise between low insertion loss compared to the straight waveguide (0.75 dB) and high extinction ratio. Starting from a pre-bias of -1 V the optical transmission drops by 4.5 dB with a voltage swing of only 2.0 Vpp as shown in Fig. 2(b). It is evident that the change in absorption mainly translates to a change in the optical transmission instead of a resonance wavelength shift. This relatively low change in transmission, which during dynamic operation translates into extinction ratio, is due to the coupling of the microdisk to the silicon waveguide and the

small overlap of the optical mode with the absorptive multiple-quantum-well material designed for lasing operation [3]. To further improve the extinction ratio the lasing material may be adopted to provide a larger absorption coefficient. Alternatively, the coupling may be optimized towards critical coupling, and the overlap of the optical mode with the quantum well should be improved by, e.g., growing a larger number of quantum wells [11].

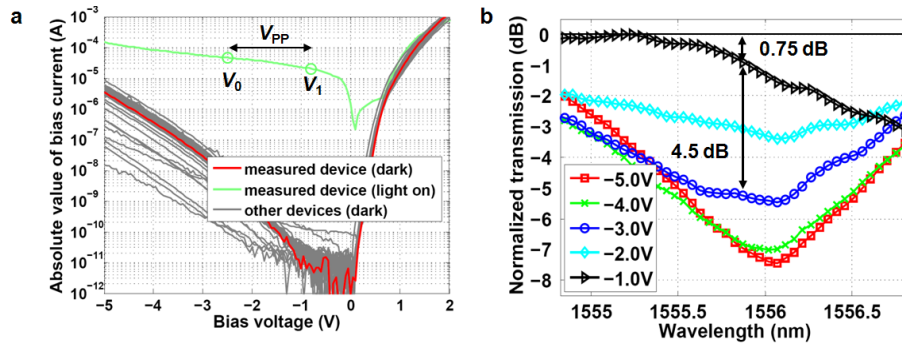


Fig. 2. (a) Static electrical characteristics of the InP microdisk with and without light in the waveguide. The image also displays the dark IV-curves for more than 30 devices on the same chip. (b) Static optical modulation characteristics of the InP microdisk. Transmission characteristics of one device for several negative bias voltages.

3. Operation as a modulator

During the dynamic operation experiments the InP microdisk was driven with a one-drive-level of $V_1 = -0.875\text{V}$ and a zero level of $V_0 = -2.5\text{V}$, resulting in a peak-to-peak swing of $V_{pp} = 1.625\text{V}$. The eye diagrams of the InP microdisk driven by a non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) lengths of $2^{31} - 1$ are displayed in Fig. 3. The eye diagrams displayed in Fig. 2(a) and Fig. 2(b) are for 2.5 Gb/s and 5.0 Gb/s and a NRZ PRBS pattern length of $2^{31} - 1$. The eye diagrams at 10 Gb/s are shown in Fig. 2(d) and Fig. 2(e) for a NRZ PRBS lengths of $2^7 - 1$ and $2^{31} - 1$, respectively. As can be seen from Figs. 2(b) and 2(c), the extinction ratio of the InP microdisk modulator was about 4.5 dB for 2.5 Gb/s and 5.0 Gb/s. For 10 Gb/s, the extinction ratio was reduced to 3.2 dB for a pattern length of $2^7 - 1$ and to 2.2 dB for $2^{31} - 1$ due to pattern effects. Because the device is electrically isolated from the silicon substrate long consecutive identical digits may shift the electrical operation point of the device. This in turn degrades the extinction ratio, which translates to an increase in the power penalties as shown in Fig. 4. To investigate the speed limitations of the modulation process we performed small-signal S21 measurements and extracted a 3dB-bandwidth in excess of 16 GHz as shown in Fig. 4(a), which is mainly governed by the parasitic of the device. Further deduction of the parasitics, in particular the pad capacitance, would result in an even larger 3dB-bandwidth enabling operation up to 20 Gb/s. BER measurements were performed to quantify the quality of the modulated optical signal. The measurements were carried out at 2.5 Gb/s, 5.0 Gb/s and 10 Gb/s and with two NRZ-PRBS lengths of $2^7 - 1$ and $2^{31} - 1$. Operation with a BER below 1×10^{-9} was achieved up to 10 Gb/s at both PRBS lengths as shown in Fig. 4(b). The power penalty compared with the commercial lithium niobate

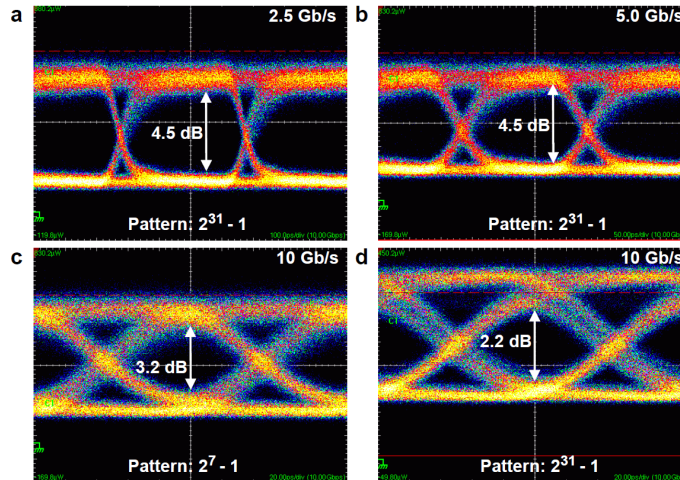


Fig. 3. Eye diagrams for (a) 2.5, (b) 5.0 and (d) 10 Gb/s and a pattern length of $2^{31} - 1$. Figure 2(c) shows the measurements at 10 Gb/s and a reduced pattern length of $2^7 - 1$.

reference modulator at 2.5 Gb/s and 5.0 Gb/s was 3.1 dB. For 10 Gb/s the penalty slightly increases to 4.7 dB for a pattern length of $2^7 - 1$. At a PRBS length of $2^{31} - 1$ the power penalty increases to 7.0 dB. Reference measurements were made with a commercial 40 Gb/s lithium niobate modulator. During the reference measurements the optical signal was attenuated and subsequently amplified by an erbium-doped fibre amplifier (EDFA) to obtain the same amplifier noise as for the microdisk modulator. Therefore the commercial modulator required more than -10 dBm received power to recover the signal without errors.

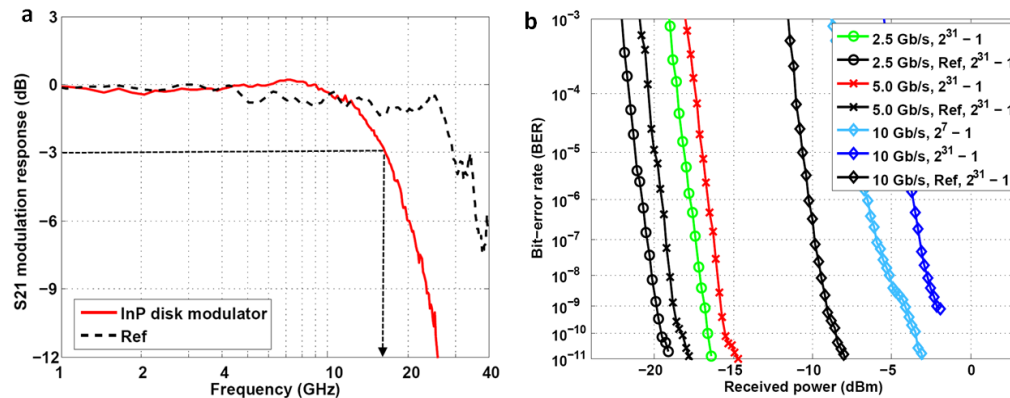


Fig. 4. High-speed measurements of the InP microdisk used as a modulator. (a) Small-signal S21 parameter measurements. (b) Bit-error rate measurements of the InP microdisk modulator and a commercial modulator with bit rates of 2.5, 5.0 and 10.0 Gb/s for different NRZ-PRBS lengths.

4. Operation as a photo detector

The InP microdisk can also be used as a resonant photo detector. When injecting light pulses on resonance wavelengths of the device, the absorption induced by the QCSE results in substantial photocurrent as shown in Fig. 5(a) when the wavelength is on-resonance with the cavity modes. The sharp optical resonances can be used to detect signals at the resonant wavelengths and can be beneficial for forming wavelength selective optical detectors in wavelength division multiplexing systems for instance. The responsivity shown in Fig. 5(b) has been computed by normalizing the photocurrent to the power in the waveguide. A negative bias voltage as low as 1 V is sufficient to achieve unity responsivity, whereas a bias

voltage of -5 V yields a responsivity larger than 5 A/W due to the high electric field in the non-doped region of the devices which is sufficient to create an avalanche effect [12]. For evaluating the signal quality of the detection process, BER measurements with a PRBS pattern length of $2^{31} - 1$ have been performed at a wavelength of 1555.6 nm and a negative bias voltage of 1.7 V. Error-free operation could be achieved for 2.5 and 5.0 Gb/s as shown in Fig. 6(a). Operation with a BER below 1×10^{-3} (i.e., below the forward error-correction (FEC) limit) could be achieved at 10 Gb/s. The photocurrent is translated into voltage using the 50Ω input impedance of the attached electrical amplifier instead of a transimpedance amplifier (TIA), resulting in a peak-to-peak voltage swing of only a few millivolts. This small electrical signal was then electrically amplified by 50 dB with a cascade of electrical amplifiers with a bandwidth of 12 GHz and a noise figure of 6 dB inducing substantial noise. Still, an open eye was achieved for 10 Gb/s as shown in Fig. 6(a) (inset), corresponding to a BER of 1×10^{-3} .

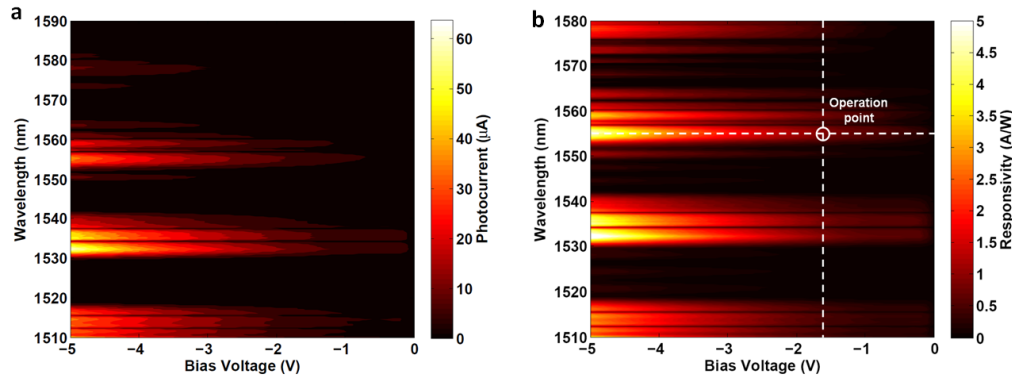


Fig. 5. (a) Spectral response of the photocurrent generated in the device under external illumination. (b) Spectral responsivity plot. The operation point for the high-speed experiments below was 1555.6 nm and -1.7 V.

To gain insight into the actual speed limitations of the device we performed a small-signal analysis and measured the S_{21} parameter. The reference measurement was made with a 40 Gb/s lithium niobate modulator and a commercial 43 Gb/s photo receiver. For the InP microdisk device we measured a 3 dB-O/E bandwidth of 8 GHz (see Fig. 6(b)) indicating that the device can be used as a photo receiver up to 10 Gb/s when co-integrating a TIA providing a sufficiently large voltage swing for subsequent electrical amplification.

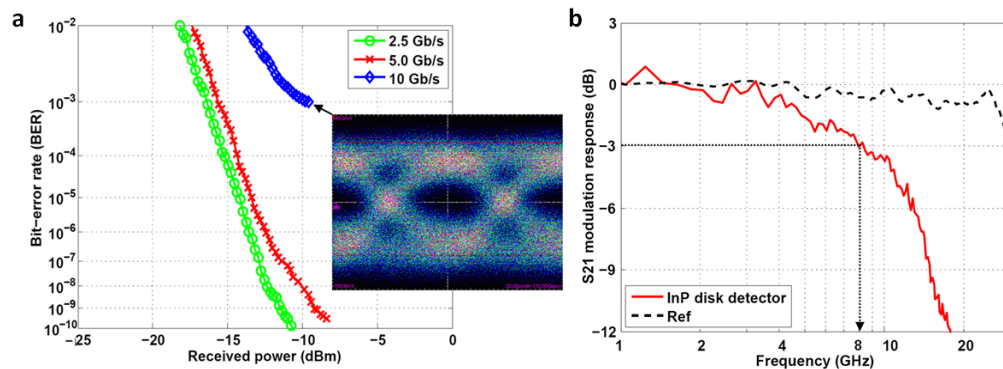


Fig. 6. Dynamic characteristics of the InP microdisk used as photo detector: Bit-error rate measurements at data rates of 2.5 , 5.0 and 10.0 Gb/s.

Conclusion

We have demonstrated the potential of reversely biased InP microdisks heterogeneously integrated on top of an SOI waveguide as high-speed electro-optic modulators and photo detectors. Operated as a modulator we presented static extinction ratios of 4.5 dB for a bias swing of only 2.0 V_{pp}. For speeds up to 10 Gb/s, we have successfully demonstrated operation with a BER lower than 1×10^{-9} . Compared with a commercial lithium niobate modulator, we found power penalties of about 3.1 dB for 2.5 Gb/s and 5 Gb/s and 7.0 dB at 10 Gb/s due to the limited extinction ratio.

When operating the device as a resonant photo detector, we demonstrated operation up to 10 Gb/s. Error-free operation could be achieved for 2.5 and 5 Gb/s and operation below the FEC limit was shown for 10 Gb/s. It is expected that a co-integration of the InP disk used as a detector with a TIA results in error-free operation that speed because of its sufficiently large S₂₁-bandwidth of 8 GHz. The device combines low footprint and high operation speed. This, together with the possibility of co-integrating lasers with modulators and photo detectors using the same epitaxial material and processing scheme, makes the presented device very attractive for integrated photonics. The presented approach demonstrates the possibility using the same device as either the signal generating or the detecting device enabling high-speed half-duplex on-chip optical links. The device performance of the microdisk modulator can be further improved. By adapting the optical coupling between the disk and the silicon waveguide the modulation extinction ratio can be increased by matching the roundtrip absorption and the coupling loss to achieve critical coupling. Furthermore, the operation speed can be improved by reducing the parasitical capacity between the top contact pad and the bottom contact metallization.

Acknowledgments

This work was supported by the European Union FP7-ICT project "HISTORIC" under contract number 223876. The authors acknowledge technical support by L. Van Landschoot, P. Mechet (Gent University), T. De Vries, B. Smallbrugge (TU Eindhoven) and H. Steinauer (IBM).