Silicon-Organic hybrid Fabrication platform for Integrated circuits

Intermediate report on recent achievements

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List of Partners concerned

Partner number	Partner name	Partner short name	Country	Date enter project	Date exit project
1 (coordinator)	Karlsruhe Institute of Technology (formerly University of Karlsruhe)	KIT	Germany	M1	M42
2	SELEX - Sistemi Integrati	SELEX	Italy	M1	M42
3	Interuniversity Microelectronics Centre - IMEC	IMEC	Belgium	M1	M42
4	Rainbow Photonics AG	RB	Switzerland	M1	M42
5	GigOptix-Helix AG	GO	Switzerland	M1	M42
6	Research and Education Laboratory in Information Technologies	AIT	Greece	M1	M42
7	The University of Sydney, Centre for Ultrahigh bandwidth Devices for Optical Systems	CUDOS	Australia	M1	M42

[1] **PU** = Public
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CO = Confidential, only for members of the consortium (including the Commission Services)

Deliverable Responsible

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Executive Summary

This report summarizes advances since the beginning of 2011 in the project for the general public.
Precedence is given for publications in journals and on conferences or exploitation efforts.

Change Records

Version	Date	**Changes**	Author
0.1 (draft)	13/12/2012	Start	AIT – zaki@ait.gr
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Contents

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Timeline
Start Date: 01/01/2010
End Date: 30/06/2013

Budget
Overall Cost: >3.5 M€
EC Funding: 2.5 M€

Proof-of-concept of
- The silicon-organic hybrid fabrication platform, which is to be created
- Implementation of high speed electro-optic modulator to show the platform's potential
- Looking into applications beyond data / telecom domain, enabled by this platform

Project Partners
- Karlsruhe Institute of Technology (KIT), DE
- Selex Sistemi Integrati SPA, IT
- IMEC, BE
- Rainbow Photonics AG, CH
- GigOptix-Helix AG, CH
- Research And Education Laboratory In Information Technologies (AIT), GR
- The University of Sydney (CUDOS), AU

Vision & Aim

In the SOFI project, new active optical waveguides and integrated optoelectronic circuits based on a novel silicon-organic hybrid technology are introduced. **The technology is based on the low-cost CMOS process technology for fabrication of the optical waveguides - allowing for the convergence of electronics with optics. It is complemented by an organic layer that brings in new functionalities** so far not available in silicon. Recent experiments have shown that such a technology can boost the signal processing in silicon far beyond 100 Gbit/s - which corresponds to a tripling of the state-of-the art bitrate.
SOFI focuses on a proof-of-concept implementation of ultra-fast, ultra-low energy optical phase modulator waveguides such as needed in optical communications. These devices will ultimately be used to demonstrate an integrated circuit enabling the aggregation of low-bitrate electrical signals into a 100 Gbit/s OFDM data-stream **having low energy consumption.**
However, the SOFI technology is even more fundamental. By varying the characteristics of the organic layer one may also envision new sensing applications for environment and medicine.
The suggested approach is practical and disruptive. It combines the silicon CMOS technology and its standardized processes with the manifold possibilities offered by novel organic materials. This way, for instance, the processing speed limitations inherent in silicon are overcome, and an order-of-magnitude improvement can be achieved. More importantly, the new technology provides the lowest power consumption. The potential for low power consumption is attributed to the tiny dimensions of the devices and to the fact, that optical switching is performed in the highly nonlinear cladding organic material rather than in silicon.

Main Objectives

1. Development of a silicon-organic hybrid (SOH) integrated optics platform
   - Overcome silicon related limitations such as the missing electro-optic effect
   - Deal with all technological aspects such as deposition of organics, poling, metallization & prototype packaging
2. Realization of EO phase modulator with 100 GHz electro-optic bandwidth at 1550 nm
   - This will ultimately increase optical processing speeds beyond today's limits of silicon
3. Demonstration of integrated optical circuit for higher order signal modulation formats at 100 Gbit/s
   - Mach Zehnder modulator configuration
   - Aiming for 50 Gbit/s QPSK, 100 Gbit/s OFDM in system application scenario
4. Look into silicon-organic hybrid technology for other purposes than data / telecom applications
5. Benchmarking with respect to other data / telecom technologies
   - Evaluate potential of organic material with respect to inorganic material (i.e. chalcogenides)
   - Comparison to state-of-the-art LiNbO3 modulators

Technical Approach and Achievements

The SOFI project demonstrated high-speed **silicon electro-optic modulators based on the Pockels effect** in poled polymers with chromophores**.** To performance, **data transmission at 42.7 Gbps with a bit-error-ratio (BER) smaller than 3×10^{-10}** has been shown and published. Mach-Zehnder modulators have been fabricated to work at 25 Gbd. Main advantages of this technology for modulators are that it allows, on the Silicon platform!, for very linear phase shifts ideally suited for higher-order modulation formats.

To complement functionality of photonic integrated circuits, the SOFI project demonstrated ultra-low power consumption phase shifters based on liquid crystals useful for adjusting integrated circuits for higher order modulation formats. Also a Silicon-Organic Hybrid laser has been shown.

To guide SOFI to address actual challenges of commercial relevance AIT has identified the system specifications and component requirements for the SOFI silicon organic hybrid (SOH) modulators. These activities took into account current standardization efforts, recent advances in 100 Gb/s and beyond high speed transmission systems as well as 10 Gb/s and beyond access networks which all rely on the generation of advanced modulation formats (Figure 1). These advances represent a promising context for the application of the SOFI SOH as a low-cost and high performance technology capable to provide modulator components, meeting the specifications of new generation high speed optical transmission interfaces.

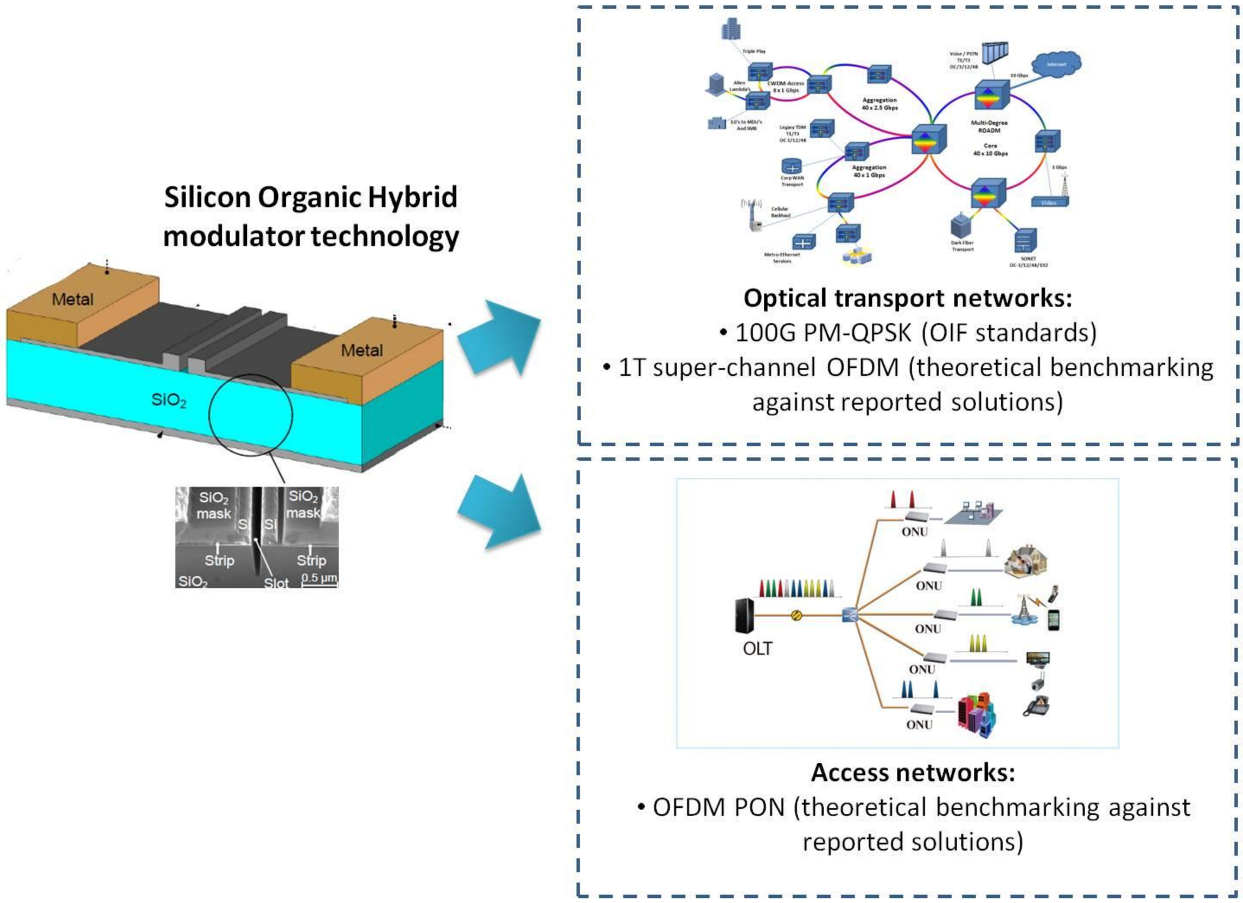

Figure 1 Specification definition structure of SOH modulator technology for long and short reach optical networks.

Design of the optical waveguides and high-speed RF-electrodes is led by *Karlsruhe Institute of Technology (KIT)*. During this core development stage, simulations and design decisions have been made, which determine the performance of the SOH modulators. The devices owe their exceptional properties to so-called socket waveguide geometry, see Figure 2. Characterization and performance analysis (system experiments) have also been done at KIT leading to the result summarized in the box above. Subcomponents such as transitions from strip to socket waveguides have been developed and published. In addition the SOH concept is extended further by making use of liquid crystals for phase shifters needed to adjust photonic integrated circuits.

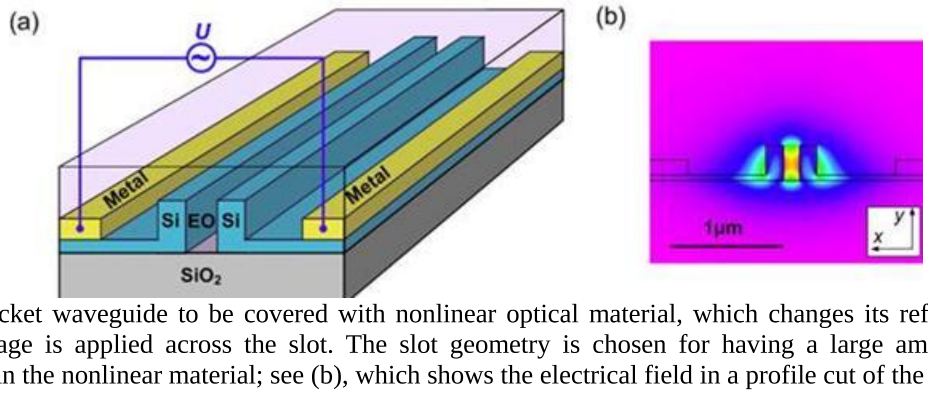

Figure 2 Socket waveguide to be covered with nonlinear optical material, which changes its refractive index when a voltage is applied across the slot. The slot geometry is chosen for having a large amount of light propagating in the nonlinear material; see (b), which shows the electrical field in a profile cut of the waveguide.

The fabrication **of silicon-on-insulator waveguides in a CMOS line is done by *IMEC***, where the 3 SOFI runs have been already done. Ion implants as well as metallization are developed for use with integrated circuits of optical waveguides.

To give SOFI devices their functionality a cladding is deposited on top of the silicon waveguides.

→ Organic crystal cladding: ***Rainbow Photonics* has developed new techniques for the deposition of single-crystalline electro-optic organic thin films on silicon chips**
Several organic crystalline materials and deposition techniques are being tested for this purpose. Melt growth has been found in particular promising for the aims of SOFI, due to the possibility of filling nanostructures like slot waveguides with less than 100-nm in size.

→ Polymer cladding: ***GigOptix-Helix'* main contributions are the provision of the electro-optic polymers**, by coordinating the exchange of sample material and work instructions between GigOptix Bothell and the consortium, **as well as the exploitation and dissemination activities**. Furthermore, *GO* contributed to the identification of emerging applications. After having enabled the deposition of EO polymers while filling the narrow slot of the waveguide, see next figure, they currently focus on processing steps for the poling of the polymer (aligning molecules to obtain the Pockel's effect)

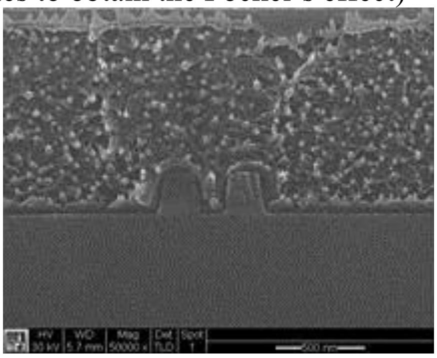

Figure 3 Picture showing the EO polymer filling the waveguide slot, an essential requirement to make the modulator work

→ Inorganic cladding: To evaluate the potential of organic materials with respect to inorganic materials ***CUDOS (University of Sydney)* has deposited chalcogenides**.

To assure the potential of commercial applicability of devices developed in SOFI, **SELEX addresses packaging and RF design**. One possibility currently pursued is described here: The work flow for the wedge-bonding technique directly in a standard packaging module (Figure 4) consists of three main steps:

1. After the chip has been fixed and glued to the metallic enclosure, the electrodes are bonded to the 50 Ohm load and to the RF input connector. A microstrip alumina transition from coaxial connector to coplanar waveguide electrodes could be adopted.
2. The fibers are aligned to the In/Out grating couplers, glued and UV cured.
3. Finally the cover is mounted on the package and the fibers, passing through it by way of two slits, are fixed with an epoxy resin.

SOFI activities have been made public (list starts from July 2011 (M19)

KIT, IMEC, GO, SELEX

These papers from KIT and partners have been made possible by SOFI:

- **"Silicon-organic hybrid fabrication platform for integrated circuits" (Invited),** D. Korn, L. Alloatti, M. Lauermann, J. Pfeifle, R. Palmer, P.C. Schindler, W. Freude, C. Koos, J. Leuthold, Hui Yu, W. Bogaerts, K. Komorowska, R. Baets, J. Van Campenhout, P. Verheyen, J. Wouters, M. Moelants, P. Absil, A. Secchi, M. Dispenza, S. Wehrli, M. Bossard, P. Zakynthinos, I. Tomkos, Paper Th.A5.5, ICTON 2012, Coventry, UK
- **Silicon-Organic Hybrid (SOH) Lasers at Telecommunication Wavelengths.** Paper ID number is: 1360268. Matthias Lauermann; Dietmar Korn; Patrick Appel; Luca Alloatti; Wolfgang Freude; Juerg Leuthold; Christian Koos. 17-21 June, 2012 at the Cheyenne Mountain Resort, Colorado Springs, Colorado, USA.
- **First Silicon-Organic Hybrid Laser at Telecommunication Wavelength.** Dietmar Korn; Matthias Lauermann; Patrick Appel; Luca Alloatti; Robert Palmer; Wolfgang Freude; Juerg Leuthold; Christian Koos. Pres. number: CTu2I.1, CLEO: 2012 in San Jose, CA.
- **Detection or Modulation at 35 Gbit/s with a Standard CMOS-processed Optical Waveguide.** Dietmar Korn; Hui Yu; David Hillerkuss; Luca Alloatti; Christoph Mattern; Wim Bogaerts; Katarzyna Komorowska; Roel Baets; Joris Van Campenhout; Peter Verheyen; Johan Wouters; Myriam Moelants; Philippe Absil; Wolfgang Freude; Christian Koos; Juerg Leuthold , Pres. number: CTu1A.1, CLEO: 2012 in San Jose, CA.
- **Highly Efficient Strip-to-Slot Mode Converters.** Palmer, R.; Alloatti, L.; Korn, D.; Heni, W.; Schindler, P.; Bolten, J.; Karl, M.; Waldow, M.; Wahlbrink, T.; Freude, W.; Koos, C.; Leuthold, J.; CLEO 2012, San José (CA), USA, Paper CM4M1, May 2012
- **Nonlinear optics on the silicon platform.** Freude, W.; Alloatti, L.; Melikyan, A.; Palmer, R.; Korn, D.; Lindenmann, N.; Vallaitis, T.; Hillerkuss, D.; Li, J.; Barklund, A.; Dinu, R.; Wieland, J.; Fournier, M.; Fedeli, J.; Walheim, S.; Leufke, P. M.; Ulrich, S.; Ye, J.; Vincze, P.; Hahn, H.; Yu, H.; Bogaerts, W.; Dumont, P.; Baets, R.; Breiten, B.; Diederich, F.; Beels, M. T.; Biaggio, I.; Schimmel, Th.; Koos, C.; Leuthold, J.; Optical Fiber Communication Conference (OFC'12), Paper OTh3H.6 Los Angeles (CA), USA, 04.–08.03.2012 **(invited)**.
- **Loss reduction of silicon slot waveguides with ALD-grown thin films.** Säynätjoki, A.; Karvonen, L.; Alasaarela, T.; Korn, D.; Alloatti, L.; Tervonen, A.; Palmer, R.; Koos, C.; Leuthold, J.; Freude, W.; Honkanen, S. K.; OPTO SPIE Photonics West - Society of Photo-Optical Instrumentation Engineers (OPTO-SPIE'12), San Francisco (CA), USA, Paper 8266-11 Jan. 21-26, 2012
- **Silicon nanophotonics and silicon-organic hybrid (SOH) integration.** Koos, C; Alloatti, L.; Korn, D.; Palmer, R.; Vallaitis, T.; Bonk, R.; Hillerkuss, D.; Li, J.; Bogaerts, W.; Dumon, P.; Baetes, R.; Scimeca, M.L.; Biaggio, I.; Barklund, A.; Dinu, R.; Wieland, J.; Fournier, M.; Fedeli, J.; Freude, W.; Leuthold, J.; Gerneral Assembly and Scientific Symposium, 2011 XXXth URSI Istanbul August 2011 doi: 10.1109/URSIGASS.2011.6050595
- **Performance tradeoff between lateral and interdigitated doping patterns for high speed carrier-depletion based silicon modulators.** Yu, H.; Pantouvaki, M.; Van Campenhout, J.; Korn , D.; Komorowska, K.; Dumon, P.; Li, Y.; Verheyen, P.; Absil,

P.; Alloatti, L.; Hillerkss, D.; Leuthold, J.; Baets, R. and Bogaerts, W.; Optics Express, Vol. 20, Issue 12, pp. 12926-12938, June 2012, dx.doi.org/10.1364/OE.20.012926

RB

- P. Günter, "**Organic and inorganic crystalline wires and thin films for hybrid integrated optics**" (Invited talk) Frontiers in Optics 2011 / Laser Science XXVII (16. - 21. 10. 2011) San Jose (U.S.A)

- "**Organic single crystalline electro-optic films for hybrid integration with silicon photonic wires**" by P. Günter, B. Ruiz, M. Jazbinsek (Oral presentation), SPIE Photonics West (January 22–26, 2012), San Francisco USA

- Eun-Young Choi, Mojca Jazbinsek, Seung-Heon Lee, Peter Günter, Hoseop Yun, Soon W. Leed and O-Pil Kwon, **"Co-crystal structure selection of nonlinear optical analogue polyenes"**, CrystEngComm, 2012, 14, 4306–4311

AIT

- P. Zakynthinos, L. Stampoulidis, E. Kehayas and I. Tomkos, "**Silicon-Organic Hybrid Modulators for High Speed Transmission Systems"** Fifth International Conference Micro&Nano2012" on Micro - Nanoelectronics, Nanotechnologies and MEMS, Crete, Greece, Oct. 2012
- AIT contributed to the preparation of the white paper on the European Silicon Photonics cluster with title "Silicon Photonics Progress in Europe