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)	UKA	Germany	M1	M36
2	SELEX - Sistemi Integrati	SELEX	Italy	M1	M36
3	Interuniversity Microelectronics Centre - IMEC	IMEC	Belgium	M1	M36
4	Rainbow Photonics AG	RB	Switzerland	M1	M36
5	GigOptix-Helix AG	GO	Switzerland	M1	M36
6	Research and Education Laboratory in Information Technologies	AIT	Greece	M1	M36
7	The University of Sydney, Centre for Ultrahigh bandwidth Devices for Optical Systems	CUDOS	Australia	M1	M36

[1] **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
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 start 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)	2011-06-23	Start	IPQ – korn@kit.edu
1 (submission)	2011-06-30		IPQ – korn@kit.edu

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Timeline
Start Date: 01/01/2010
End Date: 31/12/2012

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 the world’s first high-speed (>10 GHz) **silicon electro-optic modulator based on the Pockels effect.** To confirm its performance, **data transmission at 42.7 Gbps with a bit-error-ratio (BER) smaller than 3×10^{-10}** has been shown and published (see last section of document).

To guide SOFI **to address actual challenges of commercial relevance, *AIT* has identified a number of potential applications of SOFI devices** which exploit electrical and linear / nonlinear optical properties of SOH waveguide structures.

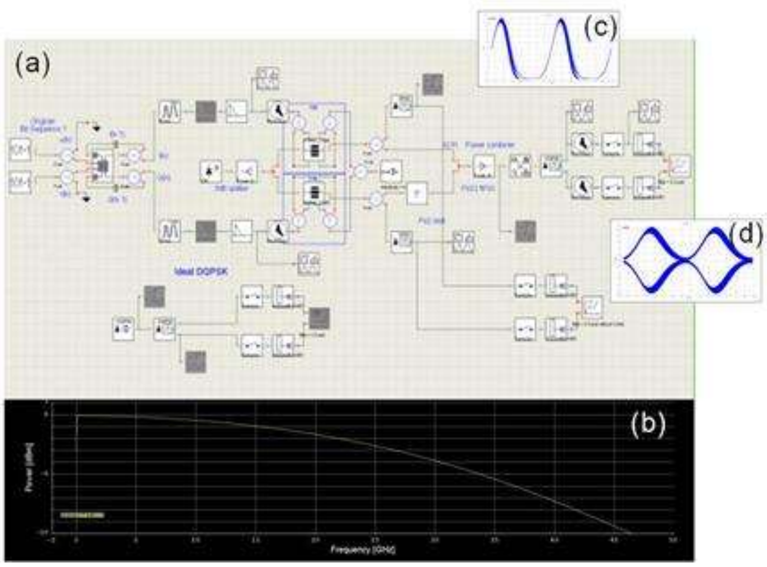

Figure 1 Modeling highlights: a) SOFI IQ modulator and coherent receiver model based on VPI, b) typical Mach-Zehnder modulator response c) and d) modulator output and demodulated trace**.**

The modeling work of AIT in this period was focused on upgrading the SOFI simulation platform. The platform upgrade process involved the substitution of the "black-box" component models (based on ideal parameters) used so far, with custom component models that will be more close to what is technically achievable within the project. As a first-pass study, AIT has incorporated data from commercial devices (electro-optic modulators and balanced photodetectors) in the SOFI modeling platform and has investigated the response of the platform in a series of theoretical experiments. The second-pass study is in progress following the feedback from fabrication partners on the SOH modulator expected performance.

Design of the optical waveguides and high-speed RF-electrodes is led by *Karlsruhe Institute of Technology (KIT)*. During this development stage, simulations and design decisions have been made, which determine the performance of the SOH modulators. The devices measured so far have been designed by *KIT* and owe their exceptional properties to a so-called socket waveguide geometry, see Figure 2. Characterization and performance analysis (system experiment) have also been done at *KIT* leading to the result summarized in the box above. Recent activities were related to poling of the used polymers.

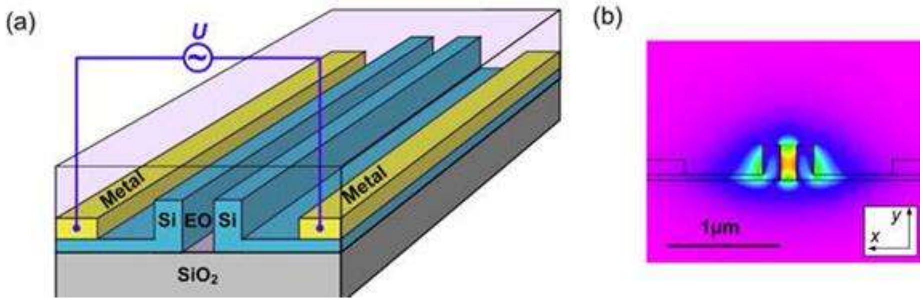

Figure 2 Socket waveguide to be covered with nonlinear optical material, which changes its refractive index when a voltage is applied across the slot. The slot geometry is chosen for having a large amount of light propagating in the nonlinear material; see (b), which shows the electrical field in a profile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

The fabrication **of silicon-on-insulator waveguides in a CMOS line is done by *IMEC***, where the 1st SOFI dedicated run is currently in process. Ion implants as well as metallization are developed for use with integrated circuits of optical waveguides.
IMEC is developing and optimizing processes for slot and socket waveguide patterning aiming for lower optical losses due to reduced scattering and decreasing slot width, which improves modulation efficiency of the SOH modulators.

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

→ Organic crystal cladding: ***Rainbow Photonics* is developing new techniques for the deposition of single-crystalline electro-optic organic thin films**
There are basically two types of organic electro-optic (EO) crystalline materials. On the one hand we have conventional molecular crystals, such as COANP, DAN, and BNA, which exhibit a relatively low electro-optic figure of merit $n^3r < 40$ pm/V, but can be processed from melt, which Rb has shown to be essential for the growth within the micro- and nanostructures as required in SOFI. On the other hand there are the most efficient organic nonlinear optical crystals, such as DAST, DSTMS, DAPSH, OH1, with a figure of merit more than one order of magnitude larger, $n^3r > 400$ pm/V, but more difficult to process. Such crystals have been

until now only grown with good quality from solution RB is developing new processes for melt deposition of the most efficient organic crystalline materials on silicon chip.

→ 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. This period focused poling efficiency for EO.

→ 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**. Most recently feeding lines and tapers have been simulated and optimized.

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

RB
Rainbow Photonics was present at the SPIE Photonics West conference and exhibition, Jan. 25-27 2011 in San Francisco USA, with the company booth, where RB was also distributing a flyer promoting the SOFI project.

Rainbow Photonics was present at the CLEO Munich conference and the accompanying Laser World of Photonics exhibition, May 22-26 2011 in Munich, Germany, with the company booth, where RB was distributing a flyer promoting the SOFI project.

At the CLEO Munich conference RB presented the following paper (oral contributed):
M. Jazbinsek, S.J. Kwon, P. Günter, "Quasi-Epitaxial Single-Crystalline Organic OH1 Films with High Electro-Optic Activity on Inorganic Structures for Large-Scale Photonic Integration

AIT
has presented a conference paper at IEEE ICT-Conference in Cyprus, that includes the latest results from the studies performed on the potentials of the SOFI devices in high speed telecom systems and has prepared another relevant presentation for an invited paper at ICTON 2011 in Stockholm

KIT
These papers from KIT and partners have been made possible by SOFI:
'42.7 Gbit/s electro-optic modulator in silicon technology'
Alloatti, L.; Korn, D.; Palmer, R.; Hillerkuss, D.; Li, J.; Barklund, A.; Dinu, R.; Wieland, J.; Fournier, M.; Fedeli, J.; Yu, H.; Bogaerts, W.; Dumon, P.; Baets, R.; Koos, C.; Freude, W. and Leuthold J.

Optics Express, Vol. 19, Issue 12, pp. 11841-11851, June 2011
doi:10.1364/OE.19.011841

'Reduced propagation loss in silicon strip and slot waveguides coated by atomic layer deposition'
Alasaarela, T.; Korn, D.; Alloatti, L.; Säynätjoki, A.; Tervonen, A.; Palmer, R.; Leuthold, J., Freude, W.; Honkanen, S.
Optics Express, Vol. 19, Issue 12, pp. 11529-11538, June 2011
doi:10.1364/OE.19.011529

The following conference publication resulted from SOFI work in 2010:
'Smooth and ultra-precise silicon nanowires fabricated by conventional optical lithography'
R. Palmer, L. Alloatti, D. Korn, M. Moosmann, K. Huska, U. Lemmer, D. Gerthsen, Th. Schimmel, W. Freude, C. Koos, J. Leuthold
CLEO 2011, Baltimore (Maryland), USA, 1.5.–6.5.2011. Paper CThZ1

‘Silicon Nanophotonics and Silicon-Organic Hybrid (SOH) Integration’

C. Koos, T. Vallaitis, L. Alloatti, D. Korn, R. Palmer, D. Hillerkuss, J. Li, W. Bogaerts, P. Dumon, R. Baets, M. L. Scimeca, I. Biaggio, A. Barklund, R. Dinu, J. Wieland, M. Fournier, J. Fedeli, W. Freude, and J. Leuthold
IPR Toronto 2011, USA