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Executive summary

The SEQUOIA project intended to make significant advances in silicon photonic integrated circuits (PICs) by heterogeneously integrating novel III-V materials, namely quantum dot (Qdot)- and quantum dash (Qdash)-based materials on silicon wafers, through wafer bonding, and also by exploiting novel device concepts through hybrid III-V/silicon integration. These new complex hybrid PICs would offer better performance and enhanced functionality through the use of new materials and novel integration processes. The main objectives of the project were focused on the Qdot/Qdash material elaboration for wafer bonding on Si, on the bonding of Qdot/Qdash wafers on Si and on the building blocks for future complex PICs. Hybrid laser & Si-modulator- based transmitter demonstrations were a second set of objectives for the project.

Bonding of III-V wafers onto silicon required that some specific points were taken into account, and some modifications had to be made on the process of epitaxial growth of the materials. First, the growth sequence of the laser structures, in particular the pn-junction, had to be inverted, i.e., the laser growth had to start with p-doped layers first, followed by the active zone and continued with the n-doped layers. In addition, the surface of the laser structure to be bonded on silicon had to be in close proximity to the active zone to allow an efficient overlap with the silicon waveguide. In order to achieve high-quality bonding, the top surface of the Qdot/Qdash wafers had to have very low defect density and be very flat.

The main objective of the SEQUOIA project was to develop a wafer bonding technique allowing in particular a high-yield heterogeneous integration of Qdot/Qdash wafers on SOI wafers for the fabrication of hybrid III-V/Si PICs. High QD wafer surface quality was achieved and wafer-bonding successful at the end of the project, paving the way for frequency comb laser sources to be integrated in high density WDM PICs.

Another objective of SEQUOIA project was to develop silicon building blocks such as modulators, filters, and grating couplers for the fabrication of hybrid III-V/Si PICs. This objective was successfully attained throughout the project, and state-of-the-art or performance setting devices were designed, fabricated and fully demonstrated, such as echelle-grating based multiplexers, ring resonator (RR)-based multiplexer-modulators.

The following objective was the design of the first generation transmitter (Tx) PICs. Two types of Tx PICs were studied inside this project: Qdot/Qdash-based directly modulated lasers (DMLs) and silicon ring resonator filters, and QDot/Qdash based comb lasers and silicon ring resonator modulators. WDM operation was targeted, with the final objective of achieving 400 Gb/s with 16 channels. The application fields would be the transceivers with short (less than 10 km) and medium (from 10 to 40 km) reaches to interconnect core routers and high performance computers in data centers or telecommunication network centers. In the situation where the QD or QDa-based comb lasers were not available till the end of the project, all other building blocks were implemented, demonstrated and assessed. DMLs with RR-based extinction ratio (ER) enhancement devices achieved outstanding performance: 25Gbit/s over more than 20km error-free transmission. RR-based modulators at 25Gbit/s were also demonstrated. These assessed building blocks, along with the upcoming comb laser sources, pave the way for high bit-rate WDM Tx.

The final objective was to disseminate the research results achieved by the project and to elaborate an industrial exploitation plan. This objective was also achieved. The dissemination activities of the project have been concentrated in five directions: publications in scientific journals
and international conferences (more than 54 publications, including 24 invited papers, and 7 review articles); participation and support of summer schools (Ghent in 2014); organisation of an international workshop related to III-V on silicon (ECOC 2014 and 2016); press releases and articles in public magazines and establishment of a public project WEB site. The exploitation plans of partners were developed thanks to the panel of advisory board; and each partner has determined its own exploitation plans for industrialization of the research results from SEQUOIA project.
**Summary description of project context and objectives**

The SEQUOIA project intended to make significant advances in silicon photonic integrated circuits (PICs) by heterogeneously integrating novel III-V materials, namely quantum dot (Qdot)- and quantum dash (Qdash)-based materials on silicon wafers, through wafer bonding, and also by exploiting novel device concepts through hybrid III-V/silicon integration. These new complex hybrid PICs would offer better performance and enhanced functionality through the use of new materials and novel integration processes. The main objectives of the project were focused on the Qdot/Qdash material elaboration for wafer bonding on Si, on the bonding of Qdot/Qdash wafers on Si and on the building blocks for future complex PICs. Hybrid laser & Si-modulator-based transmitter demonstrations were a second set of objectives for the project.

Bonding of III-V wafers onto silicon required that some specific points were taken into account, and some modifications had to be made on the process of epitaxial growth of the materials. First, the growth sequence of the laser structures, in particular the pn-junction, had to be inverted, i.e., the laser growth had to start with p-doped layers first, followed by the active zone and continued with the ndoped layers. In addition, the surface of the laser structure to be bonded on silicon had to be in close proximity to the active zone to allow an efficient overlap with the silicon waveguide. In order to achieve high-quality bonding, the top surface of the Qdot/Qdash wafers had to have very low defect density and be very flat.

The main objective of the SEQUOIA project was to develop a wafer bonding technique allowing in particular a high-yield heterogeneous integration of Qdot/Qdash wafers on SOI wafers for the fabrication of hybrid III-V/Si PICs. The wafer-scale integration of the innovative Qdot/Qdash materials on silicon would ensure the potential for cost-effective volume production of highly sophisticated devices and PICs, as well as very high integration density combined with enhanced functionality.

Another objective of SEQUOIA project was to develop silicon building blocks such as modulators, filters, and grating couplers for the fabrication of hybrid III-V/Si PICs.

The following objective was the design of the first generation transmitter (Tx) PICs. Two types of Tx PICs were studied inside this project: Qdot/Qdash-based directly modulated lasers (DMLs) and silicon ring resonator filters, and QDot/Qdash based comb lasers and silicon ring resonator modulators. WDM operation was targeted, with the final objective of achieving 400 Gb/s with 16 channels. The application fields would be the transceivers with short (less than 10 km) and medium (from 10 to 40 km) reaches to interconnect core routers and high performance computers in data centers or telecommunication network centers.

The final objective was to disseminate the research results achieved by the project and to elaborate an industrial exploitation plan.
Description of the main S&T results/foregrounds

The project was structured in 5 technical work packages (WP). WP1, led by III-V Lab, was devoted to specifications and exploitation. WP2, led by UKAS, was focused on the material development for Qdot/Qdash-based lasers on Si. WP3, led by CEA, worked on important building blocks such as silicon modulators, wavelength multiplexers and output grating couplers. Then there were two WPs on WDM PICs: WP4 on 400 Gbit/s Tx PICs based on chirp-managed-lasers (CMLs), and WP5 on 400 Gbit/s Tx PICs integrating Qdot/Qdash-based lasers to generate WDM combs and silicon-based modulators.

In WP1 detailed specifications were given in D1.01 for hybrid lasers and other key building blocks such as wavelength multiplexer, ring-resonator modulator and fiber coupler. And performance of WDM Tx PICs was assessed, and perspectives towards industrial exploitation were given in D1.02.

In WP2, the general quality of the QDot/QDash materials was confirmed by the demonstration of room temperature operating ridge waveguide lasers (Ith < 20 mA, Pout > 13 dBm for 1.3 \( \mu \)m Qdot and 1.5 \( \mu \)m Qdash material; Ith < 50 mA, Pout > 13 dBm for 1.5 \( \mu \)m high-speed Qdot material). Due to the challenging surface quality request for molecular bonding, Task 2.2 was significantly delayed. For GaAs based epitaxial laser structures there was only a slight improvement at the end of the first period, in defect density necessary to allow first successful bonding. Then much effort was focused on decreasing the defect density, resulting in successful wafer bonding of QD-wafers on SOI. However, no stop-etch layer was grown on these wafers, so no further processing was possible at the 3rd period of the project.

For InP based epitaxy carried out at UKAS, the complex generation of surface defects and related multiple sources had been well understood since the end of the 1st period. All sources for defect generation could be cancelled out. After system modification all requests in surface quality were fulfilled, and 1.55-\( \mu \)m QD wafers were grown and sent to CEA for bonding on SOI. At III-V Lab the main difficulty was related to the availability of the MBE machine for the growth of inverted quantum dash materials. Due to these difficulties, a significant delay of 12 months was to be taken into account. QDa wafers were grown and successfully bonded during the last period. However, the photoluminescence wavelength of these wafers was not centered at 1.55\( \mu \)m and no further processing was possible. Growth of new QDa-wafers was programmed for further wafer bonding.

In WP3, all tasks progressed toward the realization of advanced passive and active building blocks for 16\( \times \) 25 Gb/s WDM transmitter PICs, with some results very close to the specifications targets expected in the DoW. The design silicon ring modulators (Task 3.1) for both operating wavelengths was complete at the end of the 1st period, and the active device fabrication mask implemented in the 2nd period. The parametric cells developed for these components permitted a quick integration with the hybrid lasers onto the mask SEQ3. Tasks 3.2 (multiplexers), 3.3 (grating couplers) and 3.4 (CML ring resonators) shared the same mask SEQ2, and the fabrication was completed. Furthermore, the fabrication and characterization of the first generation of grating coupler was performed (performances closes to the requirements), and the feedback measurement set-up qualified up to -25dB feedback measurements (1.31um). The second generation of grating couplers was designed, which reached exactly the specifications of the DoW by taking advantage of a dedicated passive fabrication run (SEQ2). Echelle grating multiplexers with state-of-the-art setting performances were fabricated and characterized at the end of the 2nd period.

This WP was completed at the end of the 2nd period, so no activity is reported for the 3rd and last period.
In WP4, hybrid III-V/Si quantum-well DFB lasers were demonstrated, and integrated with micro-ring-resonators (MRRs) for CMLs. The improvement of the extinction ratio by the MRR was clearly observed. For the main demonstrator dealing with the integration of DFB laser array and MRR together with AWG, the design of all building blocks was made. The final layout was completed. The details were given in D4.01. 10Gbit/s, and then 25Gbit/s DML with either a separate MRR or a fully integrated MRR were demonstrated and set the state-of-the-art in the domain. Furthermore, an original scheme using MRR to enhance a PAM-4 signal quality was implemented and demonstrated. All these results were reported in deliverable D4.02.

In WP5, design of chirped DBRs for comb-laser was developed for GaAs platform and adjusted for better manufacturability. In parallel, designs of waveguides and tapers in III-V semiconductor materials were developed as well as Bragg grating reflectors for Si platform. Designs of micro-ring modulators operating at wavelengths around 1.31 and 1.55um were also performed. Final mask design of the Tx PIC composed of the comb laser and MRR modulators was completed (SQ3A & SQ3B). SOI using these mask set-ups was complete and back-end processing on III-V is still ongoing.

Regarding the dissemination activities in WP6, 47 conference contributions (23 of them were invited talks) and 7 journal paper submissions took place. In addition the visibility of the SEQUOIA consortium and the project goals were significantly increased by contributing an overview lecture on the "Silicon Photonics Summer School" in Ghent in July 2014 and by organizing an international workshop on "Which Laser Sources for Silicon Photonics?" at the ECOC 2014 conference in Cannes. This workshop got an amazing interest with more than 200 participants and a very prominent list of distinguished speakers who contributed also on the two panel discussions included in the workshop. In 2016, a second workshop was organized together with the EU project consortium "BigPipe" on "Next Generation Ultra-Broadband Silicon Photonics Based Integrated Circuits" at ECOC, September 2016 in Düsseldorf, Germany. The workshop was jointly organized by the following people from the two consortia: Guang-Hua DUAN, III-V Lab, France (Sequoia); Abderrahim Ramdane, CNRS, France (BigPipe); Johann Peter Reithmaier, Univ. Kassel, Germany (Sequoia); Jeremy Witzens, RWTH Aachen Univ., Germany (BigPipe).

As a basis element for dissemination a public WEB site (http://www.unikassel.de/projekte/SEQUOIA/home.htm) was established since the third project month.

An industrial exploitation panel had also been settled up, and three meetings with the industrial advisors took place.

In terms of project management, the coordinator organized the monthly phone meetings, bi-annually face-to-face project meetings and also some dedicated phone meetings. There was a good communication and coordination inside the consortium.
The potential impact

The dissemination activities for the whole project duration is summarized, which consists of mainly four contributions:
(a) publications in scientific journals and international conferences
(b) participation and support of summer schools
(c) organisation of an international workshop related to III-V on silicon
(d) press releases and articles in public magazines

(a) Publications in scientific journals and international conferences

Peer reviewed journal papers

Invited conference papers
[8] J.P. Reithmaier, "III - V quantum dot/dash material on Si platform for high bit rate optical communication", Summer School on Silicon Photonics, University of Ghent, Belgium (invited lecture, July 2014).


**Contributed conference papers**

[32] S. Banyoudeh, J.P. Reithmaier, "Recent advances in growth of high density InP based InAs/InGaAlAs quantum dots with reduced size inhomogeneity", Int. Conf. on Molecular Beam Epitaxy (ICMBE), Flagstaff, Arizona, USA (September, 2014).


[35] uddeh, A. Abdollahinia, V. Sichkovskyi, J.P. Reithmaier, "High temperature operation of 1.55 μm InAs quantum dot lasers with high T₀ and T₁ values", European Semiconductor Laser Workshop, Madrid, Spain (September 2015).


[38] O. Eyal, G. Eisenstein, S. Banyoudeh, A. Abdollahinia, F. Schnabel and J.P. Reithmaier, "High-Speed InP-Based Quantum Dot Lasers With Low Temperature Sensitivity", submitted to Conf. on Lasers & Electro-Optics (CLEO), San José, CA, USA (June, 2016).


[43] V. Cristofori, V. Kamchevska, Y. Ding, A. Shen, G.-H. Duan, C. Peucheret and L. K. Oxenløwe, “Error-
free Dispersion-uncompensated Transmission at 20 Gb/s over SSMF using a Hybrid III/V-SOI DML with
Gain Section Quantum Dot Multi-Wavelength Hybrid III/VI-Si Laser“, ECOC, Düsseldorf, (Sept. 2016).
[45] V. Cristofori, F. Da Ros, Y. Ding, A. Shen, A. Gallet, D. Make, G.-H. Duan, L. K. Oxenløwe, and C.
Peucheret, “Direct modulation of a hybrid III-V/Si DFB laser with MRR filtering for 22.5-Gb/s error-free
dispersion-uncompensated transmission over 2.5-km SSMF,” European Conference on Optical
[46] V. Cristofori, V. Kamchevska, Y. Ding, A. Shen, G.-H. Duan, C. Peucheret, and L. K. Oxenløwe, “Error-
free dispersion-uncompensated transmission at 20 Gb/s over SSMF using a hybrid III-V/SOI DML with MRR
filtering,” Conference on Lasers and Electro-Optics, CLEO’2016, paper STu1G.4, San Jose, California, USA,
(June 2016).
[47] A. Abdollahinia, S. Banyoudeh, Ori Eyal, G. Eisenstein, J.P. Reithmaier, "Improved dynamic properties
of directly modulated high-speed 1.5 µm quantum dot lasers", Compound semiconductor week (CSW, ISCS +
IPRM), Berlin, Germany (May, 2017), Conf. Proceed., C7.6.
[48] A. Abdollahinia, A. Rippien, S. Banyoudeh, J.P. Reithmaier, "Highly Temperature-Stable 1.5 µm
Quantum Dot Lasers", Congress of the International Commission of Optics (ICO), Tokyo, Japan (August,
exploiting the frequency chirping properties of silicon ring-resonator modulators,” Asia Communications and
[50] V. Cristofori, F. Da Ros, O. Ozolins, M. Chaibi, L. Bramerie, Y. Ding, X. Pang, A. Shen, A. Gallet, G.-
over 2.5-km SSMF by silicon MRR enhanced 1.55-µm III-V/SOI DML,” IEEE Photonics Conference, IPC
[51] V. Cristofori, F. Da Ros, M. E. Chaibi, Y. Ding, L. Bramerie, A. Shen, A. Gallet, G.-H. Duan, K. Hassan,
S. Olivier, L. K. Oxenløwe, and C. Peucheret, “1.5-µm directly modulated transmission over 66 km of SSMF
with an integrated hybrid III-V/SOI DFB laser,” International Conference on Group IV Photonics, GFP 2017,
[52] F. Da Ros, V. Cristofori, O. Ozolins, M. E. Chaibi, X. Pang, G. Jacobsen, S. Popov, M. Galili, L. K.
Oxenløwe, and C. Peucheret, “4-PAM dispersion-uncompensated transmission with microring resonator
enhanced 1.55-µm DML,” Conference on Lasers and Electro-Optics, CLEO 2017, paper STu1M.5, San Jose,
California, USA, (May 2017).
transmission over 100-km SSMF using SSB filtering with two silicon micro-ring resonators,” Conference on
Lasers and Electro-Optics, CLEO 2017, paper STu1M.4, San Jose, California, USA, (May 2017).
[54] V. Cristofori, F. Da Ros, M. E. Chaibi, Y. Ding, L. Bramerie, A. Shen, A. Gallet, G.-H. Duan, L. K.
Oxenløwe, and C. Peucheret, “Directly modulated and ER enhanced hybrid III-V/SOI DFB laser operating up
to 20 Gb/s for extended reach applications in PONs,” Optical Fiber Communication Conference, OFC 2017,
paper Tu3G.7, Los Angeles, California, USA, (Mar. 2017).

(b) Participation and support of summer schools

The Sequoia consortium contributed to the Silicon Photonics Summer School, 29.06. - 04.07.14,
Ghent University, Belgium. This summer school was organized by the European technology
platform PLAT4M. It was about 120 attendees on the summer school. The SEQUOIA project
contributed by a lecture of J.P. Reithmaier, who gave an overview about the SEQUOIA project and
goals as well as the current status of 1.3/1.55 µm QD lasers and molecular wafer bonding. The
The SEQUOIA project initiated and organized an international workshop on "Which Laser Sources for Silicon Photonics?". The workshop organizers were: Guang-Hua Duan from III-V Lab, France, and Johann Peter Reithmaier from INA, University of Kassel, Germany. The workshop took place at Sunday afternoon (14:00 – 17:30) at the European Conference of Optical Communication, Cannes, September 21, 2014. The workshop program with 11 distinguished lectures given by major players in this field. They have given an excellent overview of the field covering all important technologies currently important from already mature hybrid single device bonding over wafer bonding of different types and direct epitaxy of III-V materials on silicon. The workshop was very successful with more than 200 attendees and vital discussions could be initiated within two panel discussions chaired by the two organizers.

ECOC Workshop 2016

In 2016, a second workshop was organized together with the EU project consortium "BigPipe" on "Next Generation Ultra-Broadband Silicon Photonics Based Integrated Circuits" at ECOC, September 2016 in Düsseldorf, Germany. The workshop was jointly organized by the following people from the two consortia:

- Guang-Hua DUAN, III-V Lab, France (Sequoia)
- Abderrahim Ramdane, CNRS, France (BigPipe)
- Johann Peter Reithmaier, Univ. Kassel, Germany (Sequoia)
- Jeremy Witzens, RWTH Aachen Univ., Germany (BigPipe)

Scope of Workshop

Increasing front panel data densities of data center switches as well as increasing reach and data rate of data center state-of-the-art optical interconnects has motivated the emergence of Silicon Photonics based integrated circuits. In parallel, metro and long-haul networks require transceivers with reduced size and power consumption. Silicon photonics is also a candidate for those markets. This Workshop will gather prominent speakers from industry and academia and intends to give an update on the state
of the art on silicon photonics based integrated circuits, with emphasis on the following two key areas:
- Efficient laser source solutions for silicon photonics with advanced material systems such as quantum dots.
- Silicon based Photonic integrated circuits exploring the wavelength division multiplexing.

(d) Press releases and articles in public magazines

An article for a more public audience was published in Compound Semiconductor about InP-based QD lasers and their impact on datacom application. In particular the SEQUOIA project was highlighted for a potential approach of this technology. In figure below, the cover page of the issue and the title page of the article is shown.

In order to ensure a permanent focus of all Participants on the exploitation aspects a specific Exploitation Advisory Panel has been installed. This Panel includes one representative from each partner:
1. Guang-Hua Duan (III-V LAB)
2. Igor Krestnikov (INNOLUME) - Chairman
3. Johann Peter Reithmaier (UNI KASSEL)
4. Karim Hassan (CEA-LETI)
5. Valentina Cristofori (DTU)
6. Christophe Peucheret (UR1)

Also representatives from relevant component manufactures and integrated photonics stakeholders have been invited. The following experts have kindly agreed to participate in the Exploitation Advisory Panel:
7. Young-Kai Chen (Alcatel Lucent Bell Labs, USA)
8. Kwangwoong Kim (Alcatel Lucent Bell Labs, South Korea)
9. Wilfried Idler (Alcatel Lucent Bell Labs, Germany)
10. Charles Baudot (ST Microelectronics, France)

Exploitation plans of partners can be formulated as following:

→ III-V lab
  - Foundary model with setup of Pilot Production Line; further transfer of the technology to industrial partners for larger production
  - Form a rich patent portfolio in the field of hybrid PICs

→ INNO
  - Expansion to market segments in datacom applications
  - Further product improvements to spread to other applications
  - Patenting to secure the technology

→ CEA
  - Strength the know-how on the adaptation of standard CMOS to nanophotonic devices
  - Link between fundamental research and industry
  - Pilot line for bridging the gap between MPW-based fabrication and large-volume manufacturing

→ UKAS
  - Pilot line fabrication with transfer of the technology to
  - industrial partner
  - spin-off company
  - Transfer of master and PhD students to industrial partners
- Protest IP by patents embedded into the licensing strategy of the university
  - DTU
    - Transfer of master and PhD students to industrial partners
    - Possible formation of new start-up companies
  - URI
    - Expertise in the field of optically filtered directly modulated lasers will be transferred to a new generation of the researchers