Nanowire based Tandem Solar Cells

Results

Project Information

Nano-Tandem
Grant agreement ID: 641023

Funded under
H2020-EU.3.3.5.

Overall budget
€ 4 332 341,50

EU contribution
€ 3 561 841,50

Coordinated by
LUNDS UNIVERSITET
Sweden

Start date
1 May 2015
End date
30 April 2019

This project is featured in...

RESULTS PACK
Harnessing solar power: The future shines bright
29 July 2019

Deliverables
Report on feasibility of different emitter structures for direct growth of III–V nanowires

Summary report regarding the feasibility of different emitter structures for the direct growth of III–V nanowires with low interface resistance (< 10 mOhmcm) and low emitter recombination in the silicon sub-cell. Especially the feasibility of the back-end processing has to be shown and potential consequences for the nanowire growth will be discussed. The report will present experimental results of at least 3 different single-junction silicon solar cell designs with different emitter structure including Quantum Efficiency and IV-characteristics of devices. Measurements of emitter profiles, surface roughness and defectivity will be presented.

Report on optimized particle patterning with redesigned master structures or processing

Depending on optical simulations as well as electro-optical characterization performed in WP6 it is likely that pattern parameters (pitch, diameters or shape of particles) will need to be optimized. Also a close link to the partners doing the epitaxy in WP2 will be important to have a feedback to optimize the quality of the catalyst arrays. The report will describe the measures being taken to meet these demands.

Report on fabrication of nanotube templates for template-assisted epitaxy on Si

The templates are defined using metal particle etch-masks and sacrificial layers compatible with a Si PV cell substrate.

Report on the status of the different NIL based techniques

The status of the different patterning methods will be reported here with respect to yield and feasibility of the methods for large scale area patterning of active catalyst materials (patterning of metal particles on minimum 90 % of a 2” wafer). Process parameter window will be stated as well as dimensions with respect to catalyst diameter and pitch achievable. The report will include an assessment on the quality of NWs grown from the catalysts with respect to optical properties, life time of carriers and PL energy and luminescence intensity.

Report on feasibility of different emitter structures for III-V nanowire transfer

Summary report regarding the feasibility of different emitter structures for the transfer of III-V nanowires to Silicon with low interface resistance and low emitter recombination in the silicon sub-cell. Especially the feasibility of the back-end processing has to be shown. The surface has to be suitable for attaching the III-V nano-wires (planarity, low roughness, no contamination) and realize low ohmic resistance and low parasitic absorption (< 10%).

Report on the generation and properties of aerosol particles
Achieved yield, density and size distribution of nanoparticles with requirement of up to 200 nm in diameter, and a feasibility assessment regarding their use as Aerotaxy seed particles.

Publishable summary on the electrical properties of the NW/Si interface achieved with the three planned approaches
Publishable summary of D4.3

Final summary report on solar cell performance
The deliverable will summarize the electrical and optical characterizations performed on the nanowire multi-junction cells. Besides the calibration at standard testing conditions (STC, AM1.5g) also measurements under varying intensity and temperature will be performed. Additionally absorption and uniformity mapping results will be summarized.

Evaluation of the impact of Nano-Tandem scientific achievements
A comprehensive evaluation of all impacts of the Nano-Tandem project will be provided covering all scientific, technological and industrial outcomes of the project.

Publishable summary on the preliminary life cycle assessment
Publishable summary of D7.1

Publishable summary on the NW crystalline and optical structure
Publishable summary of D4.1

Report on the electrical properties of Esaki diodes between axial NW segments
The report will contain the results achieved on Esaki tunnelling diodes with respect to low bias resistance and the maximum doping achieved in the materials which will be related to the doping level necessary for degenerate doping. Dopant incorporation homogeneity will be included, as well as the results from Hall type of characterization, CV characterization, back gated type of measurements as well as resistivity in the materials.

First report on STC efficiency of nanowire solar cells
This report will summarize the first calibrated efficiency measurements performed on nanowire multi-junction cells at standard testing conditions (STC AM1.5g spectrum). The measurements are performed using calibration routines for multi-junction solar cells and include measurements of Quantum efficiency, active cell area and IV-characteristics under a spectrally adjustable simulator.

Report on the status of Au-assisted nanowire growth on InP and GaAs substrates and growth of nanowires by use of Aerotaxy
The deliverable will include description of growth schemes for optimal pattern preservation (> 95% vertically standing NWs), details on synthesis of the different materials with respect to materials composition and quality as a function of precursor molar fractions and growth temperature (PL emission at band gap of 1.7 eV for GaInP and GaAsP). It will also contain details on achieved doping levels in the nanowire materials grown by the different methods and details of the contact region between the substrate and the nanowires as determined by XRD and TEM, and results from wafer recycling (at least 3 times substrate re-use verified).

Publishable summary on template-assisted epitaxy of InGaP and GaAsP nanowires on Si.

Publishable summary of D2.1

Report on growth of doped ternary NW materials for pn-junctions. This includes the effect of the different dopants (TESn, H2S, CP2Mg and DEZn on the growth dynamics and dopant incorporation if the ternary NW materials (targeted n type degenerate doping of 1x1019 for n and p type GaInP and GaAsP). It will contain an evaluation of the feasibility of using the different dopants and will lead to a choice of dopant for use in the project. The feasibility of using the different dopants in an Esaki diode in combination with the degenerately doped substrate, and in between segments in the NW will be evaluated (Esaki tunneling diode in 1 mm2 cells characterized).

Publishable summary on the final life cycle assessment

Publishable summary of D7.3

Publishable summary on the life cycle costs, including estimated production costs

Publishable summary of D7.2

Report on adaption of EQE and IV measurement equipment for nanowire solar cells. The deliverable will summarize the adaption that need to be performed to the measurement equipment at ISE CalLab in order to measure the nanowire multi-junction cells. This included an adaption of the bias light for EQE measurement and verification of the suitability of the multisource simulator or potential adaption of its simulator spectrum to measure nano-wire solar cells with up to 4 cm2 area

Report on the electrical design of tandem cell

The deliverable will contain electrical design recommendation for a high-efficiency tandem solar cell. The design variables include the doping profile in the nanowire and in the substrate and requirements on surface passivation quality, emitter and base thickness as well as the electrical properties of contact and insulation layers. A table summarizing the theoretical design specifications will be included.

Report on realization of integrated light trapping structures into bottom cell
Progress report about the realization of the integration of light trapping structures into the Silicon bottom cell. This will allow current matching to the used top cell design. Special attention needs to be paid to checking the feasibility of the back-end processing. Performance of the light trapping will be confirmed by producing silicon test solar cell devices (> 1 cm²) and measurement of reflection properties and Quantum Efficiency in the spectral range of 300–1250 nm. The current enhancement induced by the light trapping structure will be at least 1 mA/cm².

Report on suitable geometry and material of nanowire array subcell
D6.2 Report on suitable geometry and material of nanowire array subcell The deliverable will contain recommendation of suitable III–V material for the nanowires, the geometry of the nanowires (nanowire diameter and length, and array period), and design for the processing layers for electrical contacting in order to maximize the conventional Shockley-Queisser efficiency limit of the multi-junction tandem solar cell. These recommendations are used for deciding on the geometry for the solar cell in M24 (MS3).

Report on nanowire tandem junction growth for solar energy harvesting
The deliverable will contain details on growth of nanowire tandem solar cells by use of the in MS2.1 selected growth method. The structure will be described; including the choice of all parameter for the optimized structure including obtained doping levels, crystal structure, reproducibility and photovoltaic efficiency (target 25% efficiency on minimum 2x2 cm² area).

Exploitation plan – preliminary version
A first exploitation plan will be settled at month 36 and updated up to the end of the project.

Publishable summary on the compositional homogeneity and optical properties of ternary III–V nanowires
Publishable summary of D4.2

Dissemination Strategy and Plan
This will describe the dissemination (Task 8.1) in detail.

Final plan for the exploitation and dissemination of foreground
The final exploitation plan will be delivered at Month 48 with extensive updates with respect to the preliminary version at Month 36.

Other (1)

Organization of a workshop to support exchange of scientific and technological knowledge
One international workshop will be arranged by ULUND during the second half of the project to disseminate the scientific results and create a link with other PV projects in Europe.

**Websites, patent fillings, videos etc. (1)**

- Project website established

A website will be set up both for consortium members and public access. It will be regularly maintained during and after the project duration, in order to report project activities, progress and achievements.

**Publications**

**Peer reviewed articles (35)**

- **III-V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration**
  
  **Author(s):** Romain Cariou, Jan Benick, Frank Feldmann, Oliver Höhn, Hubert Hauser, Paul Beutel, Nasser Razek, Markus Wimplinger, Benedikt Bläsi, David Lackner, Martin Hermle, Gerald Siefer, Stefan W. Glunz, Andreas W. Bett, Frank Dimroth
  
  **Published in:** Nature Energy, Issue 3/4, 2018, Page(s) 326-333, ISSN 2058-7546
  
  **DOI:** 10.1038/s41560-018-0125-0

- **Green and Clean: Reviewing the Justification of Claims for Nanomaterials from a Sustainability Point of View**
  
  **Author(s):** Georgios Pallas, Willie Peijnenburg, Jeroen Guinée, Reinout Heijungs, Martina Vijver
  
  **Published in:** Sustainability, Issue 10/3, 2018, Page(s) 689, ISSN 2071-1050
  
  **DOI:** 10.3390/su10030689

- **Room-Temperature Lasing from Monolithically Integrated GaAs Microdisks on Silicon**
  
  **Author(s):** Stephan Wirths, Benedikt F. Mayer, Heinz Schmid, Marilyne Sousa, Johannes Gooth, Heike Riel, Kirsten E. Moselund
  
  **Published in:** ACS Nano, Issue 12/3, 2018, Page(s) 2169-2175, ISSN 1936-0851
  
  **DOI:** 10.1021/acsnano.7b07911

- **GaAs Nanowire pn-Junctions Produced by Low-Cost and High-Throughput Aerotaxy**
Optimized efficiency in InP nanowire solar cells with accurate 1D analysis

Author(s): E. Barrigón, O. Hultin, D. Lindgren, F. Yadegari, M. H. Magnusson, L. Samuelson, L. I. M. Johansson, M. T. Björk
Published in: Nano Letters, Issue 18/2, 2017, Page(s) 1088-1092, ISSN 1530-6984
DOI: 10.1021/acs.nanolett.7b04609

Intersubband Quantum Disc-in-Nanowire Photodetectors with Normal-Incidence Response in the Long-Wavelength Infrared

Author(s): Yang Chen, Pyry Kivisaari, Mats-Erik Pistol, Nicklas Anttu
Published in: Nanotechnology, Issue 29/4, 2018, Page(s) 045401, ISSN 0957-4484
DOI: 10.1088/1361-6528/aa9e73

Observation of Twin-free GaAs Nanowire Growth Using Template-Assisted Selective Epitaxy

Author(s): Mohammad Karimi, Magnus Heurlin, Steven Limpert, Vishal Jain, Xulu Zeng, Irene Geijselaers, Ali Nowzari, Ying Fu, Lars Samuelson, Heiner Linke, Magnus T. Borgström, Håkan Pettersson
Published in: Nano Letters, Issue 18/1, 2017, Page(s) 365-372, ISSN 1530-6984
DOI: 10.1021/acs.nanolett.7b04217

InP/InAsP Nanowire-Based Spatially Separate Absorption and Multiplication Avalanche Photodetectors

Author(s): Vishal Jain, Magnus Heurlin, Enrique Barrigon, Lorenzo Bosco, Ali Nowzari, Shishir Shroff, Virginia Boix, Mohammad Karimi, Reza J. Jam, Alexander Berg, Lars Samuelson, Magnus T. Borgström, Federico Capasso, Håkan Pettersson
Published in: ACS Photonics, Issue 4/11, 2017, Page(s) 2693-2698, ISSN 2330-4022
DOI: 10.1021/acs.photonics.7b00389

Optical analysis of a III-V-nanowire-array-on-Si dual junction solar cell

Author(s): Yang Chen, Oliver Höhn, Nico Tucher, Mats-Erik Pistol, Nicklas Anttu
Published in: Optics Express, Issue 25/16, 2017, Page(s) A665, ISSN 1094-4087
DOI: 10.1364/oe.25.00a665
Room-temperature InP/InAsP Quantum Discs-in-Nanowire Infrared Photodetectors

**Author(s):** Mohammad Karimi, Vishal Jain, Magnus Heurlin, Ali Nowzari, Laiq Hussain, David Lindgren, Jan Eric Stehr, Irina A. Buyanova, Anders Gustafsson, Lars Samuelson, Magnus T. Borgström, Håkan Pettersson

**Published in:** Nano Letters, Issue 17/6, 2017, Page(s) 3356-3362, ISSN 1530-6984

**DOI:** 10.1021/acs.nanolett.6b05114

Absorption and transmission of light in III–V nanowire arrays for tandem solar cell applications

**Author(s):** Nicklas Anttu, Vilgailė Dagytė, Xulu Zeng, Gaute Otnes, Magnus Borgström

**Published in:** Nanotechnology, Issue 28/20, 2017, Page(s) 205203, ISSN 0957-4484

**DOI:** 10.1088/1361-6528/aa6aee

In x Ga 1– x P Nanowire Growth Dynamics Strongly Affected by Doping Using Diethylzinc

**Author(s):** Gaute Otnes, Magnus Heurlin, Xulu Zeng, Magnus T. Borgström

**Published in:** Nano Letters, Issue 17/2, 2017, Page(s) 702-707, ISSN 1530-6984

**DOI:** 10.1021/acs.nanolett.6b03795

Simplifying Nanowire Hall Effect Characterization by Using a Three-Probe Device Design

**Author(s):** Olof Hultin, Gaute Otnes, Lars Samuelson, Kristian Storm

**Published in:** Nano Letters, Issue 17/2, 2017, Page(s) 1121-1126, ISSN 1530-6984

**DOI:** 10.1021/acs.nanolett.6b04723

Towards high efficiency nanowire solar cells

**Author(s):** Gaute Otnes, Magnus T. Borgström

**Published in:** Nano Today, Issue 12, 2017, Page(s) 31-45, ISSN 1748-0132

**DOI:** 10.1016/j.nantod.2016.10.007

Electrical and optical evaluation of n-type doping in In x Ga (1– x ) P nanowires

**Author(s):** Xulu Zeng, Renato T Mourão, Gaute Otnes, Olof Hultin, Vilgailė Dagytė, Magnus Heurlin, Magnus T Borgström

**Published in:** Nanotechnology, Issue 29/25, 2018, Page(s) 255701, ISSN 0957-4484

**DOI:** 10.1088/1361-6528/aabaa5

InP/GaInP nanowire tunnel diodes

**Author(s):** Xulu Zeng, Gaute Otnes, Magnus Heurlin, Renato T. Mourão, Magnus T. Borgström

**Published in:** Nano Research, Issue 11/5, 2018, Page(s) 2523-2531, ISSN
Understanding InP Nanowire Array Solar Cell Performance by Nanoprobe-Enabled Single Nanowire Measurements

Author(s): Gaute Otnes, Enrique Barrigón, Christian Sundvall, K. Erik Svensson, Magnus Heurlin, Gerald Siefer, Lars Samuelson, Ingvar Åberg, Magnus T. Borgström

Published in: Nano Letters, Issue 18/5, 2018, Page(s) 3038-3046, ISSN 1530-6984
DOI: 10.1021/acs.nanolett.8b00494

Towards Nanowire Tandem Junction Solar Cells on Silicon

Author(s): Magnus T. Borgstrom, Martin H. Magnusson, Frank Dimroth, Gerald Siefer, Oliver Hohn, Heike Riel, Heinz Schmid, Stephan Wirths, Mikael Björk, Ingvar Aberg, Willie Peijnenburg, Martina Vijver, Maria Tchernycheva, Valerio Piazza, Lars Samuelson

Published in: IEEE Journal of Photovoltaics, Issue Volume: 8, Issue: 3, 2018, Page(s) 1-8, ISSN 2156-3381
DOI: 10.1109/jphotov.2018.2816264

Optimization of the short-circuit current in an InP nanowire array solar cell through opto-electronic modeling

Author(s): Yang Chen, Pyry Kivisaari, Mats-Erik Pistol, Nicklas Anttu

Published in: Nanotechnology, Issue 27/43, 2016, Page(s) 435404, ISSN 0957-4484
DOI: 10.1088/0957-4484/27/43/435404

Performance of GaAs Nanowire Array Solar Cells for Varying Incidence Angles

Author(s): Omid Madani Ghahfarokhi, Nicklas Anttu, Lars Samuelson, Ingvar Aberg

Published in: IEEE Journal of Photovoltaics, Issue 6/6, 2016, Page(s) 1502-1508, ISSN 2156-3381
DOI: 10.1109/JPHOTOV.2016.2604564

Design for strong absorption in a nanowire array tandem solar cell

Author(s): Yang Chen, Mats-Erik Pistol, Nicklas Anttu

Published in: Scientific Reports, Issue 6, 2016, Page(s) 32349, ISSN 2045-2322
DOI: 10.1038/srep32349

Strategies to obtain pattern fidelity in nanowire growth from large-area surfaces patterned using nanoimprint lithography

9 of 13
InP nanowire p-type doping via Zinc indiffusion

Author(s): Gaute Otnes, Magnus Heurlin, Mariusz Graczyk, Jesper Wallentin, Daniel Jacobsson, Alexander Berg, Ivan Maximov, Magnus T. Borgström
Published in: Nano Research, Issue 9/10, 2016, Page(s) 2852-2861, ISSN 1998-0124
DOI: 10.1007/s12274-016-1165-z

GaAsP Nanowires Grown by Aerotaxy

Author(s): Tuomas Haggren, Gaute Otnes, Renato Mourão, Vilgaile Dagyte, Olof Hultin, Fredrik Lindelöw, Magnus Borgström, Lars Samuelson
Published in: Journal of Crystal Growth, Issue 451, 2016, Page(s) 18-26, ISSN 0022-0248
DOI: 10.1016/j.jcrysgro.2016.06.020

Modal analysis of resonant and non-resonant optical response in semiconductor nanowire arrays

Author(s): Wondwosen Metaferia, Axel R. Persson, Kilian Mergenthaler, Fangfang Yang, Wei Zhang, Arkady Yartsev, Reine Wallenberg, Mats-Erik Pistol, Knut Deppert, Lars Samuelson, Martin H. Magnusson
Published in: Nano Letters, Issue 16/9, 2016, Page(s) 5701-5707, ISSN 1530-6984
DOI: 10.1021/acs.nanolett.6b02367

Nanoscale investigation of a radial p–n junction in self-catalyzed GaAs nanowires grown on Si (111)

Author(s): Valerio Piazza, Marco Vettori, Ahmed Ali Ahmed, Pierre Lavenus, Fabien Bayle, Nicolas Chauvin, François H. Julien, Philippe Regreny, Gilles Patriarche, Alain Fave, Michel Gendry, Maria Tchernycheva
Published in: Nanoscale, Issue 10/43, 2018, Page(s) 20207-20217, ISSN 2040-3364
DOI: 10.1039/C8NR03827A

Tailored emission to boost open-circuit voltage in solar cells

Author(s): Nicklas Anttu, Pyry Kivisaari, Yang Chen
Published in: Journal of Physics Communications, Issue 3/5, 2019, Page(s) 055009, ISSN 2399-6528
DOI: 10.1088/2399-6528/ab1cc4

Synthesis and Applications of III–V Nanowires
Three-Dimensional Imaging of Beam-Induced Biasing of InP/GaInP Tunnel Diodes

Author(s): Cristina Cordoba, Xulu Zeng, Daniel Wolf, Axel Lubk, Enrique Barrigón, Magnus T. Borgström, Karen L. Kavanagh
Published in: Nano Letters, Issue 19/6, 2019, Page(s) 3490-3497, ISSN 1530-6984
DOI: 10.1021/acs.nanolett.9b00249

Investigation of GaN nanowires containing AlN/GaN multiple quantum discs by EBIC and CL techniques

Author(s): Valerio Piazza, Andrey V Babichev, Lorenzo Mancini, Martina Morassi, Patrick Quach, Fabien Bayle, Ludovic Largeau, François H Julien, Pierre Rale, Stéphane Collin, Jean-Christophe Harmand, Noelle Gogneau, Maria Tchernycheva
Published in: Nanotechnology, Issue 30/21, 2019, Page(s) 214006, ISSN 0957-4484
DOI: 10.1088/1361-6528/ab055e

Growth kinetics of Ga x In (1– x ) P nanowires using triethylgallium as Ga precursor

Author(s): Vilgailė Dagytė, Magnus Heurlin, Xulu Zeng, Magnus T Borgström
Published in: Nanotechnology, Issue 29/39, 2018, Page(s) 394001, ISSN 0957-4484
DOI: 10.1088/1361-6528/aad1d2

Dopant-Induced Modifications of Ga x In (1– x ) P Nanowire-Based p–n Junctions Monolithically Integrated on Si(111)

Author(s): Nicolas Bologna, Stephan Wirths, Luca Francaviglia, Marco Campanini, Heinz Schmid, Vasileios Theofylaktpoulos, Kirsten E. Moselund, Anna Fontcuberta i Morral, Rolf Erni, Heike Riel, Marta D. Rossell
Published in: ACS Applied Materials & Interfaces, Issue 10/38, 2018, Page(s) 32588-32596, ISSN 1944-8244
DOI: 10.1021/acsami.8b10770

n -type doping and morphology of GaAs nanowires in Aerotaxy

Author(s): Wondwosen Metaferia, Sudhakar Sivakumar, Axel R Persson, Irene Geijseelaers, L Reine Wallenberg, Knut Deppert, Lars Samuelson, Martin H Magnusson
Published in: Nanotechnology, Issue 29/28, 2018, Page(s) 285601, ISSN 0957-
Electron Tomography Reveals the Droplet Covered Surface Structure of Nanowires Grown by Aerotaxy

**Author(s):** Axel R. Persson, Wondwosen Metaferia, Sudhakar Sivakumar, Lars Samuelson, Martin H. Magnusson, Reine Wallenberg  
**Published in:** Small, Issue 14/33, 2018, Page(s) 1801285, ISSN 1613-6810  
**DOI:** 10.1002/smll.201801285

Connection between modeled blackbody radiation and dipole emission in large-area nanostructures

**Author(s):** Nicklas Anttu  
**Published in:** Optics Letters, Issue 41/7, 2016, Page(s) 1494, ISSN 0146-9592  
**DOI:** 10.1364/OL.41.001494

Conference proceedings (2)

**Photonic structures for III-V//Si multijunction solar cells with efficiency >33%**

**Author(s):** Benedikt Bläsi, Oliver Höhn, Hubert Hauser, Romain Cariou, Jan Benick, Frank Feldmann, Paul Beutel, David Lackner, Martin Hermle, Gerald Siefer, Stefan W. Glunz, Andreas W. Bett, Frank Dimroth, Nico Tucher  
**Published in:** Photonics for Solar Energy Systems VII, 2018, Page(s) 2  
**DOI:** 10.1117/12.2307831

**Monolithic integration of III-V nanostructures for electronic and photonic applications**

**Author(s):** Kirsten E. Moselund, Benedikt Mayer, Heinz Schmid, Heike Riel, Yannick Baumgartner, Stephan Wirths, Svenja Mauthe, Lukas Czornomaz, Marilyne Sousa Petit, Clarissa Convertino  
**Published in:** Low-Dimensional Materials and Devices 2017, 2017, Page(s) 19  
**DOI:** 10.1117/12.2275871

**Last update:** 5 June 2020  
**Record number:** 193777  
**Permalink:** https://cordis.europa.eu/project/id/641023/results  

© European Union, 2021