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Rapport d'activité final du Projet "Unconventional Principles of Thermoelectric Generation"

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J.F. Robillard. Rapport d'activité final du Projet "Unconventional Principles of Thermoelectric Generation": ERC StG 338179. Institut d'Electonique, Microélectronique et de nanotechnologie - UMR8520. 2024. hal-04540093

HAL Id: hal-04540093

<https://hal.science/hal-04540093>

Submitted on 10 Apr 2024

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European Research Council
Executive Agency



Project No: 338179

Project Acronym: UPTEG

Project Full Name: Unconventional Principles of ThermoElectric
Generation

ERC-SG

Final Activity Report

Period covered: from 01/10/2013 to 31/07/2019

Start date of project: 01/10/2013

Duration: 70

Principal Investigator name:

Dr. Jean-François Sebastien Denis ROBILLARD

Date of preparation: 16/09/2019

Date of submission (SESAM): 27/09/2019

Report submitted by:

YNCREA HAUTS DE FRANCE

Final Activity Report

GENERAL INFORMATION

Project No.:	338179
Project acronym:	UPTEG
Project full name:	Unconventional Principles of ThermoElectric Generation
Project starting date:	01/10/2013
Project duration [months]:	70
Principal Investigator name:	Dr. Jean-François Sebastien Denis ROBILLARD
Host Institution name:	YNCREA HAUTS DE FRANCE
Date of submission:	27/09/2019

Final Activity Report

Summary of the major project achievements over the entire lifetime of the project

The information provided in this section will only be available to ERC staff, to members of the ERC panels, and to the Scientific Council

Explain in a clear manner the work performed during the entire lifetime of the project along the main objectives/activities of the project listed in the Description of Work (DoW). Please indicate the publications linked to these objectives/activities.

Please specify the outcome in terms of:

- research and technological achievements along the main objectives/activities (in line with the DoW)

Preliminary remark: The UPTEG project aimed at developing two types of thermoelectric energy harvesters, each one relying on a highly innovative principle. In this report, all items will be addressed with respect to these two types of converters. This doesn't mean that the team and the research effort has been split on two independent sub-topics. On the contrary, several techniques and skills developed during the project were shared between the two approaches.

The Phononic Engineering Converters (PEC), aim at upgrading silicon's thermoelectric properties at a competitive level with respect to state-of-the-art materials by means of artificial nano-patterning. Here is a summary, a list of the main achievements and associated publications related to the PEC sub-part of the project.

Summary PEC.

The objective of demonstrating a proof-of-concept for the PEC is clearly achieved beyond expectations. A significant number of milestones were obtained and published in articles and oral communications. The main result is the fabrication of integrated thermoelectric demonstrators based on silicon-on-insulator wafers. In these demonstrators, silicon in the form of Nano patterned thin-films (60 nm) is used as the thermoelectric material which is in itself a great achievement. The devices are fabricated using CMOS compatible processes and exhibit power generation from few $\mu\text{W}/\text{cm}^2$ to some mW/cm^2 , under temperature differences from a few K to 200K across the thermopiles. These numbers are at the state-of-the-art for silicon nanostructures and feature the distinctive advantage of being fully compatible and ready for a transfer into silicon mainstream fabrication facilities. This very last result is still under consideration for publication in Nano Energy. The draft paper is attached to this report.

List of main achievements PEC.

A first workpackage was dedicated to the modeling and simulation tasks to better anticipate on the capabilities of the PEC approach. In that frame, molecular dynamics studies, finite elements and numerical models were used.

“Toward quantitative modelling of silicon phononic thermocrystals”, Appl. Phys. Lett. 106, 11 (2015) 114104

“Unconventional thin-film thermoelectric converters: structure, simulation, and comparative study” J. Electron. Mater. 43, 6 (2014) 2109-2114

“Thermoelectric energy conversion: how good can silicon be?” Mater. Lett. 157 (2015) 193-196

A second workpackage was dedicated to the material engineering. In that frame processes were developed to: i) structure, ii) suspend, iii) characterize thermally and electrically, silicon ultra-thin membranes.

“Phononic engineering of silicon using “dots on the fly” e-beam lithography and plasma etching” Microelectronics Engineering 121 (2014) 131-134

“Fabrication of thin-film silicon membranes with phononic crystals for thermal conductivity measurements IEEE Electron Device Lett. 37, 10 (2016) 1358-1361

“Fabrication of large-scale, ultra-thin, free-standing silicon membranes by laser ablation”, (draft attached)

Finally, the converter prototype was fabricated and characterized in the frame of the Converter Integration work package.

“Single-Crystal Silicon Thermoelectrics by Phonon Engineering” (submitted to Nano Energy, draft attached)

List of side results that were obtained thanks to the UPTEG project in association with collaborators.

“Effective in-plane and cross-plane thermal conductivities of nanophononic-photonic membrane strips with sub-100 nm thickness and pitches” (Manuscript in preparation for ACS Nano – draft Attached)

“Native-oxide limited cross-plane thermal transport in suspended silicon membranes revealed by scanning thermal microscopy”, Appl. Phys. Lett. 111, 6 (2017) 063106

“Electronic contribution in heat transfer at metal-semiconductor and metal silicide-semiconductor interfaces”, Sci. Rep. 8 (2018) 11352

“Influence of amorphous layers on the thermal conductivity of phononic crystals”, Phys. Rev. B 97, 11 (2018) 115435

“Thermal conductivity of deca-nanometric patterned Si membranes by multiscale simulations” , Int. J. Heat Mass Transf. 126, Part B (2018) 830-835

Sub-objectives that were not achieved PEC.

i) demonstration of a mechanically flexible PEC converter

ii) use of SiGe in place of Si.

The Micro-Thermionic Converters (MTC), are using electronic thermo-emission across a vacuum gap enabled by a low workfunction coatings. In this work, the concept of thermionic converter is revisited based on low workfunction coatings and benefiting from mainstream fabrication technologies of MEMS to fabricate electrode pairs with controlled micrometer gaps. This approach features higher risk-higher gain as compared to the PEC approach. Here is a summary, a list of the main achievements and associated publications related to the MTC sub-part of the project.

Summary MTC.

A first workpackage regarding material engineering was lead. The development of alkali oxide coatings (Cs and K) is studied by evaporation of dispensers in oxidizing atmosphere onto silicon wafers. The thermo-emitted current and surface work function is studied in-situ by Kelvin probe technique, photoemission and thermo-emission current measurements. These first work were quite successful, showing the superior ability of Cs oxide coatings to decrease silicon's surface work function by 3 eV. The methodology of measurement itself being quite original.

In a second step, regarding device integration, the work of T; Zhu has shown an original way to suspend the top layer of a silicon-on-insulator wafer while preserving supporting pillars. The cross section of these pillars being well controlled and small in order to reduce the heat losses as much as possible.

Despite a fully fabricated device, at the end of the project, it was impossible to measure its operation in the ultra-high vacuum equipment due to delicate electrical insulation and defects in the sample. Though nothing fundamentally contradicts the validity of the approach, it seems that an additional technical gap remains to reach a demonstration.

Finally, we evaluated the feasibility of using atomic layer deposition in collaboration with Univ. Helsinki in the frame of a subcontracting contract. The challenge here is to deposit the right oxide phase on silicon samples and transferring these in appropriate conditions for the rest of the fabrication process. Though samples were duly fabricated and tested, showing reduced work function, it remains a challenge to prepare the surface with the right composition and preserve them from further oxidation.

List of main achievements MTC.

“Low work function thin film growth for high efficiency thermionic energy converter: coupled Kelvin probe and photoemission study of potassium oxide”

Phys. Status Solidi A-Appl. Mat. Sci. 211, 6 (2014) 1334-1337

“Synthesis and characterization of low work function alkali oxide thin films for unconventional thermionic energy converters” J. Appl. Phys. 120, 20 (2016) 205108

Sub-objectives that were not achieved PEC.

i) Integration of the MTC was done but no operation demonstrated.

- novel and/or unconventional methodologies

PEC: The application of Phononic Engineering to silicon and its integration into actual energy converters was unreported yet. From the methodology standpoint we choose to use electron beam lithography coupled to plasma etching as a versatile tool to realize the patterning of silicon. The original part of the process is the use of the "Dots-on-the-fly" methodology which allows the writing of dense arrays of dot patterns in a non-conventional mode of the e-beam setup. In this mode, tuning the charge dose enable for a precise control of the holes radius. This is a useful result (published in Microelectronic Engineering) since the ratio holes/membrane is a key parameter to control the thermal conductivity.

MTC: The methodology of in-situ characterization with photoemission, thermoemission and Kelvin probe measurement in a consistent way proved original and useful.

- inter and cross disciplinary developments

PEC: In the frame of the membrane thermal characterization it appeared quickly that dedicated metrology methods should be developed. Indeed, unlike bulk thermoelectric materials that can be handled easily, the Phononic membranes are relatively delicate to manipulate and the thermal and electrical contacts required for characterization would be difficult to build after fabrication. On the contrary it appeared natural to fabricate electro-thermal measurement devices around the membranes on the same wafer benefiting from the conventional micro-fabrication techniques for silicon-on-insulator devices. This choice in itself is not absolutely new. The real breakthrough relies in the cross check we have been able to perform with two other techniques: Raman thermometry and Scanning Thermal microscopy. Indeed, measuring thermal conductivity at nanoscale remains a difficult task with errors frequently in the 10% range. One main reason for this lies in the difficulty to reduce couplings between the sample and its surroundings to negligible quantities. For these reasons we got in contact with Centre de Thermique et d'Energétique de Lyon (CETHIL-INSA Lyon), represented by J.-M. Bluet and P.-O. Chapuis. From this collaboration have emerged several long term ideas. Testing these ideas on actual devices that could benefit from the cross disciplinary efforts between micro-fabrication processes and nanoscale thermal characterization.

- knowledge and technology transfer

An ERC Proof-of-Concept application (called ANISO) was filed in 2018 to evaluate the transfer potential of an outcome of our research on heat transfer in ultra-thin silicon membranes. To summarize this result (not published since a patent application is foreseen), a way to modulated heat spreading in the top layer of SOI technology is found that could help in the thermal management of heat sensitive parts of integrated circuits. Though unsuccessful, the evaluation report was encouraging and the PI is strongly willing to resubmit this application in 2020.

A French TTO was contacted to obtain guidance. The status of the analysis, is that a proof-of-concept work is relevant to quantify to potential of this transfer.

- enhancing the immediate research environment

The necessary equipment and research environment available at IEMN/Yncréa Hauts-de-France were already quite suitable for the project. Especially, the micro-nanofabrication facilities are well equipped, which explains why no equipment cost were induced. However, the ERC UPTEG enabled our group to run and upgrade two experimental setups:

- The Ultra-High Vacuum setup for low-work function alkali oxide deposition and characterization.
- The Raman thermometry bench

Additionally, the grant enabled us to communicate our results in major conferences in the field which was beneficial for the group as a whole and specially for the PhD students to be introduced in the research community.

- establishment and/or consolidation of the research group and team composition

The project started on October 1st, 2013. At the beginning of the project, the PI was already employed by the Host Institution. Here is a list of personnel involved in the project and main contributions.

- * Emmanuel Dubois (involved at 23% in average) Senior staff is a recognized specialist of silicon micro-nanoelectronics.
- * Yves Deblock (research Engineer) and François Vaurette (research Engineer) (involved at 15% each in average) are research engineers actively involved in the lithography and etching processes extensively used in the project. Their expertise is also useful to bring PhD students the necessary trainings on fabrication equipments.
- * Valentina Giorgis (Post-Doc) was hired to work more specifically on the synthesis of low work function coatings.
- * Pascale Diener (Post-Doc) studied the mechanical properties of the membranes and the feasibility of transferring membranes onto flexible substrates.
- * Di Zhou (Post-Doc) worked on the technology processes for encapsulation and suspension of membranes by means of laser ablation.
- * Fikre Gebreyohannes (Engineer) worked on electrical engineering and characterization of the prototypes.
- * Thierno-Moussa Bah (Engineer) finished his PhD and contributed significantly to the project.
- * Maciej Haras (PhD, Polish, Electrical engineering)
- * Valeria Lacatena (PhD Italian, Micro and Nano Fab)
- * Francois Morini (PhD, French, Materials synthesis)
- * Stanislav Didenko (PhD, Russian, Physicist) worked on heat transfer and thermal characterization of suspended silicon membranes
- * Tianqi Zhu (PhD, Chinese, Electronics Engineer) worked on the MTC integration.

- others

The project involved further the PI in the scientific community of nanoscale heat transfer. The technological approach of the project enable the fabrication of samples dedicated for thermal characterization. The support from ERC and the demonstration at several conferences (eMRS, Eurotherm, Int. Conf. on Thermoelectric, ISPSA) has attracted attention from this community.

- * The project lead to 6 PhD defenses. (F. Morini, M. Haras, V. Lacatena, S. Didenko, T. M. Bah and T. Zhu (planned Nov. 2019))
- * In that frame a strong collaboration started with CETHIL-INSA de Lyon. One of the team members, V. Lacatena was sent to this Institute to perform experiments. As a follow-up of this cooperation, our group has joined a consortium of a French ANR grant called TIPTOP on the development of specific thermal characterization tools and methods.
- * Several invited talks were given (CECAM Workshop Mainz 2015, CMOSETR Grenoble 2014, IPSSA Jeju South Korea 2014, ISPSA 2018...)

- * The PI was invited to join a Scientific Committee for Symposium U - eMRS Fall 2015.
- * The PI has had a chance to get additional support from the French high performance computing (HPC) facility GENCI.
- * 5 trainees have currently working on the project. One of them being a student from the host institution.

Publishable brief summary of the achievement of the project

This section, which should not exceed 1 page (approx. 600 words), might be used for dissemination of the project progress/results to the general public/scientific community. For this reason, please do not reproduce here the project abstract, which is already available in CORDIS.

Stand alone description of the project and its outcomes

Thermoelectric energy harvesting offers strong advantages to supply low power electronics such as sensing, wireless, mobile and communicating devices that are increasingly changing our environment. Thermal energy sources are indeed abundant and widespread in our homes, factories and even our own body can be seen as a heat source. This matches very well the power needs of Ambient Intelligence, Internet of Things and Body Area Networks. Unfortunately, state-of-the-art thermoelectric converters still rely on rare and potentially harmful elements and feature low compatibility with low-cost mainstream production lines. The "Unconventional Principles of ThermoElectric Generation" project (UPTEG), explored two radically new approaches to overcome these limitations.

First, the project aimed at making an artificial thermoelectric material out of silicon, one of the most abundant element on earth which is also at the heart of today's information technologies. To that end, a new process was developed to fabricate fully suspended silicon thin films patterned at the nano scale following the concept of Phononic Engineering Converters. This concept uses a pattern of holes at the right length scale to hinder the heat flow while preserving electrical current conduction, resulting in augmented thermoelectric performance of the material. This approach led to several remarkable results. First, we simulated, estimated and designed thin-film planar converters architectures. We then developed a versatile process that enables the fabrication of a variety of devices fully compatible with silicon MEMS technologies. In addition, we quantified heat transport at nanoscale using three complementary methods, namely: Electro-thermal, Raman thermometry and Scanning Thermal Microscopy. Not only the results show the consistency of these methodologies for the first time, they also demonstrate that heat conduction has been divided by a factor 15. From the fundamental point of view, these artificial materials could solve the well known "phonon glass, electron crystal" dilemma faced in thermoelectricity. Finally, a demonstrator was fabricated and characterized that shows the efficient heat gradient management and power generation in the silicon thin-films. The output power, up to a few mW/cm² under 50 degrees' temperature difference constitutes a new state-of-the-art for crystalline silicon thermoelectric converters.

A secondary concept of energy harvesting, even more advanced, explored thermo-electronic emission of current between a pair of electrodes separated by a vacuum gap, the whole system being applied a temperature gradient. The concept of a thermionic converter offers potentially very high harvesting efficiencies but has always been technologically limited by the difficulty to manage enormous heat gradients and the so-called space charge effect that occurs when high current densities are involved. UPTEG brought important building blocks towards such converters by showing cesium oxide as a low work function material for silicon electrodes and proposing a micro-thermionic converter architecture.

In total 14 scientists, engineers and students were involved in the project with the decisive support of the ERC, CNRS/IEMN and Yncréa Hauts-de-France. The results of UPTEG led to the defense of 6 PhDs, the publication of 10 articles and 24 oral communications. Today more than ever, the outcomes of UPTEG supports the idea that an abundant, inexpensive and environmentally benign material like silicon could be at the heart of future thermoelectricity.

Overall assessment of the achievements and success of the project

The information provided in this section will only be available to ERC staff, to members of the ERC panels, and to the Scientific Council

To what extent have you achieved your objectives?

Generally speaking, the overall completion of scientific and technical objectives is very good. Though it is a quite rough estimation I would admit that 80% of the expectations are met. The main objective, which was to demonstrate the feasibility of thermoelectric power generation based on crystalline silicon has now a proof-of-concept. This is a remarkable result, still under evaluation but there is no doubt that the principle of phonon-engineering to reduce thermal conductivity while preserving sufficient electrical conductivity in silicon is validated. Another outcome of the project, is the establishment of planar architectures for this purpose with numerous publications on this topic. Finally, other results may be further valorised by technology transfer and publications. For that reason, I expect that 5 additional articles and maybe one patent will add to the existing outcomes of the project.

What are the most important conclusions of your research?

The main conclusion of the PEC part of the project is the feasibility, to harvest thermoelectric energy with crystalline silicon. This in itself is now an established result. The distinctive result here is the demonstration of an actual device using silicon membranes obtained from a commercial silicon-on-insulator wafer. The result in terms of power density is at state-of-the art for silicon.

The second important conclusion is the feasibility of inducing artificially an anisotropic heat guiding thanks to the concept of phononic engineering.

To what extent have you gone beyond the state of the art?

The notion of using phonon engineering in thin membranes to reduce thermal conductivity had been proposed recently and is still the object of active research. To our knowledge we are the first group show its actual use in the frame of thermoelectric energy conversion.

What is the impact of the project (within the scientific community and on society)?

It is yet difficult to evaluate the impact of the project on society. If any, it will be on a longer timescale. The project has a strong technological content and the “time-to-market” may be long in this case. However, during the project, at least one example of potentially transferable knowledge has been identified.

Regarding the impact on the scientific community, as say earlier, our group has had many collaborations with the community of heat transfer at micro-nanoscale for and thanks to the project. One striking fact about these collaborations is the difficulty to find samples with desired properties to test various transfer regimes. All of these regimes have potential interest for information and communication technology. As such, we do believe that many opportunities rely in those collaborations by crossing our know-how (micro-nanofabrication, silicon technologies) with the heat transfer research.

How effectively has the project helped you start or consolidate your research group? (for Starting Grants/Consolidators Grants only)

The PI is associated to the Silicon Microelectronics Group at IEMN. The group has been very active and its composition evolved rapidly at the beginning of the project since some members were already on-site. In total, during the project, 3 senior Staff, 6 PhD students, 4 Post-docs and 2 Engineers have been employed/contributed to the project. This is to me an out

standing result. with several positive consequences:

- The topic of non-conventional thermoelectricity emerged in our institute and is now established.
- Knowledge and know-how has been efficiently accumulated and transferred with the group.
- Today, our activity is recognized outside of the institute by invitations, citations and collaborations.
- The group is now extending its activities to other related topics, such as: thermal metrology at nano scale, thermal management in integrated circuits, Phase Change Memories.
- A network is starting to build up thanks to the alumni of the group, many of which are active either in academia or microelectronics industry.

However, while the project has been a real booster for the group, it has taken the form of non-permanent positions. To strengthen the group with permanent staff remains a challenge.

How well have you been supported by your Host Institution?

The Host Institution has fully respected the terms of the Supplementary Agreement. Especially, the PI was given full autonomy in terms of recruitment, management, valorisation of the results. The PI was also given full access to the technical resources.

Changes occurred in the legal status of the Host Institution which changed from “ISEN” to “Yncrea Hauts-de-France”. The transition period has induced some changes and delays in the communication of financial information and some difficulties for time reporting. However, these issues had minor impact on the project.

What difference did the ERC make?

The support from the ERC was absolutely decisive to the following aspects of the research:

- Obviously, the amount of the grant enabled an intensive and quick set-up of the research team. The main effect has been to obtain a critical number of experienced people working at the same time, in the same place and dedicated 100% to the project. I do believe that this was a key for knowledge transfer between team members and a source of great motivation for all.
- The support of the ERC is also seen as a label of quality and trust for the research we lead. It was a great opportunity for us to communicate and start collaborations.
- Finally, the autonomy that follows the award of the grant is actually a strong asset. The PI can use its time to fully focus on the project.

How many people completed a PhD in the framework of the project?	6
Comments:	This number is higher than what was planned in the DoW. Indeed, some PhD students had started their program earlier than UPTEG but achieved a very significant part (>70%) of their work within the project. This is the case of V. Lacatena, M. Haras and F. Morini. T.-M. Bah started his PhD in the frame of a collaboration with STMicroelectronics. He only worked a couple of month within UPTEG. However, his contribution to the project was major and synergetic.
How many people started a PhD in the framework of the project?	2
Comments:	T. Zhu and S. Didenko started and achieved their PhD during the project. The defence of S. Didenko occurred in June 2019 and the defence of T. Zhu is planned in Nov. 2019.

List of free Keywords

Thermoelectricity, Energy harvesting, Thermoelectric Converters, Micropower sources, Silicon, CMOS, MEMS, Semiconductor thin-films, Micro-fabrication technologies, Phononic Engineering, Nanoscale heat transfer, Heat guiding, Anisotropic heat transfer, Thermal management, Thermo-emission, Thermionic current, Vacuum encapsulation, Low workfunction materials, Alkali oxides

Annex: Project output records

A1. Publications

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES												
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Does the article acknowledge ERC funding?	Is open access provided to this publication ?	Type	URL
1	Phononic engineering of silicon using “dots on the fly” e-beam lithography and plasma etching 10.1016/j.mee.2014.04.034	V. Lacatena , M. Haras , J.-F. Robillard , S. Monfray , T. Skotnicki , E. Dubois	Microelectronic Engineering	Vol. 121	Elsevier	Netherlands	2014-06-01	131-134	No	Yes	Peer reviewed	http://linkinghub.elsevier.com/retrieve/pii/S0167931714001816
2	Low work function thin film growth for high efficiency thermionic energy converter: Coupled Kelvin probe and photoemission study of potassium oxide 10.1002/pssa.201300136	F. Morini , E. Dubois , J. F. Robillard , S. Monfray , T. Skotnicki	Physica Status Solidi (A) Applications and Materials	Vol. 211/Issue 6	Wiley-VCH Verlag	Germany	2014-06-01	1334-1337	No	No	Peer reviewed	http://doi.wiley.com/10.1002/pssa.201300136
3	Unconventional Thin-Film Thermoelectric Converters: Structure, Simulation, and Comparative Study 10.1007/s11664-014-2982-z	Maciej Haras , Valeria Lacatena , Stéphane Monfray , Jean-François Robillard , Thomas Skotnicki , Emmanuel Dubois	Journal of Electronic Materials	Vol. 43/Issue 6	Springer New York	United States	2014-06-01	2109-2114	No	Yes	Peer reviewed	http://link.springer.com/10.1007/s11664-014-2982-z
4	Toward quantitative modeling of silicon phononic thermocrystals 10.1063/1.4915619	V. Lacatena , M. Haras , J.-F. Robillard , S. Monfray , T. Skotnicki ,	Applied Physics Letters	Vol. 106/Issue 11	American Institute of Physics Inc.	United States	2015-03-16	114104	Yes	Yes	Peer reviewed	http://scitation.aip.org/content/aip/journal/apl/106/11/10.1063/1.4915619

		E. Dubois										
5	Thermoelectric energy conversion: How good can silicon be? 10.1016/j.matlet.2015.05.012	Maciej Haras , Valeria La catena , François Morini , Jean-François Robillard , Stéphane Monfray , Thomas Skotnicki , Emmanuel Dubois	Materials Letters	Vol. 157	Elsevier	Netherlands	2015-10-01	193-196	Yes	Yes	Peer reviewed	http://linkinghub.elsevier.com/retrieve/pii/S0167577X15007235
6	Fabrication of Thin-Film Silicon Membranes With Phononic Crystals for Thermal Conductivity Measurements 10.1109/LED.2016.2600590	Maciej Haras , Valeria La catena , Thierno Moussa Bah , Stanislav Didenko , Jean-Francois Robillard , Stephane Monfray , Thomas Skotnicki , Emmanuel Dubois	IEEE Electron Device Letters	Vol. 37/Issue 10	Institute of Electrical and Electronics Engineers Inc.	United States	2016-10-01	1358-1361	Yes	Yes	Peer reviewed	http://ieeexplore.ieee.org/document/7556325/
7	Synthesis and characterization of low work function alkali oxide thin films for unconventional thermionic energy converters 10.1063/1.4968532	V. Giorgis , F. Morini , T. Zhu , J.-F. Robillard , X. Wallart , J.-L. Codron , E. Dubois	Journal of Applied Physics	Vol. 120/Issue 20	American Institute of Physics Inc.	United States	2016-11-28	205108	Yes	Yes	Peer reviewed	http://scitation.aip.org/content/aip/journal/jap/120/20/10.1063/1.4968532
8	Native-oxide limited cross-plane thermal transport in suspended silicon membranes revealed by scanning thermal microscopy 10.1063/1.4997914	A. M. Masoud , J.-M. Bluet , V. La catena , M. Haras , J.-F. Robillard , P.-O. Chapuis	Applied Physics Letters	Vol. 111/Issue 6	American Institute of Physics Inc.	United States	2017-08-07	063106	Yes	Yes	Peer reviewed	http://aip.scitation.org/doi/10.1063/1.4997914
9	Influence of amorphous layers on the	Maxime	Physical Review B - Con	Vol.	American Physical		2018-03-01	115435	Yes	Yes	Peer	https://link.ap

	thermal conductivity of phononic crystals 10.1103/PhysRevB.97.115435	Verdier , David Lacroix , Stanislav Didenko , Jean-François Robillard , Evelyne Lampin , Thierno-Moussa Bah , Konstantinos Termentzidis	densed Matter and Materials Physics	97/Issue 11	Society						reviewed	s.org/doi/10.1103/PhysRevB.97.115435
10	Electronic contribution in heat transfer at metal-semiconductor and metal silicide-semiconductor interfaces 10.1038/s41598-018-29505-4	Georges Hamaoui , Nicolas Horny , Zilong Hua , Tianqi Zhu , Jean-François Robillard , Austin Fleming , Heng Ban , Mihai Chirtoc	Scientific Reports	Vol. 8/Issue 1	Nature Publishing Group	United Kingdom	2018-12-01	11352 1-9			Peer reviewed	http://www.nature.com/articles/s41598-018-29505-4
	Fabrication of integrated micrometer platform for thermoelectric measurements ht tp://dx.doi.org/10.1109/IEDM.2014.7047012	Maciej Haras , V. Lacatena , F. Morini , J-F. Robillard , S. Monfray , T. Skotnicki , E. Dubois	2014 IEEE International Electron Devices Meeting		IEEE		2014-12-01	8.5.1-8.5.4	Yes	Yes	Conference	http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7047012
	Thermoélectricité non-conventionnelle basée sur les technologies silicium en films minces	Maciej Haras			Université de Lille 1	Villeneuve d'Ascq, FRANCE	2016-01-07		Yes	Yes	Thesis	
	Thermoélectricité non-conventionnelle basée sur l'émission thermoélectronique	François Morini			Université de Lille 1	Villeneuve d'Ascq, FRANCE	2015-06-25		Yes	Yes	Thesis	
	Fabrication and thermal characterization of phononic engineered silicon membranes for thermoelectric applications	Valeria Lacatena			Université de Lille 1	Villeneuve d'Ascq, FRANCE	2016-06-01		Yes	Yes	Thesis	
	Artificially Induced Anisotropy of Thermal Conductivity in 2D Si	Stanislav Didenko			Université de Lille	Lille, France	2019-06-17		Yes	Yes	Thesis	

	Phononic Membranes											
	Development and Characterization of a Thermoelectric Harvester demonstrator using Phonon Engineered membranes	Thierno Moussa Bah			Université de Lille	Lille, France	2019-07-20		Yes	Yes	Thesis	

A2. Research expeditions

List of expeditions		
Period (start-end)	Place	Purpose

A3. Awards and recognitions

List of awards and recognitions					
Award type	Title of the award	Person to whom the award was made	Year	Short description of the reason the award was made (if applicable)	Any further information / clarification
Research Prize / Research Medal	2nd prize for the best thesis awarded by the Research Council of Lille Catholic University	Maciej	2014	This prize awards research work from PhD students for their excellence and impact on society. M. Haras won the 2nd prize among 15 candidates and had a chance to present his results before the research community of the Catholic University of Lille.	2014 - M. Haras - 2nd prize for the best thesis awarded by the Research Council of Lille Catholic University, Edition 2014.
Research Prize / Research Medal	Young Scientist Award of the eMRS Spring Conference : Symposium D	Valeria Lacatena	2014	"Young Scientist Award" of the Conference e-MRS 2014, Symposium D: Phonons and Fluctuations in low dimensional structures award to Valeria for her invited talk presented.	
Research Prize / Research Medal	3rd prize for the best thesis awarded by the Research Council of Lille Catholic University	Valeria Lacatena	2015	This prize awards research work from PhD students for their excellence and impact on society. M. Haras won the 3rd prize among 14 candidates and had a chance to present her results before the research community of the Catholic University of	2015 - V. Lacatena - 3rd prize for the best thesis awarded by the Research Council of Lille Catholic University, Edition 2015.

				Lille.	
Research Prize / Research Medal	Best Student Oral Presentation Award of the eMRS Spring Conference : Symposium M	Thierno Moussa Bah	2017	Best Oral presentation by a PhD student in this Symposium.	Benefits of a nano-patterned thin silicon film based thermoelectric generator BAH T.M., DIDENKO S., ROBILLARD J.F., MONFRAY S., SKOTNICKI T., DUBOIS E. European Materials Research Society Fall Meeting, E-MRS Fall 2017, Symposium M - Material and device integration on silicon for advanced applications, Warsaw, Poland, september 18-21, 2017, paper M.4.5
Research Prize / Research Medal	2nd prize for the best thesis awarded by the Research Council of Lille Catholic University	Thierno Moussa Bah	2018	This prize awards research work from PhD students for their excellence and impact on society. M. Haras won the 3rd prize among 14 candidates and had a chance to present her results before the research community of the Catholic University of Lille.	2018 - T. M. Bah - 2nd prize for the best thesis awarded by the Research Council of Lille Catholic University, Edition 2018.

A4. Patents, licensing, intellectual property

List of patents, licensing, intellectual property					
Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)
Patents	No		FR3029355	Thermo-Electric Generator	DUBOIS EMMANUEL, ROBIL LARD JEAN-FRANCOIS, MONFRAY STEPHANE, SKOTNICKI THOMAS

A5. Dissemination to non-academic audience

List of disseminations								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Presentations	INSTITUT SU	Présentation du Projet	18/10/2013	Lille	Scientific community	50	France

		PERIEUR D'ELECTRONIQUE ET DU NUMERIQUE	UPTEG			(higher education, Research)		
2	Presentations	INSTITUT SU PERIEUR D'ELECTRONIQUE ET DU NUMERIQUE	Le projet ERC Starting Grant UPTEG, des idées à la réalisation en passant par le montage du projet	16/05/2014	Lille	Scientific community (higher education, Research) - Civil society	50	France
3	Presentations	INSTITUT SU PERIEUR D'ELECTRONIQUE ET DU NUMERIQUE	Réunion sur le Pilier Excellence scientifique dans H2020	08/12/2014	Lille	Scientific community (higher education, Research) - Civil society	100	France
4	Other forms of dissemination	INSTITUT SU PERIEUR D'ELECTRONIQUE ET DU NUMERIQUE	CNRS-Hebdo Une ERC Starting Grant décrochée par un chercheur de l'EMN	21/06/2013	Lille	Scientific community (higher education, Research)		France
5	Media briefings	INSTITUT SU PERIEUR D'ELECTRONIQUE ET DU NUMERIQUE	Interview on WEO Local TV	01/10/2013	Lille	Scientific community (higher education, Research) - Civil society		France
6	Presentations	YNCREA HAUTS DE FRANCE	Témoignage d'un Lauréat ERC Starting Grant	13/03/2018	Lille - Campus Cité Scientifique Villeneuve d'Ascq	Scientific community (higher education, Research) - Policy makers	60	FRANCE
7	Presentations	YNCREA HAUTS DE FRANCE	Microwatt silicon thin-films thermoelectric harvesters	23/05/2019	Blois, France	Scientific community (higher education, Research)	100	Europe
8	Other forms of dissemination	YNCREA HAUTS DE FRANCE	Interview de Jean-François Robillard - Video contest	03/04/2019	Isen, Lille	Civil society	80	France
9	Presentations	YNCREA HAUTS DE FRANCE	Fabrication and thermal characterization of silicon membranes for integrated thermoelectric converters	27/08/2018	Grenoble, France	Scientific community (higher education, Research)	200	Europe

A6. Other significant outputs / information

Information on other important outputs which have arisen - wholly or partly - from this project.

Though these tools are difficultly transferable outside of the IEMN labs. It is noticeable, that the support of the ERC was decisive to run and upgrade two experimental setups:

- The Ultra-High Vacuum setup for low-work function alkali oxide deposition and characterization.
- The Raman thermometry bench

* A patent application related to the concept of PEC was filed before UPTEG. It is not possible to add it to the "IP Assets" tab.

N° de priorité : FR20140061760 20141202

Générateur thermoélectrique

Inventeurs : DUBOIS Emmanuel, ROBILLARD Jean-François, MONFRAY Stéphane, SKOTNICKI Thomas

Demandeur(s) : STMicronics Crolles 2 SAS

N° de brevet : FR3029355 (A1) 2016-06-03

Également publié en tant que : CN205028926 (U) 2016-02-10

* Project website: <https://erc-upteg.iemn.fr/>

(Only for ERC projects selected from the 2012 and 2013 calls for proposals)

This grant agreement includes special clause 39, requiring you to make best efforts towards open access to publications resulting from this project. Should, despite your best efforts, not all publications be available in open access, please give reasons why this is the case.

* In all but one case, publications are or will be provided open access through distribution of the pre-print version on the ArXiv repository.

* Only one reference (Physica Status Solidi a) is not eligible to open access right now since the policy of the editor is not know regarding this issue.

Attachments	CONFIDENTIAL- Bah_et_al_Nature_Nanotech_Manuscript.pdf, UPTEG_Publication_List.pdf
Project No.:	338179
Project acronym:	UPTEG
Project title:	Unconventional Principles of ThermoElectric Generation
Project starting date:	01/10/2013
Project duration:	70
Principal Investigator name:	Dr. Jean-François Sebastien Denis ROBILLARD
Report submitted by:	YNCREA HAUTS DE FRANCE
Date:	27/09/2019