SiNERGY

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Editorial - Project and results achieved

Energy autonomy keeps being one of the most desired enabling functionalities in the context of off-grid applications, such as continuous monitoring scenarios and distributed intelligence paradigms (Internet of Things, Trillion Sensors). SiNERGY has focused on silicon and silicon friendly materials and technologies to explore energy harvesting and storage concepts for powering microsensors nodes. Harvesting energy, tapping into environmentally available sources such as heat and vibrations, may be a good solution in man-made scenarios applications. 10-100µW/cm2 power densities seem appropriate for many such applications. Coupling those harvester devices to secondary batteries to buffer enough energy to account for the power demand peaks required by wireless nodes would be an enabling energy autonomy solution. SiNERGY has selected relevant examples of power microgeneration and storage (thermoelectric generators, mechanical harvesters and microstructrured batteries) pushing them further into their performance and development maturity. Emphasis has been placed on thin films and nanostructured materials and their integration into mechanically and thermally optimized microstructures. For bringing the eventual solutions closer to an exploitable phase, silicon technology compatible materials have been considered. Silicon micro and nanotechnologies provide an enabling path to miniaturization, 3D architectures (improved energy densities), mass production with economy of scale, and the possibility of easy integration with other microchip based devices (sensors & actuators, power management circuits, communication units...)

Silicon friendly materials and device solutions for thermoelectric harvesting. Thermoelectric microharvesters able to convert heat flows into small, yet high added value, amounts of electric power have been pursued. The activity has focused in integrating silicon nanowires as low thermal conductivity material into devices with optimized thermal and electric design. Both, bottom-up and top-down approaches for nanoobjects integration have been explored.

Silicon friendly materials and device solutions for mechanical energy harvesting. Electrostatic and piezoelectric harvesters have been explored to convert small vibrations into a useful power. In the first case, an optimized silicon based electret material has been integrated in a robust laterally moving microstructure. In the second, the integration in vertically moving microcantilevers of a piezoelectric composite based on bottom-up ZnO nanoobjects has been attempted, and a hybrid fabrication approach combining silicon and printing technology has been shown promising.

Silicon friendly materials and device solutions for solid-state microbatteries. Material and interface optimization (from a fast charge/discharge perspective) has led to the fabrication of a functional thin-film planar microbattery for on-package energy storage. Translation of this knowledge into 3D microbatteries, fully compatible with Si technology, for increased capacity and power has been attempted. Failure to identify a good solid electrolyte has prevented full success.

Integration feasibility. Even though SiNERGY focuses in materials and technologies, attention has been paid to real applications As a consequence, system integration issues have been tackled at different levels for the above microenergy devices. A gas fryer scenario has been explored for the deployment of thermal harvesters, piezoelectric devices have shown appropriate for powering remote nodes at useful duty cycles (e.g. for preventive maintenance), and the electrostatic harvester has been shown functional in a Tire Pressure Monitoring application.

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Silicon Friendly Materials and Device Solutions for Microenergy Applications

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WEBSITE:

http://www.sinergy-project.eu/

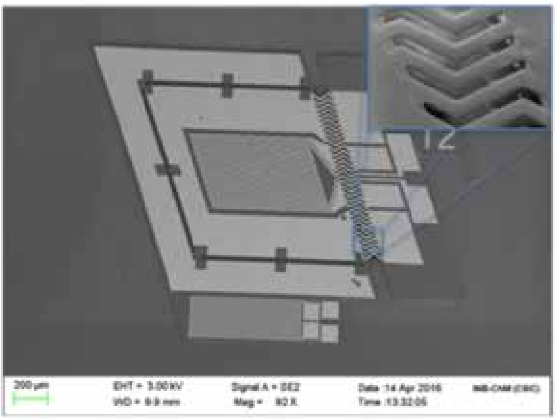
Final Achievements @ M36

WP2 Thermoelectric harvester

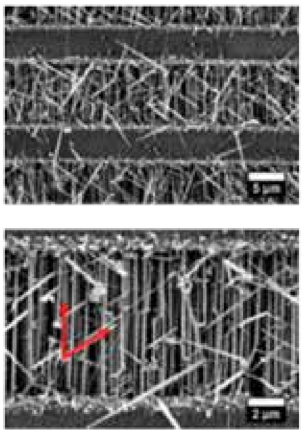
Two approaches have been pursued regarding Si NWs integration also for the second generation of thermoelectric harvesters, and both returned interesting results.

Si NWs bottom-up strategy

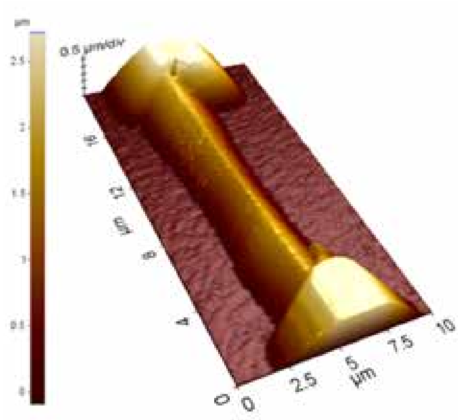
Two main issues have been tackled: improving the thermal performance of the suspended microplatform hosting the NWs, and decreasing the electrical resistance of the device. After reducing the thermal leaks through the platform supports, reducing Si-metal contact resistance, and redesigning less resistive metal tracks, 12 nW have been obtained for a 2 mm2 device, at a 300 °C hotplate temperature (20 times higher than at the onset of the project). For the first time, a ZT value have been estimated for such an arrangement of large number of nanowires, yielding 0.1 (ten times higher than bulk Si). A heat sink remains to be integrated in order to fully exploit these devices. Measurements under forced convection allow estimating attainable power densities of 3 μW/cm2 when such integration is achieved.



Use of (low thermal conductivity) thin membranes instead of bulk silicon bridges as supports



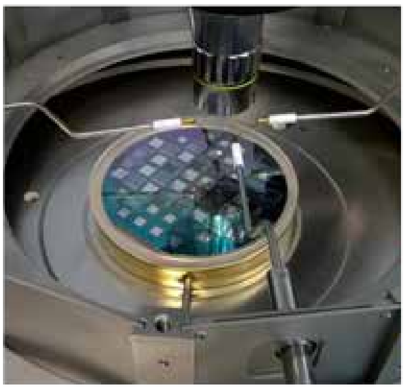
Successful integration of large number of Si NWs



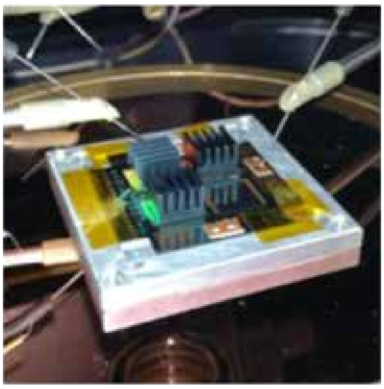
Novel SThM-AFM method for determining thermal properties of a single Si-NW

Si NWs top-down strategy

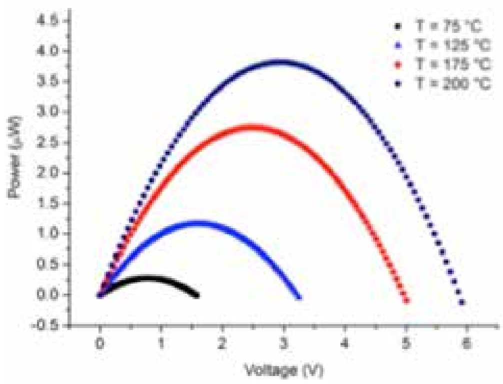
After process optimization and device redesign, second generation top-down devices were obtained with much increased process yields. Assessment of thermoelectric response was carried out on test benches simulating actual operative conditions. Comparison with first generation displays a tenfold improvement. Mini heat sinks were successfully integrated on top of the 1 cm2 devices. According to the open circuit voltage and the power densities obtained, μW applications can be served with arrangements of a few cm2 and standard power management circuits.



Wafer with top-down SiNWs microgenerators

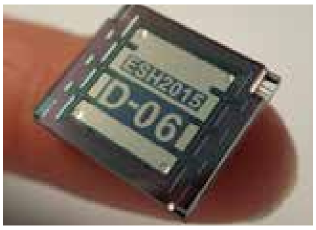


Micro-thermoharvesters with heat sink attached

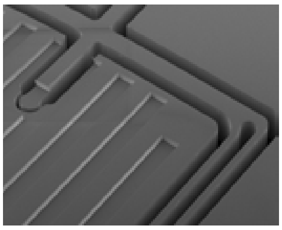


Power curves measured for a completed device

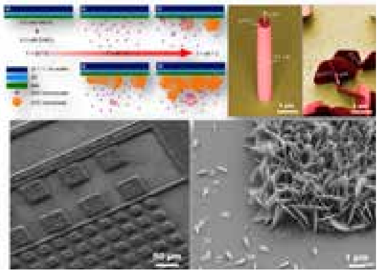
WP3 Electrostatic as well as piezoelectric energy harvesters are being developed in parallel, able to convert mechanical vibrations into usable electric energy via a silicon spring-suspended proof mass and a variable capacitor. A new design and fabrication route for the electrostatic harvesters, with integrated shock absorbers and hermetic vacuum waferbond, generated mechanically robust devices, more sensitive, 50x more efficient power conversion. A novel method to grow piezoelectric nanosheets at wafer-scale, low temperature and inexpensive have been developed. Recently, these nanomaterials have been patterned and integrated with MEMS devices and inkjet printing to obtain piezoelectric energy harvesters. This hybrid integration becomes an alternative to the already mature technologies based on AlN and PVDF used in this project to develop some prototypes which can generate several hundreds of μWs under certain ambient vibrations.



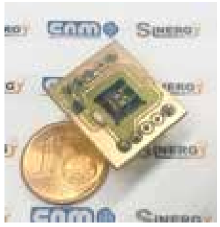
2nd generation device



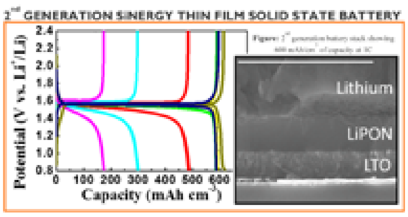
SEM picture of Si springs, patterned electret and shock absorbers



Graphical abstract of the selective area growth of high-quality ZnO nanosheets assisted by patternable AlN seed layer for wafer-level integration



AlN-based device

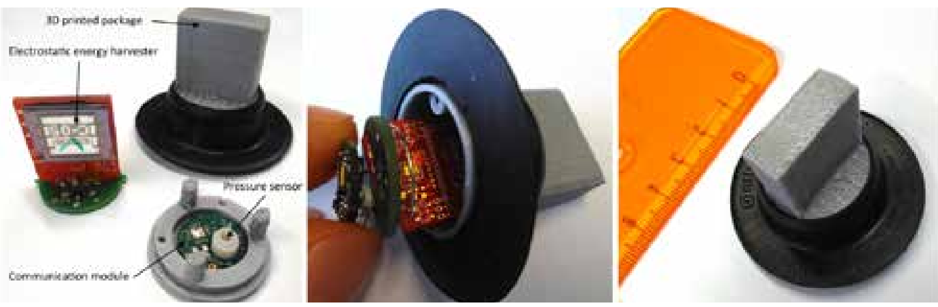


WP4 The SiNERGY 2nd generation thin film solid state micro-battery has been fabricated and characterized. The most stable battery stack consists of a $Li_4Ti_5O_{12}$ cathode layer prepared by RF-sputtering (1.55 V vs Li+/Li) and post treatment annealed, an electrolyte layer of LiPON prepared by RF-sputtering at optimum N_2 gas flow and an anode layer consisting of a lithium metal thin film prepared by thermal evaporation. Cyclic voltammetry and charge-discharge measurements show that the device can obtain ~600mAh/cm^3 at 1 C rate with high Coulombic efficiency of the stack showing high performance on kinetics. At 10 C rate the battery stack still achieves 50% maximum capacity. Additionally, the possibilities of an alternative cathode, $LiMn_2O_4$ (LMO), deposited by PLD have been proven in a thin film battery configuration (1.8 V) using an aqueous electrolyte and Zn as anode. It shows excellent stability (> 300 cycles) and a very fast recharge keeping 70% of nominal capacity at 30 C. Finally, a first hybrid 3D battery (4.2 V) has been achieved based on LMO obtained after post-lithiation of a conformal deposition of EMD MnO_2 in a silicon substrate with high aspect ratio pillars. A solid composite electrolyte and a Li anode completed the battery, which shows a capacity improvement due to the 3D geometrical multiplication factor.

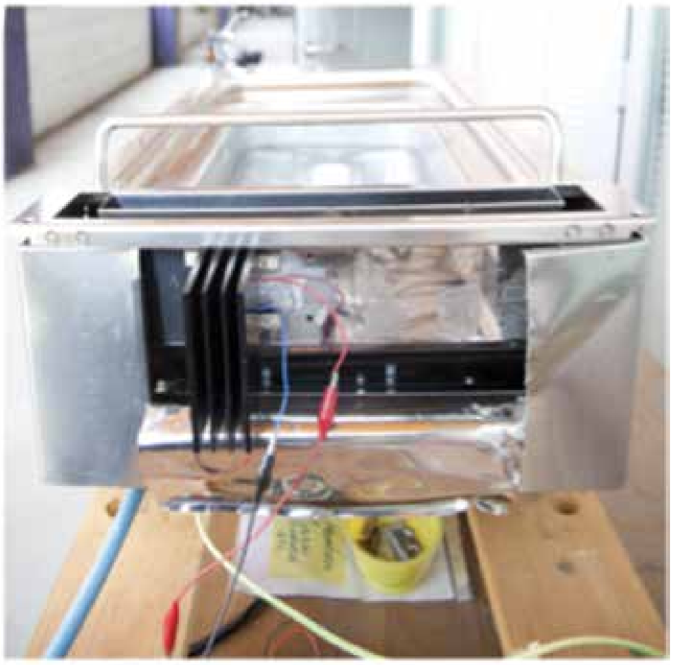
Figure: 2nd generation battery

WP5
Fully autonomous tire pressure monitoring system (TPMS):

The electrostatic vibration energy harvester developed by Imec-NL was combined with the ultra-low power TPMS module of STE, as shown in the pictures. The module did not contain a battery and only the power generated by the harvester was used. The system was tested in the lab and was fully operational at very low vibration levels. At those low vibration level (~10-4 g2/Hz) the pressure was measured and sent every 10 seconds. The power needed was only ~4μW!! This results was possible due to development of STE's ultra low power TPMS module and the improvements on the energy harvester. The energy harvester improvements (part of WP3) resulted in higher power generation at lower excitations and much better reliability.



Components of the TPMS patch



Fully autonomous oil temperature sensor

A second scenario considered was a gas fryer where oil temperature would need periodic control. A thorough study of the different hot surfaces where to place a thermoelectric harvester was done and the fryer chimney was selected as it also allowed access to a cold side. The suitability of the scenario was proven by using a commercial 9 cm2 BiTe thermogenerator, a J-type thermocouple sensor and STE communication module. A T communication every few seconds after a few minutes of setting the fire on ensued. Results with top-down devices reported above show that 8 SiNERGY devices (8 x 1 cm2) can replace the commercial device with similar results and the advantage of being able to operate at higher temperatures (tests were done with boiling water instead of oil to avoid early degradation of the BiTe device.)

Test set-up in an Electrolux gas fryer. A large heat sink is needed to keep a workable delta T in such a hot environment

Consortium

Consejo Superior de Investigaciones Científicas (CSIC) is an autonomous multisectorial, multi-disciplinary public research body affiliated to the Spanish Ministry of Science and Technology. CSIC is composed of around 110 research institutes in all research areas, and is the major Public Research Body in Spain, and the third inEurope.

Confindustria Emilia-Romagna Ricerca (CERR), is the company of Confindustria Emilia-Romagna specifically created to support the associated enterprises network in the area of research, innovation, technology development and technology transfer. It assists enterprises in their innovation, plays a key role in the governance of the regional High-Technology-Network

Electrolux Italia S.p.A., with 5.000 employees, is a historic European leader in household appliances for Research, Design and Manufacturing. The Company is controlled by the Swedish Electrolux AB which is a global leader in household appliances and similar equipment for professional use, selling more than 40 million of products in 150 countries

Catalonia Institute for Energy Research (IREC) is a research institution under the trust of different governmental and private organizations. IREC is organized in two Applied Research Areas: Advanced Materials and Bioenergy and Biofuels and three Technological Areas: Electrical Engineering, Energy Efficiency and Offshore Wind Energy.

IMEC is a world leading R&D lab for nano-electronics. Imec scientists and engineers research and develop exploratory and emerging technology in ICT, healthcare and energy for a better, healthier life in a sustainable environment through innovations in nano electronics. Imec has its headquarters in Leuven, Belgium, where the main labs and state-of-the-art Clean Rooms are located.

Stichting IMEC Nederland (IMEC-NL) is the Dutch research branch of the independent nano electronics research center imec, is together with TNO, one of the two pillars of the Holst Centre. Its research focuses on next generation wireless autonomous transducer solutions.

STE Engineering was established earlier in the 1965: founder Guido Moiraghi is recognised has one of the pioneer of radiofrequency in Italy were, among the few, introduced radio communication products for voice and data transmission for civil and military applications (aircraft, ground and naval)

The **University of Milano-Bicocca** was established in 1998 to serve Northern Italy. The University is a gateway to professionalism and educates scientists and technicians from Italian industries, as Milan is historically open to competition, innovation, and internationalism.

Consiglio Nazionalle delle Ricerche – CNR. IMM (Institute of Microeletronics and Microsystems) includes 5 Departments, located in Bologna, Rome, Naples, Lecce and Catania. IMM belongs to the National Research Council of Italy (CNR), which is a nonprofit, partially government-funded research organization, and the organisation with legal entity to act as partner in EU Framework Programmes .