Energy Management, Conversion and Harvesting

Acoustic transformers

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Our group recently designed **cMUT-based acoustic transformers** (figure 1) with high level of **galvanic isolation** between the primary and secondary circuits. These devices aim to transmit a trigger signal from the primary circuit to the secondary circuit by using an **ultrasonic wave**. The device is made of two arrays of CMUTs respectively layered on the upper and lower faces of a Si substrate. One of the two arrays is the primary circuit and the second one is the secondary circuit. When a CW is applied to the electrical port of the primary circuit, an ultrasonic wave is generated in the substrate and then received by the second CMUT array which at end is converted into an electrical signal.
On the contrary to cMUT designed for medical imaging, here the key feature of these devices is to **maximize the coupling between cMUT and substrate**. For this, we have observed that if the resonance frequency in air of cMUT is closed to the substrate resonance (thickness mode) one can expect a high level of **electromechanical coupling**. Practically, thanks to the softening effect, cMUT are designed so that their mechanical resonances are the closest possible to the thickness resonances of the substrate (figure 2), when the applied bias voltage is close to the collapse voltage (to ensure a high electromechanical coupling coefficient). With such operating conditions, first fabricated prototypes allowed reaching a power efficiency of 36 %, with a working frequency of 12 MHz.

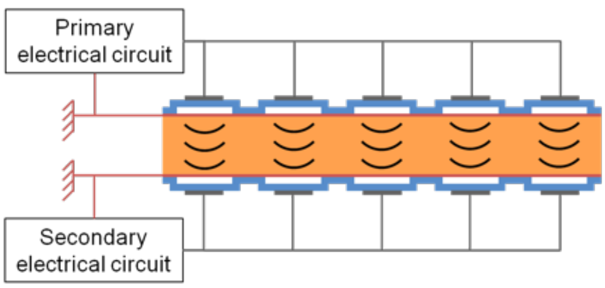

FIG 1 : Schematic representation of cMUT-based galvanic isolator.

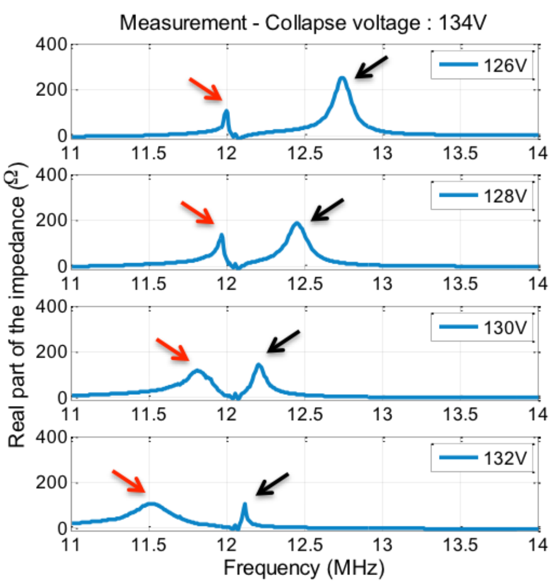

FIG 2 : Electrical impedance of the primary circuit for four bias voltages (just before the collapse event). The black arrow points out the resonance peak of the cMUT membrane. The peak shifts toward lower frequencies when the bias voltage is increased. At 130 V, the substrate resonance and cMUT resonance cross each other, i.e. this is the situation where the best mechanical coupling is reached.

Mechanical energy harvesting

Piezoelectric materials convert a physical pressure into the motion of electrons, and thus are able to harvest the unused mechanical energy of our surroundings into **electrical energy**. Various technologies of piezoelectric harvesters have been tested for energy harvesting since the early 2000s: bulk PZT (Lead Zirconate Titanate), PZT fiber composites, PZT thick or thin films, PVDF films, and more recently piezoelectric nanowires (NWs) (GaN, PZT, BatiO3, PVDF, CdS...). The densities of harvested power, comprised between 1 and 10 mW/cm^3, vary considerably according to the geometry of the device (cantilever, membrane, spiral, hybrid device...), its linear or nonlinear behavior and the piezoelectric material.

Piezoelectric thick films

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Of the various technologies and scales of piezoelectric materials, **thick films**, with thicknesses of several tens of micrometers, offer a good trade-off in order to fulfill the increasing demand of miniaturised electromechanical devices. Different deposition and patterning processes exist for thick films, such as tape **casting**, **screen-printing** or **electrophoresis deposition**.
At these thickness values, the electromechanical performance of these films tend to be lower than the bulk material of same composition. Therefore, intensive international scientific research aims to manufacture thick films with same performance as bulk materials. Recent works (part of which emerges from collaborations with GREMAN) at academic or industrial level, showed that today there are some technological solutions with real perspectives of up-scaling (piezoelectric coupling coefficients of 40%), for medical or industrial applications.
The exploitation of these technologies, for **energy harvesting devices integration**, is thus appearing as a real industrial opportunity. Since 2014, a common laboratory between GREMAN and VERMON company, named **Lab-TMEMS** and supported by ANR LabCOM funding, is exploring the potential of **piezoelectric thick films** for **mechanical energy harvesting**. Two different technologies are under investigation : **PZT thick films** (figure 3) obtained by thinning bulk material (PhD thesis of Thien HOANG started in Nov. 2015, under a CIFRE-French Ministry of Research Training in Industry Convention with VERMON), and **lead-free KNN thick films** deposited by electrophoresis technique (PhD thesis of Hugo MERCIER started in Sept. 2015, under joint supervision with Josef Stefan Institute, Slovenia).

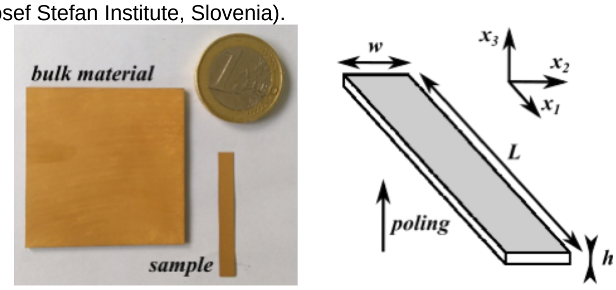

FIG 3: Photograph and schematic representation of the 3mm x 39mm x 150m thinned PZT under investigation for mechanical energy harvesting

ZnO Nanowires (NWs)

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A possible route to cheaper the **piezoelectric energy harvesting devices** is using low cost manufacturing : **hydrothermal synthesis** appears as an interesting candidate, compared to MEMS technologies, that are often proposed in academic research. In 2007, a new type of microgenerators based on piezoelectric semiconducting NWs has shown promising performance for electromechanical conversion. Since then, there is a tremendous interest for using these one-dimensional (1D) **piezoelectric nanostructures** for mechanical energy harvesting.

Indeed, in some aspects, they possess superior properties compared to their bulk counterpart: high surface to volume ratio, high piezoelectric coefficients, higher sensitivity to low frequency motion, high mechanical strength, flexibility, mechanical robustness, piezoelectric and semiconducting properties. Such aspects are still far from being completely explored: coupled physical properties, scale effects (surface or volume phenomena), etc. Among several materials, **ZnO NWs** is one of the most promising candidates. It has high values of **piezoelectric coefficients**, it can be grown at low temperature on almost any substrates, the carrier density can be tuned by moderate temperature annealing, Schottky and Ohmic contacts are studied for many years, and finally, it is environmentally friendly (lead-free). Today, the output power density generated by the best prototypes in the literature reaches about 5 µW/cm2 [L. Lin et al., Nano Energy 2 (2013) 75-81]. The peak values of generated voltage can reach about 30 V and typical currents are in the range of µA.
GREMAN has a well-known expertise in all the aspects of piezoelectricity, and more specifically on **piezoelectric nanowires** for more than 7 years. It has started by modeling aspects and it is reaching now the level of **ZnO-based piezoelectric generators**. The whole device is designed and fabricated in GREMAN: growth of the ZnO nanowires, device fabrication and characterization. GREMAN's technology is now mature enough on silicon substrates to be optimised for specific applications, specific loads and specific flexible substrates. Today the heart of the project is to develop a prototype that integrates, on the same flexible chip, a **microgenerator** that converts this ambient mechanical energy into electrical energy that can recharge a **lithium battery**, through a specific electrical converter (figure 4). Since the efficiency of such a mechanical harvesting device strongly depends on the matching between: a piezoelectric microgenerator, the power management block, the electrical load block (a Li battery), we propose in this project to have an integrative approach: studying and designing the whole energy conversion chain. The **piezoelectric microgenerator** is a **ZnO** -polymer composite device that will be optimized in order to fulfill the requirements of the other sub-systems, power management block and Li battery. The prototype will be tested using a dedicated test bench developed at GREMAN in operating conditions close to the targeted mechanical sources - fluid flows (like wind or river), parasitic vibration (in engines or rotating machines, for example) or human movements (voluntary motion like walking or hand movements).

Consult project website

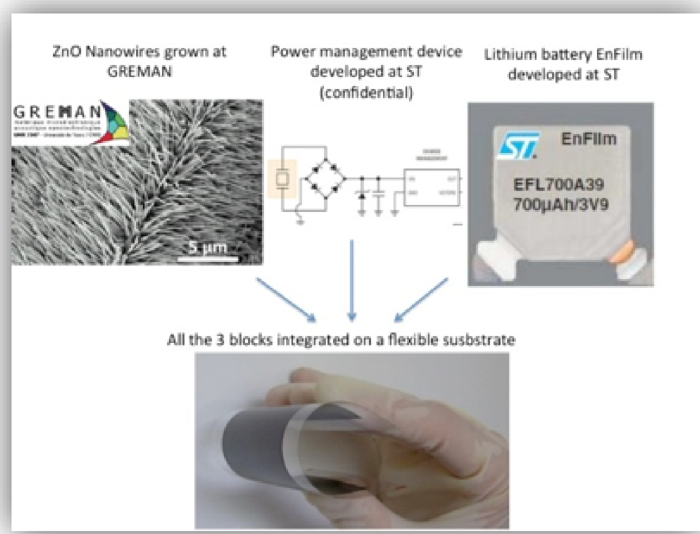

FIG 4: ZnO nanowire based microgenerator harvesting ambient mechanical energy in order to recharge a lithium battery through a specific electrical converter