Innovative Nano-materials and Architectures forIntegrated Piezoelectric Energy Harvesting Applications

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Abstract In an era of shrinking conventional energy resources, the development of low-power-consumption portable devices, sensors and body-implantable devices, the concept of generating power by harvesting energy from the ambient environment and biomechanical movements are attracting huge interest. The most efficient way to harvest electrical energy is to utilize the piezoelectricity of ferroelectrics. In the paper, a practical example of self-assembled ferroelectric at nano-scale, deposited on a substrate, is presented, being the base for the development of a high-performance energy-harvesting device. The device concept, the signal processing unit and the potential applications are finally presented.

Keywords: piezoelectricity of ferroelectrics, self-assembled integrated piezoelectric device, selective wave-to-energy conversion, intelligent energy harvesting concept

1. Introduction

Ferroelectric are widely used in many applications that require a size down to the nanometer range. At the nanometre scale, however, the properties of the materials differ from those in the bulk. In the past 10 years, the interest in the preparation of defined-shape ferroelectric particles has increased tremendously, firstly due to their unique shape- and size-dependent properties, and secondly because they represent a challenge to fabricate nanostructures by their self-assembly. The anisotropic properties of the crystallites represent an advantage when self-assembly is performed with the help of an electric and/or magnetic field. Taking into account that the piezoelectric constant, which is a key parameter for electro-mechanical conversion, decrease with particle size, the piezoelectric generators with larger particles are expected to produce a larger output of harvested energy. The design and fabrication of an energy-harvesting device from the defined-shape ferroelectric particles is also an innovation, which is important from the scientific and technical points of view. The former importance refers to an understanding of the correlations between the nano-material composition, shape, size and piezoelectric performance. From the perspective of technical innovation, the new nanostructured ferroelectric is expected to realize a variety of energy-harvesting options from the surrounding environment, with a selective wave-to-energy conversion for versatile applications. The robust design and fabrication of the energy-harvesting device and their integration into a successful energy-management concept is of the highest importance for industry, and represents an applicative original aspect. Despite some solutions for piezo-ceramic harvesters which are suggested in the literature, there is no specification for an integrated, versatile solution for broad technical use, and/or of advances towards an intelligent harvester concept related to both Li batteries and ultra-capacitors, which is the real need in all energy applications.

2. Ferroelectric materials at nano-scale

The research was focused on ferromagnetic thin films, deposited on nonmagnetic substrates, due to the opportunity of obtaining new architectures of Ferro-magnets of restricted dimensionality and the related technological potential of achieving multilayer structures with predefined oscillatory magnetic coupling. Nano-structured systems started from ferroelectric particles with defined-shape were made in laboratory based on the effect of Au-induced perpendicular magnetization in Fe films, grown on Si. The perpendicular magnetization was achieved by pondering the anisotropy of architecture, i.e.: the surface anisotropy, which determines perpendicular orientation of magnetization, and respectively the shape anisotropy, which tends to rotate the magnetization into the film plane (Kuncser *et al*., 2010; Jepu *et al*., 2014; Polosan *et al*., 2015). The thin-film properties significantly depended on deposition conditions, in particular, the growth temperature.

The obtained thin Au-Fe film has been investigated by electron microscopy using JEM-ARM200F Analytical Electron Microscope. Conventional transmission electron microscopy (CTEM) and selected area electron diffraction (SAED) shown a polycrystalline 80 nm thin-film with a smooth surface, on a silicon substrate and a thin layer of silicon oxide in between, Figures 1 and 2.

Defined crystallographic planes of Au have been identified in detailed CTEM pattern at higher magnification, Figure 3.

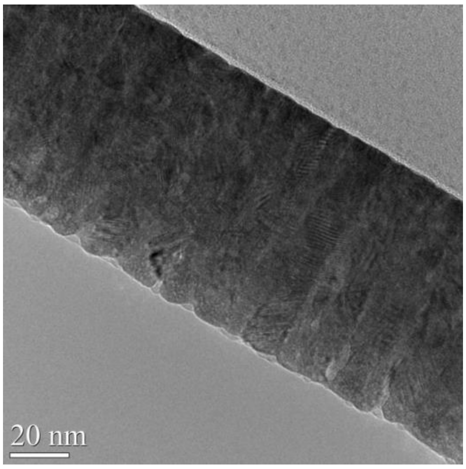

Figure 1. CTEM image of thin Au-Fe film

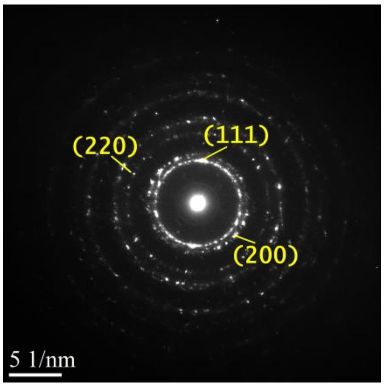

Figure 2. SAED pattern of thin Au-Fe film

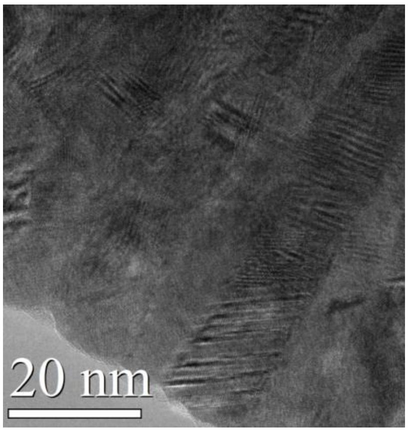

Figure 3. CTEM image of thin Au-Fe film at high magnification

The purely Z-contrast STEM (Scanning Transmission Electron Microscopy) imaging shown the same thin-film characteristics. Darker areas on the image bellow, Figures 4, can be associated to Fe-rich areas (lower Z number). Additionally, the associated EDS spectra obtained from the experimental film, Figure 5, shown the existence of atomic components: Au (deposited film), Fe (deposited clusters), Si (substrate material), C (organic contamination), Cu (material from grid).

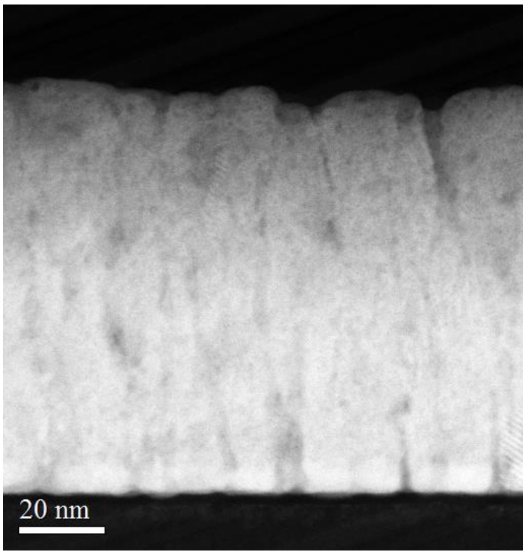

Figure 4. STEM image of thin Au-Fe film

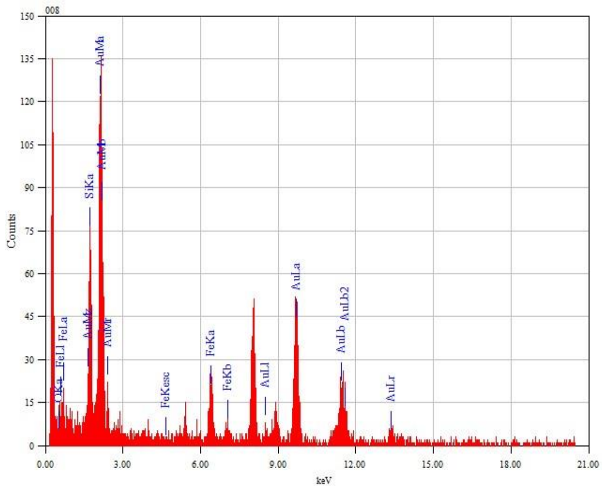

Figure 5. EDS spectra of thin Au-Fe film

3. Concept and development of integrated nano-piezo-devices

The concept of integrated nano-piezo-device for energy harvesting is presented in Figure 6. Extended tests for the determination of the dielectric properties of thin films in different frequency ranges (from radiofrequency to microwave domain) were performed, for various compositions on different substrates. For some particular compositions, the tunability was also checked. Finally, the polarization electric field (P-E) hysteresis and $\mathbf{d_{33}}$ piezoelectric coefficient were measured. Prior to measuring the piezoelectricity, the samples were pre-poled in an electric field of defined intensity. Some results are summarized in Figure 7.

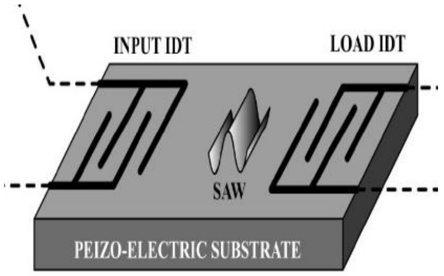

Figure 6. The concept of integrated nano-piezo-device for energy harvesting

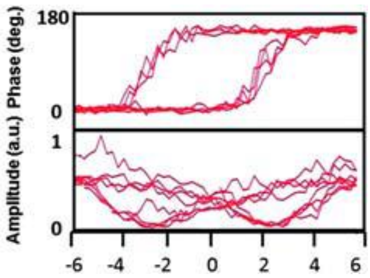

Figure 7. Polarization-electric field / hysteresis

The research was followed by the practical design of integrated nano-piezo-devices, based on preliminary electromagnetic properties, via Comsol Multiphysics software, an example being presented in Figure 8.

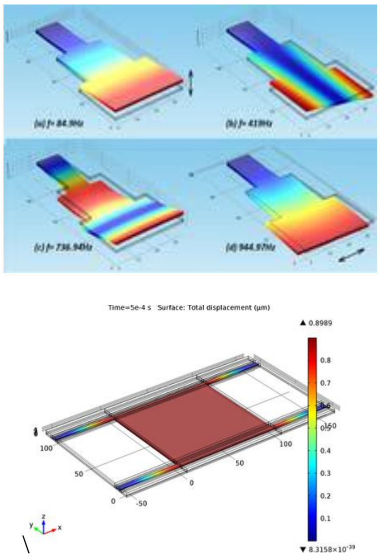

Figure 8. Design of integrated nano-piezo-devices

The design was followed by modelling and simulation of mechanical-thermal-process associated to electrical phenomena at different frequencies, under which the tailored structures are intended to be exploited.

The last stage was the manufacture of some prototypes of nano-piezo devices, e.g. in Figure 9, which were tested in environmental conditions, for the evaluation of their potential of wave-to energy conversion. Finally, the technology was optimized for future large scale fabrication, by use of different variants of nanostructured materials and selective wave-to energy conversion.

Figure 9. Prototype of integrated nano-piezo-device

A dedicated test stand was used to account for the best piezo-electric features of the developed devices and validate the prototype, Figure 10 (Dicken & Mitcheson, 2012). It consists of a vibration unit/shaker, an accelerometer, a signal generator, a power amplifier and an oscilloscope. The vibration signal is generated by the signal generator, amplified via the power amplifier and finally used to control the vibration amplitude and frequency of the shaker. The piezoelectric cantilever device undergoes excitations and generates an output voltage signal, which is recorded by the oscilloscope. The resonant frequency of the system is evaluated, in order to assure the maximum output power to be obtained under vibration process, which are further submitted as key parameters to the practical application.

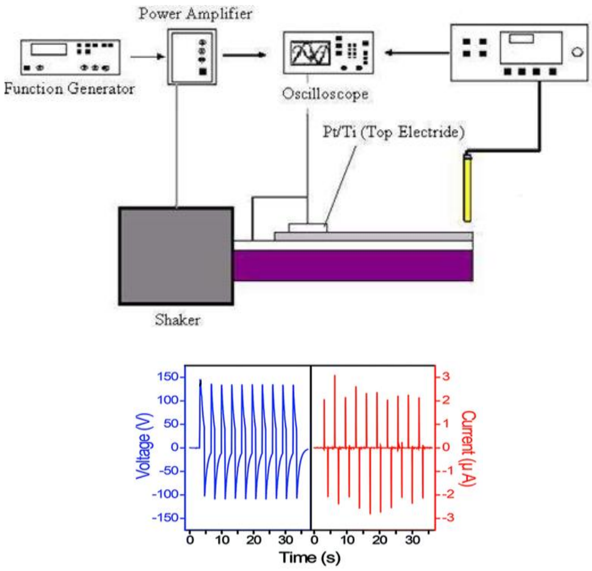

Figure 10. Test stand for piezo-electric evaluation

4. Development of energy-harvesting application with signal-processing circuitry and concept optimization for energy management

At this stage, the research is in progress, more technical solutions being technically evaluated for an intelligent harvester concept, including the developed piezo-element, a charging circuit and a storage buffer, for further connection to Li- battery or ultra-capacitors. The concept is intended to represent a clear progress related to integration rate, volume and cost, comparing to actual models on the market (mide.com; americanpiezo.com; kinergizer.com), as seen e.g. in Figure 11, where a simple signal processing unit was added to a low performance piezoelectric device, based mainly on PZT.

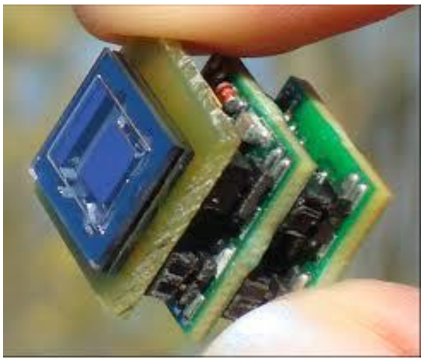

Figure 11. Piezoelectric device, PZT type

The harvested energy is accumulated in the storage element e.g. a super-capacitor, which accumulates energy to enable efficient use for short power outputs. The circuit is composed of a comparator which controls the super-capacitor's charging and discharging process. The comparator is programed with two threshold voltage levels, one for the charge regime and the other for the super-capacitor discharge limit, associated to both peak- and zero-crossing detectors. Energy conditioning is a key component of energy management system, which is monitoring the harvester minimum and maximum output supply voltage, since the input energy is random. On the other hand, the optimum control of electrical output must be also in accordance with the load condition of the required application. Basically, the block diagram of the power management circuit must include a rectifier to produce direct current from irregular alternating amplitude of the piezoelectric device, a regulation circuit in terms of DC-DC convertor to adjust and set the output voltage, and respectively a filter associated with an active full-wave rectifier to assure the power conditioning with maximum efficiency. The efficiency is expected close to 90% at e.g. 100 µA output current, mainly if using an intelligent load switch to be used to turn off loads when they are not supposed to be in use. The proposed concept should be finalized by an integrated module for energy-management with IT support, in order to tailor a competitive and intelligent piezo-harvester, with integrated signal-processing circuitry. The schematic circuitry will be fully on-chip, and will be managed by a programmable microprocessor that will command the charger regime (optimal energy consumption, optimal charge, optimal transfer to buffer etc.) and the energy transfer towards storage devices (Li battery or ultra-capacitors), with on-site evaluation of energy quality and harvester reliability, as presented in Figure 12.

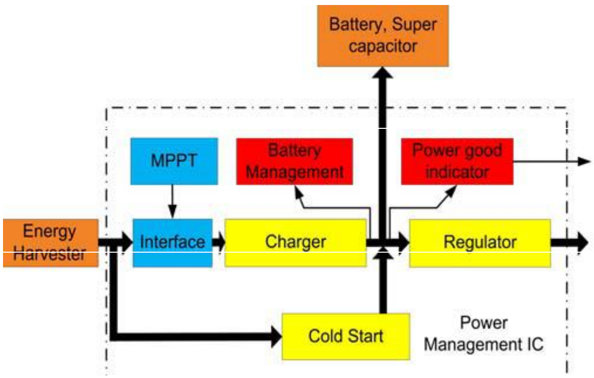

Figure 12. Concept for harvester energy management

5. Conclusions

Despite some solutions for piezo-ceramic harvesters which are suggested in the literature, there is no specification for an integrated, versatile solution for broad technical use, and/or of advances towards an intelligent harvester concept related to both Li batteries and ultra-capacitors, which is the real need in all energy applications. Our research promotes a nano-structured systems starting from ferroelectric particles with defined-shape, based on the effect of Au-induced perpendicular magnetization in Fe films, grown on Si. The predefined shape anisotropy of materials allows a versatile wave-to energy conversion at different frequencies, being ideal for consumer electronics such as in portable and in wearable devices.

The achievements are in line with the actual tendencies in intelligent harvesters development, see e.g.: Hwang *et al.*, 2015; Kang *et al.*, 2016; Hua & Han, 2016, but the new concept related to nanostructured piezoelectric materials, that we developed and use for the intelligent harvester, represents a clear progress.

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