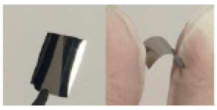

Magnetocaloric films for microscale thermal energy harvesting

In the last couple of decades, Magnetocaloric (MC) materials studies have undergone major advancements paving the way to novel energy conversion applications. Among them, a rather new field of research is represented by the possibility to design MEMS scale devices scavenging low grade heat to produce electric energy. The working principle relies on the thermal response of a material to the application/removal of a magnetic field. Indeed, a flexible, free-standing, magnetocaloric film can be used as an active substance in a compact, high throughput micro-device working as a generator, or as a cooler, depending on its design. A Gd film presenting all the characteristics required to be deployed in a MEMS generator has been recently produced thanks to the collaboration between the "Growth and properties of hybrid thin film systems" group, at INSP, and the "Magnetic Materials for Energy" group, at SATIE (ENS Paris Saclay).

Most of the state-of-the-art energy conversion devices (either cooler, or generator) using magnetocaloric materials as an active principle, needs, to accomplish a working cycle, a pump acting on a fluid heat exchanger, and a motor to move the MC material within the magnetic field. These components represent a major issue for reaching high working frequencies (viz. power), better efficiencies, and for device miniaturization. A flexible, free-standing MC film represents an unique opportunity towards novel, smaller, designs where the film moves between the heat reservoirs behaving as the caloric substance, and as the heat exchanger at the same time. Furthermore, both the caloric effect, and the film movement are actuated by the magnetic field playing the role of the motor and of the pump at once. Fig.1 shows an example of such a design, where a thermo-magnetic generator working over a Brayton cycle (two adiabats and two iso-field transformations) uses as active substance a Gd free-standing film mounted on piezoelectric beams to recover part of the mechanical energy associated with the displacement between reservoirs.
Beside the need for excellent MC properties (i.e. ΔTadia is the key material parameter to maximize the power-output, as shown in Fig.1 on the right), high film diffusivity, and smooth surface state on both sides, are of the utmost relevance in order to achieve a fast and efficient heat transfer through solid-solid direct contact between Gd and the reservoirs. Moreover, film flexibility, and stable magnetic properties under strain, are key issues for film deploying in the device, and to allow a fast switch between reservoirs (i.e. adiabatic transformation), and an optimal thermal contact between a compliant MC membrane and the surfaces of the hot source, and of the heat sink.

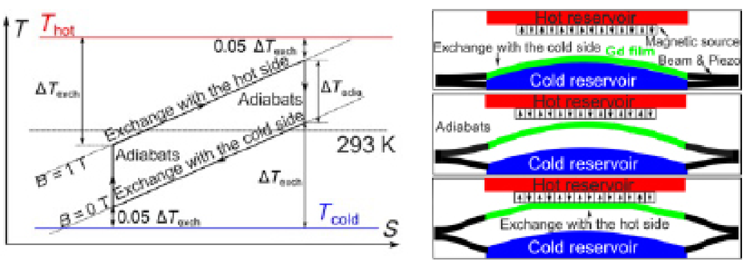

Figure 1
Left: Schematic drawing of a possible thermal energy harvesting device. The adiabatic magnetization and demagnetization (adiabats) are represented in the central frame (the MC material moving upward to magnetize and downward to demagnetize), the top and bottom drawings show the constant applied field and heat exchange transformations (cooling and heating, respectively). The schematic device drawing emphasizes the relevance of the Gd film flexibility in order to achieve an optimal thermal contact with the reservoirs.
Right: a Brayton thermodynamic cycle; the amplitude of the two vertical transformations (i.e. adiabats) is bounded by the adiabatic temperature change of the material ΔTadia showing the relevance of this parameter to get an high throughput working cycle.

Following these specifications 17 µm thick Gd films have been deposited on silicon substrates by DC sputtering in Ar atmosphere. In order to pull out the Gd layer from the substrate, the film has been pushed against a convex surface after performing a superficial cut on the free side of the silicon substrate as shown in Fig.2a. This allows the substrate to be broken without damaging the Gd film. After substrate removal the freestanding film still shows excellent magnetic properties, and the surfaces on both sides are smooth. Furthermore, the freestanding film is flexible, as shown in Fig.2b, and its properties are stable against strain application. It is worth noting that the film thickness, the growth temperature, and the choice of the capping layer, have been the key issues to get high quality, freestanding films of large surface (i.e. 35 x 35 mm2). Eventually, XRD analysis, and AFM characterization, show lattice parameters of the freestanding film in agreement with the values of bulk high purity Gd, and an average roughness below 11 nm.

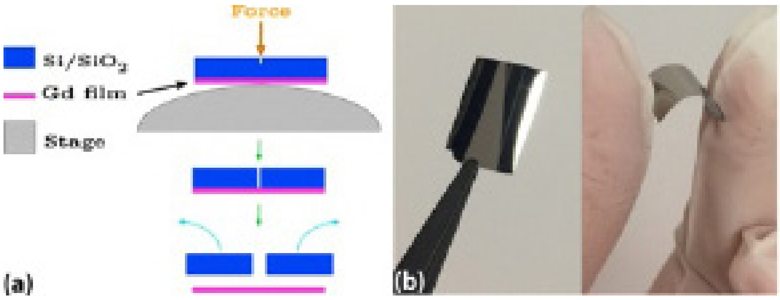

Figure 2
Left: Schematic for the separation of the Si/SiO_2 substrate from the Gd film. Right: picture of the freestanding Gd film.

Using a finite-time thermodynamic approach it has been shown that a thermomagnetic harvester, using a Gd MC film showing the properties of the one produced at INSP would reach an output-power well beyond most of the devices reported in the literature, particularly when working on small temperature gradients. Such device would reach the throughput needed to power-up small IoT wireless sensors, as well as bio-medical implants.

Reference

"Magnetocaloric Effect in Flexible, Free-Standing Gadolinium Thick Films for Energy Conversion Applications"
Doan Nguyen Ba, Yunlin Zheng, Loic Becerra, Massimiliano Marangolo, Morgan Almanza, and Martino LoBue
Physical Review Applied 15, 064045 (2021)

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