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Porous ZnO thin films on paper substrates for the development of piezoelectric nanogenerators and self-powered sensors

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Introduction

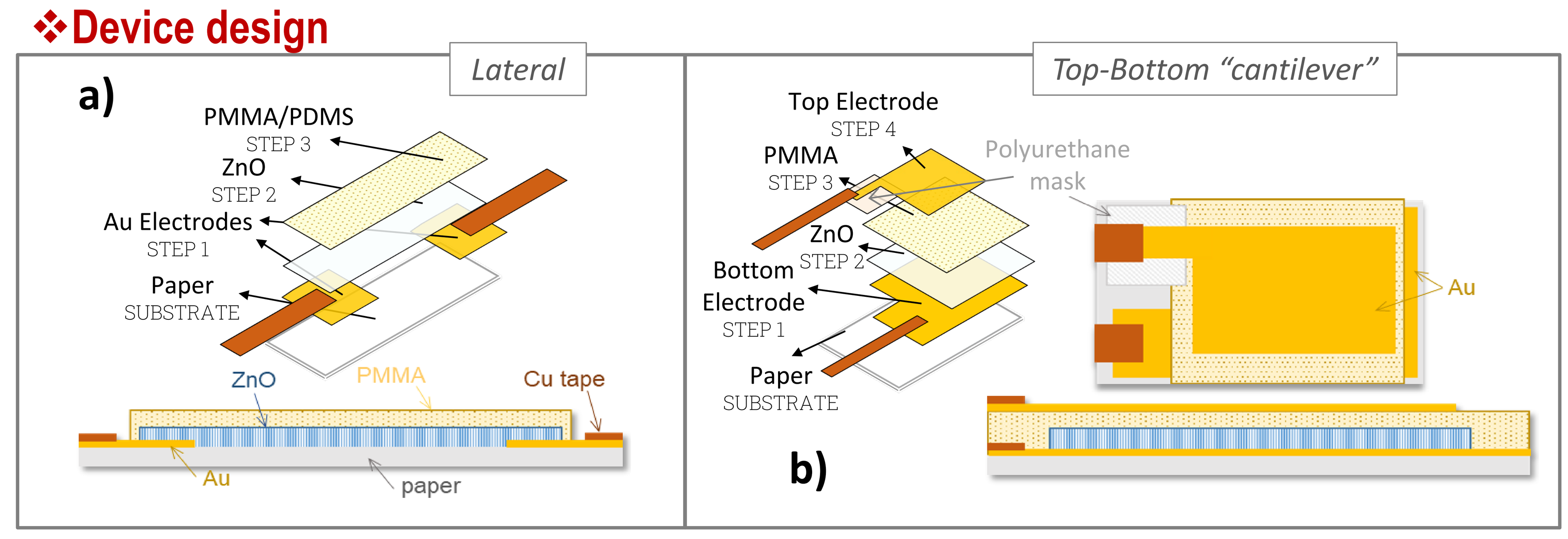
The increasing demand for powering wireless devices has spurred the development of energy harvesting solutions in recent years, such as piezoelectric, pyroelectric, triboelectric, and thermoelectric nanogenerators. These systems can convert ambient kinetic or thermal energy into electrical energy, which can then be used to power a small energy storage system or the device itself [1]. Paper, as one of the most common materials in daily life, has gained interest as a potential substrate for flexible electronics [2] due to its advantages of being lightweight, portable, disposable, recyclable, biodegradable, and easy to fabricate.

In this communication, we show how to use plasma-assisted vacuum deposition [3] to fabricate mechanically sensitive paper-based sensors and energy harvesting systems [4]. Two configurations have been designed to produce these completely bendable and foldable devices, depending on their contact architecture (i.e., laterally or top-bottom). Polymeric coatings have been successfully developed to protect the functional material and the paper substrate, and also to act as a dielectric layer in the devices. Different devices with functional polycrystalline ZnO piezoelectric surfaces were manufactured and characterized, and their electrical outputs were analyzed and compared under several activation conditions. As examples of application, signals were recorded from the devices as they were moving within the air turbulences produced by a fan and also under handwriting.

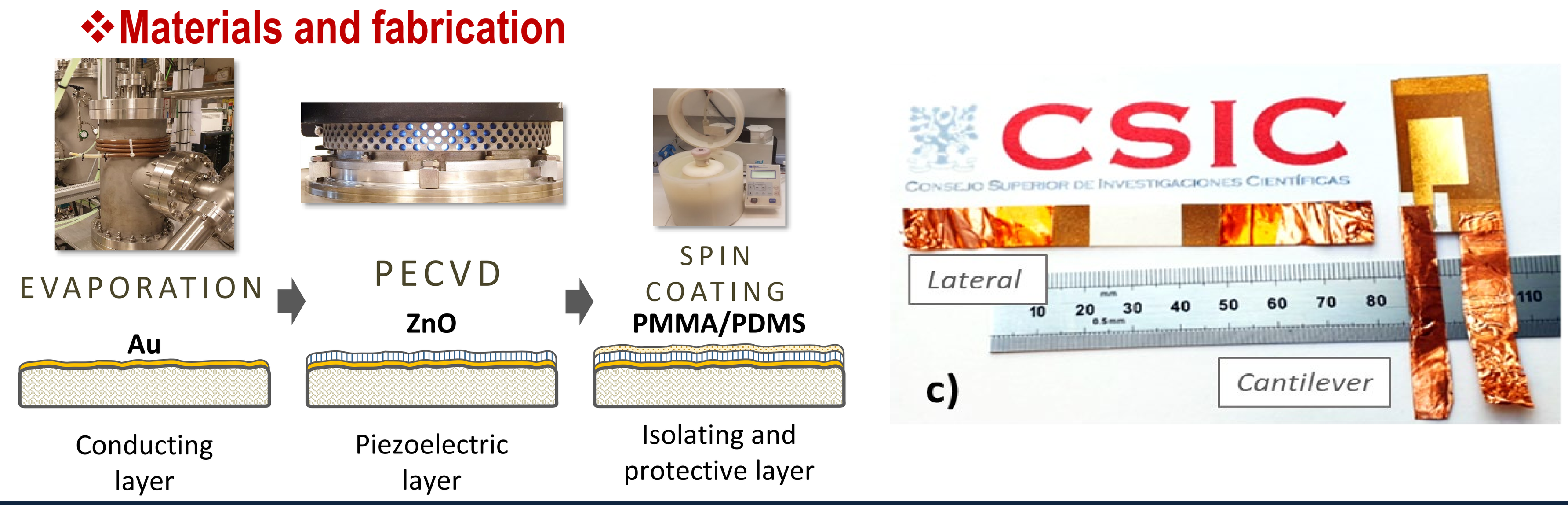
The procedure followed for the fabrication of the functional surfaces is mainly based on vacuum and plasma depositions, such as Plasma Enhanced Chemical Vapor Deposition (PECVD) and sputtering. These deposition techniques allow the integration of multiple devices using a one-reactor synthetic process and are scalable to large area deposition. The use of inexpensive paper substrates, simple geometries, and efficient and industrially scalable deposition processes has the potential to lead to low-cost devices.

Experimental

Device design

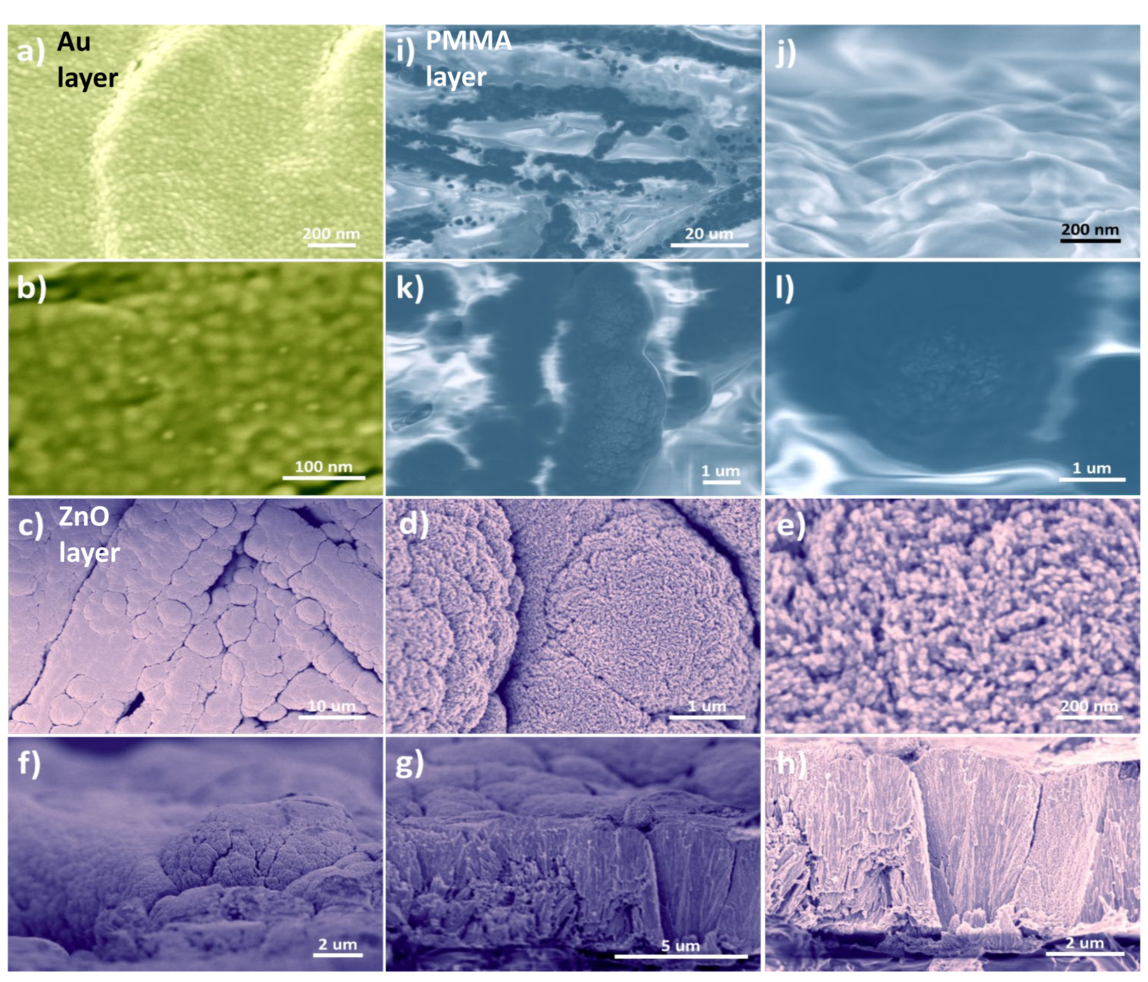


Materials and fabrication



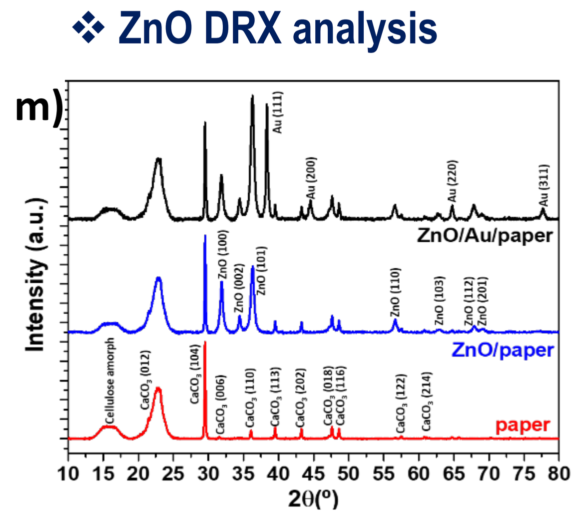
Results

SEM characterizations

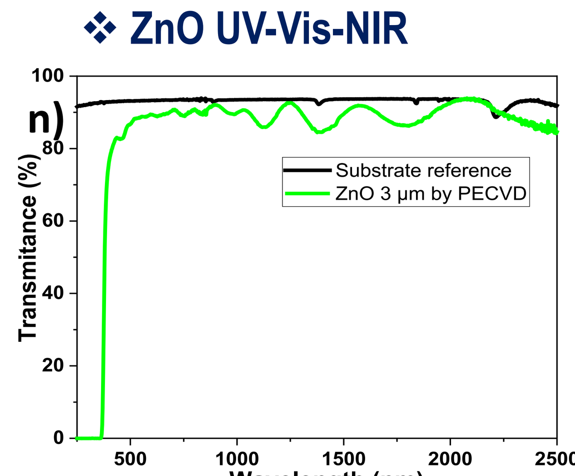


- Direct depositions at room temperature.
- Dual roughness due to paper fibers and granular nanostructure.
- Au conformal thin film (a-b). Directly deposited on the paper and PMMA. Film thickness ~100 nm - Sheet resistance < 3 Ω/sq
- ZnO polycrystalline wurtzite by PECVD (c-h). Conformal layer showing paper fiber structure at microscale (c). Randomly oriented grains at nanoscale (e). At the meso-scale (d), the morphology of the thin film present globular formations at the skullcaps of the coated nanofibers (d, f) and hand-fan like cross sections (g-h).
- ZnO texturization changes due to the effect of the Au interface favoring (101) cristal plane (m). UV-Vis-NIR characterization on fused silica substrate (n) shows the high transparency of ZnO films.
- PMMA conformal thin film (i-l) by spin coating improves mechanical stability, distributes strain and provides water resistance (see below).

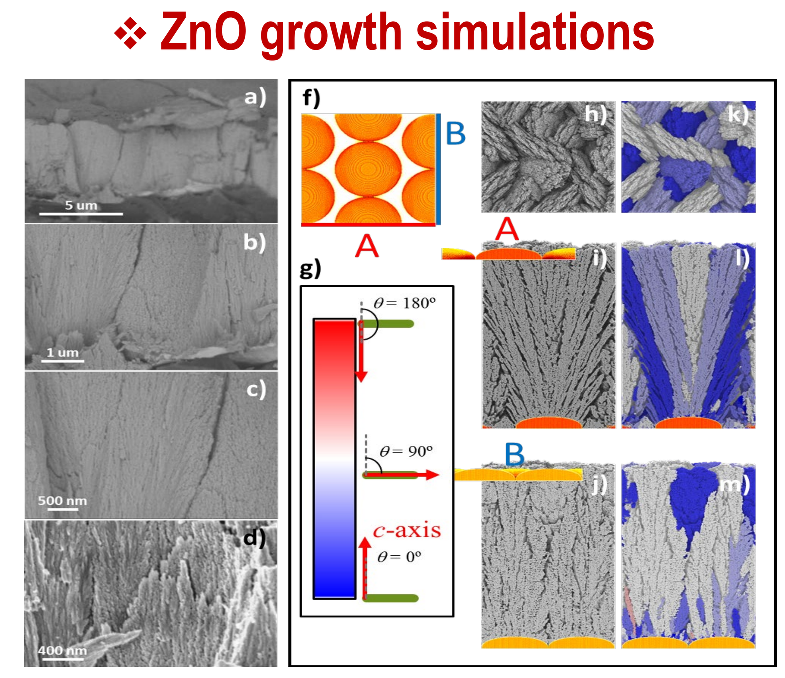
ZnO DRX analysis



ZnO UV-Vis-NIR



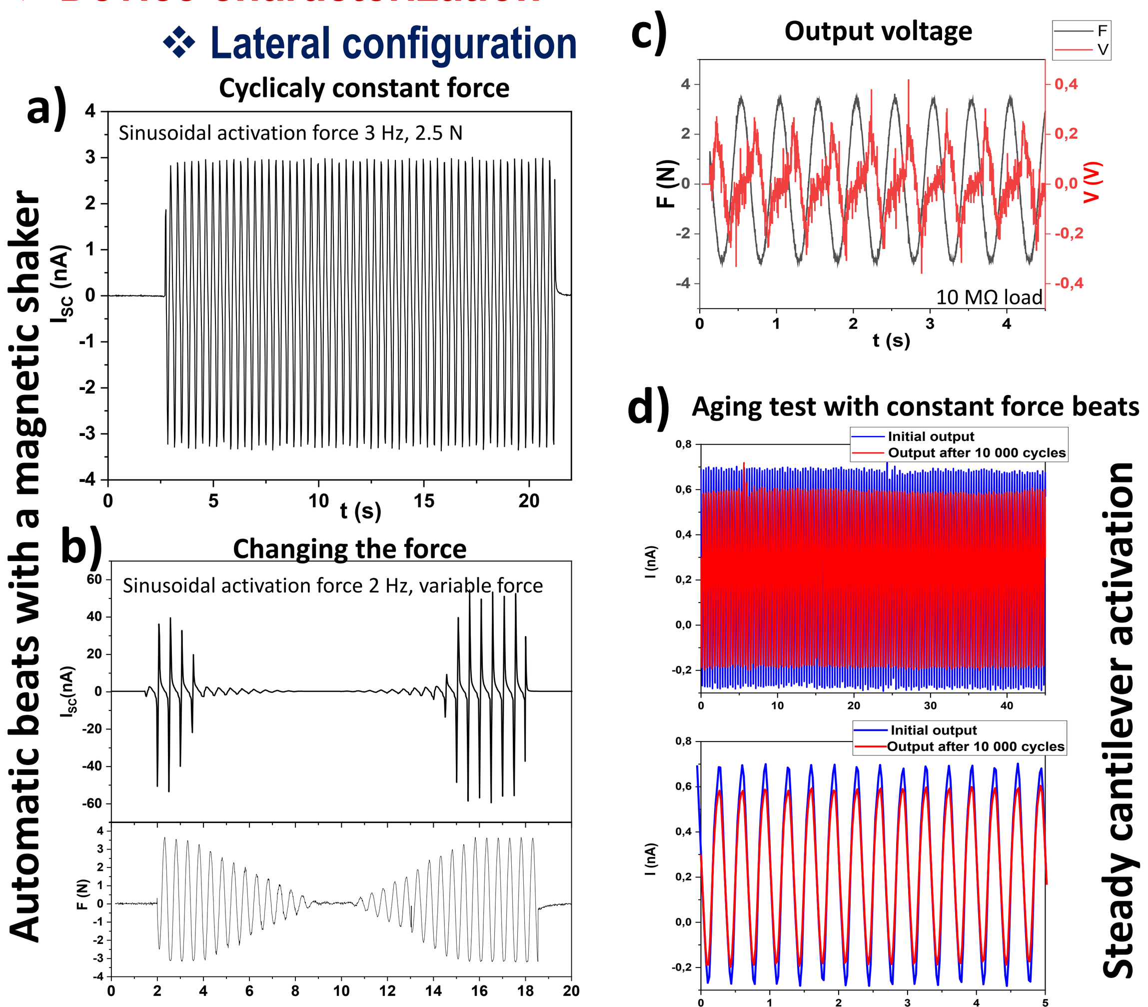
ZnO growth simulations



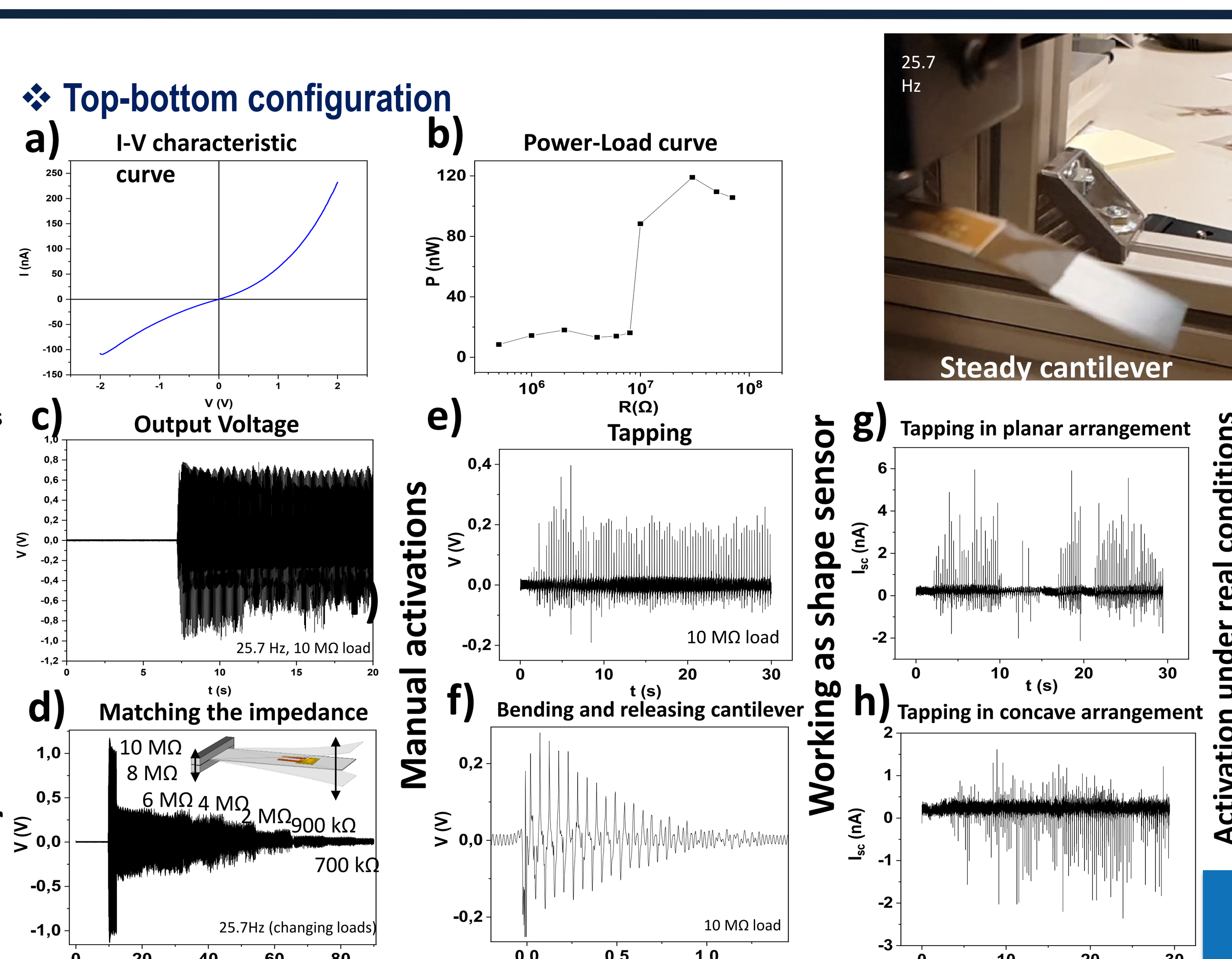
- Kinetic Monte Carlo simulations [5].
- Crystalline texture and morphology of ZnO wurtzite highly dependent on the substrate and interfacial topography.
- By increasing the deposition rate it is possible to reduce the dependence of the film nanostructure on the substrate morphology.

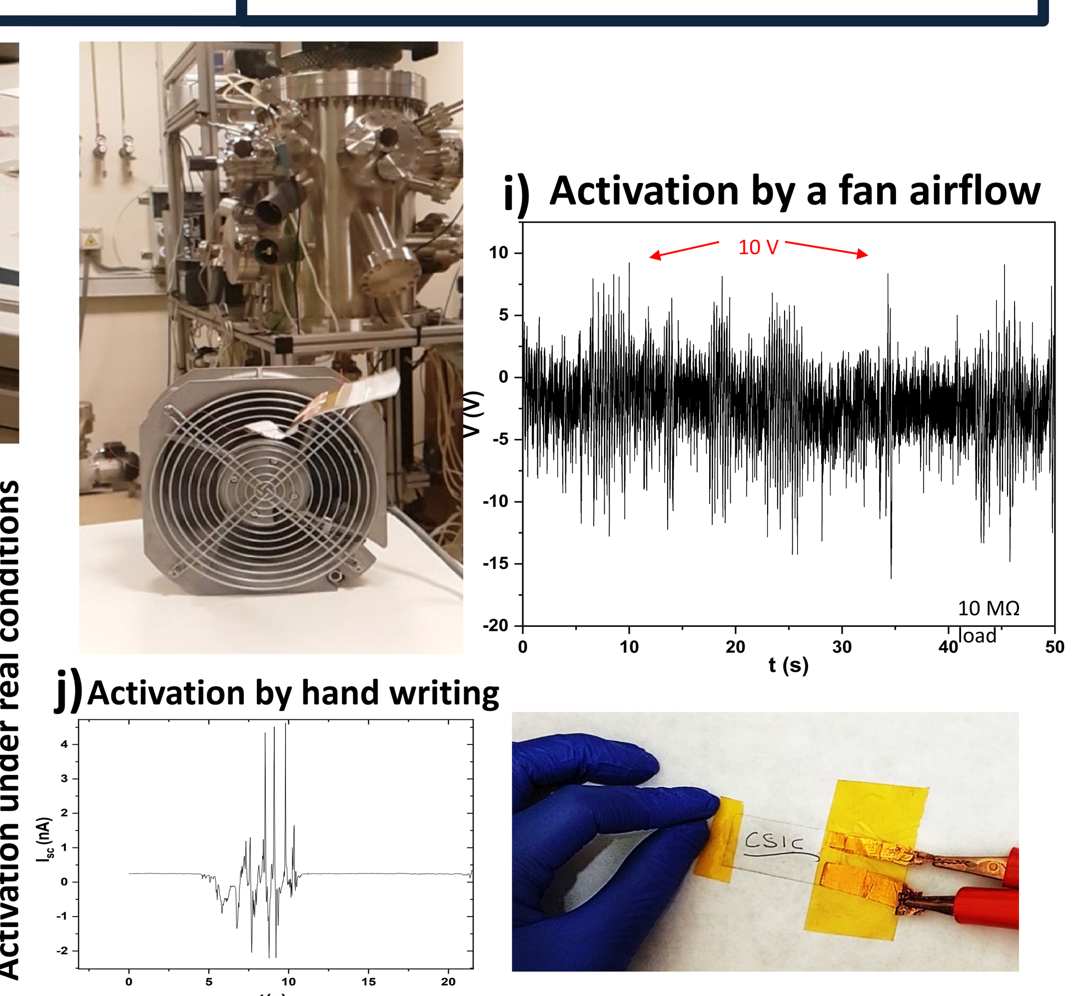
Device characterization

Lateral configuration



Top-bottom configuration





Conclusions

- ✓ Plasma–vacuum depositions allow the direct deposition of functional materials on untreated paper substrates at low power consumption
- ✓ Energy efficient, solventless and industrially scalable synthetic procedures.
- ✓ As paper is highly flexible and foldable, and due to the fair adhesion of the films in the cellulose microstructure, manufactured devices are able to adapt to any kind of deformations, even those produced by an airflow generating an output signal.
- ✓ Synthetic protocol provides robust systems mechanically stable after thousands of successive activation tests.
- ✓ New alternative path to fabricate flexible and durable paper-based self-powered sensors and piezoelectric nanogenerators. Besides, the transparency of the functional surfaces allow to implement the devices on printed paper.

References

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