

Inorganic piezoelectric screen-printed layers for MicroElectroMechanicalSystems (MEMS): solutions to reduce the environmental footprint

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Short abstract

The scientific community is increasingly seeking to reduce the environmental impact of electronic manufacturing processes, whether in terms of the manufacturing stages, their energy consumption and/ or in the choice of materials. Printed electronics have always appealed to manufacturers and particularly the screen-printing technique as it enables both prototyping and mass production of components. Here, we are focusing on a fully printed piezoelectric component for vibration energy harvesting. It is composed of a metallic stainless-steel cantilever with a piezoelectric ceramic layer in sandwich between electrodes. Using Spark Plasma Sintering (SPS) with a specifically designed mold to finely control the applied pressure, it is possible to sinter in a single step ceramic thick films in a short time (<5 min) and at lower temperature (<600 °C) than by conventional sintering (>850 °C). Combining this innovating SPS approach with the development of a green water-based ink, we have successfully produced a multilayer structure based on lead-free piezoelectric material ($\text{K}_{0.5}\text{Na}_{0.5}\text{NbO}_3$) without dopants which exhibits promising dielectric properties, indicative of adequate microstructure and interface quality with regards to the electrodes.

Keywords: screen-printing, lead free piezoelectric, water-based ink, Spark Plasma Sintering

1. Introduction and background

Among the various technologies currently available for film deposition in microelectronics, screen-printing stands out as one of the simplest, most versatile, and most cost-effective methods [Thiyagarajan et al. 2025, Zhang et al 2021, Mattana and Briand 2016, Wiklund et al. 2021]. Its main advantages lie in the low capital investment required for equipment and the wide range of compatible materials, including both substrates and pastes. However, conventional screen-printing technology remains limited by a typically minimum line width of approximately 100 μm , 50 μm being achievable with specific screens. To overcome this limitation and meet integration and/or performance requirements, several modifications to the standard process have been developed. Polymer thick films, for example, represent a significant advancement, enabling a wide range of applications on flexible substrates. Screen-printing has also been successfully applied to the fabrication of Microelectromechanical Systems (MEMS) through the introduction of sacrificial layers. This approach has enabled the realization of organic or inorganic free-standing microstructures designed for physical or chemical sensing [Debéda et al. 2014, Rivadeneyra et al. 2015]. The specific composition of the printed sacrificial layer, combined with optimized thermal treatment, resulted in free-standing microstructures with properties suitable for sensing applications. More recently, the community has been devoting considerable attention to reduce the environmental footprint of printed components [Zikulnig et al. 2025, Tsikriteas et al. 2024]. Considering piezoelectric ceramics, micromachining of bulk or tape-cast piezoceramics is well suited to planar devices (discs, plates, simple multilayer stacks), but shows clear limitations for complex shapes, including machining-induced damage and performance loss, poor suitability for

highly 3D or topology-optimized structures, and significant material waste. For greater design freedom and rapid iteration, 3D additive manufacturing is an attractive option, although it still faces challenges such as feedstock formulation, porosity control and polarization integration [Bhandari et al. 2025]. In contrast, screen-printing is a very mature technology that has been widely used for many decades and enables the fabrication of piezoelectric ceramic thick films in a robust, low-cost, scalable and substrate-flexible manner, providing functional layers with good piezoelectric response that are particularly advantageous for planar or mildly structured architectures. For such piezoelectric thick films applied to MEMS, achieving dense functional layers is essential. To this end, the standard screen-printing process was adapted by introducing a pressing step prior to sintering. When combined with the sacrificial layer technique, this modification led to the fabrication of fully released, highly dense disks exhibiting piezoelectric properties comparable to those of bulk ceramics [Santawitee et al., 2020]. More recently, with the objective of reducing the fabrication steps, sintering in one step of a whole printed multilayer component composed of a lead-free piezoelectric material (KNN in sandwich between electrodes) has been achieved thanks to an field assisted sintering method, the Spark Plasma Sintering. Moreover, care has been taken in the choice of materials and the formulation of the inks to reduce the environmental impact.

In this work, our approach to develop all printed ceramic piezoelectric MEMS with the lowest environmental footprint is proposed. The starting material choices, formulation of pastes and design are described before moving to microstructural and dielectric characterizations performed on the first ceramics printed MEMS based on lead free piezoelectric material ($\text{K}_{0.5}\text{Na}_{0.5}\text{NbO}_3$) and sintered by SPS using an innovative mold.

2. Materials and methods

2.1 Materials

2.1.1 Starting materials (powder and substrate)

The piezoelectric harvester is a simple beam structure on which the lead-free active layer and its electrode are printed. Commercial $\text{K}_{0.5}\text{Na}_{0.5}\text{NbO}_3$ piezoelectric nanopowder from CerPoTech (99.99 %, Norway) is used. The morphology of the KNN powder particles observed by Transmission Electron Microscopy is cuboid-shaped with minimum diameter of ca. 20nm. The cantilever is metallic, made of stainless steel SS304 100 μm thick compatible with the process and with mechanical properties in accordance with the application [Colin et al. 2013].

2.1.2 Pastes

A commercial paste based on gold (8836-S from Ferro) is used for the harvester electrode with a sheet resistance of 7.5 $\text{m}\Omega/\text{square}$ at 12.5 μm , after sintering at 850 °C. A KNN paste based on ethylcellulose and terpeneol was first prepared similarly as the PZT (PbZrTiO_3) based paste prepared by santawitee et al. [Santawitee, 2020]. The paste was not homogeneous and agglomerates were present even after sonication dispersion in alcohol and a three-roll milling step after the binder incorporation. Based on these results and Dynamic Light measurements (Figure 1a), a water based ink (10 g) was formulated according to the following procedure: a) Weigh out 30 wt% KNN powder b) Add 40 wt% water to disperse the KNN powder c) Put the suspension for 4 hours in an ultrasonic bath d) Add 30 wt% EDOLAN, a polyurethane-based polymer and 1.2 wt% (0.12 g) of HEC Hydroxyethyl cellulose (HEC) to adjust the viscosity e) Stir with a magnet for 12 hours. The viscosity was compared for the PZT (Santawitee et al. 2020) and KNN pastes. The rheological measurements were performed at 25°C using an Anton Paar MCR 302 rheometer, with 25mm parallel discs, a 0.5-mm gap, and 200 measurement points at a rate of

one point per second. The results (Figure 1b) showed similar viscosity suitable for screen-printing with a viscosity of ~ 200 Pa.s at a shear rate of 0.3 s^{-1} .

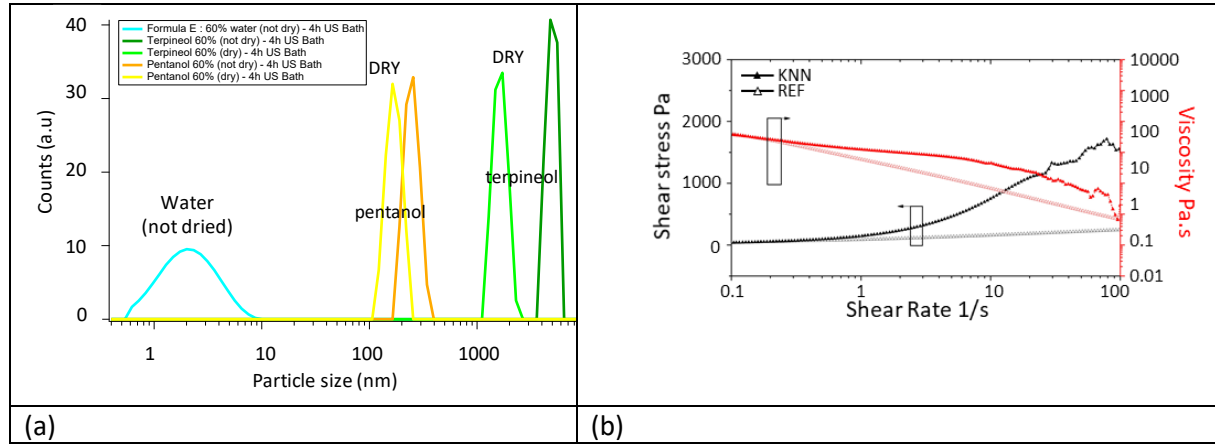


Figure 1: (a) Dynamic Light Scattering of the nanosized powder in different solutions, after 4 hours of sonication (b) Comparison of viscosity (dashed line) and shear stress for PZT based ink prepared according to [Santawitee et al. 2020] and KNN paste

2.2 Screen-printing

The goal is to print on the stainless-steel substrate (dimension $15\text{mm} \times 5\text{mm} \times 100\mu\text{m}$) the bottom gold electrode, the KNN piezoelectric layer and the top gold electrode (Figure 2a).

A stainless mesh screen is used for the printing of the electrodes (325 threads per inch, $15\mu\text{m}$ photopolymer). Design is first done for bottom and top electrodes. Then, because it was observed that KNN has a very good adhesion directly onto the stainless substrate after the thermal treatment, the bottom electrode has been removed. This helps to reduce the environmental footprint, as the printed gold electrode makes a significant contribution to the life cycle assessment [Aloui et al. 2025]. For the KNN printing, a stencil, $100 \mu\text{m}$ thick was micromachined (Figure 2b). The printing conditions are for the Au electrode and KNN piezoelectric layer respectively: pressure: $7\text{kg}/6\text{kg}$; squeegee speed 7cm/s ; 4cm/s ; off-contact : $0.6 \text{ mm}/0\text{mm}$.

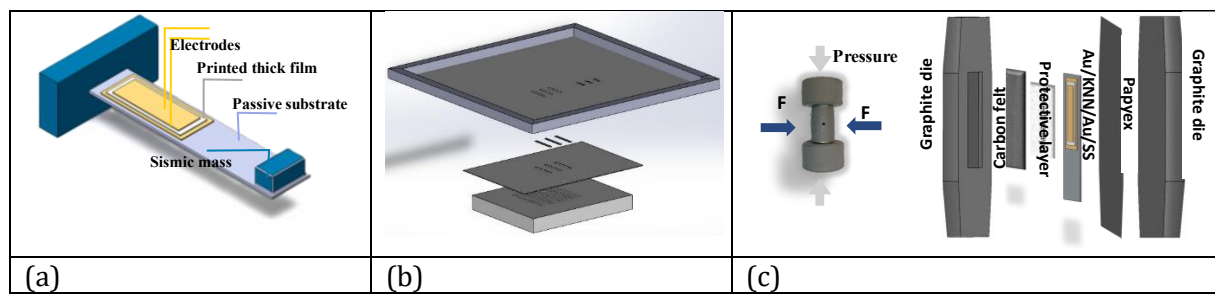


Figure 2: (a) design of the cantilever vibration energy harvester (b) Schemes of the stencil used and the set-up to fix the stainless steel cantilever and (c) Principle of SPS and modified

2.3 Spark Plasma Sintering (SPS)

SPS equipment (Dr. Sinter SPS 515S) is used to sinter the printed layer. This technique enables rapid sintering of powders or, in our case, of printed layers by applying pressure and a pulsed electric current to a graphite mold. The current causes the material to heat up very rapidly through the Joule effect. The multilayers have been sintered within a specific mold designed (figure 2c) [Chung and Debéda 2024] that allows reduction and homogenization of the pressure applied on the layers. The conditions of sintering, previously optimized with a ceramic (diameter

10mm at 700 °C, 15 min, 400 °C/min) [Bencharef et al. 2026] were then adapted, taking into account the smaller volume to densify. They were fixed at 580 °C, 3 min, ramp 400 °C/min with a standard sequence for the pulsed current.

2.4 Characterizations

Thickness profiles are measured with a Keyence microscope. Thanks to Scanning Electronic Microscop (SEM) microstructures and interfaces are observed. Dielectric properties are measured at room temperature using a HP-4194 impedance analyzer. A heat treatment at 100°C for 1 hour under vacuum is carried out before each measurement to remove the adsorbed water from the KNN known to be hydrophilic [Levassort et al. 2014].

3. Results and discussion

After optimization of the squeegee speed, a $\approx 50 \mu\text{m}$ thick KNN layer has been printed with a good quality (Figure 3a). The drying has been led at room temperature to achieve the best quality. The Au has been then printed and dried at 120 °C. The multilayer was then placed in the dedicated mold, with a protective layer based on SrCO_3 on the top. This allows to avoid the post-annealing that is usually required to re-oxidize the layer [Debéda et al. 2020] after SPS. Figure 3 shows the printed layers after drying (a) with the thickness profile (b) showing the good layer homogeneity. A good integrity of the layer after sintering at 580 °C during 3 min and removal of the protective layer SrCO_3 is shown. The white color of the KNN layer is the proof of the benefit effect of the SrCO_3 layer impeding the reduction of the KNN in the environment of low oxygen partial pressure. Microsection shows a homogeneous microstructure for both the electrode and the KNN. The optimized temperature for the Au commercial electrode should be 850 °C but the SPS treatment nevertheless allows a good Au sintering thanks to the pressure application combined to the temperature. Good interfaces, with no interdiffusion layers are observed, being attributed to the SPS conditions (quick ramp and pulse sequence). Dielectric properties (Figure 4) are very satisfying with this KNN in sandwich between the Au top electrode and the stainless-steel (e.g. bottom electrode). The relative permittivity is close to 100 on the frequency range investigated, and losses are ≤ 0.1 . This value is lower than that of ceramics due to residual porosity. Compared with the screen-printed layers produced by Pavlic *et al.* and Kmet *et al.* at temperatures above 1000 °C and with dopants (Table 1), the three-fold reduction in relative permittivity and a loss factor of 0.1 for pure KNN demonstrate the potential of this method, which achieves drastic reductions in processing time and temperature without the need for additives. The nanoscale size also enhances the powder's reactivity with a reduction of more than 250 °C compared to sintering of PZT layers by SPS [Taborda et al. 2020] .

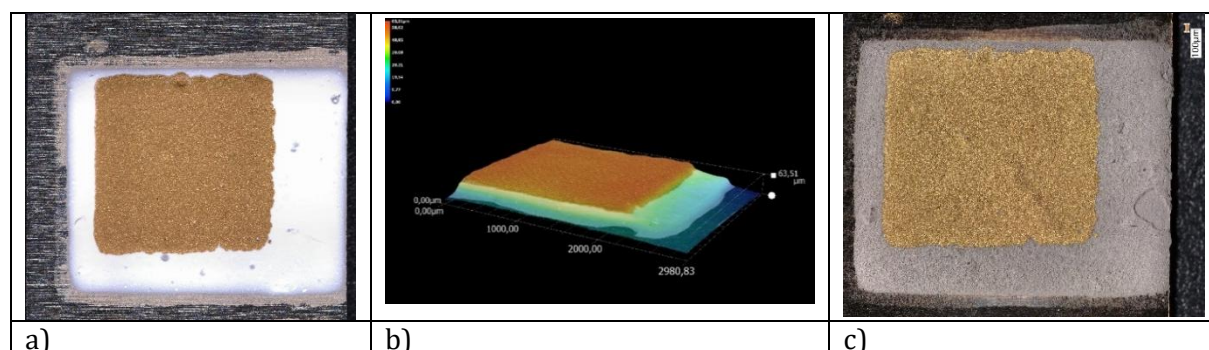


Figure 3: Multilayer stainless steel/ KNN/ Au (a) Dried layers (b) Profile after drying (c) Fired layers (SPS 3 min, 580 °C, 20 MPa)

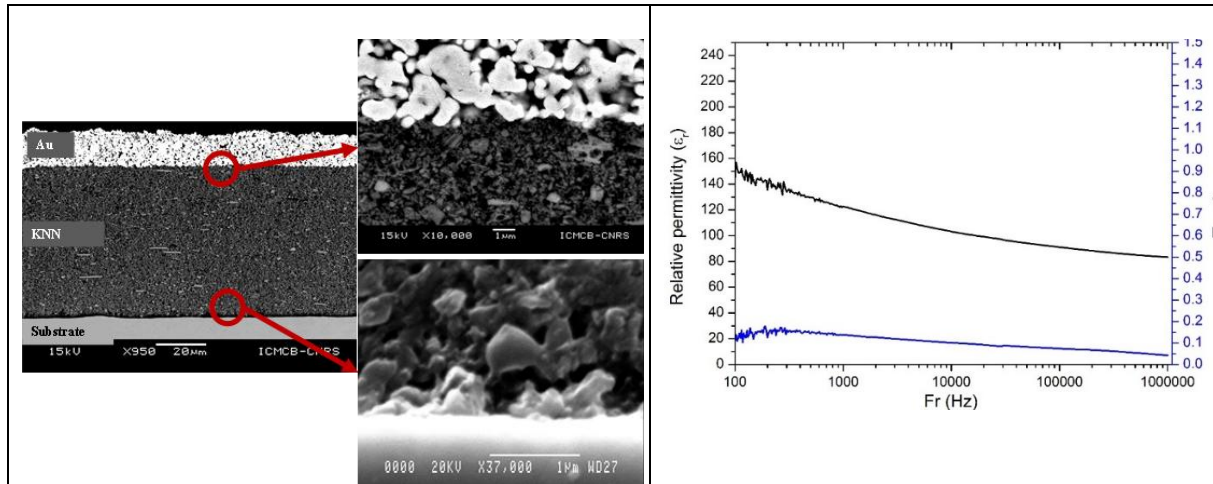


Figure 4: SEM image (left) with zoom of interfaces and dielectric response at room temperature (right) of SPS-sintered multilayer sintered at 580 °C, 3 min, 20 MPa

Table 1: Comparison of properties of KNN screen-printed layers

Reference	This work	Bencharef, 2026	Pavlič, 2014	Kmet, 2021
Active material	Pure KNN thick film	Pure KNN ceramic	KNN (+sintering aid KNG)	KNN-KCT-CuO
KNN Paste formulation	Water based	-	Solvent based	Solvent based
Multilayer structure / KNN thickness	Stainless steel/KNN/ printed Au // e= 40 µm	Sputtered Au/KNN/ sputtered Au // e= 1 mm	Alumina / printed Pt/KNN/printed Pt// e= 60 µm	Alumina/ printed Pt/KNN/ sputtered Cr/Au // e= 30 µm
Sintering conditions	SPS, 580 °C, 3 min, 400 °C/min, 20 MPa	SPS, 700 °C, 15 min, 400 °C/min, 100 MPa	Isotatic pressure 300 MPa + Conventiounal 1100 °C, 2 h, 5 °C/min	Isostatic pressure 200 MPa + Conventiounal 1100 °C, 2 h, 5 °C/min
Grain size/ Density	≈200 nm/ ≈94 %	≈ 300 nm/ ≈96 %	≈5-10 µm / -	≈2 µm/ ≈ 87 %
Relative permittivity (10kHz)	≈ 100	600	≈ 300	≈ 200
Dielectric loss (10kHz)	0.1	0.04	0.08	0.04

4. Conclusions

Undoped piezoelectric KNN nanopowder was used to prepare a screen-printable water-based ink and improve the sintering reactivity. Spark Plasma Sintering (SPS) was proved to be particularly efficient for low-temperature densification in one step of the KNN printed layer, avoiding the annealing step usually carried out to reoxidize the KNN layer. This approach dedicated to simplify the process ie. with less step, energy cost and waste, was successful demonstrated with a whole printed multilayer on a metallic substrate designed for future piezoelectric energy harvesting. Dielectric properties in the range of those reported in literature were obtained with this screen-printed KNN elaborated with a green solvent, and with a lower thermal treatment (< 600 °C) and shorter time (5 min). Chemistry, grain size and interface are key parameters to achieve good electromechanical properties for future vibration piezoelectric energy harvesting. Work is in progress to assess the piezoelectric properties after the polarization.

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