Key Engineering Materials
ISSN: 1662-9795, Vol. 1047, pp 115-125

Submitted: 2025-12-31
Revised: 2026-02-21
Accepted: 2026-02-25
Online: 2026-04-13

Implementing Inkjet Printing to Manufacture Piezopolymer Films for Sensing Applications

Vasileios Stratiotou-Efstratiadis[1,2,a], Apostolos Argyros[1,2,b], Giorgos Sarmas[3,c], Giannis Oikonomou[3,d], Dimitris Dimitriou[3,e], Nikolaos Chrysochoidis[3,f], Dimitris Saravanos[3,g], Georgios Maliaris[4,h], Vasileios Mpinas[5,i], Nikolaos Michailidis[1,2,j*]

[1]Physical Metallurgy Laboratory, School of Mechanical Engineering, Aristotle University of Thessaloniki. University Campus, 54124 Thessaloniki, Greece

[2]Centre for Research & Development of Advanced Materials (CERDAM), Center for Interdisciplinary Research and Innovation (CIRI), Balkan Centre, Building B', 10th km Thessaloniki-Thermi Road, 57001, Thessaloniki, Greece

[3]Department of Mechanical Engineering & Aeronautics, University of Patras, 26504 Rio-Patras, Greece

[4]Additive Manufacturing Laboratory, Department of Chemistry, School of Science, Democritus University of Thrace, 65404 Kavala, Greece

[5]Physical Chemistry Laboratory, Department of Chemistry, Aristotle University of Thessaloniki. University Campus, 54124 Thessaloniki, Greece

[a]vstratio@auth.gr, [b]aargyros@auth.gr, [c]sarmas.g@ac.upatras.gr, [d]oikonomou.ioannis@ac.upatras.gr, [e]d.dimitriou@ac.upatras.gr, [f]nchr@mech.upatras.gr, [g]dsaravanos@upatras.gr, [h]gmaliari@duth.gr, [i]vbinas@chem.auth.gr, [j*]nmichail@auth.gr

Keywords: piezoelectric, PVDF, poling, inkjet printing.

Abstract. The study explores the integration of additive manufacturing for the development of 4D-printed piezopolymer metamaterials, aiming to create dynamic, multifunctional structures capable of distributed sensing and energy harvesting. The focus is on Polyvinylidene fluoride (PVDF), a partially fluorinated polymer renowned for its strong electromechanical coupling, specifically within its polar β-phase. To harness these properties, three distinct experimental strategies were evaluated for integrating PVDF with conductive electrodes necessary for electrical poling: direct 3D printing with manually applied silver paste, printing directly onto pre-integrated aluminium foil substrates, and a novel chemical solvent-based deposition using a DMF/acetone mixture. While high-precision inkjet printing was initially tested for electrode deposition, it demonstrated significant limitations in scalability, throughput, and durability, particularly suffering from structural degradation during the post-poling silicon oil removal process. Consequently, the study advocates for a robust, hybrid multi-material extrusion platform. This approach will enable the simultaneous, monolithic deposition of structural PVDF thermoplastics and highly conductive thixotropic inks.

Introduction

Polyvinylidene fluoride (PVDF) is a type of fluoropolymer, a class of polymers that incorporate fluorine atoms within their molecular structures (polymerization of $H_2C=CF_2$ monomer) [1]. Fluoropolymers are generally classified into perfluoropolymers and partially fluorinated polymers. In perfluoropolymers, all hydrogen atoms in the polymer backbone are replaced by fluorine, whereas in partially fluorinated polymers, both hydrogen and fluorine atoms coexist in the polymer structure. PVDF falls into the latter category.

Fluoropolymers exhibit remarkable chemical resistance, excellent weatherability, low surface energy, and a high dielectric constant. These characteristics stem from the electronic properties of fluorine, the high stability of carbon-fluorine covalent bonds, and the inter and intramolecular interactions within the polymer chains [1].

PVDF demonstrates excellent resistance to a wide range of aggressive chemicals, along with enhanced thermal stability and high mechanical strength [2]. It can be found with several polymorphic phases and crystalline forms depending on its synthesis method. The main phases of PVDF are:

- The alpha (α) phase is the most thermodynamically stable form of PVDF. It features an orthorhombic crystalline structure, a non-polar nature, and lacks both piezoelectric and ferroelectric properties.
- The beta (β) phase is particularly significant for piezoelectric, pyroelectric, and ferroelectric applications due to its highly polar structure and strong electromechanical coupling.
- The gamma (γ) phase serves as an intermediate state between the α and β phases, displaying partial dipole alignment. However, it is not as polar as the β phase.
- The delta (δ) phase is essentially a polarized version of the α-phase, produced under an external electric field. It retains an orthorhombic structure but demonstrates some degree of polar behavior compared to the α-phase.
- There is also epsilon (ε) phase, which is the least common and less understood phase. It is reported in high-pressure crystallization conditions.

The β-phase is the most sought-after due to its strong piezoelectric and ferroelectric behavior, while the α-phase is the most naturally occurring [3]. The β-phase, characterized by an all-trans chain conformation, aligns dipoles in the same direction, leading to stronger polarization and improved piezoelectric properties [4]. PVDF demonstrates resistance to strong acids. However, compared to other fluoropolymers, its overall chemical resistance is lower [5]. When exposed to strong polar aprotic solvents like dimethylacetamide (DMAc) or dimethylformamide (DMF), its crystalline structure, and strong fluorine-carbon bonds deteriorate. Ethanol and/or acetone can be used as co-solvents to adjust viscosity, drying rate, or film properties.

The aim of this study involves 3D printing of passive piezopolymer microstructures to evaluate material deposition quality, geometric precision, and mechanical performance. Building on these insights, the next step is the fabrication of functional piezopolymer configurations, incorporating active elements to assess their electromechanical response. To achieve this, the research explores optimization of additive manufacturing (AM) processes, ensuring precise material distribution, controlled porosity, and enhanced structural integrity. Material extrusion (MEX) AM is chosen for the 3D printing of PVDF films, and inkjet printing is used as the AM process of electrode deposition.

Materials & Methods

PVDF filament used in the present study was the Adamant S1 PVDF, procured from add:north. The silver ink used, EM-Tec-C33, was procured from Micro to Nano Innovative Microscopy Supplies. PVDF films were printed using in a Voron Trident 300 3D-printer, optimizing the printing pattern, focusing on parameters such as print speed, overlapping of infill and perimeters, extrusion multiplier, to enhance print quality and structural integrity. As seen in Fig. 1. different infill printing patterns were tested. Concentric infill pattern was chosen as the prefered one for the manufacturing of the films as it offered better results regarding voids, gaps, overlapping and speed.

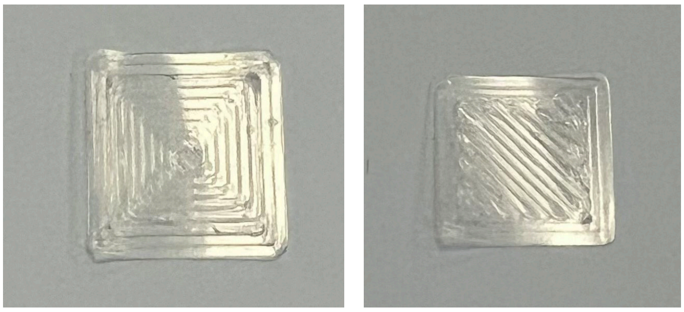


Fig. 1. Printing patterns of PVDF film; concentric (left), aligned rectilinear (right).

To systematically determine the most effective method for integrating PVDF with conductive electrodes for subsequent electrical poling, three distinct experimental strategies were evaluated.

These approaches ranged from direct AM techniques to chemical solvent-based deposition, with each phase designed to address specific challenges related to material adhesion, surface morphology, and electromechanical compatibility.

The first phase of the study focused on the direct 3D printing of PVDF onto the printer bed to assess its processability, adhesion characteristics, and overall structural integrity after deposition. The printed samples were visually examined for uniformity, layer adhesion, and surface morphology, as these are critical factors influencing subsequent poling and electrode integration. To evaluate poling feasibility in a controlled manner, a conductive paste was manually applied to the printed PVDF surface to form the first electrode layer, as seen in Fig. 2. The initial application utilized a manual coating or painting method to ensure uniform coverage, allowing for the measurement of the coated electrode layer's resistance. This provided a preliminary assessment of electrode efficiency before transitioning to a fully integrated setup, where the deposition will eventually be automated using a pneumatic extruder.

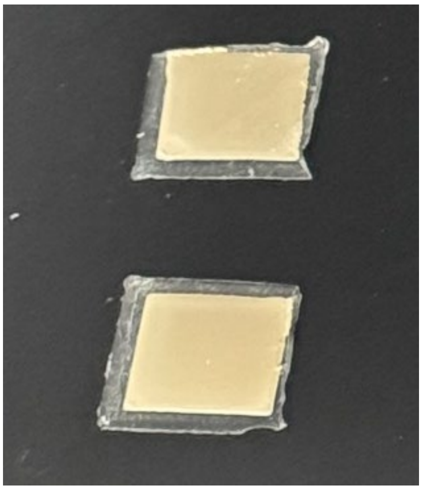


Fig. 2. PVDF films coated with silver paste.

Building upon the direct printing method, the second approach involved printing PVDF directly onto aluminium foil, which serves as a pre-integrated electrode for the poling process. To ensure optimal adhesion and minimize sample warping, the printing was tested on both the rough and smooth sides of the foil. The electrical conductivity of the aluminium-PVDF interface will be characterized to determine the effectiveness of the aluminium as an electrode in this specific configuration. Additionally, adhesion tests will evaluate how well the PVDF bonds to each side of the foil, ultimately determining the mechanical and electrical suitability of aluminium foil both as a substrate and an electrode for PVDF poling applications. Fig. 3 shows the prints on the smooth (left) and rough (right) side of the foil.

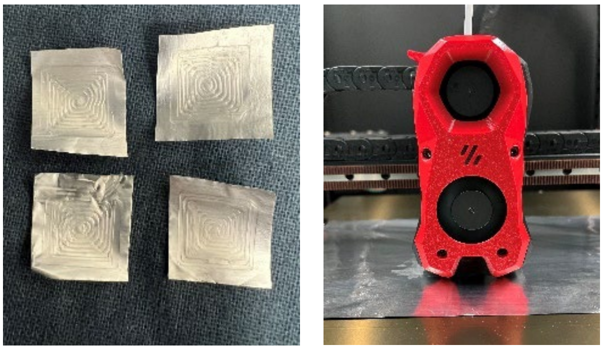


Fig. 3. Results of 3D printing PVDF onto the aluminium foil.

In the final approach, a chemical deposition method was explored by dissolving PVDF in a carefully formulated solvent mixture of DMF and acetone. Based on literature recommendations, these solvents were selected for their ability to dissolve PVDF effectively while maintaining the appropriate viscosity and evaporation rate. The primary goal was to formulate a solution that enabled uniform deposition onto electrodes without introducing defects like incomplete wetting or adhesion irregularities. Key factors evaluated during this stage included the interfacial adhesion between the PVDF and the electrode, as well as the impact of deposition parameters on poling efficiency. Fig. 4 showcases the dilution of PVDF in DMF and acetone solution.

Fig. 4. Stirring of PVDF in DMF and acetone solution.

Two specific experiments were conducted:

- Experiment 1 (Temperature and Evaporation): Initially, 0.5 g of PVDF was added to a mixture of 5 g DMF and 5 g acetone at ambient temperature and mixed using a magnetic stirrer. After 20 minutes, most of the PVDF remained intact, prompting a temperature increase to 60 °C, which successfully diluted the polymer. The temperature was then raised to 120 °C to evaporate the solvents, leaving the PVDF securely adhered to the glass surface. Notably, the introduction of water to the mixture led to the formation of a foam-like structure, as seen in Fig. 5.
- Experiment 2 (Saturation Limits): A second experiment was conducted to determine the maximum amount of PVDF that could be diluted to create a saturated solution. At ambient temperature, 0.5 g of PVDF was added to 6 g of DMF and stirred. After 20 minutes with the PVDF largely intact, the temperature was raised to 35 °C, resulting in almost immediate dilution. This step was repeated until a total of 1.5 g of PVDF (25% wt.) was successfully added. As the solution became highly viscous, 1 g of acetone was introduced before increasing the temperature to initiate solvent evaporation. Consistent with the first experiment, adding water resulted in a foam-like structure, again shown in Fig. 5.

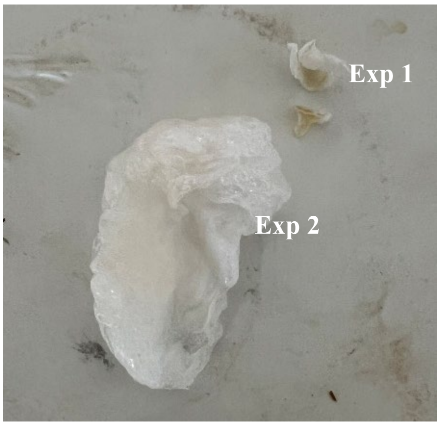


Fig. 5. Foam-like structure of PVDF during both experiments.

Building upon the insights gained from the isolated experiments, a hybrid approach was developed to leverage the strengths of both the integrated aluminium foil electrodes and the solvent-based PVDF formulations. To optimize the electromechanical interface between the solid PVDF and the aluminium substrate, a targeted formulation of 1 g of PVDF, 5 g of acetone, and 5 g of DMF was magnetically stirred until the solvents began to evaporate. Rather than relying on conventional commercial adhesives, this customized solution was applied as an active bonding layer to secure the 3D-printed PVDF film directly to the rough side of the aluminium foil. Observations indicated that applying a sufficient volume of this diluted PVDF is critical; inadequate application left the printed film highly susceptible to severe warping. Utilizing a diluted PVDF solution as the binding agent offered substantial advantages over traditional glues. The carefully balanced DMF and acetone mixture provided optimal viscosity and a controlled evaporation rate, facilitating uniform deposition without excessive residue or film defects. Furthermore, because the adhesive shared the exact chemical composition of the piezoelectric film, it ensured superior chemical compatibility, improved interfacial contact, and enhanced mechanical stability. Crucially for these applications, this homogeneous interface promoted better charge transfer and minimized interface electrical resistance, leading to a seamless integration that ultimately improved the efficiency and durability of the subsequent poling process. As a final variation of this combined approach, the 3D-printing step was bypassed entirely. Instead of adhering a pre-fabricated printed film to the substrate, a droplet of the diluted PVDF solution was deposited directly onto the shiny side of the aluminium foil electrode, as shown in Fig. 6. This direct-cast method allowed the solution to cure in place, successfully forming a thin, fully integrated piezoelectric film straight onto the conductive surface.

Differential scanning calorimetry (DSC) analysis was performed on PVDF filament to elucidate the influence of printing conditions on the material's microstructure and phase composition. Thermal profiling was conducted at a heating rate of 10 °C/min under an inert nitrogen atmosphere (25 to 320 °C) utilizing a DSC-25 apparatus (TA Instruments).

Fig. 6. Combination of approaches 2 and 3 with diluted PVDF instead of glue is used.

Scanning electron microscopy (SEM) was performed to observe the morphology of samples. SEM uses a focused beam of high-energy electrons to generate signals at the surface of solid samples. The signals reveal information about the external morphology (texture), chemical composition, and internal crystalline structure of the sample. SEM analyses took place using Phenom ProX G5 from Thermo Fischer Scientific, using long lifetime thermionic source (CeB_6), with light optical magnification range: 20–134x and electron optical magnification range: 160–350,000x [6]. It is also equipped with an integrated energy-dispersive X-ray diffraction (EDX) detector, which makes elemental analysis of the sample possible.

Inkjet printing is a versatile, non-contact drop-on-demand (DoD) deposition AM method, widely used for the deposition of functional materials, such as conductive inks, onto polymeric substrates. In this process, precisely controlled droplets of ink are ejected through micron-scale nozzles to form thin, patterned conductive traces. The method offers high spatial resolution, minimal material waste, and compatibility with flexible or temperature-sensitive substrates, such as PVDF [7]. Unlike conventional lithography or screen printing, the inkjet process does not require contact with the substrate surface, minimizing contamination and mechanical stress. This feature makes it highly suitable for delicate and flexible materials such as PVDF [7]. Using inkjet for the deposition of electrodes on the piezoelectric layer offers several advantages, such as: precise patterning, minimal invasive disruption of the mechanical integrity of the film, and seamless integration into the multi-material printing workflow [8]. At its core, the system uses a piezo-driven print cartridge that houses an array of microscopic nozzles and an ink reservoir filled with the functional fluid. The working mechanism is initiated when a precise, electronically controlled voltage pulse (defined by a user-programmed waveform) is applied to a piezoelectric element associated with an ink chamber. This voltage causes the piezoelectric material to rapidly deform (expand or contract), which in turn generates a pressure wave within the ink chamber [7], [9]. This transient pressure wave forces a tiny, uniform droplet of ink, to be ejected from the nozzle orifice and propelled toward the substrate. The printer utilizes a drop watcher camera system to observe and optimize the fluid's jetting characteristics (velocity, size, and trajectory), and a heated vacuum platen to precisely secure and thermally condition the PVDF substrate, ensuring accurate drop placement and print fidelity. The inkjet printer used in this study was Dimatix Materials Printer DMP-2850, by Fujifilm (Tokyo, Japan), which provided the necessary high-precision, non-contact, DoD piezoelectric technology for the accurate deposition of conductive ink.

Following the printing of the PVDF film and its integrated bottom electrode, electrical poling was required to activate the material's piezoelectric behavior. Electric poling involves the application of a strong electric field essential for aligning the molecular dipole of the electroactive β-phase of the PVDF, which are initially randomly oriented. The magnitude of the electric field should be both greater than the material's coercive electric field and below its dielectric breakdown threshold. To preserve the new molecular arrangement, the component is cooled down to room temperature before the voltage is removed. Among various poling techniques associated with PVDF films, contact and corona poling are widely utilized.

Corona poling is a non-contact poling technique where the air between the material and the high voltage point (usually needle) is ionized, and there is also a grounded electrode at the bottom of the material. On the other hand, in contact poling, the material is placed between two electrodes and exposed to an electric field at elevated temperatures to improve the mobility of the polymer's dipoles. The one electrode, typically the bottom, is grounded, and a high voltage is applied on the top electrode. This drives a highly robust orientation of the dipoles, which maximizes remanent polarization and significantly boosts the resulting electromechanical output [10]. Contact poling was favoured over the corona method due to its straightforward application and adaptability to non-planar, complex geometries. Also, the electrode pair that is used in contact poling can ensure a wider and more homogenized application of electric field to the material compared to the corona poling technique. Since only one electrode is printed and the contact poling requires two electrodes, another electrode is added using conductive epoxy with careful hand lay-up [11].

Results

A multimeter was used to measure the resistance of the manually coated 3D printed samples and 3D printed PVDF on both sides of the aluminium foil. The resistance measurement of the first approach sample can be seen in Fig. 7. The resistance was equal to 0.73 Ω, meaning that the material coated with the silver paste became conductive. Fig. 8 a presents the resistance equal to 0.53 Ω of the rough side of the foil, which is in contact with the highly polished rollers during its manufacturing, presenting lower oxidation, hence lower resistance. However, Fig. 8 b presents the 3D printed sample of the second approach on the smooth side of the foil, resulting in a higher resistance of 15.05 Ω.

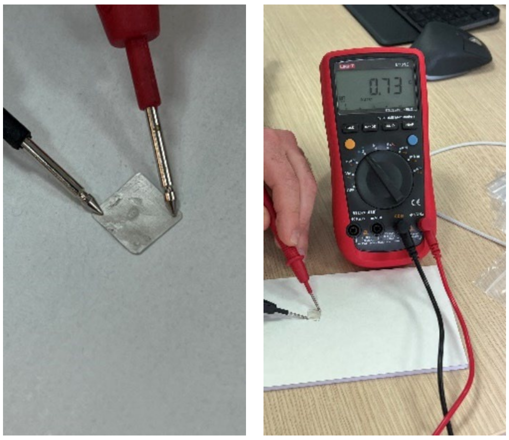


Fig. 7. Resistance measurement of approach 1 3D printed, silver coated sample.

Approach 3 led to poor adhesion between the diluted PVDF and the aluminium foil and no samples remained functional, hence resistance could not be measured.

DSC measurements revealed the typical thermal response of PVDF under the examined conditions (Fig. 9). The thermograms highlighted a prominent endothermic signature (around 130 °C) indicative of primary crystalline melting, complemented by a secondary, less intense peak associated with the breakdown of semi-ordered domains (around 45 °C). No other thermal events were detected beyond these points, validating that PVDF matrix remained thermally stable throughout the required extrusion and post-print processing.

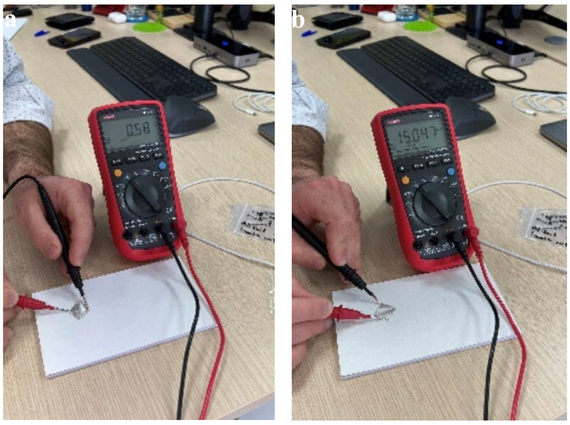


Fig. 8. Resistance measurement of approach 2 printed sample on the (a) rough and (b) smooth side of the aluminium foil.

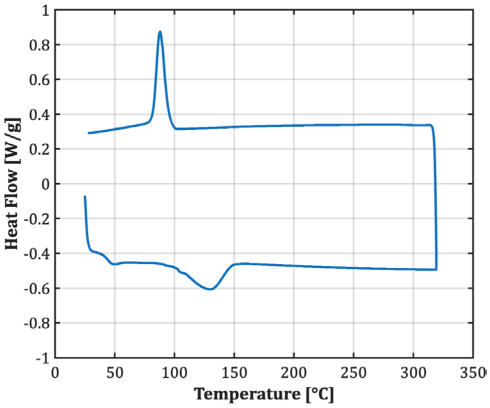
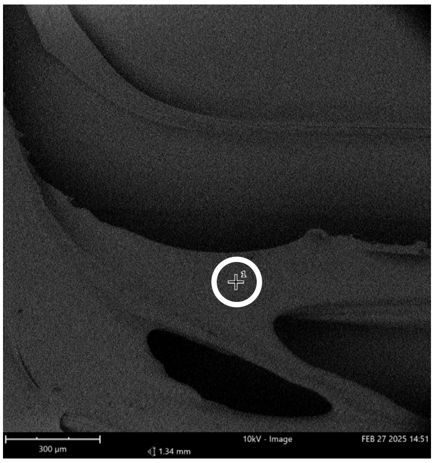


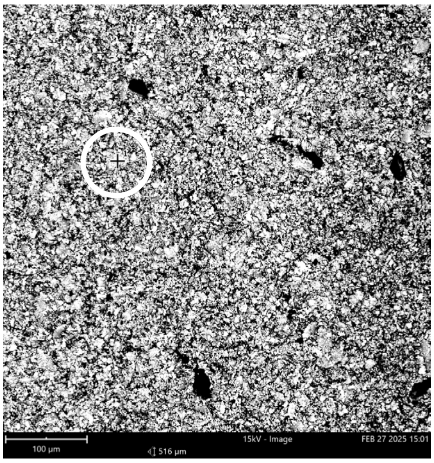
Fig. 9. DSC analysis of PVDF filament melts.

From the SEM analysis, as expected, pure PVDF 3D printed samples contain carbon and fluorine, as seen in Fig. 10. In the case of the 3D printed silver coated, approach 1, samples, a uniform film of silver paste can be seen in Fig. 11. The point of element identification is fully coated, as no fluorine is visible. Finally, Fig. 12 presents a more zoomed-in image of the silver surface.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	58.33	46.95
9	F	Fluorine	41.67	53.05

Fig. 10. SEM analysis of pure PVDF 3D printed film.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
47	Ag	Silver	56.91	86.99
6	C	Carbon	43.09	13.01

Fig. 11. SEM analysis of silver coated PVDF 3D printed approach 1 sample.

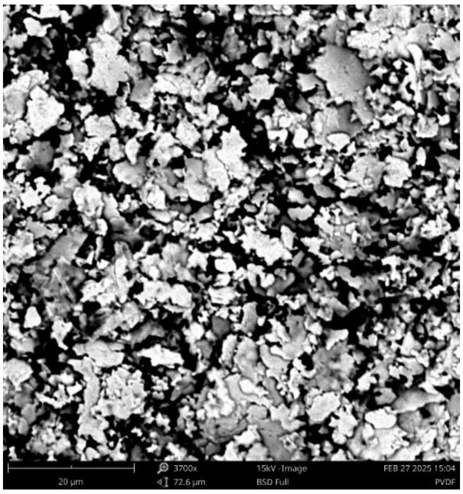


Fig. 12. Zoomed-in image of silver coated PVDF 3D printed approach 1 sample.

As the aforementioned methods of manufacturing electrodes did not provide sufficient mechanical and electrical properties, inkjet printing was implemented to manufacture the electrodes. To enhance the surface energy and chemical reactivity of the PVDF substrate, a preliminary plasma pretreatment step was executed, using PiezoBrush PZ3, from Intertronics (Oxfordshire, UK). The process involved exposure of the polymer surface to low-pressure gas plasma, leading to physical etching (micro-roughening) and chemical functionalization (introducing polar groups like -OH and -

COOH) [12]. The plasma treatment successfully increased the surface wettability, as seen in Fig. 13 (image captured from the inkjet printer). This crucial modification ensured the optimal spreading and adhesion of the printed silver ink, preventing the "beading up" effect and guaranteeing the formation of a uniform electrode. The ink used was JS-A211 Silver Nanoparticle Ink, from Novacentrix (Texas, USA).

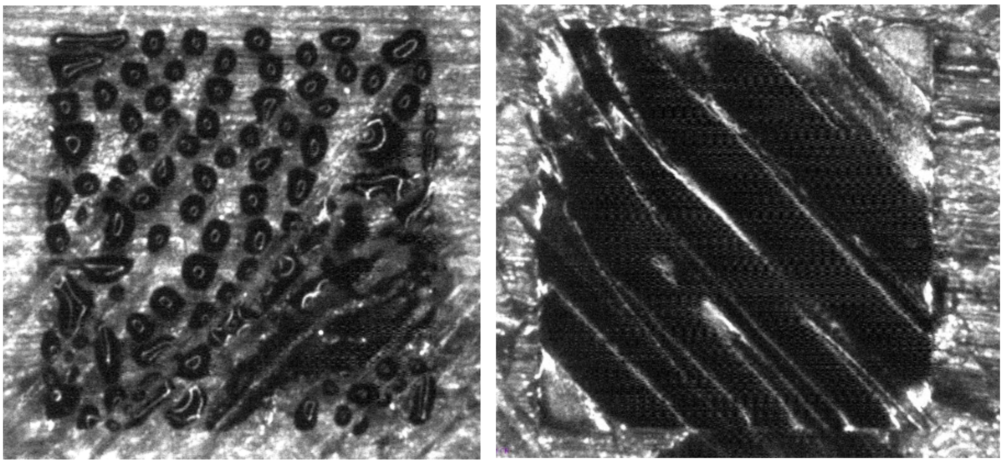


Fig. 13. Inkjet printing of silver ink onto PVDF substrates without (left) and with (right) plasma pre-treatment.

The printing of electrodes onto multiple PVDF substrates can be seen in Fig. 14 a, and a sample with 3 layers of silver ink can be seen in Fig. 14 b (image captured from the inkjet printer).

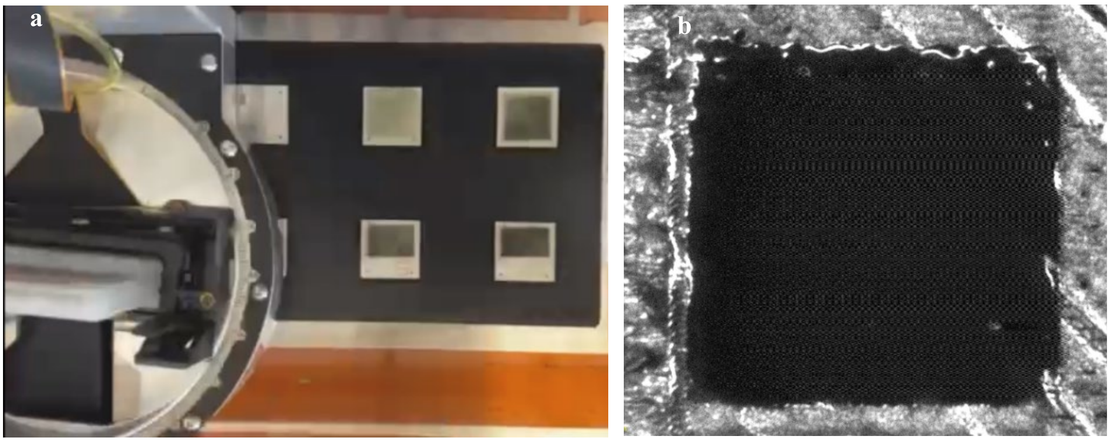


Fig. 14. (a) Inkjet printing of silver ink onto plasma pretreated PVDF substrates, (b) 3 layers of ink printed on sample.

Despite inkjet printing offering high-precision electrode fabrication using silver ink on PVDF, this technique suffered from several practical limitations that restrict its scalability for manufacturing large-format or structurally complex devices. First of all, during the poling process silicon oil was used to avoid electrical breakdown, provide uniform field distribution, and prevent arcing. After poling of inkjet-printed samples, it was observed that they exhibited structural degradation (the ink wore off) during the washing/ removal of the silicon oil, as seen in Fig. 15. The observed degradation of the films indicated insufficient mechanical and interlayer cohesion of the ink-based structures. The washing step induced significant wear and material loss, compromising structural integrity and functional reliability.

Moreover, high printing times were inherent to inkjet deposition, resulting in poor throughput for complex geometries. Furthermore, the use of specialized inks introduced frequent issues such as nozzle clogging due to particle agglomeration, viscosity shifts, and solvent evaporation, necessitating time-consuming maintenance [8]. Other challenges included the limited achievable film thickness per pass, requiring multiple layers to build up adequate conductivity, and the substantial time and energy required for the mandatory plasma pretreatment process to attain high wettability. Additionally, the significant recurrent cost of specialized cartridges represented a substantial financial burden for research and development compared to the relatively inexpensive consumables used in MEX [9]. Consequently, for the large-scale and rapid fabrication of integrated devices, especially those demanding the simultaneous deposition of structural substrates and functional elements, a robust, high-speed technique like multi-material 3D printing will be chosen.

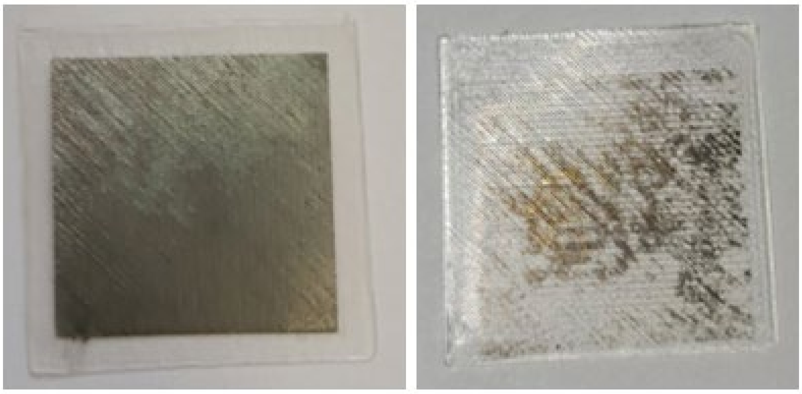


Fig. 15. Inkjet printed sample, before and after the removal of the silicon oil.

Summary

In this study, AM is utilized for 4D printing applications to develop piezopolymer metamaterials intended for distributed sensing and energy harvesting. Specifically, 3D printed PVDF films were manufactured and tested. Three distinct experimental integration strategies were evaluated: direct 3D printing of PVDF films with manually applied silver paste, printing directly onto aluminium foil substrates, and a novel chemical solvent-based deposition using a DMF and acetone mixture. 3D printed films were comprehensively characterized to prove the feasibility of the proposed approaches. DSC validated that the PVDF matrix remained thermally stable throughout the extrusion and post-print processing. Additionally, SEM and electrical resistance measurements confirmed the successful formation and structural composition of the conductive layers. While high-precision inkjet printing, aided by plasma pretreatment to increase surface wettability, was initially explored for electrode deposition, it demonstrated significant practical limitations. These included poor scalability, high printing times, nozzle clogging, and severe structural degradation (ink wear-off) during the post-poling silicon oil removal process. Consequently, this study advocates for a robust, high-speed multi-material extrusion (MEX) technique for the simultaneous deposition of structural substrates and functional elements as future work. This multi-material hybrid MEX platform unlocks new possibilities for the design and application of functional piezopolymers. By upscaling the proposed manufacturing method, it becomes possible to transition from isolated, simple planar films to intricate, volumetrically complex designs, such as multi-layered piezoelectric stacks, spatially distributed sensor arrays, and architected metamaterial lattices. Future research will focus on fully exploiting the scalability of the multi-material AM setup to fabricate highly complex, 3D-piezoelectric metamaterials, by optimizing the simultaneous printing of the thermoplastic matrix and the highly conductive thixotropic inks to further minimize interfacial resistance and improve overall structural integrity. A primary objective will be to transition from single-layer films and electrodes to large-scale architected structures, to evaluate their real-world performance in distributed structural health monitoring and energy harvesting applications.

Acknowledgement

Research project 4D-PIEZOUMME funded this work, which is implemented in the framework of H.F.R.I. call “Basic research Financing (Horizontal support of all Sciences)” under National Recovery and Resilience Plan “Greece 2.0” funded by the European Union – NextGenerationEU (H.F.R.I. Project No: 16580).

References

[1] Smart, B. E., Feiringa, A. E., Krespana, C. G., Hungb, M., Resnickb, P. R., et al., 1995, New industrial fluoropolymer science and technology, Macromol. Symposia, 98:753–767, DOI:10.1002/masy.19950980164.

[2] Tsonos, C., Pandis, C., Soin, N., Sakellari, D., Myrovali, E., et al., 2015, Multifunctional nanocomposites of poly(vinylidene fluoride) reinforced by carbon nanotubes and magnetite nanoparticles, Express Polymer Letters, 9/12:1104–1118, DOI:10.3144/expresspolymlett.2015.99.

[3] Jang, S., Baek, G., Cheon, M., Lee, C., Kim, T., et al., 2025, Studies on phase transformations and crystallinity changes of PVDF thin films via hot-pressing treatment, Polymer, 320/128094:1–8, DOI:10.1016/j.polymer.2025.128094.

[4] Ahn, Y., Lim, J. Y., Hong, S. M., Lee, J., Ha, J., et al., 2013, Enhanced piezoelectric properties of electrospun poly(vinylidene fluoride)/multiwalled carbon nanotube composites due to high β-phase formation in poly(vinylidene fluoride), Journal of Physical Chemistry C, 117/22:11791–11799, DOI:10.1021/jp4011026.

[5] Teng, H., 2012, Overview of the development of the fluoropolymer industry, Applied Sciences, 2/2:496–512, DOI:10.3390/app2020496.

[6] Inc., T. F. S., Thermofischer (SEM). [Online]. Available: https://assets.thermofisher.com/TFS-Assets/MSD/Datasheets/desktop-sem-datasheet-prox-DS0300.pdf. [Accessed: 10-Aug-2022].

[7] Cao, T., Yang, Z., Zhang, H., Wang, Y., 2024, Heliyon Inkjet printing quality improvement research progress : A review, Heliyon, 10/10:e30163, DOI:10.1016/j.heliyon.2024.e30163.

[8] Ko, S. H., Pan, H., Grigoropoulos, C. P., Luscombe, C. K., Frechet, J. M., et al., 2007, All-inkjet-printed flexible electronics fabrication on a polymer substrate by low-temperature high-resolution selective laser sintering of metal nanoparticles, Nanotechnology, 18/345202:1–8, DOI:10.1088/0957-4484/18/34/345202.

[9] Hutchings, I. M., Martin, G. M., 2012, Inkjet Technology for Digital Fabrication. Chichester: John Wiley & Sons.

[10] Kim, H., Torres, F., Wu, Y., Villagran, D., 2017, Integrated 3D printing and corona poling process of PVDF piezoelectric films for pressure sensor application, Smart Materials and Structures, 26/8:1–9, DOI:10.1088/1361-665X/aa738e.

[11] Wu, L., Jin, Z., Liu, Y., Ning, H., Liu, X., et al., 2022, Recent advances in the preparation of PVDF-based piezoelectric materials, Nanotechnology Reviews, 11:1386–1407, DOI:10.1515/ntrev-2022-0082.

[12] Pascu, M., Nicolas, D., Poncin-epaillard, F., Vasile, C., 2006, Surface modification of PVDF by plasma treatment for electroless metallization, Journal of Optoelectronics and Advanced Materials, 8/3:1062–1064, DOI:10.1002/3527605584.ch13.