Ion-Selective Sensors with Interdigitated Electrodes by Aerosol Jet Printing for Biomedical and Industrial Fields: a Preliminary Investigation

Giorgia Polidori
Department of Information Engineering
University of Brescia
Brescia, Italy
giorgia.polidori@unibs.it

Soufiane Mahraoui
Department of Information Engineering
University of Brescia
Brescia, Italy
soufiane.mahraoui@unibs.it

Mauro Serpelloni
Department of Information Engineering
University of Brescia
Brescia, Italy
mauro.serpelloni@unibs.it

***Abstract*— The development of portable and scalable ion-selective sensors (ISEs) is a critical step toward enabling real-time monitoring in biomedical diagnostics and industrial process control. This study focuses on the fabrication of potentiometric sensors with interdigitated electrodes (IDEs) using Aerosol Jet Printing (AJP) on Kapton and ceramic substrates. Multi-Walled Carbon Nanotubes (MWCNTs) were employed as the interface material, leveraging their proven ability to enhance signal performance, as identified in previous research.**

Structural characterization through profilometric and microscopic analyses confirmed the uniformity and accuracy of the printed interdigitated sensors, showing trace widths of 210 µm (Working Electrode) and 190 µm (Reference Electrode) with a spacing of 380 µm. The height of the traces increased from 3 µm (Ag/AgCl deposition) to 7.58 µm (final Ion Selective Membrane deposition). Potentiometric measurements demonstrated a good Limit of Detection (4.8×10^{-6} M) and a sensitivity of 46.68 mV/decade with a high linearity coefficient ($R^2 = 0.999$) in capturing potassium ions. Potassium was selected as a model analyte due to its dual importance in physiological and industrial systems.

These preliminary findings highlight the feasibility and potential of AJP-fabricated sensors with MWCNTs interfaces for accurate ion detection in complex matrices. The scalability of this approach, combined with the versatility of MWCNTs-based materials, paves the way for the development of advanced multi-ion sensing platforms. Future improvements will focus on enhancing deposition uniformity and expanding detection capabilities to other relevant ions such as sodium and calcium.

Keywords*— *solid-contact ion-selective electrodes; potassium ion detection; printed electrochemical sensors; wearable sensors; biomedical monitoring

I. Introduction

Electrochemical ion-selective sensors (ISEs) are emerging as key tools for accurate and continuous monitoring of specific ions in complex biological systems, with applications ranging from medical diagnostics to human health monitoring [1]. These sensors operate based on the principles of potentiometry, where the potential difference generated between a working electrode and a reference electrode correlates with the ion activity in a solution. Unlike traditional laboratory methods, ISEs offer the advantage of real-time, in situ measurements, making them suitable for both biomedical and environmental applications [2]. Among these, potassium-sensing sensors (K^+) play a particularly important role, given the critical function of this ion in numerous physiological processes. Potassium plays a crucial role in maintaining cellular homeostasis, nerve signal transmission, and muscle function, and its dysregulation is associated with critical conditions such as cardiac arrhythmias, renal dysfunction, and muscle disorders. Electrochemical sensors designed for potassium detection rely on Ion Selective Membranes (ISM) that incorporate ionophores – molecules that facilitate the selective transport of potassium ions across the membrane – ensuring high specificity in complex biological fluids [3]. This electrolyte is integral to the maintenance of intracellular and extracellular ion gradients, regulated by complex mechanisms involving cell membrane pumps and ion channels. Such precise regulation underscores the necessity of sensors capable of capturing even the slightest changes in potassium levels. Significant alterations in its concentrations can indicate serious clinical conditions, such as hypokalemia or hyperkalemia, often related to cardiac, renal, or metabolic diseases [4]. Consequently, the availability of accurate and reliable sensors for real-time potassium monitoring is a priority in biomedical research and the development of advanced diagnostic technologies.

Conventional potassium monitoring relies on laboratory methods such as flame photometry, spectroscopy, and, although less common, ion chromatography [5]. These traditional laboratory techniques, while highly accurate, are often cumbersome, expensive, and not suitable for real-time or point-of-care applications. In response to these limitations, electrochemical sensors have emerged as promising alternatives, offering portability, simplicity, and potential for integration into wearable or decentralized diagnostic systems. Recent advancements include the integration of microneedle-based potassium sensors for minimally invasive monitoring in interstitial fluid [6]. These technologies have demonstrated promising applications in continuous monitoring scenarios, including wearable devices, thereby enhancing patient comfort and adherence in chronic disease management [7].

A key factor in the advancement of these sensors is the use of printed electronics, which enables the precise, scalable and cost-effective fabrication of complex sensor architectures. Among various techniques, Aerosol Jet Printing (AJP) stands out for its ability to deposit materials with high accuracy and minimal waste on a wide variety of substrates, including flexible and rigid surfaces. AJP has demonstrated its effectiveness in the fabrication of sensors for potentiometric, voltammetric, amperometric, and impedimetric measurements, as well as in their integration with conventional integrated circuits (ICs) to form flexible hybrid systems [8]. These systems combine sensing, data processing and wireless communication, enabling fully operational solutions for soil monitoring and other applications. In addition, this printing technique enables

intricate designs, such as interdigitated electrodes (IDEs), with a resolution that makes it a suitable and consonant choice for the development of next-generation electrochemical sensors. A crucial advantage of using IDEs in potentiometric sensors is that they eliminate the need for a counter electrode, unlike traditional three-electrode electrochemical systems. This simplification reduces fabrication complexity and allows for direct potentiometric readout using only a working and reference electrode. Moreover, since IDEs offer a high surface-to-volume ratio and enhanced ion interaction due to their interdigitated geometry, they improve signal stability and response time, making them particularly effective for miniaturized, printed sensors [9], [10].

This study introduces a novel potassium-selective sensor fabricated using Aerosol Jet Printing (AJP) on flexible Kapton and ceramic substrates. The sensor integrates IDEs and a polyvinyl chloride (PVC)-based membrane, leveraging Multi-Walled Carbon Nanotubes (MWCNTs) as the interface material for enhanced electrical performance [11]. The PVC-based membrane, which incorporates potassium-selective ionophores, plays a key role in the sensor's functionality. Acting as the ion-selective recognition layer, the membrane facilitates selective binding of potassium ions, ensuring accurate potentiometric measurements. Its polymeric nature provides flexibility and compatibility with the printed substrates, while its chemical composition ensures stability and durability in varying environmental and biological conditions [12].

Since IDE-based potentiometric sensors do not require a counter electrode, their fabrication via AJP becomes even more efficient, reducing the number of printed layers and simplifying the overall device architecture. This advantage can not only promote improved reproducibility, but also contributes to the development of scalable and cost-effective sensing platforms for medical and industrial applications [13].

Therefore, the main objective of this study is to demonstrate the feasibility of using Aerosol Jet Printing (AJP) to fabricate miniaturized, scalable, and potassium-selective potentiometric sensors with interdigitated electrodes. Specifically, the work seeks to evaluate the structural integrity through profilometric and microscopic studies, electrochemical performance, and material compatibility of sensors incorporating MWCNT-based interfaces and ion-selective PVC membranes printed on flexible (Kapton) and rigid (ceramic) substrates. Focusing on potassium as a model ion, these sensors have significant potential for integration into wearable devices for real-time monitoring of electrolytes in body [14], with applications in medical diagnostics [15], personalized healthcare, and industrial process control. Future developments will aim to refine the membrane composition, exploring alternative polymers and ionophores to enhance selectivity, extend the sensor's operational lifespan, and reduce cross-interference with other ions present in biological fluids.

II. Materials and Methods

A. Ion-Selective State Sensors Design and Composition

Sensors fabricated using Aerosol Jet Printer (AJ300, Optomec, Albuquerque, NM, USA) technology have a standardized structure. A total of twenty sensors were generated, ten with Kapton substrate and ten with ceramic substrate, characterized by: conductive inks such as carbon used for making the Working Electrode (WE) (C ink, EXP 2652-28, Creative Materials Inc., Ayer, MA, USA) and silver-silver chloride ink (Ag/AgCl ink, XA-3773, Fujikura Kasei Company Ltd., Tokyo, Japan) used for making the Reference Electrode (RE); interface material such as Multi-Wall Carbon Nanotubes (MWCNTs), to improve conductivity and interaction with the membrane; and ion-sensitive membrane based on PolyVinyl Chloride (PVC), specifically for detecting potassium ions.

The membrane was prepared using a classical approach, fabricated by [16], including potassium-specific ionophores. This structure and composition allow effective detection of potassium ions. The potassium-selective membrane was printed with AJP directly on the WE to ensure uniformity and reproducibility. This configuration avoids the need for a counter electrode, as no current flows during potentiometric measurements. The sensors were printed on ceramic and Kapton substrates, chosen for their robustness and flexibility respectively.

The geometric design chosen for the sensor is interdigitated (Fig. 1). This configuration offers several advantages over conventional circular geometries typically found in commercially available sensors. Due to its comb-like structure, the interdigitated electrode design provides a significantly larger active surface area, promoting enhanced interaction with the sample and thereby improving sensitivity. Furthermore, this geometry allows for a more efficient distribution of the electric field, resulting in higher signal-to-noise ratios and better detection limits. Additionally, the interdigitated electrode array (IDEA) design is well-suited for integration with microelectronic systems, enabling the development of compact, multi-sensor platforms for multicomponent analysis, as demonstrated in previous studies [17]. Such integration is particularly advantageous for potentiometric sensing applications, where improved sensitivity and miniaturization are crucial.

The geometry was created with 2D (Fig. 1A) and 3D (Fig. 1B) CAD software, where there are nine interdigitations with a track thickness of 220 µm and a track spacing of 380 µm.

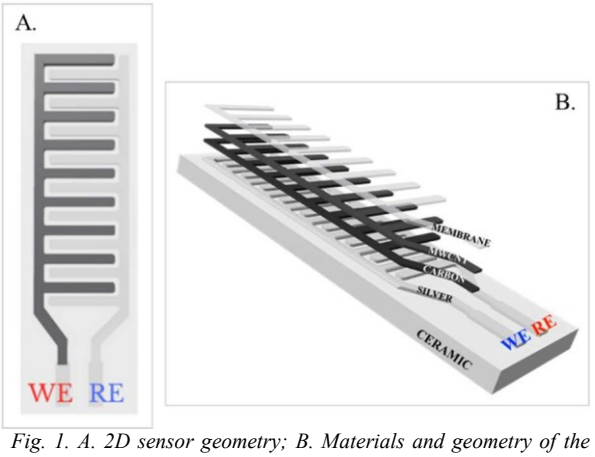

Fig. 1. A. 2D sensor geometry; B. Materials and geometry of the 3D sensor.

B. Parameters & Aerosol Jet Printing (AJP) Process

Aerosol Jet Printing (AJP) technology has been evaluated for sensor fabrication because of its ability to print on a

variety of substrates, both two-dimensional (2D) and three-dimensional (3D). This approach allows for complete interconnections on the sensor, including conductive inks, interface materials and membranes.

One of the main features of the AJP is the support of multiple ink input mechanisms, allowing materials to be combined or modified during the printing process. This makes AJP a particularly suitable technology for rapid development and optimization of custom sensors.

AJP utilizes two main atomization techniques depending on the properties of the ink and the requirements of the printing process [18]. The two different atomization processes can be seen in Fig. 2.

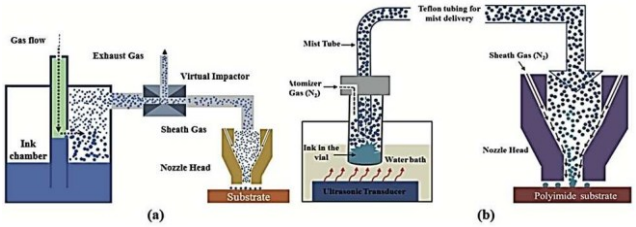

Fig. 2. (a) Pneumatic Atomizer. (b) Ultrasound Atomizer. [19]

One of the two processes is the pneumatic atomizer in which gas is introduced into a sealed chamber containing the ink, forming droplets between 1 and 5 µm in diameter. These droplets are transported to the nozzle via a flow of inert gas and deposited on the substrate. This method supports ink viscosities between 1 and 1000 centipoise (cPs), allowing the creation of traces 10-20 µm wide. However, a minimum ink volume of 40 mL is required for proper atomization. The other process is the ultrasonic atomizer, in which the piezoelectric transducer immersed in water generates microdroplets from the ink, which are directed onto the substrate by a flow of inert gas. This method is limited to inks with viscosities between 1 and 20 cPs, but requires only 1 mL of ink for atomization.

The printing flow was optimized for two types of substrates: ceramic and Kapton. Ten sensors were printed for each substrate, for a total of twenty devices. Initially, silver-silver chloride (Ag/AgCl) was printed, which was applied for the working (WE) and reference (RE) electrodes. Subsequently, the substrates were baked in an oven at 125 °C for 30 min. For the WE working, carbon was then printed and heated at 175 °C for 15 minutes so that the conductive ink would set. Next, conductive paste was deposited to form the contacts, then it was connected with two conductive wires and then heated to 120°C for 3 hours so as to ensure adhesion. Next, printing of the MWCNTs was performed to fabricate the working electrode with subsequent heating to fix the material at 40°C for 1 hour. Finally, the membrane was printed by the ultrasound atomizer technique on the WE and dried at room temperature for 3 hours.

The materials that make up the sensor and their positioning are shown in Fig. 1B. Ten sensors were printed for each substrate, for a total of twenty sensors. Finally, both a metrological and a morphological characterization was carried out for both types of substrates.

The choice of transduction material was dictated by the evaluation of the metrological characteristics previously carried out for all the various interface materials. The process parameters of AJP printing are shown in the following Table 1. For the MWCNTs, the printing technique adopted was that with the pneumatic atomizer, as the amount of material available exceeded 40 mL.

Tab. 1 AJP process parameters. SF: Sheat Flow (SCCM); AT: Atomizer Flow (SCCM); EF; Exhaust Flow (SCCM); PS: Print Speed (mm/s); PT: Plate Temperature (°C); CT: Curing Temperature (°C); Ct: Curing time (min); TS: Tip Size (µm); T: Technique; PC: Piezoelectric Current (mA): RT: Refrigerator temperature (°C). P: Pneumatic; U: Ultrasound.

	Ag/AgCl	***Carbon***	***MWCNTs***	***ISM***
SF	*250*	*910*	*600*	*80*
AF	1100	1300	850	50
EF	1040	1000	650	-
PS	2.5	2.5	2	1
PT	75	75	40	-
CT	125	175	60	room
Ct	30	15	60	180
TS	750	750	750	-
T	P	P	P	U
PC	-	-	-	460
RT	-	-	-	21

C. Morphological Characterization

Morphological characterization included optical and profilometric evaluation. Images were acquired using an NB50T optical microscope (Orma Scientific, Sesto San Giovanni, Milan, Italy) with a trinocular zoom system of 0.8×-5× and light-emitting diode (LED) illumination, at scales of 0.09 mm, 0.15 mm and 0.47 mm. This made it possible to visualize the width of the traces and thus the distance between them through the evaluation on both substrates of the different deposited layers: Ag/AgCl, carbon, MWCNTs and ISM. As the membrane is transparent, it was not possible to acquire images for the ceramic substrate, but only for the Kapton substrate. However, for a more detailed analysis, the Profilm3D® profilometer (Filmetrics Headquarters, 10655 Roselle St. San Diego, CA 92121) was used. Again, the profilometer's criteria for reflective substrates prevented the thickness reading on the opaque ceramic substrate.

D. Potentiometric Experimental Framework

Measurements were performed with a Palmsens3 EIS portable potentiostat (Palmsens, Compact Electrochemical Interfaces, Houten, Utrecht, The Netherlands), which enables potentiometric measurements.

As can be seen form the Fig. 3, the potentiostat is connected to a computer that records the device's measurements. The connection to the sensor was established manually by soldering wires directly from the potentiostat to the electrode terminals. Each sensor was mounted in a small beaker containing 100 mL of distilled water and the solution was continuously stirred at 200 r/min through an ARGO LAB M2-D Pro magnetic stirrer (Giorgio Bormac S.r.l., Carpi, Italy) placed underneath it. This ensured homogeneity during the measurement process. Every 100 seconds, a micropipette of potassium chloride (KCl) is added to the solution, which is agitated by the stirrer to accelerate equilibrium. After each test, each sensor is cleaned with distilled water for approximately 60 seconds before being dried at room temperature.

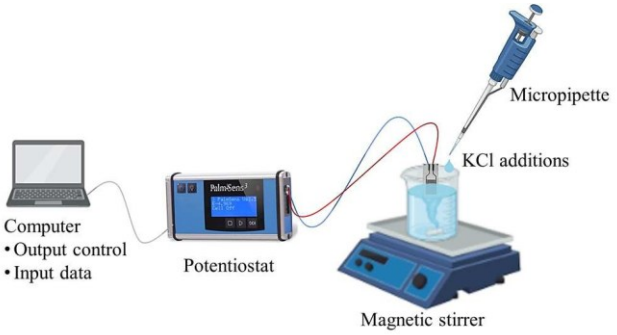

Fig.3. Experimental set up

Table 2 illustrates the additions of KCl into the distilled water solution with the micropipette every 100 seconds, for a total of five additions, or one addition every decade (range 10^{-6} – 10^{-2}), for a 600-second experiment.

To calculate the additions, the classical formula for dilutions $C_iV_i=C_fV_f$ was used, where C_i and V_i are the initial concentration and initial volume in the micropipette, respectively. C_f is the final concentration desired to be obtained in the solution, and V_f is the sum of 100 ml of distilled water and the volume of KCl added with the micropipette.

Tab.2. KCl additions.

C_f [M]	C_i [M]	Micropipette volume (V_i) [µL]
10^{-6}	0.01	10
10^{-5}	0.01	90
10^{-4}	0.34	26
10^{-3}	0.34	266
10^{-2}	1	912

III. Results

A. Morphological Characterization

The sensor printed on the ceramic substrate is shown in Fig. 4.

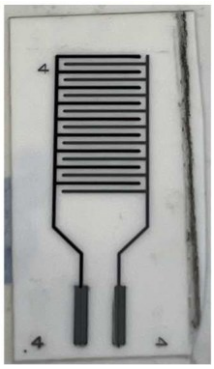

Fig.4. Interdigitated sensor printed in AJP on a ceramic substrate.

Through the microscope, a track width of 190 µm was assessed for RE, as only Ag/AgCl was present, while for WE, after carbon deposition, a track width of 210 µm was seen. The spacing between the two tracks was 380 µm. The microscope image with 0.15 mm scale can be seen in Fig. 5.

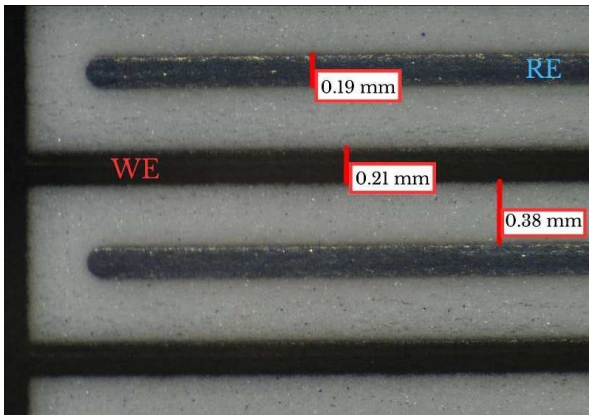

Fig.5. Interdigitated sensor printed in AJP on a ceramic substrate viewable under a microscope with 0.15 mm scale.

Morphological acquisition by profilometer was performed on the initial deposition for the WE of Ag/AgCl in 3D (Fig. 6A) and 1D (Fig. 6B), and it can be seen that the trace height reached 3 µm. Next, carbon was deposited only on the WE, unlike Ag/AgCl, which was deposited by both WE and RE.

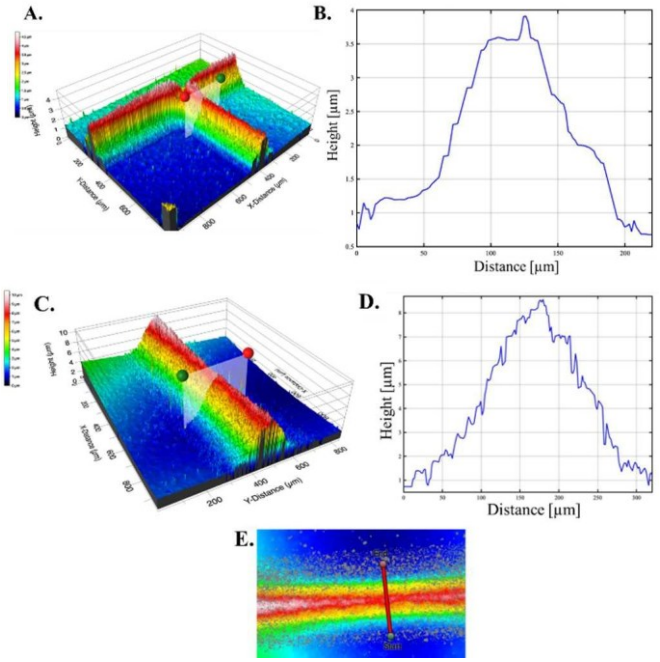

Fig.6. Profilometric evaluation for initial WE deposition. A. Ag/AgCl deposition in 3D; B. Ag/AgCl deposition in 1D; C. 3D morphology of Ag/AgCl and carbon deposition; D. 1D trace of Ag/AgCl and carbon deposition; E. 2D trace of Ag/AgCl and carbon deposition.

Afterwards, MWCNTs were printed on both substrates, and it can be seen from Fig. 7 that the material is not uniformly deposited (in gray).

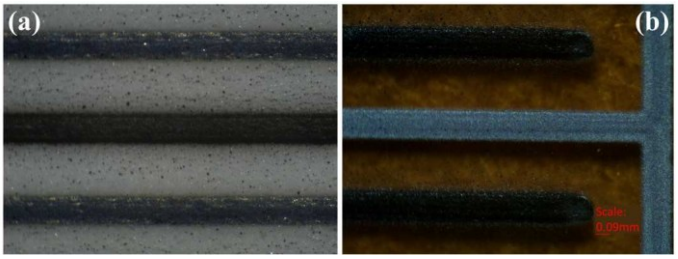

Fig.7. Optic evaluation for MWCNTs at a 0.09 mm scale. (a) Sensor on ceramic substrate; (b) Sensor on Kapton substrate.

Once the membrane was deposited, images were captured only for the Kapton substrate (being transparent, it is not visible on the ceramic substrate). As can be seen from Fig. 8, the membrane is observed to have a width of 510 µm, the smallest distance from the RE measured 190 µm and the largest measured 293 µm. However, for a more detailed analysis, the profilometer shows a trace width of 300 µm and a final thickness of 7.58 µm for WE.

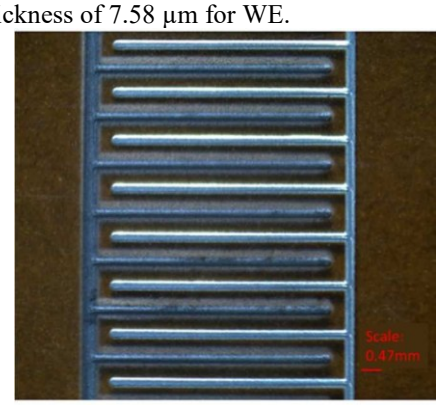

Fig.8. ISM printed by AJP on Kapton substrate at a 0.47 mm scale.

To summarize it, all the specific characteristics of the heights and widths of the inks used to print the sensor can be seen in Fig. 9 and Table 3. Also, a distance between the traces of 335 µm can be seen.

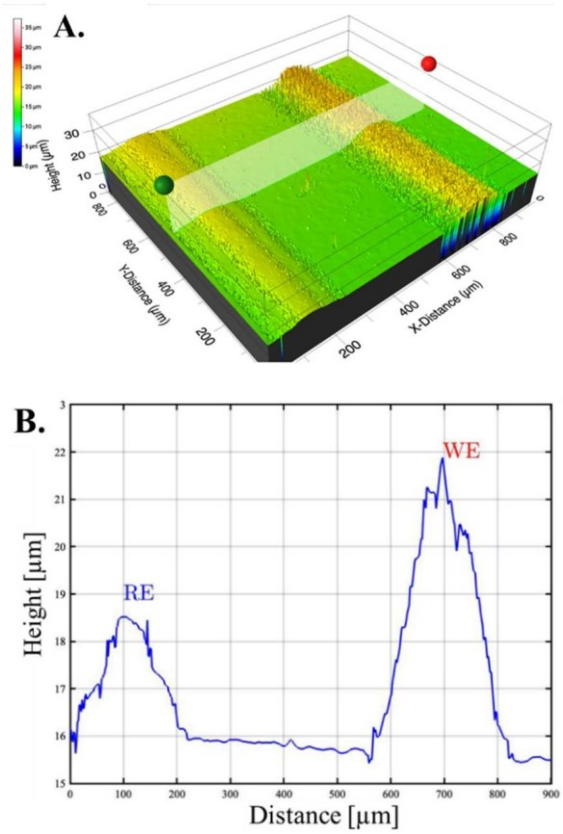

Fig.9. Track spacing. A. 3D; B. 1D.

Tab. 3 Morphology of the final interdigitated sensor.

	Width (µm)	Height (µm)
RE	190	1.3
WE	300	7.58

B. *Electrochemical Characterization*

Characterization was conducted by evaluating sensitivity and Limit of Detection (LOD) on a test performed on a single sensor with a ceramic substrate. Fig. 10 shows the plot of potential versus time for a test in which the membrane, at the concentration of 10^{-2}, fails to detect ions accurately. This phenomenon results in a signal that decreases rather than remaining stable, highlighting a limitation in the membrane's ability to detect at such high concentrations. At a concentration of 10^{-2} the signal clearly decreases due to membrane thickness, sure enough Tingting Han *et al.* demonstrated an abnormal potentiometric response of thin-layer ISM [20].

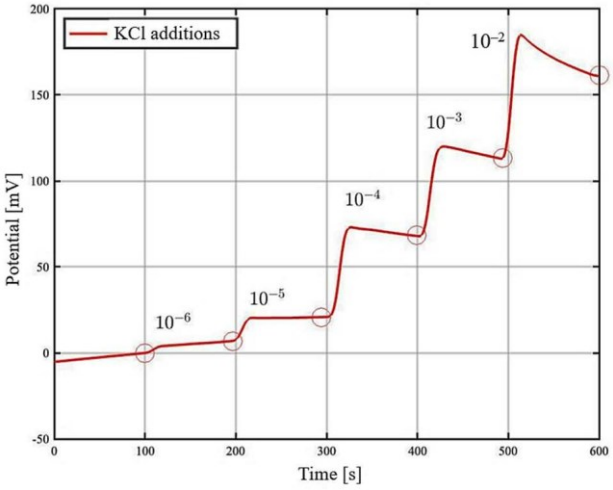

Fig.10. Potential-time graph for a test

The calibration line (Fig. 11) was performed for a single test on a single ceramic sensor and found to be 46.6835 - log(C) + 254.30 [mV], with a sensitivity of 46.68 mV/dec and a linearity coefficient R^2 of 0.999. The LOD of 4.8 x 10^{-6} was then evaluated.

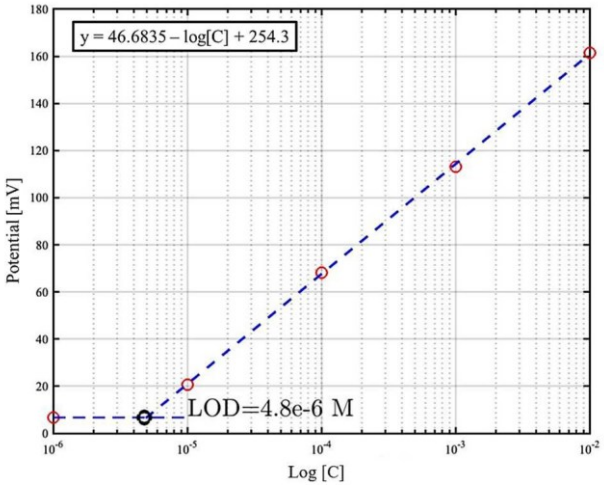

Fig.11. Calibration straight line and Limit of Detection (LOD) for the average of 3 tests

IV. Conclusion and Future Developments

This study demonstrated the feasibility of fabricating potentiometric ion-selective sensors by Aerosol Jet Printing (AJP) using interdigitated electrodes on Kapton and ceramic substrates and Multi-Wall Carbon Nanotube (MWCNTs) interfaces. The sensors exhibited high accuracy in deposition, confirmed by profilometric and microscopic analyses. The

uniform trace widths and spacing were measured as follows: WE width of 210 µm, RE width of 190 µm, trace spacing of 380 µm, and a final trace height of 7.58 µm after ISM deposition. The nonuniform distribution of MWCNTs, due to overspray caused by the low viscosity of MWCNTs ink (about 3 cPs), remains a challenge, potentially leading to short circuits and reduced sensitivity.

Electrochemical characterization indicated a sensitivity of 46.68 mV/decade and a Limit of Detection (LOD) of 4.8×10^{-6} M, with a strong linearity coefficient of $R^2 = 0.999$. Although the sensor showed reliable detection for low concentrations of potassium ions, its performance declined at higher concentrations (10^{-2} M) due to membrane thickness issues. These results confirm the reliability of the sensor for low-concentration detection, making it suitable for various biomedical and industrial applications.

The adoption of an interdigitated electrode geometry proves to be advantageous compared to commercially available circular geometries, as its comb-like structure offers a larger active surface area, more efficient electric field distribution, and improved sensitivity. Moreover, it enables significant membrane savings by requiring a smaller membrane area to achieve effective detection.

Aerosol Jet Printing (AJP) was selected for its unique ability to print on flexible substrates, such as Kapton, which can be adhered to curved or irregular surfaces like container walls, enhancing the versatility of the sensors. Additionally, AJP allows the possibility of future developments involving 3D substrates, enabling the fabrication of complex and conformable sensor systems.

Future improvements will focus on optimizing MWCNTs deposition to ensure uniformity, enhancing membrane performance at higher concentrations, and expanding detection capabilities to include other essential ions such as sodium and calcium. Furthermore, developing sensors on 3D-printed substrates will be a promising approach to improve integration and adaptability for real-time diagnostics and industrial process control. Overall, this study represents a significant step forward in developing scalable, portable, and accurate ion detection systems.

REFERENCES

[1] R. Sharma, M. Geranpayehvaghei, F. Ejeian, A. Razmjou, and M. Asadnia, "Recent advances in polymeric nanostructured ion selective membranes for biomedical applications," *Talanta*, vol. 235, no. August, p. 122815, 2021, doi: 10.1016/j.talanta.2021.122815.

[2] F. Criscuolo, M. I. N. Hanitra, I. Taurino, S. Carrara, and G. De Micheli, "All-Solid-State Ion-Selective Electrodes: A Tutorial for Correct Practice," *IEEE Sens. J.*, vol. 21, no. 20, pp. 22143–22154, 2021, doi: 10.1109/JSEN.2021.3099209.

[3] G. Polidori, S. Tonello, and M. Serpelloni, "Ion-Selective All-Solid-State Printed Sensors: A Systematic Review," *IEEE Sens. J.*, vol. 24, no. 6, pp. 7375–7394, Mar. 2024, doi: 10.1109/JSEN.2024.3354321.

[4] C. M. Weaver, "Potassium and health," *Adv. Nutr.*, vol. 4, no. 3, pp. 368S-377S, 2013, doi: 10.3945/an.112.003533.

[5] B. S. Yu, L. H. Nie, and S. Z. Yao, "Ion chromatographic study of sodium, potassium and ammonium in human body fluids with bulk coustic wave detection," *J. Chromatogr. B Biomed. Appl.*, vol. 693, no. 1, pp. 43–49, 1997, doi: 10.1016/S0378-4347(97)00019-4.

[6] Z. Wu *et al.*, "Interstitial fluid-based wearable biosensors for minimally invasive healthcare and biomedical applications," *Commun. Mater.*, vol. 5, no. 1, 2024, doi: 10.1038/s43246-024-00468-6.

[7] J. Baranwal, B. Barse, G. Gatto, and G. Broncova, "Electrochemical Sensors and Their Applications: A Review," 2022.

[8] Y. Dong, X. Min, and W. S. Kim, "A 3-D-Printed Integrated PCB-Based Electrochemical Sensor System," *IEEE Sens. J.*, vol. 18, no. 7, pp. 2959–2966, 2018, doi: 10.1109/JSEN.2018.2801459.

[9] "Aerosol-Jet Printed Sensors for Environmental Safety and Health Monitoring: A Review." doi: 10.1002/admt.202300030.

[10] Y. Khan, A. Thielens, S. Muin, J. Ting, C. Baumbauer, and A. C. Arias, "A New Frontier of Printed Electronics: Flexible Hybrid Electronics," *Adv. Mater.*, vol. 32, no. 15, pp. 1–29, 2020, doi: 10.1002/adma.201905279.

[11] S. Li, X. Feng, H. Liu, K. Wang, Y. Z. Long, and S. Ramakrishna, "Preparation and application of carbon nanotubes flexible sensors," *J. Semicond.*, vol. 40, no. 11, 2019, doi: 10.1088/1674-4926/40/11/111606.

[12] L. van de Velde, E. d'Angremont, and W. Olthuis, "Solid contact potassium selective electrodes for biomedical applications – a review," *Talanta*, vol. 160, pp. 56–65, 2016, doi: 10.1016/j.talanta.2016.06.050.

[13] N. Afsarimanesh, A. Nag, M. E. E. Alahi, T. Han, and S. C. Mukhopadhyay, "Interdigital sensors: Biomedical, environmental and industrial applications," *Sensors Actuators, A Phys.*, vol. 305, p. 111923, 2020, doi: 10.1016/j.sna.2020.111923.

[14] S. Jo, D. Sung, S. Kim, and J. Koo, "A review of wearable biosensors for sweat analysis," *Biomed. Eng. Lett.*, vol. 11, no. 2, pp. 117–129, 2021, doi: 10.1007/s13534-021-00191-y.

[15] A. la Grasta, M. De Carlo, A. Di Nisio, F. Dell'Olio, and V. M. N. Passaro, "Potentiometric Chloride Ion Biosensor for Cystic Fibrosis Diagnosis and Management: Modeling and Design," *Sensors*, vol. 23, no. 5. 2023. doi: 10.3390/s23052491.

[16] G. Polidori, S. Tonello, M. Serpelloni, M. Giamberini, X. Montane, and J. A. Reina, "Preliminary Study on Printed Membrane by Aerosol Jet for Ion Detection in Industrial Field," *2024 IEEE Int. Work. Metrol. Ind. 4.0 IoT, MetroInd4.0 IoT 2024 - Proc.*, pp. 1–6, 2024, doi: 10.1109/MetroInd4.0IoT61288.2024.10584232.

[17] A. Bratov, N. Abramova, and A. Ipatov, "Recent trends in potentiometric sensor arrays-A review," *Anal. Chim. Acta*, vol. 678, no. 2, pp. 149–159, 2010, doi: 10.1016/j.aca.2010.08.035.

[18] N. J. Wilkinson, M. A. A. Smith, R. W. Kay, and R. A. Harris, "A review of aerosol jet printing—a non-traditional hybrid process for micro-manufacturing," *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 11, pp. 4599–4619, 2019, doi: 10.1007/s00170-019-03438-2.

[19] S. A. and A. B. Saleem Khan, "Smart Manufacturing Technologies for Printed Electronics," *Intech*, vol. 11, no. tourism, p. 13, 2019, [Online]. Available: https://www.intechopen.com/chapters/69281

[20] T. Han, A. V. Kalinichev, Z. Mousavi, K. N. Mikhelson, and J. Bobacka, "Anomalous potentiometric response of solid-contact ion-selective electrodes with thin-layer membranes," *Sensors Actuators B Chem.*, vol. 357, no. January, p. 131416, 2022, doi: 10.1016/j.snb.2022.131416.