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Processing-dependent Thermal Response of Nanostructured Platinum Thin Films Fabricated via Spark Ablation

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Abstract— In this work, we report a simple, scalable, and dry fabrication technique for realizing thin-film platinum resistance temperature detectors (RTDs), utilizing spark ablation technology. Pure spark-ablated platinum nanoparticles, with an average diameter of around 2.2 nm, were directly deposited through chemical-free impaction printing onto the substrate, enabling direct sensor patterning without complex processing steps. Experimental investigations revealed that higher deposition speeds produce sparser and thermally unstable films, with 1 mm/min identified as the optimal printing rate. Additionally, it was established that the film temperature coefficient of resistance (TCR) improves with increasing layer thickness, achieving a maximum mean TCR of $2.17 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$ for an 8-layer RTD. The printed Pt sensor demonstrated linear temperature-resistance characteristics while maintaining high stability and repeatability over multiple thermal cycles, spanning 25–200 °C. This study lays the groundwork for advancing practical and cost-effective printed thermal sensing technologies.

Keywords—Platinum, Resistive Temperature Detectors, Printed, Spark Ablation, Nanoparticles

I. INTRODUCTION

With continual advancements in technology, the demand for effective temperature monitoring has grown substantially across industries, driven by the need to improve reliability and safety, and ensure consistent performance [1]. For instance, continuous thermal monitoring of industrial electronics could help in early fault diagnosis of critical components. This would allow for predictive maintenance strategies that reduce costs by scheduling repairs only when actually needed [2]. Among industrial temperature sensing solutions, resistance temperature detectors (RTDs) are gaining traction due to their exceptional stability and linear response characteristics, even in challenging environments. The resistance of the sensing layer, typically made from pure metal, usually increases with temperature, which is known as positive temperature coefficient (PTC) behaviour. This is primarily due to the scattering of electrons by lattice vibrations. As the temperature of the metal increases, the number of phonons generated within the material increases and they collide with the free electrons responsible for conducting, causing them to scatter. At the macroscopic level, this leads to an increase in the electrical resistivity of the material [3].

Recent research has provided valuable insights into the performance and reliability of thin-film RTDs. Platinum (Pt) has been highlighted as an exceptional heat-sensitive material due to its high melting point (1772 °C), chemical stability even at elevated temperatures, and relative high TCR and linearity over a wide temperature range. This simplifies the interpretation of sensor data, making their implementation in hardware devices more smooth and efficient [4, 5].

While integration of sensors into the existing hardware technologies enhances system functionality, it also inevitably adds to the overall system cost, making their affordability a key factor for widespread adoption [6]. Traditional microfabrication methods rely on subtractive methods such as blanket material deposition, photolithography, and etching for each layer in the device stack [7]. Printed sensors present a promising low-cost alternative; however, they also come with certain limitations. Some of these techniques often necessitate the utilization of hazardous and expensive precursors, leading to the generation of chemical waste byproducts. Besides, the properties of the nano-ink plays a key role in determining their suitability with the printing technology as well as the quality of the resulting thin films. Additionally, the presence of potential surface contaminants can reduce the conductivity of nano-inks, posing additional barriers to the eco-friendly development of sensors [8,9]. This highlights the need for extensive research in advanced sensor fabrication technologies that minimize material usage, fabrication complexity, and reduce costs to fully leverage their capabilities.

In this work, we demonstrate for the first time the use of spark ablation combined with impaction printing to fabricate nanostructured platinum (Pt) thin films for temperature sensing applications. The custom nature of this process will enable direct integration of the sensor architecture into compact or irregularly shaped areas, where conventional off-the-shelf sensors cannot be effectively deployed. Spark ablation is a dry, versatile, and chemical-free technique that requires only a controlled atmospheric-pressure gaseous environment and a pair of electrically conductive electrodes for the synthesis of nanoparticles (NPs) [10]. Additionally, it functions on-demand with short warm-up time, thus minimizing material wastage and energy usage. The aerosol containing the NPs can be deposited by inertial impaction on a range of substrates, as long as they are compatible with ~1 mbar vacuum [11,12].

This study presents that by systematically adjusting the key processing parameters, a precise control over the electrical and thermal behavior of the printed films can be achieved. We demonstrate that it is possible to enhance the temperature coefficient of resistance (TCR) from $1.4 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$ to $2.17 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$. Furthermore, the fabricated Pt RTD exhibited good repeatability and stability, even without the use of any protective layer. This approach represents a significant advancement towards eliminating the need for lithographic or wet-chemical processing steps, thus enabling direct patterning of the functional sensor on the desired substrate and providing a more efficient alternative to the conventional fabrication methods.

II. EXPERIMENTAL SECTION

A. Material synthesis and deposition

Platinum nanoparticles were synthesized using a spark ablation generator (VSP G1, VSParticle B.V.) equipped with a pair of 99.999% pure platinum electrodes, placed with a gap of 1 mm between them. The process is driven by a high-voltage, repetitive spark discharge between the opposing electrodes, resulting in the ablation of electrode material and the formation of a supersaturated metal vapor. This vapor is subsequently carried away by a nitrogen carrier gas, flowing at 1.5 L/min around the electrodes. During the ultrafast quenching caused by the rapid cooling from the carrier gas, nuclei form and grow by condensation, eventually resulting in nanoparticles with diameters below 20 nm [10,13]. The aerosol is then directed to an impaction printer where a pressure drop across the nozzle accelerates the gas stream and imparts sufficient inertia to the nanoparticles to impact and immobilize on the substrate. Here, a nozzle with a throughput of 0.08 L/min was employed, positioned 0.5 mm above the substrate, and integrated with programmable XYZ motion to enable precise patterning control. Fig. 1 provides a schematic representation of the nanoparticle synthesis and deposition process.

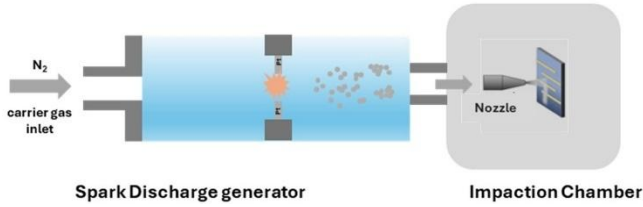


Fig. 1. Schematic of the experimental setup consisting of a spark generator connected to a printing chamber with XYZ-stage that contains the sample.

It is to be noted that, at higher spark energies, unwanted clusters and overspray of NPs across the printed trace were found. This was due to the increased particle generation at higher energies, which heightened the likelihood of particle collisions while in the aerosol state. Thus, to avoid non-uniform layer thicknesses, an optimized spark current of 5 mA and voltage of 1 kV were used in this study.

The platinum thin films were printed on 10 mm x 10 mm Si chips, patterned with 10/100 nm Cr/Au electrodes for four-point electrical measurements. Prior to the temperature-dependent studies, the printed films were annealed at 600 °C for approximately 1 hour in an N₂ atmosphere to stabilize the nanostructured Pt thin film layer.

B. Characterization

The change in resistance of the nanostructured platinum sensing layer was measured using a Cascade probe station with temperature control, in combination with an E5270B outfitted with E5287A HRSMUs. Temperature-dependent characterizations were carried out over the range of 25 to 200 °C in ambient conditions. The temperature of resistance (TCR), a critical parameter for characterizing the performance of the temperature sensor, was determined by:

$$TCR = \frac{R_T - R_0}{R_0(T - T_0)} \quad (1)$$

Where, R_0 and R_T represent the resistance of the sensing layer

at room temperature (25 °C) and that of the measured temperature, respectively.

The morphology of the platinum film printed using the optimized processing conditions was analyzed using a Hitachi Regulus 8230 scanning electron microscope (SEM) operated at 2kV acceleration voltage. The surface roughness was analyzed using a Bruker Dimension FastScan Atomic Force Microscopy (AFM) and the scanning image was processed using the Gwyddion Software. X-ray diffraction (XRD) analysis was performed using a Bruker D8 Discover diffractometer with Cu K α radiation and Crystallography Open Database, entry 1011103 was used for XRD confirmation.

III. RESULTS AND DISCUSSION

A. Morphology

Fig. 2 (a) represents the SEM micrograph of the as-deposited platinum film prepared at a deposition speed of 1 mm/min. Following annealing at 600 °C (Fig. 2(b)), the surface of the Platinum thin film became more uniform, with the nanoparticles nearly fully coalesced. Although small voids were visible in the annealed film, there was no indication of surface degradation.

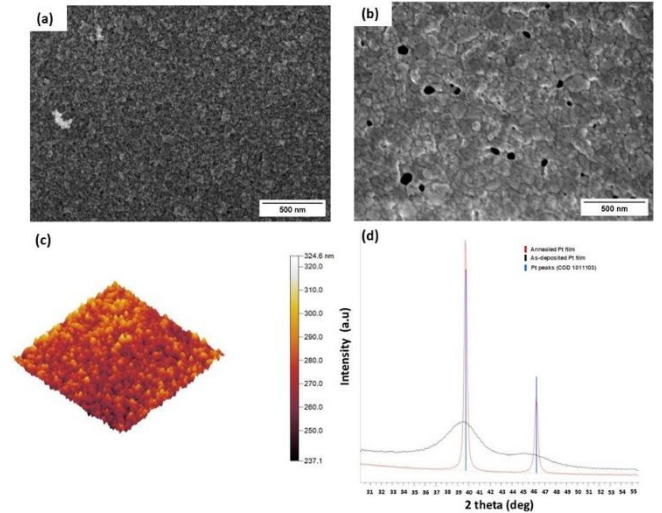


Fig. 2. SEM micrograph (a) Prior annealing, (b) Post-annealing at 600 °C for 1 hr, (c) AFM surface topography before annealing, of the 8-layer traces film printed at 1 mm/min; (d) XRD spectrum of the unannealed and annealed Pt films deposited at 1 mm/min

The sensing layer surface was further characterized using AFM, as shown in Fig. 2(c), with a scan area of $3.8 \times 3.8 \mu\text{m}$. The average surface roughness, R_a for the as-deposited film was measured as 8.7 nm.

XRD analysis (Fig. 2(d)) of the as-deposited film shows broad diffraction peaks before annealing, likely due to the small crystallite size. After annealing, coalescence of the smaller crystallites leads to more dominant and intense diffraction peaks. The grain size of each printed layer was determined from the XRD spectrum, using the Scherrer equation, applied to the highest peak. The average size of the as-deposited Pt nanoparticles was found to be 2.2 nm, whereas, for the annealed sample the crystalline size obtained was 29 nm.

B. Sensor Characterization

First, the influence of printing speed on the resistive properties of the spark-ablated Pt films was investigated using stage movement speeds ranging from 0.3 mm/min (lowest possible) to 8 mm/min. Higher printing speeds yielded thinner, sparser films, resulting in increased resistivity (Fig. 3). Although the films printed at speeds above 1 mm/min exhibited higher resistivity, they were found to be extremely sparse, exhibiting increased inter-particle separation, which could potentially compromise their thermal stability. Based on these findings, a deposition speed of 1 mm/min was chosen as the optimized setting, offering a practical trade-off between thermal sensitivity and processing efficiency.

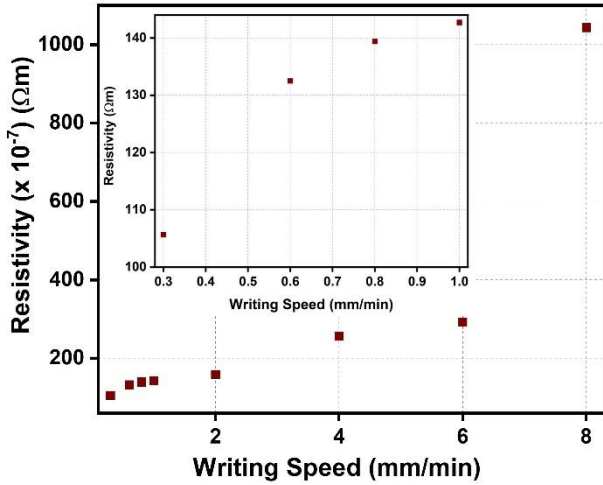


Fig. 3. Variation of film resistivity at different printing speeds. Inset: close-up of the slowest printing speeds. At the highest speed the resistivity rapidly rises due to increasing sparsity of the film.

To further optimize the performance of the printed Pt films, the influence of film thickness was explored, revealing two main trends. First, as expected, the film resistivity drops with increasing layer thickness. Second, as shown in Fig. 4 (a), the TCR increases with the increasing thickness of the Pt layer. This could be due to the fact that for thin metallic films, when the grain size and thickness drop below, or are comparable to, the mean free path of the charge carriers, grain boundary scattering becomes dominant (also known as the size effect) [14,15]. Moreover, the presence of a greater number of isolated Pt islands in thinner films increases surface scattering, which further contributes to the reduction of the TCR. However, when the film thickness exceeds 450 nm, the layer starts cracking, and delamination is observed post-annealing. Incorporating an adhesion layer could enhance film adhesion and help prevent delamination [10]. Across the samples, the mean TCR ranged from $1.91 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$ to a maximum of $2.17 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$ for the Pt film fabricated with 8-layer traces under optimized conditions. The TCR achieved is comparable to that of the Pt RTD with SiCN/YSZ protective layer, fabricated via direct-writing [16], the aerosol-jet printed hybrid ink (Ag, Cu, and Ni) RTD [17] and, sputter deposited Pt RTD on Al₂O₃ substrate [5].

In order to get an insight into the repeatability and stability of the Pt thin film RTD, three consecutive cycles of heating and cooling were performed. Notably, no thermal hysteresis was observed (illustrated in Fig. 4 (b)), even in the absence of an encapsulation layer, in contrast to earlier studies [16-18], thus showing excellent repeatability and linearity. A transient

response analysis was performed at temperatures ranging from 25 °C to 200 °C, in 25 °C increments. The RTD, again, exhibited an outstanding thermal stability over a continuous 70-minute duration (Fig. 5).

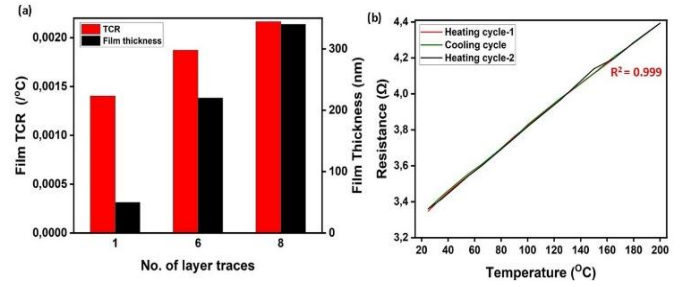


Fig. 4. (a) Mean TCR of the films printed with different layer thicknesses at 1 mm/min, (b) Resistance variation of the film printed with 8-layer traces for three consecutive thermal cycles

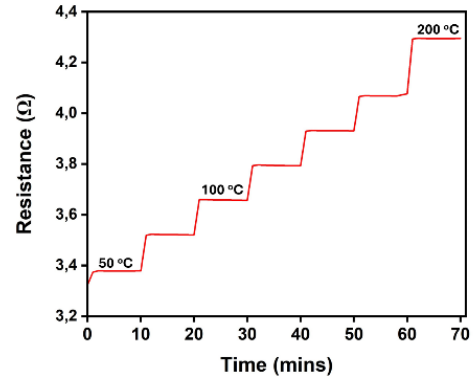


Fig. 5. Transient Response of the printed Pt RTD

IV. CONCLUSION

This work presents a novel, chemical-free fabrication method for platinum thin-film RTDs based on spark ablation. For the first time, we demonstrated it is possible to fine-tune the process parameters to engineer the thermal sensitivity of the printed Pt RTD. The RTDs exhibited a linear resistive response to temperature variation, achieving a maximum mean TCR of around $2.17 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$ for an 8-layer film. Transient response measurements confirmed the stability and reliability of the sensor, thus demonstrating its practical viability. Studies are ongoing with the aim of further optimizing the film properties and assessing its performance at elevated temperatures and longer durations. The relatively high TCR and linearity obtained at such low film thickness, even without the use of a protective encapsulation, as compared to existing technologies, coupled with the simplicity of the fabrication process, highlights the strong potential of spark-ablated Pt films for temperature-sensing applications.

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