Surface-Modified Nylon Textile for Wearable rGO/MOx-Based Chemiresistive Gas Sensors

R. Maryam[1], C. Riccardi[1]
[1] Department of Physics, University of Milano Bicocca, Milan 20126, Italy

Air pollution causes millions of deaths each year, with pollutants from vehicles, industries, and fuel combustion posing serious health risks. Among these, NO_2 is particularly harmful due to its damaging effects on the respiratory system. The development of gas-sensing technologies has driven the need for reliable environmental monitoring. While metal oxide (MOx) sensors offer good sensitivity, their high power consumption limits wearable applications[1, 2]. Combining MOx materials with two-dimensional (2D) materials improves sensor performance and enables low-power operation[3]. As a result, textile-based wearable gas sensors have emerged as promising platforms for real-time monitoring[4]. In this study, nylon textile was selected as the sensing substrate due to its flexibility, light weight, durability, and suitability for smart textiles. To enhance the adhesion of the rGO/MOx sensing layer, the nylon surface was modified by plasma etching, which increases surface roughness and introduces functional groups, improving coating stability and sensor performance. Plasma treatment offers multiple possibilities for enhancing polymer and textile surfaces by adjusting parameters such as power, pressure, gas flow, and treatment duration[5, 6]. As a clean, efficient, and cost-effective surface modification technique, non-thermal plasma alters surface roughness, wettability and hydrophilic/hydrophobic characteristics while preserving the bulk properties of the material[7]. In addition, ionic liquids have been explored as sustainable textile-processing media for fibre functionalisation and the development of advanced functional textiles[8]. This research aims to investigate plasma-induced surface modification and ageing behaviour of polymer materials, and to apply this understanding toward the development of a flexible, low-cost textile-based sensing platform using hand-embroidered electrodes and graphene-based functional materials.

Experimental Setup for Nylon samples

The oxygen plasma treatment was performed on nylon samples (3×3 cm²) in a cylindrical vacuum chamber. High-purity O_2 gas was introduced into the chamber, and the discharge was ignited by a 13.56 MHz RF power supply (100 W) connected through an automated matching network to a perforated stainless-steel electrode. Before processing, the chamber was evacuated using a rotary pump. The plasma treatments were carried out at a fixed pressure of 0.1 mbar for 4 min.

Oxygen plasma treatment transformed the nylon surface from hydrophobic (107.8°) to superhydrophilic (<5°), greatly enhancing its wettability. This improved surface promotes better ink spreading and adhesion, which is beneficial for high-quality printed sensor fabrication. Scanning Electron Microscopy (SEM) was used to investigate the surface morphology of nylon textile before and after oxygen plasma treatment. SEM analysis was performed on the untreated sample (P1) and the sample treated with oxygen plasma for 4 minutes (P4). SEM images of the untreated nylon (P1) exhibit a uniform and smooth surface with no surface damage. At 100 mm, the woven fabric composition is well maintained. The surface is relatively featureless and smooth, as shown in Figure 1 (left)

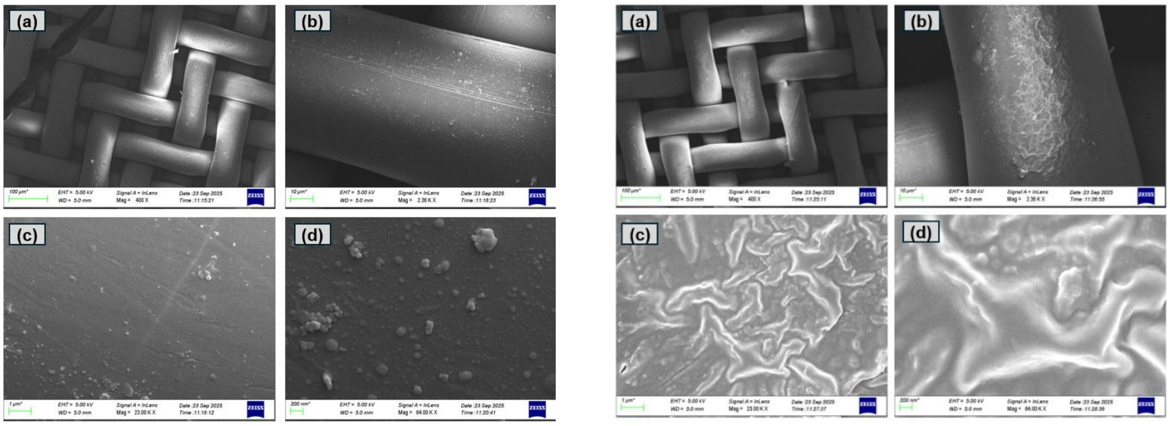

Figure 1. SEM micrographs of nylon textile **before treatment (left)** and **after (right)** oxygen plasma treatment at different magnifications:

In Figure 1 (right), SEM images of nylon textile treated for 4 minutes (P4) are examined immediately after plasma treatment. At 100 mm, the woven structure remains the same even at longer plasma time, showing that prolonged plasma also does not result in damage at the macroscopic level. At 1 mm, this sample significantly enhanced the roughness of the surface. Wrinkled, Etched patterns and irregular surface morphology can be seen, indicating more extensive interactions with the polymer during the plasma treatment. However, at the 200 nm scale, the wrinkled structure and some deep grooves are also observed.

- **Formulation of rGO/CuO ink**

The rGO/CuO nanocomposite was synthesized via a one-pot hydrothermal method and formulated into a stable sensing ink. XRD confirmed the successful formation of crystalline CuO and rGO, while SEM revealed a porous, interconnected morphology with uniformly distributed CuO nanostructures, providing a high surface area for enhanced gas sensing.

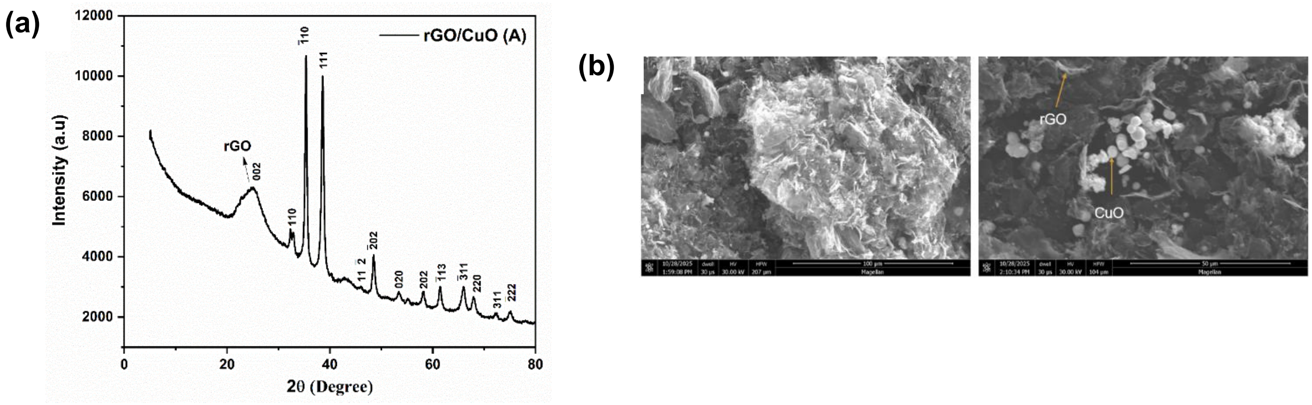

Figure 2. a) XRD of rGO/CuO b) SEM images of rGO/CuO

- **Effect of rGO/Metal Oxide Deposition on Plasma-Treated Nylon**

Figure 3 shows SEM images of rGO/CuO-coated nylon fibres on untreated and oxygen plasma-treated substrates. The untreated nylon exhibits a smooth surface with non-uniform rGO/CuO agglomeration, whereas the plasma-treated nylon shows improved coating adhesion and more uniform material distribution due to the increased surface roughness and surface activation induced by plasma treatment. The enhanced surface roughness and activation induced by oxygen plasma treatment improve the adhesion of the deposited material, leading to better coating uniformity and reduced agglomeration, which are beneficial for wearable gas-sensing applications.

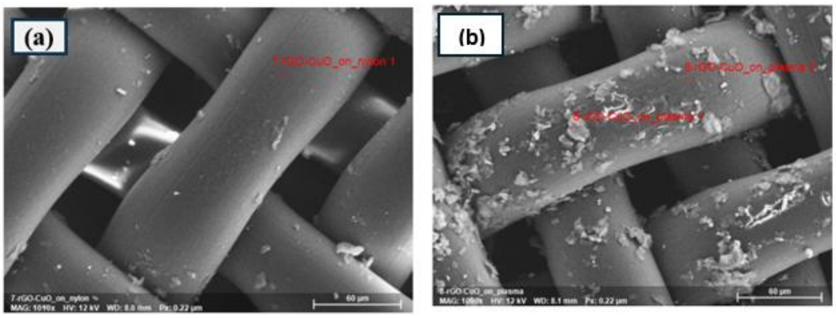

Figure 3 SEM images of rGO/CuO deposited on a) untreated nylon b) plasma-treated nylon

- **Fabrication of Smart Textile Gas Sensors Using Hand-Embroidered and Inkjet Printing Electrodes with rGO–Metal Oxide Inks**

Interdigitated electrodes (IDEs) were fabricated on nylon using hand embroidery with silver-coated conductive thread, followed by drop-casting of the sensing ink at 80 °C (Figure 4a). Figure 4(b) shows an alternative inkjet-printed silver electrode pattern on UV–ozone-treated nylon, where five printed layers produced continuous, well-defined electrodes for future sensing applications. Figure 4(c) shows inkjet-printed PEDOTPSS electrodes; although conductive after five layers, their poor wetting and inconsistent gas sensing performance with an rGO/$CuCoO_x$ sensing layer led to the adoption of a simplified four-line silver electrode design (Device 7).

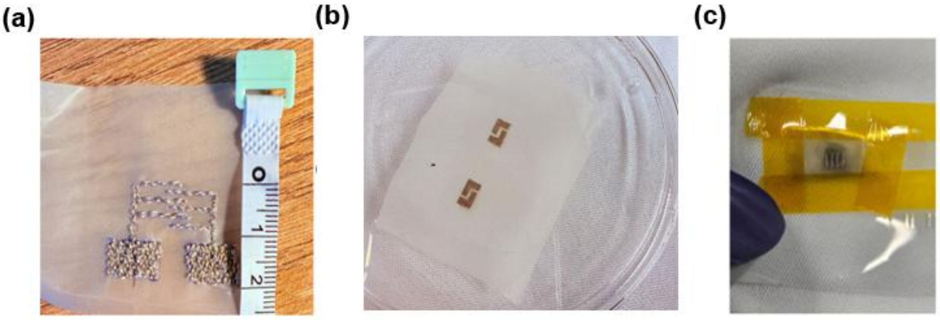

Figure 4 a) Hand-embroidered device. (b) Inkjet-printed silver electrodes on nylon. (c) Device 7 with silver/PEDOT electrodes and rGO/$CuCoO_x$.

- **Sensing Mechanism and Performance of the Embroidered Device**

Figure 5 shows the gas response of the hand-embroidered sensor using rGO/CuO ink with 10 ppm NO_2 gas concentrations. The gas response (S) can be $S = (R_{air} - R_{gas})/R_{gas} \times 100$

where R_{air} is the resistance at the initial stage, when no gas is exposed, and R_{gas} is the resistance when the targeted gas is exposed. The response value for the first cycle is 14.34%, calculated by using the above equation, multiplying by 100. The sensing interval was lasted about 297 seconds, or around 5 minutes at 10 ppm NO_2.

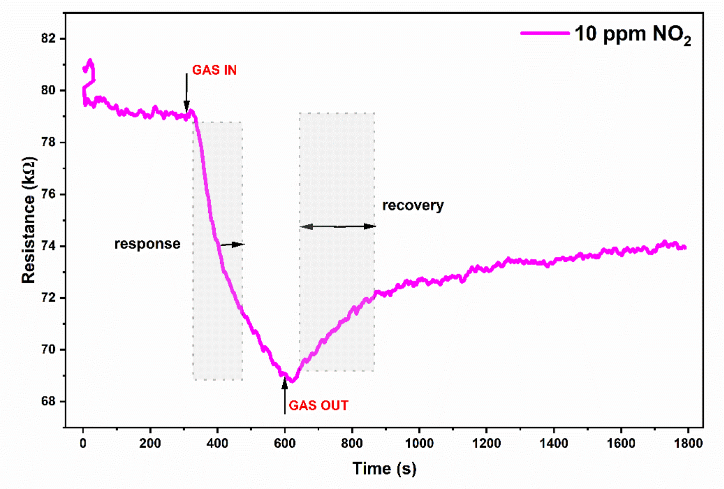

Figure 5. Resistance (kΩ) vs Time (s) graph of Embroidered IDE-rGO/CuO Gas Sensor at 10 ppm NO_2

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