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Vapor-Channeled Porous Pressure Sensors

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Summary: The superior performance of porous thin-film sensors over the bulk counterparts is constrained by the current porosity induction technology. The state-of-the-art porous sensors are expensive, time and energy intensive, and require high temperature etching steps. In this work, we overcome this issue by realizing a novel mechanism of porosity induction in 2D nanoparticle infused flexible, polymer nanocomposites. Thereby, giving a new direction to low-cost, rapid design, scalable porous nanocomposite design for pressure sensing applications.

Keywords: Porous nanocomposites, pressure sensor, tactile sensing, micro-channels, piezoresistive.

Introduction, Background and Motivation

Porous thin films have been explored for their superior mechanical deformability, higher strain transduction, and high sensitivity in applications involving multi-axis strain/pressure stimulus[1, 2]. However, the fabrication of porous thin films, particularly 2D-material infused nanocomposites has been challenging; owing to the complex, chemically intensive, and energy-inefficient processing[3]. This has severely restricted the projected potential of porous sensors in applications such as robotics, tactile sensing, smart automation, healthcare, sports science, etc.

Embedding porosity is a key method for achieving near-ideal flexible pressure sensors from conventional nanocomposites. These pores act as zero-stiffness dopants, lowering the matrix modulus and thus boosting flexibility, pressure sensitivity, and dynamic sensing range. Recently, various methods such as scaffolding, templating, 3D molds, have been employed to fabricate porous pressure sensors. These methods are passive in terms of transporting the active 2D nanoparticles to regions of maximum strain translation. They follow a bake-first approach, in which the pores are formed after the polymer has solidified. This prevents the dynamics re-adjustment of 2D nanoparticles into microchannel or region of maximum strain[4].

We introduce a novel, easily fabricated porous nanocomposite of vapor-channeled PDMS and graphene nanoplatelets that dramatically enhances pressure sensing. Our optimized ”parallel bake” process creates tunable porosity, yielding a 7-fold increase in pressure sensitivity and a 2.25-fold wider sensing range compared to non-porous counterparts. This technology enables integrated pressure sensors for applications in smart healthcare, sports science, and gait assessment.

Description of Porosity Introduction

The porous structure for our pressure sensor leverages a novel, vapor-induced pore/channel formation within the GNP/PDMS nanocomposite (Process flow shown in Fig. 1). This method employs a two-stage bake cycle: a brief, intense hot-bake (140^{o}C-45 seconds) followed by a prolonged, low-temperature open bake (60^{o}C-4 hours). Initially, high-temperature curing of ethanol-mixed GNP/PDMS triggers bubble nucleation. As these bubbles ascend, they strategically redistribute GNPs into the resulting micro-channels via capillary action. This continuous bubble movement, coupled with the high curing temperature, ensures robust channel formation, which is subsequently stabilized by extended open bake. The final product is a porous thin film with a high concentration of GNPs precisely located within the micro-channels.

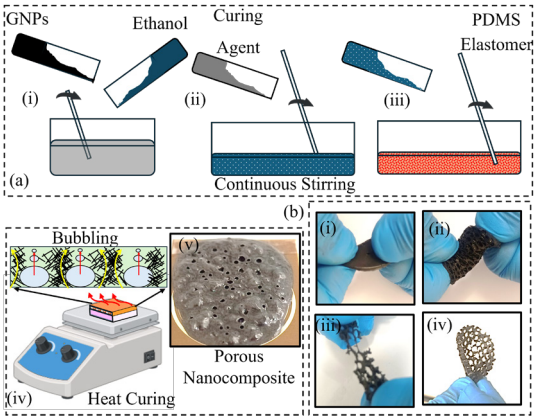

Fig. 1: a) Process flow for porous piezoresistive nanocomposite;i) ethanol/GNP mix ii) mixing the curing agent; iii) PDMS elastomer mixing; iv) 2-step baking; v) final porous film. b) The flexibility of porous nanocomposite as i) compressed; ii) twistable; iii stretchable; iv) bendable.

Results and Discussions

The porosity of the nanocomposite is primarily determined by the initial volume of ethanol and the hot baking temperature. Our work uti-

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lizes only 5% GNP/PDMS and demonstrates that hot bake temperatures of 100^{o}C and above are crucial for reliable ethanol bubbling and channel formation; lower temperatures resulted in prolonged saturation times and inconsistent channel development. The hot bake saturation time and temperature define our innovative bake cycle.

Fig. 2a reveals that for a 5% GNP/PDMS nanocomposite, saturation time increases linearly with ethanol volume at a constant hot bake temperature. Notably, at higher temperatures ($>$120^{o}C), lower ethanol volumes lead to smaller pores and lower pore density with scattered distribution, while higher ethanol volumes result in larger pores (implied). Therefore, achieving a specific pore size and density necessitates an optimized ethanol volume. The increase in pore density drastically reduces the initial resistance of the nanocomposite pressure sensor by forming denser micro-channels (Fig. 2 b. Crucially, pore size dictates the GNP concentration and stiffness of these channels. Larger pores create thinner, higher-GNP channels with lower resistance but increased stiffness. This requires a trade-off: optimizing the pore size balances strainability, initial resistance, and pore density to maximize sensor sensitivity.

Mechanical and Electrical Characterization

The mechanical and electrical characterization of the fabricated porous 5% GNP/PDMS nanocomposite is performed with a universal testing machine (UTM−X350−20) using a 2000 Kgf load cell and integrated with Keithley 2450 source−meter. The peak loading and peak %stress varies is obtained as ∼487 N and 68.97% (Fig. 2 c. Furthermore, the initial(unloaded) resistance R_o is calculated as 2.5 K. The force is applied from 0−700 N (corresponding to applied pressure of 0−3 MPa) with a speed of 1mm/min. The % relative resistance change (%RRC) shows a conventional "linear−saturation" trend over the applied forcing range. The linear region extends to 2.5 MPa and the corresponding pressure sensitivity of 33.2% MPa^1 is achieved (Fig. 2 c). Piezoresistive sensitivity, quantified by the gauge factor (GF). Porous GNP/PDMS demonstrated significantly enhanced sensitivity with two distinct linear regions; GF = 0.66 (0−45% strain) and GF = 1.72 ($>$45%). This substantial improvement in sensitivity and sensing range is attributed to the enhanced deformation limit and the formation of high−concentration GNP micro−channels, enabling intricate sensing via GNP tunneling, overlapping, and disconnection.

Application: Tactile Pressure Sensor

Finally, the vapor channeled porous GNP/PDMS is is fabricated on a flexible polyamide substrate (1.5cm $\times$ 1.5cm) with copper/gold interdigitated electrodes. The fabricated piezoresistive sensor is deployed as a tactile pressure sensor to detect varying finger taps as shown in Fig. 2d. The

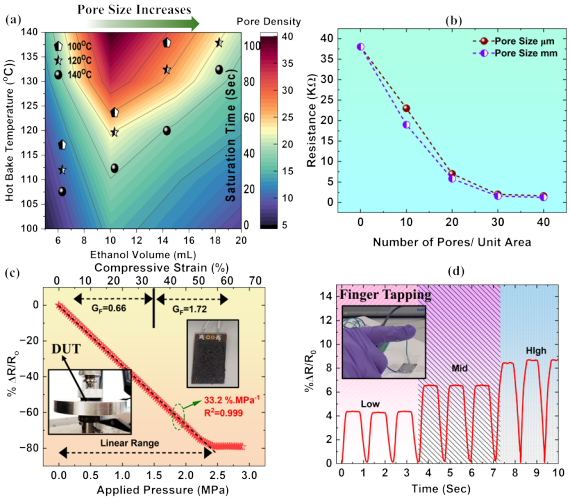

Fig. 2: a) 2D-map showing dependence of hot-bake pore size, pore density, saturation time on initial ethanol volume. b) Corelation between pore density at different pore sizes on initial nanocomposite resistance. c) Sensitivity and GF calculation of the porous nanocomposite. d) A finger tap response of the prepared porous pressure sensor.

sensor reliably detects a wide range of finger tap strengths (low, mid, high), exhibiting a stable and repeatable response, even for forces as low as 0.12 MPa (%RRC=4.2).

Nonetheless, this work can be extended to any flexible polymer nanocomposite irrespective of the transduction mechanism and therefore offers a new direction in porous sensors.

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