

A New Approach for Production of Nanofilament-Based Chemoresistive Sensors

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Summary:

Nanofilament bridges offer a route to low-power chemoresistive sensors. From nanoporous layers (NPLs) consisting of 5 nm particles, which can be produced by a one-step spark-ablation and impaction-printing process, we produce such nanofilaments by current-driven sintering. They are supported by the un-sintered matrix of the original NPL, which has a negligible conductivity with respect to the filaments. Current limitation basically tunes the number of filaments formed. This scalable approach may extend to many metals and alloys as Joule-heated sensing materials for extremely low-power sensor operation.

Keywords: chemoresistive sensor, nanofilaments, nanofibers, nanoporous, nanoparticulate layer, current-driven sintering

Background, Motivation and Objective

Nanofilaments or nanofibers that bridge electrodes offer promising platforms for chemoresistive sensors [1,2]. Joule heating can raise these structures to the required operating temperature, while the temperature-dependent sensor response can improve selectivity. Because heating is localized within the sensing material, power consumption is far lower than in conventional MEMS devices that use separate heaters. However, lithography-based fabrication of chemoresistive sensors typically involves multiple process steps [2]. Recent work has shown that spark-ablation nanoparticle generation in a gas environment combined with impaction printing can produce nanoporous layers (NPLs) in a single step [3]. In particular, the VSParticle VSP-G1 used with the VSP-P1 has demonstrated unique chemoresistive sensing properties [4]. As-deposited NPLs usually require annealing to sinter the typically 5 nm particles to remove highly resistive barriers between them. The spark-ablation-printing approach is inexpensive and scalable. Its unique flexibility regarding composition and structure of nanoparticulate layers, make it a versatile platform for optimizing sensor properties [6].

This study focuses on sintering such NPLs by passing an electric current through them. The objective is to form conductive nanofilaments between the electrodes through current-driven sintering. The remaining un-sintered particle-particle junctions in the NPL then act as a supporting network that holds the conductive filaments in

place, while contributing negligibly to the overall conductivity.

Description of the New Method

A Pd NPL track approximately 1 mm long, 60 μm wide, and 1 μm thick was printed on a test chip (Fig. 1), bridging the electrodes. The circuit shown in Fig. 2 was used to measure its electrical characteristics during electrical sintering.

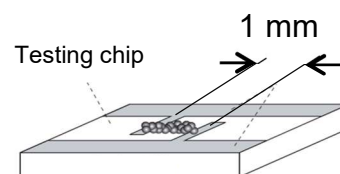


Fig. 1. Testing chip

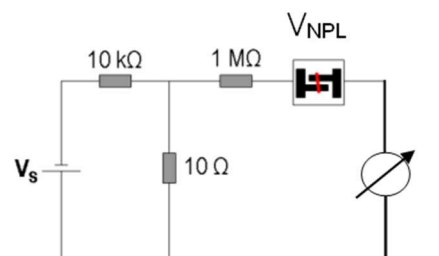


Fig. 2. Testing circuit

Results and Interpretation

The resistance of an un-sintered NPL of metallic nanoparticles is initially governed by contact resistances between particles. A gradual increase in V_{NPL} produces a sharp, three-order-of-magnitude rise in current at the sintering voltage, $V_s =$

1.2 mV (Fig. 3), indicating the formation of metal-metal connections along particle chains that bridge the electrodes, as illustrated in Fig. 4b) and c). By Ohm's law, an increasing current I at constant voltage shows that conductance rises proportionally with current during sintering.

This behavior is consistent with a model in which the sintering voltage creates a sufficiently large voltage drop across a specific barrier resistance between two nanoparticles to trigger sintering. Once one contact in an electrode-bridging chain sinters, the remaining contacts in that chain experience larger voltage drops, initiating a runaway process that sinters an entire chain, which is then a conducting filament. If the current I between the electrodes is not limited, the same process forms a second nanofilament and then additional ones until current limitation is reached. Assuming similar conductance for all filaments, I is proportional to the number of conducting filaments formed. Estimating the conductance of a chain-like nanofilament composed of 5 nm particles over a length of 1–2 mm therefore allows the approximate number of nanofilaments to be derived from the measured current. Fig. 4 illustrates the sintering states corresponding to the estimated corresponding electrode-to-electrode resistances. The resulting structure c) consists of conducting filaments suspended within a matrix of un-sintered NPL. Allen et al. [5] previously demonstrated the transition shown in Fig. 4a) directly to Fig. 4d), in which particles sinter and coalesce into a highly conducting bridge. Our results show that current limitation can be adjusted to generate a controlled number of nanofilaments embedded within an NPL. Although the model assumes similar resistances for all formed chains and neglects nanofilament branching, it captures the key features of the process.

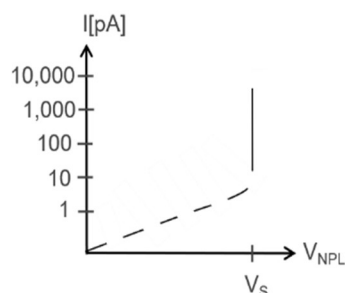


Fig. 3. Plot of the current vs. Voltage during NPL sintering through slow current increase above $V_S = 1.2$ mV. The dashed line is qualitative and was not measured, while the solid line corresponds to the measured data.

This approach can be applied to a wide range of metals and alloys. Its extension to metal oxide semiconductors remains to be tested. During sensor operation, Joule heating is expected to be adjustable within a wide temperature range,

in which the filaments remain stable. Such tests remain to be carried out. Because thermal coupling to the supporting network is minimal, the power consumption is expected to be extremely low compared with any previously reported concept.

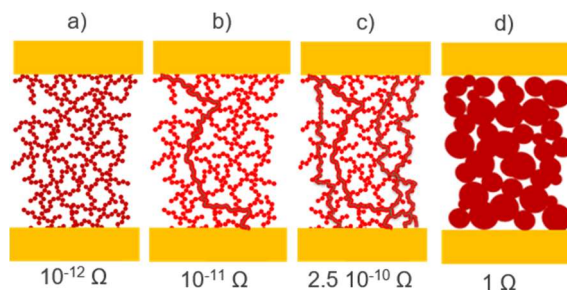


Fig. 4. Illustration of sintering model consistent with measurement: a) NPL before sintering; b)-c) Formation of 1-4 conducting filaments; d) Sintering and coalescence forms strongly conducting connection [5]

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