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Laser synthesized gold nanoparticles for high sensitive strain gauges

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ABSTRACT

We demonstrate high strain sensitivity property of gold nanoparticle (Au-NP) thin films fabricated on flexible polydimethylsiloxane (PDMS) substrates. This behavior is attributed to quantum tunneling effect that is highly dependent on nanoparticle separation. Au-NPs were synthesized in water by nanosecond laser ablation method. The clean surface providing high tunneling decay constant, size of the Au-NPs and Au-NPs aggregate clusters offer advantages for high sensitivity strain sensor. We prepared Au-NPs films on flexible PDMS substrate by using hands-on drop-cast method. To obtain high gauge factor (g factor), we investigated the nanoparticles concentration on the substrate. Laser-generated Au-NPs films demonstrated g factor of ~300 for higher than 0.22% strain and ~80 for the strain lower than 0.22% strain, which is favorably comparable to reported sensitivities for strain sensors based on Au-NPs. Mechanical characterizations for the prolonged working durations suggest long term stability of the strain sensors. We discuss several models describing conductance of films in low and high strain regimes.

1. Introduction

Strain gauges, which convert strain input to resistance change, find wide application in transduction of mechanical signals. Strain gauges based on metal and semiconductor films are commonly used in sensing. The sensitivity of a strain gauge is expressed by the g factor, which can be calculated by the following equation:

$$g = \frac{\Delta R}{R\varepsilon} \quad (1)$$

where ΔR is the change in resistance upon applied strain; R is the initial resistance; and ε is the applied strain. The conventional metal film strain sensors have long lifetimes and are relatively robust to environmental effects such as changes in temperature and humidity. On the other hand, these sensors present low sensitivity due to the limited g factors. Semiconductor based strain sensors have fundamentally different operation mechanism, namely modification of band structure, effective mass and mobility. Moreover, they are more sensitive, but may require temperature compensation. In addition, the sensitivity of these sensors decrease under high strains and a breakdown strain ~0.6% resulting in limited operation range [1,2].

Thin films based on nanomaterials have found wide applications in fields of optics, biology and detection. Metallic nanoparticles have gained significant attention mainly because of their unique optical, electrical and catalytic properties. In the literature, the conduction behavior between chemically synthesized nanoparticles has been intensively studied [3,4]. The conduction of n-alkanelthiol-stabilized Au-NP films was shown to have exponential decay dependence to the length of ligands' alkanethiolate chains. This effect was suggested to be attributed to quantum tunneling effect [3,4]. The quantum tunneling effect is highly dependent on width of the potential barrier. Thus, it was anticipated that the Au-NPs films can be used as highly-sensitive strain gauges. In principle, such films can be used in other types of sensors. For instance, one can measure the change conductance to observe the effect of chemical modification or attachment of biomolecules, which occurs due to changes in the tunneling barrier width and height.

The use of Au-NPs in strain sensing has previously been reported in literature. Herrmann et al. demonstrated the high capability of Au-NP films to sense small linear strains [5]. The Au-NP strain gauges were shown to be nearly two orders of magnitude sensitive than the conventional strain gauges [5]. Vossmeyer et al. demonstrated lower sensitivity Au-NP strain sensors fabricated on flexible substrates by depositing 12-dodecylamine-stabilized Au-NPs via layer by layer self-assembly on oxidized flexible polyethylene. This technique provides high adhesion of Au-NPs on the substrate because of linker compound, 1,9-nonanedithiol, which also increases the mechanical robustness of sensors [6]. Ressier et al. developed stop-and-go convective self-assembly method to fabricate few micrometer wires based on Au-NPs, and demonstrated that monolayer wires of Au-NPs have higher strain sensitivity – g factor of 132 – than multilayer wires [7–9].

Presence of chemical stabilizers on Au-NP surfaces potentially decrease strain sensitivity. Thin films based on metal nanoparticles

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having clean surfaces were predicted to have improved g factors [5]. Recently, Tanner et al. demonstrated that Platinum (Pt) nanoparticle coatings obtained by sputtering in vacuum present high g factors (700). They also studied how surface density affects the sensitivity of such devices [10,11]. Nanoparticles free of chemical stabilizers can be obtained by laser ablation method [12,13]. Unique laser-matter interaction properties open the door to the generation of a variety of nanoparticles [14]. Compared with other nanoparticle synthesis methods, laser ablation, especially in liquids, is a versatile method for generating colloidal, highly pure, and surfactant-free nanoparticles. In this paper, we have studied the conduction properties of thin films of Au-NPs, prepared by nanosecond laser ablation in deionized water. Au-NP thin films were obtained by simply drop-casting Au-NP colloidal solution on the PDMS substrates.

2. Experimental details

2.1. Au-NP synthesis by laser ablation in liquid

Au-NPs were obtained by laser ablation in deionized water. Gold block (99.999%, Kurt J. Lesker) was cleaned by sonification in acetone prior to laser ablation without any additional purification. The generation of colloidal nanoparticles from Au block was carried out by using a commercial pulsed ND:YLF laser (wavelength: $\lambda = 527$ nm, 16 W average power, pulse duration $t = 100$ ns, pulse energy $E = 16$ mJ for 1 kHz). The cleaned Au block was placed in a glass vessel containing 23.5 mL of pure deionized water. The laser beam was focused on the target by using a plano-convex lens with focal length of 50 mm. The height of liquid layer over the gold target is ~5 mm. The laser ablation was carried out for ~10 min, and the laser beam is scanned over the target surface. During the laser ablation, the formation of colloidal nanoparticle solution with dispersed Au-NPs in liquid media was observed as a color change of the deionized water. After the laser irradiation, the color of the Au-NPs solution became dark-red.

The structure of Au-NPs generated by nanosecond pulsed laser ablation were studied by TEM (TEM model FEI – Tecnai G2F30) system. Sample for TEM analysis was prepared by drop-casting solutions onto carbon-coated grid. Representative TEM image of the Au-NPs is shown in Fig. 1, showing well dispersed, spherical-like NPs. Size distribution was measured from TEM image where 100 particles' approximate diameters were measured. Size distribution of Au-NPs is given in Fig. 1 inset. An average nanoparticles size of 13 nm is seen, with a distribution covering the range from 2 to 25 nm.

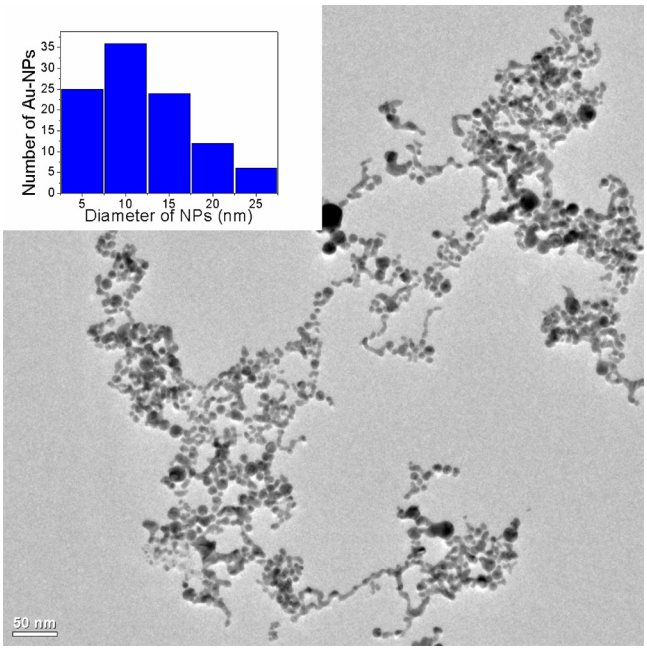

Fig. 1. TEM image of Au-NPs. The inset shows the histogram of size distribution calculated from TEM images.

2.2. Strain sensor fabrication

Thin films of Au-NPs have been produced by drop-casting on several substrates. It was observed that, uniformity of the films were poor on SiO_2 and silicon substrates due to their hydrophilic surfaces. Au-NPs on glass and silicon were randomly distributed and intensively located at the edge of the initial Au-NP droplet's contact area. On the other hand, PDMS substrate presents low surface energy, thus a hydrophobic surface. The high contact angle and low surface energy enables to uniformly precipitate particles and highly concentrate them on the surface. After droplet was completely dried, a dark blue spot was formed on the surface of PDMS. Au-NP thin films obtained on PDMS were uniformly distributed (Fig. 2a). Contacts were obtained using a shadow mask and a 350 μm gap was formed by coating 80 nm Pt film using sputtering (PECS Gatan 682) (Fig. 2b).

Scanning electron microscope (SEM) (FEI Nova NanoSEM 600) was used to further investigate the localization of Au-NPs on the PDMS substrate. In the SEM image, aggregated clusters can be

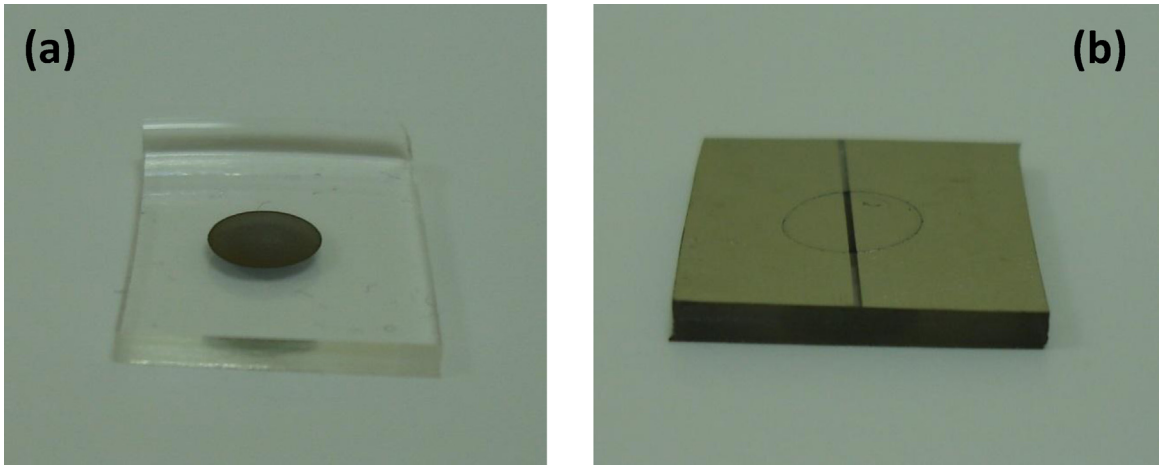

Fig. 2. Au-NPs film on PDMS substrate. (a) Au-NPs film after droplet was dried. (b) After Pt contacts were deposited by PECS.