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Thermal properties of infrared absorbent gold nanoparticle coatings for MEMS applications

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ABSTRACT

This report presents characterization of the optical absorption and thermal properties of a thin-film platinum device coated with gold nanoparticles. These particles are engineered to have a light absorption peak near 808 nm. The response of bare and particle-coated thin-film platinum was examined under an 808 nm infrared laser. The results show that a particle coating is a significant factor in the thermal efficiency. This work is the foundation for wavelength-specific microelectromechanical actuators powered by infrared light.

1. Introduction

Bioengineering has benefitted greatly from advances in microelectromechanical systems (MEMS). Small-scale actuators and switches have potential in areas such as microscale pumping [1] and cell manipulation [2]. Powering these micro devices is often a challenge because of the invasive wiring needed. Tissue-permeant infrared (IR) light has been used in theraputic applications [3], and provides a noninvasive energy transfer method for heating nanoparticles with enhanced IR absorbtion for cancer cell ablation [4]. Depositing these particles onto a MEMS device could provide new optically induced functionality if the absorption behavior remains the same.

The potential to use this heating method to provide thermal energy in MEMS applications has not been thoroughly investigated. However, many MEMS are thermally driven such as thermal expansion based actuators [5] and microfluidic pumping elements [6]. The most common MEMS heating mechanism is direct current (Joule) heating, but this requires wiring to the active region which is undesirable in biomedical applications. Coatings such as platinum black have produced absorbing layers for thermal infrared detectors [7] and inkjet printing has been used to localize absorption at the macro scale [8], but these layers are not wavelength-selective. Wavelength-matched air gaps work well to tune thermal absorbers, but the absorbance wavelength must be decided at the start of the process, and will be the same for all devices on a wafer [9]. An optically induced temperature gradient using wavelength-selective printable or spinnable coatings would provide a more versatile method of wireless and non-invasive thermal actuation. This project aims to provide fundamental understanding of the particle and surface interaction that is required for developing bioengineering applications based on a hybrid of infrared resonant gold nanoparticles and MEMS structures.

Metal nanoparticles are one of the basic building blocks of nanotechnology. Gold nanoparticles (GNPs) have attracted enormous attention in chemistry, biomedicine, and electronics due to their very small size, oxide-free surfaces, bio-conjugation properties, good biocompatibility, and unique optical properties. Specifically, because of their optical activity in the near infrared (NIR), GNPs are extensively utilized in immunoassay [10,11] and drug delivery systems [12] as well as imaging, detection [13], and thermal therapy for cancer [14].

2. Plasmonic heating principle and fabrication

Each particle acts as a plasmonic heater. This property of the GNPs is based on a phenomenon called surface plasmon resonance. The mean free path in gold is around 50 nm [15]. Therefore most of the interaction in a gold nanoparticle is with the surface. Incoming light energy causes the electrons on the shell of the GNP to oscillate and a resonance condition can be reached if the wavelength is larger than the particle dimension. The migrating charge on the particle surface causes a changing electric field to induce heating.

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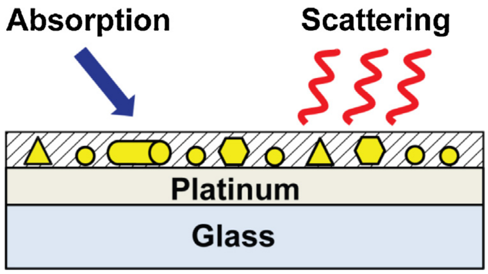

Fig. 1. An overview of the system being characterized in this work. Particles are coated onto a Pt trace on a glass substrate. Light at a certain wavelength is applied. Absorbed light will provide additional thermal energy to the system.

The absorption and electric field created are affected by the particle geometry [16]. The particle solution used in this report contains a mixture of particle shapes and is engineered to converge on the desired absorption properties.

For this work, the absorption of the particles when coated on a platinum layer is of interest. A metal surface is a typical feature in MEMS structures, and the particle interaction and thermal properties under laser light will be important in designing mechanical behavior. Fig. 1 contains a schematic of the working principle. The platinum thin film serves as a resistive temperature sensor to measure the thermal properties. Selected areas of the MEMS structures will be heated and thermal gradients may even be created from a single light source by patterning the particle deposition.

2.1. Device fabrication

A meandering thin-film platinum resistor was developed to monitor the behavior of deposited nanoparticles under near IR stimulation. This structure allows for accurate measuring of the surface temperature and is explained in further detail in Section 3.2. The hybrid optothermal test structures are created by combining the resistor with the GNPs. Platinum is used as the surface layer because of its biocompatibility and functionality in high-displacement MEMS actuators [17].

Gold nanoparticles with precisely controlled near infrared (NIR) absorption were synthesized by one-step reaction of chloroauric acid and sodium thiosulfate, without assistance of additional templates, capping reagents or seeds assembly. The NIR absorption wavelengths and average particle size increase with increasing molar ratio of $HAuCl_4/Na_2S_2O_3$. This provides the base for synthesis of gold nanoparticles with tunable NIR absorption wavelength. The nanoparticles produced from this reaction include small spherical colloidal gold particles with resonance at 530 nm and anisotropic gold nanostructures with NIR resonance. The pseudo-spherical crystals have diameters in the range of 15–45 nm, and the edges of the nanoplates are in the range of 40–90 nm. The tunable peak range for the particles used is from 800 to 1100 nm [18]. Other work has shown that geometry selective processing can yield gold nanorod solutions that have a peak absorbance between 600 and 1000 nm [19].

The planar resistors were fabricated with a single mask cleanroom fabrication sequence. First, photoresist was deposited and patterned to define the metal features on the surface of a 500 μm thick borosilicate float glass wafer. A 200 nm layer of platinum was deposited by sputtering after a brief deposition of titanium to aid adhesion. The intended metal geometry was defined via liftoff of the photoresist. After drying, the planar resistor is complete and can be coated with nanoparticles.

The spectrum of the GNPs used for this experiment is shown in Fig. 2(a), and the absorption peaks of each type of GNP are clearly seen. The particles are coated onto the center square in Fig. 2(b).

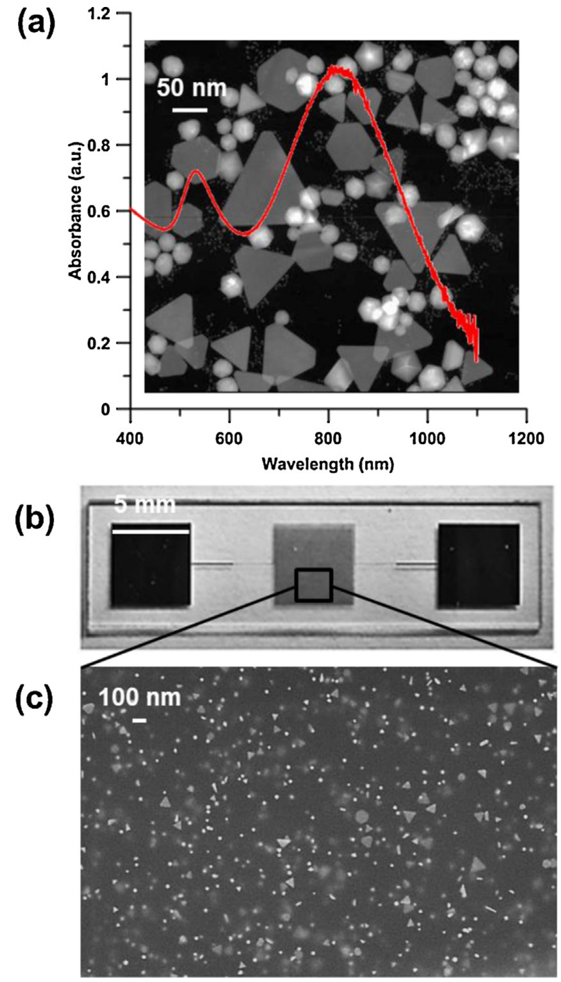

Fig. 2. (a) Optical absorption spectrum of synthesized gold nanoparticles, with a TEM image of particles as background. (b) Fabricated planar resistor used to gather temperature measurements. (c) SEM images of GNPs with PVP polymer matrix after spin-coating on the platinum test surface.

This region contains a long (0.58 m) thin-film resistor trace with a 20 μm width and 200 nm thickness that zigzags to fit within a 5 mm square. The left and right solid blocks are bonding pads for interfacing with the test surface. SEM images were taken after GNPs were distributed on the surface. The particle distribution on the platinum surface can be seen in Fig. 2(c). Samples were prepared by spin-on deposition of gold nanoparticle solutions with optical density (OD) of 100 onto an air plasma treated surface. The OD is a measure of the particle concentration in a fluid medium.

2.2. Particle dispersion

The NIR resonant GNPs were found to most evenly disperse with spin-on coating at 4000 rpm as compared to simple drying droplet or inkjet printing methods. However, if the particles were in a water medium, the adhesion was not sufficient for any of the substance to remain on the surface and coat the device when the spinning was applied. The polymer polyvinylpyrrolidone (PVP) has been used in other work as a suspension for nanoparticles [20], and was included in the liquid medium at 8% concentration to act as a matrix for the particles on the surface. This allowed for a uniform film to remain across the test resistor. The average film thickness was measured to be approximately 150–200 nm. A PVP film without GNPs was shown to have the same thermal behavior as a bare surface to ensure the GNPs are the active heating element.