Tungsten Refractory Plasmonic Material for High Fluence Bowtie Nano-antenna

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Abstract— In general, noble metals based nano-antennas cannot work at high power applications such as heat resisted magnetic recording, solar thermo-photovoltaics, and nano-scale heat transfer systems. These antennas are prone to being damaged at sufficiently high energy density due to their small footprint and low Tamman temperature. This paper proposes tungsten refractory plasmonic material based nano-antennas as an alternative gold nano-antennas: we show that the antennas can handle 300 times higher fluence than gold (Au) counterpart. In addition, it can achieve 7.22 higher magnitude of electric field intensity than gold antennas.

Keywords-Absorption; high fluence; nano-antenna; surface plasmon resonanace.

I. INTRODUCTION

Radio antennas were invented to allow the transmission of information through free-space. Nano-antennas are very small replicas of radio antennas, but working at optical frequencies. The freely propagating visible and infrared optical radiation can be coupled to the nano-antenna and localized in a sub-wavelength region, boosting the interaction of light with nanoscale matter[1].These high electric fields enhancement could be used in different applications such as solar energy harvesting[2] and enhancement of surface enhanced Raman spectroscopy (SERS) signals [3].

However, the antennas produce large amount of heat due to the intraband transitions of metals when they are illuminated by external light sources [4]. The accumulation of heating in small volume of antennas can affect the properties of the nano-antennas due to melting of the devices, resulting in a change of their shape[5]. As a result, the resonance may be shifted, with the electric field enhancement being significantly reduced[6]. Especially, the noble metal based antennas, for example gold antenna are not suitable for high temperature applications such as heat-assisted magnetic recording (HAMR)[7], solar thermos-photovoltaics[8], and nano-scale heat transfer system[9] because the gold antennas can melt at low fluence (e.g. 250 µW, or 0.059 J/m2 fluence)[10].

In order to overcome the above limitations, the antennas can be designed in materials that can handle high temperatures and work under harsh conditions. Guler et al. [11] mentioned that the refractory plasmonic materials, those generally have high melting temperature may be the alternative materials of gold or silver to work under high power laser applications where, it may produce high local temperature.

In this article, the bowtie nano-antennas are fabricated using gold (Au) and tungsten (W) and experimentally show that tungsten antennas can handle about 300 times higher fluence than that of gold counterpart.

II. THEORETICAL ANALYSIS

Fig. 1 shows a standard bowtie shape nano-antenna which is chosen to compare tungsten and gold nano-antennas. The bowtie structure is defined by the length of each triangle *l*, width of the triangle *w*, apex angle *α*, gap between two triangles g, and thickness *H*. The optical properties of the nano-antennas are calculated by optimizing the parameters at the wavelength of 1053 nm. The optimum length is 190 nm, and 145 nm, for gold and chromium, respectively. The gap width, thickness and apex angle are always kept fixed to 50 nm, 100 nm and 90^0.

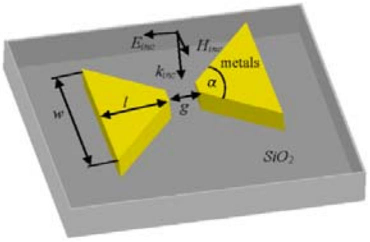

Fig. 1. Schematic diagram of single bow-tie nano-antenna.

Firstly, we have numerically calculated the electric field enhancement factor of the antennas for the optimized parameters using finite-difference time-domain (FDTD) method from the following equation,

$$F_{rel} = \frac{\left|E_{gap\ ,peak}\right|}{\left|E_{inc\ ,peak}\right|} \qquad (1)$$

where $\left|E_{gap,peak}\right|$ is the magnitude of the electric field calculated in subwavelength gap, and $\left|E_{inc,peak}\right|$ is the magnitude of electric field of incoming light.

Figs. 2(a) and Figs. 2(b-c) show the electric field enhancement factor and the electric field intensity distribution at the wavelength of 1053 nm along the vertical direction for gold, and tungsten, respectively. Fig. 2(a) shows that the gold bowtie antenna has comparatively higher electric field enhancement at the mid-point of the gap than the tungsten. On the other hand, from Figs. 2(b-c), it is observed that the electric field is not uniform for gold antennas, however- the electric field is strongly uniform for tungsten leading to a more uniform energy distribution. This uniform distribution of energy can slow down the temperature rise in the antennas.

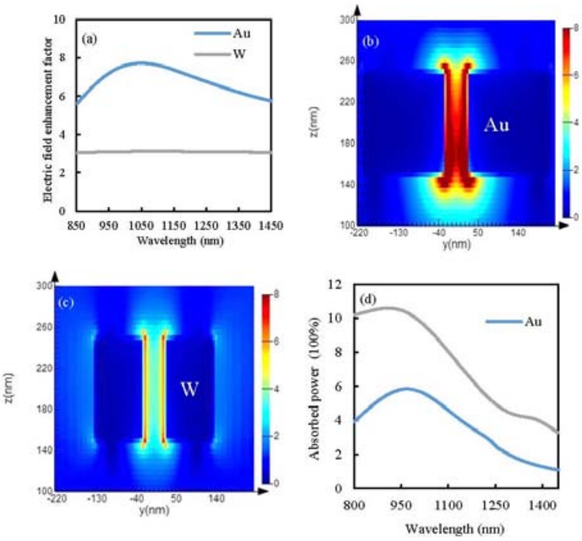

Fig. 2. (a) The electric field enhancement factor for the gold, and tungsten bowtie nano-antennas and electric field intensity profile in the y-z (E_{inc}-k_{inc}) plane of (b) gold and (c) tungsten for the optimized parameters at the wavelength of 1053 nm and (d) Comparison of the absorbed power (heat generation) for tungsten and gold.

The main drawbacks in the field of thermoplasmonics is the temperature rise in the nano-antennas from continuous laser illumination, which eventually destroys them. Generally, these heat produce due to absorption of light within the antenna[12]. For a better understanding regarding the thermal behavior of our antennas, we have computed the absorption of power which are shown in Fig. 2(d). This figure shows that tungsten has a bit higher absorptance than the gold at the wavelength of 1053 nm because tungsten has comparatively higher imaginary dielectric constants at this wavelength[13] - therefore, it will generally produce larger heat than gold- however, it has nearly three times higher Tamman temperature than gold~~,~~ the antennas shape will not be changed until temperature rise in the metals exceeds their Tamman temperature. When the temperature in the surface of antennas higher than the Tamman temperature, the atoms diffusion and mobility increases significantly, resulting sintering or morphology changing of antennas [14, 15]. The bulk melting points for gold, and tungsten is 1064.18^{o}C, and 3422^{o}C, respectively.

The main parameter that leads to the melting of the metallic regions is the energy density or fluence[12]. The energy and fluence for a single pulse of a Q-switched laser are given by,

$$W_{single\text{-}pulse} = \int_{t_1}^{t_2} P(t)dt = P_{peak}\tau_{eff}$$

$$F_{single\text{-}pulse} = W_{single\text{-}pulse}\frac{4}{\pi\phi_{spot}^{2}}$$

where, $P(t)$ is the instantaneous value of the power, t_1 and t_2 are the arbitrary instants when the pulse is not negligible and τ_{eff} is the effective duration of the pulse. $\boldsymbol{\varphi}_{\text{spot}}$ represent the spot size of the laser beam.

III. EXPERIMENTAL ANALYSIS

The antennas are fabricated by firstly depositing different metals using electron-beam evaporator or sputter system. The thickness of the metals in each of the three samples is chosen as 100 nm and for the gold sample, the metal was deposited by Temescal BJD-2000 E-beam/Thermal Evaporator system at the rate of 5 nm/s. A 2 nm titanium layer is used to provide good adhesion between gold and the substrate. The nano-antenna patterns were milled by FEI Helios NanoLab 600 dual beam focused ion beam (FIB) system. For the characterization of the power handling capacity of the fabricated antennas, we used a commercial Q-switched laser with pulse duration of 10 ns and repetition rate of 1.4 kHz.

Figs. 3(a) and (c) show the scanning electron microscope (SEM) image of a gold and tungsten nano-antennas with no laser exposure. Thereafter, the antennas are exposed to different fluences: we start from a fluence of 0.01 J/m^2, then increase the flunce by 0.012 J/m^2 (step size) until the gold antenna is damaged at 0.056 J/m^2. Fig. 3(b) shows the damaged antenna at this fluence. In case of tungsten, we start with the exposing fluence of the gold threshold value, and increase the fluence until the antenna is damaged. An SEM image of the destroyed tungsten nano-antenna is shown in Fig. 3(d). The threshold damage fluence of this antenna is about 16.16 J/m^2. Most of the damage occurs in the metallic regions due to the higher absorptance of tungsten.

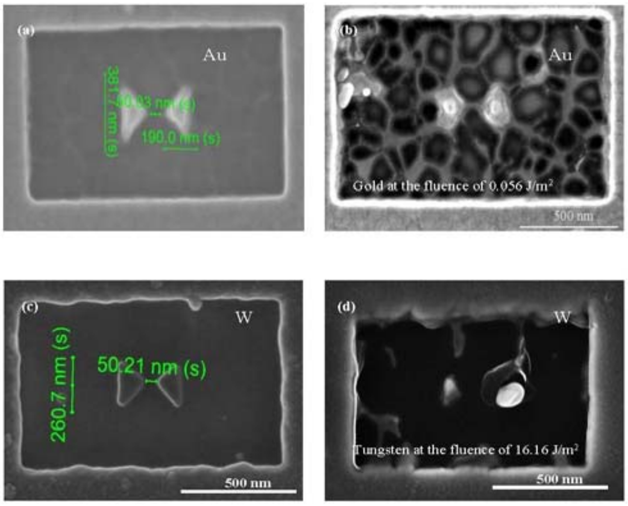

Fig. 3. SEM images of the studied nano-antennas; (a) gold without laser exposure, and (b) under 0.056 J/m^2 fluence showing melting of nano-antennas; tungsten nano-antennas (c) without laser exposure and (d) under 16.16 J/m^2 fluence showing melting of nano-antennas.

In comparison with gold, the damage fluence is 300 times higher than that of gold antennas. In addition, we can easily calculate the magnitude of electric field intensity in the gap for different antennas from equation 1 for given electric field enhancement factors because the incident electric field E_{inc} is proportional to square root of the fluence of a laser since spot size and repetition rate are constant. So, from these calculation, we can find that tungsten antennas can achieve 7.22 times higher magnitude of electric fields than gold nano-antennas when they operate at their threshold fluence. The possible explanation for the improved performance of tungsten antenna could be its high Tamman temperature and uniform energy distribution.

CONCLUSION

In conclusion, we have fabricated and characterized a new high power bowtie nano-antenna based on refractory plasmonic material, tungsten that can operate under high power laser pulses as well as high temperature compared with noble metal, gold . The results reveal that tungsten can operate under 300 times higher fluence as well as it can achieve 7.22 times higher magnitude of electric fields than gold nano-antennas when they operate at their threshold fluences due to its high melting temperature and combined absorption mechanisms. Therefore, it may be useful to work with high power lasers.

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