Thermoreflectance Imaging of Optically Pumped Gap Plasmon Structures

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Abstract: We developed a fast, high-resolution thermoreflectance imaging-based technique to map the temperature distribution of gap plasmon structures subject to laser irradiation, and observed 120 K temperature rise with 3 mW/μm^2 irradiance.

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1. Introduction

Because of large inherent optical losses, plasmonic systems have yet to find their use in commercialized optical communication and sub-diffraction imaging. However, they are promising candidates for optical heating purposes where optical energy is converted into heat. Many applications, such as nanoparticle manipulation [1], solar thermophotovoltaics (STPV) [2], and catalysis [3], can benefit from efficient plasmonic heaters.

To date, the most commonly used techniques to characterize plasmonic heaters are thermal cameras with a microbolometer [4] and thermal microscopy based on the temperature-dependent photoluminescence of thermographic phosphor (TGP) [5]. Thermal cameras cannot achieve spatial resolution smaller than ~2 um, and the TGP method requires special sample preparation such as tagging sample with a TGP thin film. Thermoreflectance imaging (TRI) [6], originally employed to inspect electrical self-heating in microelectronics, provides excellent solution to the limitations imposed by the aforementioned techniques. In this paper, we present our experimental studies on a gap plasmon type heater.

2. Plasmonic heater design and characterization

We design a gap plasmon structure as an optical heater which consists of (from top to bottom) 30 nm thick gold nanodisk, 20 nm thick aluminum oxide (Al_2O_3) spacer layer, and 100 nm thick gold reflector (see Figure 1(a)). The substrate supporting the structure is chosen to be SiO_2 for its low thermal conductivity to minimize heat-sink effect. The bottom right inset of Figure 1(a) clearly shows the gap plasmon mode on plasmonic resonance, where the magnetic field is squeezed into the Al_2O_3 spacer layer between gold nanodisk and gold reflector. We fabricate 7 different nanodisk arrays with disk radii ranging from 30 to 90 nm and a fixed period of 300 nm, which exhibit varying resonance peaks in the wavelength range of 600 to 1200 nm, as is evident from Figure 1(b). Next, we carry out optically pumped TRI measurement to characterize the optical heating on the fabricated gap plasmon structures. As is illustrated in Figure 1(c), a modulated (with 2.5 ms pulse width and 10% duty cycle) 825 nm (indicated by red vertical line in Figure 1(b)) continuous-wave (CW) pump laser beam is focused by a 100X objective lens and incident on the sample. A portion of the laser power is absorbed by the gap plasmon structure and dissipated to electron oscillations in the gold nanodisk and gold reflector, which then causes local temperature fluctuation due to electron-electron and electron-phonon interactions. A large-area 530 nm LED probe beam then senses the change in the temperature-dependent reflectance ΔR between high and low temperatures (corresponding to pump laser on and off) on each image pixel, which combined with the pre-calibrated thermoreflectance coefficient can be used to calculate the temperature rise on each pixel, hence allows us to map the temperature distribution. This technique grants us a spatial resolution of 200 nm, but it is to be noted that the TRI technique is far-field optical imaging approach thus the resolution cannot go beyond diffraction limit. In order to see the correlation between heating and optical absorption (and possibly gold nanodisk fill fraction), we carry out TRI measurement with 825 nm pump laser on the 7 nanodisk arrays with varying disk radii, i.e. varying optical absorption at 825 nm. In Figure 1(d) we plot the measured temperature rise inside the laser spot, and the measured optical absorption, versus disk radius. The plot shows excellent overlap between the trends of temperature rise and optical absorption, indicating that optical heating is largely correlated with optical absorption, but loosely with the gold nanodisk fill fraction. Notably, the remarkably high 120 K temperature rise with a moderate 10 mW laser power makes our system a very efficient plasmonic heater.

3. Summary

We have designed, fabricated, and characterized an efficient plasmonic heating system using a gap plasmon structure which achieves 120 K temperature rise with 3 mW/μm^2 irradiance. The thermoreflectance imaging system used in our experiment proves to be promising for plasmonic heating characterization.

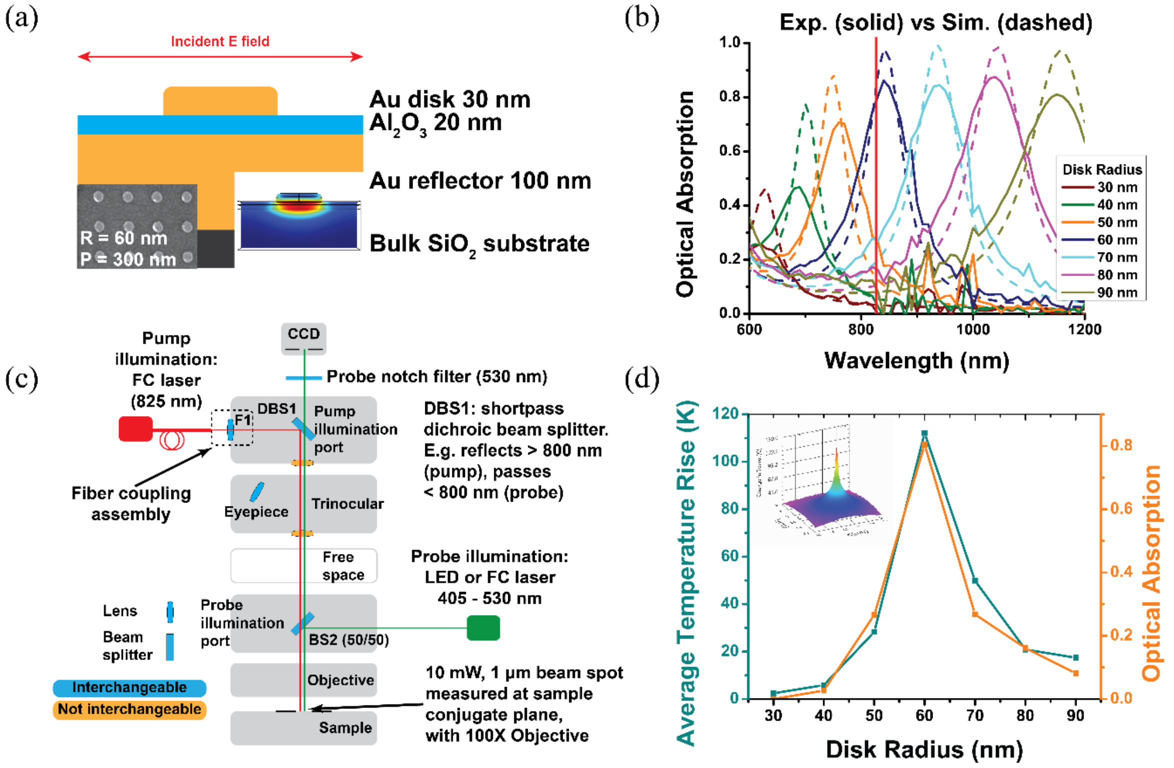

Figure 1. (a) Cross-sectional schematic of one unit cell of the gap plasmon structure design. The number in nanometer following each layer material indicates the thickness of the corresponding layer. Bottom left inset: scanning electron micrograph (SEM) of fabricated gold nanodisks on $Al_2O_3/Au/SiO_2$ substrate, the disk radius is 60 nm and period is 300 nm. Bottom right inset: simulated magnetic field intensity distribution at plasmonic resonance. This plot does not show the bulk SiO_2 substrate. (b) Measured (solid) and simulated (dashed) optical absorption of nanodisk arrays with different radii. The red vertical line indicates the wavelength of the pump laser used in the thermoreflectance imaging (TRI) measurement. (c) Experimental setup of TRI. The sample is heated with an 825 nm pump laser, the change in reflectance ΔR on each pixel in probed by a 530 nm LED. Temperature rise is calculated from ΔR and pre-calibrated thermoreflectance coefficient. (d) Measured average temperature rise inside the laser spot from TRI (green curve, left axis), and measured optical absorption (orange curve, right axis) on 7 nanodisk arrays with radii ranging from 30 to 90 nm. Inset: an exemplary thermal image obtained from the TRI measurement, with x-y plane denoting an area of 22 × 22 μm^2 and the z scale showing a temperature rise of 13~148 K.

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4. References

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