Enhanced thermal emission from individual antenna-like nanoheaters

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Abstract: Here we report polarization-sensitive, thermal radiation measurements of individual, antenna-like, thin film Platinum nanoheaters. These heaters confine the lateral extent of the heated area to dimensions smaller (or comparable) to the thermal emission wavelengths. For very narrow heater structures the polarization of the thermal radiation shows a very high extinction ratio as well as a dipolar-like angular radiation pattern. A simple analysis of the radiation intensities suggests a significant enhancement of the thermal radiation for these very narrow heater structures.

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1. Introduction

The control of spectral and directional properties of thermal radiation using nanostructures has recently attracted a lot of interest because of a number of interesting applications such as thermophotovoltaic (TPV) energy conversion, solar energy utilization, space thermal management, and high-efficiency light sources. While a lot of attention is directed towards manipulating the spectral distribution of the thermal emission [1-5], it was also shown that surface patterned materials (with surface grating or photonic crystals that support surface modes) can have narrow angular and narrow-band thermal emission properties, which show spatial and temporal coherence [6-8]. Such coherence effects are especially interesting for thermal near-field microscopy [9].

In this paper we investigate experimentally the thermal radiation from individual, elongated, antenna-like (i.e. rectangular) thin film Platinum nanoheaters, which confine the lateral extent of the hotspot to dimensions smaller than the thermal emission wavelengths. The temperature of the nanoheaters can be increased up to 900°C by passing a current through the structures, and the thermal radiation is detected with an infrared microscope. Specifically, for very narrow heaters we measure highly polarized thermal radiation signals with large extinction ratios as well as a dipolar-like angular radiation pattern. A simple analysis of the measured radiation intensities suggests a significant radiation enhancement for very narrow and antenna-like nanoheaters.

2. Experiment

The experimental setup is illustrated in Fig. 1. Thin film, rectangular shape Platinum nanoheaters (with width w, length l, thickness=40 nm, and resistivity= 25 Ω cm) with two source (current) and two sense leads (voltage) have been fabricated on a Si/SiO$_2$ (thickness 2 µm) substrate using state of the art e-beam lithography. In this study, the majority of heaters are 6 µm long with different heater widths ranging from 4 µm down to 0.125 µm. The temperature behavior (i.e. thermal resistance) of these heaters is ascertained by carefully measuring the IV characteristics. Accurate measurements of the heater resistance are achieved employing a four point probe measurement with a continuous monitoring of the nanoheater resistance. In combination with the measured temperature coefficient of resistance (~ 2000 ppm/K) the thermal resistance of the nanoheater is determined, which ranges from 36 K/mW (for l= 6 µm, w= 4µm) to 114 K/mW (l= 6 µm w=0.125 µm). It is important to maintain the temperature of the nanoheater constant during the experiment. In separate sets of experiments we established that the nanoheater thermal resistance is constant despite drifting electrical resistances due to annealing. This observation is consistent with electro-thermal modeling results which show that the thermal resistance of nanoheaters has a very weak dependence on the thermal conductance of the Pt. Consequently, we controlled the heater temperatures quite accurately (estimated to be ~ +/-2 %) by maintaining constant DC power dissipation in the nanoheater using a digital feedback loop (see also Ref.[10]).

The thermal emission from the nanoheater is picked up with a high numerical aperture IR lens, analyzed by a linear polarizer and imaged onto a liquid nitrogen cooled InSb camera detector (sensitivity in the 1-5 um spectral region) with a built in shortpass filter at 4.1 µm wavelength [11]. Both from thermal simulations and measurements, the thermal emission is originating from the nanoheaters with negligible contribution from the current and voltage leads. The temperatures of the nanoheater were between 80°C and 800°C during the experiments, which corresponds in accordance to Wien’s displacement law to respective peak emission wavelength between $\lambda_{BB}=8.2$ and 2.7 µm. We note that the wavelength response of the camera is fixed while the emission spectrum changes for increasing temperatures (as well
as for different heater geometries), which somewhat complicates the interpretation of emission data [12]. A simple model for the spectral response of the microscope/detector, which includes the fixed responsivity of InSb detector, the temperature dependent Planck function, and a constant emissivity for the nanoheater over the entire temperature range from 100°C to 800°C predicts that the detected signal of the sample scales with $\sim T^{3.74}$. This is in reasonable agreement with experimental data [12].

Fig. 1. Schematic of the experimental setup. The sample is shown as a SEM image where we overlaid a calculated temperature field (see text for details).

In the experiments, we recorded the radiation signal (i.e. the raw signal from the InSb detector) as a function of the angle of the polarizer $\theta$ with and without the nanoheater powered up. The polarization signal obtained when the heater is off was subtracted from all polarization traces when the heater is powered up, in order to eliminate a residual background signal. Fig. 2 shows typical thermal emission data of a nanoheater ($l=14\mu$m, $w=0.5\mu$m) powered up to 172°C as a function of the angle of the linear polarizer. For heaters with widths smaller than 1 µm, the data shows a very pronounced dipolar-like polarization pattern with the peaks aligned to the heater direction. If the heater is rotated by 90 degrees, the polarization pattern is shifted accordingly as shown in Fig. 2. For wider heaters the polarization direction and the polarization contrast diminishes rapidly with the main polarization shifting by 90 degrees with peaks aligned perpendicular to the heater direction, which will be discussed elsewhere. Performing the same experiments for Pt thin films, we do not observe any polarization signal at any temperatures.

For representation purposes we fit the polarization curves with the function $I(\theta) = I_p \cos(\theta)^2 + I_u$, where $I_p$ and $I_u$ represent the amplitude (polarized) and offset (unpolarized or isotropic part) of the measured emission signal. In the following we refer to the ratio between the maximum ($I_p$) and minimum ($I_u$) of the radiation signal in Fig. 2 as the extinction ratio ($E = I_p / I_u$). The inserts in Fig. 2 show a scanning thermal microscope image where a thermocouple tip [13] maps the temperature field of a typical nanoheater (here $l=10$ µm and $w=0.8$ µm). The thermal images show that the heat is very nicely confined to the
nanoheater dimensions (although the tip convolutes (i.e. broadens) the observed image somewhat (see also [14] for additional information)).

![Diagram](image)

Fig. 2. The thermal radiation signal as a function of the angle of the polarizer exhibits a dipole-like behavior. If the heater is rotated by 90 degrees the polarization pattern is shifted accordingly. The inserts show scanning thermal microscope images of a nanoheater (see text for more details).

Figure 3A shows the extinction ratio (E) as a function of heater width at constant heater length (l=6 µm) for various heater temperatures. The data reveals a strong increase in the extinction ratio (i.e. from 0 to ~5) suggesting that the thermally-driven charge fluctuations are getting more and more confined as the width of the heater is narrowed.

In the following we quantify the magnitudes of the radiation signals for the different heater geometries and temperatures. Therefore, we integrate the total ($I(\theta)$) and the unpolarized part ($I_u$) of the radiation signal of Fig. 2 (over a $2\pi$ interval) and define an radiation efficiency for the total and unpolarized thermal emission signal, respectively by dividing through the average measured temperature dependence ($T^{3.34}$) and the heater area ($A=w l$):

$$
R_{total} = \frac{\int_0^{2\pi} I(\theta) d\theta}{AT^{3.34}}
$$

$$
R_{unpol} = \frac{2\pi I_u}{AT^{3.34}}
$$

(1)

In Fig. 3B and 3C we have plotted the total and unpolarized radiation efficiency as a function of heater width for the same data set as shown in Fig. 3A. Eq.(1) is analogous to Stefan-Boltzmann’s law and thus the radiation efficiency may be interpreted as an (apparent) spectral emissivity. Referring to Fig. 3B, an almost constant radiation efficiency is observed for wider heaters, which is consistent with the predictions of Stefan-Boltzmann’s law. However and most interestingly, Fig. 3B demonstrates a substantial increase in radiation efficiency for each temperature (ranging from 4.6x at 180°C to 5.5x at 500°C) for very narrow heaters. In order to have an independent reference for larger heater widths in Fig. 3B we have measured the emissivity (up to 420°C) of the same Pt film (used to fabricate the nanoheaters) in our experimental setup yielding ~0.1 at room temperature with a slight temperature dependence ($1.1 \times 10^{-4} /K$), which is excellent agreement with published emissivity data on bulk Pt samples [15]. For comparison the unpolarized radiation efficiency in Fig. 3C changes much less for the various heater sizes (i.e., Fig. 3B and 3C are shown on the same y-axis).
The relatively small dependence of $R_{\text{unpol}}$ on heater width indicates that the actual hotspot dimensions scale directly with the heater size, which is an underlying assumption in Fig. 3B, where we claim an appreciable enhancement in the total radiation efficiency. This assumption (i.e., that the hotspot scales directly with the heater size) is also supported by thermo-electrical FE modeling calculations for the temperature fields of each nanoheater, which show that the substrate is a good heat sink effectively preventing heat spreading [14]. The calculated thermal resistances agree well with the measurements, demonstrating that the predicted temperature fields are accurately reproduced by the thermal model [14]. Weighting the FE predicted thermal maps for the nanoheater with the derived temperature dependences and integrating laterally over the hotspots, shows that the hotspot scales directly with the heater dimensions. Finally, further support for this assumption comes from the fact that the Pt nanoheater is fabricated on Si and SiO$_2$, both materials with low emissivity at these temperatures (i.e., the radiation is sub bandgap for Si at these heater temperatures and emission frequencies). Consequently, any potential lateral heat spreading would contribute significantly less to the radiation signal than the heated area within the Pt nanoheater.

While it is unclear how much of the radiation enhancement in Fig. 3B originates from a change in the emission spectrum or from additional surface roughness or from possible interference effects with reflections from the Si/SiO$_2$ interface in the substrate, it is very conceivable that some of this enhancement is due to the geometrical confinement of the heat to the antenna-like shape of the nanoheater, which increases the polarizability and thus emissivity of the nanoheater [16]. Referring to fluctuation-dissipation theory [17], randomly fluctuating electric fields are induced, where every (heated) volume within the nanoheater contains currents and can be thought of as a dipolar antenna that emits radiation. Naturally, in
a bulk material the phase relation between these dipoles is random (the thermal emission is incoherent, unpolarized and isotropic) but the situation fundamentally changes as the hotspot becomes smaller than the wavelength, where the phase relations are defined simply by the close proximity and geometrical alignment of the emitting dipoles.

Further support for our interpretations comes from Fig. 4, where we have measured the angular radiation pattern from the nanoheaters at 500 °C for two different heaters, having widths of \( w=0.3 \, \mu m \) and \( w=0.5 \, \mu m \) and lengths 3 \( \mu m \) and 5 \( \mu m \). In order to enhance the angular resolution we used a lower NA lens (~0.28) and rotated the sample in 2.5 degree steps about the axis in the plane of the substrate and perpendicular to the long axis of the heater. After each rotation the sample was manually focused using infrared camera (Merlin, FLIR Technology). An AC voltage (25Hz) was supplied to the nanoheater and the thermal emission was measured by an InSb detector (without short pass filter) demodulating the amplitude of the signal at twice the modulation frequency. Fig. 4 shows a dipolar-like thermal emission pattern that narrows (more directed) substantially with decreasing heater width.

![Angular thermal radiation patterns for two nanoheaters with different width. The axis of rotation lies in the plane of the substrate and perpendicular to the long axis of the heater.](image)

3. Conclusions

In summary, we have investigated the thermal emission properties of individual rectangular thin film nanoheaters with dimensions comparable or smaller than the emission wavelengths. A high extinction ratio as well as a dipolar-like angular radiation pattern for very narrow (antenna-like) nanoheaters has been observed. Simple considerations suggest an appreciable enhancement of the thermal light emission from small antenna-like nanoheaters. We believe that the small dimensions of the nanoheater effectively avoid spatial decoherence between the thermally-induced dipoles within the nanoheater. The antenna-like polarization pattern suggests a high degree of spatial and temporal coherence of charge fluctuations within the heaters. This could result in strong infra-red near-fields, which could be deployed in ATR (attenuated total reflectance) IR spectroscopy. The results are also important for improving the understanding of thermal radiation from nanostructures, coherence effects of thermal emission, for nanometer-scale near-field radiative transfer as well as IR near-field microscopy.

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