Measurement of Transient Thermal Responses of Nanofilms under Radiative Heating from Pulsed Laser Induced Plasma

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INTRODUCTION

The direct measurement of transient surface temperature on a substrate subjected to impulsive radiation is a non-trivial task. The transient temperature measurement sensors commercially available have rise times ranging from μsec to milliseconds. Thermocouples normally have rise time in milliseconds[1] while the rise time of a fiber optic temperature probe is approximately 1μs[2]. Pulsed laser excitation applications require giga-hertz frequency range sensing techniques (nanosecond measurements). For this reason, various indirect nanosecond transient temperature measurement techniques were introduced for measuring the surface temperature of the substrate in direct laser heating applications, employing photodiodes[3] and charge coupled devices [4].

The objective of the current study is to develop an indirect transient temperature measurement technique for the estimation of surface temperature of a semiconductor substrate processed with Laser Induced Plasma (LIP) nanoparticle removal technique. The expansion, saturation and decay of the plasma resulted from the dielectric break down of air; due to focusing of a nanosecond pulsed laser is a nanosecond phenomenon, and is a source of impulsive radiation and subsequent thermo-mechanical excitation of the substrate film which is placed few millimeters away from the path of the laser beam. In this transient temperature measurement technique, the LIP radiation energy per pulse is measured and the measured energy is superimposed over the known LIP irradiation profile. This renormalized intensity profile is used as the actual radiation profile for the temperature estimation.

EXPERIMENTAL PROCEDURE

The temporal profile (band-width: 580-700 nm) of the laser induced optical-emission reported in[5] is used as the radiation profile of LIP. The peak plasma intensity is expected to attain its maximum at the end of the laser pulse (Fig. 1(*a*)) as the plasma formed absorbs all the incident laser radiation, and thus the profile reported in[5] was normalized in the first 45 ns period and then approximated by a function to extrapolate the profile until 400 ns, as the plasma intensity diminishes after 400 ns[5]. The normalized plasma radiation intensity profile used as a boundary condition is depicted in Fig. 1(*a*). The LIP radiation profile was calibrated by measuring the peak radiation energy using a volume absorber energy/power meter. The measured energy was then related to the plasma radiation intensity based on the dimensions of the sensor area of the power meter.

A set of experiments (Fig. 1(*b*)) were conducted to determine radiation energy from the LIP core utilizing a 370 mJ, 1064 nm Nd: YAG pulsed laser (5 ns pulse width, 5 mm beam diameter). The laser beam was focused using a 100 mm focal length convex lens. The thermal head used to measure the radiation energy of the plasma was a medium power volume absorber power/energy meter. The display unit coupled to the power meter was a radiant power energy meter. The smaller the gap distance *d* (Fig. 1(*b*)), the higher are the pressure and the temperature, which might result in the damage of the probe. The laser was fired in single shot mode and the corresponding total radiation energy deposited on the sensor area was recorded. The radiation energy measured at different gap distances (22 mm to 3 mm) are shown in inset of Fig.1(*a*). The average corresponding peak intensity I_0 obtained in single shot mode at these gap distances was then calculated based on the dimension of the sensor area ($\phi = 17$ mm). The estimated intensities of the LIP at different gap distances, d = 3 mm, 5 mm and 10 mm are 8.1471 GW/m^2, 5.2608 GW/m^2 and 1.8225 GW/m^2 respectively. Further, the intensity was fitted to estimate the plasma intensity at any gap distance. It was assumed that the radiation intensity profile acting at all the gap distances would arrive uniformly at the probe surface, as the radiation of the plasma propagates with the speed of electromagnetic waves except that the magnitude would be a function of gap distance. The normalized intensity profile was then multiplied by the magnitude of the radiation intensity to obtain the intensity profile at that particular gap distance. The one-dimensional heat conduction equation is used to approximate the surface temperature of the nanofilms when the intensity of LIP radiation is known. The close form solution of the one-dimensional heat equation when the surface is uniformly excited by square pulse is described in [6]. The radiation intensity profile for LIP at a gap distance of 2.5 mm is obtained by multiplying the normalized intensity profile (Fig.1 (*a*)) with a factor of 9.09, which is the laser intensity at 2.5 mm obtained by extrapolating the data from the experiment described above. In order to use the close-form solution to estimate the surface temperature, the intensity profile is divided into square pulses with a pulse width of 1 ns. Then the surface temperature profiles are obtained by the convolution of the individual square profiles with the close form solution. The individual temperature profiles are then summed up to obtain the surface temperature profile. Fig. 1(*c*) shows the transient surface temperature profile due to LIP radiation excitation obtained for a peak intensity of 1 GW/m^2.

RESULTS AND CONCLUSIONS

The transient thermoelastic response of the chromium film under nanosecond-scale (impulsive) radiation excitation was obtained and analyzed. The peak temperature rise on the surface of the chromium film for a peak intensity of 1 GW/m^2 is 8 K (Fig. 1(*c*)) and the peak surface temperature rise for a peak intensity of 9.09 GW/ m^2 (at gap distance of 2.5 mm) is estimated as 72.04 K. The close form solution for one dimensional heat conduction equation, when intensity with a square profile is uniformly prescribed on a metal surface is used. The surface temperature for the plasma radiation profile is determined by convoluting the radiation profile with the close form solution.

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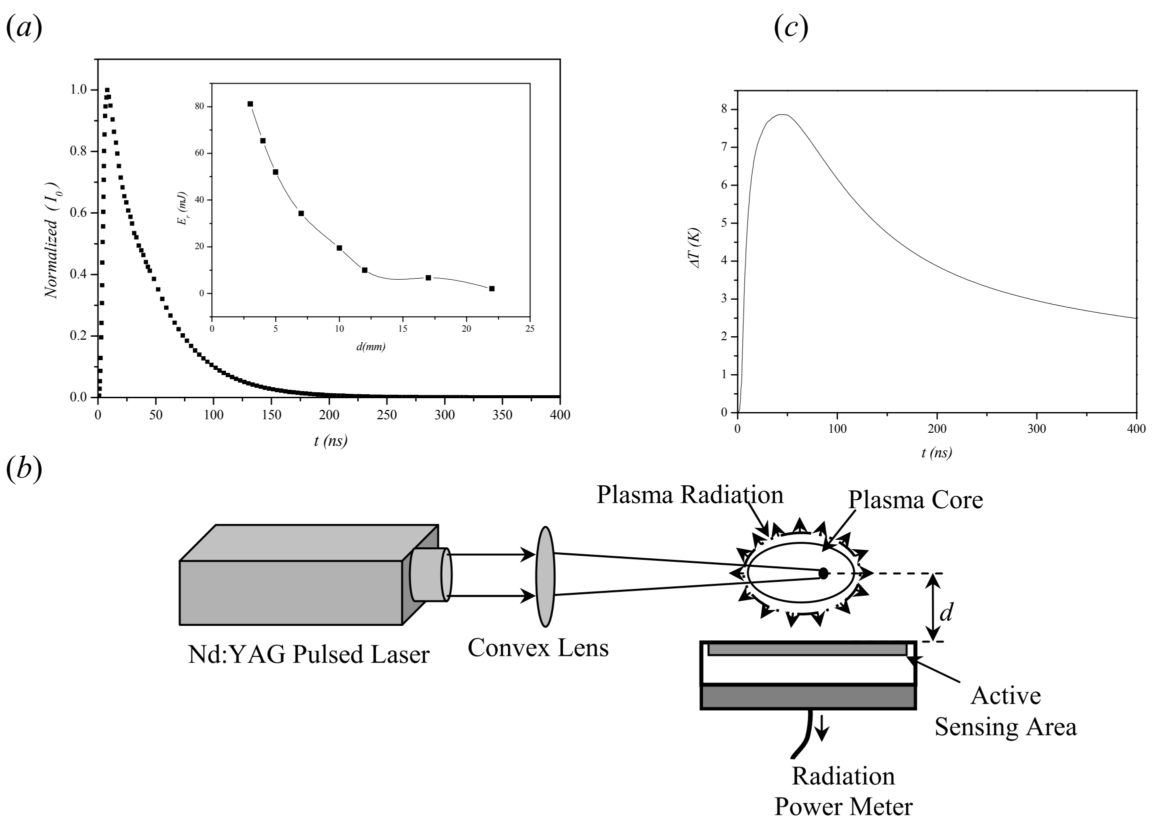

Figure 1(*a*). The intensity profile of the LIP approximated by normalizing the laser induced-optical emission in time (t) measured by [5]. The radiation energy obtained at various gap distances is plotted in the inset, (*b*) schematic of the LIP radiation energy measurement experimental setup and (*c*) the transient temperature profile on the surface of the chromium film subjected to nanosecond impulsive radiation of LIP.