Noncontact nanosecond-time-resolution temperature measurement in excimer laser heating of Ni–P disk substrates

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The thermal emission from a Ni–P disk substrate heated by a pulsed excimer laser is measured with nanosecond time resolution. A fast InGaAs photodetector is employed to capture the thermal emission signal. The spectral surface reflectivity is simultaneously measured *in situ*. The transient surface temperature is derived from the spectral thermal emission signal on the basis of Planck's blackbody radiation intensity distribution. The experimental results and analytical solutions are compared and an important parameter involving the thermal diffusivity and conductivity in the transient temperature response of the material is evaluated. © *1997 American Institute of Physics.* [S0003-6951(97)01248-5]

Control of the surface temperature during pulsed laser processing of materials is of critical importance. Development of noncontact, short time-scale surface temperature measurement methods as well as other *in situ* optical diagnostics including time-resolved reflectivity and transmissivity probes is necessary. For example, time-resolved reflectivity measurement was conducted in the pulsed laser heating of silicon and germanium samples.[1,2] Nanosecond time-scale temperature measurement during pulsed laser heating of tungsten was carried out using blackbody radiation distribution.[3] A noncontact nanosecond-time resolution pyrometer was developed to study the transient temperature field development in the pulsed laser melting of polycrystalline silicon (*p*-Si) films on transparent substrates.[4] In this study, the maximum thermal emission signal was only several millivolts with relatively low signal-to-noise ratio.

Amorphous Ni–P disk substrates have been widely used in the hard disk industry because of their excellent smoothness. Laser texturing of high-density magnetic disks has attracted great interest as a novel industrial application improving the tribological performance and durability.[5,6] It was shown that the texture feature formation is very sensitive to surface temperature.[6] However, numerical modeling was hindered by lack of knowledge of the thermal properties of the Ni–P alloy at high temperatures.[7] Due to the composition of the volatile phosphorous (12 wt %), it is difficult to evaluate the thermal properties at high temperatures by conventional methods. The thermal properties of NiP reported by Lu *et al.*[8] are valid only in the temperature range of 300–400 K.

It is the aim of this work to develop a nonintrusive nanosecond-time-resolution experimental method to measure the transient surface temperature response of Ni–P disk substrates to nanosecond excimer laser heating. The transient surface temperature is derived from the measured spectral thermal emission signal based on Planck's blackbody radiation intensity distribution. The thermal diffusivity and conductivity for the Ni–P substrate are evaluated by comparing the experimental results with analytical solutions.

A schematic of the experimental setup is shown in Fig. 1(a). The Ni–P disk substrate surface is heated by a KrF excimer laser beam [$\lambda = 248$ nm, full-width at half-maximum (FWHM)=23 ns]. The pulse duration of the excimer laser beam is measured using a fast silicon PIN photodiode having a rise/fall time less than 1 ns and a digitizing oscilloscope with 1 GHz sampling speed (1 ns time resolution). A beam splitter is used to reflect 10% of the main beam to an energy meter which is employed to monitor the laser pulse energy. A tunnel-type beam homogenizer is used to ensure spatial uniformity of the laser beam. The variation of the laser light intensity on the sample surface is less than 10% over the central 90% portion of the laser beam. The excimer laser beam is focused onto the sample surface to a spot size of about 5.5 mm×1.5 mm by two ultraviolet lenses.

Two lenses (2 in. diam) with focal lengths of 65 mm are used to image the center area of the laser-heated spot onto

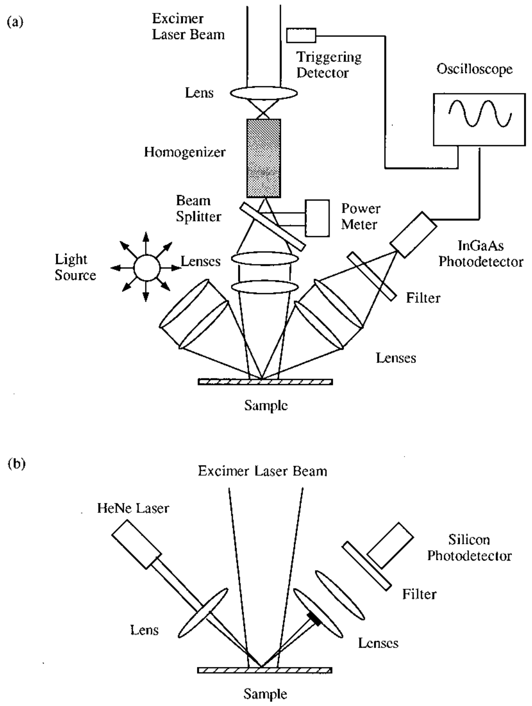

FIG. 1. (a) Experimental setup for the surface temperature measurement and (b) experimental setup for scattering measurement.

[a)] Electronic mail: cgrigoro@euler.berkeley.edu the active area of the detector in a 1:1 transfer ratio. The InGaAs photodetector (New Focus, model 1811) has a rise/fall time of 1 ns, a conversion gain of 3.2×10^4 V/W, and responsivity of 0.8 A/W at 1.5 μm. The active area of this detector is 0.07 mm^2, which compared with the heated spot size of 5.5 mm×1.5 mm, is small enough to ensure uniform temperature in the detected region. To distinguish the spectral thermal emission signal and enhance the accuracy of the measurement, four band pass filters with wavelengths of 1.2, 1.4, 1.5, and 1.6 μm, respectively, and bandwidths of about 0.08 μm are employed.

Since surface emissivity information is needed for determination of surface temperature, the transient reflectivity as a function of the temperature, wavelength, and surface conditions is simultaneously measured *in situ*. A 150 W Xenon short arc lamp is used to supply the light source. The beam is focused onto the sample surface by two lenses. The reflected portion of this beam is refocused onto the InGaAs detector through the same lens system that is used for collecting the thermal emission. The reflectivity is obtained by subtracting the signal with the light source off (i.e., the pure thermal emission signal) from the one with the light source on. The incident intensity of the light source at room temperature and at each wavelength is measured using a metallic mirror with high reflectivity in the near-infrared range.

In order to check possible diffuse surface reflectance effects during the excimer laser heating, a HeNe laser beam ($\lambda = 632.8$ nm) is also focused on the heated area. The light reflected from the incident HeNe beam is refocused onto a silicon PIN photodiode (New Focus, model 1611) as shown in Fig. 1(b). However, a small part of the center area of the refocusing lens is covered to block the specular reflected component. In this manner, only diffuse reflected light is transmitted through the lenses and collected by the detector. A fresh spot on the Ni–P disk substrate is used for each excimer laser pulse. The fluorescence effect is examined and no signal is detected if the sample is removed.

The thermal emission signal collected by the detector can be expressed by

$$\nu(T) = \frac{R_\Omega A}{\pi} \int_{\lambda 2}^{\lambda 1} \int_{\phi 2}^{\phi 1} \int_{\theta 2}^{\theta 1} \varepsilon'_\lambda(\lambda,\theta,\phi,T)\,\tau(\lambda) \times G(\lambda)\, e_{\lambda b}(\lambda,T)\, d\theta\, d\phi\, d\lambda, \tag{1}$$

where T is the temperature; θ and ϕ are the polar and azimuthal angles, λ is the wavelength; R_Ω is the impedance of the oscilloscope (50 Ω); A is the area on the sample which is sensed by the detector; $\varepsilon'_\lambda(\lambda,\theta,\phi,T)$ is the directional spectral emissivity; $\tau(\lambda)$ is the spectral transmittance of the lenses and the filter in the optical path; $G(\lambda)$ is the responsivity (A/W) of the InGaAs detector at different wavelengths; and $e_{\lambda b}$ is the blackbody emissive power which follows Planck's blackbody radiation intensity distribution law:[9]

$$e_{\lambda b} = \frac{2\pi C_1}{\lambda^5 \exp(C_2/\lambda T) - 1}. \tag{2}$$

In the above, C_1 and C_2 are the blackbody radiation constants; $C_1 = 3.7420\times10^8$ W $\mu\text{m}^4/\text{m}^2$, $C_2 = 1.4388\times10^4$ K μm.

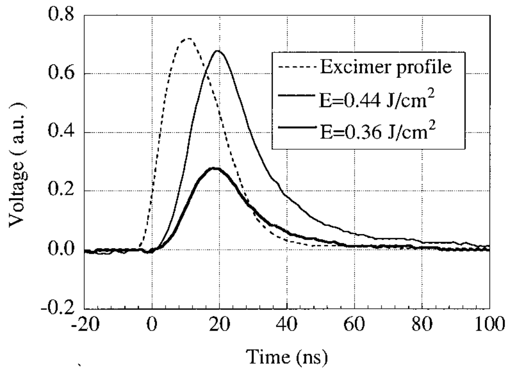

FIG. 2. Typical thermal emission signals at laser fluences of 0.44 and 0.36 J/cm^2 and excimer laser pulse profile.

On the basis of the reflected light measurements, the diffuse scattered reflection is very small compared with the specular reflection. The heated surface can therefore be considered as optically smooth. Therefore, the directional spectral emissivity $\varepsilon'_\lambda(\lambda,\theta,\phi,T)$ can be related to the specular reflectivity by

$$\epsilon'_\lambda(\lambda,\theta,\phi,T) = 1 - R'(\lambda,\theta,\phi,T), \tag{3}$$

where $R'(\lambda,\theta,\phi,T)$ is the specular reflectivity of the surface.

Once the specular reflectivity of the surface is measured, the transient surface temperature can be obtained by solving Eq. (1). However, in order to enhance the accuracy of the measurement, four different wavelength signals as discussed previously are measured and compared by the following:

$$F(T) = \left|\frac{\nu_{o,1.6}}{\nu_{o,1.4}} - \frac{\nu_{e,1.6}}{\nu_{e,1.4}}\right| + \left|\frac{\nu_{o,1.5}}{\nu_{o,1.4}} - \frac{\nu_{e,1.5}}{\nu_{e,1.4}}\right| + \left|\frac{\nu_{o,1.2}}{\nu_{o,1.4}} - \frac{\nu_{e,1.2}}{\nu_{e,1.4}}\right|, \tag{4}$$

where $\nu_{o,1.2}$, $\nu_{o,1.4}$, $\nu_{o,1.5}$, and $\nu_{o,1.6}$ are the measured oscilloscope readings at these four wavelengths, and $\nu_{e,1.2}$, $\nu_{e,1.4}$, $\nu_{e,1.5}$, and $\nu_{e,1.6}$ are the corresponding temperature-dependent values from Eq. (1). The surface temperature is obtained by minimizing $F(T)$.

Before carrying out the measurement on the Ni–P disk substrate, a bulk crystalline silicon wafer was used as a test sample. The experimental results of the melting temperature, melting-time duration, and surface peak temperature showed very good agreement with previous experimental results and numerical predictions.[4]

Typical thermal emission signals from the Ni–P sample are shown in Fig. 2. It is seen that the maximum surface temperature occurs during the falling intensity period of the excimer laser pulse. The delay time of the peak surface temperature with respect to the instant of the peak intensity of the laser pulse is about 11 ns. It is noted that the emission signals are robust due to the high conversion gain and near-infrared responsivity of the InGaAs detector. For the amorphous Ni–P alloy, the experimental results show that the directional specular reflectivity has a certain wavelength dependence but little temperature dependence for laser fluences less then 0.8 J/cm^2. The excimer laser heated samples are further analyzed by energy disperse spectroscopy. No detectable chemical composition change is found even at the high-

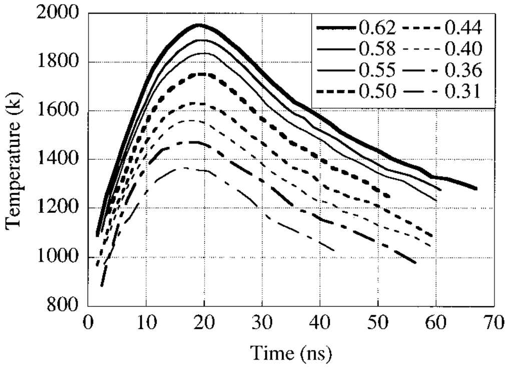

FIG. 3. Transient temperature profiles at different laser fluences (J/cm^2).

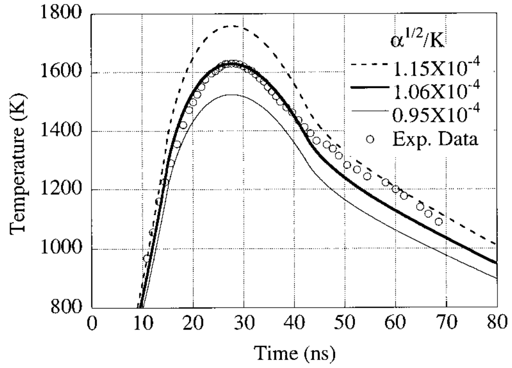

FIG. 4. Fitting the analytical solutions to the experimentally obtained surface temperature profile. The unit of $\alpha^{1/2}/K$ is K s$^{1/2}$ m^2/J.

est laser fluence (0.8 J/cm^2) used in this experiment, which indicates no phosphorous mass loss by evaporation.

The peak surface temperature is first evaluated by Eq. (4) using the thermal emission signals obtained at the same laser fluence but at four different wavelengths. The transient surface temperatures at other times are compared with the peak surface temperature and derived from the following equation:

$$\frac{\nu_o(t)}{\nu_{o,\max}}=\frac{\nu_e(T)}{\nu_{e,\max}(T_{\max})}, \tag{5}$$

where $\nu_{o,\max}$ and $\nu_o(t)$ are the voltages measured at the time instant of the maximum signal and at another time, t; $\nu_{e\max}(T_{\max})$ and $\nu_e(T)$ are derived from Eq. (1) at the respective maximum surface temperature $T_{\max}$ and temperature, T. Figure 3 shows the transient surface temperature profiles at different laser fluences. The error of the temperature evaluation by this method is within ± 50 K.

Thermal properties of the Ni–P disk substrate are evaluated by fitting the heat conduction analytical solution of the surface temperature to the experimentally obtained temperature profile. The components of the complex refractive index (n,k) at the excimer laser wavelength are measured by spectroscopic ellipsometry in the temperature range from 300 to 650 K. The normal reflectivity of the surface R_λ is given by

$$R_\lambda=\frac{(n-1)^2+k^2}{(n+1)^2+k^2}.$$

For the excimer laser wavelength, R_λ is about 0.31 for laser fluences between 0.2 and 0.8 J/cm^2. Due to the small thermal diffusion depth and the small radiation penetration length, the heat conduction problem can be treated as one-dimensional. At $t=0$, the sample is at the ambient temperature, T_∞; the surface heat flux boundary condition is prescribed by $-K\partial T/\partial x|_{x=0}=(1-R_\lambda)I(t)$, where K is the material thermal conductivity and $I(t)$ is the laser pulse intensity incident on the surface as a function of time.

The analytical transient surface temperature solution is obtained for constant thermal properties by using Duhamel's superposition theorem:

$$T-T_\infty=\frac{\sqrt{\alpha}}{K}\,\frac{2}{\pi}\,(1-R_\lambda)\int_0^t\sqrt{t-\tau}\,\frac{\partial I(\tau)}{\partial\tau}\,d\tau. \tag{6}$$

In the above equation, α is the thermal diffusivity. The transient surface temperature is solved for the measured pulse profile $I(t)$.

The analytical surface temperature solutions are compared with the experimental temperature profile. The best fit gives the parameter $\alpha^{1/2}/K$ of 1.06×10^{-4} K s$^{1/2}$ m^2/J for Ni–P disk substrate as shown in Fig. 4. Since $\alpha=K/(\rho C_p)$, K can be found if ρ and C_p are given. Therefore, by comparing the experimental results with analytical solutions, the material response to nanosecond pulsed laser induced high temperature processes such as laser texturing can be quantified.

In summary, thermal emission from a pulsed excimer laser heated Ni–P disk substrate is measured with nanosecond-time resolution. A fast InGaAs photodetector is employed to capture the thermal emission signal. The spectral surface reflectivity is simultaneously measured *in situ*. The transient surface temperature is derived from the spectral thermal emission signal utilizing Planck's blackbody radiation intensity distribution. The experimental results and analytical solutions are compared and an important parameter involving the thermal diffusivity and conductivity is evaluated.

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