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Determination of Thermophysical Properties for Polymer Films using Conduction Analysis of Laser Heating

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Determination of the thermophysical properties of thin film materials is important for modeling and optimizing laser microvia drilling of organic substrates in microelectronics applications. Techniques to measure the density, thermal conductivity, thermal diffusivity, thermal decomposition point, and specific ablation heat of thin polymer films are described. An experimental apparatus was set up for laser heating of the sample. To measure the thermal diffusivity, an analytic heat transfer model is developed. One-dimensional heat conduction is assumed due to the small thickness of the film compared to the radius of the laser beam. The value of thermal diffusivity is obtained by fitting the experimental data to the theory. The specific ablation heat is obtained by measuring the mass loss during laser ablation. The experimental apparatus and the property determination methodology can also be applied to thin samples of other materials.

KEY WORDS: laser heating; polymers; thermal conductivity; thermal diffusivity.

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1. INTRODUCTION

Organic substrates are widely used in flip chip microelectronic packaging because of their unique electronic, thermophysical, and mechanical properties. A variety of polymer materials such as FR4 (Flame Retardant 4) resin, tetrafunctional phenolics, cyanate ester, polyimides, and BT (Bismaleimide Triazine) are used [1] to manufacture substrates and printed circuit boards (PCB). An emerging material for high-density packaging in microelectronics applications is an inorganic particle-filled epoxy. The material used in this study is 30–40 mass% silica-filled epoxy. Lasers are used to drill closely spaced microvias in the substrates to allow novel architecture with transistors and other microelectronics devices in close proximity. Thermophysical properties of the polymer should be known to produce high-quality microvias such as nontapered and polymer char-free holes without any heat-affected zone.

Different measurement systems are used to determine the thermal conductivity and diffusivity. Traditionally there are three measurement techniques: (a) steady-state heating, (b) periodic heating, and (c) pulsed heating [2] for thermal conductivity and diffusivity. The pulsed heating technique is particularly useful for measuring the thermal diffusivity of thin plates. In the steady-state heating method, the steady state is attained after a relatively long time and, therefore, the heat loss has a great influence on the data [3]. Morikawa and Hashimoto [4] have employed alternating current (AC) joule heating to induce periodic heating in order to measure the thermal diffusivity of polyethylene terephthalate and polyethylene naphthalate. The flash method developed by Parker et al. in 1961 [5] has become one of the most popular pulsed heating techniques [6]. The thermal diffusivity of most materials including semi-transparent materials [7], anisotropic media [8], and thin films [9] can be measured by the flash method. The flash method involves pulsed heating of the sample in order to apply a heat flux just to the sample surface instantaneously. Femtosecond lasers may achieve spatially confined and temporally very fast heating conditions for certain materials. However, the finite heat pulse duration, finite absorption depth, and thermal response time of the material may affect the accuracy of measurement for thin films. Taketoshi et al. [10] employed a complex thermoreflectance technique to measure the thermal diffusivity of submicrometer thin films.

During laser drilling of microvias in polymers, various physicochemical phenomena such as gas diffusion, phase transitions (e.g., solid → glassy phase → melt → vapor), chemical degradation, and chemical reactions may occur before reaching the thermal decomposition temperature T_{d} [11]. These processes may occur concurrently, leading to the ablation of materials and thus provide a mechanism for laser microvia drilling. To account for the energy involved in these phenomena, "specific ablation heat," representing the amount of heat needed to ablate a unit mass of the polymeric material at its thermal decomposition temperature, is measured in this study. The substrate surface temperature quickly stabilizes after the chemical degradation of the polymer and tends to remain constant under a quasi-steady-state condition during laser microvia drilling [12]. Thus, the surface temperature, which is termed as the thermal decomposition point, can be considered to be constant and the corresponding heat input may be taken as the specific ablation heat. This specific ablation heat is similar to the term "latent heat of vaporization" used to define the heat input for boiling materials at their respective boiling temperature.

Most measurements of the latent heat of vaporization are based on calorimetric method [13,14]. Recently Godts et al. [15] discussed a simple flow-meter method to determine the latent heat of vaporization. A laser heating-based simple and general experimental setup is investigated in the present article to measure the thermophysical properties of 30–40 mass% silica-filled epoxy. Higher concentration of the filler increases the thermal conductivity in the temperature range used in this article, because of the relatively higher thermal conductivity of fused silica. A 10% increase of the mass fraction of the filler can result in about 25% increase of the composite thermal conductivity [16]. The size effect of the filled particle is not pronounced since the temperature range for the experiment is much higher than 20 K [16]. The thermophysical properties measured in this study are average values for the temperature range 20–200 °C at standard atmospheric pressure. Higher temperatures can result in higher thermal conductivities for non-metals.

2. EXPERIMENTAL PROCEDURE

The experimental setup to measure the thermal diffusivity and conductivity of the polymer is shown in Fig. 1. A Nd:YAG laser of wavelength $1.06\,\mu$m is used to heat the sample. The optical property of the polymer material is such that the Nd:YAG laser beam propagates through the polymer sheet with an absorption coefficient of $4.1\times10^4\,\mathrm{m}^{-1}$ which is calculated by $\mu = -\ln(\frac{T}{1-R})/d$, where μ is the absorption coefficient and d is the thickness of the polymer. R and T are the reflectance and transmittance measured by the Cary 500 Scan spectrophotometer. Thus, the laser beam deposits its energy inside the sheet and acts as a volumetric heat source to heat up the material. The temperatures of the front and rear surfaces of the sheet are measured with an infrared optical pyrometer with an

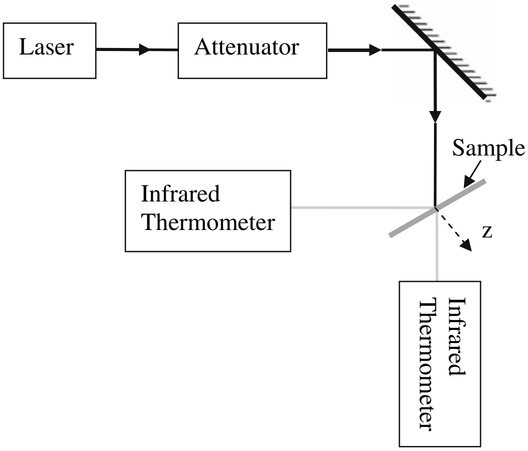

Fig. 1. Experimental setup for temperature measurements to determine the thermal conductivity and thermal diffusivity of the polymer sample.

uncertainty of 0.3% + 2 K. As the amount of absorbed energy increases, the polymer material becomes soft and then decomposes into gases. The temperature at which the polymer begins to decompose is referred to as the decomposition point. To determine the thermal diffusivity, the decomposition should be avoided. The temperature field in the polymer sheet attains a steady state after a short period of time due to the heat loss from the sheet to the surrounding environment. After the steady state is established, the laser irradiation is stopped and the temperature at the rear surface of the sheet is recorded as a function of time until the temperature drops to room temperature. This temporal profile of the temperature is fitted to the analytic solution of a thermal model to determine the thermal diffusivity. By estimating the heat transfer coefficient of the surrounding air [17], the thermal conductivity of the polymer can be obtained from the convection boundary condition at the sheet–air interface.

The specific ablation heat is determined using an experimental setup shown in Fig. 2. Since the specific ablation heat is considered in this study to represent the heat input to the material at the chemical degradation temperature during the laser drilling of microvias in polymers, the polymer sheet used in the measurement should be identical to the polymer sheet used as build-up substrates for a given microelectronics application. This special consideration in selecting the sample for experimental studies will allow an estimation of the specific ablation heat that can be used for modeling the actual microvia drilling process. Since the actual build-up

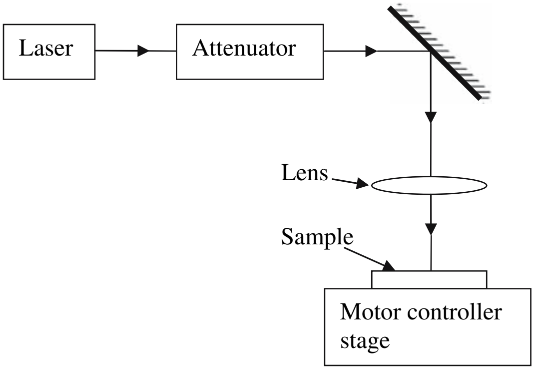

Fig. 2. Experimental setup for laser-induced vaporization and thermal decomposition of the polymer sample to determine a characteristic value of the specific ablation heat.

substrate consists of multilayer polymer layers and copper metallizations, laminated polymer film on a copper cladded core was used as a sample in this study. The laser power incident on the front surface of the sample was measured with a power meter. A portion of the incident laser energy is reflected and the rest is absorbed by the polymer. Since the wavelength of the Nd:YAG laser was 1.06 μm, the reflectivity of the polymer (R_{poly}) was measured with an infrared spectrometer and its value is listed in Table I. For the specific ablation heat determination experiment, a laser beam of relatively high irradiance was used. The absorbed laser energy heats the polymer to its decomposition temperature and causes ablation of the material. The specific ablation heat can be calculated by knowing the loss of mass due to ablation and the absorbed laser energy. Due to the low thermal conductivity and the small size of the laser beam, the heat loss due to conduction, convection, and radiation is negligible compared to the reflected laser energy. If the heat loss is not ignored, it can be considered together with reflection in a single coefficient—absorptivity A, which is described in the following section. The loss of mass is determined by weighing the sample before and after the laser ablation experiment. Since the polymer sheet is very thin and the diameter of the laser spot is very small, the loss of mass would be very small if the laser beam is irradiated to a single spot on the sample and it would be difficult to determine such a small change in the mass. So the sample was moved with an x–y stage to induce laser irradiation over a large surface area in order to increase the loss of mass. The controller of the stage was a VXM stepper motor controller with two Vexta PK266 motors. The motion of the stage was

Table I. Values of Different Thermophysical Properties Obtained in this Study for a Typical Polymer Build-up Film

Thermal conductivity	$0.18\,\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$
Thermal diffusivity	$1.2\times10^{-7}\,\mathrm{m^2{\cdot}s^{-1}}$
Specific heat	$1.04\times10^{3}\,\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$
Density	$1.44\times10^{3}\,\mathrm{kg{\cdot}m^{-3}}$
Thermal decomposition point	539 K
Specific ablation heat	$4.96\,\mathrm{MJ{\cdot}kg^{-1}}$
Reflectance	68.56%
Absorption coefficient at wavelength 1.06 μm	$4.1\times10^{4}\,\mathrm{m^{-1}}$

programed with the Velmex COSMOS software. A quartz crystal microbalance was used to measure the mass loss after the laser ablation experiment. The density of the polymer was determined by measuring the mass of a polymer sheet with the microbalance and by knowing the volume of the sheet. The surface area and thickness of the sheet were 36×24 mm and 97 μm, respectively. The value of the density is listed in Table I.

3. THERMAL MODELING FOR MATERIAL PROPERTY DETERMINATION

Analytic thermal models are used to evaluate the thermophysical properties of the polymer sheet. To measure the thermal conductivity and thermal diffusivity, a one-dimensional heat conduction model is considered to be appropriate since the polymer sheet is very thin (97 μm) compared to the diameter of the laser beam (2 mm). The polymer material, such as the silica-filled epoxy resin widely used as the organic high density interconnecting substrates, is considered isotropic. The thermophysical properties are also considered independent of temperature. The absorbed laser energy is assumed to be transformed into thermal energy instantaneously. If the polymer material is considered as a grey body, the emissivity is equal to the absorptivity which is found to be 0.3 based on spectrophotometric measurements on the reflectivity and transmissivity of the sample. The radiative heat loss from this grey body can be calculated from $E_g = \varepsilon\sigma(T^4 - T_0^4)$, where ε is the emissivity. σ is the Stefan–Boltzmann constant, and T_0 is the surrounding (room) temperature. The temperature of the polymer T was kept at about 196 °C to avoid any thermal decomposition for the conductivity determination experiments. This value of the temperature yields a radiative heat loss of less than 8% of the heat conduction and heat convection.

The laser irradiance on the sample was kept low using a large diameter (2 mm) laser beam in the experiments for measuring the thermal conductivity and thermal diffusivity. Typical samples for these experiments were sheets of polymers. Low irradiance is necessary to prevent localized melting or oxidation of the sample in order to achieve just conduction heat transfer in the sample. At the same time, however, the temperature of the sample should be sufficiently high to measure the temperatures at the front and rear surfaces accurately. Most of the laser light passes through the sample since the polymer sheet is semi-transparent. A black coating was painted on the front surface of the polymer sheet to enhance the absorption of laser energy at the front surface, which raised the temperature of the polymer sample significantly. The black coating was very thin compared to the polymer sheet and was able to absorb most of the laser energy. So surface heating instead of volumetric heating can be used in the thermal model.

To measure the specific ablation heat, however, a certain amount of the sample needs to be ablated, which was readily achieved using a small diameter ($60\,\mu$m) laser beam and, therefore, the black coating was not used in the laser ablation experiments. The ablation of a very small amount of the materials with a scanning laser beam allows us to consider an overall energy balance instead of the differential heat conduction equation. Since it is difficult to distinguish the onsets of vaporization and thermal decomposition of the polymer material, we attempt to obtain a characteristic value for these physical phenomena so that the value of this material property can be used for analyzing the laser microvia drilling of actual polymer substrates. The experimental sample for the laser ablation studies is, therefore, chosen to be the laminated polymer substrates with copper metallization.

3.1. Determination of the Ratio of Heat Transfer Coefficient (k) to Thermal Conductivity (k), i.e., h/k, and Thermal Conductivity Using Steady-State Thermal Analysis

For evaluating first the heat transfer parameter (h/k) and then the thermal conductivity, a laser beam of relatively low irradiance is used to establish a steady-state temperature field in the sample. The vaporization of the polymer is avoided in the experiment in order to induce conductive heat transfer in the sample without any phase (solid → glassy phase → liquid → vapor) change.

The governing equation for the steady-state heat conduction is

$$\frac{\partial^2 T}{\partial z^2} = 0 \tag{1}$$

for $0 < z < d$, where z and t are the axial and time variables, respectively, and d is the thickness of the polymer sheet. The z-axis, which is in the direction of laser beam propagation, is directed along the thickness of the sample with the origin at the front surface of the sample. Here T is the excess temperature above room temperature, i.e., $T = T_\mathrm{a} - T_0$, where T_a and T_0 are the actual temperature of the sample and room temperature, respectively.

The boundary conditions for Eq. (1) can be written as

$$T = T_\mathrm{f} \quad \text{at } z = 0 \tag{2}$$

and

$$-\frac{\partial T}{\partial z} = \frac{h}{k} T, \quad \text{at } z = d, \tag{3}$$

where T_f is the temperature at the front surface of the sample, which is measured with an infrared optical pyrometer. h is the heat transfer coefficient of the surrounding air, and k is the thermal conductivity of the polymer material.

The solution to Eq. (1) subject to boundary conditions, Eqs. (2) and (3), is

$$T = -\frac{(h/k)T_\mathrm{f}}{(h/k)d + 1} z + T_\mathrm{f}. \tag{4}$$

Knowing T at a certain value of z, the unknown parameter h/k can be determined from Eq. (4) and then the thermal conductivity k can be obtained for a given value of h prevailing during the experiment. Although the heat transfer coefficient of surrounding air can be estimated from Ref. 16, the uncertainty in the value of h will affect the accuracy of the measurement technique. To exclude this uncertainty, h/k is treated as a single parameter and the temperature T is measured at $z = d$, which is referred to as the rear surface temperature T_r. Substituting T_r into Eq. (4), h/k can be obtained from the following expression:

$$h/k = \frac{T_\mathrm{f} - T_\mathrm{r}}{T_\mathrm{r} d}. \tag{5}$$

Since T_f, T_r, and d are measured directly, the value of h/k would be accurate and will allow determination of the thermal diffusivity as discussed in the following section.

To determine the thermal conductivity, however, we need to rely on the estimated value of h so that k can be obtained by the following expression:

$$k = \frac{hT_\mathrm{r}d}{T_\mathrm{f} - T_\mathrm{r}}. \tag{6}$$

Thus, the value of k is expected to be less accurate than the value of the thermal diffusivity.

From Eqs. (4) and (5), the steady-state temperature distribution in the sample can be rewritten as

$$T = T_\mathrm{f} - (T_\mathrm{f} - T_\mathrm{r})\frac{z}{d} \tag{7}$$

which is used as the initial condition in the following thermal model to determine the thermal diffusivity of the sample.

3.2. Determination of Thermal Diffusivity and Specific Heat Capacity Using Transient Thermal Analysis

Laser irradiation is stopped when the steady state is reached in the experiment mentioned in Section 3.1, resulting in cooling of the sample. The temperature distribution during the cooling period is analyzed using the following transient thermal model:

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \tag{8}$$

where α is the thermal diffusivity of the polymer. The initial condition for Eq. (8) is taken as the steady-state temperature distribution in the sample (Eq. (7)) at the moment the laser irradiation is stopped.

The boundary conditions are:

$$\frac{\partial T}{\partial z} = \frac{h}{k}T \quad \text{at } z = 0, \tag{9}$$

and

$$-\frac{\partial T}{\partial z} = \frac{h}{k}T \quad \text{at } z = d, \tag{10}$$

where h/k is obtained in Section 3.1.

The solution to the heat conduction problem given by Eqs. (8)–(10) is

$$T(z,t)=\sum_{m=1}^{\infty}\frac{\exp(-\alpha\lambda_{\mathrm{m}}^{2}t)}{N(\lambda_{\mathrm{m}})}Z(\lambda_{\mathrm{m}},z)\int_{0}^{d}Z(\lambda_{\mathrm{m}},z)\left(T_{\mathrm{f}}-(T_{\mathrm{f}}-T_{\mathrm{r}})\frac{z}{d}\right)dz \quad (11)$$

where the normalization constant is

$$N(\lambda_{\mathrm{m}})=\frac{1}{2}\left[\left(\lambda_{\mathrm{m}}^{2}+(h/k)^{2}\right)\left(d+\frac{h/k}{\lambda_{\mathrm{m}}^{2}+(h/k)^{2}}\right)+h/k\right] \quad (12)$$

and the eigenfunction is

$$Z(\lambda_{\mathrm{m}},z)=\lambda_{\mathrm{m}}\cos(\lambda_{\mathrm{m}}z)+(h/k)\sin(\lambda_{\mathrm{m}}z). \quad (13)$$

The eigenvalues λ_{m} are the roots of the following transcendental equation:

$$\tan(\lambda_{\mathrm{m}}d)=\frac{2\lambda_{\mathrm{m}}h/k}{\lambda_{\mathrm{m}}^{2}-(h/k)^{2}}. \quad (14)$$

Thus, the transient temperature field can be calculated using Eq. (11). Since the temporal change in temperature at the rear surface is recorded during the experiment, the theoretical temperature profile, $T(d,t)$, obtained from Eq. (11) is fitted to the experimental temperature profile by choosing an appropriate value of the thermal diffusivity.

The specific heat capacity at constant pressure, C_p, can be obtained using the expression $\alpha=k/(\rho C_p)$, where ρ is the density measured by the method mentioned earlier.

3.3. Determination of the Thermal Decomposition Point and Specific Ablation Heat Using Overall Energy Balance

To measure the thermal decomposition temperature T_{d}, the optical pyrometer is used to monitor the heating process. As the amount of absorbed laser energy increases, the polymer material decomposes into gases. The inception of gas formation is observed visually. When the polymer sheet just begins to liberate gases, the surface temperature of the sample is recorded with the optical pyrometer as the thermal decomposition point.

To measure the specific ablation heat, the following overall energy balance equation is used:

$$P(1-R_{\mathrm{poly}})A\tau=\Delta m[E_{\mathrm{v}}+C_p(T_{\mathrm{d}}-T_0)] \quad (15)$$

where P is the average power of the incident Nd:YAG laser beam, R_{poly} is the reflectance of the polymer sheet, τ is the laser ablation experiment

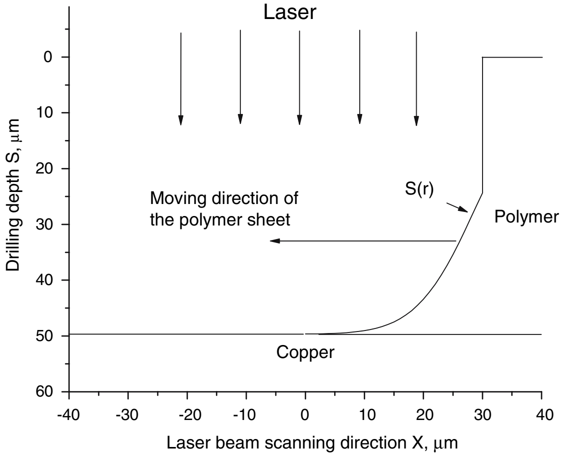

Fig. 3. Curved ablation front surface, $s(r)$, formed in the polymer during laser ablation experiment with a scanning laser beam. This curved profile is taken into account in the calculation for determining the specific ablation heat.

time, and Δm is the loss of mass during the experiment. T_0 is the surrounding (room) temperature. E_v is the specific ablation heat that we want to determine. After a fraction of the incident laser energy is reflected at the front surface of the sample, the rest of the laser energy penetrates into the sample since the polymer is semi-transparent. The absorption of this transmitted energy can be divided into three parts: (a) energy absorbed by the polymer when the beam propagates from the front surface to the copper layer, (b) energy absorbed by the copper layer, and (c) energy absorbed by the polymer when the laser beam propagates upward to the front surface after being reflected by the copper layer. The absorptivity A in Eq. (15) refers to the ratio of the total amount of energy absorbed by the polymer to the total energy penetrated into the sample. The value of A is evaluated using the Bouguer–Lambert law as discussed below.

During laser irradiation of the sample as shown in Fig. 3, the laser beam penetrating into the substrate is absorbed by the sample with an absorption coefficient μ. The laser irradiance propagating downward inside the polymer can be expressed as

$$I_{ip} = I_e \exp(-\mu z), \tag{16}$$

where I_e is a fraction of the incident laser irradiance that enters into the polymer sheet.

For a Gaussian beam, I_e is related to the incident laser irradiance by the following expression:

$$I_e = I_0(1 - R_{\text{poly}})\exp(-2r^2/r_0^2)\Phi(t), \tag{17}$$

where I_0 is the irradiance at the laser beam center, r is the radial distance from the laser beam center, r_0 is the radius of the incident laser beam, and $\Phi(t)$ represents the following laser pulse shape function in this study.

$$\Phi(t) = \begin{cases} 1 & \text{for} \quad nt_p < t \leqslant nt_p + t_{\text{on}} \qquad n = 1, 2, 3, \ldots, \infty \\ 0 & \text{for} \quad nt_p + t_{\text{on}} < t \leqslant (n+1)t_p \end{cases} \tag{18}$$

where t_{on} is the pulse-on time and t_p is the period (pulse-on plus pulse-off time) for rectangular pulse shape. I_0 is given by

$$I_0 = 2Pt_p/(\pi r_0^2 t_{\text{on}}), \tag{19}$$

for a rectangular pulse shape considered in this study.

The laser beam does not penetrate the copper layer. The irradiance of the laser beam coming out of the polymer after being reflected by the copper layer can be expressed as

$$I_{\text{out}} = I_e R_{\text{cu}} \exp[-2\mu(d - s(r))] \tag{20}$$

and the laser irradiance absorbed by the copper can be expressed as

$$I_{\text{cu}} = I_e(1 - R_{\text{cu}})\exp[-\mu(d - s(r))] \tag{21}$$

where the absorption coefficient μ is $4.1 \times 10^4\,\text{m}^{-1}$ [18]. The reflectivity of the copper layer R_{cu} is 97.2% at 1.06 μm wavelength [19]. Since the laser beam moves relative to the sample in this experiment, a quasi-steady state is established with a curved surface in the polymer representing its ablation front as shown in Fig. 3. The profile of this ablation front $s(r)$ is calculated using a thermal model in Ref. 20. Now the absorptivity A for Eq. (15) can be obtained by the following expression:

$$A = \frac{\int_0^{r_0}\int_0^{2\pi} (I_e - I_{\text{out}} - I_{\text{cu}}) r\,d\theta\,dr}{\int_0^{r_0}\int_0^{2\pi} I_e r\,d\theta\,dr} \tag{22}$$

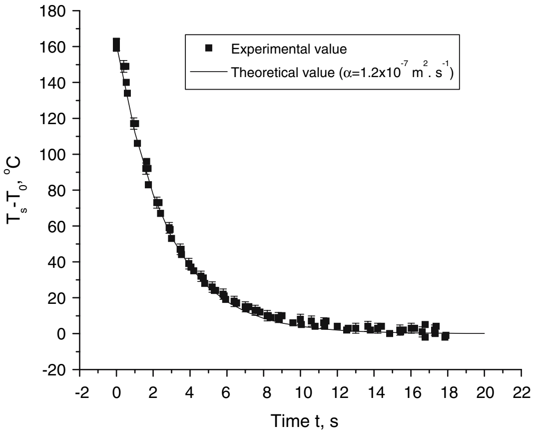

Fig. 4. Comparison of the experimental and theoretical temperature variations at the bottom surface of the polymer sample as a function of time after stopping the laser irradiation, enabling the determination of thermal diffusivity.

4. RESULTS AND DISCUSSION

Based on the above-mentioned methods, the thermophysical properties of the polymer sample are obtained as listed in Table I. The thermal conductivity was found to be $0.18\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ which is an average value over the temperature range, i.e., the steady-state temperature distribution that existed in the sample during experiment. Garret and Rossenberg [16] reported a thermal conductivity of $0.3\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ at 300 K for substrates made up of Araldite MY 740, HY 906, DY 062, and 44 mass% glass-filler materials. The discrepancy between these two studies may be due to the different types of polymers used. The average temperature of the sample was 196 °C in this study. Knowing the thermal conductivity and the heat transfer coefficient of the surrounding air, the theoretical temperature profile $T(d,t)$ is calculated using Eq. (7) to fit the experimental data for a particular value of thermal diffusivity as shown in Fig. 4. This measured thermal diffusivity is found to be $1.2 \times 10^{-7}\ \mathrm{m^2 \cdot s^{-1}}$ which is the representative value at the mean temperature of the transient process. The specific heat capacity is then calculated to be $C_p = k/(\rho\alpha) = 1.04 \times 10^3\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$.

While conducting the temperature measurement experiment, the laser power was varied and the temperature of the sample was recorded when the steady state was achieved for each laser power. The steady-state surface temperature is presented in Fig. 5 as a function of laser power for

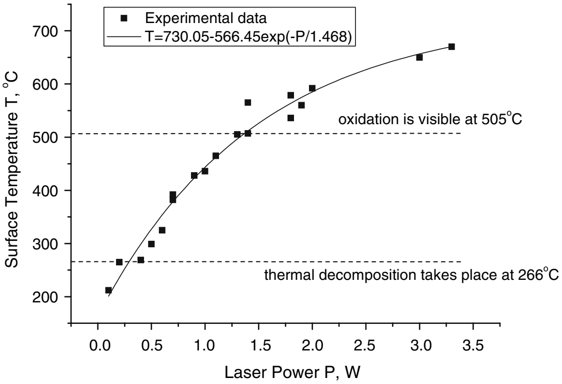

Fig. 5. Steady-state temperature at the top surface of the polymer sample due to a continuous wave stationary laser beam of radius 2 mm for different laser powers.

a given laser beam diameter (2 mm). As the laser power increases, the surface temperature will increase due to the increasing heat flux at the surface of the sample. When the surface temperature reaches 266 °C, the polymer begins to liberate gases indicating the onset of thermal decomposition. Chemical reaction occurs between the polymer and the oxygen of the air during the experiment. The oxidation becomes visibly intense with burning flames at the surface temperature 505 °C. Figure 5 shows that the polymer temperature continues to rise as the laser power increases and eventually the temperature approaches a constant value of 730 °C. This indicates that the thermal decomposition occurs over a range of temperature, which may occur because the polymer material in this study is a multicomponent system consisting of polymeric chains of different lengths, binders, and fused silica. The temperature range for thermal decomposition is from 266 to 730 °C. Vaporization/boiling generally occurs at a fixed temperature for single component materials. It is, however, expected to occur over a range of temperature for multicomponent materials such as the polymer. Since it is very difficult to distinguish between the thermal decomposition and vaporization, these two phenomena are considered to occur in the same temperature range in this study.

The sample used for measuring the specific ablation heat was a laminated multilayer polymer sheet with a copper layer. The surface area and the thickness of the sheet above the copper layer were (15.9×12.6 mm) and 50 μm, respectively. The sample was placed in air and was scanned with a laser beam of average power 1.25 W at the scanning speed of 2 mm$\cdot$ s^{-1}; 40 tracks of width 60 μm each were created on the sample surface. So the

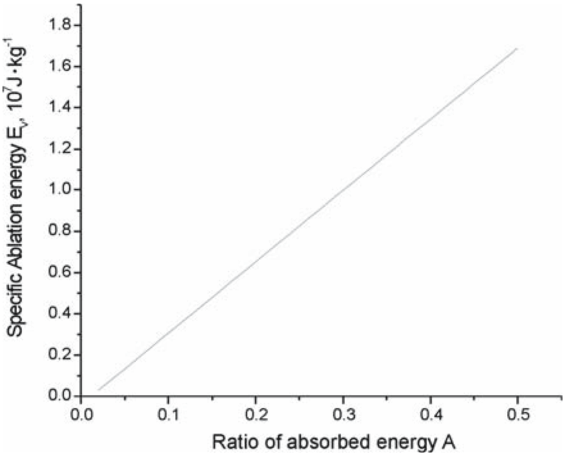

Fig. 6. Specific ablation heat as a function of the ratio of the absorbed laser energy to the total amount of laser energy entered into the polymer sample.

sample was irradiated with the laser beam for a duration of $\tau = 159.4\,\text{s}$. The loss of mass was measured with a microbalance, which was found to be 1.81 mg. The specific ablation heat depends on the ratio of the energy absorbed by the polymer material to the energy penetrating into the sample, A, as shown in Fig. 6. By selecting an appropriate value of A, the specific ablation heat E_V can be determined accurately. Taking A as 0.155 based on the model in Ref. 19, the specific ablation heat is calculated to be $4.96\times10^6\,\text{J}\cdot\text{kg}^{-1}$. For the specific ablation heat measurement, the interactions between the laser and polymer are complex which include pyrolysis and oxidation depending on the ambient conditions around the interaction zone. The specific ablation heat provides a simplified description for the heat transfer mechanism during laser removal of polymeric materials such as laser microvia drilling. The value of this energy was determined in this study based on experiments conducted in air which may cause both pyrolysis and combustion. In other environments such as inert gases or pure oxygen, the measured data can be different due to different physicochemical phenomena. The polymeric material would be pyrolized in an inert environment, whereas complete combustion would occur in pure oxygen environments.

5. CONCLUSION

A simple laser heating method is presented to measure the thermal conductivity, specific heat capacity at constant pressure, density, thermal decomposition temperature and specific ablation heat for epoxy resin sheets of high-glass transition temperature filled with fused silica. A constant value of thermal diffusivity fits the theory and experimental data over a large range of temperature, indicating that the thermal diffusivity of the polymer material may be considered constant over this temperature range. The complex interactions between the laser and polymers may be represented by a single material property which is referred to as the specific ablation heat. These thermophysical properties can be used for modeling and understanding laser microvia drilling processes.

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