355 nm Nd:YAG laser ablation of polyimide and its thermal effect

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Abstract

Ablation results of polyimide (PI) by a single pulse of an acoustic–optical Q-switched Nd:YAG laser at 355 nm are reported for the first time and are compared with the results for RCC1 (resin coated copper, trade mark of Allied Signal) and PI at other wavelengths. The difference of the ablation depth of PI from that of RCC1 is small for a same fluence ranging from 3 to 184 J cm\(^{-2}\), especially the ablation depth of the two materials is nearly the same for a same fluence ranging from 5 to 100 J cm\(^{-2}\), although the ablation threshold of the former is much lower than that of the latter, which are 0.1 and 0.7 J cm\(^{-2}\), respectively. Comparing the ablation results of PI at 355 nm with those at shorter wavelengths, both the threshold and slope of the ablation rate against the fluence are higher than those at shorter wavelengths. At the same time, melting is evident in the process. The temperature profile and temperature change with time caused by the laser at different wavelengths and different pulse frequencies are calculated, the calculated results being in agreement with the experimental studies reported by previous authors. It is shown that the advantage of the small thermal effect occurring in the acoustic–optical Q-switched laser ablation is offset significantly because of a small absorption coefficient for laser energy, although the ablation rates can be increased at a relatively high power density.

Keywords: Laser ablation; Polyimide; RCC1

1. Introduction

Laser drilling microvias in high density printed circuit boards has increased rapidly in the last 4 years and is becoming the dominant technology in some countries [1]. The main laser sources used in the PCB drilling include the CO\(_2\) laser, the excimer laser, and the 266 and 355 nm Nd:YAG laser. The main issues in the laser drilling of PCBs are the ablation rate and the thermal effect caused by the laser energy, which can result in volcano-shaped delamination at the copper–dielectric interface [2]. Some measures, including reducing the pulse width, choosing an appropriate laser wavelength and making the copper layer more massive, can reduce the delamination to some extent. For example, delamination can be avoided if the thickness of the copper is greater than 36 \(\mu\)m for a 1.06 \(\mu\)m wavelength YAG laser where the pulse width is 0.2 ms [3], or if the thickness was as small as 9 \(\mu\)m for a 10.6 \(\mu\)m wavelength CO\(_2\) laser where the pulse width is between 65 and 250 \(\mu\)s [4]. However, whilst these measures improve hole quality, they also make the ablation rate and throughput decrease: a compromise has to be made to give consideration to both hole quality and productivity.

Although extensive studies on the ablation of polyimide using different UV wavelength lasers have been carried out, including a 193 nm, and a 248 nm laser for a fluence below 10 J cm\(^{-2}\) [5–8], a 308 nm for a fluence below 100 J cm\(^{-2}\) [9,10] and a 351 nm laser for a fluence below 0.16 J cm\(^{-2}\) [8], investigation on acoustic–optical Q-switched 355 nm YAG laser ablation of polyimide (PI) has not been reported previously. Although it is claimed that the laser drilling of polymers of PCB at 355 nm is a photochemical process, increasingly more studies [10–12] have shown that the thermal effect cannot be neglected for the UV laser ablation of polymers. Even for deep UV laser ablation of PI, which is thought to be dominated by the photochemical effect [8], the surface temperature can be as high as 1600 K [11] when the laser power is at threshold level and the laser wavelength is at 193 nm. At the same time, nearly all of the laser energy is transformed into the heat for 308 nm laser ablation of polymethyl methacrylate (PMMA) [8]. It is believed that for the 355 nm laser ablation of polymers, the thermal effect should not be ignored also.

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In this paper, the morphology of the ablated crater of PI is analyzed with a conventional light microscope, a scanning electron microscope (SEM) and an atomic force microscope (AFM). The diameter and the depth of laser ablation of PI by a single acoustic–optical Q-switched pulse at 355 nm are reported for the first time. The temperature profiles caused by laser pulses of different pulse repetition rates at the ablation threshold power density were calculated. The effects of the absorption coefficient on the temperature profile were analyzed.

2. Experimental

The experimental method is the same as that reported earlier [13]. The Nd:YAG laser is frequency-tripled and is operated at 355 nm. Because of the frequency conversion process, the output beam is oval, of about 4:5, and with small satellite spots. The energy of these ‘side lobes’ is about a few percent of that of the main spot. Fig. 1a–c shows the SEM (magnified 500 times) images of ablated PI by one single pulse of 13 and 494 μJ, and the image (magnified 250 times) by a pulse of 494 μJ, respectively. Figs. 2 and 3 show an image of a crater that was ablated by a single-shot pulse of 494 μJ taken by a conventional light microscope and an image ablated by a pulse of 211 μJ taken by an AFM, respectively. The plain part at the bottom of the AFM graph indicates that the crater depth is out of the measurable range of the microscope. It was shown that the morphology is significantly different from that of ablated RCC reported previously by Yung et al. [13]. A melting zone exists at the edge of ablated crater of the PI, whereas at the edge of the crater of RCC there are stalagmitic residues. There are some ripples appearing at bottom of the craters that was ablated by a laser beam with relatively high fluence. The melting residues and stalagmitic residues can be seen on the surface of polymers ablated at other power levels. The results indicate that the thermal effect in the process of 355 nm laser drilling of PI cannot be ignored.

Figs. 4 and 5 show the ablation depth and diameter of PI and RCC, respectively, for different levels of fluence. The pulse repetition rates that were used to ablate PI and RCC were 1.000 and 1.754 kHz, and the corresponding pulse widths (full width between half maximum, FWHM) are 21 and 26 ns, respectively. It can be seen from these figures that the difference of the ablation depth between PI and RCC is small when the laser fluence is the same and within the range 3–184 J cm⁻². Especially, when the fluence ranges from 5 to 100 J cm⁻², there is almost no difference between the ablation depth for the two materials. However, the ablation diameter of PI is much larger than that of RCC, which indicates that the ablation threshold of PI is much lower than that of RCC. Extrapolating the curve of ablation depth, the same conclusion (that PI has a lower ablation threshold) can be obtained.
Table 1 gives the ablation rates and threshold fluence of PI at 355 nm and other wavelengths obtained in previous studies [5–10,14,15]. It can be seen from the table that the ablation rate of polyimide at 355 nm is much higher than that at shorter wavelengths. For example, when the fluence is 3 J cm$^{-2}$, the ablation depths at 193, 248, 308 and 355 nm are 0.25, 0.6, 1.2 and 2 μm, respectively. Further, the ablation threshold of 0.1 J cm$^{-2}$ or 4.8 MW cm$^{-2}$ at 355 nm is higher than the threshold at 193, 248 and 308 nm which is from 0.02 to 0.07 J cm$^{-2}$.

3. Temperature calculation

When the laser power density is below the threshold, all of the absorbed laser energy will be converted into heat [8,16]. Experimental measurements and simulation calculations show that the peak surface temperature of PI can be as high as 1660 K when the laser wavelength is 193 nm and the threshold power density is 36 mJ cm$^{-2}$ [11].

To estimate the thermal effect caused by the 355 nm laser ablation of PI, the temperature field is calculated. The properties of the polyimide are shown in Table 2 [11]. For an acoustic–optical Q-switched pulse, the full temporal width of the laser pulse is generally less than 200 ns. The heat diffusion distance $4kT$ is therefore no more than 0.5 μm, which is approximately equal to the optical penetration depth $\lambda^{-1}$. Since both of the dimensions are much smaller than the diameter of a focused laser beam and the thickness of a polymer film of PCB, the heat-conduction equation can be linearized and the ablated polymer can be regarded as a semi-infinite body. When the initial temperatures are a uniform field, the temperature increment of different depths $x$ at the time $t$ can be given by an analytic solution [17]:

$$\Delta T(x, t) = \frac{1 - R}{K} I_0 f(x, t)$$

(1)

where $R$ is the reflectivity of the polymer to the laser beam, and $f(x, t)$ is

$$f(x, t) = 2x(\kappa t)^{1/2} \text{erfc}\left(\frac{x}{2(\kappa t)^{1/2}}\right) - \exp(-2x)$$

$$+ \frac{1}{2} \exp(\kappa x^2 t + zx) \text{erfc}\left(x(\kappa t)^{1/2} + \frac{x}{2(\kappa t)^{1/2}}\right)$$

$$+ \frac{1}{2} \exp(\kappa x^2 t - zx) \text{erfc}\left(x(\kappa t)^{1/2} - \frac{x}{2(\kappa t)^{1/2}}\right)$$

(2)
increment of 1355
is necessary to note that the calculated surface temperature fluence at different wavelengths of 248, 308 and 355 nm. It
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longer wavelengths.
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$$D \frac{\hat{I}}{x} = \text{Heaviside functions} \ [10].$$

The temperature profile would be

$$\Delta T(x, t = t_{\text{off}}) = \frac{1}{K_x} \sum_{i=1}^{N} |I_0(t_{\text{on}})| f(x, t_{\text{on}})$$

$$-I_0(t_{\text{on}}) f(x, t_{\text{on}}), \quad 0 < t < \tau$$

$$\Delta T(x, t) = \frac{1}{K_x} \sum_{i=1}^{N} |I_0(t_{\text{on}})| f(x, t - t_{\text{on}})$$

$$-I_0(t_{\text{on}}) f(x, t - t_{\text{on}}), \quad \tau < t < \frac{1}{f}$$

Table 3 shows the temperature increment at x=0, 1, 2, 3, 4 μm, which are caused by a single pulse with threshold fluence at different wavelengths of 248, 308 and 355 nm. It is necessary to note that the calculated surface temperature increment of 1355°C at 248 nm is in agreement with the experimental study reported previously, which is 1660 K [11]. It can be seen from Table 2 that the temperature increment in the substrate caused by the 355 nm laser is larger than that by a shorter wavelength laser, although the surface temperature of the former is lower, the reason being that the polymer has a smaller absorption coefficient for longer wavelengths.

Another effect of a small absorption coefficient of the polymer to the laser beam is that it increases the thermal damage in the process. When opaque materials with a large absorption coefficient is ablated by a Q-switched pulse laser, the ablated surface quality can be satisfactory and little thermal damage occurs because of its short pulse width and small duty ratio. However, for those materials with a small absorption coefficient, it makes the material more difficult to cool down before the start of the next pulse. Figs. 7–9 show that the influences of the absorption coefficient x on the surface temperature change from the first pulse to the beginning of the second pulse at different repetition rates of 1, 10 and 20 kHz. As the repetition rate increases, the pulse width and the duty ratio increase, and the temperature at the beginning of the next pulse is greater. For an absorption coefficient of 0.2×10^−5 cm^−1, the temperature increments at the beginning of the second pulse are 35, 108 and 149 K, respectively, when the pulse repetition rate is 1, 10 and 20 kHz, and they are 13, 40 and 57 K for an absorption coefficient of 2.6×10^−5 cm^−1. Under the action of multi-pulses, the polymer is repeatedly heated and cooled, i.e., a small absorption coefficient will cause an increase in the ablation threshold, the slope of ablation rate against the fluence, and also in the thermal damage to the substrate. It is

where ierfc is the integral of the error function erfc:

$$\text{ierfc}(y) = \int_{y}^{\infty} \text{erfc}(s) \, ds$$

$$\text{erfc}(y) = \frac{2}{\sqrt{\pi}} \int_{y}^{\infty} e^{-x^2} \, ds$$

A temperature field caused by a pulse with a general shape (refer to Fig. 6) can be calculated through synthesizing the pulse shape from a linear combination of step-on, step-off Heaviside functions [10]. The temperature profile would be

$$\Delta T(x, t) = \frac{1}{K_x} \sum_{i=1}^{N} |I_0(t_{\text{on}})| f(x, t_{\text{on}})$$

$$-I_0(t_{\text{on}}) f(x, t_{\text{on}}), \quad 0 < t < \tau$$

$$\Delta T(x, t) = \frac{1}{K_x} \sum_{i=1}^{N} |I_0(t_{\text{on}})| f(x, t - t_{\text{on}})$$

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<table>
<thead>
<tr>
<th>Absorption coefficient α at 355 nm (cm^−1)</th>
<th>Thermal conductivity K (W cm^−1 K^−1)</th>
<th>Thermal diffusivity α (cm^2 s^−1)</th>
<th>Heat capacity c (J g^−1 K^−1)</th>
<th>Density ρ (g cm^−3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide</td>
<td>0.2×10^5</td>
<td>1.4×10^−3</td>
<td>0.177+2.91×10^−7t−5.52×10^−7t^2</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Where:

$$\text{ierfc}(y) = \int_{y}^{\infty} \text{erfc}(s) \, ds$$

$$\text{erfc}(y) = \frac{2}{\sqrt{\pi}} \int_{y}^{\infty} e^{-x^2} \, ds$$

A temperature field caused by a pulse with a general shape (refer to Fig. 6) can be calculated through synthesizing the pulse shape from a linear combination of step-on, step-off Heaviside functions [10].
therefore the copper layer is not so massive, a big absorption coefficient is expected in order to decrease the thermal effect. However, this will make the ablation rate at relatively high laser power density range not so high. A further quantitative study is needed in order to be able to choose optimal materials properties and laser ablation parameters based on the required hole size and construction of the Cu and the dielectric.

4. Conclusions

1. The difference between the ablation depth of PI and that of RCC is small for the same fluence ranging from 3 to 184 J cm$^{-2}$: especially, they are nearly the same at the same fluence ranging from 5 to 100 J cm$^{-2}$, although the ablation threshold of the former is much lower than that of the latter, which are 0.1 and 0.7 J cm$^{-2}$, respectively.

2. Comparing the ablation results of PI by 355 nm laser with those at shorter wavelengths, both the threshold and slope of the ablation rate against the fluence are higher at 355 nm than those at shorter wavelengths. The ablation rate can be as high as 2–14 μm for a fluence range from 3 to 184 J cm$^{-2}$.

3. Evident melting occurs in the process of 355 nm laser ablation of PI, and indicates that a photothermal mechanism has contributed to the ablation process.

4. Compared with the absorption coefficient of PI at 248 nm, the absorption coefficient at 355 nm is smaller by about an order of magnitude. It is shown that the advantage of a small thermal effect occurring in the acoustic–optical Q-switched laser ablation is offset significantly because of the smaller absorption coefficient, although the ablation rates can be increased at a relatively high power density range.

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