MŰEGYETEM 1782

TECHNOLOGY OF POLYIMIDE LASER ABLATION

SUMMARY OF PHD THESIS

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2008

Introduction

New technologies, integrating the advantages and potential of laser material processing, are being continuously introduced in the production of electronic appliances. Laser direct imaging and laser drilling of printed wiring boards have become standard technologies and so has engraving of bar codes and data matrix codes. Dozens of laser-system manufacturers offer their products when there is need for laser production technology.

Reduction of sizes of electronic components and products had been constantly followed by the expansion of lasers, quite until the sizes of the structures to be formed have reached the size of the processing “tool”, the laser focal spot. The application of lasers in mass-production of specific products and special materials may have difficulties in the resolution range of 5-10 µm. The reason for this is also because the work-piece is often built up from several material layers, some of them may be patterned. The interaction of these layers and the laser beam is different. On the other hand the properties of materials may change in the zones affected by the laser.

Laser material processing systems available nowadays are not capable of considering the above aspects and this impedes the development of new and currently unachievable applications. The progress is also hampered by the lack of knowledge on some mechanisms of laser-material interaction and on the change of material properties during laser processing.

My research work is concentrating on UV Nd:YAG solid state laser interaction with polyimide, the most widely applied material of flexible circuit substrates, mostly focusing on the establishment of a phenomenological model of laser ablation.

Removal of material from polyimide foils by laser ablation has been investigated for over 25 years. Most of the research works have been, however, completed by excimer laser sources. UV Nd:YAG laser sources appeared in the research laboratories only about 10 years ago. There are significant differences between the beams of the two laser types which also affect the mechanisms of material removal. The energy distribution of UV Nd:YAG laser beams is Gaussian and their pulse repetition frequency (PRF) can exceed 100 kHz. These features may be advantageous for material processing over the homogeneous-like excimer beams with a maximal PRF of a few kilohertz. Faster and more flexible production might be introduced achieving higher resolution in some applications. Still, relatively low research activity has been associated with UV Nd:YAG laser ablation of polyimides.

Researches documented in the literature mainly focus on the basic mechanisms of laser ablation, describing and modeling the accompanying physical and chemical processes. My research work has been launched by unanswered questions in specific industrial projects, as the results presented in literature were not applicable on the UV Nd:YAG laser processing of multilayer, patterned flexible circuit substrates.

I have established a new model in order to be able to take relevant aspects into account. Neglecting e.g. the Gaussian energy distribution of the beam would not allow the determination of the dimensions of the ablated volumes with the desired resolution, i.e. around 5-10 µm. Models dealing with homogenous fluence (energy/unit area) are not suitable for the precise description of material removal by Gaussian beams. In addition, the models in the literature generally do not consider consecutive laser pulses (shots).

Most of the modeling results of UV Nd:YAG laser researches could not be exploited in my work either, as these also neglect the Gaussian distribution of the UV Nd:YAG laser beam and mainly deal with the effects of the first laser pulse only.

Objectives

The purpose of my research has been the establishment and verification of a model that enables the determination of the ablated volume pulse by pulse, in the scope of specific materials, also considering the layer structure of the work piece. On the basis of the model a simulation tool may be developed, which would generate the production plans of laser process from the CAD documentation of the product.

The aim of the model is to determine the volume of ablated polyimide by a laser pulse with a specific energy, taking two relevant considerations into account. These are the actual pattern of the copper layer and the accumulated heat inside the polyimide layer caused by the successive laser shots.

The accumulated heat changes the interaction of the laser beam and the polyimide. The patterned copper layer modifies the heat conduction paths and thus has an influence on the temperature of the affected and ablated volumes. Larger copper areas will conduct away more heat, which leads to smaller ablated polyimide volumes. Research works presented in the literature on polyimide ablation do not consider the attached copper layer, so I aimed at highlighting this effect and prove its importance.

Ablation threshold has got key importance in the determination of ablation rate (ablated depth per pulse). This is expressed by the threshold fluence value in the literature. The temperature dependence of the threshold fluence is, however, not interpreted and this impedes the consideration of the accumulated heat. My model aims at the expression of ablation threshold by temperature, which is also characteristic to the specific material. In this way the main processes of laser ablation can all be described by the heat or temperature. In the model the laser pulse energy is transformed to temperature increase, the material is removed from the bulk when its temperature exceeds the ablation temperature threshold and the effect of the layer structure and its pattern is considered with heat conduction.

The model includes the following aspects, to be able to predict the ablated volume pulse by pulse:

- the energy of the laser pulse is transformed into temperature increase with regard

  - to the Gaussian energy distribution of the beam,
  - to all losses of energy before its absorption inside the material (expressed with the introduced Coupling Efficiency Factor, CEF),
  - to all losses of the transformation of absorbed energy into heat (expressed with Transformation Efficiency Factor, TEF).
- the ablation temperature threshold needs to be defined and interpreted, as well as a method is required to find its value for specific materials,
- a simulation tool needs to be developed for the determination of the ablated volumes in order to validate the model and also for simulating laser manufacturing processes.

Experimental

The research described in the thesis has mainly been completed by a Coherent AVIA 355-4500 type UV Nd:YAG laser source, with a beam wavelength of 355 nm. The beam is deflected by a Raylase Razorscan scan-head and the positioning of the work piece is done by translation stages with a resolution of 1 µm. The optical elements of the system yield a minimal focal spot diameter of 30 µm. The highest pulse energy of the source is around 200 µJ.

Laser ablation experiments have been carried out on polyimide, which is one of the most frequently used materials of flexible circuit substrates. Three polyimide products have been investigated: Kapton® HN (Du Pont Inc.), Upilex® S (Ube Industries Inc.), Apical® NP (Kaneka Texas Corp.) All three materials have unique thermal properties, as these are stable below 500˚C and sublimate above this temperature.

The interaction of a 355 nm laser beam and the above materials is dominated by photothermal processes, while the effect of the photochemical processes (i.e. bond breaking) has got less importance. As the absorption of the radiation is exponential the ablated depth is in the range of a few micrometers.

Ablation experiments have been carried out with different variations of the parameters. The measurement method of the ablation rate should be emphasized here. The techniques usually employed and described in the literature (e.g. the analysis of the result of one laser shot by atomic force microscope) are not applicable in my model, as the values determined by these methods for the first pulses interacting with unaffected material are not valid for the following pulses. The ablation rate in my research was determined by the complete punching of polyimide foil, and dividing the thickness of the foil by the number of necessary laser pulses. The method is also advantageous because the measurement can be fulfilled by an optical microscope at 500-1000x magnification.

The ablation rate experiments have also been carried out at different substrate temperatures. Special considerations have been made to prepare stages for decreasing and increasing the temperature of the flexible substrate. Experiments were completed from minus 178˚C up to 220˚C.

Novel scientific results

Thesis 1: I realized and verified that the existence and actual pattern of the copper layer cannot be neglected when the polyimide layer of flexible substrates is processed by a 355 nm, Q-switched UV Nd:YAG laser beam. The accumulated heat and its distribution in the polyimide layer have to be taken into account when determining the ablated volume pulse by pulse. (When a Upilex® S polyimide foil with a thickness of 125 µm is processed, the attached copper layer can decrease the ablated thickness by 6-8 µm compared to a copperless substrate.) The energy of the laser pulses can deform or even ablate copper pads or wires if these are connected to the surroundings with higher heat resistance than larger copper areas, because the 355 nm beam is also well absorbed by copper.

Publications in relation with thesis 1: L3, L4, R5, R6, R7, R8, R9, R10

Thesis 2: I established a thermal ablation model for the processing of polyimide based flexible circuit substrates by UV Nd:YAG lasers, that enables the prediction of the ablated volume pulse by pulse, also considering the layer structure of the substrate and the accumulated heat. This provides the possibility of calculating the necessary technological parameters on the basis of the circuit pattern, which may lead to higher resolution compared to the trial-and-error way of optimization of laser processing. I introduced the efficiency factors for the coupling of the pulse energy into the material (CEF) and for the transformation of energy into heat (TEF), and their product, ETF (Energy to Temperature increase transformation efficiency Factor), where the last can be determined experimentally. From these considerations I set up a simple equation between the laser pulse energy and the increase of temperature within the material. This enables the determination of the temperature increase in any position of the material, also taking the Gaussian energy distribution into account.

Publications in relation with thesis 2: L1, L2, R3, R4, R5

Thesis 3: I introduced and interpreted the concept of the ablation temperature threshold (T_{th}), which is the highest possible temperature where the material is still not ablated.

I introduced the ablation energy threshold (E_{th}) for beams with Gaussian energy distribution instead of the ablation fluence threshold (F_{th}) which is defined for homogeneous laser beams. I presented that the ablation energy threshold (E_{th}) can be determined experimentally and is also capable of characterizing the ablation threshold and the calculation the of ablation rate.

I deducted the equation for the relation of the pulse energy and the maximal possible heat increase on the basis of the ablation energy threshold (E_{th}). I realized that the ablation temperature threshold (T_{th}) is the sum of the maximal possible temperature increase and the initial temperature of the substrate.

I determined the ablation energy threshold (E_{th}) value of Upilex® S polyimide at 25˚C, 50 kHz PRF with a Q-switched UV Nd:YAG laser characterized by 355 nm wavelength, 30 ns pulse width and 30 µm focal spot diameter. The value of E_{th} is 1,75 µJ. The effective absorption coefficient was also determined, it is 1,4 µm^{-1}.

Publications in relation with thesis 3: L1, L2, R1, R3, R4, R5

Thesis 4: I developed an experimental method for the determination of the ablation temperature threshold (T_{th}) value. The main point about this is that ablation threshold energies (E_{th}) of a polyimide material are determined at three different initial substrate temperatures by the measurement of the ablation rate. By substituting the energy threshold values into the deducted equations the ablation temperature threshold (T_{th}) and ETF can be calculated.

I determined the ETF value (20% ±1%) and the ablation temperature threshold (647˚C ±26˚C) of Upilex® S polyimide. The T_{th} value is in good correlation with an analytical result from the literature.

Publications in relation with thesis 4: L1, L2, R1, R3, R4, R5

Thesis 5: With a software tool developed for the simulation of the formation of holes generated by laser punching (on the basis of the described ablation model and the heat distribution equations), I presented that the model is capable of the determination of the ablated volume per pulse and the number of laser shots required to punch the polyimide foil. In this way the model can be applied for technology optimization. The depth of simulated and the experimental blind-holes fit within 3 µm in case of a 50 µm thick Kapton® HN polyimide foil.

I presented the sensitivity of the model on its two main input parameters. If the ablation temperature threshold value is determined within 50˚C accuracy then the prediction of the ablation rate will have a maximal error of 0,03 µm. ETF value determined within 2% causes a maximal error of 0,06 µm in the prediction of the ablation rate.

Publications in relation with thesis 5: L1, L2, R2, R3, R4

Exploitation of results – further research tasks

My research resulted in a model that describes the temperature change within the material, finds the ablated volume and manages the heat accumulation and the effect of the layer structure by the heat conduction. The main input parameters of the model were also determined during my research for specific materials.

The aim of the presented results is their integration into laser processing systems. For the controlled formation of structures with laser a pulse-by-pulse manufacturing plan needs to be produced with regard to the pattern of the copper layer.

To exploit the presented model a simulation tool is required, which can handle all three mentioned aspects: coupling the pulse energy into the material, removing the material considered ablated and the general mechanisms of the heat distribution. The simulation must be done with at least 50 nm resolution, while the surface of the treated volume can be in the range of a few mm^2, and the thickness of the structure is 25-125 µm. The high number of required cells poses serious difficulties.

The problem is being solved at BME-ETT with special simulation techniques that allow the handling of the above mentioned volumes. One of these considerations is the mesh with adaptive resolution.

The application possibility of results gained from the research will be investigated with other polymers and other laser sources used in electronics technology. This can be for example laser direct patterning of the solder mask layer on flexible or rigid substrates, as this has become a general technology for engraving data matrix codes. Due to the reduction of the available area for the matrix code and the higher amount of information to be stored in it the bit dimensions are also decreased. Getting closer to the limits of processability poses reliability problems.

List of publications related with the theses

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