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LASER MIKROMACHINING OF FLEXIBLE SUBSTRATES FOR THREE DIMENSIONAL FORMATIONS

PH.D. THESIS

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BUDAPEST
2010

Introduction

Due to the advance of microelectronic industry the expansion of the more advanced, smaller pitch sized electronic devices required more and more developed printed wiring boards. In addition to rigid substrates flexible substrates are already a high potential for interconnects and mounting surfaces. These carriers could be folded to three-dimensional layouts. The aim is to use flexible substrates as a reliable three-dimensional printed wiring board for packaged component

The downsizing and the increase of operating speed needs implementing of new technological processes and / or requires new materials in microelectronics. Among the new technological processes the laser micro-technique has an increasing role. The laser micro- or nanomachining common positive features is that they are faster, more flexible, more controllable and, in some cases, cheaper than some traditional techniques. In the field of industrial material processing the CO2 and Nd:YAG lasers are widely used. The wavelength and operational differences determine their potential applications where it has to consider that the laser-matter interaction could depend on the substrate and the type of the laser beam too. The electricity industry used polymers for long time exclusively in isolation. However, the polymers can be used for a variety in microelectronics. They are as follows: insulation, enclosure material, a protective layer, a carrier, and materials of active components. Nowadays, the advanced flexible circuit substrates are polymer-based

In my research work I examined the flexible circuit carriers as one of the most commonly used material. The polyimide has been assessed, mainly with the aim to examine the possibility if it is capable for three-dimensional circuit's carrier. For micromachining purposes of the substrate I needed high-precision laser equipment, for which purpose the department's UV Nd: YAG laser suitable.

The problem of forming polyimides plastically to three dimensional substrate have begun to explore already in 1976 (IEEE Transaction on Manufacturing Technology). Laser micro-machining may be the key to an effective three-dimensional shaping of the flexible substrate. Along the laser cuts the substrate bends and due to the rigidity of the copper it is capable to hold itself as a "self-maintaining" three-dimensional shape.

The shaping, bending induced prolongation and wrinkles is one, while copper conductor's mechanical and electrical degradation are the other problems. Literature determine the minimum bend radius, which is approx the 3-6 times of the substrate's thickness, but for non symmetrical flexible structures a more complex strain-force calculation is needed.

The laser micromachining of polyimides is an old theme. This thematic area of the laser ablation has been investigated for about 25 years, which is the base of micromachining. In this case, the material is removed from some square microns to square millimeters of surface by removing material in the depth of the order of micrometers. During my work the shape of the laser cuts could be established in different forms (V, U, ... in cross sections). In the past the micromachining was mainly reached by pulses of excimer laser source, while the last ten years X-ray lithography, electron lithography, scanning ion beam lithography and UV Nd:YAG lasers are used in research laboratories.

Aim of the research

The research aims to develop a micromachining technology, which allows to plan the laser-assisted predictable shaping of polyimide substrates. This will allow a three-dimensional folded interconnect circuit development. Based on the prepared model we will be capable of developing a tool which could automatically prepare the three dimensional laser machining CAM files from design rules and manufacturing documentations.

My laser model for micro-machining is motivated by scientific curiosity as in the literature no such studies have been taken into account for laser assisted micro-machining for creating three-dimensional flexible polyimide substrates. The most common methods are concentrated in applying only the drilling, cutting and engraving, a few publications have dealt with the selective material removing, but these are full material removing, while my experiments are based on selective material removing for ductility.

The laser model is a duty to answer how the energy of laser scans affect the substrate's temperature, and if the scans could be treated as separate cases or whether temperature accumulation should take into account. From the simulation's result it will be pre-defined how much material can be removed from the polyimide in function of the speed of the laser beam, performance and energy of laser pulses. The simulation results are experimentally verified and the measured and calculated values were compared.

In the literature and in the latest research two types of three-dimensional designs trends are followed:

- In integrated circuit component level, the goal is to stack the silicon chips to each other. Inside the packaging vertical space is utilized by unbreakable bonds. Silicon chips are subsequently separated and bonded to each other by micro bonds or solder bumps.
  An only research stage procedure utilizes wafer level bonding. The wafers are bonded to each other by through silicon-wafer vias (TVS). Thereby establishing a vertical direction wiring lines.
- There is also a technology for three-dimensional arrangement of packaged components o. In this case, after a two-dimensional design and layout, the flexible substrate could be bended to the box without any additional pretreatment. The mechanical stability of the flexible substrate is solved by gluing. This is necessary because although the flexible substrate, which due to its high flexibility could return to original two-dimensional form.

I look for the answer to the second case how the encapsulated components could be mounted on a flexible substrate, how it could be bend to a three-dimensional shape. Since the laser experiments and models based on a well-controlled substrate micromachining, so the adoption of laser technology could eliminate the 2D back forming. The carrier is capable applying of a "self-maintaining" three-dimensional shape.

My literature research was revealed that in folded substrates case, additional problems could reveal as heat accumulation caused by inner IC-s. They could be overheated. Placing a heat sink inside the package is difficult task to solve. In my researches I looked for a solution. With Finite Element Modeling the temperature distribution inside the package has been simulated. In case of high-performance ICs the maximum operating temperature can be calculated.

Experimental methods

My Ph.D. research work was carried out by using a frequency tripled Coherent AVIA 355-4500 UV Nd:YAG laser (355 nm wavelength). The laser beam deflection is made by Raylase Razorscan scan-head with sample positioning of 1 micron. The positioning of the sample is solved by a precision XY table. The beam's minimum diameter occurred to 25 μm at focus due to the quality of optical elements. The maximum laser pulse energy is approx. 200 μJ.

My studies in the field of electronic technology is concentrated at one of the most commonly used flexible circuit substrate material, the polyimide. I focused at the following DuPont product: Kapton® HN (Pyralux) with three different adhesive-polyimide-copper composition, respectively: FR9120R, FR9130R and FR9150E, with thicknesses 50-25-35, 75-25-30, 125-25-35 μm. These materials are solid at least 500˚C, above this temperature it could be ablated. This ablation condition is easy to follow by the simulation.

I have measured the polyimide's reflection and transmission spectrum with UV spectrophotometer at 355-nm wavelength. The laser beam reflection the surface occurred approx. 6%, while the 99% of remaining energy is absorbed, so 93%of the input power is concentrated at heat ablation process. The exponential absorption of radiation at simulations are also shown.

The selective material removing experiments are performed at various laser power settings. The laser scanning speed is regulated to the value of energy per surface area. Shapes and sizes of developed forms are determined by cross-sectional images using a microscope. The penetration depth of several microns can provide results with sufficient accuracy in optical methods although the literature procedures (eg, atomic force microscopy, …) may be applied.

The mechanical parameters of the micro machined flexible substrate are compared with standard measurement methods to the untouched substrate. One procedure was to determine the tensile strength of the substrate. Standard shape and size specimens cut from the substrate which are connected to an automatic logging system. For measuring the tensile strength a continuous force-displacement function has been recorded.

The flexible substrate's dynamical behaviors are also examined. In this arrangement the dynamic bending caused copper resistance increase was measured. Since the standard meander-shaped specimen conductor's break or resistance increase could be easily registered. The electrical resistance of the substrate in function of the taken to cycles have been automatically recorded, and then compared to a simple carrier. In light of the results I can assume that the dynamic mechanical properties of the laser machined polyimide-copper system has increased substantially: the lifetime is increased with 500 %.

Thesises

1. THESIS: I have created a automatic simulation model for laser micromachining the polyimide-based flexible circuit carrier's dielectric layer with 355-nm wavelength UV Nd:YAG laser. I determined this using a laser scan while evolving temperature distribution. It was proved that after a 100 ms cycle time laser scanning, the carrier temperature can cool down, thus no account is taken of heat accumulation. Measuring cross-sectional samples confirmed the simulation results are correct, and with high confidence (90%) describe the temperature distribution along the laser line. The variable-resolution grid model during simulation used for finite element method of calculation, where near the laser beam penetration the grid size is 1 µm, while away from the centre linearly increased to 60 µm.

Publications: L1, R1

2. THESIS: A new method was developed to create three-dimensional shapes, which is the basis of the laser micro machined "V" cross-cuttings at polyimide substrates. During selective material removal process, while the the creation "V" shape is done by several parallel laser scanning steps toward the center of the symmetrical axis. This allows the carrier to bend at pre-defined line and angle.

   With measurements I have proved that bending the polyimide-copper-based flexible circuit with a number of same "V" shaped cuts result in safe bend radius 1/6 as in the literature available. This folding does not damage the copper layer. Modeling the cut's angle and number it is proved that with juxtaposition of 9 degrees 10 pc cuts, the mechanical stress may be reduced to 85%, as compared to the simple substrate. This is further reduced by 20% if the the cuts are put 10 µm away from each other.

Publications: L2, L3, L5, 0, R3, R7, R9, (L4, R5, R8, R10)

3. TÉZIS: With experiments and with standard tests I have proved that the proposed use of the system to mechanical deformation stability is not compromised. The tensile strength of the thinned the polyimide layer at bending edges reduced only a 15%, while during dynamic stress test, the lifetime is increased by 500%.

Publications: L4, L5, R2, R3, R4

4. THESIS: I made according to previous theses, based on a cube shaped contained number of ICs a three-dimensional representation of the physical circuit and its thermal model. I have proved that an appropriate cooling technology of integrated circuits operating temperature will not exceed the recommended 85°C. Five pieces of IC placed in the frame pages, and the sixth plate is connected to a specific heat pipe cooling system. A model of cross-section of the warmest point in the bottom of integrated circuit formed, which is approx. 70°C.

Publications: L3, R2, R3, R4 (L4)

Applicability of results and Future work

The research led to a model that based on the speed and performance of the laser could describe the material removing from temperature values. The ablation threshold is set and if the temperature of the substrate is higher than this value, the material will be ablated. This model can led to selective material removing of different type of shapes. Results at Ghent University and at the European Union Common BSTC Flexil project were used. Polyimide laser machining of the results of research has been successfully used in industrial circumstances (Freudenberg Mectec Hungary Bt, Bosch Hungary Ltd.), and references to more independent internationally recognized.

The presented results are intended for use in the industry have already studied. It has not been introduced in a three-dimensional development of encapsulated components. The laser-aided design of structures for the introduction is costly and time consuming task, but it hase great advantage when used with electronics. Another advantage of applying high-performance electronics that the heat sinks are not separate ones, it could be sufficient for 5 different ICs.

At the BME-ETT, with number of prototypes have been demonstrated that the developed technology solutions is useful for the industry in long term time scale.

The research results obtained from the applicability of other electronic technology used in lasers and polymers, also to be investigated. Cost-effective product performance due to widespread flexible carrier expects to PET (polyethylene terephthalate) and PEN (polyester naphthalate) substrate. However, due to a lower melting point requires greater attention, and not only the UV wavelength is absorbed, but also the visible or infrared wavelengths.

Further research areas could of components "x" - "y" dimensions out of the "z" dimension, including the CAD program to develop 3D designing programs. Components could be positioned in three dimensions to improve size / volume ratio.

List of corresponding publications

Papers published in journals:

L1. **Berényi R.:** Simulating the Laser Micromachining of a 3D flexible Structure, MICROSYSTEM TECHNOLOGIES 3: pp. 1855-1860.(2009), DOI: 10.1007/s00542-009-0914-2. IF:1.229.

L2. **Berényi R.,** Illyefalvi-Vitéz Zs.: 3D Flexible Package Formation using Laser Micromachining, PERIODICA POLYTECHNICA-ELECTRICAL ENGINEERING 52:(1) pp. 39-44 (2008),

L3. **Berényi R.:** Prototyping of a reliable 3D flexible IC cube package by laser micromachining, MICROELECTRONICS AND RELIABILITY 49: pp. 800-805. (2009), doi:10.1016/j.microrel.2009.03.015, IF:1,29.

L4. **Berényi R.:** Prototyping of a Reliable 3D Folded Package by Laser Micromachining, MICRO AND NANOSYSTEMS 1:(2) pp. 133-138. (2009), 1876-4029/09

L5. **Berényi R.:** Mechanical Study of a Micro-Machined Flexible Substrate, JOURNAL OF THEORETICAL AND APPLIED MECHANICS 39: pp. 89-100. (2009)

L6. **Berenyi R.:** Mechanical Scope of a Laser Micro-Machined Flexible Substrate. ELECTROSCOPE 2009: pp. 1-6. (2009)

Papers published in proceedings of international conferences in English:

R1. **Berényi R.:** Simulation of Laser Micro-Machining: Electronic Devices and Systems Conference. Brno, Csehország, 2009.09.02-2009.09.03. Brno: (IEEE), pp. 42-51.

R2. **Berényi R.:** Mechanical Study of a Micro-Machined Flexible Substrate, Electronic Devices and Systems Conference. Brno, Csehország, 2009.09.02-2009.09.03. Brno: (IEEE), pp. 239-247.

R3. **Berényi R.:** Mechanical Simulation of a Flexible Package, 31st International Spring Seminar on Electronics Technology, International Spring Seminar on Electronics Technology 2008. , Magyarország-2008.05.11. Budapest. (IEEE) pp. 664-669.

R4. **Berényi R.**, Gábor Juhász, Zsolt Illyefalvi-Vitéz: Laser Manufacturing of Mechanical Structures in Flexible Substrates for Lifetime Increasing, Electronics Systeminregration Technology Conference, 2006, Dresden, Germany, 05-07, Szept. 2006, (IEEE), pp. 1-7

R5. **Berényi R.**, Illyefalvi-Vitéz Zs.: Laser manufacturing of mechanical structures in Flexible substrates. Polytronic, 2005, Wroclaw, Poland, 23-26, Octobre, 2005., (IEEE) pp. 204-209

R6. Balogh B., Gordon P., **Berényi R.**, Illyefalvi-Vitéz Zs.: Effect of Patterned Copper Layer on Selective Polymer Removal by 355 nm Laser. Polytronic 2004, Portland, Oregon, USA 12-15 September 2004. pp.:237-241

R7. Gordon P., **Berényi R.**, Balogh B.: Controlled Laser Ablation of Polyimide Substrates. 36TH IMAPS 2003, Boston, Massachusetts, USA November 16-20,2003 pp.725-730.

R8. Gordon P., **Berényi R.**: Laser Processing of Flexible Substrates. IMAPS, Denver, USA, 3-6 September 4-6, 2002, pp.494-499.

R9. **Berényi R.**, Balogh B., Gordon P., Illyefalvi-Vitéz Zs.: Investigation of a laser assisted 3D bending technology for high density flexible circuits. IMAPS, 2005, Brugge, Belgium, 12-15, June, 2005., pp. 278-282

R10. Balogh B., Gordon P., **Berényi R.**, Zsolt Illyefalvi-Vitez: Investigation of laser-polymer interaction for controllable window opening. 27th European Microelectronics and Packaging Symposium, 2004, Prague, Czech Republic, June 16-18, 2004, (IEEE) pp.477-482.

Other publications

Paper published in national journal:

L7. **Berényi R.:** Fémezési technológia és lézeres furatkészítés furatfémezett flexibilis hordozók előállítására. **HÍRADÁSTECHNIKA 59:**(1) *pp. 47-50.* (2004)

Papers published in proceedings of international conferences in English:

R11. Medgyes B, **Berényi R**, Jakab L, Harsanyi G: Real-time monitoring of electrochemical migration during environmental tests. 32nd International Spring Seminar on Electronics Technology. Brno, Csehország, 2009.05.13-2009.05.17. (IEEE). pp.: 1-6.

R12. **Berényi R.**, Sántha H., Balogh B., Harsanyi G. :Utilization of laser technologies in the preparation of the physical structure of a miniature electrochemical cell used for biosensor researches. Polytronic 2004, Portland, Oregon, USA, 12-15 September 2004. pp.: 257-261

R13. Illyefalvi-Vitez Zs., **Berényi R**, Gordon P., Pinkola J., Ruszinko R.: Laser Processing of Polymer Layers of Laminated and Flexible Substrates. 53rd Electronic Components and Technology Conference, Sheraton New Orleans, Louisiana, USA May 27-30, 2003. (IEEE) pp.:142-147.

R14. **Berényi R.**: Laser Processing of Solder Resist Layers on Laminated Substrates. 26th International Spring Seminar on Electronics Technology, Stará Lesná, Slovak Republic, May 8-11, 2003. (IEEE) pp.:313-316.

R15. Gordon P, **Berényi R.**, Nyitrai Zs. :Laser Processing of Flexible Substrates. 23-26 june, 2002, Polytronic 2002 Conference, Zalaegerszeg pp.183-187

R16. Gordon P., **Berényi R.**: Laser Processing of Flexible Substrates, 25th International Spring Seminar on Electronics Technology, Prague, Czech Republic, 11-14 May, 2002, (IEEE) pp.:246-249.

R17. Illyefalvi-Vitéz Zs., **Berényi R.**, Gordon P., Pinkola J., Ruszinkó M. and Jan Vanfleteren: Laser Via Genereation into Flexible Substrates.: First International IEEE Conference On Polymers and Adhesives in Microelectronics and Photonics. 2001 Conference, Potsdam, Germany, October 21-24, 2001, pp.230-235.

R18. Illyefalvi-Vitéz Zs., Gordon P., Pinkola J., **Berényi R.**, Balogh B.: Application of Laser Processing for Fabrication of High Density Interconnections. International Symposium for Design and Technology of Electronic Packages, 2004, Bucarest, Romania, 23-26 September, (IEEE) 2004. pp.:9-13:

R19. **Berényi R.,** Deak J.: Low cost manufacturing of double-sided polyimide flexible substrates using unique plating technology and laser ablation. 27th European Microelectronics and Packaging Symposium, 2004, Prague, Czech Republic, June 16-18,2004, (IEEE) pp.:99-104.

R20. **Berényi R.**, Nyitrai Zs.: Large Window Opening into Flexible Substrates. 8th International Symposium for Design and Technology of Electronic Packages, Cluj-Napoca, Romania, 19-22 September, 2002 , pp. 71-74.

R21. **Berényi R.**, Gordon P., Illyefalvi-Vitéz Zs.: Laser Via Generation Techniques for Printed Wiring Boards. The 7TH Internaional Symposium for Design and Technology of Electronic Modules. 2001 Conference, Bucharest, Romania ,September 20,2001 pp.1-6.