High-precision cutting of polyimide film using femtosecond laser for the application in flexible electronics

D V Ganin, K E Lapshin, A Z Obidin and S K Vartapetov
Physics Instrumentation Centre of Prokhorov General Physics Institute, Russian Academy of Sciences, Troitsk, 142190 Moscow, Russia
E-mail: ganin@optosystems.ru

Abstract. The experimental results of cutting a polyimide film on the optical glass substrate by means of femtosecond lasers are given. Two modes of laser cutting of this film without damages to a glass base are determined. The first is the photo graphitization using a high repetition rate femtosecond laser. The second is ablative, under the effect of femtosecond laser pulses with high energy and low repetition rate. Cutting of semiconductor chips formed on the polyimide film surface is successfully demonstrated.

1. Introduction
Laser fabrication with high-energy femtosecond (fs) lasers has great advantages such as highest precision of micromachining, absence of heat affected zone, ability of 3D direct writing without surface damage, so femtosecond laser has become a powerful tool for high-precision micromachining.

Figure 1. The scheme of laminated layers on the glass substrate.

The development of flexible electronics is one of the main mission of the modern semiconductor industry. Production of amorphous oxide transistors on the surface of thin polymer films opens up wide possibilities for the creation of flexible electronics, in particular, RFID tags, flexible displays and integrated circuits [1]. The most promising technology for manufacturing flexible semiconductor chips and integrated circuits is a method where thin-film IGZO (indium-gallium-zinc oxide) transistors [2] are formed on the polyimide film surface with optical glass substrate (motherglass).

One of the technological problems in the producing of flexible electronics devices is cutting a polyimide film – chip carrier into individual chips after their formation (Figure 1) without glass substrate damage, as it is reusable.

The solution to the good quality polymer chip cutting is to use lasers of ultrashort pulses. No heat-affected zone due to the short pulse duration, high localization of laser exposure due to multiphoton absorption and high pulse repetition rate allows efficiently using femtosecond lasers for polymer film
cutting with high performance, while avoiding most of the drawbacks of other technologies. The effect of laser radiation on polymer materials can lead to photochemical conversion to amorphous porous carbon [3–6], and as a result, to a change in optical, electrical and other properties of polymer films, as well as for direct ablation of the material.

In this paper, we demonstrate the possibility of high-precision cutting of a polyimide film with semiconductor integrated circuits formed on its surface, without damaging the glass substrate.

2. Experimental Setup and Samples

Experimental setup is shown on figure 2. We used two different femtosecond laser systems. The first source was a femtosecond Yb regenerative laser system (Avesta Project, RYF-10/35) generating a laser pulses with energies of up to 150 μJ, a wavelength of 1025 nm, pulse duration of 350 fs and a repetition rate from 1 to 2000 Hz. The second source was a femtosecond fiber Yb laser (Optosystems, Fl300) with pulse energies of up to 1 μJ, a wavelength of 1053 nm, pulse duration of 350 fs and a repetition rate of 2 MHz.

![Figure 2. Scheme of experimental setup: (1) femtosecond laser beam; (2) beam expander; (3) focusing lens on Z-stage; (4) sample; (5) XY translation stage.](image)

To control the power and the pulse energy of the linear-polarized laser beam, we used a rotatable half-wave plate and thin film polarizer. Beam expander with 4x magnification was used to expand laser beam. A lens of 54-18-23-1064 nm, Special Optics with a working distance (WD) of 23 mm, N.A. = 0.39 was used as a focusing system. The lens was mounted on Z-translator to control the radiation focal depth. Radiation was focused into the sample mounted on XY translator. Pictures of exposure of fs laser pulses were obtained using an optical microscope (Nikon LV100D) in transmitted light in phase-contrast mode, which allows you to see the presence/absence of damage to the surface of the glass substrate.

3. Cutting Flexible Electronic Chips with Ultrashort Pulse Lasers

Our experiments have shown that cutting of polyimide film – chip carrier can be successfully performed by femtosecond lasers without damaging the glass substrate. The use of two FS lasers with different energy-repetition rate characteristics has shown two fundamentally different film cutting processes – photochemical and ablative.

3.1. Ablative Cutting

The use of the first laser source with a pulse energy reduced to 2 μJ results “ablative” mode, when the material is ablated from the zone of exposure (Figure 3) to femtosecond laser pulses. The bulk of the material is removed during ablation, and the surface surrounding the cut is significantly contaminated. The graphite (soot) layer on the cutting edges also worth noting. No melting of the area surrounding the cut is observed. The following parameters were used: scanning speed 3 mm / sec, laser pulses were focused under the surface of the film at a depth of 40 μm.
3.2. Photochemical Cutting

Fundamentally different cutting mode is implemented when using a fs laser with high repetition rate (1 MHz) and low pulse energy <120 nJ, where the area of exposure to FS pulses undergoes photochemical transformations (Figure 4). There are photochemical transformations of the polyimide film – “soot” is formed in the area of exposure to fs pulses. This soot is very brittle and can be easily removed by mechanical cleaning or flushing. Photochemical cutting mode can be high performance way for cutting polyimide film-carrier in flexible electronics.

4. Discussion of the Results

In “ablative” cutting mode, it is possible to provide a uniform cut with sharp edges. In the above experiments, the degree of overlap between adjacent focal spots during the scanning process was 25%. Using the focusing lens with NA = 0.39 allowed to reach the cutting width of 20 µm. Relatively high pulse energies have a significant probability of damage to the glass substrate without precise radiation focusing in the desired area. Surface damage or change in the glass refractive index was observed in experiments when focusing pulses to a depth greater than 70 µm.

“Ablative” cutting mode using a standard femtosecond fibre laser (1 MHz, 2 µJ, 350 fs) allows achieving cutting speeds of 250 mm/sec. The speed may be increased when using more efficient laser, provided no strong influence of thermal accumulation effects. Additional studies on selection of the optimal scanning parameters, along with the optical system optimization will reduce the cutting width, improve its quality and increase efficiency.

“Photochemical” cutting mode has its own features. Low pulse energies below the glass damage threshold, do not leave traces of impact on the glass substrate regardless of focusing precision. This cutting mode is realized in the heat accumulation mode. In our opinion, photochemical decomposition of the polyimide film occurs at high temperatures, and a graphitized substance formed has a noticeable electrical conductivity. Specific electrical conductivity of the graphitized line measured by the method...
similar to the one proposed in [4] was about $10^4$ S/m, which is consistent with the data of [7] on the polyimide film graphitization by heating.

Possible surface contamination with degradation products is an undesirable effect. Also it is worth noting that typical cutting width is about 100 µm. We think such a high cutting width is due to photochemical and thermal processes as a result of heat accumulation and diffusion. At the same time, there is a range of parameters where the cutting width of less than 50 µm and the cutting speed of 50 mm/sec can be achieved.

Direct laser graphitization of the polyimide film can be applied in electronics and terahertz optics [7,8].

5. Conclusion
The use of two fs laser sources with different energy-repetition rate characteristics showed the presence of two fundamentally different polyimide film cutting methods. Both methods have their advantages and drawbacks. The advantages of “ablative” cutting include good cutting quality, no large contamination and possibility to change the cutting width. At the same time there are some drawbacks, in particular possible damage to the substrate without high-precision focusing, and the need of high-energy fs laser source.

The advantages of “photochemical” cutting include technology simplicity, low fs laser pulse energy requirements, high performance, no damages to the substrate. The drawbacks include film surface contamination and relatively high cut width.

Acknowledgements
This work was partially supported by Foundation for Assistance to Small Innovative Enterprises in Science and Technology, program U.M.N.I.K. (10624GU/2016 No. 0023590), and the Competitiveness Program of National Research Nuclear University MEPhI.

References
[1] Nomura K, Takagi A, Kamiya T, Ohta H, Hirano M and Hosono H 2006 Amorphous oxide semiconductors for high-performance flexible thin-film transistors Japanese J. Appl. Physics, Part 1 Regul. Pap. Short Notes Rev. Pap. 45 4303–8
[2] Nag M, Bhoolokam A, Smout S, Willegems M, Muller R, Myny K, Schols S, Ameyes M, Genoe J, Ke T H, Vicca P, Ellis T, Cobb B, Kumar A, Steen J-L, P J van der, Gelinck G, Fukui Y, Obata K, Groeseneken G, Heremans P and Steudel S 2015 Circuits and AMOLED display with self-aligned a-IGZO TFTs on polyimide foil J. Soc. Inf. Disp. 22 509–17
[3] Least B T and Willis D A 2013 Modification of polyimide wetting properties by laser ablated conical microstructures Appl. Surf. Sci. 273 1–11
[4] Morita N, Shimotsuma Y, Nishi M, Sakakura M, Miura K and Hirao K 2014 Direct microcarbonization inside polyamide using focused femtosecond laser pulses Appl. Phys. Lett. 105
[5] Cai J, Lv C and Watanabe A 2016 Cost-effective fabrication of high-performance flexible all-solid-state carbon micro-supercapacitors by blue-violet laser direct writing and further surface treatment J. Mater. Chem. A 4 1671–9
[6] Gao W, Singh N, Song L, Liu Z, Reddy A L M, Ci L, Vajtai R, Zhang Q, Wei B and Ajayan P M 2011 Direct laser writing of micro-supercapacitors on hydrated graphite oxide films. Nat. Nanotechnol. 6 496–500
[7] Venkatachalam S, Bertin D, Ducournau G, Lampin J F and Hourlier D 2016 Kapton-derived carbon as efficient terahertz absorbers Carbon N. Y. 100 158–64
[8] In J Bin, Hsia B, Yoo J H, Hyun S, Carraro C, Maboudian R and Grigoropoulos C P 2015 Facile fabrication of flexible all solid-state micro-supercapacitor by direct laser writing of porous carbon in polyimide Carbon N. Y. 83 144–51