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Laser-assisted selective fabrication of copper traces on polymers by electro-plating

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Abstract

Selective deposition of metals on dielectric materials is widely used in electronic industry, making electro-conductive connections between circuit elements. We report a new low-cost laser-assisted method for selective deposition of copper tracks on polymer surfaces by electro-plating. The technique uses a laser for selective modification of polymer surface. The electrical conductivity of some polymers could be increased due to laser irradiation. Polyimide (PI) Kapton® film was used in our experiments. Samples were patterned using nanosecond and picosecond lasers working at the 1064 nm wavelength. The experiments were performed using average powers ranging from 4 to 8.5 W in 0.25 W increments, pulse repetition rates from 10 to 100 kHz and a constant scanning speed of 100 mm/s. The sheet resistance was measured using the four-probe method, and it was reduced to < 10 Ω per square after the laser patterning. Analysis of Raman spectra of specimens patterned areas were performed. Afterwards, different thicknesses of copper layer were deposited on the modified surface by electro-plating.

Our selective laser-assisted technology allows fabrication of copper tracks on complex shape dielectric materials. The technology could be used in production of molded interconnect devices (MID), where the main technological problem and achievable task is the low cost fabrication of copper tracks.

Keywords: laser, electro-plating, polymer, deposition;

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1. Introduction

The technologies of selective fabrication of copper tracks on dielectrics shows huge potential for nowadays and future electronics applications. There are several laser-assisted techniques for the production of copper tracks on dielectric materials. First of all, laser direct structuring (LDS). That is a two-step method, where initially, an electric pattern is written by laser on the surface of dielectric material. Further, the material is immersed into the electroless copper bath, where copper deposits the laser-activated patterned area[1]. The disadvantage of this method is that here must be used special materials, doped with inorganic metallic compounds for laser activation. That leads to an increase in the process price; also, the components with metallic impurities are not suitable for some applications. Due to these impurities, could be additional noises in applications, such as electronics or telecommunications. Another method is a laser-induced forward transfer (LIFT). The principle of this technique is that thin donor material is placed above the specimen, and the laser exposition is used to transfer the material from thin donor to specimen[2]. The disadvantage of this technique is weak adhesion between the transferred donor and the substrate. Also, very little research was done with 3D substrates. Another method is laser-induced surface activation (LISA). It is a three-step process: firstly, the specimen is laser treated in distilled water; further, it is immersed into the palladium solution to activate the patterned area, and finally, the specimen is copper plated using an electroless plating method[3].

There are few novel methods for electronic tracks manufacturing not requiring laser, such as inkjet/aerosol printing techniques. The principle is that special metallic ink/aerosol, due to formed high pressure in a ceramic dish, is sprayed on the substrate[4][5]. The methods are expensive, and printing on 3D substrates is very complex.

From all of the described methods, only the LDS method is used widely in the manufacturing of electronic devices. All of these methods have unsolved issues.

In our research, we applied an alternative method. Our laser-assisted technology consists of two main steps: firstly, the electric circuit is laser written on a dielectric surface. Then, the sample is immersed into the electrolytic solution, where laser-patterned areas are copper deposited. Surface conductivity measurements and Raman spectroscopy were applied to characterize the laser-modified polymer surface. Parameters of electro-plating were varied to get a uniform copper layer on laser-treated areas. The main advantage of the method is that direct electro-plating on polymers allows a very fast, selective and low-cost metal deposition process compared with other alternative technologies, like PVD coating, painting with conductive ink, etc.

2. Experimental

2.1. Materials

Polyimide Kapton® films from DuPont with a thickness of 127 µm were used in our experiments. All the samples were cleaned with ethanol (Sigma Aldrich) before the experiments.

2.2. Laser treatment

Two different lasers were used for sample patterning in our experiments. Nanosecond solid-state laser Baltic (Ekspla) was operating at the fundamental wavelength of 1064 nm. The pulse duration of this laser was 30 ns, and the pulse repetition rate was tuned from 10 to 100 kHz. The output power was varied in the range of 4 to 11.5 W in 0.25 W increments. Another laser was a picosecond solid-state Atlantic (Ekspla). This laser generated 9 ps pulses at a repetition rate from 10 to 100 kHz. The output power of the laser was used in the range of 4 W to 8.5 W in 0.25 W increments. Pulse energies of up to 115 µJ were used.

For laser beam positioning SCANgine (IntelliSCAN) galvanometer scanner was used. Beam positioning speed was 100 mm/s during our experiment. Telecentric F-theta objective with the focal length of 160 mm was used for sample patterning. Beam spot diameter at the focal plane was 52 µm (measured at $1/e^2$ energy level) with both lasers. Laser line overlapping – hatch was 28 % when a sample was at the focal plane. The laser fluence was determined by dividing the pulse energy from the beam spot area. Irradiation dose was evaluated by multiplying laser fluence by the number of pulses per beam spot area and scanned line overlapping.

Optimal processing parameters, like scanning speed or repetition rate, were found during the testing fabrications and kept constant in the later experiments. The matrixes of laser patterned areas were used in a search for optimal parameters. The principle of this method is that the matrix of small squares was fabricated on the sample by changing one parameter value when fabricating squares in a row and changing another parameter value when fabricating the next square in a column. All other parameters, except those two, were kept constant. Further, the fabricated areas were analyzed according to fabrication speed, fabricated surface quality, etc., until the combination of optimal parameters were found.

2.3. Electro-plating

Kapton PI film was connected to the cathode terminal for copper deposition, and a copper rod (Cu) was connected to the anode terminal. Electro-plating was performed in the electrolytic solution, which consisted of deionized water (H_2O), sulfuric acid (H_2SO_4), hydrochloric acid (HCl) and copper sulfate ($CuSO_4$). The current density of 1 A/dm^2 was used, and the plating process time was 45 min in our experiments (see Fig. 1).

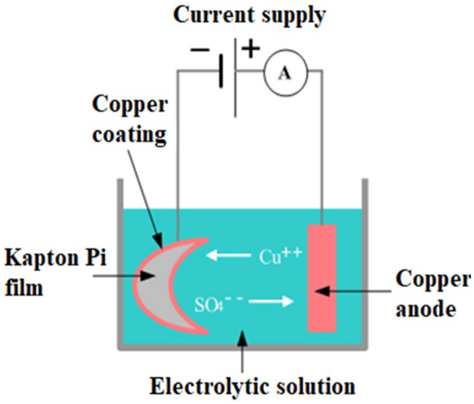

Fig. 1 Electroplating scheme.

2.4. Sheet resistance measurement

Sheet resistance measurements were performed using the four-probe method. The principle of this method is that four probes were aligned in a row, with a distance of 1 mm between probes. While the current passing through outer probes, the inner probes were measuring the voltage. These values allowed us to calculate the surface resistance. Keithley 2602A from Tektronix was used in our experiments (see Fig. 2).

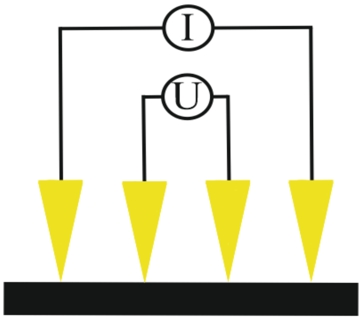

Fig. 2 Principle of the four-probe method, used in sheet resistance measurement.

3. Results and discussion

Kapton PI films were placed at the focal plane of the laser beam and patterned with the nanosecond or picosecond laser. In this method, the irradiation doses were increased after each exposure. The doses were increased by 16 J/cm^2 and after each sample exposition, sheet resistance measurements were performed. The same set of irradiation doses was used in both ns and ps regimes. Changes in the sheet resistance appeared when the irradiation doses were higher than 148 J/cm^2 in the ns regime and 130 J/cm^2 in the ps regime. The sheet resistance of the laser-patterned surface started to decrease at those values, and carbon-like structures began to form on the surface of samples (see Fig. 3).

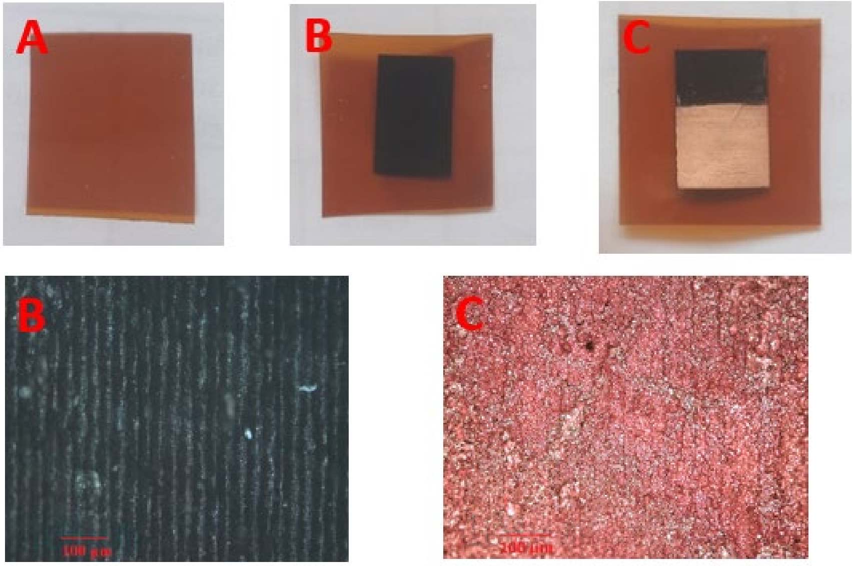

Fig. 3 Polymer Kapton PI film before laser patterning (A), after the laser patterning (B) and after the copper electro-plating process (C).

The achieved sheet resistance was 354 Ω/square during the nanosecond laser irradiation with 302 J/cm^2, and one order lower values were obtained after the picosecond laser irradiation. The lowest sheet resistance at this regime was 30 Ω/square when the irradiation dose was 217 J/cm^2 (see Fig. 4).

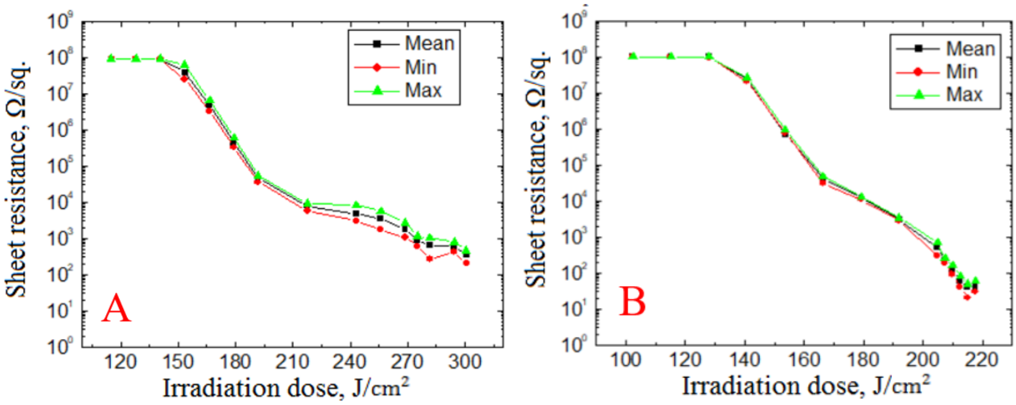

Fig. 4 Dependence of the polymer Kapton® sheet resistance on the irradiation dose after patterning with nanosecond (A) and picosecond laser pulses (B).

Irradiation with higher doses leads to the damage of the sample. The patterned surface becomes cracked and improper for further use. Patterning repeatability was better using the ps-laser treatment. Using the ns-regime, thin PI samples were deformed due to excessive heating at irradiation doses higher than 200 J/cm^2. Therefore, the experiments were continued only using the ps-regime.

Selective copper deposition on the laser-patterned surface was possible when the sheet resistance was 10 000 Ω/square or lower for both ns- and ps-regimes of the patterning. Electro-plating occurred when the polyimide sample was irradiated the dose not less than 180 J/cm^2.

The second processing method of Kapton PI films was performed with the picosecond laser when the sample was now placed at a non-focal plane and patterned with a defocused laser beam. Different beam spot sizes could be achieved by changing the sample position relatively to the laser beam focal plane. The specimen was moved away from the focal plane as much as 6 mm, and that caused a spot size to change from 52 µm at the focal plane to 342 µm at 6 mm below the focal plane (see Fig. 5). The same effect was achieved when the sample was lifted closer to the focusing lens by 6 mm. Increasing in beam diameter caused a lower energy density; however, the exposure time was longer due to enlargement of the beam diameter and a fixed translation speed. Using this sample processing method, grey coloured graphite-like structures were formed on the surface of Kapton PI film after patterning at 6 mm below the focal plane with a spot size of 342 µm. The sheet resistance of the formed graphite-like structures was very low, and it was 8 Ω/square. This structure started to appear when the irradiation dose was higher than 140 J/cm^2, and the same structure with the same sheet resistance was forming after increasing the irradiation dose.

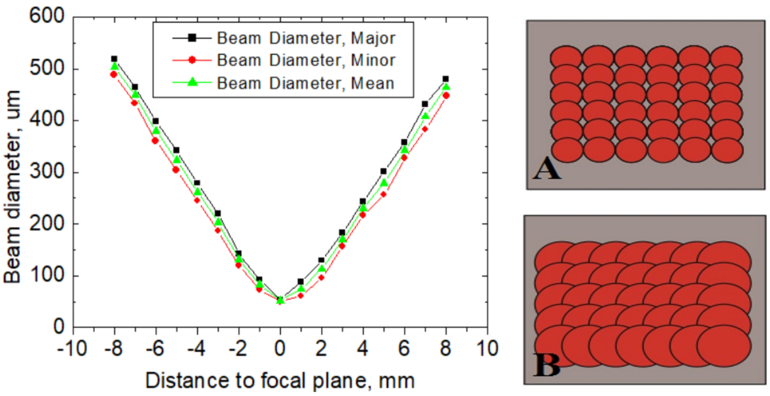

Fig. 5 Beam diameter dependence on the distance from the focal plane. The beam diameter at the focal plane was 52 µm and 8 mm below the focal plane. The diameter was 464 µm. At the focal plane, almost non-overlapping spots were obtained (A). Increasing defocusing, overlap increased due to significant larger beam diameter (B).

Raman microscope Alpha300R from WITec was used to investigate alterations in polyimide film after irradiation with a focused and defocused beam of the ps-laser. Analysis of Raman spectra of samples patterned at focal plane showed that D and G peaks dominated in this regime. Raman spectra of Kapton PI films, patterned with the defocused ps-laser beam, exhibited sharp high-intensity 2D peaks, which is evident in graphene formation during laser treatment.

I(2D)/I(G) ratio of 0.5 confirms the formation of multi-layer graphene structures. A significant decrease of the I(D)/I(G) ratio from 1.19 in the focal plane to 0.72 – achieved using a defocused beam confirms a considerable decrease of structural defects in laser formed graphene structures (See Fig. 6).

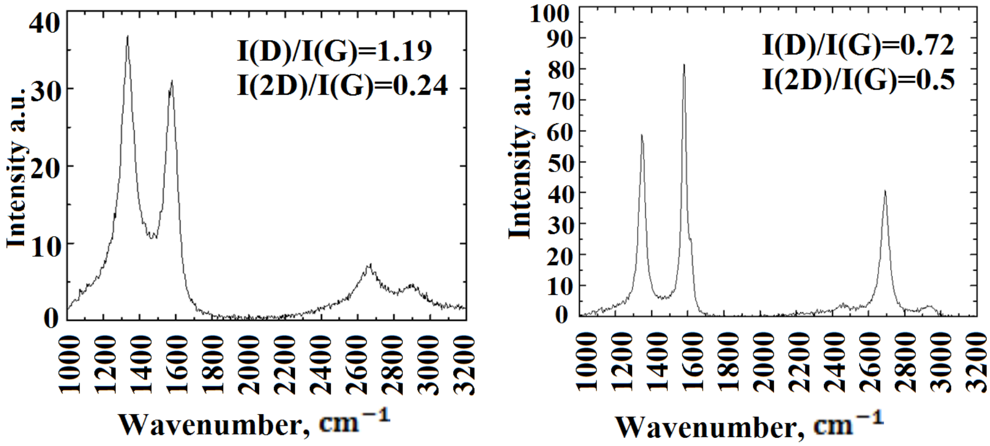

Fig. 6 Raman spectra of Kapton PI film patterned at the focal plane. Beam spot diameter was 52 µm at sample (A). Raman spectra of Kapton PI film patterned with a defocused beam. Beam spot diameter was 342 µm at sample (B).

The samples, fabricated with the defocused beam, with formed low-resistance graphite-like structures, were electro-plated as well. The plating process was faster than the plating process of those samples, which were patterned at the focal plane. Homogeneous, thin copper layers could be electro-plated on this type of samples with the metal layer thickness of 3-5 µm, while the thickness of the copper layer of 10-20 µm was required to get full coverage laser-treated area on the samples, patterned at the focal plane.

4. Conclusions

A wide range of different laser parameters was investigated in this study. It was shown that laser parameters have a significant impact on sheet resistance and the quality of the patterned surface. Patterning with focused high-intensity beam led to the formation of carbon structures, whose sheet resistance was strongly dependent on the irradiation dose in this regime. By adjusting the irradiation dose, the sheet resistance of the formed structures could be adjusted as well. Another patterning regime was found after the irradiation with the low-intensity defocused beam. Graphite like structures with very low sheet resistance was formed on the sample.

The electro-plating process was faster on Kapton PI samples, which were patterned in a defocused regime. Thinner copper layer, with the thickness of 3-5 µm were electro-plated on the samples processed in this regime. In contrast, 10-20 µm thickness of the copper layer was getting, after electro-plating samples processed in the focal plane.

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