3D laser writing in-line process for the rapid fabrication of flexible electronic devices

Georges Dubourg, Saša Marjanović, Cedo Zlebic, Jovan Matovic and Vesna Crnojević Bengin

University of Novi Sad, Faculty of Technical Sciences, Trg D. Obradovica 6, 21000 Novi Sad, Serbia
Email: georgesdubourg@uns.ac.rs

ABSTRACT

In this work, we present the fabrication of a strain sensor integrating a Wheatstone bridge made of organic resistors in only one step of patterning by using a promising approach of 3D direct laser writing. This processing method consists to adapt the power of the laser in function of the optical properties of the materials in order to pattern selectively, layer by layer, several materials in the same run. With this approach, we have achieved the fabrication of a piezoresistive sensor composed of a Kapton cantilever and a graphene strain gauge directly connected to a Wheatstone bridge integrating graphene resistor and copper conducting lines. The characterization of the resulting device has shown a high sensibility with a gauge factor of 20, proving the potential of this flexible piezoresistive sensor to be used for the development of low-cost flexible electronic devices like touch panels.

Keywords: flexible electronic, graphene, laser micromachining.

1 INTRODUCTION

The development of flexible electronic devices is attracting considerable attention of researchers and industries. Compared to classical silicon based electronics, flexible electronic offers a wide range of new applications in terms of flexibility, and potentially reduces the cost of fabrication [1].

But, to maintain, a fabrication cost as low as possible, rapid and low-cost fabrication processes have to be developed since most of times, their micromachining uses the patterning methods used for the micromachining of rigid substrates such as printing techniques which often require high temperature processes, expensive and long production steps [2].

Then, an interesting alternative is the direct laser writing technique since it is relatively fast, and is also suitable for the patterning of a large range of materials including metals, plastic and organic materials [3],[4]. Nevertheless, for both, laser writing or printing techniques, the fabrication of complex microdevices which require the introduction of several layers and materials, needs additional steps like alignment and baking steps, which increase the time and cost of fabrication. Here, we propose a promising processing method based on a direct laser writing technique that allows the rapid patterning of several layers in only one step. This method consists to adapt the power of the laser in function with the optical properties of the different materials comprising the device.

With this approach, we have fabricated a strain sensor composed of a flexible Kapton mechanical structure integrating a graphene strain gauge which is directly connected to a Wheatstone bridge made of graphene resistors and copper conducting lines.

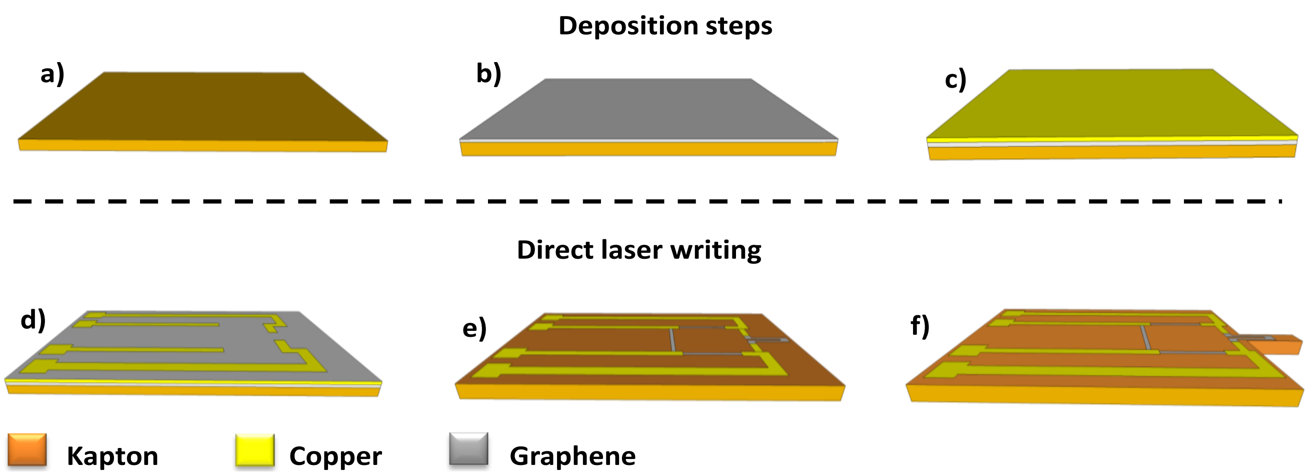

Figure 1 : Fabrication process of the piezoresistive cantilever sensor. a) Cleaning of the Kapton polyimide substrate. b) Deposition of the graphene layer. c) Deposition of the copper layer. d), e) and f) Successive direct laser writing process of the copper layer, the graphene layer and the Kapton film respectively.

2 MATERIALS AND METHOD

The fabrication process of the strain sensor is shown in figure 1

Initially, a graphene ink (Innophene Co.) (Figure 1b) and a copper layer (Figure 1c) were successively deposited by spin-coating and electron-beam evaporation respectively onto a Kapton polyimide film previously treated with oxygen plasma to improve its surface properties (Figure 1a).

Afterward, the resulting layers were structured in a single step by selective laser writing.

In order to do that, each layer was successively irradiated with a short pulse laser (Nd:YAG-1064 nm, Rofin) whose the power of the laser was adapted in function with the absorbance of the material.

The main laser parameters that can be controlled are the frequency of the pulse, the speed of the displacement of the laser and the current applied to the laser. The power of laser depends on the frequency of the pulse and the current applied to the laser, and the resolution of the lines written by le laser depends on the frequency of the laser and its speed. Then, to obtain well-defined lines, the maximum frequency available (65 kHz) and a low speed (80mm/s) were chosen, and were kept similar for the patterning of the three successive layers. Thereby, the power of the laser was adapted to the absorbance of the material by acting on the current applied to the laser.

The first step of the process is the patterning of the copper layer to define the conducting lines and contact pads of the device. The copper layer has an absorbance which is similar to the subsequent layer made of graphene. Therefore, the graphene layer can be also etched during the patterning of the copper by the laser if the current is too high. But, the copper is a reflective material and it has a low transmittance. Hence, the energy transmitted to the graphene layer through the copper one is relatively low.

Consequently, by decreasing drastically the current applied to the laser as low as possible (22.2 A), the effect of the laser on the graphene layer was avoided, and the selective writing of the copper layer (Figure 1d) was achieved without damaging the graphene layer.

Next, the graphene was also selectively patterned for the fabrication of the strain gauge and the resistors of the Wheatstone bridge (Figure 1e) by applying a lower current (22.6 A) than the one (23 A) required for the structuration of the Kapton structure (Figure 1f) since its absorbance is higher than the one of the Kapton.

Therefore, by setting the different parameters in the same stage, a flexible strain sensor composed of a cantilever integrating a graphene piezoresistor and a Wheatstone bridge was patterned in the same run by successive and selective laser writings without alignment and chemical steps, without clean room facilities and in less than 10 minutes.

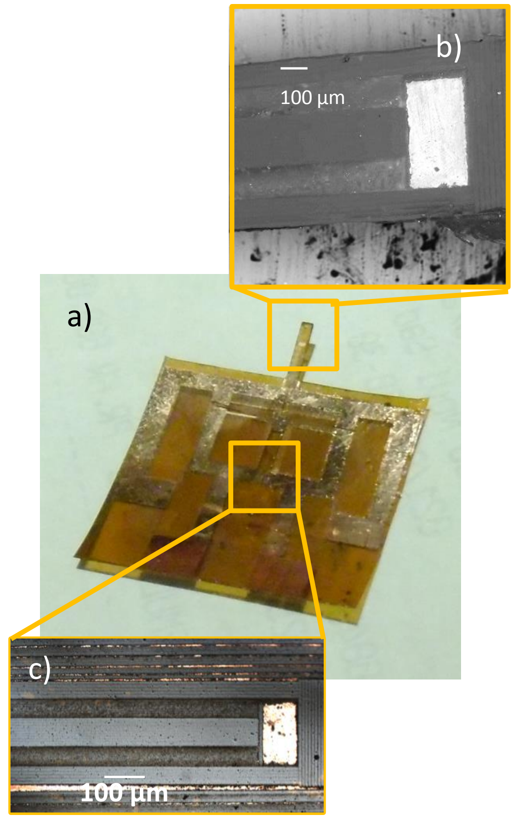

Figure 2 : a) Optical image of the resulting piezoresistive sensor made of flexible Kapton film. a) SEM image of the tip of the cantilever. c) Zoom-in view on the graphene resistor.

3 DEVICE CHARACTERIZATION

The final dimensions of the resulting piezoresistive cantilever shown in figure 2 are 4000 µm long, 700 µm wide and 25 µm thick, and are in agreement with the initial drawings. The piezoresistor is composed of two arms characterized by a length of 3000 µm, a width of 80 µm and a thickness of 200 nm resulting to a resistance of 7060 Ω. The conducting lines and contact pads made of copper are characterized by a thickness of 60 nm.

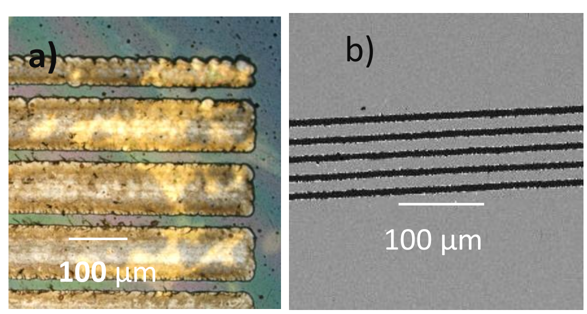

Figure 3 : a) optical image of the graphene patterned lines. b) SEM image of the copper patterned lines

Moreover, the width of the graphene and copper lines can be reduced to 30 µm as we can see in the Figure 3 a and b respectively.

Next, the sensitivity of the piezoresistive sensor was electromechanically characterized by applying a force at the cantilever while measuring the resistance changes (Source Meter Keithley 2410) as described in [5].

Figure 4 shows the evolution of the resistance as a function of the applied strain.

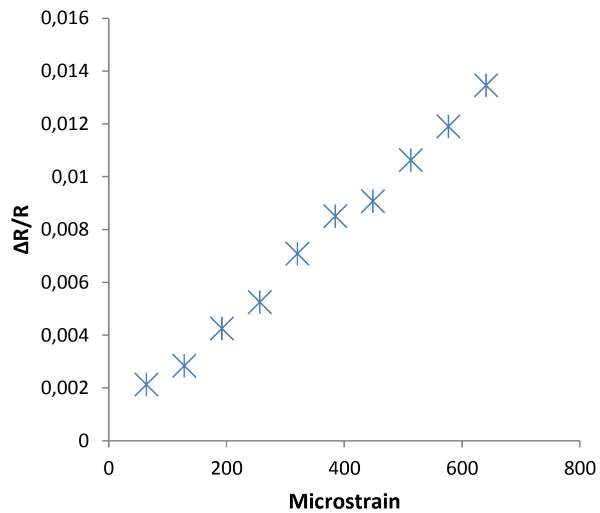

Figure 4 : Resistance change of the graphene piezoresistor integrated on the Kapton cantilever as a function of applied strain.

The sensitivity of the strain sensor defined by its gauge factor (the slope of the curve) was calculated to be 20 which is relatively high compared to the reported sensitivity values of graphene piezoresistive devices [6], [7].

Afterward, the piezoresistor integrated in the Wheatstone bridge was characterized. In that configuration, the resistance change of the piezoresistor generates a voltage change between the potentials A and B (Figure 5a).

The resistance values of the piezoresistor and the resistors R_1, R_2, R_3 are 33110 Ω, 33108 Ω, 33011 Ω, 33112 Ω respectively.

In order to characterize the device, a voltage of 3 V was applied in the Wheatstone bridge, and a deflection of the cantilever was generated thanks to a stylus while measuring the voltage change.

In the Figure 5b we can see the evolution of the voltage as a function of the deflection of the cantilever. The experimental results indicate that the measured voltage at the output of the Wheatstone bridge increases as the deflection of the cantilever increases. These results prove the capability to the fabricated device to be used as low-cost flexible strain sensor.

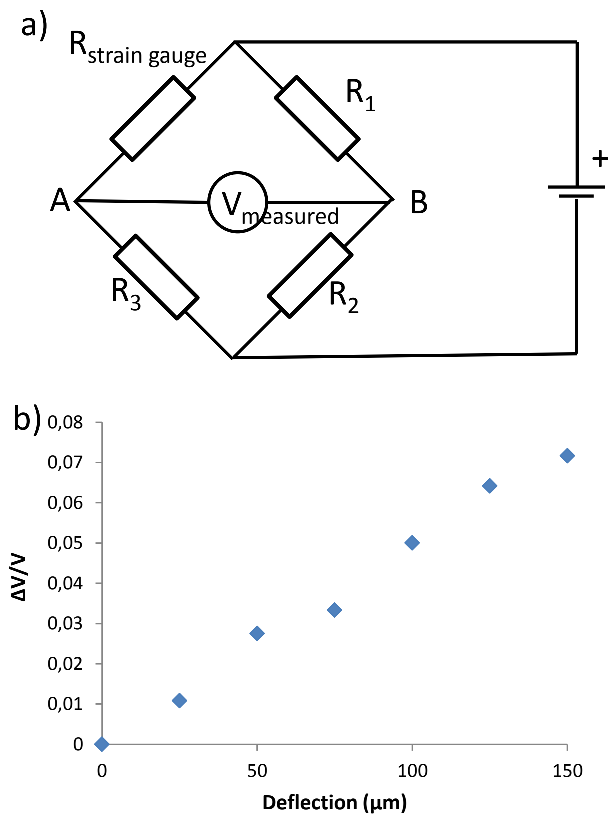

Figure 5 : a) Schematic of the Wheatstone bridge associated to the piezoresistor. b) Voltage change as function of the cantilever deflection.

4 CONCLUSION

The different materials constituting the flexible piezoresistive sensor directly integrating a Wheatstone bridge were patterned using a single-step, rapid and low-cost fabrication process. The proposed process is an original approach of the direct laser writing technique which consists to adapt the power of the laser in function with the optical properties of the materials to design selectively, layer by layer, several materials in the same run.

This approach is particularly interesting for the development of flexible electronic devices since it can be applied to a large panel of materials including metals, organic materials and plastics, but also, for the fabrication of microscale devices.

In addition, the electromechanical characterization has shown the ability of the resulting device to sense strain with a good sensitivity since high gauge factor has been obtained.

REFERENCES

[1] S. Sugiyama, S. Amaya, D. Viet Dao, “Development of polymer MEMS process technology as an

approach to a sustainable production system," Adv. Nat. Sci.:Nanosci.Nanotechnol. 3, 009-015, 2012

[2] M. Acuautla, S. Bernardinia, L. Gallais, M. Bendahan "Direct laser patterning of a gas sensor on flexible substrate" Procedia Engineering., 87, 899 – 902, 2014

[3] J. B. In, B. Hsi, J.H. Yoo, S. Hyun, C. Carraro, R. Maboudian, C. P. Grigoropoulos," Facile fabrication of flexible all solid-state micro-supercapacitor by direct laser writing of porous carbon in polyimidee" Carbon, 83,144–151, 2015

[4] L. Gallais, E. Bergeret, B. Wang, M. Guerin, E. Bènevent, "Ultrafast laser ablation of metal films on flexible substrates," Appl Phys A, 115, 177–188, 2014

[5] C. Zlebic, M. Kisic, N. Blaz, A. Menicanin, S. Kojic, L. Zivanov, M. Damnjanovic, "Ink-jet printed strain sensor on polyimide substrate," Electronics Technology (ISSE), 409 – 414, 2013

[6] Y. Lee, S. Bae, H. Jang, S. Jang, S. E. Zhu, S. H. Sim, Y.I. Song , B. Hee Hong, J. H. Ahn," Wafer-Scale Synthesis and Transfer of Graphene Films," Nano Lett., 10, 2010, 490–493, 2010

[7] V. Eswaraiah, K. Balasubramaniam, S. Ramaprabhu, "One-pot synthesis of conducting graphene–polymer composites and their strain sensing application" Nanoscale, 4, 2012, 1258-1262, 2012