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Femtosecond Laser 3D-printing of Conductive Microelectronics for Potential Biomedical Applications

Omid Dadras-Toussi, Milad Khorrami, and Mohammad Reza Abidian, *Member, IEEE*

***Abstract*— Development of soft and conductive micro devices represents a demanding research topic in various biomedical applications, particularly organic bioelectronics. Among various fabrication methods, two-photon polymerization (2PP) using a wide range of photocurable inks is a promising 3D printing technique for construction of structures in submicron resolution. Herein, we introduce a novel conductive photosensitive resin by using poly (3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) and poly(ethylene glycol) diacrylate), and fabricate 3D conductive polymeric microstructures via 2PP. In the developed resin, presence of PEDOT:PSS significantly enhances the electrical conductivity of microstructures (~ 10 orders of magnitude).**

***Clinical Relevance*— Conductive microdevices based on the PEDOT:PSS-doped resin open new avenues in a broad range of biomedical research areas including neural interfaces, biosensors, and bioelectronics.**

I. Introduction

Development of soft and conductive micro-devices is of great interest in various fields including biomedical research, electronics, and robotics [1-6]. Additive manufacturing, also known as 3D printing, is the construction of a three dimensional object sometimes with complex shapes and geometries from a digital model in which the material is added together typically layer by layer [7-9]. Among 3D printing technologies, two-photon polymerization (2PP) is the most precise process capable of creating high-resolution and complex structures down to sub 100 nm. The photosensitive resins can be doped with various chemical and/or physical cues, which could potentially tune mechanical, biological, thermal, optical, electrical, and magnetic properties of the 3D-printed architectures for specific applications [10]. 2PP lithography can therefore be an ideal tool for fabrication of multi-functionalized and well-defined biomedical devices.

More recently, significant research effort has been devoted towards engineering of conductive microstructures via 2PP [11]. To that end, incorporation of organic / inorganic conductive fillers such as metallic nanoparticles [12, 13], graphene [14], carbon nanotubes [15], and conjugated polymers (CPs) [16] within the photocurable resins has been explored for enhancement of conductivity of 2PP-fabricated constructs. Among these conductive fillers, CPs are excellent candidates for manufacturing of soft and conductive microstructures using 2PP process as they offer high electrical conductivity, soft mechanical properties, and outstanding chemical stability [11, 17-24]. Previously, Kurselis and coworkers introduced a two-step process for fabrication of conductive microstructures by adding 3,4-ethylenedioxythiophene (EDOT) monomer into the poly(ethylene glycol) diacrylate (PEGDA) resin, followed by oxidative polymerization of EDOT loaded inside the 2PP-fabricated structures [16]. However, the electrical conductivity of 2PP-fabricated structures was moderately improved (up to 4 S/m), presumably due to the limited solubility of the EDOT monomer in the resin and low doping level of chemically polymerized PEDOT. To address this challenge, here we report that direct incorporation of poly (3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) in a PEGDA-based resin significantly enhances the conductivity of microstructures (from ~ 10^{-6} to > 10^{4} S/m). To showcase the full potential of 2PP lithography, the developed resin has been fabricated into conductive microstructures for microelectronic device applications. These electroactive microdevices can be potentially employed in a wide range of biomedical applications including neural probes, biosensors, and bioactuators.

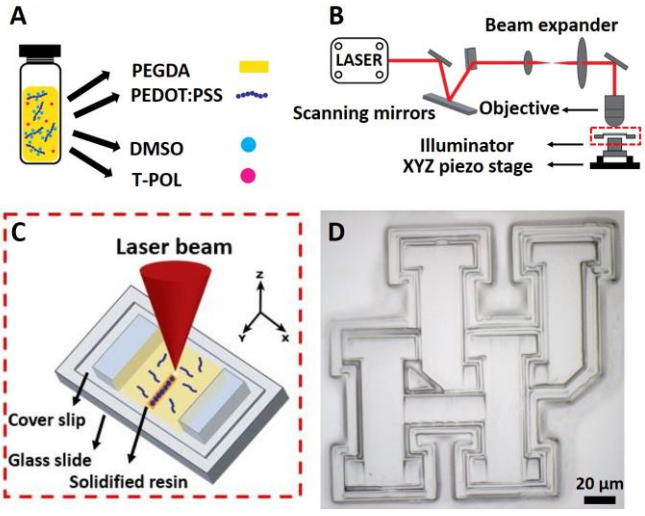

Figure 1 A) Resin components, B) Laser setup, C) 2PP-fabrication on the glass substrate. Focused laser beam crosslinked the resin at the glass interface, and simultaneous 3D movement of XYZ stages led to fabrication of microstructures on the upper coverslip, and D) Optical micrograph of University of Houston logo fabricated via 2PP.

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O. D. is with the Dept. of Biomedical Engineering at the University of Houston, Houston, TX 77205 USA (email: odadrastoussi@uh.edu).

M. K. is with the Dept. of Biomedical Engineering at the University of Houston, Houston, TX 77205 USA (email: mkhorrami@uh.edu).

M. R. A is with the Dept. of Biomedical Engineering at the University of Houston, Houston, TX 77205 USA (Phone 713-743-0869, fax: 713-743-0226, email: mabidian@uh.edu).

II. Materials and Methods

A. Materials

Poly(ethylene glycol) diacrylate (PEGDA) (M_n=700), high conductivity grade of poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) 1.0 wt.% in H_2O, and 3-(trimethoxysilyl) propyl methacrylate were all purchased from Sigma Aldrich. Ethyl (2,4,6-trimethylbenzoyl) phenylphosphinate (T-POL) was ordered from Oakwood Chemical. Micro cover glasses (22 mm × 30 mm), ethanol (200 proof), dimethyl sulfoxide (DMSO) (molecular biology grade), and phosphate buffered saline (PBS) tablets (100 ml-Biotechnology) were purchased from VWR.

B. Resin formulation and preparation

Liquid resins were prepared by mixing 0.1-0.5 wt% PEDOT:PSS, 25 wt% DMSO, 2 wt% T-POL, and 72.5-72.9 wt% PEGDA. Non-conductive resin contained neither PEDOT:PSS nor DMSO. The liquid mixtures were stirred for 2 h, then degassed for 1 h to eliminate air bubbles.

C. Surface treatment

In order to improve the attachment of microstructures to glass surface, cover glasses were salinized prior to 2PP-fabrication. Salinization solution was prepared by mixing 1 ml 3-(trimethoxysilyl) propyl methacrylate, 200 ml ethanol, and 6 ml dilute acetic acid (1:10 v/v acetic acid: deionized water). 200 µl of the solution was placed onto each micro cover glass and incubated for 5 min. The cover glasses were then rinsed in ethanol and thoroughly air-dried.

D. Design of Microstructures

All microstructures were designed using Autodesk Fusion 360 Software. Sketches were imported into the nfab software (version: 5.0.14, Newport) in stereolithography format for 2PP fabrication.

E. Two-photon polymerization

The space between two supports on a glass slide was filled with a droplet of homogeneous resin, and a coverslip was fixed on top. The substrate was placed on the sample holder located on a piezo stage (VP-5ZA, Newport) and XY-stages (XMS 160, Newport) which were connected to a computer-controlled Motion Controller / Driver (XPS, Newport). An ultrafast Ti:Sappphire laser (Maitai Deepsee, Spectra Physics) was tightly focused at the glass interface using a 40X objective (Plan N-FN22, OLYMPUS). A femtosecond laser beam was used at wavelength of 780 nm and laser power of 1.7 mW, which was irradiated through Ti-sapphire oscillator operating at 80 MHz repetition rate. Laser operation and stages movement were controlled by Mai Tai™ software (version: 2x, Spectra Physics) and nfab software (version: 5.0.14, Newport), respectively. Microstructures were fabricated on the upper coverslip at stage velocity of 50 µm/s. After 2PP-fabrication, the coverslip was removed and gently soaked in ethanol for 30 s to wash off the non-illuminated resin.

F. Conductivity / conductance measurements

Current-voltage (I-V) measurements (two probe method) was carried out using semiconductor device parameter analyzer (B1500A, Keysight). Probe tips with diameter of 1 µm (Signatone), which were connected to source measure unit (SMU-8, Keysight), touched two ends of the microstructure simultaneously while altered voltage was applied in the range of -3V to 3V (50 mV increasing step) and transient current was automatically recorded. Data were analyzed using Easy EXPERT group+ software (Keysight Technologies Inc.). Electrical conductance was derived from the slope of the I-V curve, and electrical conductivity was calculated using the conductance value and geometry of the microstructure.

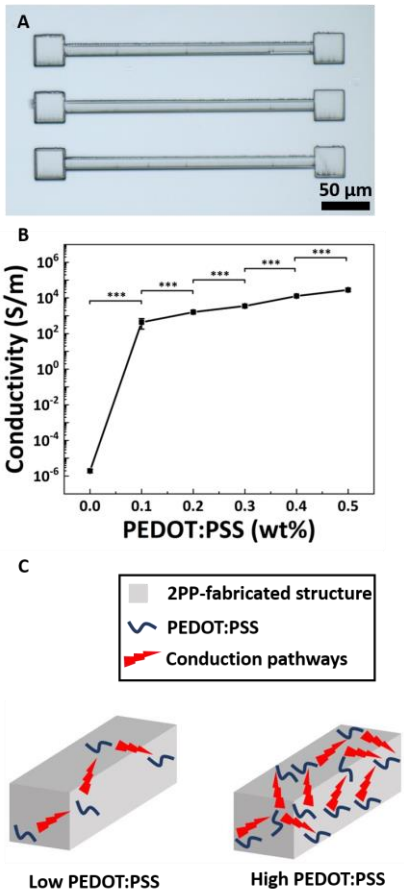

Figure 2 A) Optical micrograph of parallel 2PP-fabricated micro-bars for electrical characterization, B) Electrical conductivity as a function of PEDOT:PSS concentration in the resin. Data is shown in mean ± SD (n=3). *** demonstrates significance level of $p < 0.001$, and C) An illustration showing the hypothesis for the conductivity of PEGDA-PEDOT:PSS microstructures.

G. Impedance spectroscopy and cyclic voltammetry

Autolab PGSTAT 302N (USA METROHM) and Nova Frequency Response Analyzer software (version: 2.1, USA METROHM) were used for electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV). 3-electrode setup including Platinum counter electrode, Ag/AgCl reference electrode and working electrode were immersed in the electrolyte solution (PBS, pH=7.4). Impedance was measured by a sinusoidal alternating current signal (amplitude: 10 mV) in the frequency range of 1-10^5 Hz. For CV, working electrode potential was swept from -0.8 V to 0.4 V with respect to the reference electrode at a constant scan rate of 0.1 V/s (staircase method). The third cycle of CV was used due to its ion exchange stability. For calculation of charge storage capacity, the surface area under CV curve was integrated using OriginPro software (2018, Origin Lab), and the value was

divided by the scan rate. Capacitance value was obtained by dividing the charge storage capacity to the potential sweep range (1.2 V).

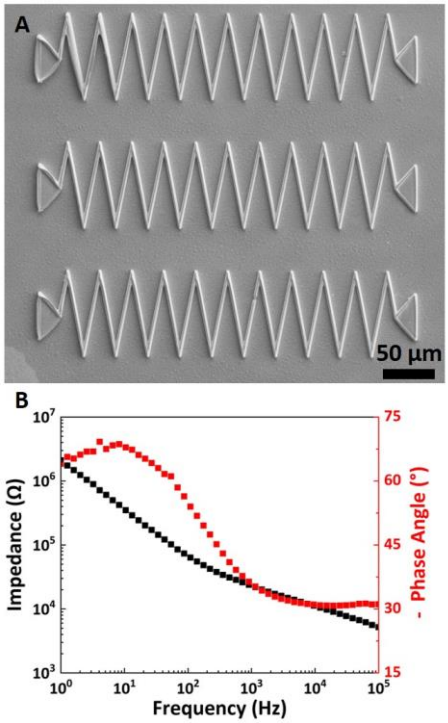

Figure 3 A) Scanning electron micrograph (SEM) of a zig-zag array fabricated by 2PP, and B) Impedance spectroscopy and phase angle graphs of the zig-zag array in a frequency range of 1-10^5 Hz.

III. Results and Discussion

A. Resin formulation and characterization

The developed resin was composed of PEGDA (polymer crosslinker), PEDOT:PSS (conductive agent), DMSO (solvent for conductive agent), and T-POL (photo initiator) (Fig. 1A). Addition of DMSO led to homogenous dispersion of PEDOT:PSS in the PEGDA blend and increased its solubility in the resin. Maximum solubility of PEDOT:PSS in the resin was observed at 0.5 wt% concentration, while the higher amounts resulted in agglomeration and precipitation of PEDOT:PSS shortly after mixing. The setup for laser and optics for 2PP process are schematically shown in Fig. 1B. Irradiation of femtosecond laser pulses solidified the resin at the focal point and structures were fabricated upside down on the upper coverslip through layer by layer scanning of the laser (Fig. 1C). Fig. 1D displays the optical micrograph of University of Houston logo (UH) which was fabricated via 2PP. A wide range of high-resolution and well-defined microstructures can be constructed with the experimental setup and PEDOT:PSS-doped resin (Fig. 3A and Fig. 4A).

Next, the effect of PEDOT:PSS concentration ranging from 0 to 0.5 wt% on the electrical conductivity of microstructures was investigated (Fig. 2). First, micro-bars with dimensions of 265 µm × 10 µm × 10 µm (length × width × height) were fabricated (Fig. 2A), followed by performing I-V measurements. As shown in Fig. 2B, addition of 0.1 wt% PEDOT:PSS to the resin significantly enhanced the conductivity from $1.94\times10^{-6}\pm 4.05\times10^{-7}$ S/m to $4.33\times10^{2} \pm 2.55\times10^{2}$ S/m (p<0.001). More importantly, at 0.5 wt% PEDOT:PSS, the electrical conductivity increased to $2.81\times10^{4} \pm 4.34\times10^{3}$ S/m (n=3, mean ± SD). In other words, direct inclusion of 0.5 wt% PEDOT:PSS in a PEGDA-based resin remarkably enhanced the conductivity of 2PP-fabricated microstructures over 10 orders of magnitude (p<0.001). It is worth noting that the conductivity was 4 orders of magnitude higher than the value reported by Kueselis *et. al.* (4 S/m) in a relevant work [16]. We hypothesize that conductivity dependence on PEDOT:PSS concentration is associated with the growth of interconnected 3D conduction pathways in the microstructures (Fig. 2C).

B. Zig-zag array

Using 2PP experimental setup and the conductive resin, a microelectronic device based on an array of zig-zag lines was designed and fabricated (Fig. 3A). Electrical performance of the zig zag array was characterized by electrochemical impedance spectroscopy. Fig. 3B illustrates the impedance and the phase angle of a zig-zag line with dimensions of 300 µm × 1 µm × 2 µm (length × width × height) over a frequency range of 1-10^5 Hz. As shown in the phase angle graph, the microdevice primarily functioned as a capacitor over frequency range of 1-100 Hz. In contrast, lines exhibited more resistive properties in higher frequencies (> 100 Hz) since the phase angle values were in the range of 30º - 45º. Moreover, it was observed that in the biologically relevant frequency of 910 Hz [25], the impedance was 63.5 kΩ. This impedance trend can be presumably explained by presence of PEDOT:PSS conductive networks in the PEGDA matrix, which inherently possess both capacitive and resistive components.

C. Capacitor array

Energy storage is a crucial element of biomedical microdevices such as wearable biosensors, chip-scale epidermal electronics, and deep brain stimulators [26]. To further demonstrate the capability of our new resin for fabrication of such electronics, we developed and characterized 2PP-fabricated micro-capacitors (Fig. 4). As shown in Fig. 4A, each capacitor consisted of a maze pattern of lines with thickness and height of 2 µm and 1 µm, respectively. Each line was connected to a cubic terminal with dimensions of 20 µm × 20 µm × 2 µm (length × width × height). To examine the charge storage capacity, the capacitors were subjected to CV [27] (Fig. 4B), which was performed in a potential sweep in the range of -0.8 V to 0.4 V with scan rate of 0.1 V/s. Charge storage capacity and capacitance of the capacitor was measured to be 531.6 nC and 443 nF, respectively.

IV. Conclusion

In summary, we have formulated and characterized a novel conductive resin for 2PP lithography by inclusion of PEDOT:PSS. We successfully demonstrated that direct incorporation of 0.5 wt% PEDOT:PSS considerably enhanced the conductivity of otherwise insulating 2PP-fabricated microstructures over 10 orders of magnitude. Fabrication and characterization of functional microdevices based on PEDOT:PSS-doped resin confirm that they are

electrically functional, and promise their application in a broad range of biomedical research areas, including flexible microelectronics, biosensing, soft robotics, and neural recording / stimulation.

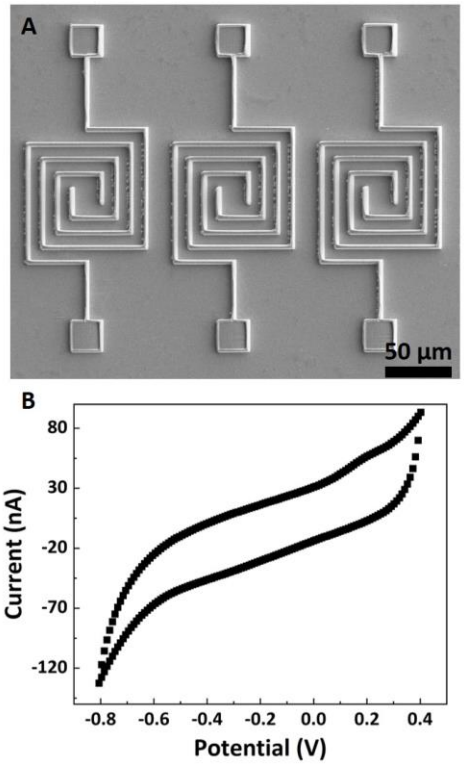

Figure 4 A) SEM of an array of micro-capacitors fabricated via 2PP, and B) CV of one capacitor in the potential range of -0.8 V to 0.4 V and scan rate of 0.1 V/s.

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