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All-polymer *RC* filter circuits fabricated with inkjet printing technology

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Abstract

All-polymer *RC* filter circuits by all-inkjet printing technology are fabricated for the first time. Conductive polymers such as polyaniline and poly(3, 4-ethylenedioxythiophene) have been used as the electrode material of the capacitor as well as the resistor material. The fabrication process and the characteristics of the printed capacitor and *RC* filter have been demonstrated. Simulation of the printed *RC* circuit has been demonstrated and compared with the experimental measurement results. A detail discussion has been given about the all-polymer capacitor and *RC* filter.

Keywords: RC filters; Inkjet printing; Conductive polymers; PEDOT/PSS; PANI; Frequency

1. Introduction

The discovery of high conductivity in doped polyacetylene in 1977 [1] has been attracting considerable interests in the application of polymers as the semiconducting and conducting materials, and this made three scientists to win 2000 Nobel Prize in Chemistry. Since then a lot of researchers have been working on the mechanism of polymer conduction and polymer microelectronic devices. The first organic thin film transistor was reported in 1983 [2]. After that, the first all-polymer thin film transistor was fabricated in 1990 [3]. Garnier et al. [4] reported their first all-polymer transistor by screen-printing technology in 1994. By the end of 2000, large-scale and all-polymer integrated circuits [5] and complementary integrated circuits based on organic transistors [6] have also been demonstrated, providing the potential for a cheap alternative to amorphous silicon thin film transistor technology. Organic or polymer semiconductor devices are catching considerable attention due to their potential low cost and easy processing advantages. Within the last decade, the science and technology of conducting polymers have been greatly improved. The conductivity of some conjugated polymers has been made comparable to that of copper [35]. In addition to their potential low-cost feature and processing advantages, the processibility of some commonly used polymers is also increased. It is not surprising that conjugated polymers are of great interest both in industry and academia. They are potentially useful in a number of applications where high speeds are not essential, for example, low-cost memory devices, such as smart cards and electronic luggage tags [7], gas sensors [8], etc.

Being different from their solid-state counterparts, conducting polymers, often referred to as conjugated polymers, have different properties. Most of them have very low mobilities [25]. To date, the application of polymers is limited to low-speed areas. And because the chemical and physical properties are various among different polymers, several techniques have been employed in fabrication of polymer thin films, such as lithography, thermal evaporation, spin coating, dipping coating, printing, layer-by-layer self-assembly, and spraying coating [30–34].

Compared to various other printing techniques, such as screen-printing [9–11] and micro-contact printing [12,13], inkjet printing [14,15,23] has caught more and

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more attention due to its unique characteristics, such as volatility, simplicity, compatibility with a lot of substrates, non-contact patterning and low cost. Inkjet printing has the promise to become a low cost manufacturing process, and has already been used to fabricate all-polymer transistors [14–17], polymer light emitting diodes [18–20], and nanoparticle micro-electromechanical systems [21].

In this paper, the all-polymer *RC* filter circuit with inkjet printing technique is reported. To our knowledge, it is the first report about this kind of passive electronic component and circuit.

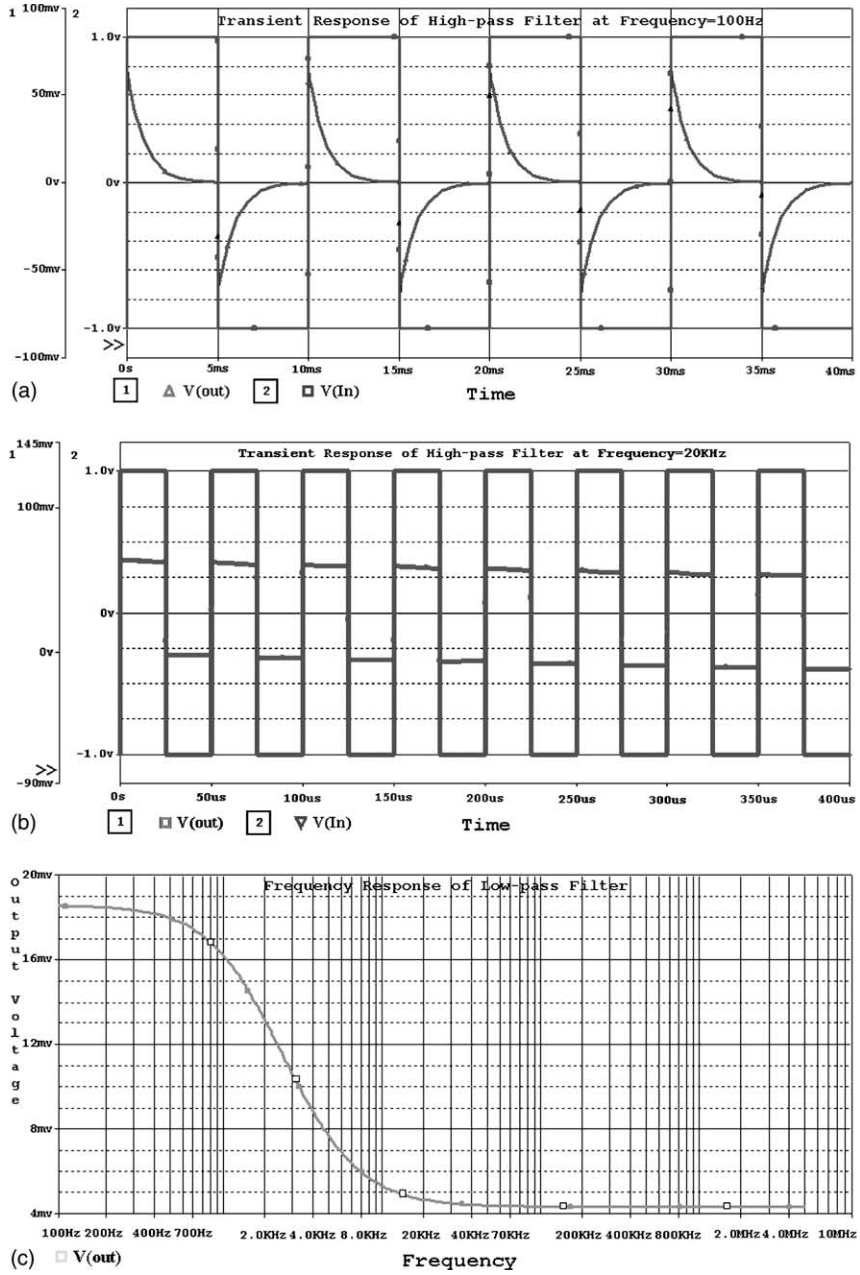


Fig. 1. Simulation results of polymer low-pass and high-pass filters, (a) High-pass transient response at frequency = 100 Hz, (b) High-pass transient response at frequency = 20 kHz, (c) frequency response of low-pass filter, (d) low-pass transient response at frequency = 800 Hz, (e) low-pass transient response at frequency = 1.5 kHz.

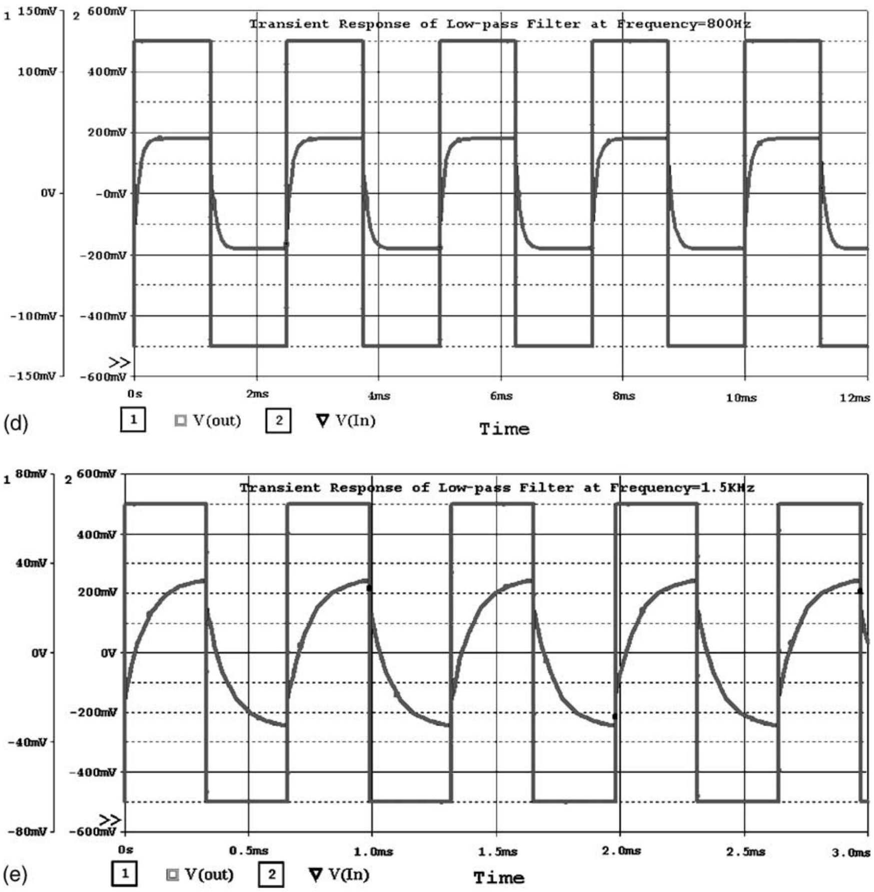


Fig. 1 (*continued*)

2. Analysis and simulation

Because our devices were made of polymer materials and fabricated by the inkjet printing technique, there are many variables to determine the circuit behaviors upon the outcoming of a realistic device. For example, the thicknesses of the printed polymer thin films are very important to determine the conductivity. Fluctuation in conductivity of thin films will result in unpredictable device characteristics. For *RC* filters, accurate parameters of resistors and capacitors are essential for obtaining precise cutting-off of the input signals. When the films are printed too thin, the conductivity will be greatly reduced, and even large discontinuousness will occur in the films. Annealing temperature and time change in concentration of solutions and evaporation of solvents all contribute to the uncertainty of the thickness of polymer thin films. As well as the interaction between two different kinds of polymers, contamination brought by inkjet printers also adversely influences the characteristics of devices. On the other hand, based on our experimental results on electrical characterization of polymer materials, polyaniline and poly(3,4-ethylenedioxythiophene) PEDOT/poly(styrene sulfonic acid) (PSS), it is found that the *I–V* characteristics of inkjet printed polymer thin films are very similar and distributed in a tolerable range for different processing conditions. Therefore, the characteristics of polymer thin film devices are reproducible with carefully designed processing techniques.

Compared with its solid-state counterparts, polymer electronics have been much less known not only in theory, but also in practice. And based on their successful experience in solid-state device fabrication, simulation tools also gain much attention from polymer device engineers, although up to now very few simulation tools are designed for polymer devices and it could be difficult to have some universal tools to simulate different kinds of polymers in the near future. Some researchers have done a lot of work on numerical simulation of different kinds of charge transport models [26–28], and some have used specially designed software to study *I–V* characteristics of polymer diodes [29]. In our work, Pspice is used to simulate the characteristics of our polymers based on our equivalent circuit analysis. Fig. 1 shows the simulation results of our high-pass low-pass filters and Fig. 2 shows the equivalent circuits of our real devices.

As observed in the experiment, when the probing position is carefully selected on the top electrode of the capacitors, very small resistance in series of the testing circuit can be achieved. If assuming that R_2 is equal to zero, then the equivalent circuit for our experiment is illustrated as Fig. 2(b).

According to circuit analysis, the voltage equation of the equivalent circuit is given by

$$V_i(t) = V_1(t) + V_0(t) = V_1(t) + V_2(t) + V_c(t) \tag{1}$$

Substitute the expressions of $V_1(t)$ and $V_c(t)$, Eq. (2) is obtained as the following

$$\begin{aligned} V_i(t) &= R_1 i_2(t) + \frac{R_1}{R_3} V_0(t) + R_2 i_2(t) \\ &\quad + \frac{1}{R_2 C} \int_0^t V_2(t)\,\mathrm{d}t \\ &= \frac{R_1 + R_2}{R_2} V_2(t) + \frac{R_1}{R_3} V_0(t) + \frac{1}{R_2 C} \int_0^t V_2(t)\,\mathrm{d}t \end{aligned} \tag{2}$$

Differentiating Eq. (2) and followed by Laplace transform, we get

$$V_0(s) = \frac{\tau_1 s + 1}{\tau_2 s + 1} \left(\frac{V_i(s)}{900} \right) \tag{3}$$

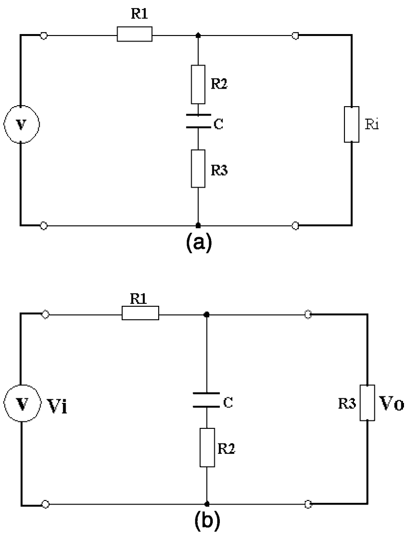


Fig. 2. (a) Equivalent circuit of the real device, simulation results are shown in Fig. 1. R_i is the input resistance of the instrument. R_i is considered very large compared to the overall impedance of the circuit in ideal case. Normally R_i is in the range of 1–5 MΩ in most cases. (b) Equivalent circuit of the real device when R_2 is considered as 0 Ω if careful probing is achieved.

where

$$\tau_1 = R_2 C \quad \tau_2 = \frac{R_1 R_2 + R_1 R_3 + R_2 R_3}{R_1 + R_2} C$$

As shown by Eq. (3), decrease in the amplitude of output is very large. This is mainly due to the very large resistance of the capacitor electrodes and possible large series resistance by casual selection of probe sites on the electrodes. Recorded experimental data show that for the device with the parameters in Eq. (3), when it reaches the cut-off frequency, the output will further decrease as described by theoretical analysis, but it stops decreasing with constant remaining voltage in amplitude. In our experimental data, this remaining voltage is close to our theoretical value. The recorded value is about 4.6 mV while the theoretical value is 5.5 mV.

3. Materials

In order to use an inkjet printer to print out the polymer micro-electric devices, the material must be air-stable and solution processable. Two kinds of conductive polymers, PEDOT doped with PSS (Baytron P® from Bayer Company) and polynaniline (PANI) (from Aldrich company), have been used in the fabrication of devices.

PEDOT, a kind of polythiophene, has caught much attention during the last several years. Its high stability enables it to various applications, such as antistatic and electrostatic coatings, and metallization of insulators [24]. After drying, the remaining PEDOT/PSS film is highly conductive, transparent and mechanically durable with a dark blue color.

PANI is one of the most commonly used conductive polymers due to its relatively superior stability. It is made soluble through the use of soluble counterions that associate with the dopant ions on the polymer backbone. Current commercial applications include battery electrodes, conductive coatings for electrostatic speakers, capacitor electrolytes [22], transparent conductive coatings, etc.

Here, the viscosity should be considered into the printing process because a solution with a viscosity over 5 mPa s would not be easy to print out through the tiny nozzles. The original PEDOT/PSS solution was diluted with water so that it could be printed out from the commercial printer without jamming the printer head. The configuration for the printing setup is set at "photo 720 dpi with finest detail". Fig. 3, taken by Olympus AX70 optical microscope by Nikon codpix995 digital camera, shows two layers of the printed PEDOT/PSS thin film. It is obvious that the printed PEDOT/PSS is very continuous and no pinholes exist in the middle.

For the insulating material, first the polytetrafluoroethylene (PTFE) was selected. PTFE is a good in-

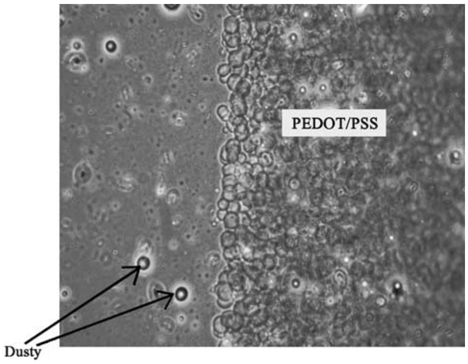


Fig. 3. The printed PEDOT/PSS layer as the electrode of capacitor.

sulating material for spin coating, but it is not suitable for inkjet printing because it is easy to clog the printer nozzles and very difficult to clean. Poly(4-vinylphenol) (PVPh) is another insulating polymer, often dissolved in alcohol or acetone for spin-coating processing. However, alcohol or acetone dissolved PVPh cannot be used for inkjet printing because these solvents are easy to volatile, leaving PVPh particles to block the printer nozzle and difficult to clean. Finally the PVPh (from Aldrich company) dissolved in the 1-methyl-2-pyrrolidinone was used.

4. Experiments

The inkjet printer used in our experiments was the commercially available Epson Stylus color 480 SXU printer with a resolution of 720 by 720 dpi. Fig. 4 shows the structure of the all polymer capacitor and *RC* filter. First, two layers of PEDOT were printed to act as the bottom electrode. Each layer of PEDOT is heated on a hot plate at 50 °C for 2 min to dry it completely. In our other experiment, it is found that certain minutes of annealing immediately after printing helps make the thin film more continuous. Then three layers of PVPh, as the insulating layer, were printed sequentially on top of the previous pattern. More layers of PVPh were printed in order to ensure that no pinholes form in the insulating layers and thus avoid a short circuit between the two electrodes. Finally two layers of PEDOT 2 mm by 2 mm were printed on top of PVPh layer and then heated at the same annealing condition.

Fig. 4c is the pattern design for our *RC* filter. The resistors in the *RC* configuration were printed at the same time the bottom electrode of the capacitor was printed. There was no physically existing connection wire between the two components. The main reason for this design is due to the high sheet resistance of the printed PEDOT layer (larger than 10^6 $\Omega/\Box$), which is believed mainly due to the charge trapping in the conjugated polymers. Conductive glue (epoxy) is used to attach three metal wires as the electric leads on the two electrodes of capacitor as well as the resistor, in order to connect the *RC* circuit to the function generator and oscilloscope. Fig. 5 shows the pictures of the printed polymer *RC* circuits.

5. Results and discussion

In our measurements, the HP54653A digital oscilloscope made by Hewlett-Packard Corporation was used to record our experimental data. The input signals were square waves generated by a function generator. In order to make the amplitudes of the output compatible with those of the input signals, 10× attenuation in the input amplitudes were employed.

In Fig. 6b, the waveform of the output signal is very similar to that of the input signal at high frequency. In other words, *RC* is much larger than the period of the input signal in Fig. 6a, when *RC* is equal or comparable to the period of the input signal, then the output waveform shows obvious differential characteristics. In

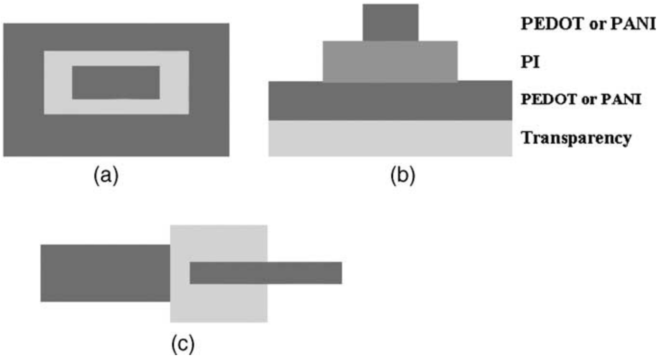


Fig. 4. (a) Structure of the all polymer capacitor, (b) cross-section of the all polymer capacitor, (c) Structure of the all polymer *RC* filter.

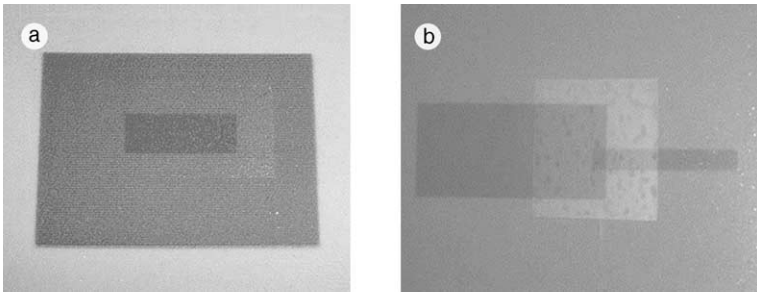
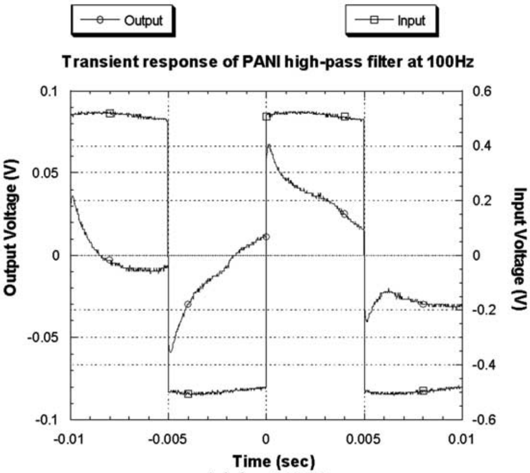
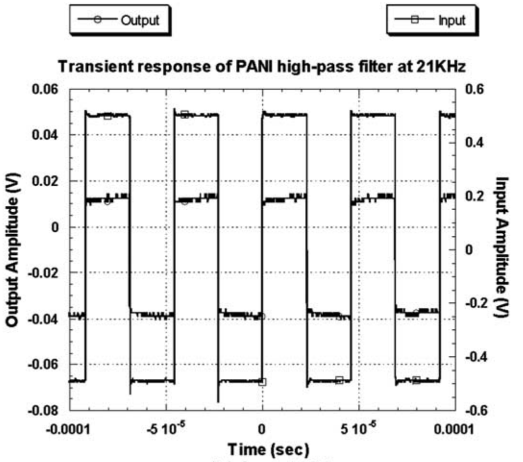


Fig. 5. (a) Picture of polyaniline *RC* filter. (b) Picture of PEDOT/PSS *RC* filter.

addition, it is found in Fig. 7a that the waveform of the output signal is identical to the input when *RC* is much less than the period of the input signal. And when the period of the input signal is further decreased, or the frequency is further increased, not only is the amplitude of the output decreased, but also the waveform is

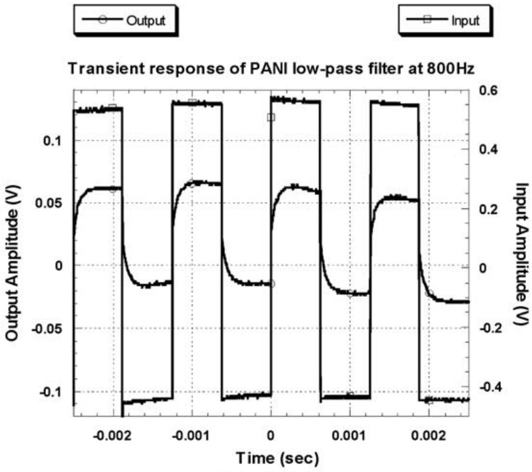


(a) f = 100 Hz

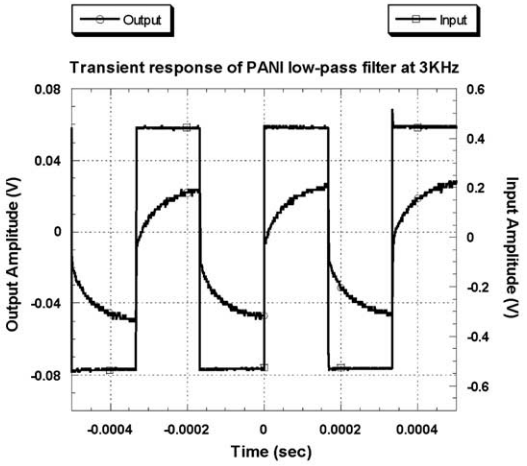


(b) f = 21 KHz

Fig. 6. Recorded output waveforms of PANI *RC* high-pass filter at different input frequencies.



(a) f = 800 Hz



(b) f = 1.5 KHz

Fig. 7. Recorded waveforms of PANI low-pass filter at different frequencies.

changed in which the output shows integration characteristic when *RC* is equal or comparable to the period of the input.

6. Conclusions

The fabrication of all polymer capacitor and *RC* circuits has been demonstrated successfully with the all inkjet printing method. This is due to the solution processability and high performance of the conductive polymers, such as PANI and PEDOT/PSS. Theoretical analysis and experiment results show that the *RC* filter circuits function well. This means that inkjet printing can offer us potential lower cost over lithographic fabrication of micro-electronic devices, and may lead to new applications in the future.

Acknowledgements

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