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Rapid Laser Annealing Method for Printing Silver Electrodes in Organic Thin-Film Transistors

Chuan Liu[1], Kairong Huang[1], Fuhua Dai[1], Xuying Liu[2] and Takeo Minari[2]

[1] State Key Lab of Opto-Electronic Materials & Technologies, Guangdong Province Key Lab of Display Material and Technology, School of Electronics and Information Technology,
Sun Yat-Sen University
Guangzhou 510275, China
Phone: +86-181-0270-6826 E-mail: liuchuan5@mail.sysu.edu.cn
[2] Center for Functional Sensor & Actuator (CFSN) and World Premier International Center for Materials Nanoarchitectonics (WPI-MANA)
National Institute for Materials Science (NIMS)
Tsukuba, Ibaraki 305-044, Japan

Abstract

The rapid sintering of printable metal nanoparticle inks is vital for the industrial mass production of electronic devices. In this study, we report a rapid laser annealing method for printed Ag nanoparticle-based inks. Compared to conventional thermal annealing, laser annealing significantly reduces the processing time from 3600 to 10 seconds while preventing damage caused by excessive heat. The organic thin-film transistor with laser-annealed Ag source/drain electrodes achieved good performance with a saturated mobility of 1.68 cm^{2}V^{-1}s^{-1}, high reliability factor of 86.75%, and large saturated drain current resulting from the small channel resistance. This rapid laser annealing method is feasible for printing flexible electronics using metal nanoparticle-based inks in industrial mass production.

1. Introduction

Printed electronics have received considerable attention in recent years due to their low cost compared to electronics prepared using the conventional vacuum fabrication process. In addition, solution-based printing and inkjet printing can effectively reduce material waste, making printing a more environmentally friendly approach. Furthermore, printing methods are compatible with the high-throughput roll-to-roll process, making it possible to achieve large-area flexible devices. For printing electronics, metal nanoparticle ink is widely used in printing electrodes and interconnected wires. To improve the patterns obtained by printing, ink is modified with organic functional groups, thus annealing process is needed.[1] The annealing process commonly involves long-term heating, which results in two critical drawbacks: long-term heating is not suitable for flexible plastic substrates; and the annealing time is too long for application in industrial roll-to-roll processes.

In this study, we report a rapid laser annealing method for Ag nanoparticle ink with a much shorter processing time and comparable performance with respect to thermal annealing. The organic thin-film transistors (OTFT) formed with laser-annealed Ag source/drain electrodes showed good performance with a saturated mobility of 1.68 cm^{2}V^{-1}s^{-1}, demonstrating good potential for use in printed flexible electronics.

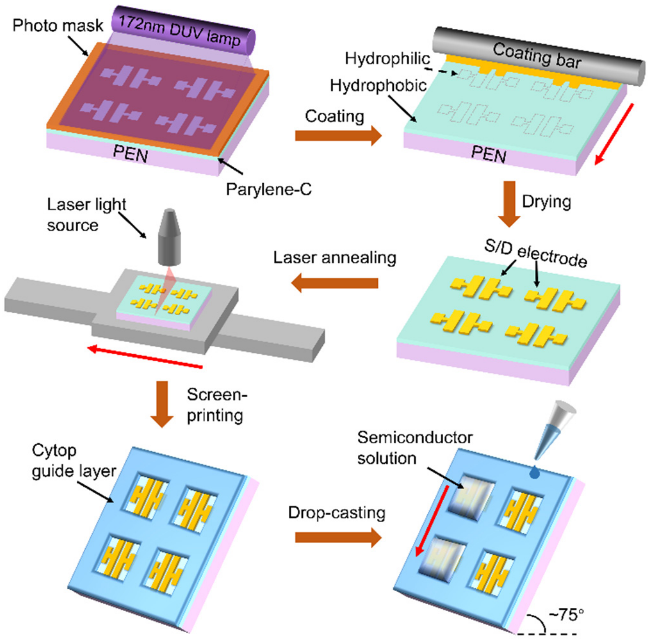

Fig. 1 Schematic illustration showing the direct coating of an Ag electrodes on a PEN substrate with laser annealing and depositing of a semiconductor for a flexible OTFT array.

2. Results and discussion

The fabrication processes of OTFT with laser-annealing Ag source/drain electrodes are shown in **Fig. 1**. The PEN substrate was deposited with Parylene-C as modification layer, and the samples were selectively exposed 30s through a photomask in deep UV system. With the effect of hydrophilic and hydrophobic, Ag nanoparticle ink was directly coating and assembled in the hydrophilic pattern and became Ag electrodes with channel lengths and widths of 100 and 650 µm, respectively.[2] Then, the electrodes samples were sintering with heating or laser projection.

For laser annealing, the sample was placed on a horizontal moving platform, which can control the process time, and annealed using a laser diode irradiation light source (wavelength = 939.8 nm; L13920-511, Hamamatsu Inc.). In this experiment, the laser annealed sample was irradiated by laser light at an output current of 40 A for 10 s. For comparison, thermal annealed sample was baked at 140°C for 1 h under ambient conditions. Organic semiconductor area was patterned by CYTOP with screen coating, followed by drop-casting C8-BTBT solution into the pattern. After the semiconductor solution dried and crystallized, the Cytop guide layer was removed by washing the sample with Cytop solvent 180. Finally, Parylene-C dielectric layer was deposited and top gate electrodes were produced by direct coating under DUV.

The electrical properties of C8-BTBT OTFTs fabricated with laser-annealed Ag source/drain electrodes are shown in **Fig. 2**. The OTFTs showed good device performance without hysteresis. The apparent mobility was extracted from the transfer curve using the equation $\mu_{\mathrm{app}} = \frac{2L}{WC_{\mathrm{i}}}\left(\frac{\partial\sqrt{I_{\mathrm{D}}}}{\partial V_{\mathrm{G}}}\right)$ in saturated regime, where I_D is the drain current, W and L are the width and length of the TFT, respectively, and Ci is the capacitance of the gate dielectric per unit area.

Notably, μ_{app} of the laser-annealed device increased more rapidly with V_G and reached a peak value when $V_G < -10$ V. This indicates some injection barrier at the interface between the electrodes and semiconductor. For better comparison, the reported μ_{sat} is extracted from the slope of certain segment $I_D^{0.5}$–V_G curve. As suggested by Choi,[3] the reliability factor r should be presented to avoid erroneous mobilities. In the saturation regime, r can be calculated by following equation:

$$r_{\mathrm{sat}} = \left(\frac{\sqrt{|I_{\mathrm{D}}|^{\max}} - \sqrt{|I_{\mathrm{D}}{}^{0}|}}{|V_{\mathrm{G}}|^{\max}}\right)^{2} / \left(\frac{WC_{\mathrm{i}}}{2L}\mu_{\mathrm{sat}}\right)_{\mathrm{reported}},$$

where $|I_D|^{max}$ is the experimental maximum drain current reached at the maximum gate voltage $|V_G|^{max}$, and I_D^0 is the drain current at $V_G = 0$. To prevent artificial error, we accounted for it instead of assuming it to be zero. The OTFTs formed with the laser annealed electrodes under the optimum parameters (40 A for 10 s) exhibited a μ_{sat} of 1.68 $cm^2V^{-1}s^{-1}$ and a high r of 86.75%, which satisfies the standard for high-quality OTFTs (r > 75%). In this case, the OTFT exhibited a close-to-ideal linear transfer characteristic and negligible V_{TH} (−2.31 V). In comparison, the OTFT with thermally annealed electrodes showed a slightly superlinear feature in the square-root of transfer curve and larger V_{TH} (−6.96 V). Although the calculated mobility of this OTFT was higher (1.77 cm2$V^{-1}s^{-1}$), its reliability factor was lower (67.23%). Based on the measured r, the equivalent electrical performance was represented by the effective carrier mobility $\mu_{eff} = r \times \mu_{sat}$. The laser-annealed device exhibited a higher μ_{eff} (1.46 $cm^2V^{-1}s^{-1}$) than the thermally annealed device (1.19 $cm^2V^{-1}s^{-1}$). The parameters determined for both devices are summarized in **Table I**. Overall, the performance of the laser-annealed devices is comparable with or better than that of the thermally annealed device.

Table I Extracted parameters of the OTFTs

Method	Time	μ_{sat} ($cm^2V^{-1}s^{-1}$)	r(%)	μ_{eff} ($cm^2V^{-1}s^{-1}$)	V_{TH}(V)
Thermal	1h	1.77	67.23	1.19	-6.96
laser	10s	1.68	86.75	1.46	-2.31

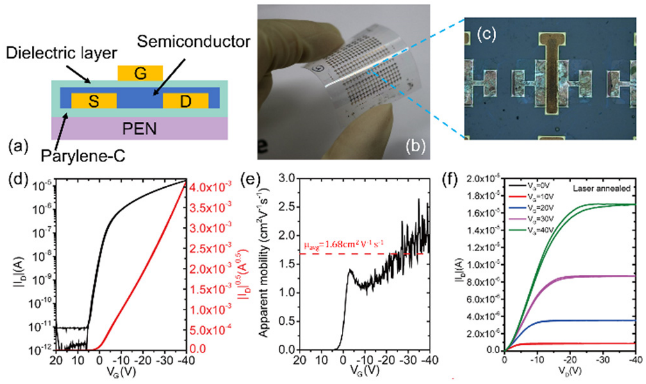

Fig. 2 (a) Structure of a single bottom-contact/top-gate OTFT. (b) Image of an OTFT array on a flexible PEN substrate. (c) Microscopic image of a single OTFT. (d-f) The electrical properties of C8-BTBT OTFT with laser-annealed Ag source/drain electrodes.

We have scanned the surface morphology of Ag films on PEN substrate scanned with 3D microscope. After laser annealing with 40A laser output current for 10 s, the roughness dramatically decreased with σ = 31.47 nm, which is comparable to or even better than thermal annealing (σ = 32.71 nm). Therefore, the laser-annealed device has some advantages over the thermally annealed device. Firstly, the higher quality crystals of semiconductor, due to the slightly better surface morphology of laser annealed electrodes, can reduce channel resistance in OTFT, thereby higher reliability factor and effective mobility. Secondly, because of the smaller channel resistance, the laser-annealed device has a larger saturated drain current than the thermally annealed device. Finally, laser annealing has a much shorter processing time than thermal annealing but results in comparable performance. Thus, laser annealing shows great potential for industrial mass production, including in roll-to-roll processing.

3. Conclusion

We have reported a rapid laser annealing method for printed Ag nanoparticle inks modified with organic functional groups. OTFT devices with laser annealed Ag source/drain electrodes exhibited good performance with the saturated mobility value of 1.68 $cm^2V^{-1}s^{-1}$ and high reliability factor r = 86.75%. Laser annealed samples achieved comparable performance to thermal sintered samples and significantly reduces the processing time from an hour to 10 seconds. Therefore, rapid laser annealing provides a feasible method to solve the application of the anneal-needed metal nanoparticle ink in industrial mass production for printed flexible electronics.

References

[1] S. Wünscher, R. Abbel, J. Perelaer and U.S. Schubert, J. Mater. Chem. C. **2** (2014)10232.
[2] X. Liu, M. Kanehara, C. Liu, K. Sakamoto, T. Yasuda, J. Takeya and T. Minari, Adv. Mater. **28** (2016) 6568.
[3] H.H. Choi, K. Cho, C.D. Frisbie, H. Sirringhaus and V. Podzorov, Nat. Mater. **17** (2017) 2.