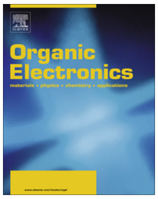
Organic Electronics 26 (2015) 355–358

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel



# Patchable thin-film strain gauges based on pentacene transistors

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ARTICLE INFO

*Article history:*
Received 2 July 2015
Received in revised form 27 July 2015
Accepted 6 August 2015

*Keywords:*
Patchable electronics
Strain gauges
Organic thin-film transistors
Pentacene
Polyurethaneacrylate

ABSTRACT

We present a patchable thin-film strain gauge for which output current responds sensitively to external strain. For this work, integrated organic thin-film transistors using pentacene as an active component were fabricated on a freestanding polyurethaneacrylate film with high flexibility and adhesive properties providing patchability. The device can be easily mounted onto non-flat surfaces, and the output characteristics show a strong correlation with the structural strain of freestanding polymeric film, which allows the external strain applied to the device to be gauged. In addition, a surface shape can be detected after mounting the device onto a non-flat surface, and the thickness of a complex structure can be inversely calculated using a calibration curve. It is anticipated that these results will be applied to the development of various patchable sensors and thickness measurement systems, which can lead to further applications.

## 1. Introduction

Organic electronics have been a topic of interest in the past few decades, and extensive research has been carried out for their practical applications in such products as organic light-emitting diodes (OLEDs), organic thin-film transistors (OTFTs), and organic photovoltaics (OPVs) [1–6]. Most organic electronic devices have been developed and improved for their uses as component elements in the fields of semiconductors and displays thus far [7,8]. Unconventional functionalities that can be successfully introduced to organic electronic devices, such as flexibility and patchability, are also receiving much attention and extending applications of these devices in recent years [9–13]. In this context, considerable research has been performed to understand and characterize the behaviors of organic electronic devices according to substrate deformation, which can induce structural stress and strain. Since uniform performance is normally preferred for stable operation, major efforts have been devoted to the development of flexible and patchable electronics that are not affected by the substrate deformation. On the other hand, devices for which performance is sensitive to changes in structural stress and strain of the substrate can be applied as sensors and gauges for detecting stress and strain [14–17]. Particularly small carbon-based materials, such as pentacene, rubrene, fullerene, and carbon nano-tube, not only have flexibilities in comparison with inorganic materials, but also show sensitive responses to structural stress and strain compared to polymers [14,18–20]. These materials are mostly applicable to sensors and gauges for detecting stress and strain.

Here we demonstrate a patchable thin-film strain gauge for which output current sensitively changes in response to external strain, based on the flexible OTFT structure. For this work, we have fabricated the integrated OTFTs using pentacene as an active component on a freestanding polyurethaneacrylate (PUA) film with high flexibility and adhesive properties providing patchability [21–23]. Performance of the device was investigated according to the curvature of the freestanding film, which clarified that the output current of the device varies with the direction of bending and the radius of the freestanding film. The output current of the device basically shows a one-to-one correspondence with the curvature of the freestanding film, and thus a surface shape can be detected after mounting the device onto non-flat surface (i.e., concave or convex). In addition, we show that even the thickness of a complex structure, such as a cup-shaped or bottle-shaped structure, can be estimated by mounting the device to the inside and outside of the structure. The results strongly suggest great potential not only for the development of various patchable sensors for stress, strain, and surface shape, but also for new class of thickness measurement systems, which can lead to their further applications in many fields of science and engineering.

## 2. Experiment

Patchable thin-film strain gauges based on the flexible OTFT structure were fabricated on freestanding PUA film (see Fig. 1).

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http://dx.doi.org/10.1016/j.orgel.2015.08.005
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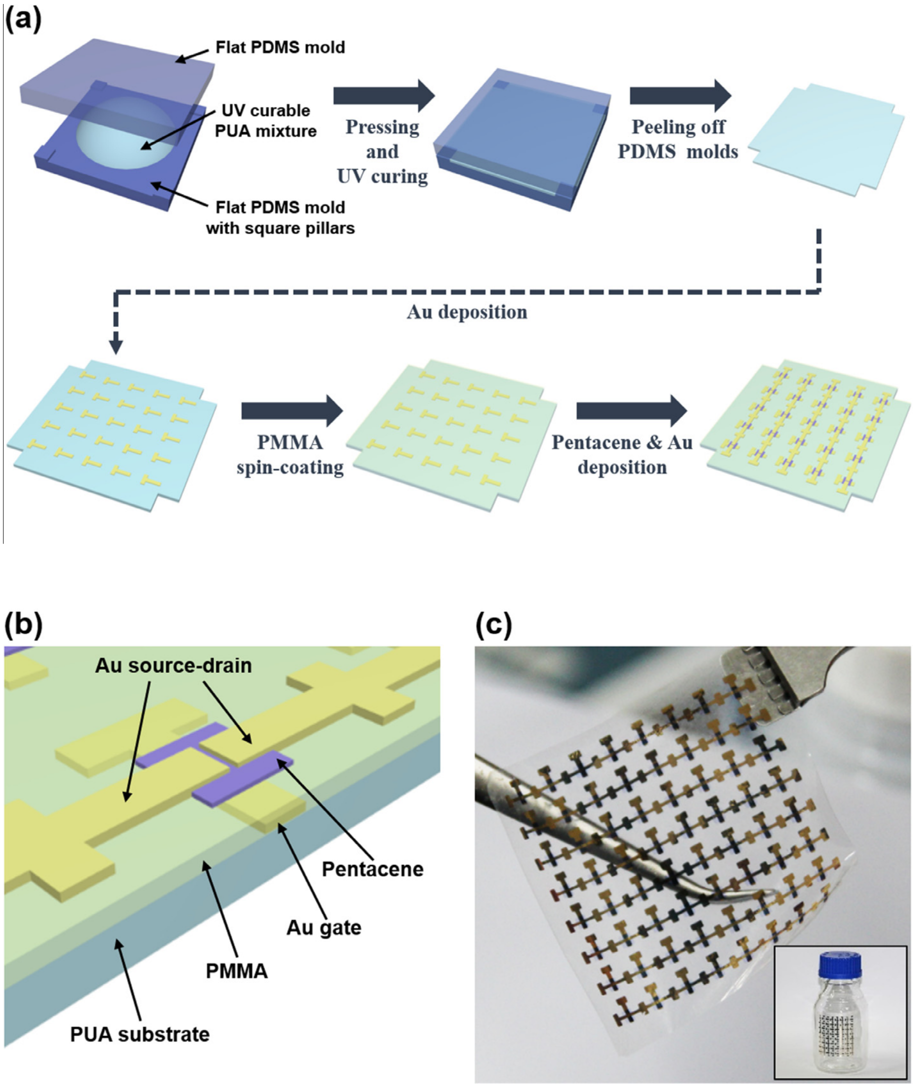

**Fig. 1.** (a) Schematic illustration of the preparation of freestanding PUA film and patchable thin-film strain gauges based on the flexible OTFT structure. The remaining unsaturated acrylate in the PUA material provides adhesive properties even after thermal annealing processes at ~80 °C. (b) Flexible OTFT structure with a bottom-gate configuration prepared as in (a). (c) Photograph of integrated patchable thin-film strain gauges prepared on the freestanding PUA film. [Inset: photograph of (c) mounted on the cylindrical bottle structure that induces external strain on the devices.]

For preparation of the freestanding PUA film, an ultra-violet (UV) curable PUA mixture, synthesized in accordance with previous reports, was drop-dispensed onto a flat polydimethylsiloxane (PDMS) substrate and subsequently covered with another flat PDMS mold. Square PDMS pillars with a height of 50 µm were used for a fixed gap distance between the two PDMS molds as shown in Fig. 1a, and excess PUA mixture was squeezed out by applying pressure from one end of the sample toward the other end using a roller. Due to the properties of conformal contact of PDMS, the pillars and the mold were easily brought into contact after this sequential rolling, and a uniform thickness (50 µm) of the PUA mixture between the two PDMS molds was easily achieved. Subsequently, the PUA mixture was exposed to UV light ($\lambda$ ~365 nm) for several minutes through the UV transparent PDMS molds. After UV curing, the two PDMS molds were easily peeled off from the cured PUA film, and free-standing PUA film with a uniform thickness of 50 µm was prepared.

OTFTs fabricated on freestanding PUA film have a bottom-gate configuration as illustrated in Fig. 1b [i.e., gold (Au)/poly(methylmethacrylate) (PMMA)/pentacene/Au]. The Au electrodes (70 nm) and the pentacene layer (70 nm) were individually deposited by thermal evaporation in a vacuum chamber. For the PMMA insulating layer, 10 wt% of PMMA in toluene was spin-coated, and then thermally annealed at ~80 °C on a hot plate for 2 h. The channel length between the Au source and drain electrodes was 120 µm. To deposit each element with proper alignment and shape, the freestanding PUA substrate was attached and fixed on the glass substrate, and the substrates maintained a planar geometry during the whole fabrication process. Note that the remaining unsaturated acrylate in the PUA material after UV curing provides adhesive properties in addition to high flexibility, and thus the freestanding PUA film can be mounted even onto non-flat surfaces of various materials with conformal contact. Such adhesive properties of the PUA film are not significantly weakened after thermal annealing processes at ~80 °C, as opposed to those at high temperatures above 150 °C. To analyze the fabricated device, electrical performance was measured with a semiconductor parameter analyzer (4200-SCS, Keithley).

## 3. Discussion

We investigated the field-effect transistor (FET) characteristics of the device according to the structural strain induced from elastic deformation of the freestanding PUA film, and results are shown in