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Printed pressure sensor matrix with organic field-effect transistors

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ABSTRACT

The paper presents the construction and fabrication method of a pressure sensor matrix with organic field-effect transistors. The sensor structure consists of a matrix of air-gap transistors which is realized by roll-to-roll processing and laminating methods. High aspect ratio spacer structures are made by inkjet printing.The sensor cell transistor senses the applied force on the top substrate due to changes in the air-gap dimension. The sensor matrix has measurement range of 0.4 kPa^{-1}–4.4 kPa^{-1}, sensitivity 0.4 ± 0.1 kPa^{-1} and time response better than 300 ms. The structure is scalable and it has a sensitivity comparable to state of the art pressure sensor matrices that use organic field-effect transistors. Its fabrication process, however, includes standard, low cost mass production steps of printed electronics and it can be transferred to a roll-to-roll process.

1. Introduction

Pressure sensor matrices offer a unique solution to the measurement of real-time pressure and touch profiles on different surfaces, and can be used in many applications. For example robotic devices capable of adjusting the amount of force needed to hold and use different objects have been demonstrated where the pressure sensor matrix enables robotic systems with human-like sensing capabilities [1,2]. New concepts of user interfaces based on pressure sensitivity have been proposed [3]. Usage of a pressure sensor matrix allows digitizing information in medicine [4,5]. There are multiple applications of pressure sensor matrixes in sports [6–8].

Different concepts of pressure sensor matrices have been demonstrated previously based on resistive [9–11], capacitive [12,13], piezoelectric [14,15], piezoresistive [16] and optical operating principles [17]. However many of them have low sensitivity, they are expensive and/or they are not suitable for integration into flexible substrates.

A pressure sensor matrix based on pressure-sensitive rubber and organic transistors embedded on a plastic film is proposed in [16]. The matrix, consisting of an organic transistor, is used to read out pressure data from sensors based on pressure-sensitive rubber. Although the mobility of organic semiconductors is known to be about two or three orders of magnitude less than that of poly- and single-crystalline silicon, the slower speed is tolerable for many applications. A pressure sensor matrix based on organic transistors and using a capacitive sensing principle is proposed in [18,19]. The matrix consists of transistors with a flexible polydimethylsiloxane (PDMS) polymer film on top and an array of tiny square pyramids is moulded into the film. The flexible film acts as the dielectric material at the gate electrodes of a transistor made from a single crystal rubrene semiconductor [18] or spin coated polymer semiconductor [19]. The capacitance of the pyramidal film changes as the pyramids are squeezed, changing the transistor's current. The pressure sensor matrix has high sensitivity. It is suitable for integration on flexible substrates. However, only laboratory prototypes of such sensor matrix, predominantly made by subtractive photolithographic processes, have been demonstrated so far [2,19–22]. The next important step is to find a way to fabricate the pressure sensor matrix at a low cost.

We believe that a fabrication method utilizing printed electronics processes is the optimal technology to bring pressure sensor matrix fabrication into production scale. Different printing technologies are utilized for realization of various mechanical and electrical structures. Gravure printing was used to make spacer structures in [23]. Inkjet printing was used for cell gap spacers in liquid crystal displays by [24], optical microlenses by [25] and high pillars by [26]. Lamination of separately processed foils has been used for TFT fabrication in [19,27].

Printed electronics manufacturing methods offer a low cost alternative to current electronics manufacturing processes. Additionally, printed electronics processing can yield very large volumes in a short time, still offering the customization possibility for dedicated applications. Methods of printed electronics have been utilized previously for the fabrication of pressure sensor matrices. A pressure sensor matrix based on organic transistors was

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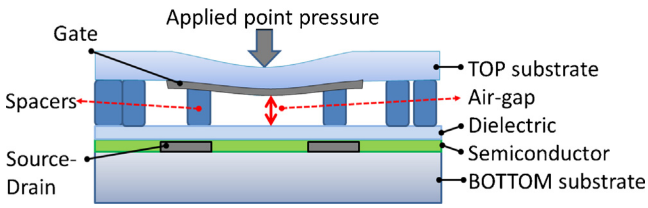

Fig. 1. Schematic illustration of the device structure and operation principle. The applied pressure changes the gate distance from the channel. The displacement can be seen in the source-drain current of the air-gap transistor.

fabricated by inkjet printing in [28]. Applying pressure to the organic active layer of the transistors induces a reversible change in their conductivity. However the sensors have low sensitivity. A screen printed pressure sensor array with *poly* (*vinylidene fluoride–trifluoroethylene*) P(VDF–TrFE) sandwiched between patterned metal layers was demonstrated in [29], but P(VDF–TrFE) is too expensive to be used in low cost applications. Screen-printed resistive pressure sensors containing graphene nanoplatelets and carbon nanotubes were presented in [30]**.** The sensor has good sensitivity but complex readout electronics should be used. In this paper we demonstrate for the first time a fully printed pressure sensor matrix with organic field-effect transistors. All fabrication steps utilized can be realized in a roll-to-roll process. With the proposed method, low cost and large arbitrary shaped sensors with good sensitivity can be fabricated on flexible surfaces. These kinds of sensors could have potential in short term disposable applications such as medical applications.

2. Structure and operation of a sensor cell

The structure of a pressure sensor cell is shown in Fig. 1 Details of the deposited layers and manufacturing processes are presented in Section 3. The sensor cell consists of two plastic foils with patterned structures on both sides, forming a transistor structure. An air-gap is formed between the foils due to a printed spacer structure. The proposed cell can be considered as an air—gap field effect transistor (FET). The theory of air gap FET's is presented elsewhere [31].

Drain current via the cell is

$$I_D = \frac{C_{press}\mu W}{L}\{(V_{GS} - V_T) - \frac{1}{2}V_{DS}\}V_{DS} \quad (1)$$

where μ is the electron mobility in the channel of the FET, W and L are width and length of the channel, V_{GS} is gate voltage, V_{DS} is source - drain voltage, V_T is threshold voltage

The value of C_{press} is the dielectric layer capacitor C_{ox} and air layer capacitor C_{air}in series and it can be expressed by

$$C_{press} = A\epsilon_0 \frac{\epsilon_{rox}}{d_{air}\epsilon_{rox} + d_{ox}} \quad (2)$$

where $\epsilon_0$is the absolute dielectric constant and ϵ_{rox} is the relative dielectric constant of the dielectric layer. The relative dielectric constant of air is considered to be 1. d_{ox} and d_{air}represent the thickness of the insulator and the air-gap, respectively, and A is the surface area of the gate.Pressure P applied to the top foil causes the foil bending. Assuming a zero initial mechanical stress of the foil the mechanical deflection of the foil membrane of circular shape at center is

$$d_{air} = \frac{3(1-\upsilon^2)P \times r^4}{16Eh^3} \quad (3)$$

where P is applied pressure, E is the Young's modulus of the foil, υ is the Poisson's modulus of the foil, and r and h are the radius and thickness of the foil membrane, respectively.

The distance d_{air} between the gate electrode and transistor channel is changed. Thus C_{press} is a function of the applied pressure in accordance with (2) consequently. Then the drain current is pressure dependent at constant gate potential in accordance with (1).

3. Manufacturing process

The manufacturing process of the cell is shown in Fig. 2. As the **bottom** foil, a roll-to-roll fabricated transistor foil was used (transistors without the top gate). In this foil, the electrodes

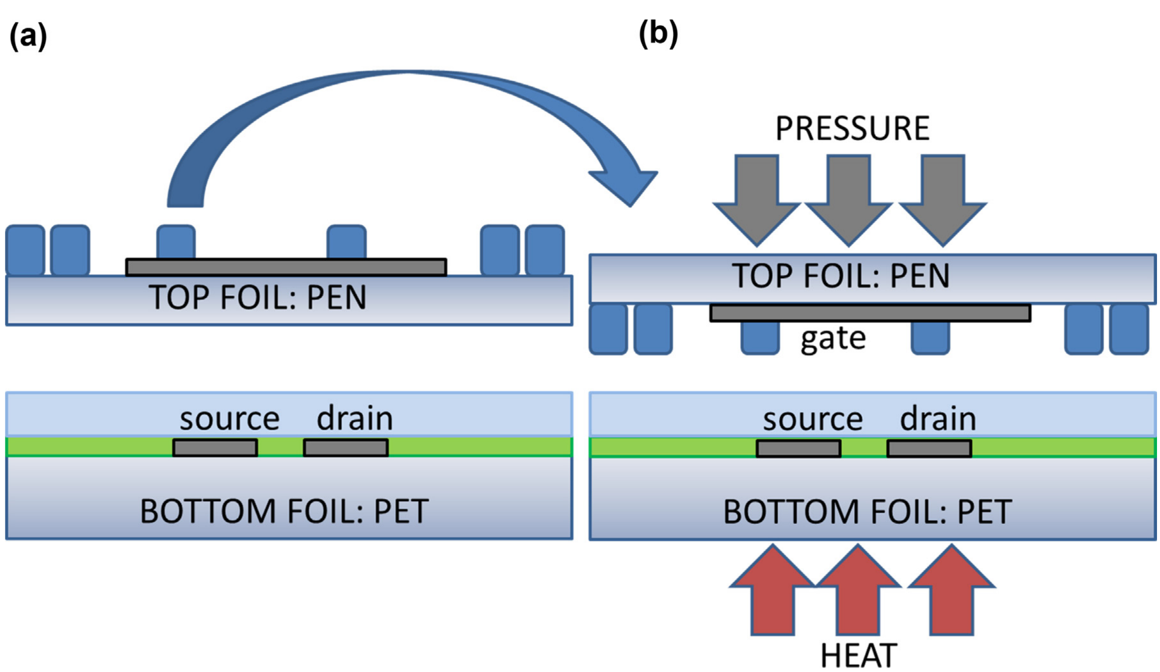

Fig. 2. Fabrication process of the sensor cell. (a) Top foil has inkjet printed electrodes and spacers. Bottom foil has roll-to-roll processed silver source and drain electrodes, and gravure printed semiconductor and dielectric layers. In (b) the lamination process is shown. Top and bottom foils are aligned and then laminated under heat and pressure.