A 100-DPI Active-Matrix Tactile Sensor Based on Carbon Nanotube TFT for Haptic Applications

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Abstract

Pressure sensing, as a crucial component of haptic or tactile sensing, plays a vital role in the areas of interactive display, robots, medical treatment, wearable electronics, etc. Active-matrix (AM) pressure sensors draw much attention due to their low crosstalk and high resolution. Here, we proposed a novel thin-film transistor (TFT)-based AM tactile pressure sensor by substituting the TFT active channel with a piezoresistive semiconductor film based on carbon nanotubes, giving a highly integrated array with 100 DPI as well as a simplified fabrication process. The device can detect pressure ranging from 0.2 kPa to 90 kPa, with a sensitivity of 2.414 kPa^{-1} and a perfect sensing linearity. Owning to the AM design, the resistance readout can be switched ON/OFF by a scan signal. Moreover, the sensor also presents a respectable durability. Due to the highly compact design, there is potential for expanding its application into haptic display, artificial intelligence, etc.

Author Keywords

Pressure sensor; tactile sensor; active matrix; TFT; semiconducting carbon nanotube; piezoresistor; haptics.

1. Introduction

Human interaction, such as haptic interaction, has become one of the most significant technologies and has been developed in many vital areas such as industrial robots, medical monitoring, and wearable systems which significantly changed human life. Pressure sensors, as an essential part of human interaction, are widely used in these areas [1,2]. Conventional pressure sensors are designed as a passive matrix (PM) by piezoresistive film, which is cheap and simple but with high crosstalk [3,4]. Lately, active-matrix (AM) pressure sensors have been studied due to their better performance of low crosstalk and higher resolution [5,6]. The presented active-matrix pressure sensors usually consist of two separate components, i.e, a switching TFT and a piezoresistive film, as shown in **Figure 1a**.

Carbon nanotubes (CNTs) are promising materials for thin film electronics due to their characteristics of high flexibility, high durability, low-temperature fabrication, transparency and so on. Based on their chirality, they can be divided into two categories: metallic and semiconducting. Metallic CNT, like metal wire, is widely used in the form of network as a conductor or piezoresistor film. Nevertheless, semiconducting CNT, whether in random network or aligned form, is typically used as the TFT channel (active layer) due to its tunable bandgap, high mobility and excellent electrostatics [7].

In this study, we proposed an ingenious tactile pressure sensor design by substituting the TFT active layer with a piezoresistive semiconductor film composed of semiconducting CNT networks (**Figure 1b**). In this case, the device can be switched on/off by both gate voltage and pressure, which becomes a dual-functional or "2-in-1" TFT. The device is highly compact, leading to a denser array with 100 dots per inch (DPI). The device structure and the fabrication process have both been dramatically simplified. The transfer characteristic shows great effectiveness in active pressure sensing, and the sensor performs a perfect sensing linearity when the pressure is beyond 10 kPa. Moreover, the sensor exhibits respectable durability and recovery.

Figure 1c shows the working principle of the CNT-TFT sensor. The bottom of the sensor is a TFT structure without the active layer. The above dual-functional flexible film is processed to be a piezoresistive film as well as a TFT active layer. In the initial state, there is little contact between the TFT and the film, causing an enormous resistance value. When the top surface is pressed, the microstructure of the film generates contacts on source (S) and drain (D) electrodes. Concurrently, a semiconducting channel is formed at the dielectric interface, resulting in a variable resistance between S and D that can be modulated by the gate voltage. Figure 1b illustrates the equivalent circuit of the sensor. Considering a scan voltage is applied on the gate electrode, the current can flow from the drain node through the semiconducting CNT layer and then be collected at the source node. When the film is pressed, the resistance decreases, leading to a varied current on the S node, and the pressure can be sensed according to the current value. On the contrary, if the gate applied no voltage, the potential barrier

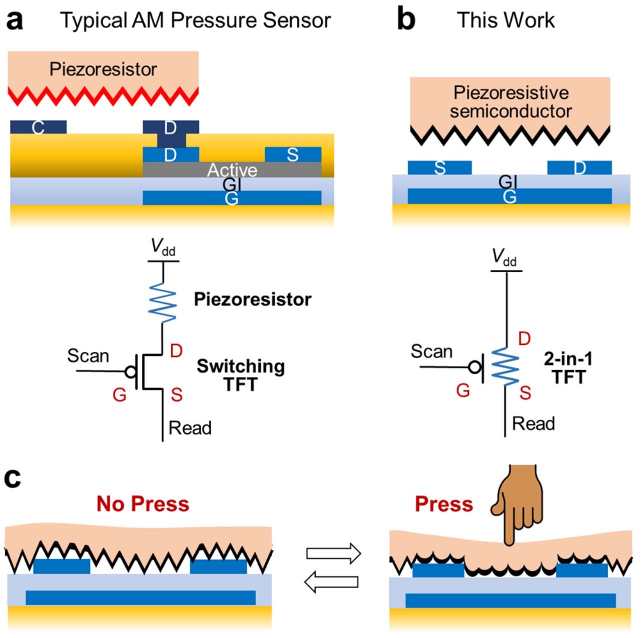

Figure 1. Schematic design and equivalent circuit of **(a)** a typical active-matrix pressure sensor cell; **(b)** the proposed "2-in-1" TFT active-matrix pressure sensor cell; **(c)** Working principle of the proposed pressure sensor.

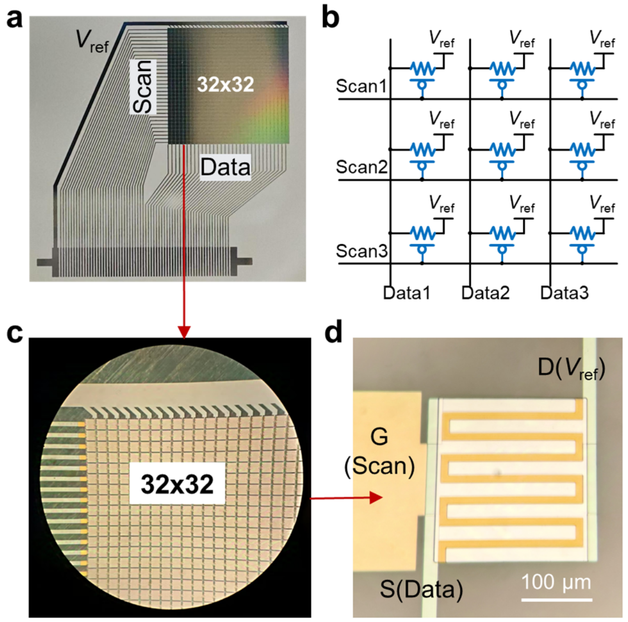

Figure 2. The fabricated 32×32 TFT sensor array: **(a)** photo of the array on a 4-inch glass wafer; **(b)** circuit schematic; **(c)** zoomed-in optical microscope (OM) photo. The pixel pitch is 250 μm. **(d)** OM photo of a TFT before piezoresistive semiconductor film lamination.

between the top electrodes and the semiconductor film would block the current flow.

2. Design and Fabrication

The fabrication process of the TFT is similar to that of a typical CNT-TFT, except that the active layer is done by lamination of a piezoresistive semiconductor film based on CNTs. We first deposited and patterned a layer of Ti/Au as bottom gate electrodes on a 4-inch glass by e-beam evaporation and photolithography. Then, a layer of HfO_2 was deposited as the gate dielectric layer by atomic layer deposition (ALD) approach. Further, the top source and drain electrodes are deposited and patterned by the same method as the gate layer. At this stage, the TFT is ready for piezoresistive semiconductor film lamination. A TFT array of 32×32 resolution is demonstrated in **Figure 2a-c,** and the enlarged photo in **Figure 2d** shows the image of a single TFT. Each TFT size is designed to be within 250 μm × 250 μm pixel pitch, corresponding to a resolution of 100 DPI, and the S/D electrodes are designed to be interdigital electrodes in order to obtain a wider channel width. Notably, the matrix can realize a 0.25 mm resolution (100 DPI), corresponding to 4 times the resolution of the human finger (about 1 mm).

Subsequently, we fabricated the dual-functional piezoresistive semiconductor film, and its procedure is demonstrated in **Figure 3a**. We first cleaned the flask with ultrasonic, isopropanol, and acetone in sequence. Then, we mixed the PDMS prepolymer and curing agent at a 10:1 mass ratio in the flask. The mixed solution was stirred at 500 rad/min for 15 min under an ice bath condition. Following this, the solution was left for 30 minutes to remove the air bubbles. After spraying a layer of release agent, we spun the solution on the microstructure mold and cured it for 2 hours at 80°C. Further, the flexible substrate was detached from the mold. Then, a layer of semiconducting CNT solution was drop-coated on the film and spinning the film. An optical image of the as-fabricated film is shown in **Figure 3b**. The PDMS film exhibits uniform pyramidal peak arrays, with each pyramid having a width and height of approximately 11 μm and 8 μm, respectively. At last, a piece with microstructures was excised from the film and placed on the fabricated TFT array, completing the TFT fabrication.

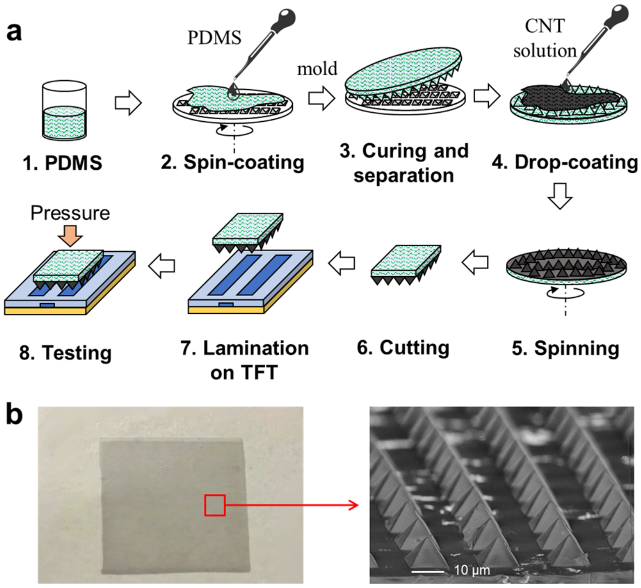

Figure 3. (a) Fabrication procedure of the dual-functional piezoelectric semiconductor film. **(b)** Optical and SEM images of the film. A layer of semiconducting CNT network is coated on the pyramids.

3. Results

Figure 4a,b demonstrates the transfer characteristic of the TFT sensor on linear and logarithmic scales, respectively. When the top surface is not pressed, the drain-source current I_{ds} is negligible due to the enormous resistance value between the S/D contacts.

When the top surface is pressed, the microstructure of the film generates a current path between the S and D electrodes, and the TFT behaves as a P-type TFT similar to typical CNT-TFTs. The I_{ds} is almost zero at the V_{gs} of ≥ -2 V, then increases exponentially as the V_{gs} further goes negative.

Additionally, the current variation rate versus pressure (sensitivity) is demonstrated in **Figure 4c**. The sensitivity of the CNT-TFT sensor is defined as:

$$S = \frac{\Delta(\Delta I / I_0)}{\Delta P} \tag{1}$$

In the equation, ΔI is the normalized current of the proposed sensor, I_0 represents the initial current of the sensor under zero pressure, and ΔP is the variation in pressure applied to the sensor.

Under the V_{gs} of -5 V and the V_{ds} of 0.1 V, there is a dramatic increase in the current variation rate within the range of 0 to 3 kPa due to the sharp area change of microstructure, resulting in a sensitivity of 2.414 kPa^{-1}. As the pressure continues to increase, the current variation rate exhibits a linear increase, with a coefficient of determination (R^2) of 0.989, and the sensitivity is 0.251 kPa^{-1}. Moreover, we demonstrated the sensor's distinct response at 0.2 kPa close to a human fingertip's sensing threshold (about 110 Pa), indicating great tactile sensing potential. The

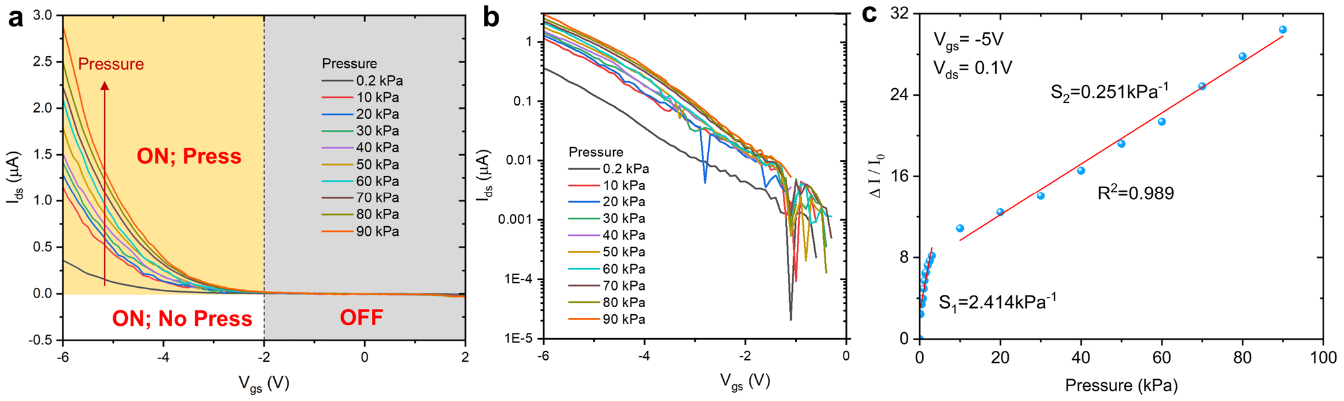

Figure 4. (a,b) The transfer characteristic of the TFT sensor under different pressures on (a) linear and (b) logarithmic scales. **(c)** The sensitivity of the TFT sensor. Significant linearity is shown with pressure above 10 kPa.

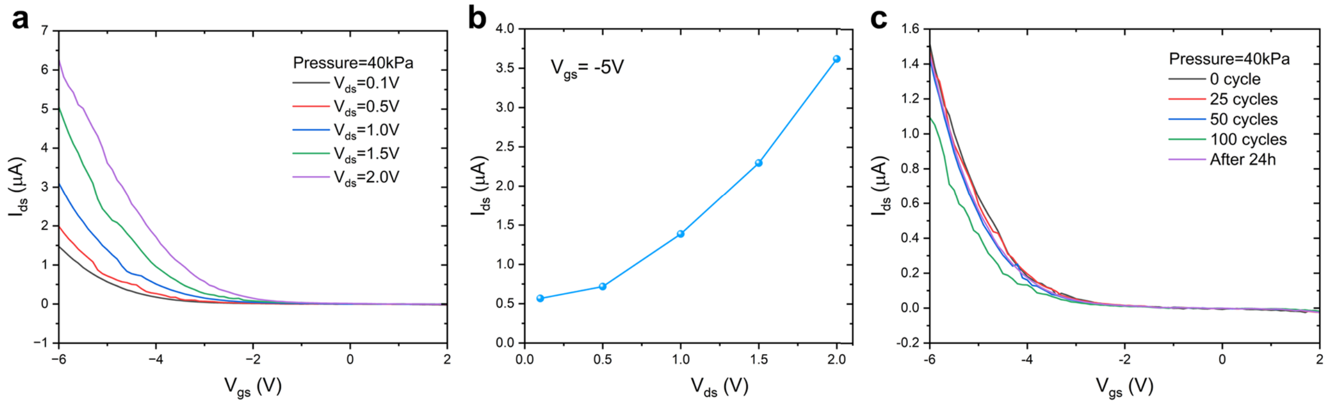

Figure 5. (a) The transfer characteristic of the TFT sensor with different V_{ds}; **(b)** The output characteristic at V_{ds}= -5V; **(c)** The durability of the TFT sensor under the pressure of 40 kPa.

sensitivity pattern can be further tuned by configuring the density of CNTs and the pitch and height of the pyramids.

Furthermore, we tested the performance of the TFT sensor under a constant pressure of 40 kPa, and the results are demonstrated in **Figure 5a**. With different V_{ds}, the transfer characteristic shows a non-linear relationship between I_{ds} and V_{gs}. Moreover, **Figure 5b** demonstrates that the I_{ds} increase exponentially as the V_{ds} increase, revealing the Schottky effect of the S/D contact [8,9], which may be induced by the discrete connection between top electrodes and piezoresistive film.

Subsequently, we presented the durability of the TFT sensor in **Figure 5c**. The output performance has a negligible variance within 50 repetitive press cycles under a pressure of 40 kPa. When the repetitive press comes to 100, there appears a slight negative shift of the TFT transfer characteristic, but it is worth noting that the performance is recovered after resting the device for 24 hours, demonstrating the superior durability of the device.

4. Conclusion

In conclusion, we proposed an ingenious AM tactile pressure sensor design that dramatically simplifies the fabrication of pressure sensors and maintains an outstanding output performance at the same time. The device is highly compact, leading to a high-resolution array with 100 DPI. The transfer characteristic of the sensor exhibits the effectiveness of active pressure sensing. Additionally, the sensor presents a respectable durability and recovery. Since the structure of the TFT sensor is simple and compact, it shows great potential in promising applications such as robotic sensing, medical monitoring, wearable electronics, vehicle sensing, etc.

5. Acknowledgements

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6. References

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