Double-gate thin film transistor with suspended-gate applicable to tactile force sensor

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Abstract

This paper presents a straightforward, low-cost, and effective integration process for the fabrication of membrane gate thin film transistors (TFTs) with an air gap. The membrane gate TFT with an air gap can be used as the highly sensitive tactile force sensor. The suspended membrane gate with an air gap as the insulator layer is formed by multiple photolithography steps and photoresist sacrificial layers. The viscosity of the photoresist and the spin speed was used to modify the thickness of the air gap during the coating process. The tactile force was measured by monitoring the drain current of the TFT as the force changed the thickness of the air gap. The sensitivity of the devices was enhanced by an optimal gate size and low Young's modulus of the gate material. This simple process has the potential for the production of small, versatile, and highly sensitive sensors.

Keywords: Mechanical sensors, Air gap, Membrane gate, Photoresist sacrifice, Tactile force sensor

1 Introduction

Recently, a range of microelectromechanical systems (MEMS) have been proposed and fabricated for a range of applications. MEMS allows the miniaturization of mechanical device structures, such as sensors, transducers, and some microelectronics [1–4]. The convergence of a complementary metal-oxide-semiconductor (CMOS) and a microelectrochemical system to produce a suspended-gate metal-oxide-semiconductor field-effect transistor (MOSFET) with an air gap was proposed as a methodology to fabricate a new generation of sensors, with some spectacular results reported [5, 6]. A suspended-gate air gap MOSFET built on a Si channel has been reported [7, 8] but the optical and mechanical properties of silicon have limited their applications in the flexible, transparent, and wearable sensors compares to the other device structures [9, 10]. For that application, suspended-gate thin-film transistors (TFTs) with organic or inorganic semiconductors have attracted considerable attention. Zang et al, reported ultra-sensitive pressure detection sensors using organic TFTs with a spectacular suspended-gate structure with an air gap as the dielectric layer [11]. Mannsfeld et al. presented a capacitive pressure sensor with a micro-structured PDMS as the dielectric layers for an organic single-crystal transistor that exhibited unprecedented sensitivity and short response times [12]. Zang et al. reported a suspended composite gate structure with Ag nanowires, Fe3O4, and PDMS for organic transistors as flexible magnetic sensors [13]. Despite these advantages, such as great sensitivity and rapid response time in recording pressure, acoustic wave realization, and magnetic fields, their device structures are incompatible with the conventional CMOS process. In addition, organic semiconductors still have issues in conductivity and stability for channel materials. Therefore, CMOS process-compatible inorganic oxide semiconductors are needed to replace their organic counterparts as a TFT channel material.
Since the high performance of an amorphous indium-gallium-zinc-oxide (IGZO) semiconductor for TFTs was presented [14], several studies have reported higher mobility, smaller subthreshold-swing, and better stability of this oxide semiconductor. Based on the enhancement of performance, IGZO thin films have replaced amorphous silicon (a-Si) in flat panel display applications. The IGZO semiconductor has advantages over organic semiconductors in terms of the optical-electric, low deposition temperature, low-cost, bendable and invisible devices, and compatibility with conventional fabrication methods [15]. On the other hand, few studies have used IGZO channel TFTs for tactile force sensors with a low-temperature process. These studies used organic or piezoelectric materials that cannot be implemented easily in conventional microfabrication. Moreover, the number of process steps is large because they combine different device structures.

This paper reports a suspended-gate TFT structure with an air gap insulator and IGZO channel for tactile force sensor applications. The devices were first built on a SiO$_2$/Si substrate by microfabrication, including multiple ultraviolet (UV) light exposure steps for the dual-gate structure. An alumina layer was deposited by a spin coating process as the protective dielectric layer, which prevents damage from the gate collapse [16]. The air gap acts as an insulator layer for TFTs and improves the sensitivity by allowing a movable suspended gate. The air gap thickness changes when a stress is applied to the gate, which leads to varying electrostatic capacitance values on the channel and exchanges into different drain currents in TFTs. The tactile pressure quantity and the sensitivity can be calculated from the measured drain current.

2 Experimental

Figure 1 presents a schematic process flow for the dual-gate TFTs with the IGZO channel. The 30 nm IGZO channel was deposited by radio frequency sputtering at room temperature and annealed at 400 °C for one hour in air ambient on SiO$_2$ (100 nm)/Si substrate for the bottom gate. A 50 nm tungsten (W) layer for the source and drain was patterned by a lift-off process and deposited by direct current (DC) magnetron sputtering. A 20 nm thick alumina (Al$_2$O$_3$) layer, as the protective dielectric layer, was coated by a spin coating solution process at a speed of 3000 rpm for 20 s. Aluminum nitrate nonhydrate (Sigma-Aldrich, 99.997% trace metals basis) and 2-methoxyethanol (Sigma-Aldrich, anhydrous 99.8%) as precursors (a 0.8 M solution was prepared and stirred for 5 h) were used for the solution. The samples were annealed at 250 °C for 1 h in air after coating. The alumina layer was patterned to open the source and drain contacts. A negative photoresist (NPR) layer as the supporter was coated and exposed to ultraviolet light for the air gap layer without a developing step. A 500 nm Ti was deposited on top of the NPR layer by DC magnetron sputter for the top gate, which is a movable structure. The gate was patterned by one more photolithography step with a positive photoresist. After the developing step, the remaining photoresist was exposed once more time to UV light before the etching stage. Ti was etched in H$_2$O$_2$:H$_2$O=1:1:20 solution for 20 s. The suspended-gate was formed in the developer solution by removing

![Fig. 1 Schematic diagram of process flow for IGZO suspended-gate TFT with an air gap](image-url)
the negative and positive photoresist above and below
the Ti gate. The thickness of each layer was analyzed by
X-ray reflectivity (XRR) measurement. The structure of
the device was examined by scanning electron micros-
copy (SEM). The transfer current was measured using an
Agilent 4155C semiconductor analyzer at room tempera-
ture in a dark chamber with and without pressure on the
gate.

3 Results and discussion
SEM confirmed the formation of a Ti suspended-gate,
200 μm in length and 50 μm in width, over the channel,
as shown in Fig. 2. In the process, the NPR was a sup-
porter to prop the Ti gate and was used to determine
the air gap thickness. The thickness of the NPR was con-
trolled by adjusting the speed of the spin coating step. In
this device, the air gap was found to be approximately
5 μm. After the vacuum drying step, there was no pho-
toressist or water observed under the Ti gate, proving
that the process can release the thin metal film as a sus-
pended-gate for TFT devices.

Figure 3 presents the transfer curves that measure from
the back gate structure with a SiO2 insulator and top gate
structure with an Al2O3 insulator. The bottom gate was
used to confirm that the channel is working after the
entire process. For the back gate structure, the device
had the W/L = 400/50 and the drain current (Id) was
measured with the gate voltage (Vg) scanned from -60
to 60 V at a drain voltage Vd = 1 V and 10 V. The field-
effect mobility of the back gate device was approximately
8.7 cm2V−1s−1. The back-gate structure was fabricated to
calculate the saturation mobility of IGZO at high Vd. For
the top gate structure, the Id was swept with Vg from −60
to 60 V at Vd = 1 V with the W/L = 50/50 based on the Ti
gate size. The pressure was placed on the surface of the
Ti suspended-gate using an insulated probe tip at the top
to increase the contact area and prevent the current to
the tip. Without the application of stress to the top gate,
there was no drain current passing through the channel,
even though the gate voltage was increased up to 60 V.
The drain current increased gradually by applying pres-
sure to the tip. The threshold voltages were also shifted
from 42 to 3.9 V. The entire enhancement in the electrical
properties shows that the suspended-gate TFT with
the IGZO channel can detect the diverse pressure. After
pushing the gate with the tip and releasing it, the drain
current did not return to the value before stressing due to
damage from pressing the gate.

In this structure, the insulator layer for oxide TFTs
involves the alumina protective dielectric. This prevents
the suspended gate from coming into contact with the
channel directly as excessive pressure is applied. Direct
contact of the suspended gate and channel leads to the
collapse of the gate and damage to the channel. The other
insulator layer is the air gap, which has the rubber sen-
sitivity role for the tactile force sensor. The pressure was
applied using an insulated probe tip. The drain current in
the saturation region of the suspended-gate TFT can be
calculated from the following equation [17]

$$I_{DS} = \frac{W \mu \text{sat} \cdot C_t}{2L} \left( V_g - V_t \right)^2$$  \hspace{1cm} (1)

where W and L are the channel width and length of
TFT, $V_g$ and $V_t$ are the gate voltage and threshold

![Fig. 2](image-url)  
**Fig. 2**  
(a) SEM image of Ti suspended-gate structure with a 200 μm-long and 50 μm-wide.  
(b) Closer look of the inserted blue round area
voltage, respectively; \( \mu_{\text{sat}} \) is the saturation mobility, and \( C_t \) is the total capacitance of the insulator layers, which is expressed as [17]:

\[
\frac{1}{C_t} = \frac{1}{C_{pd}} + \frac{1}{C_{\text{gap}}}
\]

(2)

where \( C_{pd} \) and \( C_{\text{gap}} \) are the protective dielectric (alumina) and air gap capacitance, respectively. \( C_{\text{gap}} \) can be expressed as

\[
C_{\text{gap}} = \frac{\varepsilon_{\text{air}}\varepsilon_0 A}{d_{\text{gap}}}
\]

(3)

where \( \varepsilon_{\text{air}}, \varepsilon_0, A, \) and \( d_{\text{gap}} \) are the relative dielectric constant of air, absolute dielectric constant, area of the gate of TFT, and air gap thickness, respectively. By changing \( d_{\text{gap}} \) with the pressure on the suspended gate, \( C_{\text{gap}} \) can be modulated, and \( I_{ds} \) would increase or decrease accordingly. The accurate displacements according to the air gap thicknesses from the transfer curves were calculated.

Figure 4 shows the displacement of the Ti gate simulated from the COMSOL simulation when the stress to the gate was varied from 75 to 100 kPa. In the simulation, the Ti gate has a matching size with a movable part in the practical device structure, and Young’s modulus, density, and Poisson’s ratio were 116 GPa, 4506 kg.m\(^{-3}\), and 0.3, respectively. The displacements in the middle of the gate increased from 4.5 to 5 \( \mu \)m as the pressure was increased. When the stress was higher than 100 kPa, the displacement became larger than the air gap thickness, 5 \( \mu \)m.

The applied stress corresponding to the displacement was extracted by matching the displacement from the simulation and calculation based on (3), as shown in Fig. 5a. Figure 5b shows the difference in the drain current \( \Delta I_{ds}/I_0 \) (\( \Delta I_{ds} \) is the relative change in the drain current corresponding to the change in pressure loading \( \Delta P \) and \( I_0 \) is the initial current without pressure [11]) under various pressures. The sensitivity of the devices was also calculated using the sensitivity, which was defined as \( S = (\Delta I_{ds}/I_0)/\Delta P \). The highest sensitivity was observed at the largest applied pressure of 180 Pa\(^{-1}\).

The sensitivity acquired from the measured current curve showed high practicability for a range of applications, which overcomes the difficulties of the polymer dielectric. Because the air gap is used as the dielectric layer in a field-effect transistor, a higher sensitivity target was reached with the microsensor device. Despite the great sensitivity, this structure may have problems in the recovery of the suspended gate after removing the pressure because of the thicker Ti film thickness and the large gate size. This problem can be alleviated by covering one PDMS layer as a passivation layer and improving the resilience of the metal gate [18].
4 Conclusions
A suspended-gate oxide TFT was fabricated using an IGZO channel for the tactile force sensor. Using the simple fab-compatible process with multi photolithography steps, a Ti suspended-gate, 200 μm in length and 50 μm in width, was built on the negative photoresist
supporters. The characteristics of a tactile force sensor were demonstrated by combining with the low-temperature process for IGZO TFT. From the transfer curve of oxide TFT, the sensitivity was calculated to be 180 Pa$^{-1}$ at $V_d = 1$ V and $V_g = 60$ V. The IGZO TFT with the air gap for the insulator layer enhanced the sensitivity of the sensor substantially.

**Abbreviations**
MEMS: Microelectromechanical systems; CMOS: Complementary metal-oxide-semiconductor; MOSFETs: Metal-oxide-semiconductor field-effect transistors; TFTs: Thin-film transistors; PDMS: Polydimethylsiloxane; IGZO: Indium-gallium-zinc-oxide; a-Si: Amorphous silicon; UV: Ultraviolet; W: Tungsten; DC: Direct current; NPR: Negative photoresist; XRR: X-ray reflectivity; SEM: Scanning electron microscopy.

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**Authors’ contributions**
All authors have contributed to the writing of the manuscript. All authors read and approved the final manuscript.

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**Availability of data and materials**
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**Competing interests**
The authors declare that they have no competing interests.

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