Fabrication and characterisation of field-effect transistor-type pressure sensor with metal–oxide–semiconductor/microelectromechanical systems processes

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A microfield-effect transistor pressure sensor has been fabricated using conventional complementary metal–oxide–semiconductor process and microelectromechanical systems technology. The sensor platform consisted of a field-effect transistor (FET) device, electrode and Si diaphragm. Six lithography masks were prepared to develop the sensor fabrication process for arsenic ion implantation and diffusion, gate insulation layer (SiO_2), gate metal, metal interconnection, passivation layer and bulk micromachining patterns. Pt/Ti thin films as the gate metal, interconnection and electrodes were deposited by DC/radio frequency magnetron sputtering, and patterned and etched using the reactive-ion etching process. The channel length and width between the source and the drain were approximately 10 and 5500 µm (W:L ratio = 550:1), respectively. The pressure sensor produced a change in current when pressure was applied to the sensing element and the electrical circuit was used to convert the current variation of the pressure sensor to a voltage output. The sensor response was measured using a voltage follower circuit to determine the change in drain current. The fabricated FET pressure sensor showed an almost perfect linear response for the applied pressure in the range 0–1200 kPa. The experimental results have shown that the pressure sensor had a sensitivity of 0.0096 µA/kPa.

1. Introduction: Silicon (Si) microelectromechanical system (MEMS) technology has been applied recently to the manufacture of various pressure sensors. The operational principles and methods with piezo-resistivity, capacitance, optics, resonance and acoustic transduction were used for the development of micromachined pressure sensor modelling, design and fabrication [1–4]. The advantages of micropressure sensors fabricated by MEMS technology include high performance, small size, low cost and easy mass production [5]. Among the various types of pressure sensors, piezo-resistive pressure sensors have been studied most widely for industrial applications [6].

On the other hand, pressure-sensitive field-effect transistor (FET) devices with micromachined structures have attracted considerable interest recently [7]. In particular, several types of FET pressure sensors have been designed and fabricated using the MEMS technology. The integration of MEMS with the driving, controlling and signal processing electronics on the same complementary metal–oxide–semiconductor (CMOS) substrate can enhance the sensor performance significantly, while reducing the device assembly and packaging cost [8]. Svensson *et al.* [9] presented a surface-micromachined pressure sensor based on a FET device, in which the diaphragm acted as the gate of the transistor. Hynes *et al.* [10] manufactured a FET pressure sensor using a surface micromachining process, where a sacrificial oxide layer and a poly-silicon diaphragm were deposited on the pressure sensing area. Using the CMOS and MEMS techniques, a microFET pressure sensor integrated with readout circuits could be fabricated on a chip [11].

In the work reported in this Letter, a FET-type pressure sensor was designed and fabricated using the CMOS process with the MEMS technique. The fabricated sensor device was characterised by a simple structure and easy fabrication process compared with previous results [12]. A read-out circuit was set up to convert the drain current variation to a voltage as the output. The sensing properties were examined in terms of sensitivity, linearity, response and recovery times.

2. Experiments: Fig. 1 shows a schematic diagram of the structure of the FET pressure sensor fabricated using the CMOS and MEMS processes. The pressure sensor platform consisted of a FET channel, metal electrodes and the bulk micromachined Si diaphragm. The sensing layer and the electrical channel of the transistor were located in the middle of the diaphragm, where the maximum deflection occurred with the applied pressure. The dimensions of the sensor chip and the diaphragm were 3 mm × 3 mm and 1 mm × 1 mm in area, respectively. The electrical channel length and width between the source and the drain were approximately 10 and 5500 µm, respectively, with a high width to length ratio (550:1). The deformation of the diaphragm occurs with the applied pressure and causes the change of drain current (I_D) between the source and the drain which is used to calculate the difference in the applied pressure.

The finite element method (COMSOL Multiphysics) was used to analyse the behaviour of the deflection and structural characteristics of the FET pressure sensor. For convenience, the FEA model was simplified as two layers, the diaphragm and the chip frame with a silicon material, and triangular elements were applied to mesh the model. The material properties of silicon were E (Young's modulus) = 70 GPa, ν (Poisson's ratio) = 0.3 and ρ (mass density) of 2679 kg/m^3. The boundary conditions were set as a chip frame to be fixed and a uniform pressure load was applied to the diaphragm. The stress and displacement of the diaphragm were calculated from the FEM simulation. Fig. 2 shows the simulation results for the stress distribution on the diaphragm at a pressure of 1200 kPa. The maximum strain occurred at the centre of the square diaphragm. The displacement at the centre of the membrane was approximately 1.301 µm. The effective deflection area was approximately 50% of the diaphragm region, corresponding to the sensor design. Fig. 3 shows that the relationship between the simulated displacement and applied pressure at the centre of the membrane is linear.

The sensor platform was fabricated using the conventional CMOS/MEMS process. Fig. 4 presents the process flow for sensor fabrication. Six photomasks were used for lithographic processes as the arsenic ion implantation and diffusion, gate insulation layer (SiO_2), gate and metal contact line (Pt/Ti), passivation layer and bulk micromachining patterns.

The gate metal and electrodes of the source and drain were a Pt thin film deposited by DC/radio frequency magnetron sputtering,

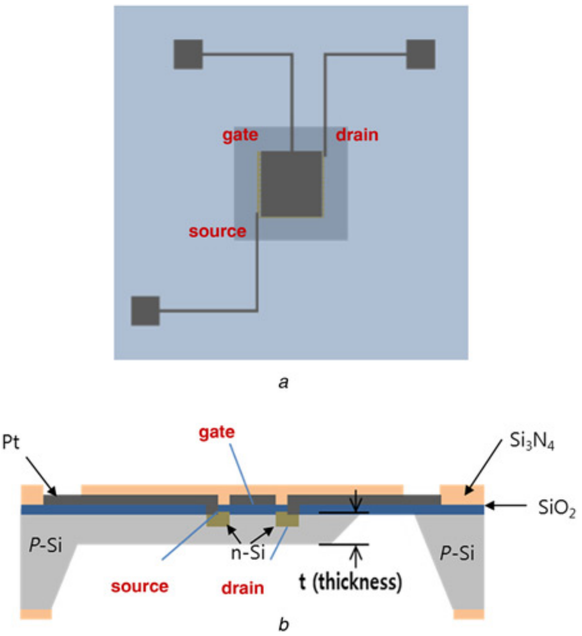

Figure 1 *Schematic diagram of the FET pressure sensor*
a Top
b Cross-sectional view of the sensing diaphragm

patterned and etched by the reactive-ion etching process. A discrete silicon island structure of the membrane was produced via two successive micromachining process steps. After the fabrication process with the wafer-level was complete, individual sensor chips were diced mounted on the sensor package with wire bonding. Fig. 5 shows the fabricated sensor package after wire bonding.

The pressure sensing response was measured using a voltage follower circuit to read the changes in the drain current of the transistor. The readout circuit was designed to convert the drain current variation to a voltage as output. The sensing signals with the applied pressure were measured as the drain current variation at the output curve of I_D against V_{DS}. The electrical measurements were performed using a current–voltage ($I-V$) source meter (Keithley 2636 A).

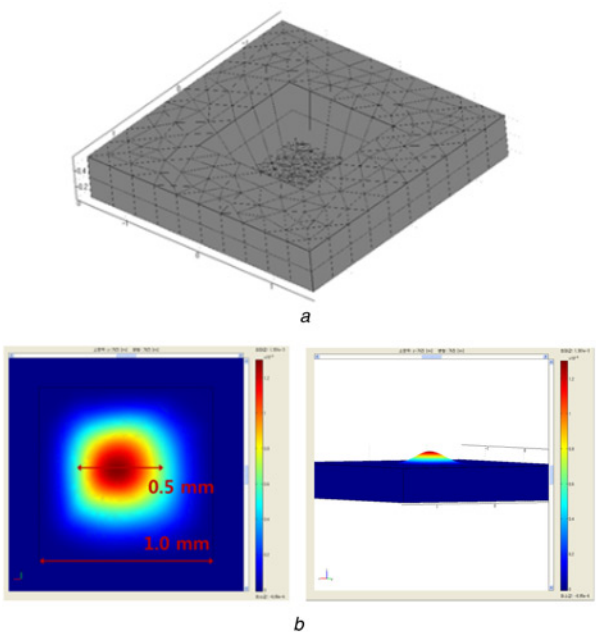

Figure 2 *FEM results for the proposed sensor design*
a Meshed FEA model
b Displacement of the diaphragm

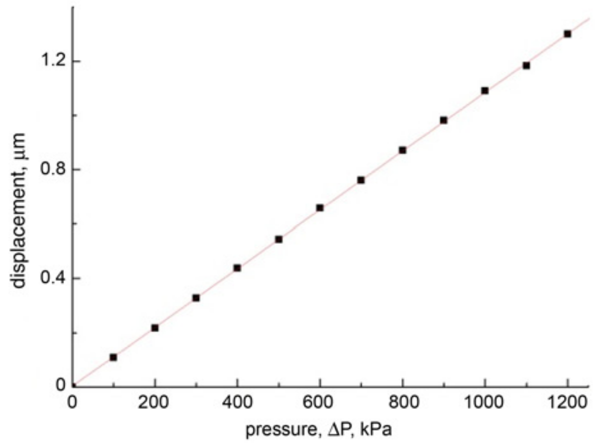

Figure 3 *Relation of simulated displacement with applied pressure at the centre of the diaphragm*

3. Results and discussion: Fig. 6 presents the $I-V$ curves of the fabricated FET sensor. As the drain voltage (V_{DS}) increased, the drain current (I_D) increased linearly and became saturated at a specific gate voltage and the I_D value increased at higher gate voltages. The saturated drain currents were 2.546, 6.108, 9.984 and 13.751 mA for $V_G = 1.0$, 2.0, 3.0 and 4.0, respectively.

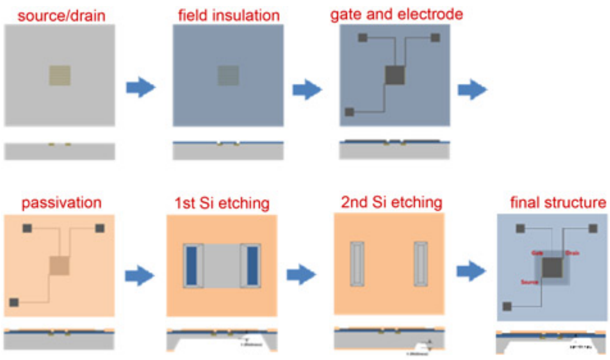

Figure 4 *Process flow for the FET pressure sensor fabrication using the CMOS/MEMS process*

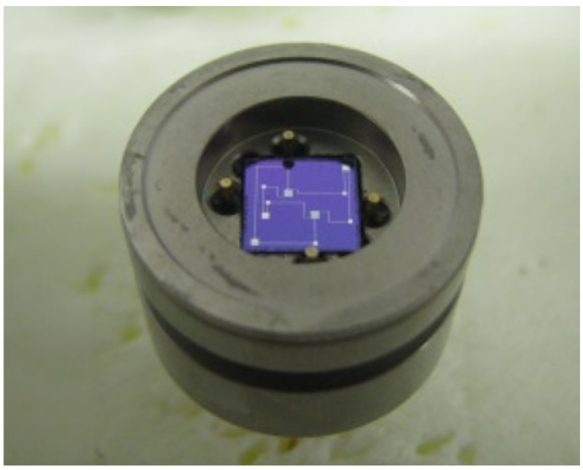

Figure 5 *Photograph of the sensor device mounted on the sensor package*

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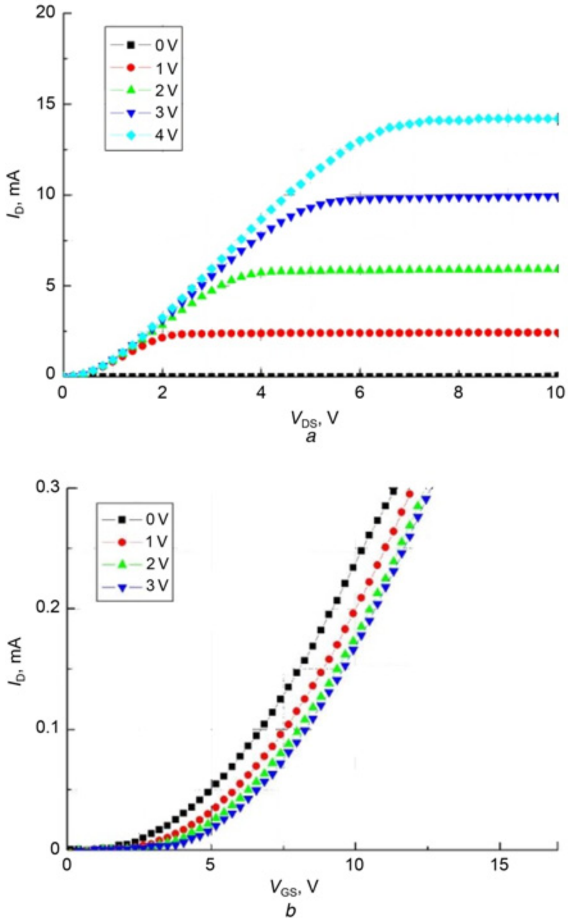

Figure 6 *Electrical characteristics of the reference FET device at various gate voltages*
a I_D–V_{DS} curve
b Transfer characteristics, I_D–V_{GS} curve

Regarding the transfer characteristics (V_{GS}–I_D) in Fig. 6*b*, the drain currents increased as a function of the secondary degree to the gate voltage, and the threshold voltage for the metal–oxide–semiconductor field-effect transistor (MOSFET) was 3.217 V (at $I_D = 0.01$ mA). The tendency of the measured electrical data was fitted well to the general behaviour of the MOSFET's characteristics.

Fig. 7 shows the typical *I*–*V* curves of the fabricated pressure sensor without the applied pressure and at an applied pressure of 1000 kPa. As the pressure was applied to the sensor diaphragm, the drain current between the source and the drain increased. As shown in the Figure, the difference between the saturated drain current at an applied pressure of 1000 kPa and that without pressure was approximately 9.873 μA.

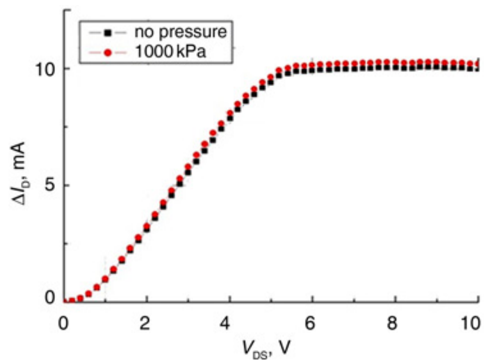

Figure 7 *I_D–V_{DS} curves of the FET pressure sensor with applied pressure. The gate voltage is 3.0 V*

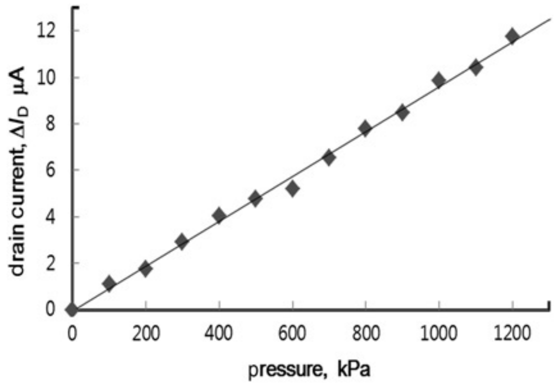

Figure 8 *Variation of the drain current with applied pressure. The gate voltage is 3.0 V*

Fig. 8 represents the variation of the drain current difference (ΔI_D) according to the applied pressure at a gate voltage (V_{GS}) of 3.0 V. The fabricated FET pressure sensor showed an almost perfect linear response for an applied pressure of 0–1200 kPa. The sensitivity as the slope of the drain current to pressure was approximately 0.0096 μA/kPa. This tendency of good linearity in the drain current difference as the applied pressure agreed well with the previous reports [12, 13].

The sensing properties of the fabricated FET pressure sensor in this Letter has promising applications in various industrial fields, such as automotive vehicles, electronic appliances and biomedical services, owing to its high sensitivity, good linearity and rapid response/recovery characteristics, particularly in the range of low pressures.

4. Conclusion: A FET pressure sensor with a micromachined structure was fabricated using the CMOS/MEMS process. The FET pressure sensor generated a change in drain current after applying pressure to the Si sensing diaphragm and its current signal was converted to an output voltage by the readout circuit. The FEM simulation results confirmed that the effective stress and displacement occurred around the FET channel on the diaphragm region. The sensing measurements have shown that the pressure sensor had a sensitivity of 0.0096 μA/kPa at $V_{DS} = 7.0$ V and $V_{GS} = 3.0$ V in the range 0–1200 kPa. The fabricated FET pressure sensor showed good pressure sensing performance with high sensitivity and rapid response/recovery properties.

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