AN ELECTRET-BASED PRESSURE SENSITIVE MOS TRANSISTOR

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ABSTRACT

The operation of the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is based on the fact that the lateral conductivity of silicon at the silicon dioxide-silicon interface strongly depends on the transverse electric field in the oxide. Adding a small air-filled spacer between metal gate and oxide, and applying a voltage across the insulator on top of the silicon, the lateral conductivity can become pressure sensitive.

The generation of the electric field in the insulator can however also be provided by means of an electret. In this paper the integrated Electret-MOSFET based pressure sensor is presented with respect to its theory, realization and performance.

THEORY

The MOS transistor has appeared to be a useful electronic component for the realization of small solid-state chemical and biochemical sensors. The purpose of this work was to investigate the application of the MOSFET as a pressure sensitive device [1], [2].

The MOSFET, as drawn in figure 1, consists of two heavily phosphorus doped silicon regions (called the source and drain) in a lightly boron doped silicon substrate (called the bulk). The electric conductivity in the source and drain is determined by electrons and in the bulk by holes. As long as no electrons are present in the bulk no current can flow between source and drain. Applying however a positive voltage to the gate with respect to the bulk a negative surface charge and thus a conductive path at the silicon-silicon dioxide interface is created.

Satisfying several conditions it appears that the current I from drain to source can be written as:

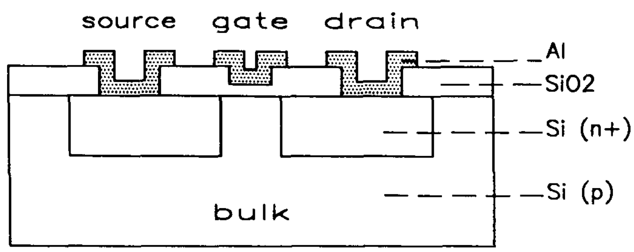

Figure 1: Cross section of the MOS transistor.

$$I = K\,C_i\,((V_{gs}-V_t)V_{ds}-0.5V_{ds}^2) \qquad \text{if } V_{ds} <= V_{gs} \qquad (1)$$

$$I = K\,C_i\,(V_{gs}-V_t)^2/2 \qquad \text{if } V_{ds} >= V_{gs} \qquad (2)$$

with K a constant, C_i the capacitance per unit area of the insulator between gate and silicon, V_{gs} the voltage between gate and source and V_{ds} the voltage between source and drain. V_t is the threshold voltage, which is the required minimum value of V_{gs} to realize a conductive path between source and drain.

The threshold voltage depends on the value of the capacitance C_i as follows:

$$V_t = V_o - Q_i/C_i \qquad (3)$$

with V_o a voltage which in our case is approximately equal to - 0.3 V and Q_i the fixed charge present at the silicon-silicon dioxide interface.

The insulator capacitance C_i is inversely proportional to the insulator thickness. In figure 2 some theoretical curves are presented of the current as a function of the oxide thickness, with the gate-source voltage as a parameter.

Adding a small air-filled spacer between gate and insulator and exposing the top side of this structure to the pressure to be measured we obtain a pressure dependent

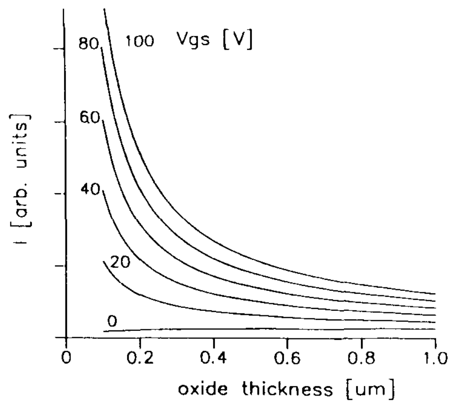

Figure 2: Theoretical behaviour of the MOSFET with variable insulator thickness.

insulator thickness (air is also an insulator), and thus a pressure sensitive MOSFET.

Considering figure 2 we observe that the sensitivity, defined as the current change to insulator thickness variations, increases almost linear with increasing V_{gs}.

The use of large, externally applied voltages is however not always practicle, and therefore we have decided to incorporate an electret with a considerable charge density.

Due to the fact that the long term stability of Teflon FEP is well known, we have used this material, and developed a technique to attach foils to a silicon wafer. In the theory we can account for an electret in different ways, as described elsewhere [2], [3]. A possibility is to consider the electret voltage, defined as the electret charge divided by the electret capacitance, to be in series with the gate voltage. Due to the fact that Teflon electrets can be charged up to 300 V, it will be clear that we obtain a pressure sensor with high sensitivity.

SENSOR FABRICATION

The sensors are fabricated by integrated circuit and thin film technologies. The sensor realization is rather complex and requires at least nine photolithography steps. The most important are described briefly.

Using the standard NMOS process of the Sensors and Actuators Laboratory of Twente University, in each 2 inch silicon wafer 300 MOSFET's are realized.

Holes through the wafer (designed as glue passage for diaphragm attachment and air duct to the air gap) nearby each MOSFET are realized by means of anisotropic silicon etching.

Teflon FEP is deposited on the whole wafer by a heat-sealing technique and afterwards patterned by a plasma-etch process [4]. This patterning is required for contacting the source, bulk and drain area's.

The Teflon is charged in vacuum by a SEM and controlled by measuring in the vacuum chamber the charge induced at the back of the silicon wafer. Knowing the radiated area we also know the charge density of the electret. We have used a value of -30 nC/cm•cm.

Finally an 8 μm aluminum diaphragm is mounted on top of the structure and glue-bonded to it via holes around the sensor. A cross section is drawn in figure 3.

EXPERIMENTAL

Using reasonable values for all parameters the pressure sensitivity of sensors with outer dimensions of 1mm * 2mm *0.3 mm has been calculated. We found a pressure sensitivity of 0.6 μA/kPa and a zero pressure current of 3 mA for a V_{ds} of 1 V.

We have measured our sensors by using a fast pressure actuator that generates pressures between -15 and +60 kPa relative to atmospheric pressure at frequencies between 0 and 100 Hz. This pressure is exposed to the top side of the sensing diaphragm while the other side is exposed to the barometric pressure via the air duct, as drawn in figure 3.

We have measured an average pressure sensitivity of about 0.2 μA/kPa in the pressure range between -15 and +60 kPa. This is three times lower than the calculated value and might be due to a smaller deflection of the diaphragm.

The linearity of these sensors is good, but they display a rather large temperature sensitivity of about 10 μA/°C, which implies that a temperature change of 1 °C corresponds to a pressure of 50 kPa. It will be clear that this temperature sensitivity has to be reduced by adding compensating electronic circuitry to the sensor.

CONCLUSIONS

Comparing the sensitivity of the electret-MOSFET pressure sensor and the piezoresistive pressure sensor it appears that the sensitivity of the first is at least ten times higher. Its

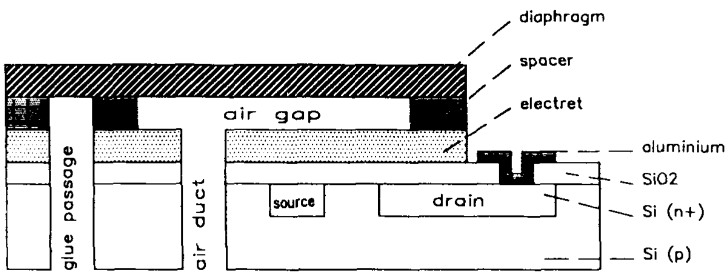

Fig. 3: Cross section of the electret MOSFET pressure sensor.

temperature sensitivity is however much larger.

The introduction of Teflon in MOSFET's is rather complex. For instance: after Teflon deposition no high temperature processing is allowed to avoid its decomposition. We discovered however that silicon dioxide can also be used as electret. This is very interesting, because it reduces the complexity of the sensor fabrication. Due to the fact that silicon dioxide electrets can be much thinner than Teflon electrets the use of silicon dioxide may yield sensors with increased sensitivity [5].

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