Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp481-482

Fabrication and Evaluation of Aluminum Nitride/MOSFET Based Strain Sensor with High Gauge Factor

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Abstract

This paper reports a microfabricated strain sensor based on aluminum nitride (AlN) combined with a metal-oxide-semiconductor field effect transistor (MOSFET). A high quality AlN thin film works as a sensing element, which is connected electrically to the gate electrode of the MOSFET for the amplification of piezoelectric response of the AlN thin film. The pseudo gauge factor (GF) of the MOSFET is evaluated from the source-drain resistance change under the application of stress to the AlN thin film and 1340 of GF is obtained.

1. Introduction

Strain sensing plays an important role in a wide range of applications such as flexible robotics, structural health monitoring and movement detection. Piezoelectric effect, which generates charges in response to external mechanical strain, has been widely utilized for strain sensors [1, 2]. Typically, the sensitivity of conventional piezoelectric strain sensors is determined by the voltage caused by strain, which is in proportional to the thickness of the piezoelectric layer. A thicker piezoelectric layer leads to a higher sensitivity while limits miniaturization of strain sensors. Piezoelectric potential gated field effect transistor (FET) has been proposed to solve this problem because the piezoelectric potential creates from the charge density change on the surface of piezoelectric layer which do not depend on the thickness of piezoelectric layer [3-6]. The generated charges are led to the gate of FET and the generated potential affects the drain-source current in FET. However, the charge leakage from the piezoelectric materials reduces the sensitivity, thus the realization of high sensitive strain sensors is still a challenge.

In this paper, we develop a low dielectric loss AlN based strain sensor which combines a piezoelectric sensing element with a silicon MOSFET with low leakage current. The pseudo GF is evaluated using four-point bending measurement.

2. Device concept and Experimental

The concept of proposal strain sensor is illustrated in Fig. 1. The strain sensor contains a piezoelectric sensing element composed of piezoelectric material AlN with leakage current smaller than 0.1 nA at 0.1 V, connected to the gate electrode of a silicon MOSFET. In this study, the piezoelectric sensing element and MOSFET were fabricated via microfabrication and standard complementary metal-oxide-semiconductor (CMOS) processes, separately. A 200 μm-thick silicon substrate with Mo(100 nm)/AlN(200 nm)/Mo(100 nm)/seed-AlN(20 nm) stacks was used. The top Mo electrode was patterned by photolithography and wet etching. The AlN layer was subsequently etched by wet etching in TMAH solution at 38 °C. The bottom Mo electrode and seed layer AlN were patterned and etched using the identical processes. SiO_2 was deposited as a protection layer by plasma enhanced chemical vapor deposition (CVD). In order to contact to the top and bottom Mo electrodes, SiO_2 was etched by buffered hydrogen fluoride (BHF). Finally, a lift-off process was used to pattern the Cr-Au electrodes. The Cr-Au thin film was deposited by electron beam evaporation.

MOSFETs were fabricated on a silicon on insulator (SOI) wafer with a 68 nm-thick active layer thickness. Fabrication process began with etching the active Si layer using HBr gas in reactive ion etching (RIE). The gate dielectric film was then formed using thermal oxidation at 850 °C. Deposition of 150 nm of polysilicon followed by RIE defined electrodes aligned to the gate dielectric. The entire device was doped with boron at a doping concentration of 5×10^{14} /cm^3 and followed by an anneal treatment. A 500 nm-thick passivation SiO_2 layer was formed using low pressure CVD. In order to open the contact holes at the source, gate and drain electrodes, the SiO_2 layer was etched by both dry and wet etching. Aluminum as the metal layer was deposited by dc sputtering and etched using Cl_2/BCl_3 gases. The MOSFETs were finally sintered at 400 °C in a hydrogen atmosphere. After the fabrication process, the piezoelectric sensing element and MOSFET were connected using Au wire bonding.

GF is a crucial parameter to characterize strain sensors, which is defined as resistance change divided by the strain. The pseudo GF of the MOSFET is evaluated from the source-drain resistance change under the application of stress to the AlN thin film. GF evaluation of the completed strain sensor was performed using a four-point bending test as shown in Fig. 2. The substrate used in this test is 20 mm length, 20 mm width and 200 μm thickness. The piezoelectric sensing element was located at the center of the silicon substrate. Applying a force to the substrate with a piezoelectric sensing element generates charge variation on the AlN thin film because of the spontaneous polarization change of AlN. Since one of the electrodes of the piezoelectric sensing element is connected to the gate of the MOSFET, charge redistribution results in a change in voltage on the gate, which causes the source-drain resistance change (ΔR). The source-drain resistance (R) was measured without applying any external load. Figure 3 shows the circuit diagram of the GF measurement setup. The MOSFET operates with V_{gs} set to 3.15 V and V_{ds} set to 3.00 V. The output current signal from MOSFET is converted into a voltage signal through a resistor.

3. Results and Discussions

The optical images of the completed piezoelectric sensing element and MOSFET are shown in Fig. 4.

I-V characteristics of the fabricated single MOSFET measured by a semiconductor parameter is shown in Fig. 5. Where the gate-source voltage V_{gs} is swept between -2 to 2 V with a drain-source voltage V_{ds} of 1 V. The drain-source current I_{ds} versus V_{gs} curve exhibits p-type MOSFET property and steep subthreshold slope. Moreover, the gate-source current I_{gs} versus V_{gs} curves shows the gate leakage is less than 1 pA, which exhibits excellent property.

The strain-gauge property of the fabricated sensor is shown in Fig. 6. We applied three load forces 200g (0.2N), 500g (0.5N) and 700g (0.7N). The center stress corresponds to 29 MPa, 73 MPa, 103 MPa calculated via four points bending principle [7]. The GF is estimated to be 1340 at strain of 0.0159% given by equation GF = $(\Delta R/R)/\Delta\varepsilon$. High strain sensitivity is realized for compressive strain. The GF is around 7 times larger than the value of state-of-the-art silicon based piezoresistive strain sensors [8]. The experimental GF is lower than theoretical calculation (1880) because there is a leak path on the gate electrode which results in reduction of the gate charge amount.

4. Conclusions

In conclusion, we have developed a strain sensor based on piezoelectric material AlN combined with a silicon MOSFET. While applying stress on the AlN sensing element, the variation of charge induced by piezoelectric effect. The charge is then fed to the gate of the MOSFET which changes the drain-source current. The GF was evaluated to be 1340 at a low strain using four-point bending method. Those results show the potential in high sensitive strain sensing applications.

Acknowledgements

Parts of this work were performed in the Micro/Nanomachining Research Education Center (MNC) and Micro System Integration Center (μSIC) of Tohoku University. We would like to thank H. Kino and T. Tanaka at Graduate School of Biomedical Engineering in Tohoku University for many helpful comments and useful discussions.

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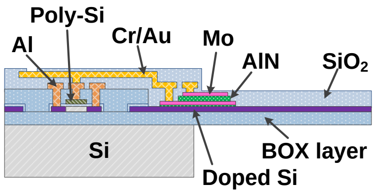

Fig. 1 Concept of the AlN/MOSFET based strain sensor.

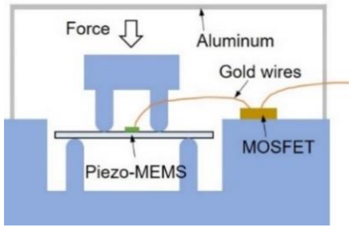

Fig. 2 Schematic illustration of GF measurement setup.

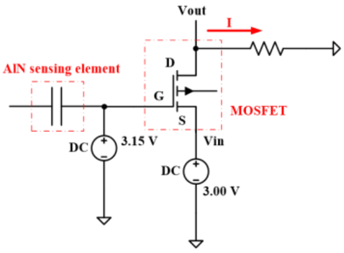

Fig. 3 Circuit diagram of the GF measurement setup.

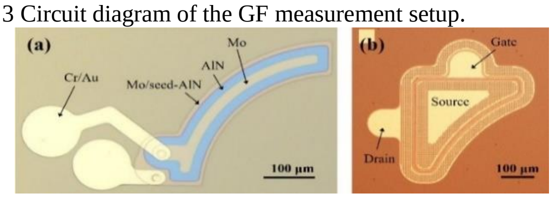

Fig. 4 Top optical images of (a) piezoelectric sensing element and (b) single unit cell MOSFET.

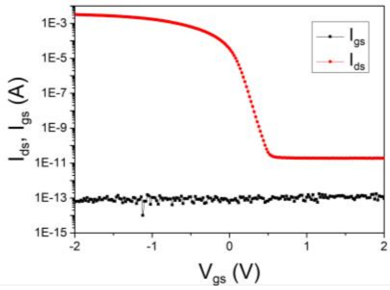

Fig. 5 I-V characteristics of the fabricated MOSFET.

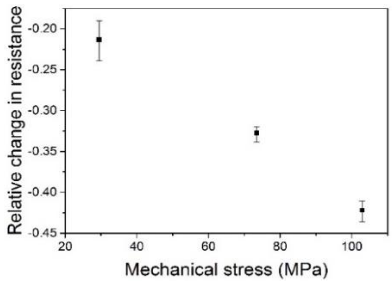

Fig. 6 Relative change in resistance as a function of compressive stress.