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Sensitivity Improvement and Operating Characteristics Analysis of the Pressure Sensitive Field Effect Transistor(PSFET) Using Highly-Oriented ZnO Piezoelectric Thin Film

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Abstract

We demonstrate the improvement of sensitivity and analysis of operating characteristics of the piezoelectric pressure sensor using ZnO piezoelectric thin film and FET(field effect transistor) for sensing applied pressure and transforming the pressure into electrical signals, respectively. The sensitivity of the PSFET(pressure sensitive field effect transistor) was improved by using highly-oriented ZnO film perpendicular to the substrate surface and the operating characteristics was investigated by monitoring output voltage with time in various static pressure levels.

Ⅰ. Introduction

Pressure sensors have been used in the fields of medical instruments as well as domestic appliances, automobiles, and industrial process monitorings. The typical pressure sensors currently used are piezoresistive[1-2] and capacitive[3-4] types. Especially, semiconductor micro pressure sensors have a great deal of attentions not only because of their small size, but also because of ease of incorporating their signal processing circuitries on the same silicon chip. However, the fabrication technologies of these sensors, silicon etching and anodic silicon to glass bonding, are not yet compatible with the standard silicon integrated circuit fabrication technology, so that the incorporation of sensors with signal processing circuitry is not yet practical. For the purpose of resolving the drawbacks, complex fabrication processes and uncompatibility with IC fabrication process, of the existing silicon pressure sensors using diaphragm, new types of pressure sensors have been reported. *Pressure sensitive field effect transistor(PSFET)*[5] is a typical one which is operated by the combination of piezoelectric effect of ZnO film formed on the FET gate and field effect of FET. Because this new pressure sensor is fabricated by the standard silicon integrated circuit technology, it is expected not only to offer major improvements in size, cost, and performance but to realize multi-sensing systems by incorporating other sensors as well as signal processing circuitries on chip. Although this type of sensors using piezoelectric effect and FET was proposed by *R. S. Muller et al*[5,6], their exact and detailed response characteristics on applied static pressure have not been reported. In this

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paper we prepared ZnO thin film by RF magnetron sputtering method and investigated the degree of c-axis orientation to obtain a highly oriented ZnO film perpendicular to the substrate surface. PSFETs were fabricated by forming the ZnO film on the FET gate under the optimal formation conditions and their performance characteristics were observed by monitoring gate voltage with time under the applied static pressure.

II. Operation mechanism of the PSFET

The schematic diagram showing the cross section of the PSFET is represented in Fig. 1 and detailed fabrication processes are given in other reference[6] . The structure is similar to that of a MOSFET except the gate SiO_2 is layered and overlaid with a thin piezoelectric ZnO film. The operation mechanisms of the PSFET can be explained by the combination of piezoelectric effect in the ZnO film and field effect of the FET. When a pressure is applied to the sensing gate including ZnO piezoelectric film, it produces a polarization charges or piezoelectric potential in the ZnO layer. The polarization charge is coupled to the inversion channel and drain current are thus modulated by the applied pressure. The quantative operation theory was described in detail by E. W. Greeneich[7] and *G. S. Yang et al*[8].

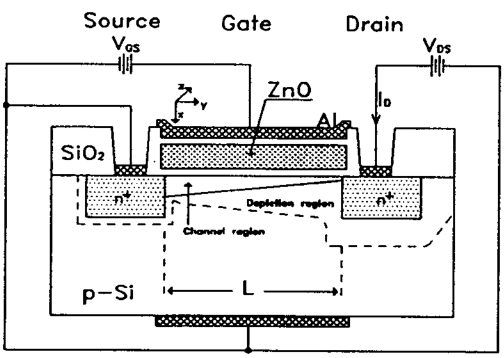


Fig. 1. Cross section of the PSFET.

III. The crystal property of ZnO film

The resistivity of sputter deposited ZnO films has been reported to be lowered by the deficiency of oxygen[9], which is the major drawback for applicating the ZnO film to pressure sensor in low frequency because piezoelectric charges produced by applied pressure is reduced by the leakage throughout the ZnO layer[10]. To increase the resistivity of the film, ZnO target was fabricated by using ZnO powder(99.9%, Aldrich) and Li_2CO_3(0.5 weight%) was doped during the target fabrication. The ZnO film prepared by this Li-doped target is expected to have higher resistivity than common target because the doped-Li can be substituted for the deficient oxygen sites[11].

The typical parameters that affect the crystal properties of the ZnO film in RF sputtering system are RF power, substrate temperature, working pressure, and reaction gas. By changing the sputtering parameters, we can obtain highly-oriented ZnO films perpendicular to the substrate surface. Table 1 represents the investigated optimal sputtering conditions.

Table 1. Optimal sputtering conditions of ZnO film

RF power	200 watt
Substrate temperature	100 ℃
Working pressure	15 mtorr
Reaction gas (Ar : O2)	1 : 1

For the high sensitivity on the applied pressure, the ZnO film formed on the FET gate must have a high c-axis orientation. Fig. 2 shows the x-ray diffractions of the ZnO films prepared under the optimal formation conditions. As shown in the figure, the only (002) direction peak appears in the 2θ axis and it therefore indicates that the film has c-axis orientation perpendicular to the

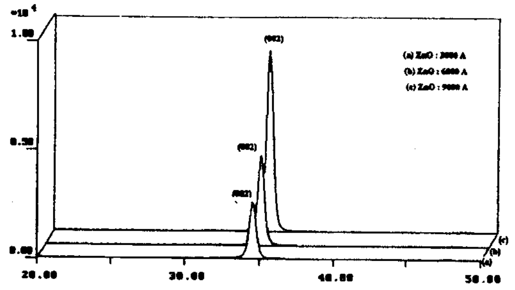


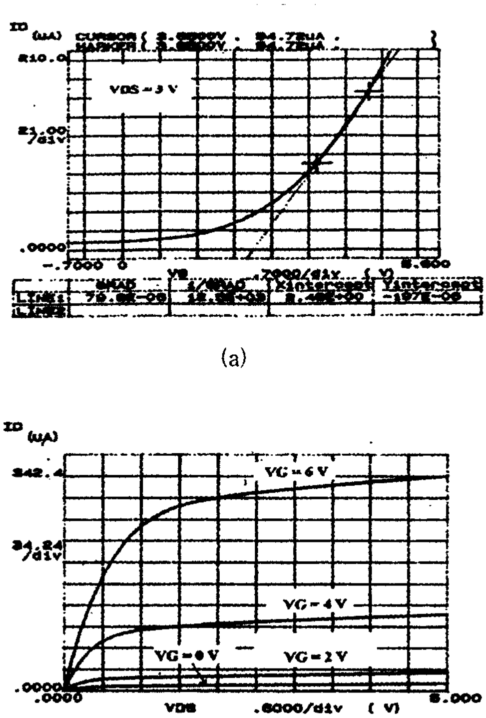
Fig. 2. X-ray diffraction patterns of ZnO films on thickness.

substrate surface. It must be noted that the ZnO films have excellent c-axis orientation in the thickness range of 3000 to 9000 Å.

IV. Characteristics of the PSFET

4-1. Operation characteristics of the PSFET

Fig. 3 shows the operation characteristics of the PSFET fabricated by forming 6000Å-ZnO and 1000Å-SiO_2 between metal and gate oxide of the MOSFET. The I-V curves of the sensors showed a slight change from initial state when it was measured again after a few seconds. After several continuos measuring, drain current under the fixed drain or gate voltage was stabilized, and the graphs in Fig. 3 represent a stabilized I-V curve after continuous biasing. As represented in transfer property of the Fig. 3 (a), the threshold voltage of the PSFET is about 2.4 V which is larger than that of typical MOSFET, and transconductance in saturation region is about 0.08 mA/V. This low transconductance over the typical MOSFET is due to the ZnO and top oxide layers because the transconductance of the MOSFET or PSFET has direct dependence on the thickness of gate insulation layer. Fig. 3 also indicates that the drain current is not zero but several micro-amperes, which means that the channel exists at the voltage much lower than threshold value. This depletion-type operation mode is caused by the ZnO film on PSFET gate where ZnO film has parasitic charges produced by excessive zinc in film or piezoelectric charges by the atmospheric pressure and internal film stress. It must be noted from Fig. 3 (b) that PSFET operates in very stable manner regardless of the relatively high threshold voltage and low transconductance.



(a)

(b)

Fig. 3. Operating characteristics of the 6000Å-ZnO PSFET.
(a) I_D - V_G, (b) I_D - V_{DS}.

4-2. Sensing characteristics of the PSFET

The pressure sensing properties of the PSFET was investigated by using the basic bias circuit represented in Fig. 4. Fig. 5 shows i_D - v_{GS} graph of the bias circuit where 'Q' and slope mean operating point(OP) and transconductance in OP, respectively. The v_{gs} in the transverse axis means an applied signal, which can be replaced by the piezoelectric potential developed in

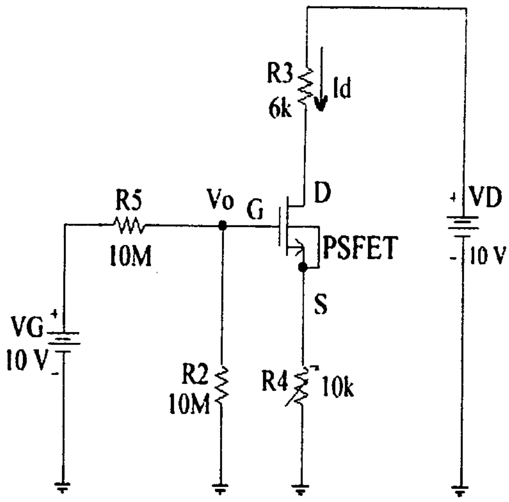


Fig. 4. The circuit for bias and pressure sensing of the PSFET.

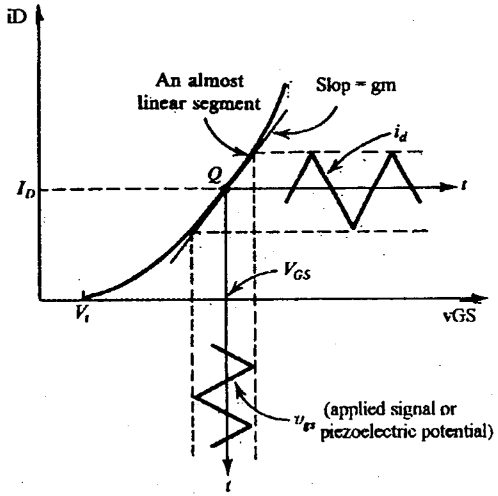


Fig. 5. Small signal operation of the PSFET bias circuit.

ZnO film by applied pressure, and i_d in the longitudinal axis indicates the corresponding variation of drain current by the applied signal or piezoelectric potential. It must be noticed that the change of drain current is directly proportional to the transconductance of the PSFET itself. In this paper the gate voltage and drain current in Fig. 4 were monitored to investigate the piezoelectric potential and corresponding drain current variation on applied pressure.

Fig. 6 shows the variation of gate voltage on applied pressure with time in each pressure levels. The "0 mmHg" at right side of the each graphs means the atmospheric pressure(760 mmHg) and each pressure levels indicate the magnitude of pressure increment from the atmospheric pressure. Vg(t=0) in the graph represents the beginning of the static pressure. As shown in the figures, the gate voltages decrease with time and the magnitude of the deviation from initial value increases in the higher pressure levels. These response characteristics of the gate voltages after pressure applied can be divided by two regions; region (b) and (c). The first region shows the fast decrease of the gate voltage, which is due to the transient response of the ZnO film. The ZnO film as well as two SiO_2 layers on the PSFET gate, which is compressed at the beginning of the pressure application, experiences transient characteristics before it reaches equilibrium state. It is expected that this transient response of the ZnO film is caused by the combined effects of the physical recovery of the ZnO film and transient characteristics of the piezoelectric dipoles after the pressure applied. The other region, followed by the fast decrease of the gate voltage, is due to the depolarization effect of the ZnO film, which makes the voltage decrease slowly. According to the *F. R. Blom, et al*[12], the low resistivity due to excessive zinc prevents any electric field building up in the film at low frequency, which is the major reason that ZnO films have been used for piezoelectric transducer operated in high frequency. The low frequency application of the ZnO film was considered to be impossible because the build-up of an electric field is counteracted by charge transport of free carriers at low frequency. For the application of the ZnO films at low frequency including dc, the resistivity of the film have to be increased or

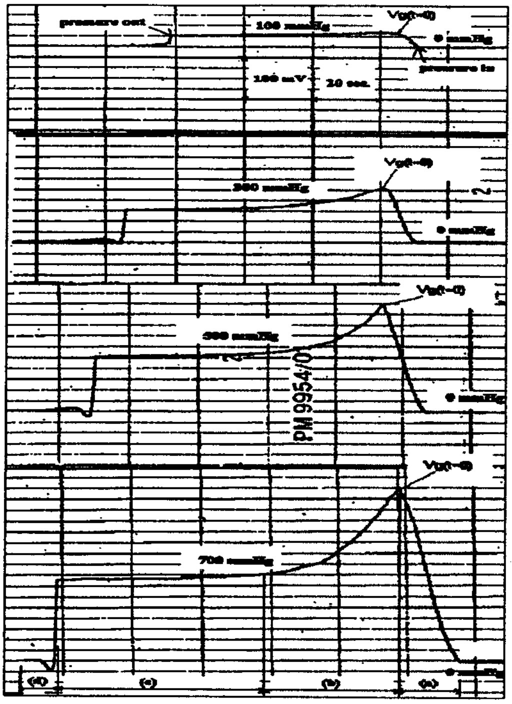


Fig. 6. The gate voltage variations with time in various applied pressures.

electric leakage path must be cut off. In this research the resistivity of the ZnO film was increased by using Li-doped ZnO target and leakage path was cut off by encapsulating the ZnO film between insulating SiO_2 layers. If the resistivity of the film is high enough and the insulating SiO_2 layers are perfectly grown without the leakage current through the PSFET gate surface, the gate voltage keeps constant without decreasing with time after the transient response of the voltage. The tiny leakage throughout the ZnO and SiO_2 layers however makes the piezoelectric potential decay with time in a constant pressure, which in turn affect the gate potential. Because the effective resistance of the gate is much higher than that of only ZnO film which makes the time constant so large, the gate voltage slowly decreases after transient response. After combining the above phenomenon, we can conclude that the transient response of the ZnO film occurs after static pressure applied, by which the gate voltage rapidly decreases. There is also a slight decrease in the gate voltage, after transient response, due to the electric leakage through the ZnO film. Fig. 6 also indicates that the response and recovery characteristics of the PSFET as well as the physical and electric properties of the ZnO film. It is shown in the graph with 700 mmHg pressure increment. The gate voltage increases with time during the region (a) where pressure is supplied gradually by using hand pump. It must be noted that region (a) takes longer time in the higher pressure levels because it takes more time for suppling higher pressure. Region (b) represents the decrease of gate voltage due to the transient response of the ZnO and insulation layers. Moreover, voltage decrease by the electric leakage through ZnO and two insulation layers is represented in region (c), and the decrease rate is much smaller than that by physical release of the ZnO film. Region (d) finally shows the recovery characteristics of the PSFET. The 95% settling time of the gate voltage varies with the magnitude of applied pressure as shown in the graphs of the Fig. 6 and it was investigated to be 10 to 20 sec.

Fig. 7 represents the gate voltages with applied pressure in various measurement delay time. It is seen from the figure that the sensitivity of the PSFET is linear after about 40 seconds. Fig. 8 shows the variation of the gate voltage in each pressure levels. As explained in the Fig. 6, the gate voltage shows slow decrease by the tiny electric leakage through ZnO film followed by the rapid decrease after pressure applied.

For the purpose of investigating the field effect on piezoelectric potentials developed by the applied pressure, we monitored the drain current on applied pressure in saturation region of the 6000Å-ZnO PSFET, which is represented in Fig. 9. The measurement delay was set to 40 seconds because gate voltage was investigated to be

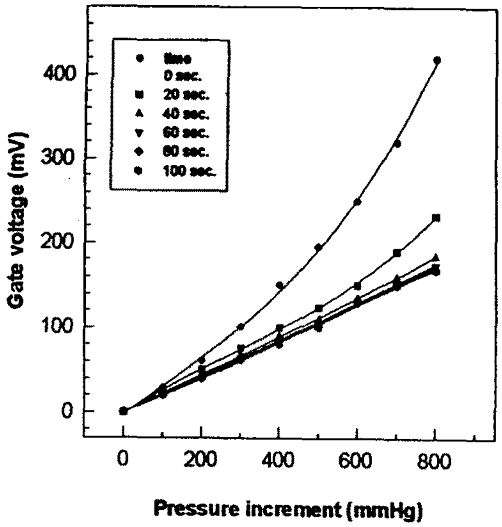


Fig. 7. The gate voltage of PSFET versus applied pressure with time.

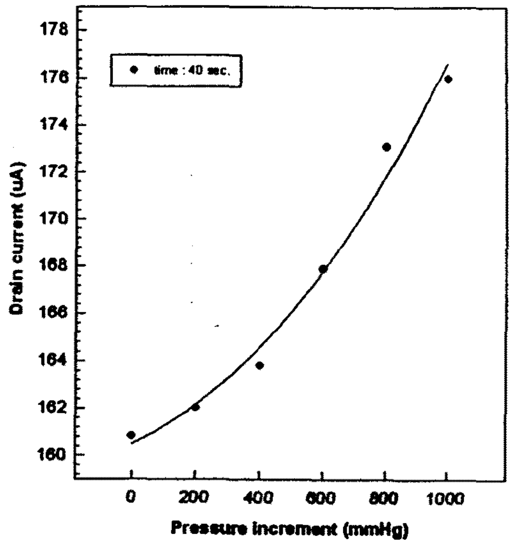


Fig. 9. Drain current on applied pressure of the 6000Å-ZnO PSFET(V_{DS}: 3V, V_{GS}: 5V).

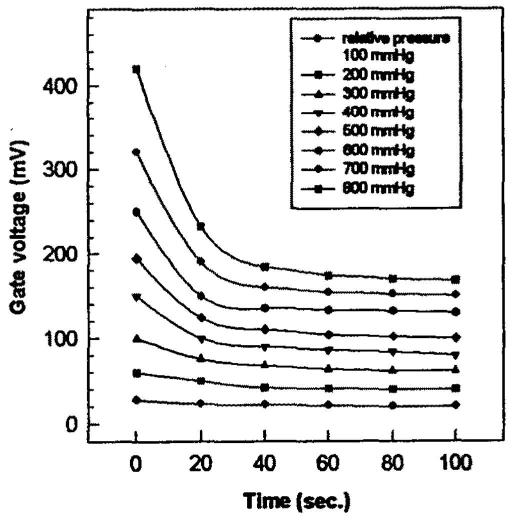


Fig. 8. The time response of the gate voltages in each applied pressure levels. ("zero" in transverse axis means Vg(t=0) in the Fig. 6.)

stabilized after about 40 seconds. As shown in the figure, the small quantity of drain current is changed on the applied pressure, which is due to the low transconductance of the PSFET as previously mentioned because the drain current variation on pressure is directly proportional to the transconductance of the PSFET.

V. Conclusions

Pressure sensitive field effect transistor(PSFET) was fabricated by forming ZnO piezoelectric film between metal and gate oxide of the MOSFET, and its operating and pressure sensing characteristics were investigated. Its operation mechanisms are by the combination of *"piezoelectric effect"* of the ZnO film and *"field effect"* of the field effect transistor.

The ZnO film known as typical piezoelectric material was prepared by the RF magnetron sputtering method. The observed optimal sputtering conditions of the ZnO film were RF power of 200W, substrate temperature of 100℃, gas pressure of 15 mtorr, and gas ratio of Ar(50%) : O_2(50%). The optimally prepared ZnO film was investigated to have an excellent c-axis orientation. For the application of the ZnO film at low frequency, resistivity of the film was increased by using Li-doped ZnO target, and electric leakage was cut off by encapsulating the ZnO film between two insulating SiO_2 layers.

The pressure sensing properties of the PSFET were observed by using the basic bias circuit where the variations of gate voltage and drain current were monitored with applied pressure. The sensitivity of the sensors were dependent on the time after pressure applied, which is due to the transient characteristics of the ZnO film and electric leakage through the ZnO and SiO_2 layers. However, the infinitesimal leakage through ZnO and SiO_2 layers is expected to be reduced by improving quality of the passivation layers. Also the transient characteristics including physical release of the ZnO film can be minimized by reducing the internal stress of the ZnO film.

The investigated sensitivity of the gate voltage was 0.21 mV/mmHg in 6000Å-ZnO PSFET, which was calculated from the graph labeled by 40 sec. in Fig. 7. It must be noted that these high sensitivities of the fabricated PSFET are due to the highly oriented ZnO film. Moreover, the gate voltage varied in linear manner although it still takes a little time(about 40 sec.) until ZnO film reaches equilibrium state. Its operating pressure range was about 760 to 1560 mmHg. And the sensitivity of the drain current was 0.02 μA/mmHg in the observed pressure range where the drain current was read after 40 seconds.

References

[1] V. Mosser, J. suski, J. Goss, and K. Suzuki, "Piezoresistive pressure sensors based polycrystalline silicon" *Sensors and Actuators, A28, 113-132, 1991.*

[2] H. Tanigawa, T. ishihara, M. Hirata, and K. Suzuki, "MOS integrated silicon pressure sensor", *IEEE Trans. Electron Devices, vol. ED-32, no. 7, pp. 1191 - 1195, July 1985.*

[3] U. Schomeberg, F. V. Schmatz, "CMOS integrated capacitive pressure transducer with on-chip electronics and digital calibration capability" *IEEE, 308 - 310, 1991.*

[4] T. Nagata, H. Terabe, "Digital compensated capacitive pressure sensor using CMOS technology for low pressure measurements", *IEEE, 304 - 307, 1991.*

[5] P. L. Cheng, R. S. Muller, R. M. White, and R. Jolly, "Thin Film ZnO-MOS Transducer with Virtually DC Response", *IEEE Ultrasonics Symposium Nov. 5-7, 1980, Boston, MA.*

[6] Jeong-Chul Lee, "Pressure sensitive field effect transistor using highly oriented ZnO piezoelectric thin film", *Thesis for the degree of master, December 1996, Kyungpook Nat'l Univ.*

[7] E. W. Greeneich and R. S. Muller, "Theorectical transducer properties of piezoelectric insulator FET transducers", *Journal of Applied Physics, Vol.46. No.11, Nov., 1975.*

[8] G. S. Yang, B. W. Cho, D. H. Kwon, K. H. Nam, and B. K. Sohn, "The operational Characteristics of a Pressure Sensitive FET Sensor Using Piezoelectric Thin Film", *Journal of the Korean Sensors Society Vol.4 No.2, pp. 1-7, May, 1995.*

[9] T. Shiosaki and A. Kawabata, "Low-frequency piezoelectric-transducer applications of ZnO films", *Appl. Phys. Lett., 25, 1974.*

[10] D. L. Pollar and R. S. Mullar, "Zinc oxide thin films for integrated sensor applications", *Tech. Digest, IEEE Solid-state Sensors Workshop, Hilton Head Island, SC, U. S. A., June 6-9, 1986.*

[11] T. Mitsuyu, S. Ono, and k. wasa, "Structures and SAW properties of rf-sputtered single-crystal films of ZnO on sapphire", *J. Appl. Phys., 51(5), May 1980.*

[12] F. R. Blom, D. J. Tntema, F. C. M. Van De Pol, M. Elwenspoek, J. H. J. Fluitman and Th. J. A. Popma, "Thin-film ZnO as Micromechanical Actuator at Low Frequencies", *Sensors and Actuators, A27-A23 (1990) 226-228.*

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『센서학회지 제2권 제2호』 논문 93-2-2-04, p. 29참조. 현재 경일대학교 전자공학과 조교수

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