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Thin-film ZnO as Micromechanical Actuator at Low Frequencies

F. R. BLOM, D. J. YNTEMA, F. C. M. VAN DE POL, M. ELWENSPOEK, J. H. J. FLUITMAN and TH. J. A. POPMA
Faculty of Electrical Engineering, University of Twente, P.O. Box 217, 7500 AE Enschede (The Netherlands)

Abstract

A new model is proposed for the low-frequency piezoelectric activity of ZnO films grown on CVD SiO_2. In this MOS structure, with ZnO as the semiconductor, a depletion layer is induced by means of a d.c. bias voltage. Using standard semiconductor theory, an expression is derived relating the electric field in this depletion layer with the driving a.c. and d.c. voltages. Due to the built-in charge at the ZnO–SiO_2 interface, a depletion layer exists, even when no d.c. bias is applied. We measured the vibration amplitude at resonance of the tip of a silicon cantilever, upon which the MOS structure was deposited, as function of a.c. and d.c. voltages. The results show good agreement with calculated curves. Therefore, it can be concluded that thin-film ZnO can be used as a piezoelectric actuator for micromechanical devices working at low frequencies.

Introduction

Thin-film ZnO is a very promising material for electromechanical transducers, since it has high piezoelectric coupling factors [1]. Unfortunately, there are several problems with this material. The most severe problem arises from the conductivity due to excessive zinc, which prevents any electric field building up in the film at low frequencies. The cut-off frequency is determined by the relaxation time τ, given by the product of the resistivity ρ and the permittivity ε of the material [2]. Consequently, ZnO films can easily be used above 1 MHz and therefore thin-film ZnO is often used as a piezoelectric transducer in the field of SAW and BAW resonators (see, e.g., refs. 2 and 3).

At low-frequency applications, however, the build-up of an electric field is counteracted by charge transport of free carriers. In the literature, solutions for this problem have been sought by increasing the resistivity of the film by doping with, for instance, lithium [2], or by encapsulating the ZnO film between insulating SiO_2 layers, hence cutting off electric leakage paths [4, 5]. The explanation Muller *et al.* [4, 5] give for the low-frequency activity of their ZnO films is the Debye length, L_D, being much larger than typical film thicknesses of 120 and 1 μm, respectively. This explanation is not valid for our ZnO films grown on CVD SiO_2 as we have determined a much smaller value for L_D, namely $L_D = 5$ nm [6]. However, earlier work in our group on micromechanical sensors demonstrated the low-frequency activity of ZnO films as piezoelectric transducers [7, 8].

In this paper we propose an explanation for the low-frequency activity of ZnO films, based on standard semiconductor theory (see ref. 9) and the electric model for these layers, which is described elsewhere [6].

Model

A sputtered ZnO film can be treated as a polycrystalline semiconductor. Low-frequency application of this piezoelectric material requires a depletion layer inside the semiconducting film to sustain an electric field, for instance by means of an MOS structure. The width of this depletion layer can be calculated as a function of the applied d.c. voltage from standard semiconductor theory. When the electric field is known, the electromechanical transduction of the piezoelectric effect can be calculated.

In the following, we shall apply this simple strategy to a ZnO film grown on CVD SiO_2, an MOS structure, depicted in Fig. 1. Also in this Figure the space charge distribution and the electric field in the different layers are shown, if a negative d.c. voltage, U_{DC}, is applied. Using Poisson's equation we can calculate the electric field in every region. Integrating over the complete MOS structure, we derive the relation for the width of the depletion layer as a function of U_{DC}, $W_d(U_{DC})$. On this d.c. voltage we superpose an a.c. signal, U_{AC}, which is so small that W_d is not influenced. In this case the electric field in the depleted ZnO, E_z, varies proportionally to U_{AC}. In order to determine the relation between E_z and

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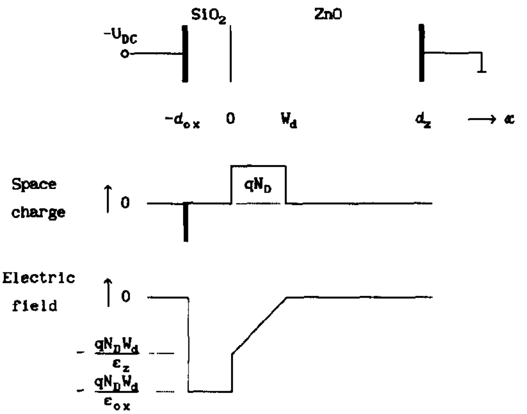

Fig 1 Cross section of the SiO_2–ZnO MOS structure with the space charge distribution and the electric field in the different regions if a negative d c voltage is applied

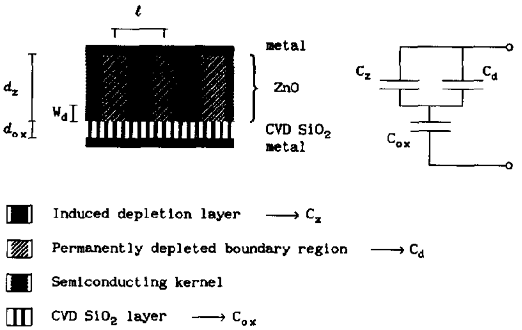

Fig 2 Schematic drawing of the MOS structure, showing the columnar structure of the ZnO layer with the permanently depleted boundary region, the semiconducting kernel and the induced depletion layer in the kernel Also important parameters and the equivalent circuit are shown

U_{AC}, we have to take a closer look at the film structure

Our ZnO films consist of columnar grains, containing a semiconducting kernel surrounded by a permanently depleted boundary region [6] This is schematically depicted in Fig 2 The equivalent circuit of the MOS structure then consists of three capacitors, one corresponding to the SiO_2 layer, C_{ox}, one to the boundary region, C_d, and one due to the induced depletion layer in the kernel, C_z With the aid of this circuit we can calculate the relation between U_{AC} and E_z, which is also dependent on U_{DC}, thus $E_z = f(U_{DC})\ U_{AC}$

Measurement Method and Sample Structure

In order to determine the piezoelectric activity of the ZnO films, we used a micromachined silicon cantilever with an MOS structure deposited top, see Fig 3 This multilayer structure is excited into a bending mode vibration by the piezoelectric effect in the depletion layer The vibration amplitude of the tip of the cantilever at resonance is measured with a heterodyne Mach Zehnder interferometer, which allows an absolute determination of the amplitude

The cantilevers are 5 mm long, 0 2 to 0 5 mm wide and 15 to 25 μm thick, depending on the batch used The ZnO film is reactively sputtered in a planar RF magnetron system from a pure Zn target using 100% O_2 The ZnO is 0 5 μm, the SiO_2 0 15 μm thick, respectively Molybdenum is used as the bottom electrode, aluminium as the top electrode material The tip of the cantilever is not deposited with thin films and serves as a mirror for the optical detection

A relation is now derived for the deflection of the tip of the silicon cantilever with an MOS structure deposited on top, due to the piezoelectric activity in the ZnO, see Fig 3 As a first order we shall approximate the activity of the complete ZnO layer with that of a layer having a thickness W_d only The electric field is applied over this thickness, resulting in a mean stress in the ZnO The real stress distribution in the ZnO layer is much more complicated, cf Fig 2, and a three-dimensional analysis is required to solve this problem Our approximation results in neglecting the upper part of the ZnO layer

Since the thickness of the ZnO layer, d_z, is much smaller than that of the silicon cantilever, d_s, we find a simple relation between the dynamic vibration amplitude of the cantilever at resonance as function of the driving a c and d c voltages

$$\delta = 3Q \frac{Y_z}{Y_s}\left(\frac{l_s}{d_s}\right)^2 d_{31} U_{AC} f(U_{DC}) \qquad (1)$$

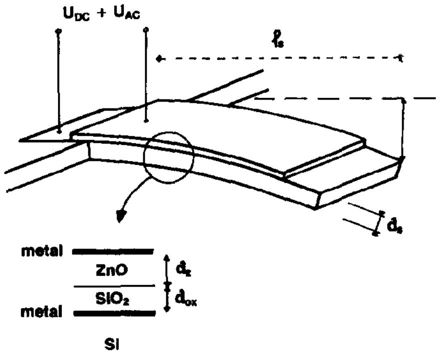

Fig 3 The multilayered cantilever in vibrationary deflection with a close-up the cross section of the SiO_2–ZnO MOS structure on top of the silicon

where Q, Y_z, Y_s, l_s and d_{31} are, respectively, the mechanical quality factor, the Young's modulus of ZnO and of Si, the length of the cantilever and the piezoelectric coefficient of ZnO

Results and Discussion

Results of measurements of the vibration amplitude of the tip of the cantilever as a function of U_{AC} and U_{DC} are shown in Fig 4 The theoretical curves, calculated according to eqn (1), are drawn as well In these calculations the bulk value of the piezoelectric coefficient d_{31} is used, namely $d_{31} = -5\ 1 \times 10^{-12}$ m/V [10] The mechanical quality factor of the cantilever is 95 ± 10

In Fig 4 it is seen that the measured results agree quite well with the calculated curves δ is proportional to U_{AC} and varies with U_{DC} in accordance to our model We also observe δ remaining constant for U_{DC} below -4 V In this case inversion occurs at the ZnO–SiO$_2$ interface and the depletion layer in the ZnO has reached its maximum width This effect is not accounted for in the calculations

Furthermore, we observe an off-set in the d c voltage of 7 ± 1 V, which is due to interface charge at the ZnO–SiO$_2$ interface This shift is in agreement with the results of C–V measurements, where a mean flat-band voltage was found of 5 ± 1 V [6] An important conclusion of this observation is that no external d c voltage is required to use the piezoelectric effect We can also apply this explanation to the results of Muller *et al* [4, 5] As outlined above, they encapsulated their ZnO films between insulating SiO$_2$ layers Because of the interface charge, they found low-frequency piezoelectric activity of the ZnO

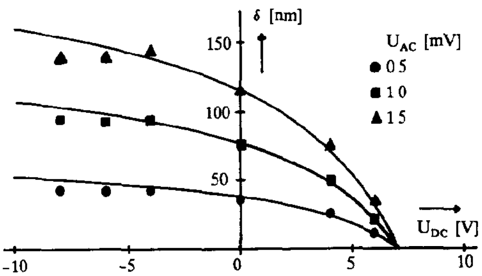

Fig 4 Measured (●, ■, ▲) and calculated (full line) values of the vibration amplitude δ of the tip of the cantilever at resonance as a function of d c and a c voltages

Conclusions

In this paper we propose a new model explaining the low-frequency application of semiconducting ZnO films Using an MOS structure with ZnO as the semiconductor, a depletion layer is induced by means of a d c voltage The electric field in this layer is proportional to the driving a c voltage Because of a built-in charge at the ZnO–SiO$_2$ interface, a depletion layer exists, even when no d c bias is applied Therefore, ZnO thin films can be applied as piezoelectric transducers for micromechanical devices working at low frequencies

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References

1 T Shiosaki and A Kawabata, Piezoelectric thin films for SAW applications, *Ferroelectrics*, *42* (1982) 219–232

2 T Shiosaki and A Kawabata, Low-frequency piezoelectric-transducer applications of ZnO film, *Appl Phys Lett*, *25* (1974) 10

3 S Ono, K Wasa and S Hayakawa, Surface-acoustic-wave properties in ZnO–SiO$_2$–Si layered structure, *Wave Electron*, *3* (1977) 35

4 D L Polla and R S Muller, 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

5 P L Chen, R S Muller, R M White and R Jolly, Thin film ZnO-MOS transducer with virtually DC response, *Proc IEEE Ultrasonics Symp*, *Boston, MA, U S A*, *Nov 1980*, p 945

6 F R Blom, F C M van de Pol, G Bauhuis and Th J A Popma, Electric model and electric properties of sputtered polycrystalline Zno films, *Thin Solid Films*, submitted for publication

7 J G Smits, H A C Tilmans, K Hoen, H Mulder, J van Vurren and G Boom, Resonant diaphragm pressure measurement system with ZnO on Si excitation, *Sensors and Actuators*, *4* (1983) 565–571

8 S Bouwstra, Scanner-research, third phase of the Integrated Laser Beam Deflector project, *Internal Rep 070 1055*, University of Twente, 1986 (in Dutch)

9 e g , S M Sze, *Semiconductor Devices*, *Physics and Technology*, Wiley, New York, 1st edn , 1985, pp 186–195, R S Muller and T I Kamins, *Device Electronics for Integrated Circuits*, Wiley, New York, 2nd edn , 1986, pp 378–394

10 K -H Hellwegei (ed), *Landolt and Börnstein, Numerical Data and Functional Relationships in Science and Technology*, Vol III-11, Springer, Berlin, 1979, p 370