Long-term effect of relative humidity on ZnO-based MEMS acoustic sensor

Mahanth Prasad[1], V. Sahula[2] and V.K. Khanna[1]

***Abstract*—This study investigated the long-term influence of relative humidity on capacitance and dissipation factor tanδ of ZnO-based MEMS acoustic sensor. Acoustic sensor chips were fabricated using silicon-on-insulator (SOI) wafers in two batches. Two different thicknesses of PECVD silicon dioxide for passivation, 0.3 µm and 0.6 µm were taken in batch # 1 and batch # 2 respectively. The initial capacitance and corresponding losses of acoustic sensor chips of both batches were measured. The devices were stored for five months in relative humidity environment between 60%-80%. The device capacitance and losses were measured again. In case of batch # 1, the capacitance of acoustic sensor chips was found to be 1.8 times higher after five months than the original values. The loss tanδ was also found to increase. But in case of batch # 2 acoustic sensor chips, negligibly small variations in capacitance and corresponding losses were observed. The investigation show that the larger thickness of PECVD silicon dioxide could protect the sensors from ambient humidity over a long period of time.**

***Index Terms*—MEMS acoustic sensor, bulk-micromachining, humidity, ZnO**

I. Introduction

Zinc oxide piezoelectric material is widely used in fabricating the acoustic sensor [1, 2], microphone and microspeaker [3]-[5]. ZnO is a very reactive material. It is easily attacked by almost all acids, bases, and even water [6]. Thus humidity monitoring and control are essential for automotive, environmental manufacturing, medical and semiconductor industries [7, 8]. The previous research [9] demonstrated that adsorption of oxygen on ZnO surface take place in a humid environment, affecting the the acoustic velocity and resonance frequency of the device. In [10], the researchers also show the change in electrical characteristics of ZnO nanowire FETs when they are exposed to wet air (80% relative humidity, RH) at room temperature for more than tens of hours. After exposure to humidity, change in threshold voltage of device and significant roughening were observed on ZnO surface. The long-term stability of such devices is affected when they need to be in contact with environment for their operations. Therefore, it is necessary to understand the storage conditions which affect the device characteristics for better understanding of the operating mechanism and stability of the devices.

This paper presents the long-term effect of humidity exposure on the device characteristics. It was observed that when the thickness of passivation layer is too small (~ 0.3 µm), the device characteristics are affected by humidity. The paper also describes that the device characteristics are less affected by humidity over a long period time, when the thickness of passivation layer is higher ($\geqslant$ 0.6 µm).

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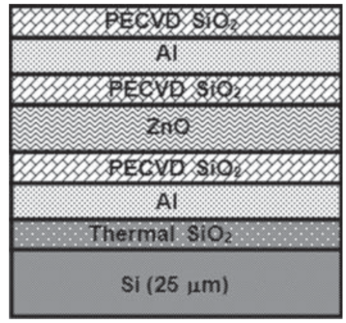


Figure 1: Cross-sectional view of the MEMS acoustic sensor.

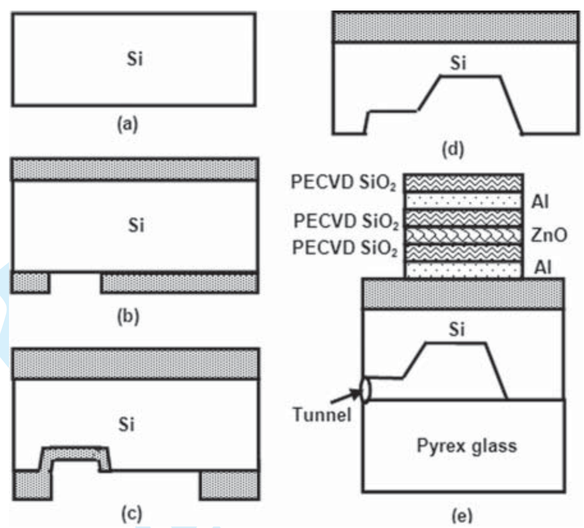


Figure 2: Flow chart for fabrication of acoustic sensor

II. Experimental Results and Discussion

A. Fabrication of MEMS Acoustic Sensor

Fabrication of ZnO-based MEMS acoustic sensor involves six mask levels: Mask # 1 for acoustic micro-tunnel; Mask # 2 for silicon diaphragm; Mask#3 for bottom electrodes; Mask # 4 for ZnO patterning; Mask # 5 for top electrodes and Mask # 6 for pad opening. The cross-sectional view of the device structure is shown in Fig. 1. The structure consists of a ZnO film covered with 0.3 µm thick plasma enhanced chemical vapor deposition (PECVD) silicon dioxide on both sides, sandwiched between two Al electrodes on a 25 µm-thick silicon diaphragm. The silicon diaphragm was fabricated by bulk-micromachining of silicon using tetra methyl ammonium hydroxide (TMAH) solution. The bottom electrode at the center of diaphragm has dimensions of 1.5 mm × 1.5 mm. Top electrode has the same dimension as bottom electrode.

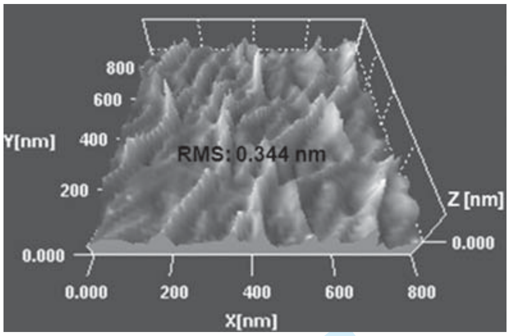
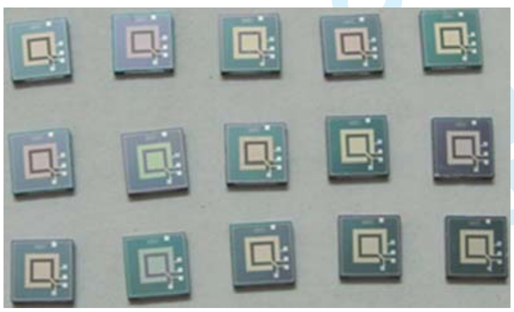


Figure 3: AFM image of ZnO deposited structure.



(a)

(b)

Figure 4: Diced acoustic sensor chips: (a) front view, and (b) back view.

ZnO and contact pads have dimensions of 3.1 mm × 3.1 mm and 0.4 mm × 0.4 mm respectively [11]. The fabrication of device is started with 4-inch SOI wafers having 25 µm thick active layer. The resistivity and thickness of buried oxide layer were taken as 10 to 20 ohm cm, and 1.0 µm respectively. The fabrication flow of the device is shown in Fig.2. Thermal oxidation of 0.5 µm thick silicon dioxide was done on these wafers at 1000 °C. Microtunnel patterning was done using S1818 positive photoresist. Silicon dioxide layer was then removed from microtunnel area for bulk-micromachining of silicon. A 35.0 µm deep and 100.0 µm wide microtunnel was fabricated using 25% tetra methyl ammonium hydroxide (TMAH solution). The tunnel depth was measured using Dektak 6M surface profile. After tunnel etching, 1.0 µm thick silicon dioxide was grown and diaphragm patterning was done using SU8 photoresist. Diaphragm of 25 µm thickness was fabricated using bulk-micromachining of silicon along with microtunnel for pressure compensation. After fabrication of micro-tunnel and silicon diaphragm, the silicon dioxide was completely removed from cavity side of the wafer for anodic bonding. A capacitor using ZnO as a dielectric layer was then fabricated on silicon diaphragm. In this process, approximately 1.0 µm thick Al layer deposited by sputtering technique was used for bottom and top electrodes. ZnO films were deposited by RF magnetron sputtering technique with a zinc target (with purity of 99.99%). The process parameters were as follows: sputtering power = 550W, pressure = 20 mtorr, gas composition = Ar and O_2 in 40:60 ratio and deposition time = 2.5 hours. An AFM study was carried out to investigate the surface roughness of deposited ZnO film, and it was found to be 0.321 nm, as illustrated in Fig.3. The thickness of ZnO film was measured using Dektak 6M surface profile, and found to be 2.4 µm. 0.3 µm thick PECVD silicon dioxide oxide layers was deposited before and after ZnO deposition to protect the inter-diffusion of Al into ZnO. Then 0.3 µm and 0.6 µm thick PECVD silicon dioxide layer was deposited as passivation layer on batch # 1 and batch # 2 wafers respectively. Finally, reactive ion etching technique was used to open the pad area for wire bonding. Dicing of fabricated wafers was then carried out using double spindle dicing machine. At the time of dicing, microtunnel was opened which related the cavity to the atmosphere. The photographs of diced acoustic sensor chips are shown in Fig. 4(a) and 4(b).

B. *Capacitance measurement of acoustic sensor chips*

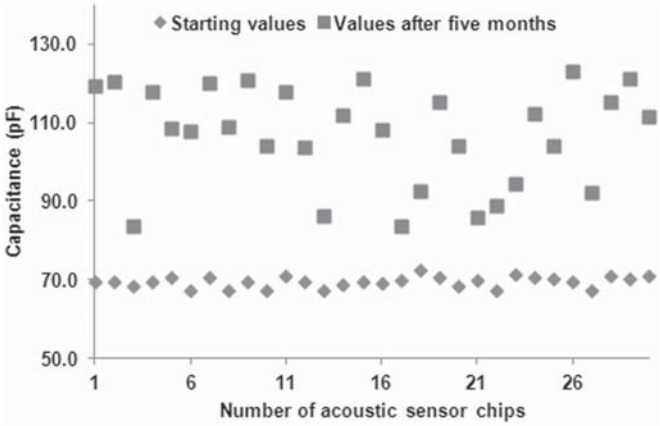
Total 37 numbers of acoustic chips; 30 nos. from batch # 1 and 07 nos. from batch # 2 were selected for measurement. The capacitance and loss ($\tan\delta$) of these chips were measured by Agilent 4284A 20Hz-1MHz Precision LCR Meter at 1 kHz. Figs. 5(a) and 5(b) show the values of capacitance versus number of chips and loss versus number of chips respectively from batch # 1. In a similar way, Figs. 6(a) and 6(b) show the values of capacitance versus number of chips and loss versus number of chips respectively from batch # 2.

III. Results and Discussion

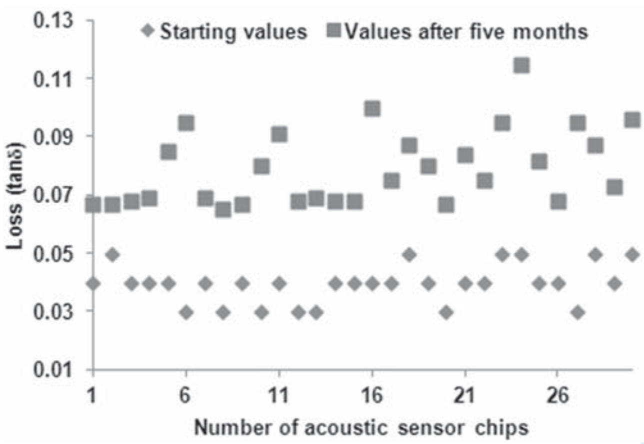
It was observed from Figs. 5(a) and 5(b) that the capacitance and loss ($\tan\delta$) of acoustic sensor chips of batch # 1 have approximately 1.8 times of starting values when measured again after five months. The relative humidity during this period was 60% to 80%. This shows that the humidity affects the capacitances of acoustic sensors chips fabricated in batch # 1. These results validate the Henry's law for low analyte concentrations. This law states that the change in dielectric constant upon water vapor adsorption, $\triangle\varepsilon$ should be positive [12] and expressed as:

$$\triangle\varepsilon \propto \phi_w \left(\varepsilon_w - \varepsilon_{air}\right) \tag{1}$$

where ε_w and ε_{air} are the dielectric constant of water and air respectively, and ϕ_w is the amount of adsorbed water,

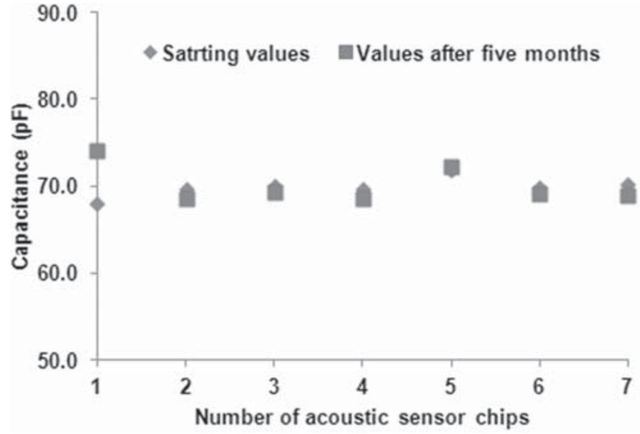


(a)

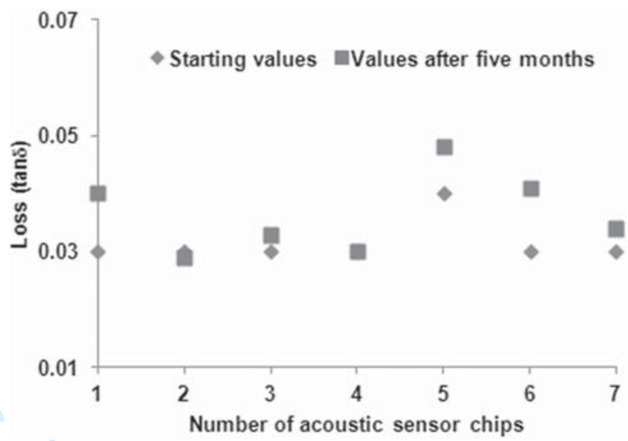


(b)

Figure 5: Measurement of: (a) capacitance of batch # 1 chips in the beginning, and after five months, (b) loss (tanδ) of batch # 1 chips at starting and after five months of the experiment.



(a)



(b)

Figure 6: Measurement of: (a) capacitance of batch # 2 chips in the beginning, and after five months, (b) loss (tanδ) of batch # 2 chips in the beginning and after five months.

expressed as volume fraction. The variation of $\triangle\varepsilon$ will lead to change the capacitance of the device. Since the thickness of passivating layer (PECVD silicon dioxide) is too small ($\sim$ 0.3 µm), and the film is also porous because of lower deposition temperature ($\sim$300 ºC), the water vapor adsorption takes place on ZnO surface because of high humidity variation in storage condition of the devices. From Eq.(1), since relative dielectric constant of water is higher than that of air, the water adsorption of ZnO surface will lead to larger change in dielectric constant, and finally larger change in capacitance. This effect is shown in Fig. 5. Also during fabrication of device, the top and bottom Al electrodes were deposited using sputtering technique, therefore these electrodes cannot form a conformal coating on ZnO because of surface of the film. Thus, there would be small gaps between ZnO and Al electrodes, which provide a channel for moisture to reach ZnO [13].

In batch # 2 acoustic sensor chips, the initial values of capacitance and loss (tanδ) is approximately same as values measured after five months in the storage condition of high humidity 60% - 80%, as shown in Figs. 6(a) and 6(b). In this case the passivating PECVD silicon dioxide thickness was higher (0.6 µm) as compared to batch#1 acoustic sensor chips.

IV. CONCLUSION

The long-term effects of humidity on the performance of ZnO-based MEMS acoustic sensor chips were studied. It was observed that for low passivating layer (PECVD silicon dioxide) thickness 0.3 µm, the dielectric constant of ZnO film changed when the acoustic sensor chips were stored in a humidly condition of 60% – 80 % over a long period of time (five months). But in case, where the passivation layer PECVD silicon dioxide thickness was higher (0.6 µm), the values of capacitances and corresponding losses were not affected. Finally it was concluded that the higher passivation layer thickness was sufficient to protect the ZnO-based devices from humidity over a long period of time.

V. ACKNOWLEDGMENT

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