Tactile Sensor Based on Flexible AlN Piezocapacitor Coupled With MOSFET

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Abstract—This paper presents tactile sensor devices based on flexible aluminum nitride (AlN) piezocapacitor coupled with the metal–oxide–semiconductor field-effect transistor (MOSFET). The AlN exhibits piezoelectric behavior without the typical requirement of high voltage for poling, and this makes it an ideal candidate for sensor, where the transducer layer is integrated with MOSFET. The AlN film used here was deposited on a polyimide substrate by room temperature RF sputtering to obtain flexible piezocapacitor. The film properties, such as orientation, roughness, elemental composition, and thickness, were investigated by the X-ray diffraction (XRD), atomic force microscopy (AFM), energy-dispersive X-ray spectroscopy (EDX), and scanning electron microscope (SEM), respectively. The tactile sensor developed by connecting the flexible AlN piezocapacitor in an extended gate configuration exhibited a sensitivity of 2.64 N$^{-1}$ for a force range 0.5–3.5 N. The developed sensor demonstrates a promising route toward the development of a complete CMOS compatible process for the development of tactile sensors.

Index Terms—AlN, piezocapacitor, tactile sensing, flexible electronics.

I. INTRODUCTION

SMART pressure or force sensors with capability to detect dynamic contact conditions are needed in robotics, human-machine interaction and biomedical instruments [1]–[4]. These sensors usually convert applied mechanical stimuli into electrical signal using transduction mechanisms such as piezoresistive, piezoelectric, inductive, and magnetism [5]. Among these the piezoelectric transduction has been widely explored to mimic the fast adapting mechanoreceptors of human skin [6], [7]. As a result, a wide range of piezoelectric materials, spanning from ceramics to polymers, have been explored to develop the piezocapacitors [8]. These piezocapacitors are either used as standalone device or are integrated or coupled with field effect transistors (FETs) [9]. The latter approach is advantageous since it enables better signal to noise ratio as it is possible to integrate the signal conditioning circuitry close to the capacitors and also allows the development of high spatial resolution tactile sensing arrays [10]–[12]. The inherent flexible devices such transistor fabricated using organic semiconductors and thin films have also been used as in combination with piezoelectric materials as transducing layer. The flexibility of both parts tends to give a better flexibility to the system. However, the challenging issues such as low mobility and reliability poses challenges for these devices as sensors under dynamic environment. That is why, in this paper we use silicon based MOSFET which has high mobility and unprecedented reliability. Nevertheless, the system can be termed as semi-flexible due to rigidity of the MOSFET. This issue could be solved by using ultra-thin silicon technology, by which it is possible to develop the bendable version of these devices if they are fabricated using silicon technology [13], [14].

The FET based approach has been explored with piezocapacitor (made of materials such as polyvinylidene fluoride (PVDF) and copolymer P(VDF-TrFE) [15], lead zirconate titanate (PZT) [9], [16], and zinc oxide (ZnO) [17]), either connected in an extended gate configuration (Fig. 1(a)) or deposited directly on the gate area of the transistor (Fig 1(b)). In these architectures, the piezopotential, generated as a result of application of force, modulates the channel current. One of the bottlenecks with these configurations where piezocapacitors integrated on FETs is that the materials (e.g. PZT, PVDF and its copolymers) they
use require high poling voltage ($\sim$100V/μm [18], [16]) to orient the dipoles in desired direction. Such high voltages pose a risk for FETs operation to the extent it often devices are permanently damaged. Naturally, the issue could be addressed by using alternative materials which do not require any poling. The devices presented in this paper demonstrate one such approach where no poling step is needed for the piezocapacitor. The piezocapacitor presented here is made of Aluminium Nitride (AlN), which is structurally piezoelectric, owing to its non-centrosymmetric wurtzite crystal [19]. Although the piezoelectric properties of AlN are inferior to other ferroelectric material such as PZT, ZnO, barium titanate and PVDF, it offers other advantages such as high signal to noise ratio, low dielectric loss tangent and hysteresis-free behavior [20]. Unlike PZT, AlN does not pose any contamination risk during CMOS fabrication and therefore it is compatible with flexible substrate [28]. The quality of the sputtered film is influenced by various parameters such as chamber pressure, gas composition, power, target to substrate distance and temperature. These parameters were carefully selected to attain a strong c-axis oriented film, which is needed for AlN to be used as the transducer. The presence of crystal orientation other than (002) such as (100) and (101) is detrimental to the piezoelectric property of the AlN film [29]. The piezoelectric AlN film used in our study was deposited using Plassys MP 900S sputter tool which has a primary load-lock chamber and a main chamber. The base pressure in the main chamber was about $5 \times 10^{-8}$ mbar. The aluminum target was 6.35 mm thick and 150 mm in diameter, with a purity of 99.99%. The reactive and sputtering gases were high-purity Nitrogen ($N_2$) and Argon (Ar), respectively. The sputtering parameters were chosen after extensive process optimization runs and the values are summarized in Table I.

The polyimide (PI) foil of thickness 80 μm from DuPont Chemicals, was degreased using ultrasonic cleaning in acetone, isopropanol and RO water and dried in an oven at 110°C to remove any moisture trace. Bottom electrode (20 nm titanium and 100 nm aluminum) was deposited on the backside of PI and then it was loaded in the sputtering tool holder with the distance between the target and the substrate set at 59 mm and no external heating was supplied to the substrate. Pre-sputtering process was carried out for 10 minutes with the closed shutter to remove any contaminant from the Al target. The sputtering was carried out for 2 hours, and finally, the top electrode (20 nm titanium and 100 nm gold) was deposited over PI-AlN stack. The effective dimension of the sensing layer was 1 cm × 1 cm, which is defined by the top metal area.

### Table I

| Parameter                  | Value |
|----------------------------|-------|
| Chamber Pressure           | 5 mtorr |
| Power                      | 500 W  |
| Nitrogen flow rate         | 50 sccm |
| Argon flow rate            | 30 sccm |

### II. Fabrication

#### A. Flexible Aluminium Nitride Piezocapacitor

The AlN films are typically deposited using molecular beam epitaxy (MBE) or chemical vapor deposition (CVD) [26], [27]. However, these methods are incompatible with flexible substrates such as polyimide as they require high deposition temperatures. For this reason, reactive RF magnetron sputtering was chosen here for the deposition of AlN at temperature which is compatible with flexible substrate [28]. The quality of the sputtered film is influenced by various parameters such as chamber pressure, gas composition, power, target to substrate distance and temperature. These parameters were carefully selected to attain a strong c-axis oriented film, which is needed for AlN to be used as the transducer. The presence of crystal orientation other than (002) such as (100) and (101) is detrimental to the piezoelectric property of the AlN film [29]. The piezoelectric AlN film used in our study was deposited using Plassys MP 900S sputter tool which has a primary load-lock chamber and a main chamber. The base pressure in the main chamber was about $5 \times 10^{-8}$ mbar. The aluminum target was 6.35 mm thick and 150 mm in diameter, with a purity of 99.99%. The reactive and sputtering gases were high-purity Nitrogen ($N_2$) and Argon (Ar), respectively. The sputtering parameters were chosen after extensive process optimization runs and the values are summarized in Table I.

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#### B. MOSFET Fabrication

The MOSFETs used in this work were fabricated using p-well, single metal and single poly process on n-type wafer with resistivity 10-50 Ω.cm. The channel length and width of
transistor are 12 μm and 2000 μm respectively. In order to attain a high transconductance, the MOSFET was fabricated to have high channel width and serpentine gate structure was chosen to accommodate high aspect ratio in compact active area of 750 μm × 1000 μm. The process start with double side polished n-type 6” wafer. The p-well was implanted through 20 nm thick screen oxide using Boron (B11) dopant with dose of 6.50×10^14. The chip micrograph and the optical image of MOSFET’s active area are shown in Fig. 2(a) and 2(b) respectively.

III. MATERIAL CHARACTERIZATION

A. XRD and d33 Measurement

The crystal orientation of the deposited film was characterized by XRD using Panalytical X’Pert PRO MPD (A3-26) and a Bruker D8 (A4-37) diffractometer, equipped with Cu sealed tube X-ray source λ = 0.154 nm. XRD measurements were conducted at X-ray tube voltage of 40 kV and a current of 40 n mA. The scan was performed for the range between 30 to 45 degrees with step size of 0.05. The XRD scan of AlN film (Fig. 3) shows a strong peak at $\theta \sim 36.01$, which is associated with (002) orientation. The full width half maximum (FWHM) value for (002) AlN was calculated to be 0.234 from the XRD data. It may be noted that the peak for (100), which appears at $\sim 33^\circ$, is absent and very low peak is observed for (101) reflection at $\sim 38^\circ$. This observation in XRD pattern suggests that the AlN film is preferentially oriented along the c-axis, required to achieve a good piezoelectric response [30].

In order to measure the transversal piezoelectric coefficient of the film, a d33 meter which operates on Berlincourt method, was used [31]. The sample was clamped centrally between the lower and upper head with diameter of $\sim 1$ mm, and was dynamically loaded with low frequency force by the upper head of the piezometer. A surface charge is generated on the top and bottom surfaces of the sample via the direct piezoelectric effect. The processing of the electrical signals from the sample, and comparison with a built-in reference, enabled us to obtain value of d33 to be 1.8 pC/N (Fig. 4). In order to increase the sensitivity of the device, a higher value of d33 is desirable. This could be achieved by optimizing the process parameters such as power, pressure, gaseous ratio, temperature, and bias voltage. In this work, we optimized the first three parameters, and so the rest two can be optimized to get even higher d33 value. For example, the substrate temperature influences the kinetic energy available to the adatoms on the surface of the deposited films. This energy increases proportionally with temperature, which helps in depositing the highly c-axis oriented films. Similarly, the negative voltage bias applied at the substrate is known to affect the landing kinetic energies of the ions, which in turn determine the crystal orientation. A higher bias voltage is thus preferred to achieve higher d33 value of the AlN film [20].

B. EDX and UV-vis-NIR

EDX analysis was carried out to confirm the film composition after deposition on silicon substrate. The silicon was chosen as the substrate for this analysis as polyimide could also give nitrogen peak which may interfere with nitrogen peak...
arising from the AlN film. EDX analysis was performed using the SEM (Hitachi SU8240) equipped with Bruker XFlash 5060 detector. The EDX spectra of the AlN film is shown in Fig. 5. The signal counts are fairly higher to confirm the presence of aluminum and nitrogen. The percentages of Al and N composition in the sputtered film are 40.36% and 38.91% respectively corresponding to Al:N ratio of 1.03:1, which is closer to the ideal stoichiometry ratio of AlN. The Si and O content observed in the EDX spectra arises from the substrate and native oxide.

The optical transmittance of the AlN deposited on fused quartz substrate was measured with a Shimadzu UV-Vis 2600 using an integrating sphere of 60 mm inner diameter. The raw data from UV–vis–NIR transmission measurements of AlN sputtered on quartz is shown in Fig. 6. The AlN films are transparent in a wide range with no observable absorption for wavelength above 300 nm. The absorbance of the film was calculated using:

$$\text{Absorbance} = 2 - \log(\text{Transmittance})$$  \hspace{1cm} (1)

And the variation of the absorption coefficient ($\alpha$) of film with respect to wavelength was then calculated using:

$$\alpha = \frac{\text{Absorbance}}{\text{Thickness}}$$  \hspace{1cm} (2)

Later on, $\alpha$ was used to estimate the optical bandgap of AlN using Tauc’s plot method [32].

$$\alpha E = B(E - E_g)^m$$  \hspace{1cm} (3)

where, $B$ is a parameter independent of the photon energy $E$, $E_g$ the optical bandgap energy and the exponent $m$, which depends on the transition between bands. Since AlN is direct bandgap material, $m$ is estimated to be 0.5. The x-intercept of the tangent in Tauc-plot, shown in Fig. 6, gives the estimated bandgap for the film. The observed value i.e. 5.8 eV is very close to ideal bandgap value of 6.0 eV [33].

**C. Surface Morphology**

AlN exhibits its largest transversal piezoelectric effect along the c-axis Therefore, it is important to optimize the process such that enough energy can be provided to the growing film for an oriented growth with high texture quality and consequently good piezoelectric properties. The cross-sectional SEM image (Fig. 7) of the film deposited using the parameters listed in Table I, reveals the columnar structure, which indicate (002) oriented film. The thickness of the film was measured to be 323 nm. The SEM image of the top surface morphology shown in the inset of Fig. 7 shows a pebble like dense structure which is associated with (002) orientation. The AFM scan in scanasyst mode on an area of 2 μm × 2 μm (Fig. 8), depicts a dense microstructures with average surface roughness of 5.18 nm. The grain size of ~16 nm was estimated using NanoScope Analysis software.

**IV. SENSOR CHARACTERIZATION**

**A. MOSFET Characterization**

The MOSFET was characterized using Keysight B1500A semiconductor device parameter analyzer to evaluate the device functionality and extract device parameters. The transfer and output curves at different gate and drain voltages are shown in Fig.9 (a) and (b) respectively. The plots show the good functioning of the devices. The key design and electrical parameters extracted from the plots are given in Table II.
Fig. 8. AFM scan of the AlN top surface showing high density nanostructure with grain size of \(\sim 16\) nm.

Fig. 9. (a) Transfer characteristics (b) Output characteristics of FET measured at different drain and gate voltages respectively.

B. Sensor Characterization

The scheme for experimental setup used here for the electromechanical characterization of the sensor is depicted in Fig. 10(b) [34]. The setup comprises of a linear motor and a load cell. The magnitude of force applied to the sensor using a linear motor was obtained using the load cell. The linear motor was controlled using a LabView program.

To investigate the sensing response of the AlN piezocapacitor, it was placed on the load cell and the force was applied in pulse mode increasing from 1N to 4N. The output piezopotential generated by the film was recorded using digital multimeter (Agilent 34461A). The sensor response to applied force is shown in Fig. 11, and the inset shows the linear response of the piezocapacitor for varying magnitude of force.

| Parameter                  | Value            |
|---------------------------|------------------|
| Channel length/width      | 12 \(\mu\)m/2000 \(\mu\)m |
| Oxide thickness           | 50 nm            |
| Mobility                  | 695 cm\(^2\)/V.s |
| Threshold voltage         | 0.68 V           |
| Maximum transconductance  | 0.44 mS          |
Later, the sensing layer was connected in extended gate configuration to the gate of MOSFET, by connecting the gate electrode with the bottom metal layer of AlN-PI stack. The extended gate configuration is preferred as it allows us to decouple the stress related variations in the MOSFET’s response. If AlN was directly deposited on the gate area, then due to well-known piezoresistive effect, the MOSFET response could also change on the application of force. Such variations could be better handled by including stress-compensation topologies in MOSFETs [13]. Due to the piezoelectric property, the charge or piezopotential is generated on AlN when an external force is applied. Since capacitor is connected to the gate of FET, the piezopotential appears at the gate terminal and leads to modulation of channel current in the MOSFET. The sensor operation limits are set by the responsiveness limits of human skin. Taking cue from the human sense of touch, researchers have listed specifications of a tactile sensor suitable for robot skin applications, such as a force range of 0.4 N – 10 N. This range includes from a feather touch to extreme cases such as lifting a heavy object. Nonetheless, the force range experienced in daily life activities such as holding a glass can range between 1 N – 5 N, which is thus chosen as the range for excitation in this work [35]–[37], [38]. During the characterization, the MOSFET was biased at drain terminal with 1 V and shares the same biasing with the top electrode of AlN sensor, and source of the MOSFET was grounded. The setup was controlled in a way that the pressing probe come down from a predefined position, apply force when in contact with the sensor, and then moves up to the previous position. This whole cycle takes ~ 3 seconds. During the application, the output signal shows quick change with ramp time of ~ 0.1 second, and then immediately falls down to initial state once the force is removed.

The drain current was recorded in response to periodic tapping force as rectangular pulse (shown in dash read line in Fig. 13(a)), using Keysight modular source measure unit (U2723A). Fig. 13(a) shows the periodic nature of normalized change in current on application of 3.5 N and Fig. 13(b) shows the sensor’s linear response to increasing force. The sensitivity (2.64 N$^{-1}$) is calculated from the slope of the plot and is defined as normalized change in drain current per unit force.

Comparing with our previous work based on P(VDF-TrFE) and its nanocomposite in combination with MOSFET and Organic FET (Table III), the presented work shows lower sensitivity. This is attributed to inherently lower piezoelectric constant of AlN. Nevertheless, there is major gain in using AlN, as there is no need for poling and thus direct deposition
conditioning electronics. The sensitivity of presented sensor was found to be 1.8 pC/N. The AlN based piezoelectric thin film of aluminum nitride (AIN) as transducer layer. The structural piezoelectric nature of AIN, along with useful properties such as no poling requirement, make it an attractive material for dynamic tactile sensing. With an optimized recipe for sputtering, the AIN on flexible polyimide foil was obtained by sputtering without any external heating. The film was characterized using XRD, SEM and AFM techniques to establish its (002) orientation. The quasi-static piezoelectric coefficient value was measured to be 1.8 PC/N. The AlN based flexible sensing layer showed a linear response to the varying force. Coupled with the MOSFET in an extended gate configuration, the sensitivity of present sensor was found to be 2.65 N⁻¹. The paper demonstrates the possibility of developing an advanced POSFET type devices, whereby AlN piezocapacitor will directly deposited on the gate area. This kind of arrangement will provide high-resolution and fast response needed for effective use of these devices in applications such as robotics and prosthetics. Another way forward will be to thin these devices up to ultra-thin regime where it can be integrated over flexible substrate as single unit devices.

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