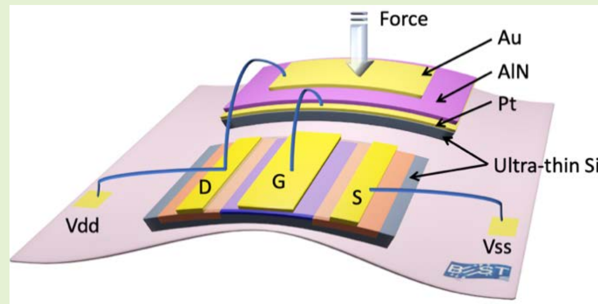
Flexible Tactile Sensors using AlN and MOSFETs based Ultra-thin Chips

Sihang Ma, Yogeenth Kumaresan, Abhishek Singh Dahiya, Leandro Lorenzelli, and Ravinder Dahiya

***Abstract*— This paper presents ultrathin chips (UTCs) based flexible tactile sensing system for dynamic contact pressure measurement. The device comprises of an AlN piezocapacitor based UTCs tightly coupled with another UTCs having metal-oxide-semiconductor field-effect transistors (MOSFETs). In this arrangement the AlN piezocapacitor forms the extended gate of MOSFETs. Both AlN piezocapacitor and MOSFET based UTCs are obtained by post-process reduction of wafer thicknesses to ~35µm using backside lapping. The performances of both UTCs were evaluated both before and after thinning and there was no noticeable performance degradation. The UTC-based AlN piezocapacitor exhibited six times higher sensitivity (43.79mV/N) than the thin film-based AlN sensors. When coupled with MOSFETs based UTC, the observed sensitivity was 0.43N^{-1}. The excellent performance, flexible form factor and compactness shows the potential of presented device in applications such minimal invasive surgical instruments where high-resolution tactile feedback is much needed.**



***Index Terms*— AlN, Flexible electronics, Piezocapacitor, Tactile sensors, Ultra-thin Chips**

I. Introduction

INSPIRED by human skin, the smart sensors and electronic skin (e-Skins) are being explored for advancements in applications such as human-machine interaction, robotics, interactive vehicles, and wearables systems for health monitoring [1-7]. In this regard, various sensing systems have been widely studied using capacitive, piezoelectric, triboelectric, piezoresistive, inductive, optical mechanisms, and their combinations [6, 8-14]. Amongst these, piezoelectric pressure sensors have drawn attention owing to their capability to detect dynamic contact forces [15, 16]. The piezoelectric sensing materials used in these sensors are either organic or inorganic.

Organic piezo materials include natural materials such as silk and collagen, and the more commonly used synthetic materials such as polyvinylidene fluoride (PVDF) and poly(*L*-lactic acid) (PLLA), etc. [17]. PVDF and its copolymer (PVDF-TrFE) have been preferred as piezo sensing layers due to their cost efficiency, chemical stability, biocompatibility, and flexibility [18-20]. However, a high voltage poling treatment (100kV/cm) is required for crystallite rearrangement and hence an improved piezoelectric effect [21, 22]. Materials such as PLLA do not require poling due to its helical structure, but they require thermal stretching and the elongated PLLA films have much lower piezoelectric constant and no spontaneous polarisation [23, 24]. The poling or stretching needed for organic piezo materials not only adds complexity to the device manufacturing but also increases the cost.

In this regard, their inorganic counterparts such as aluminium nitride (AlN), zinc oxide (ZnO), lead zirconate titanate (PZT), potassium sodium niobate (KNN) etc. offer better solution [25-28]. Amongst these, PZT is not recommended due to presence of toxic lead element (over 60 wt.%) [29]. Alternatively, KNN has been considered as an eco-friendly lead-free substitute [30, 31]. However, pure KNN has shown challenges in terms of processing due to insufficient densification and off-stoichiometry introduced by the volatility of potassium oxide, for which additional processes such as doping are inevitable [32, 33]. Although ZnO nanostructure-based piezoelectric sensors have been extensively investigated, their physical stability, caused by the nanostructure misalignment, remains a challenges when large-scale devices are needed [34]. Therefore, AlN has been chosen as the piezo sensing material in this work

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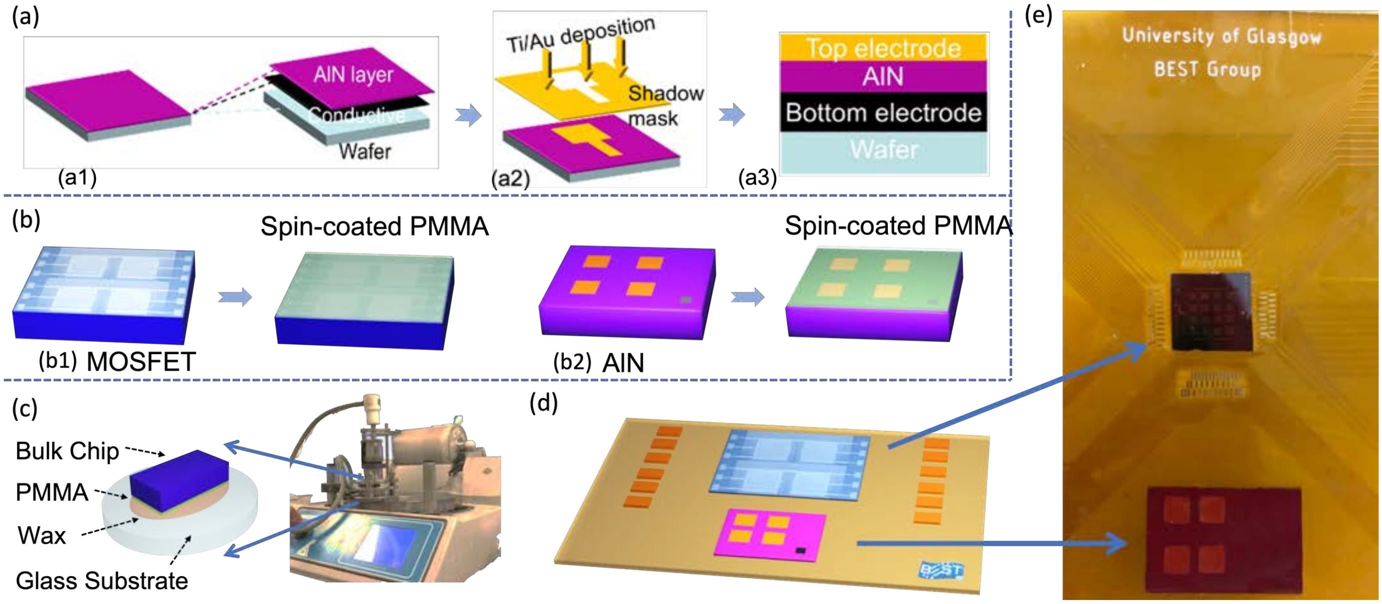

Fig. 1 Schematic illustration of realising UTC-based flexible tactile sensor using AlN piezocapacitor coupled with metal-oxide-semiconductor field-effect transistors (MOSFETs) (a) Fabrication steps of rigid AlN piezocapacitor: (a1) AlN thin layer directly fabricated on a conductive layer on top of a Si wafer; (a2) Ti/Au deposition as the top electrodes; (a3) The cross-sectional scheme of Si-based AlN piezocapacitor; (b) Thinning preparation: (b1) spin-coating PMMA sacrificial layer on the MOSFET chip; (b2) Exposing the bottom electrode of the AlN piezocapacitor followed by spin-coating PMMA layer; (c) Bulk chip firmly placed onto the sample holder via wax, attached onto the lapping machine for thinning; (d) Both UTC-based AlN piezocapacitor and MOSFETs attached on a flexible PCB.

as it exhibits efficient piezoelectric and dielectric properties, high thermal stability, as well as low dielectric loss tangent and high signal to noise ratio [35-37]. Additionally, no poling or stretching is needed [38].

As inorganic bulk piezo materials are inherently brittle and emerging applications discussed above require mechanical flexibility, recent studies have focussed on overcoming such issues. For example, AlN-based thin films can be deposited directly on polymeric substrates. However, they usually require high temperature and vacuum systems such as molecular beam epitaxy (MBE) or chemical vapour deposition (CVD) and flexible polymeric substrates are highly likely to become unstable under such condition [36]. The 'grow-transfer' method has also been explored, namely transferring the inorganic piezo material fabricated on rigid substrates to their plastic and flexible counterparts. However, the transfer process can cause lattice mismatch in the organic-inorganic interface and affect the device performance [39, 40]. Alternatively, inorganic piezo materials such as AlN can be directly deposited on bulk silicon (Si) chips and enhanced performance can be achieved. The device rigidity can be addressed by reducing the thickness of bulk Si chips via thinning technologies [41], and to realise mechanically flexible piezocapacitors. For better signal-to-noise ratio and higher spatial resolution, these piezocapacitors can be coupled with field effect transistors (FETs), as reported for some tactile sensors using conventional silicon technology and organic semiconductor-based FETs [26, 42]. In this context, Si-based rigid metal-oxide-semiconductor field-effect transistor (MOSFET) chip has also been coupled with the inorganic AlN thin film to realise extended gate piezoelectric oxide semiconductor field effect transistors (POSFETs) [36]. However, a fully flexible POSFET type arrangement is not yet reported, and the work presented in this paper is step in this direction.

The work presented here extends our initial study reported in IEEE FLEPS 2021 [43]. In conference paper, we reported AlN based ultra-thin chip (UTC). Here, we also introduce MOSFEETs based UTC and extend the previous work by connecting the flexible AlN piezocapacitors as the extended gate of flexible MOSFETs present on other UTC. Together the two UTCs (Fig. 1) lead to a POSFET device type arrangement, which can be further extended in future by directly depositing the AlN layer on the MOSFETs. Such compact arrangement is needed for tactile or haptic feedback in applications such as the end-effectors of instruments used in minimal-invasive surgery. Further, presence of transducer layer on top of MOSFETs will lead to lower cost.

This paper is organised as follows: Section II presents the device thinning process. Section III shows the device characterisation results, i.e., UTC-based AlN and MOSFET devices as well as their connection leading to POSFET type configuration. Finally, Section IV summarises key outcomes of this work.

II. Device Thinning

The AlN-based piezocapacitors were fabricated on a bulk Si substrate (~500µm thickness). The AlN sensing layer (~500nm thickness) was deposited on Pt coated Si substrates. Top electrode, Ti/Au (10/100nm), was deposited using an electron-beam (e-beam) evaporator through a hard mask with 0.5mm^2 openings. The fabrication steps of the n-type MOSFET chip with ~520µm thickness were reported in our previous work [44, 45].

To achieve the mechanical flexibility, both samples i.e., AlN piezocapacitor and MOSFET chips were thinned using backside lapping assisted with the polymethylmethacrylate (PMMA) sacrificial technique [46]. The PMMA sacrificial layer reduces the thermal stress, typically experienced by UTCs during their separation or debonding from the chuck holding them after thinning. Therefore, the same technique was adopted in this work. Prior to thinning, the AlN thin layer was carefully scratched by a diamond cutter to expose the bottom electrode (Pt). Next, the device sides of both chips were spin-coated with ~20µm-thick PMMA sacrificial layers at 1500rpm. Then, commercial quartz wax (Logitech) was applied at the centre of a glass substrate and then it was melted at 100°C using a hotplate. Subsequently, the chip was placed on top of the wax with the device side facing down. The sample was then placed under the contact pressure set up for 30 minutes at room temperature to ensure a firm attachment between the chip and the glass substrate. The sample holder was sequentially placed onto the lapping jigs through vacuum and the Logitech lapping machine was used to reduce the samples' thickness from above 500µm to ~35µm. After thinning, UTCs were separated from the glass sample holders by placing it on a hot plate to melt the wax. The residual wax and PMMA sacrificial layers were dissolved and removed using acetone solution. The scanning electron microscope (SEM) image in Fig. 2(a) shows the comparison of thickness between the bulk (~500µm) and thinned (~35µm) chip. Finally, both AlN-UTC and MOSFET-UTC were attached to a flexible PCB using the low-stress epoxy adhesive (EpoTEK 301-2), as shown in Fig. 1(e).

III. Device Characterisation

A. *AlN Piezocapacitor Characterisation*

The AlN-based piezoelectric pressure sensor was characterised using a 1004 aluminium single point low-capacity load cell with a linear motor that was controlled through a custom-made LabView programme (2018 Robotics v18.0f2, National Instruments, Texas, USA). The output piezopotential was measured by a digital multimeter (Agilent 34461A). The sensing performances of both bulk and UTC-based devices were evaluated and compared. The effect of thinning the AlN pressure sensor was firstly investigated through the measurement of capacitance before and after thinning, which indicated similar values (Fig. 2(b)). This confirms the reliability of the thinning process. Further, to evaluate the sensing response, an external force (0.1N) was applied on both bulk and UTC-based AlN devices at 0.1Hz and 0.5Hz (Fig. 2(c)-(f)). When a vertically compressive force is applied, an electric polarisation (potential) is induced in the AlN sensing layer, owing to the relative displacement of the centres of the cations and anions in the AlN, resulting in a microscale dipole moment.

Due to the generated electric field, charges accumulate at the top and bottom electrodes. According to the AlN crystal orientation, positive charges accumulate at the surface of AlN. While the pressure or force remains constant, free charges with opposite polarities are attracted to the surface (screening effect) and thus, a new equilibrium is reached. This leads to a rapid decrease in the piezo output which finally reaches to zero. When the force is released, the piezoelectric polarisation disappears, giving rise to a negative peak (electrons flows in backwards direction to achieve the new equilibrium) [47].

Next, a continuous force was applied to both bulk and UTC-based AlN devices at 0.5Hz frequency and the force was increased from 0.25N to 1N with a step of 0.25N, as shown in Fig. 3(a). The result showed a repeatable, stable, and fast response (<100ms) before and after thinning. Meanwhile, as the applied force was increased, a rise in piezopotential was observed. It is well known that for piezoelectric devices the voltage generation is directly proportional to the applied stress. Therefore, it is expected that the output voltage will be pressure

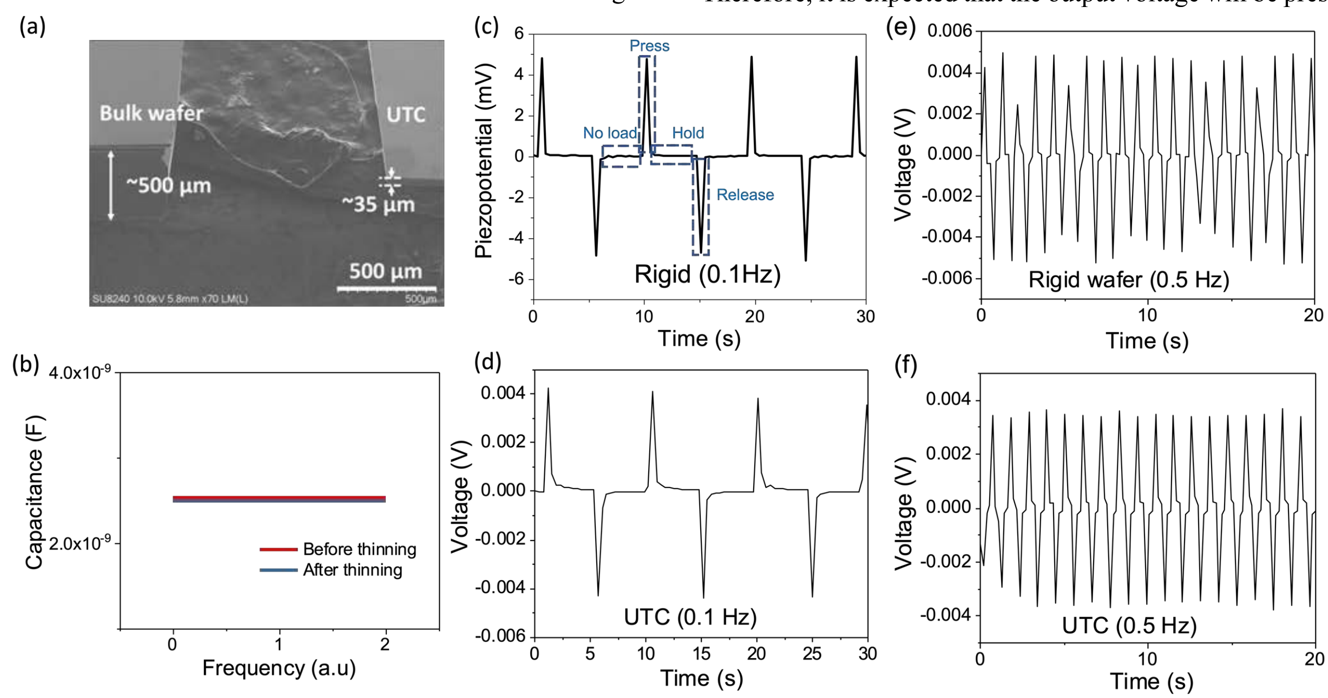

Fig. 2 AlN-based piezoelectric pressure sensor characterisation: (a) SEM image showing the thickness comparison between the bulk and thinned chips; (b) Capacitance characterisation before and after thinning; (c) and (d) Bulk and ultra-thin AlN chip under 0.1N at 0.1Hz; (e) and (f) Bulk and ultra-thin AlN chip under 0.1N at 0.5Hz.

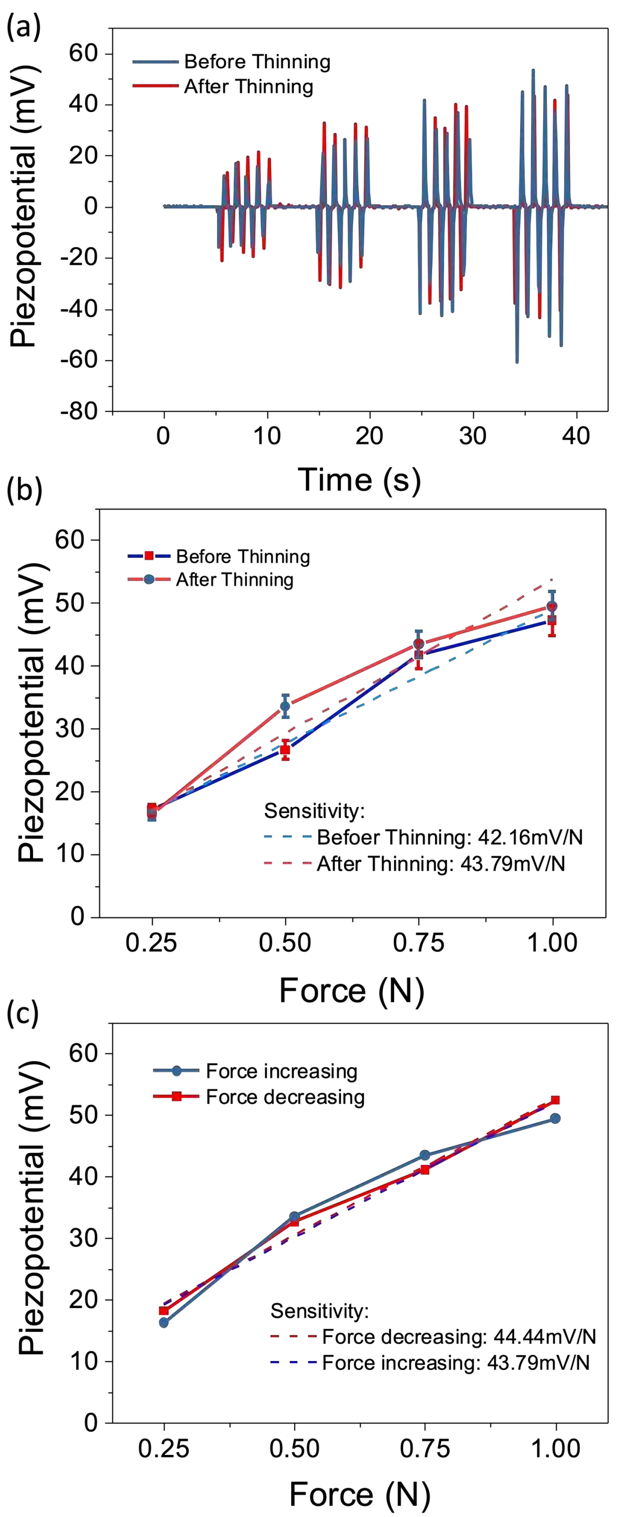

Fig. 3 The response of AlN piezocapacitors for both bulk and thinned samples: (a) Under different applied forces; (b) Comparison of sensitivities; (c) Hysteresis test for UTC-based AlN piezocapacitor.

sensitive [48]. The sensitivities of the bulk and UTC-based AlN pressure or touch sensors were extracted from Fig. 3(a). The results indicate a slight increase in sensitivity by ~3.7% after thinning, from 42.16mV/N to 43.79mV/N, which is within the acceptable limit for such deviation (Fig. 3(b)). Furthermore, compared with our previous research on tactile sensors using

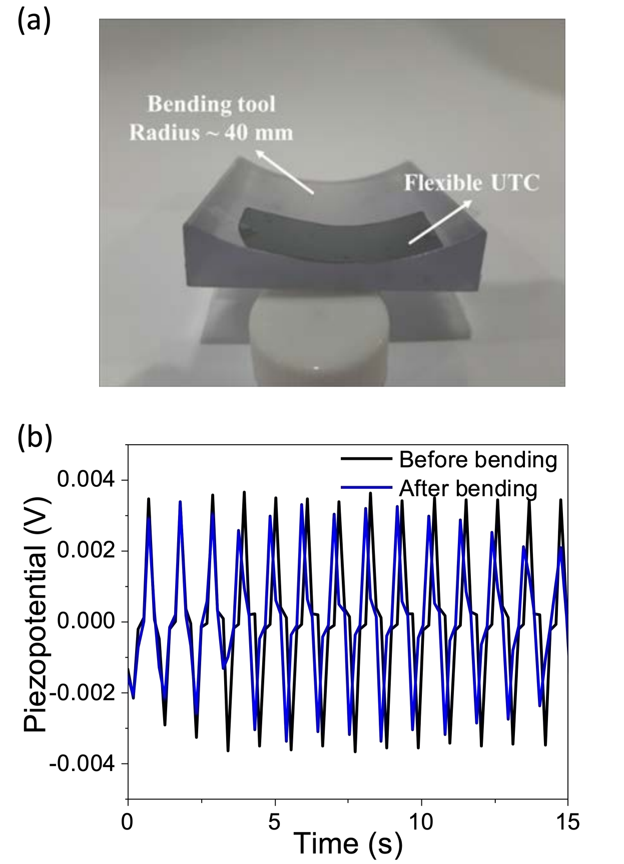

Fig. 4 AlN piezocapacitors bending test: (a) Photograph of UTC under 40mm bending; (b) Performance comparison before and after thinning under bending.

AlN thin films, the sensitivity of UTC-based AlN is drastically improved by almost six times i.e., from 7.37mV/N to 43.79mV/N. A hysteresis test for UTC-based AlN piezocapacitors was conducted by increasing and decreasing the applied force, as shown on Fig.3(c). The sensitivity extracted showed a negligible difference (1.46%). Finally, the effect of device performance under bending was studied. Fig. 4(a) displays the ultra-thin AlN piezocapacitor placed on a bending test rig with 40mm radius of curvature. Fig. 4(b) demonstrates the characterisation results for the bulk and thinned devices, showing negligible changes. The results under planar and bending conditions compared with bulk devices prove that the UTC-based AlN piezocapacitors exhibit good robustness, reliability, and sensitivity. Hence, they are suitable for high performance flexible electronics.

B. MOSFET Characterisation

To investigate the n-type MOSFET device performance, Keysight B1500A semiconductor device parameter analyser was used to obtain the transfer ($I_{ds} – V_{gs}$) and output ($I_{ds} – V_{ds}$) functions before and after thinning. Fig. 5(a) shows the transfer curves at different drain voltages (0.3V, 0.5V, 1V and 1.5V) while the gate-source voltage (V_{gs}) swept from -0.5V to 2V. The output characteristics, as shown in Fig. 5(b), demonstrates the variation of I_{ds} by sweeping V_{ds} from 0 to 2V with V_{gs} being increased at a step of 0.5V from 0.5V to 2V. Both transfer and output characteristics depict similar performances before and

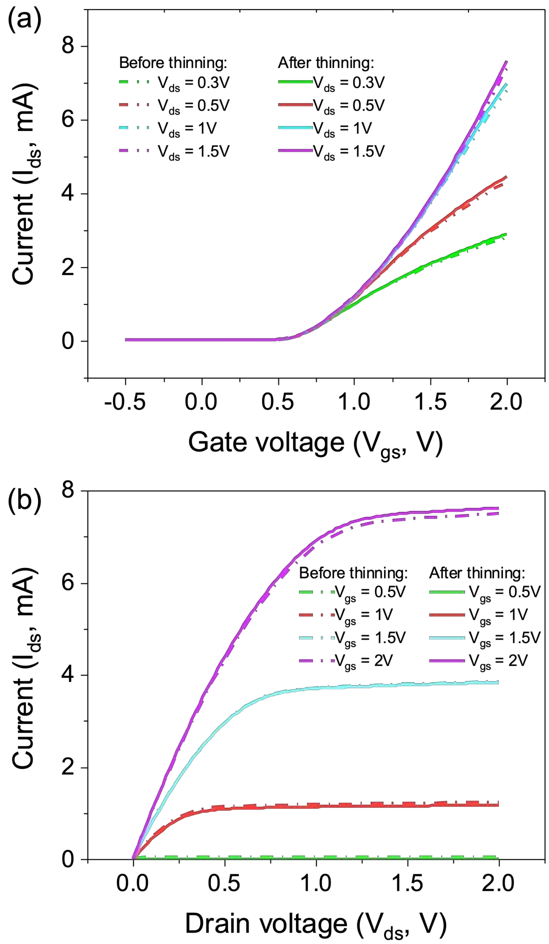

Fig. 5 MOSFET characterisation before and after thinning: (a) Transfer function; (b) Output function.

after thinning the MOSFET device. To further study the device electrical performance, the threshold voltage (V_{th}) was extracted using the linear extrapolation method. The intercept value of $I_{ds} = 0$ in the linear extrapolation of $I_{ds} – V_{gs}$ provides the value of V_{th}. The results revealed the same value of V_{th} (0.6V) before and after thinning. Next, the device field effect mobility (μ_{FE}) was evaluated by first calculating the peak transconductance (g_m) using Eq. (1).

$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}} | V_{ds} = constant \quad (1)$$

Where I_{ds} is the drain current, V_{gs} is the gate voltage and V_{ds} is the drain voltage. Then the device mobility was obtained using Eq. 2 below:

$$\mu_{FE} = \frac{g_m}{C_{ox}(W/L)V_{ds}} \quad (2)$$

where C_{OX} is the oxide capacitance (thickness of the dielectric layer, SiO_2 = 50nm), W is the gate width (W = 2000µm), and L is the gate length (L = 12µm). The extracted values for both transconductance and mobility remained same before and after thinning, i.e., 2.6mS and 780cm^2/Vs respectively.

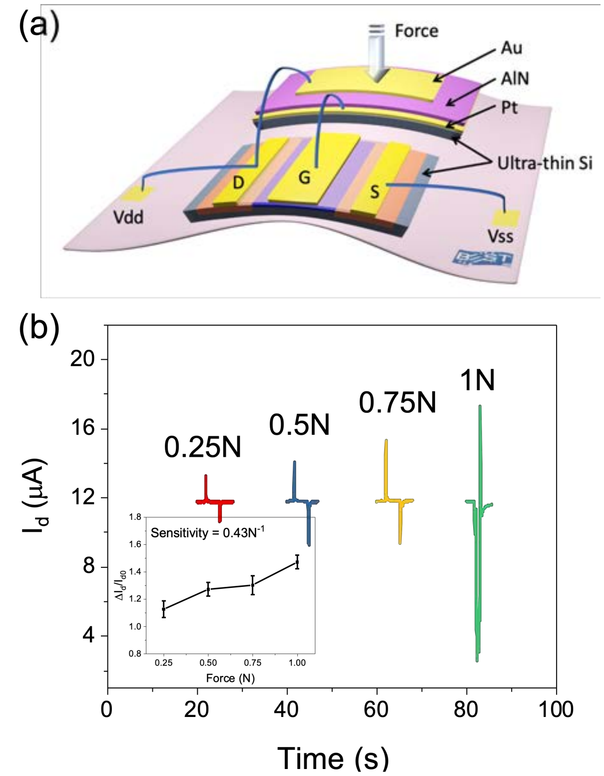

Fig. 6 (a) POSFET configuration; (b) Device characterisation under different force applied and the extracted sensitivity (inset).

C. *Tactile Sensor Characterisation*

Once the reliability of thinning process and thinned chips was confirmed, both devices were then integrated on a single flexible PI substrate to obtain flexible UTC-based tactile sensor coupled with MOSFETs. The sensor configuration is shown as Fig. 6(a), where the AlN-UTC is connected as the extended gate to the MOSFET-UTC. The device characterisation was performed by connecting the V_{dd} and V_{ss} to the Keysight modulator source measure unit (U2723A). As the range of force from human natural manipulation is less than 0.9N, the external force applied in this study ranged from 0.25 to 1N with a step of 0.25N, as shown in Fig. 6(b) [49]. Meanwhile, a biasing condition of V_{ds} = 0.2V and V_{gs} = 0V was applied to the sensor during characterisation. As explained above, with an external force applied on the AlN piezoelectric pressure sensor, a piezopotential is generated due to the charge polarisation. When the AlN pressure sensor is connected to the gate terminal of MOSFETs, as an extended gate, the generated piezopotential modulates the channel current or change in the drain current (I_{ds}). The increase in I_{ds} is proportional to the increase in the external force. The obtained peak current for different applied force was plotted to extract the sensitivity. Using this data, the device sensitivity was found to be 0.43N^{-1}.

IV. Conclusion

The UTC-based AlN piezocapacitors coupled with MOSFETs on another UTCs have been investigated here for a fully flexible POSFET like touch sensing system. To this end, The ultra-thin AlN piezocapacitor were connected to ultra-thin MOSFET chip in an extended gate configuration. The performance of both AlN piezocapacitors and MOSFETs before and after thinning demonstrates negligible changes, proving the reliability of our thinning technique using backside lapping assisted with PMMA sacrificial layer. The results show significantly higher sensitivity (43.79mV/N) of UTC-based AlN piezocapacitors with respect to AlN thin films from our previous work (7.36mV/N). The low sensitivity of the POSFET system in this work ($0.43N^{-1}$) could be due to the substrate capacitance and propagation delay caused by the extended gate. This can be improved in future by directly depositing AlN thin layer on the gate region of the MOSFETs.

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