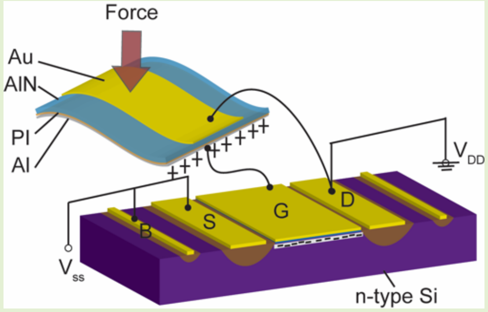
IEEE SENSORS JOURNAL, VOL. 20, NO. 13, JULY 1, 2020

Touch Sensor Based on Flexible AlN Piezocapacitor Coupled With MOSFET

Shoubhik Gupta, Nivasan Yogeswaran, Flavio Giacomozzi, Leandro Lorenzelli,
and Ravinder Dahiya, *Senior Member, IEEE*

***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 possibleto develop the bendable version of these devices if they are fabricated using silicon technology [13], [14].

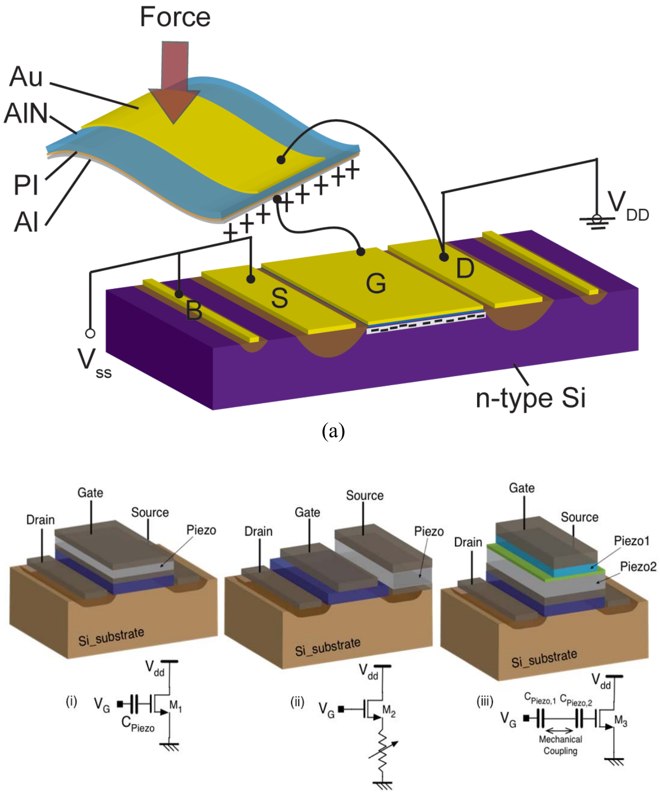
The FET based approach has been explored with piezocapacitor (made of materials such as polyvinylidene fluoride (PVDF) and copolymer P(VDF-TrFE) [15], lead zirconate titanate (PZT) [9], [16], and zinc oxide (ZnO) [17]), either connected in an extended gate configuration (Fig. 1(a)) or deposited directly 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

Manuscript received May 19, 2019; accepted July 6, 2019. Date of publication July 15, 2019; date of current version June 4, 2020. This work was supported in part by the EPSRC Engineering Fellowship for Growth through PRINTSKIN under Grant EP/M002527/1 and NEUPRINTSKIN under Grant EP/R029644/1 and in part by the European Commission under Grant Agreement PITN-GA-2012-317488-CONTEST. This paper was presented at the 2018 IEEE Sensors Conference. The associate editor coordinating the review of this paper and approving it for publication was Prof. Omer Oralkan. *(Corresponding author: Ravinder Dahiya.)*

S. Gupta, N. Yogeswaran, and R. Dahiya are with the Bendable Electronics and Sensing Technologies (BEST) Group, School of Engineering, University of Glasgow, Glasgow G12 8QQ, U.K. (e-mail: ravinder.dahiya@glasgow.ac.uk).

F. Giacomozzi and L. Lorenzelli are with the Microsystems Technology Research Unit, Fondazione Bruno Kessler, 38123 Trento, Italy.

Digital Object Identifier 10.1109/JSEN.2019.2928797



(a)

(b)

Fig. 1. (a) Illustration of sensor architecture with flexible AlN based piezocapacior connected to MOSFET in an extended gate configuration. (b) Various configuration with force sensitive transducer material directly deposited on the gate area of MOSFET or in the source-drain path.

use require high poling voltage (~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 standard IC-fabrication technology [21]. Indeed, due to this compatibility, AlN has been one of the most commonly-used piezoelectric material for wearables, electroacoustic and microphotonics devices [22]–[24].

The work presented in this paper extends the research work presented at IEEE Sensors 2018 [25]. This extended article presents an in-depth study of AlN piezoelectric film and analysis of the working of touch sensing devices. The paper is organized as follows: Section II presents the fabrication steps adopted to realize the key components of the touch sensing device i.e. flexible AlN piezocapacitor and the MOSFETs. Section III discusses the metrological analysis of AlN film, carried out to evaluate its piezoelectric properties. The electrical characterizations related to FET and the sensor are presented in Section IV. Finally, the key outcomes of the paper are summarized in Section V.

TABLE I
LIST OF SPUTTERING PARAMETERS USED FOR DEPOSITION OF AlN ON POLYIMIDE SUBSTRATE

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 5×10^{-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^{o}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.

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

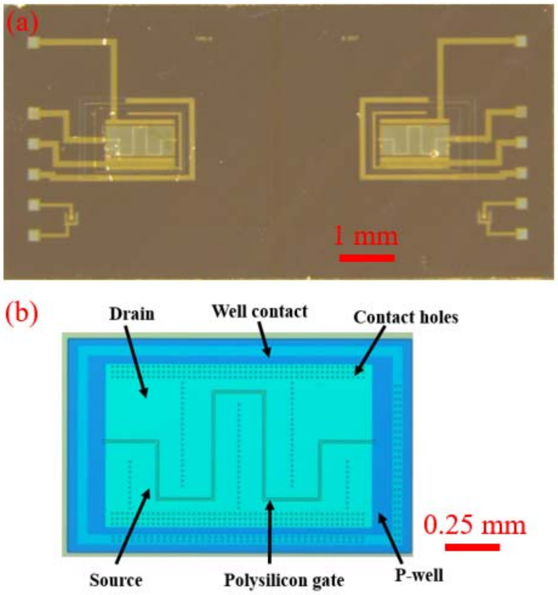


Fig. 2. (a) Micrograph of fabricated chip consisting of two individual FETs, and (b) Optical image of active region showing source, drain and gate regions.

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 d_{33} 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 $\lambda = 0.154$ 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 $2\theta{\sim}36.01$, 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 $\sim 33^{\text{o}}$, is absent and very low peak is observed for (101) reflection at $\sim 38^{\text{o}}$. 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 d_{33} 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 d_{33} to be 1.8 pC/N (Fig. 4). In order to increases to sensitivity of the device, a higher value of d_{33} 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 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 d_{33} value of the AlN film [20].

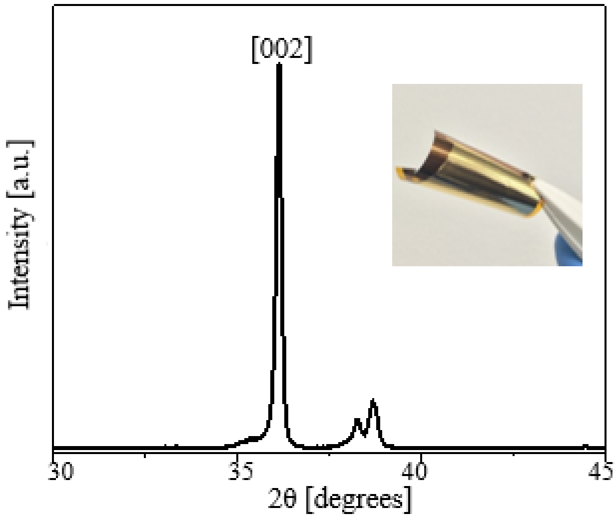


Fig. 3. XRD plot showing distinctive high peak at 36.01 degree, confirming the preferred [002] orientation growth. Inset shows the picture of sensing layer composed of AlN over PI.

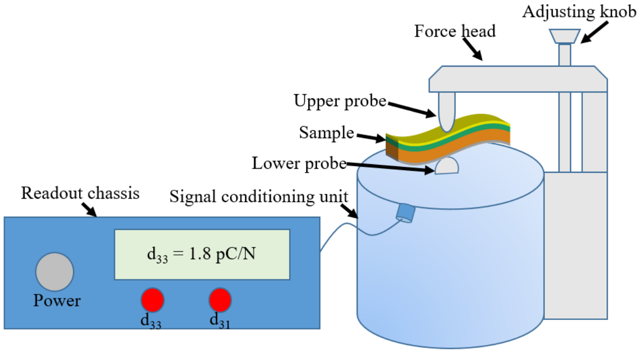


Fig. 4. The illustration of setup for d_{33} measurement showing the value of piezoelectric coefficient to be 1.8 pC/N.

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

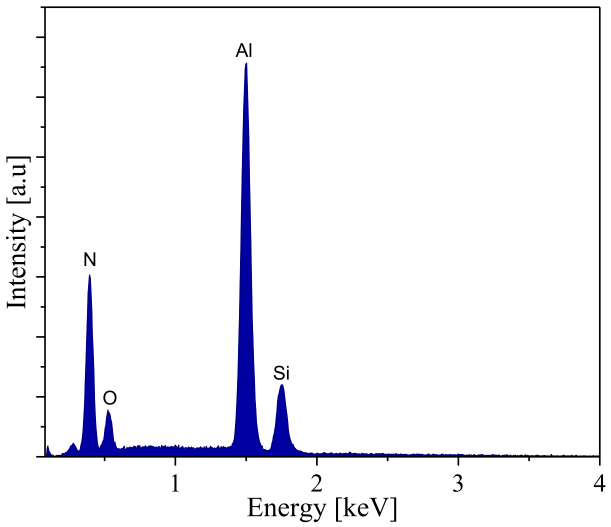


Fig. 5. EDX spectrum showing high peaks for Aluminium and Nitrogen, which are in 1.03:1 stoichiometric ratio.

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 above300 nm. The absorbance of the film was calculated using:

$$Absorbance = 2 - \log(Transmittance) \tag{1}$$

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

$$\alpha = Absorbance/Thickness \tag{2}$$

Later on, α was used to estimate the optical bandgap of AlN using Tauc's plot method [32].

$$\alpha E = B(E - E_g)^m \tag{3}$$

where, B is a parameter independent of the photon energy E, E_g the optical band gap 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 the inset 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.

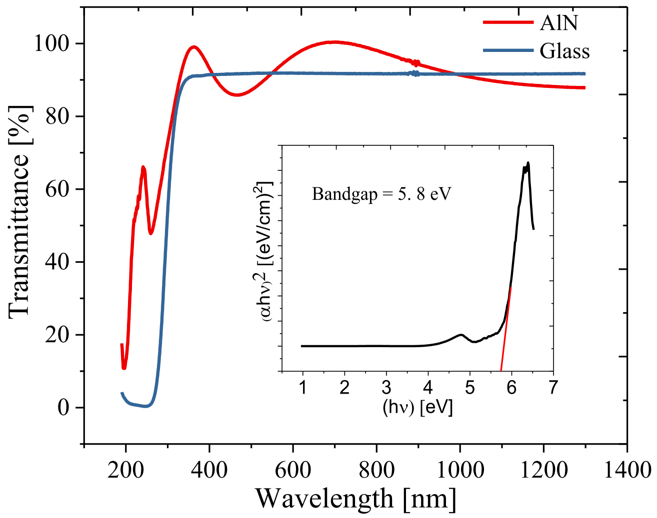


Fig. 6. Transmittance of AlN film and glass over wide range of wavelength. Inset image shows the AlN bandgap estimated using Tauc's method.

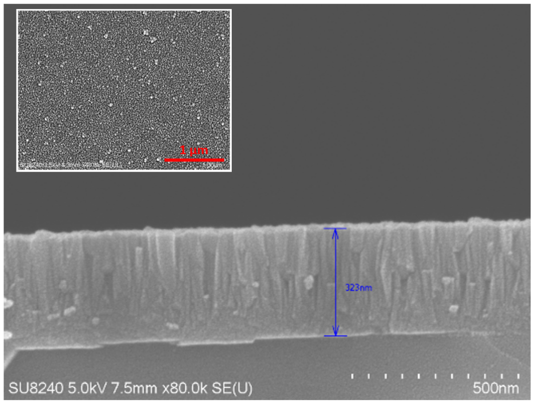


Fig. 7. Cross-sectional SEM image of the columnar structured AlN film.

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.

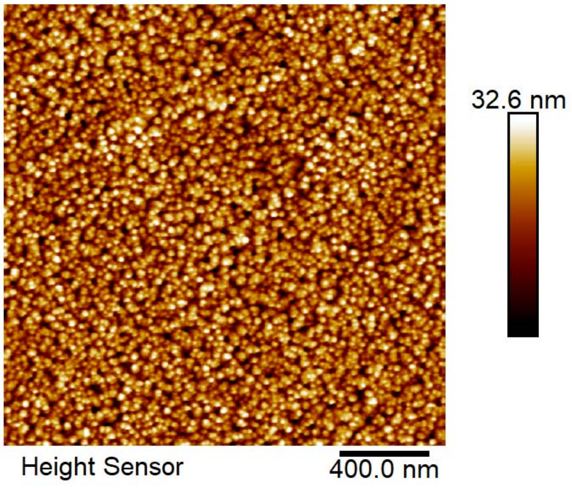


Fig. 8. AFM scan of the AlN top surface showing high density nanostructure with grain size of ~16 nm.

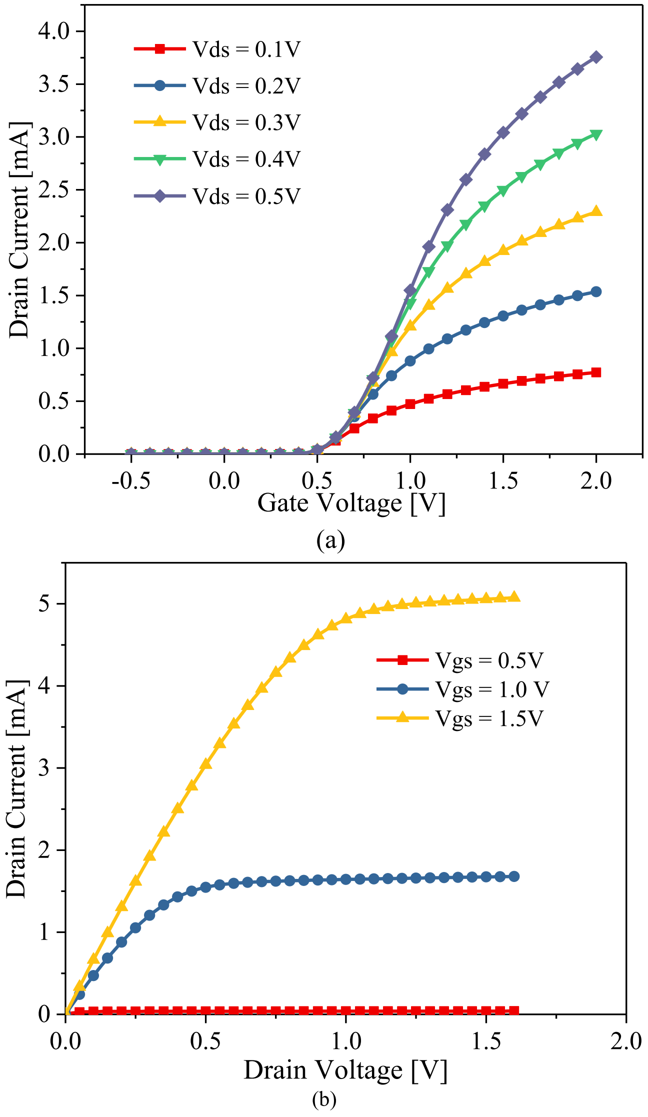


Fig. 9. (a) Transfer characteristics (b) Output characteristics of FET measured at different drain and gate voltages respectively.

TABLE II
LIST OF DESIGN AND PROCESS PARAMETERS OF FABRICATED MOSFET

Parameter	Value
Channel length/width	12 µm/2000 µm
Oxide thickness	50 nm
Mobility	695 cm^2/V.s
Threshold voltage	0.68 V
Maximum transconductance	0.44 mS

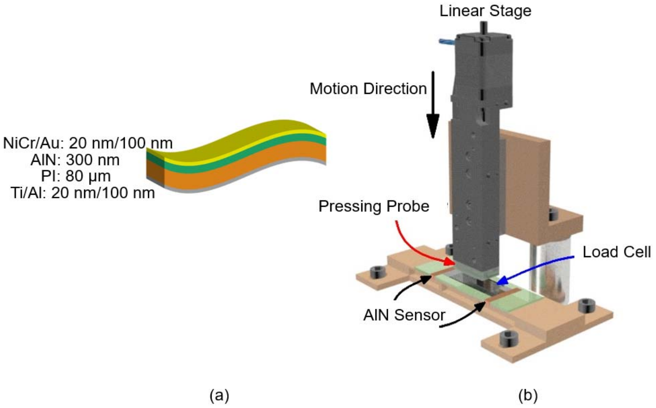


Fig. 10. Illustration of (a) 2D schematic of AlN sensor, showing the cross-sectional dimensional of different layers (b) Characterization setup used, which consisted a motor-controlled pressing arm and a load cell.

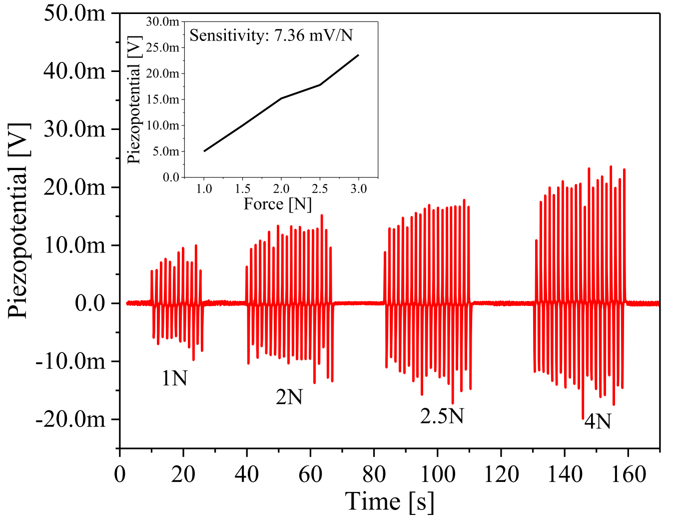


Fig. 11. Response of AlN piezocapacitor at different applied force (inset) Calibration curve.

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.

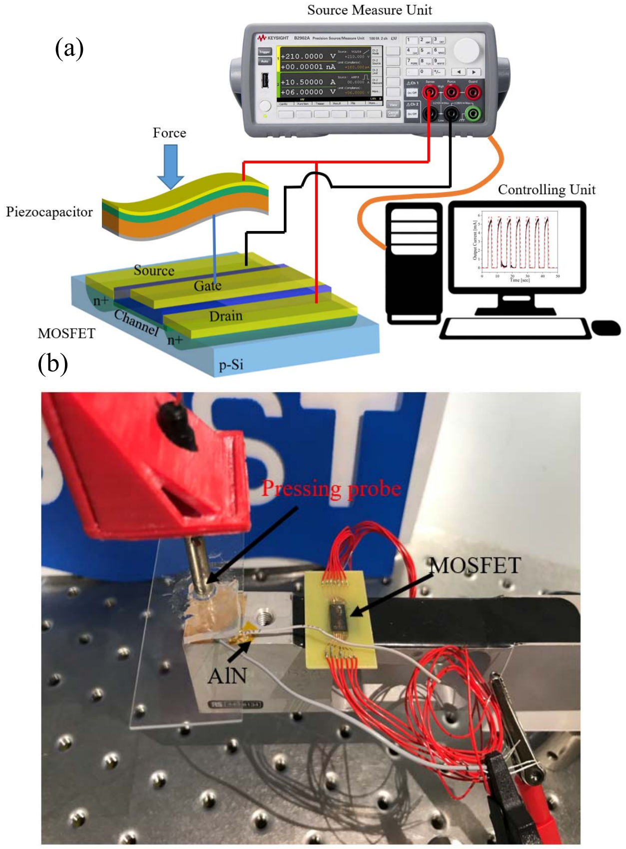


Fig. 12. (a) Illustration of characterization setup employed for evaluating sensor response. (b) Optical image capturing both components of sensor.

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 0.4N –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 1N –5N, 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 1V 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.

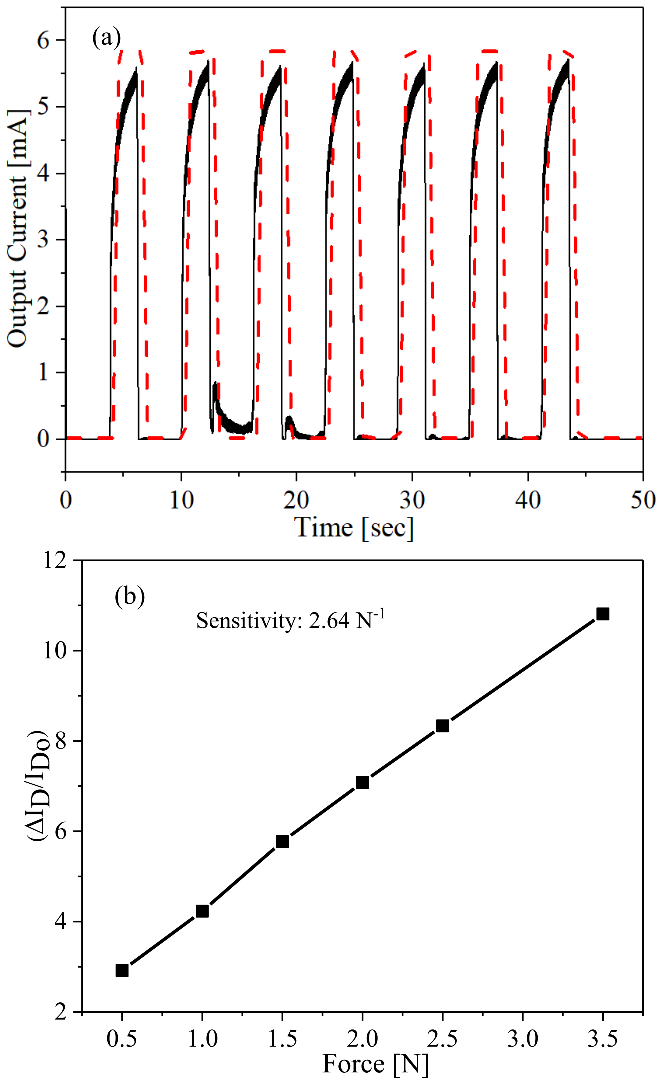


Fig. 13. (a) Sensor (i.e. MOSFET coupled with AlN) response to force of magnitude 3.5N; (b) Calibration curve showing the sensitivity of 2.64 N^{-1}.

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 3.5N 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

TABLE III
COMPARISON OF AlN BASED SENSOR WITH P(VDF-TrFE) BASED SENSORS

Parameter	Force Sensitivity (N^{-1})*	
POSFET	5	[15]
EG-OFET	8.12	[39]
EG-P(VDF-TrFE)/$BaTiO_3$	7.44	[40]
This work	2.64	--

*The sensitivties are re-calculated using the reported resistance and current value, to keep the same unit.

of MOSFETs is easy and so is the possibility for obtaining CMOS integrated sensors. Whereas the lower sensitivity could be addressed by incorporating non-chip amplifiers and signal conditioning electronics.

V. CONCLUSIONS

With continuous advancement in tactile sensing for electronic skin, various types of transduction mechanisms have been explored. This paper presented the usage of piezoelectric thin film of aluminum nitride (AlN) as transducer layer. The structural piezoelectric nature of AlN, 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 AlN 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 presented 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.

ACKNOWLEDGMENT

The authors acknowledge the support received for this work from James Watt Nanofabrication Centre (JWNC) and Electronics Systems Design Centre (ESDC).

REFERENCES

[1] R. Dahiya and M. Valle, *Robotic Tactile Sensing: Technologies and System*. Berlin, Germany: Springer, 2013.

[2] I. Graz *et al.*, "Flexible active-matrix cells with selectively poled bifunctional polymer-ceramic nanocomposite for pressure and temperature sensing skin," *J. Appl. Phys.*, vol. 106, no. 3, Aug. 2009, Art. no. 034503.

[3] Y. Liu, M. Pharr, and G. A. Salvatore, "Lab-on-Skin: A review of flexible and stretchable electronics for wearable health monitoring," *ACS Nano*, vol. 11, no. 10, pp. 9614–9635, 2017.

[4] C. Dagdeviren *et al.*, "Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation," *Extreme Mech. Lett.*, vol. 9, pp. 269–281, Dec. 2016.

[5] M. I. Tiwana, S. J. Redmond, and N. H. Lovell, "A review of tactile sensing technologies with applications in biomedical engineering," *Sens. Actuators A, Phys.*, vol. 179, pp. 17–31, Jun. 2012.

[6] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing-from humans to humanoids," *IEEE Trans. Robot.*, vol. 26, no. 1, pp. 1–20, Feb. 2010.

[7] R. Dahiya, "E-Skin: From humanoids to humans," *Proc. IEEE*, vol. 107, no. 2, pp. 247–252, Feb. 2019.

[8] J. F. Tressler, S. Alkoy, and R. E. Newnham, "Piezoelectric sensors and sensor materials," *J. Electroceram.*, vol. 2, no. 4, pp. 257–272, 1998.

[9] N. Yogeswaran *et al.*, "Piezoelectric graphene field effect transistor pressure sensors for tactile sensing," *Appl. Phys. Lett.*, vol. 113, no. 1, Jul. 2018, Art. no. 014102.

[10] L. Nela, J. Tang, Q. Cao, G. Tulevski, and S.-J. Han, "Large-area high-performance flexible pressure sensor with carbon nanotube active matrix for electronic skin," *Nano Lett.*, vol. 18, no. 3, pp. 2054–2059, 2018.

[11] C. Wang *et al.*, "User-interactive electronic skin for instantaneous pressure visualization," *Nature Mater.*, vol. 12, p. 899, Oct. 2013.

[12] G. Schwartz *et al.*, "Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring," *Nature Commun.*, vol. 4, p. 1859, May 2013.

[13] S. Gupta, W. T. Navaraj, L. Lorenzelli, and R. Dahiya, "Ultra-thin chips for high-performance flexible electronics," *NPJ Flexible Electron.*, vol. 2, no. 1, p. 8, Mar. 2018.

[14] W. T. Navaraj, S. Gupta, L. Lorenzelli, and R. Dahiya, "Wafer scale transfer of ultrathin silicon chips on flexible substrates for high performance bendable systems," *Adv. Elect. Mater.*, vol. 4, no. 4, Apr. 2018, Art. no. 1700277.

[15] R. S. Dahiya, G. Metta, M. Valle, A. Adami, and L. Lorenzelli, "Piezoelectric oxide semiconductor field effect transistor touch sensing devices," *Appl. Phys. Lett.*, vol. 95, no. 3, 2009, Art. no. 034105.

[16] C. Dagdeviren *et al.*, "Conformable amplified lead zirconate titanate sensors with enhanced piezoelectric response for cutaneous pressure monitoring," *Nature Commun.*, vol. 5, p. 4496, Aug. 2014.

[17] W. Han *et al.*, "Strain-gated piezotronic transistors based on vertical zinc oxide nanowires," *ACS Nano*, vol. 6, no. 5, pp. 3760–3766, Apr. 2012.

[18] R. S. Dahiya, A. Adami, C. Collini, and L. Lorenzelli, "POSFET tactile sensing arrays using CMOS technology," *Sens. Actuator A, Phys.*, vol. 202, pp. 226–232, Nov. 2013.

[19] F. Litimein, B. Bouhafs, Z. Dridi, and P. Ruterana, "The electronic structure of wurtzite and zincblende AlN: An *ab initio* comparative study," *New J. Phys.*, vol. 4, p. 64, Aug. 2002.

[20] A. Iqbal and F. Mohd-Yasin, "Reactive sputtering of aluminum nitride (002) thin films for piezoelectric applications: A review," *Sensors*, vol. 18, no. 6, p. 1797, Jun. 2018.

[21] E. Aksel and J. L. Jones, "Advances in lead-free piezoelectric materials for sensors and actuators," *Sensors*, vol. 10, no. 3, pp. 1935–1954, Jan. 2010.

[22] V. Mortet, A. Vasin, P.-Y. Jouan, O. Elmazria, and M.-A. Djouadi, "Aluminium nitride films deposition by reactive triode sputtering for surface acoustic wave device applications," *Surf. Coat. Technol.*, vol. 176, no. 1, pp. 88–92, Nov./Dec. 2003.

[23] P. T. Lin, H. Jung, L. C. Kimerling, A. Agarwal, and H. X. Tang, "Low-loss aluminium nitride thin film for mid-infrared microphotonics," *Laser Photon. Rev.*, vol. 8, no. 2, pp. 23–28, Mar. 2014.

[24] J. Chen, S. K. Oh, N. Nabulsi, H. Johnson, W. Wang, and J.-H. Ryou, "Biocompatible and sustainable power supply for self-powered wearable and implantable electronics using III-nitride thin-film-based flexible piezoelectric generator," *Nano Energy*, vol. 57, pp. 670–679, Mar. 2019.

[25] S. Gupta, N. Yogeswaran, F. Giacomozzi, L. Lorenzelli, and R. Dahiya, "Flexible AlN coupled MOSFET device for touch sensing," in *Proc. IEEE Sensors*, New Delhi, India, Oct. 2018, pp. 1–4.

[26] L. Rosenberger, R. Baird, E. McCullen, G. Auner, and G. Shreve, "XPS analysis of aluminum nitride films deposited by plasma source molecular beam epitaxy," *Surf. Interface Anal.*, vol. 40, no. 9, pp. 1254–1261, Sep. 2008.

[27] R. Puurunen *et al.*, "Growth of aluminium nitride on porous silica by atomic layer chemical vapour deposition," *Appl. Surf. Sci.*, vol. 165, pp. 193–202, Sep. 2000.

[28] M. Akiyama *et al.*, "Flexible piezoelectric pressure sensors using oriented aluminum nitride thin films prepared on polyethylene terephthalate films," *J. Appl. Phys.*, vol. 100, no. 11, 2006, Art. no. 114318.

[29] N. Jackson, R. O'Keeffe, F. Waldron, M. O'Neill, and A. Mathewson, "Influence of aluminum nitride crystal orientation on MEMS energy harvesting device performance," *J. Micromech. Microeng.*, vol. 23, no. 7, Jun. 2013, Art. no. 075014.

[30] A. Sanz-Hervás, M. Clement, E. Iborra, L. Vergara, J. Olivares, and J. Sangrador, "Degradation of the piezoelectric response of sputtered *c*-axis AlN thin films with traces of non-(0002) X-ray diffraction peaks," *Appl. Phys. Lett.*, vol. 88, Apr. 2006, Art. no. 161915.

[31] M. Stewart and M. G. Cain, "Direct piezoelectric measurement: The berlincourt method," in *Characterisation of Ferroelectric Bulk Materials and Thin Films*. Berlin, Germany: Springer, 2014, pp. 37–64.

[32] A. Dolgonos, T. O. Mason, and K. R. Poeppelmeier, "Direct optical band gap measurement in polycrystalline semiconductors: A critical look at the Tauc method," *J. Solid State Chem.*, vol. 240, pp. 43–48, Aug. 2016.

[33] Y. Taniyasu, M. Kasu, and T. Makimoto, "An aluminium nitride light-emitting diode with a wavelength of 210 nanometres," *Nature*, vol. 441, pp. 325–328, May 2006.

[34] C. G. Núñez, W. T. Navaraj, E. O. Polat, and R. Dahiya, "Energy-autonomous, flexible, and transparent tactile skin," *Adv. Funct. Mater.*, vol. 27, no. 18, May 2017, Art. no. 1606287.

[35] F. A. Viola, A. Spanu, P. C. Ricci, A. Bonfiglio, and P. Cosseddu, "Ultrathin, flexible and multimodal tactile sensors based on organic field-effect transistors," *Sci. Rep.*, vol. 8, no. 1, p. 8073, May 2018.

[36] M. L. Hammock, A. Chortos, B. C.-K. Tee, J. B.-H. Tok, and Z. Bao, "25th anniversary article: The evolution of electronic skin (E-Skin): A brief history, design considerations, and recent progress," *Adv. Mater.*, vol. 25, no. 42, pp. 5997–6038, Nov. 2013.

[37] Z. Ji *et al.*, "The design and characterization of a flexible tactile sensing array for robot skin," *Sensors*, vol. 16, no. 12, p. 2001, 2016.

[38] F. Vidal-Verdú *et al.*, "A large area tactile sensor patch based on commercial force sensors," *Sensors*, vol. 11, no. 5, pp. 5489–5507, 2011.

[39] S. Hannah, A. Davidson, I. Glesk, D. Uttamchandani, R. Dahiya, and H. Gleskova, "Multifunctional sensor based on organic field-effect transistor and ferroelectric poly(vinylidene fluoride trifluoroethylene)," *Org. Electron.*, vol. 56, pp. 170–177, May 2018.

[40] S. Gupta, D. Shakthivel, L. Lorenzelli, and R. Dahiya, "Temperature compensated tactile sensing using MOSFET with P(VDF-TrFE)/Ba TiO_3 capacitor as extended gate," *IEEE Sensors J.*, vol. 19, no. 2, pp. 435–442, Jan. 2019.

Shoubhik Gupta received the B.Tech. degree in electrical engineering from the Indian Institute of Technology Kanpur, India, in 2014. He is currently pursuing the Ph.D. degree with the University of Glasgow.

He was a Marie Curie Early Stage Researcher with Fondazione Bruno Kessler, Italy. He has authored 22 research articles and coauthored one book. His current research area is ultrathin silicon chips and its application in flexible electronics. He is also interested in piezoelectric materials and thin film deposition techniques.

Nivasan Yogeswaran received the B.Eng. (Hons.) degree in electronic engineering from the University of Surrey, U.K., where he specialized in devices, and the master's degree in nanoelectronics and nanotechnology from the University of Southampton, U.K. He is currently pursuing the Ph.D. degree with the University of Glasgow, U.K.

His research interests include development and investigation of graphene devices and sensors for large-area flexible electronic applications.

Flavio Giacomozzi received the Mechanical Engineering degree from the University of Padova, Padua, Italy, in 1982.

Since 1983, he has been with Fondazione Bruno Kessler (FBK, formerly ITC- IRST), Trento, Italy. From 1983 to 1988, he worked on the improvements of surfaces properties of materials. In 1988, he joined the Microelectronic Division, Center for Materials and Microsystems, FBK, where he was in charge of development of fabrication processes technological steps. Since 1996, he has been working on the development of microelectromechanical systems (MEMS) technologies and the realization of prototypes of several devices as sensors, capacitive microphones, and RF MEMS devices. He is author or coauthor of more than 120 publications in these fields and in charge of several projects.

Leandro Lorenzelli received the Laurea degree in electronic engineering from the University of Genoa, Genoa, Italy, in 1994, and the Ph. D. degree in electronics materials and technologies from the University of Trento, Trento, Italy, in 1998. During the Ph.D. course, his research activity concerned the development of electrochemical CMOS-based microsensors.

In 1998, he joined the Staff of the ITC-IRST Microsystems Division, Trento, and was involved in the realization of microsystems for biomedical, environmental, and agro-food applications. Since 2005, he has been responsible for the Microsystems Technology Research Unit, Fondazione Bruno Kessler, Trento. His main scientific interests are in the processing technologies for both bio-microelectromechanical system and microtransducers.

Ravinder Dahiya (S'05–M'09–SM'12) is Professor of Electronics and Nanoengineering with the University of Glasgow, U.K. He is the Leader of the Bendable Electronics and Sensing Technologies (BEST) research group, which conducts fundamental and applied research in the multidisciplinary fields of flexible and printable electronics, tactile sensing, electronic skin, robotics, and wearable systems. He has authored over 250 research articles, two books, two monographs, 12 patents (including seven submitted), and several book chapters. He led several international projects on e-skin, tactile sensing, robotic skin, and flexible electronics. He holds the prestigious EPSRC Fellowship. He received the Marie Curie Fellowship and the Japanese Monbusho Fellowship. Among several awards that he has received, the most recent are the 2016 Microelectronic Engineering Young Investigator Award and the 2016 Technical Achievement Award from the IEEE Sensors Council. He was the TPC Co-Chair of IEEE Sensors 2017 and IEEE Sensors 2018. He is also a Distinguished Lecturer of the IEEE Sensors Council and has been serving on the Editorial Boards of *Scientific Report* and the IEEE Sensors Journal.