Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 120 (2015) 459 – 463
Procedia Engineering
www.elsevier.com/locate/procedia

EUROSENSORS 2015

A new technology of ultrathin AlN piezoelectric sensor for pulse wave measurement

A. Bongrain[a], L. Rousseau[b], L. Valbin[b], N. Madaoui[b], G. Lissorgues[b], F.Verjus[a], PA. Chapon[a,c]

[a]*BodyCap-medical, Caen, FRANCE*
[b]*ESIEE Paris, ESYCOM, Noisy-Le-Grand, France*
[c]*UMR UCBN-INSERM U 1075 (Mobilités : Attention, Orientation et Chronobiologie). Université de Caen Basse-Normandie, Caen, France*

Key words: piezo-electric sensor, AlN, cardiac patch, cardiac pulse wave monitoring

Abstract

In this study the design and characterization of a new technology of ultrathin AlN piezoelectric sensors able to measure micro-deformations is reported. The sensors are fabricated using a CMOS compatible clean room process in which the sensitive part is embedded into a thin bio-compatible and conformal layer of parylene (total thickness below 10 µm). That makes the sensors very flexible and sensitive to micro-deformation measurements. In this study, this technology is applied to monitor heart activity: heart rate, blood pulse wave, pulse wave velocity. Blood pulse wave could be measured with a very good accuracy; this technology could thus be used for the prediction of cardiovascular diseases by analyzing the pulse wave shape.

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords:

1. Introduction

Recently, the interest and the need of very thin and flexible sensors have increased especially for the development of new medical applications. The current trend in this field is the development of user friendly medical sensors which can be used directly by the patients to monitor physiological parameters. A particular attention is given to the preservation of comfort and the decrease of the hospitalization costs. Nowadays, micro technologies make possible the development of non-invasive flexible and miniaturized sensors for physiological parameters monitoring. Indeed,recent works aim to develop flexible patches for skin temperature monitoring [1], wound infection detection

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015
doi:10.1016/j.proeng.2015.08.668

[2], sweat chemical analysis [3] , or and cardiac activity monitoring [4-8]. Most of the cardiac patches developed measure the electrical activity (ECG signal) [4-5] responsible for the myocardial contraction; few of them are able to measure the blood flow induced by the myocardial contraction. This kind of sensors could present many interests: simply heart rate monitoring, measurement of blood pulse wave and pulse wave velocity. Many cardiovascular diseases may be diagnosed from the blood pulse wave shape and pulse wave velocity is the gold standard for the evaluation of the arterial stiffness [9].Recent preliminary works report on the fabrication of similar devices based on different technologies such as polymer transistors [6], gold nanowires used as variable resistance [7] and PVDF-based piezoelectric sensors [8]. All these technologies feature high sensitivity over pressure forces and have shown the possibility to monitor the cardiac signal and the possibility of pulse wave analysis. Nevertheless the technology of polymer transistor reported in [6] needs high gate voltage (typically -100 V) while the gold nanowires patch as well as the PVDF-based sensors described in [8] need to be encapsulated in thick packaging and are not compatible with CMOS processes.

The technology developed here is based on piezoelectricity using AlN layer embedded in a biocompatible conformal and extremely thin parylene layer [10]. With these materials, the manufacturing process is completely compatible with CMOS technology, which facilitates industrialization and offers opportunity to monolithically integrate electronics on the same chip. Moreover, such technology is completely biocompatible and needs very low power supply which may allow to consider *in-vivo* applications.

2. Boddy

2.1. Transducers fabrication process

The process, described in fig 1a is optimized to allow the fabrication of small and large AlN transducers. The first metal electrode, the piezoelectric AlN layer and the second electrode layer of the transducers are successively deposited and micro-structured using standard clean room technics on a 500 nm-thick thermally grown silicon oxide on (100) silicon wafer. Two configurations are investigated for the first electrode. In the first one, aluminum is deposited by DC magnetron sputtering and patterned by photolithography and wet etching. In the second configuration, platinum patterned by lift-off is used.

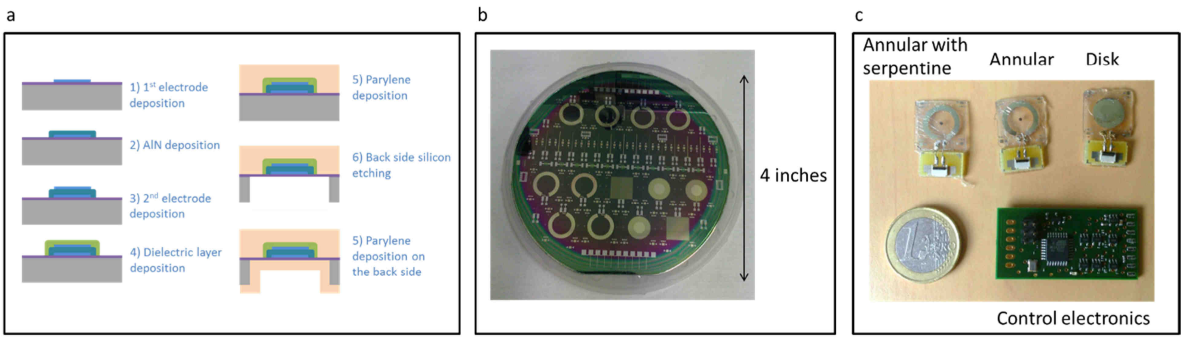

Fig. 1: (a) Illustration of the AlN transducers fabrication process, (b) picture of a processed wafer and (c) picture of fabricated sensors with the control electronic

The piezoelectric AlN layer is deposited on the first electrode using DC reactive magnetron sputtering method where an aluminum target is pulverized by a Ar/N_2 plasma. In both configurations aluminum is used as second electrode. Then a double layer of SiO_2/AlN is deposited and microstructured to shift the neutral fiber of the global structure outside the piezoelectric AlN. Structures are then insulated by a conformal deposition of parylene C by evaporation of parylene monomers. The parylene layer is processed by photolithography to open the contact electrodes in O_2/Ar plasma. The silicon is selectively etched from the back side in Deep Reactive Ion Etching (DRIE) to release the piezoelectric structures. Finally, a second parylene C deposition is achieved on the back side to encapsulate the transducer before releasing. The thicknesses of the first electrode, the AlN, the second electrode, the SiO2 layer, the second AlN layer and both parylene layers are 200 nm, 1000 µm, 200 nm, 120 nm, 900 nm and 5000 nm, respectively.

2.2. Results and discussions

A picture of a processed wafer,the different design of realized AlN transducers (circular, annular and annular with serpentine shape structures) are presented in fig 1b and fig 1c, respectively. The control electronic presented in fig 1c is composed of a small charge amplifier module connected to the sensor, a filter and a microcontroller. The communication with a PC IHM is ensured by a USB interface driven by the microcontroller.

Firstly, AlN d_{33}^f are measured on different AlN samples deposited on aluminum and on platinum along the wafers central axis to obtain a profile. Measurements were achieved by laser interferometry. The set up equipment's are described in [11]. The average measured values of d_{33}^f are presented in table 1. Typically, higher d_{33}^f are measured on AlN deposited on platinum. This result is coherent with the literature [12]. Secondly, we observed that structures realized in aluminum as first electrode feature statistically better production yield (table 1). A yield near 100% is obtained even on high surface structures. In the case of platinum as first electrode, a lower production yield is obtained; it is mainly due to short circuits occurring between the platinum electrode and the aluminum electrode.

Table 1. d33f and functional structures yield measured values for AlN layers deposited on aluminum and on platinum

First electrode material	Aluminum (*t*)	Platinum
d_{33}^f (pC/N)	2.75	3.4
Yield (%)	95-100	70-80

The AlN dielectric permittivity extracted by the capacitance and thickness measurements of different transducers having different surfaces, is found to be typically 9.1. The dielectric value obtained here is higher than the theoretical value of crystalline AlN which is around 8.5 [13] but coherent with reported values of polycrystalline AlN deposited by sputtering method [14].

The different AlN transducer design responses are also investigated on the fluidic set up which reproduces the deformation of an artery with an elastic membrane fixed on a cavity. It consists in a water column where the average pressure is controlled and a membrane mounted on a cavity connected to the water column on which the piezoelectric transducer is stuck. The response of the different AlN transducers are investigated when the fluidic pressure varies around a static pressure. Fig 2a presents the average sensitivity curves of the different design for a static pressure of 45 mmHg. As excitation signal, the pressure is oscillated by injecting and removing a small water volume in between 200 µl to 1000 µm. In this range, the associated pressure variation and membrane deflection is up to 8 mmHg and 1.5 mm, respectively. We may thus observe that the sensitivity is linear in these pressure variation range. Also, we may note that the best sensitivity is obtained for the annular structures in this configuration set up. Moreover, it is important to note that as indicated by the error bar, the standard deviation obtained for the sensitivity curves is weak. The extracted sensitivity over pressure variation of the different design is indicated on the sensitivity curve graph.

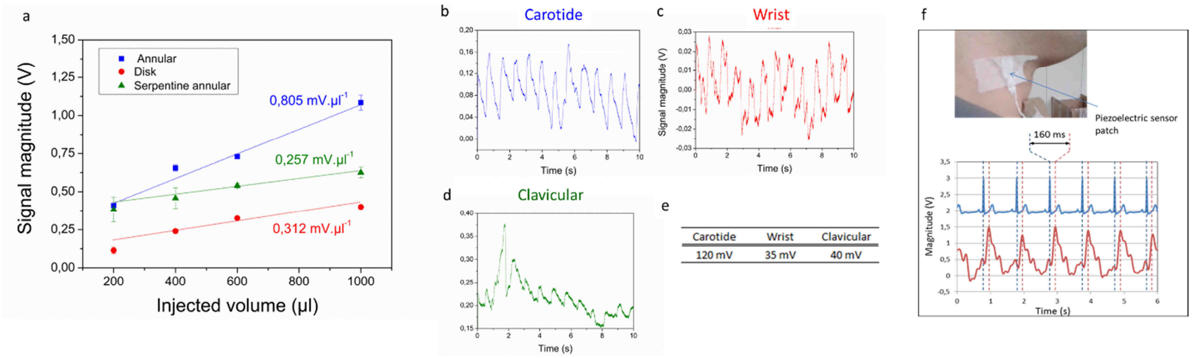

Fig.2.a) Sensitivity curves of the different AlN sensor designs over volume variation in a cavity above which is ixex a elastomer membrane, b) parallel monitored ECG and piezoelectric signals, c) puse wave signal measurement on the carotid, d) on the wrist and on the clavicular and f) typical signal magnitude on the different measurement places

Regading *on-vivo* testing, fig. 2.b, 2.c and 2.d present the cardiac signal obtained with the same transducer on the carotid, the wrist and the clavicular, respectively. Typical sensors response magnitude are summarized fig 2.f.
Signal magnitude of typically more than hundred mV was monitored on the carotid. It represents some pC in range of charge generation when we consider that the charge amplifier has a 10 pF feedback capacitor. In comparison, the signal found on the wrist and on the clavicular, is significantly lower. This result is coherent with the fact that deformation area and magnitude are smaller on these places. Indeed, the deformation magnitude of the caroted artery is typically in range of 400-500 µmfor a diameter of typically 5 to 10 mm [15]. On the wrist artery, the diameter is typically around 2 mm [16] and consequently the pulsativity is proportionally smaller.
Finally, a comparison of the ECG signal in parallel with piezo signal obtained in front of the carotid has also been performed (Fig 2.f). Both signals are clearly correlate and a systematic delay between the ECG and piezo signal is observed. This delay represents the time necessary for the blood to go from the heart to the artery measurement point. In the present case the delay is equal to 160 ms; it may be used as reference to calculate the pulse wave velocity.

3. Conclusion

We developed two versions of a CMOS compatible process for ultra-thin AlN-based piezoelectric sensors fabrication for micro deformation monitoring. The first version involves the deposition of the piezoelectric AlN on aluminum electrode while on the other version AlN is deposited on platinum. It was found that AlN features better piezoelectric properties on platinum. Nevertheless, the production yield is better and more repeatable on aluminum. Yield in between 90% to 100% are typically obtained for both optimized processes. The transducers characterized on mechanical set up feature high sensitivity over membrane deformation induced by fluidic pressure variations. The sensitivity over fluidic pressure change is evaluated to be up to pC/mmHg for the most sensitive design. In the test configuration, annular structures present the best sensitivity. Finally using these sensors, cardiac pulse wave signal was monitored with success at different point of interest and a correlation with ECG signal could be clearly established.

Acknowledgements

The authors acknowledge the European project 3DFF for partial grant funding

References

[1] A. Giuliani, M. Placidi, F. Di, A. Pucci, Reactive & Functional Polymers A new polystyrene-based ionomer / MWCNT nanocomposite for wearable skin temperature sensors, React. Funct. Polym. 76 (2014) 57–62.

[2] T.R. Dargaville, B.L. Farrugia, J. a. Broadbent, S. Pace, Z. Upton, N.H. Voelcker, Sensors and imaging for wound healing: A review, Biosens. Bioelectron. 41 (2013) 30–42.

[3] X. Huang, Y. Liu, K. Chen, W. Shin, C. Lu, G. Kong, et al., Stretchable , Wireless Sensors and Functional Substrates for Epidermal Characterization of Sweat, (2014) 1–8. doi:10.1002/smll.201400483.

[4] D.D. Mehta, N.T. Nazir, R.G. Trohman, A.S. Volgman, Single-lead portable ECG devices : Perceptions and clinical accuracy compared to conventional cardiac monitoring, J. Electrocardiol. 48 (2015) 710–716.

[5] W. Chang, T. Fang, Y. Lin, Characterization and fabrication of wireless flexible physiological monitor sensor, 143 (2008) 196–203.

[6] G. Schwartz, B.C. Tee, J. Mei, A.L. Appleton, D.H. Kim, H. Wang, et al., health monitoring, Nat. Commun. 4 (2013) 1858–1859.

[7] S. Gong, W. Schwalb, Y. Wang, Y. Chen, Y. Tang, J. Si, et al., A wearable and highly sensitive pressure sensor with ultrathin gold nanowires, Nat. Commun. 5 (2014) 1–8.

[8] Y. Chiu, W. Lin, H. Wang, S. Huang, M. Wu, Sensors and Actuators A : Physical Development of a piezoelectric polyvinylidene fluoride (PVDF) polymer-based sensor patch for simultaneous heartbeat and respiration monitoring, Sensors Actuators A. Phys. 189 (2013) 328–334.

[9] L. Peter, N. Noury, M. Cerny, A review of methods for non-invasive and continuous blood pressure monitoring : Pulse transit time method is promising ?, IRBM. 35 (2014) 271–282.

[10] *F. Verjus, L. Rousseau, L. Valbin (2013) : Procédé de fabrication d'un capteur piézoélectrique souple, Patent **n° 1354708**.*

[11] A. Bongrain, E. Scorsone, L. Rousseau, G. Lissorgues, P. Bergonzo, Realisation and characterisation of mass-based diamond micro-transducers working in dynamic mode, Sensors Actuators, B Chem. 154 (2011) 142–149.

[12] M.-A. Dubois, P. Muralt, Stress and piezoelectric properties of aluminum nitride thin film deposited onto metal electrodes by pulsed direct current reactive sputtering, J. Appl. Phys. 89 (2001) 6389-6395.

[13] T. Herzog, S. Walter, S. Hillmann, H. Heuer, Aluminum Nitride Thin Films for High Frequency Smart Ultrasonic Sensor Systems, (2012) 16–20.

[14] M. a. Moreira, I. Doi, J.F. Souza, J. a. Diniz, Electrical characterization and morphological properties of AlN films prepared by dc reactive magnetron sputtering, Microelectron. Eng. 88 (2011) 802–806.

[15] B.M. Pannier, J. Cuche, A. Benetos, P. Boutouyrie, M.E. War, Carotide artery pulsativity during parabolic flight, Acta Astronaumica 36 (1996) 433-438.

[16] J.J. Mourad, O. Hanon, X. Girerd, P. Boutouyrie, M.E. Safar, Artery Wall Thickness, The American journal of Cardiology 86 (2000) 564-567