Nano Energy (2016) 19, 532–540

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/nanoenergy

RAPID COMMUNICATION

An intelligent skin based self-powered finger motion sensor integrated with triboelectric nanogenerator

Lokesh Dhakar[a,b], Prakash Pitchappa[a], Francis Eng Hock Tay[b,c], Chengkuo Lee[a,*]

[a]*Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Singapore*
[b]*NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, 28 Medical Drive, Singapore 117456, Singapore*
[c]*Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore*

Received 16 January 2015; received in revised form 22 April 2015; accepted 22 April 2015
Available online 6 May 2015

KEYWORDS
Human motion sensor;
Intelligent sensor;
Capacitive coupling;
Triboelectric nanogenerator;
Biomechanical energy harvesting

Abstract
Tracking human gestures and movement is crucial for development of advanced input technologies and human computer interfaces. In this paper we demonstrate a novel flexible, low cost and wearable self-powered motion sensor to detect human finger motion for static positions and dynamic motion. As the finger moves to different positions, the capacitance between finger skin and device electrode changes. The device uses the change in capacitive coupling with human skin (epidermis) to measure the static and dynamic positions of finger. It is proposed that the device can utilize low frequency electric fields generated by the household power lines and equipment to passively sense the human finger movement. The device also acts as a triboelectric nanogenerator using outer epidermis as an active triboelectric layer for surface charge generation. It is shown to generate a maximum voltage of 70 V and a current area density of 2.7 μA/cm^2 at a load resistance of 5 MΩ. As a demonstration of a new approach for detection of static finger gestures and dynamic motion which is self-powered and intuitive, this work contributes towards development of self-powered sensors for human computer interfacing and osteoarthritis rehabilitation applications.

*Corresponding author at: Electrical and Computer Engineering, National University of Singapore, Engineering Drive 3, Singapore 117576. Tel.:+65 65165865; fax: +65 677911034.
E-mail address: elelc@nus.edu.sg (C. Lee).

http://dx.doi.org/10.1016/j.nanoen.2015.04.020
2211-2855/

Introduction

Detecting human motion and gestures is an important method for advanced input techniques and human computer interaction [1-3]. Human motion detection also has important applications in fall detection [4,5], elderly care [5,6] and osteoarthritis rehabilitation [7,8]. Wearable human motion detection technologies have been investigated for artificial and electronic skin applications using carbon nanotube (CNT) based strain sensors [9,10], accelerometers and gyroscopes [11]. More recently, human motion sensors have also been proposed by using triboelectrification [12]. To calculate parameters like angle or angular velocity associated with finger joints, these sensors relied on fast Fourier transform (FFT) which demands computing capacity and limits their application to only dynamic gestures. To improve the usability of the motion sensors, it is important to develop sensors which can provide electrical signal as output data for any given or static position or motion profile. The electrical output data can then readily be calibrated without much need of further processing using a microprocessor.

In this work, we propose a novel sensing mechanism which can be used to detect both static and dynamic finger joint positions. We humans are always surrounded by low frequency electric fields which are generated due to alternating current (AC) carrying power supply lines and electrical household equipment like monitors, electric oven, refrigerators etc. The effect of these low frequency electric fields on human body are well studied and are proven to be completely harmless within specified limits [13]. The electric field sensing has been utilized for sensors and studied previously. It was first proposed by Zimmerman [14] for proximity detection and human-computer interfacing. Here, we propose and demonstrate electric field based mechanism to realize flexible and wearable human motion sensors which are completely self-powered. The current carrying conductors (or power lines) are capacitively coupled to the human skin or epidermis [15] due to epidermis' conductive nature. The fabricated flexible device is assembled on epidermis which in turn leads to capacitive coupling between epidermis and device electrode. Due to the aforementioned arrangement, there is an oscillating potential signal observed at device electrode. The variation in intensity of this oscillating potential signal due to change in capacitive coupling between epidermis and flexible gold electrode is detected as a measured signal for finger motion. We demonstrate a proof of concept device to detect the motion of human finger using the proposed mechanism. As the angle at the finger joint changes, the capacitive coupling between the flexible gold electrode and epidermis changes accordingly. This change is reflected in change in the intensity of oscillating potential signal which is correlated with finger joint motion. The angle measurement data can further be extrapolated to calculate the angular velocity and acceleration of finger joints.

One of the limitations of majority of current wearable motion sensors is need of external power source. The need of external power source or battery makes the overall sensing system bulkier and shortens its life-span. Therefore sensing systems should be capable of harvesting energy from its external environment. This harvested energy can be used to power external circuit for wireless data transmission and other requirements. Moreover, having a sustainable power source also avoids the need to change a power source or battery enhancing the life-span of the overall system. Previously, ZnO nanowires [16-18] and piezo-polymers composites [19] have been used to realize flexible energy harvesting solutions. Recently, triboelectric energy harvesting has been demonstrated to be a promising alternative for harvesting biomechanical energy [20-23] due to its cost-effectiveness, easy fabrication, wide choice of materials and scalability [24-31]. Flexible triboelectric devices have been realized using graphene [32], patterned polymer films [33], paper [34] and metal-polymer composite materials [35]. Triboelectric generators have also been demonstrated by using human skin as a natural electrode [36,37] which makes them wearable and less bulky. Self-powered sensors have been demonstrated using triboelectric mechanism for pressure sensing [33], vibration sensing [38], acceleration sensing [39], chemical detection [40] and tactile sensing [21]. For the proposed device, we demonstrate energy harvesting capability based on triboelectric mechanism. The harvested biomechanical energy can be used to power auxiliary electronic circuitry for the sensor. The signal characteristics due to capacitive coupling with current carrying conductor and energy generation due to triboelectric phenomenon can easily be differentiated in terms of amplitude and frequency characteristics. The signal due to capacitive coupling of low frequency electric fields is typically very low as compared to triboelectric output but is strong enough to be detected. The device is shown to generate a maximum voltage of 70 V and a current of 2.7 $\mu A/cm^2$ at a load resistance of 5 $M\Omega$. The proposed mechanism is suitable for skin and body based wearable and flexible sensors. Our work proves that the proposed mechanism can be used for skin and body based wearable and flexible sensors for various applications in recognition of gesture and motion pattern, advanced input method for human-machine interface, and osteoarthritis rehabilitation.

Materials and methods

Fabrication of device

In the first step of device fabrication, 100 nm thick Silicon Nitride (SiN) is deposited using low pressure chemical vapor deposition (LPCVD) on a silicon (Si) wafer. Square window opening patterns of 2 $\mu m \times 2$ μm size are then etched in SiN layer using reactive ion etching (RIE). The SiN layer acts as hard mask and is used to etch Si anisotropically leading to pyramid shaped patterns using potassium hydroxide (KOH) solution (Figure 1a and c). The etched wafer is then treated with (tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane (United Chemical Technologies) to reduce the adhesion of polydimethylsiloxane (PDMS) with wafer during peeling off process. Thereafter, the patterned wafer is used as a mold and poured with 10:1 PDMS mixture and degassed in a dessicator for 4 h to let PDMS enter in KOH etched pyramid cavities in a uniform manner. The samples are then cured at 120 °C for 1 h and the micro-patterned PDMS films are

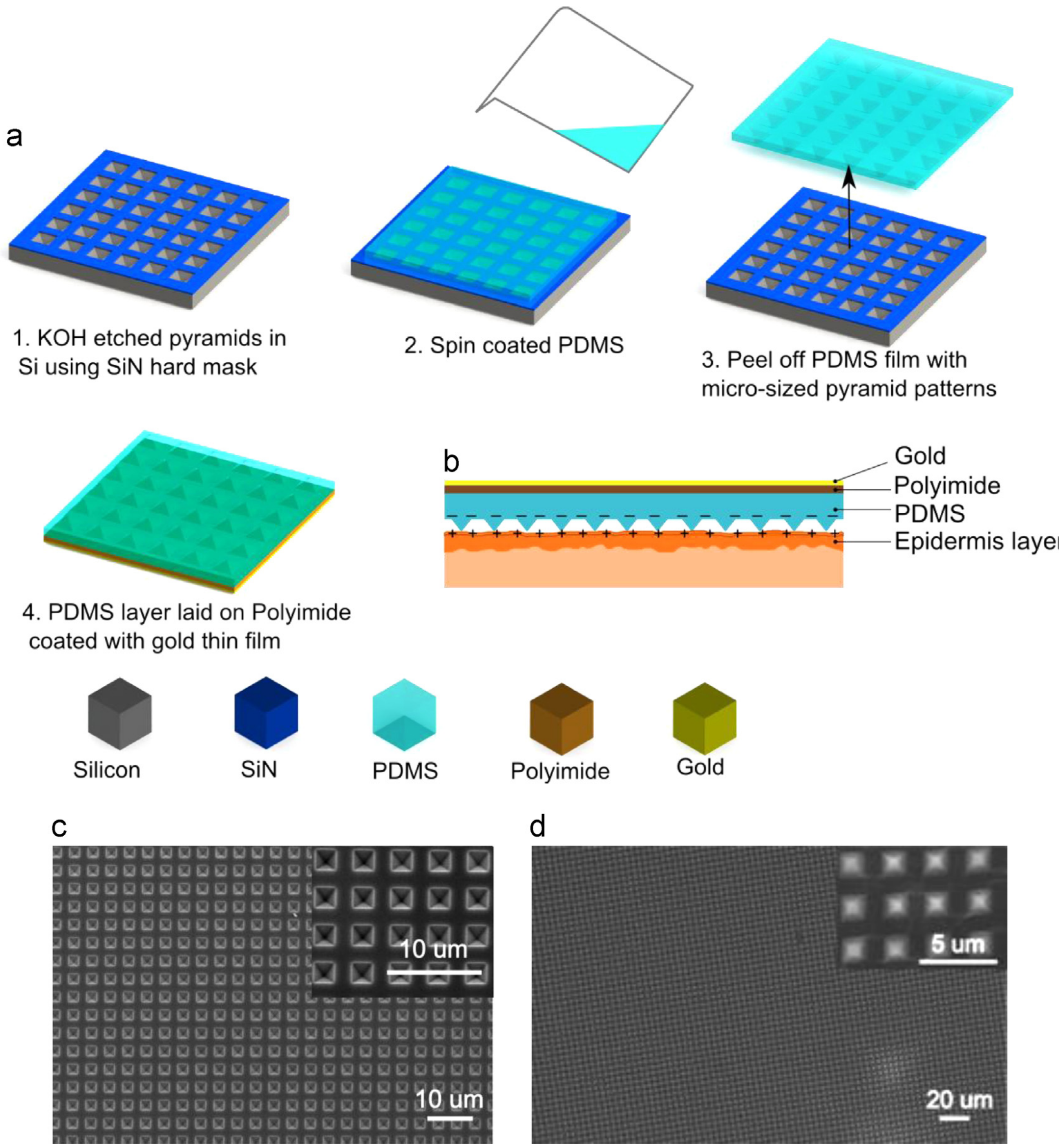

Figure 1 (a) Fabrication process flow of flexible device, (b) schematic of assembled device on epidermis layer, and (c) and (d) SEM images of pyramids etched pits in silicon wafer and pyramid structures transferred to PDMS, respectively.

peeled off from the mold (Figure 1d). These micro-patterned films are then carefully laid and bonded on a polyimide (Kapton) substrate which is already coated with a 50 nm gold film on the other side as an electrode. Polyimide is chosen as the substrate, owing to its excellent adhesion properties with gold film compared to PDMS and its superior mechanical characteristics. Polyimide layer helps to maintain the overall flexibility of device while improving the mechanical robustness. The fabricated flexible device is then assembled on epidermis layer as shown in schematic in Figure 1b.

Characterization and measurement

The topography of surfaces was characterized using Nova NANOSEM 230 from FEI. The voltage and current measurements are made using DSOX3034A oscilloscope from Agilent Technologies. For the capacitance measurement Agilent 4924A Precision Impedance Analyzer was used. Agilent 33500B waveform generator was used to generate AC signal at 1 kHz which was capacitively coupled to skin.

Working principle

Working of finger motion sensor

Humans are constantly exposed to low frequency electric fields in their daily lives. The AC carrying conductors and electrical equipment are capacitively coupled to epidermis due to its conductive characteristics [41]. A schematic diagram depicting electric field lines coupled to human body is shown in Figure 2a. Epidermis is considered as a large conductor capacitively coupled to current carrying conductor. The flexible device comprising of micro-patterned PDMS film at the top and a gold electrode at the bottom is attached to epidermis such that PDMS film is in direct contact with

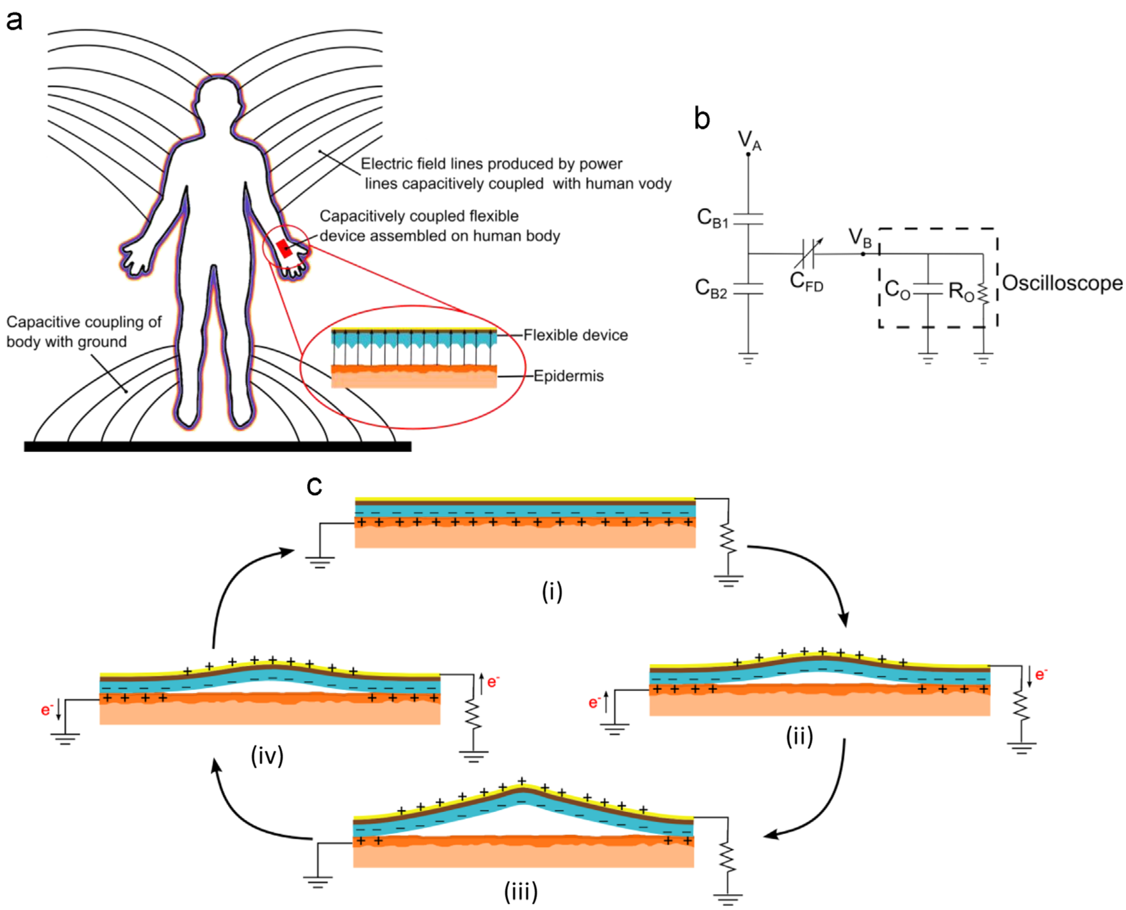

Figure 2 (a) Schematic of electric field lines coupled to human body and flexible device assembled on epidermis, (b) circuit diagram to model the capacitive couplings of human body and assembled flexible device on epidermis and (c) working mechanism of triboelectric nanogenerator utilizing skin as an active triboelectric layer for energy generation.

epidermis layer (Figure 2a inset). The space between epidermis and gold electrode is separated by a combination of air, PDMS and polyimide layers. This system of stacked layers forms a capacitive system between epidermis and gold electrode. An equivalent electrical circuit proposed in Figure 2b for this system. In this circuit, V_A is the potential at the current carrying conductor or power line which generates electric field. The epidermis is capacitively coupled to current carrying conductor and ground conductor through capacitor C_{B1} and C_{B2}, respectively. As the device is assembled on epidermis, it is coupled to epidermis through capacitance C_{FD} which is shown as a variable capacitance in the electrical circuit. The change in capacitive coupling between epidermis and gold electrode (C_{FD}) results in the change in intensity of oscillating potential signal at gold electrode. In the presented device, we correlate the change of finger joint angle, which is the physical parameter to be measured with the change in C_{FD}, using variation in intensity of oscillating potential signal. The capacitive coupling between gold electrode and conductor producing electric field lines can safely be ignored in this model as compared to C_{B1} due to its small area relative to the overall epidermis area. The oscillating potential signal from the flexible gold electrode is then measured using oscilloscope as shown in Figure 2b. C_o and R_o are used to model the oscilloscope internal capacitance and resistance, respectively. This electrical circuit was deployed to model and study the signal V_B using LTspice for various values of C_{FD} (see Supplementary information section 1 for modeling results).

Working of triboelectric nanogenerator

Apart from acting as a finger motion sensor, the device also serves dual purpose of harvesting biomechanical energy from the finger movement. It works as a single electrode triboelectric nanogenerator which was first demonstrated by Prof. Z. L. Wang's group [42,43]. It uses PDMS micropyramid patterns as one of the triboelectric layers to improve the contact area when two triboelectric layers are put in contact [44]. Epidermis is chosen as the second triboelectric layer for charge generation using triboelectric mechanism during device operation. This device configuration is also aligned with the working mechanism of motion sensor described earlier, as PDMS and epidermis are in direct contact with each other. According to triboelectric series [45], epidermis has a high tendency to lose electrons relative to PDMS, which makes epidermis a good choice for energy generation using triboelectric mechanism. The flexible device is attached on the finger such that any movement in finger motion leads to an increase in gap

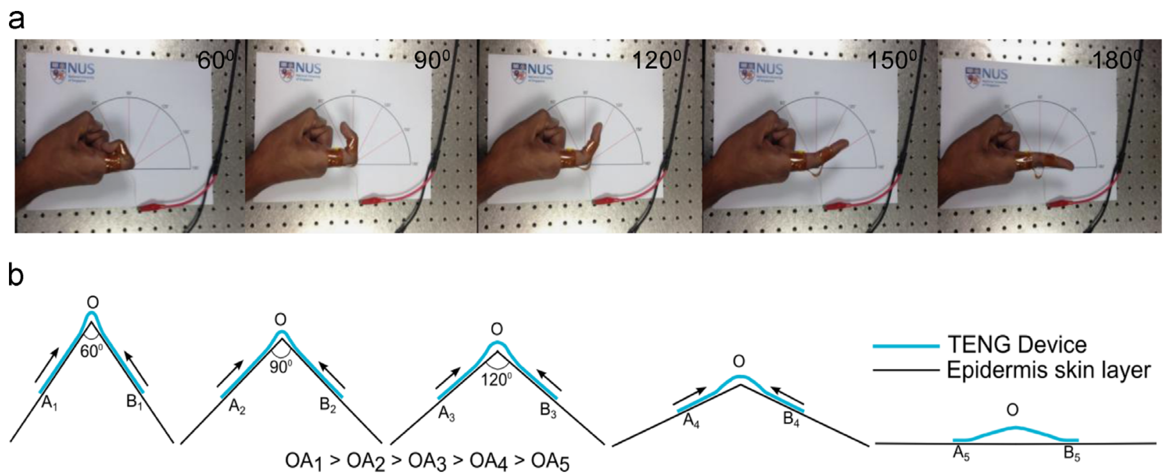

Figure 3 (a) Flexible device assembled on index finger to measure the angle at finger joint starting from 60° to 180° and (b) schematic illustration of change in capacitive coupling C_{FD} between epidermis and flexible device electrode as the finger joint angle changes.

between the PDMS layer and epidermis (Figure 3a and b). When the angle at finger joint is 60°, PDMS and epidermis are in full contact as shown in Figure 2c(i). At this point, the electric field due to the charges on epidermis and PDMS layer is negligible because of close vicinity of surfaces charges generated (Figure 2c(ii)). As the joint angle increases due to finger movement, the flexible device detaches from the epidermis. As epidermis has conductive nature and large surface area, it can be considered as ground where charges get redistributed. After the detachment of epidermis and PDMS layer, there is a potential generated at the gold electrode because of electric field generated by triboelectric surface charges. The gold electrode is connected to ground using a load resistor and the electrons (negatively charged) start moving from low potential to high potential i.e. towards the ground (Figure 2c(ii)). As the device reaches the maximum position when finger joint angle is 180° (Figure 2c(iii)), the device is in electrostatic equilibrium. Thereafter, as the finger moves in the opposite direction, the electrons start to move back towards the gold electrode (Figure 2c(iv)). As the finger completes one full cycle of 60°-180°-60°, one cycle of power generation is completed. This kind of natural motion is generated in day to day activities when we are holding objects, typing on keyboard, fist clenching and releasing etc. More importantly, such natural finger motion can be utilized to generate energy for useful purposes.

The two features of the proposed device: capacitive coupling change for motion sensing and triboelectric energy generation cycle, utilize same device configuration when assembled on epidermis. Both mechanisms work in tandem for sensing and energy generation. The finger joint motion sensor has potential applications in advanced input devices to recognize gestures and human computer interfaces. Another important application for joint motion sensing is in rehabilitation of osteoarthritis patients who suffer from difficulty in movement of finger joints. The harvested energy using triboelectrification can be used to power auxiliary electronics needed for sensor to realize a fully independent self-powered wearable sensors.

Results and discussion

The as-fabricated device was assembled on index finger to measure the angle at finger joint as shown in Figure 3a. The device is assembled such that patterned PDMS layer and epidermis are in direct contact when finger is fully bent (at angle of 60°). The range of the movement of middle joint (proximal interphalangeal joint) of index finger was measured to vary from a minimum of 60° to a maximum of 180° (angle at the joint). The schematic of the flexible device assembled on epidermis layer is shown in Figure 3b. Point O is located at the joint whereas points A_i and B_i (i=0-5, where i depicts the position of finger at an angle of 60°, 90°, 120°, 150° and 180°) are located at the end points of the flexible device where it is attached to epidermis. The epidermis is flexible and is in fully stretched position at 60° and reaches relaxed position as the joint angle increases, leading to wrinkling of the skin (epidermis) at an angle of 180°. The flexible device reaches a slack state as the joint angle increases and epidermis reaches a relaxed position. As shown in schematic diagram in Figure 3b, the points A_i and B_i starts moving towards O as joint angle increases and epidermis approaches a relaxed position. The decrement in distance OA_i ($OA_1 > OA_2 > OA_3 > OA_4 > OA_5$) leads to increased gap between the PDMS film and epidermis (Figure 3a and b). As the flexible device is assembled on epidermis, they form a capacitive system between epidermis and gold electrode. For simplicity, assuming there is only air separating the electrode and epidermis, the capacitance C_{FD} can be obtained using equivalent capacitance equation for capacitance connected in parallel configuration (Eq. (1)).

$$C_{FD} = \int_{A_i}^{B_i} \varepsilon_0 \frac{w}{d} .dl \tag{1}$$

where ε_0 is the electric constant, w is the width of flexible device, d is the gap between electrode and epidermis and varies across the epidermis surface and 'dl' is infinitesimal length across the epidermis surface. It is clear from the equation that as the average gap d increases, it will lead to

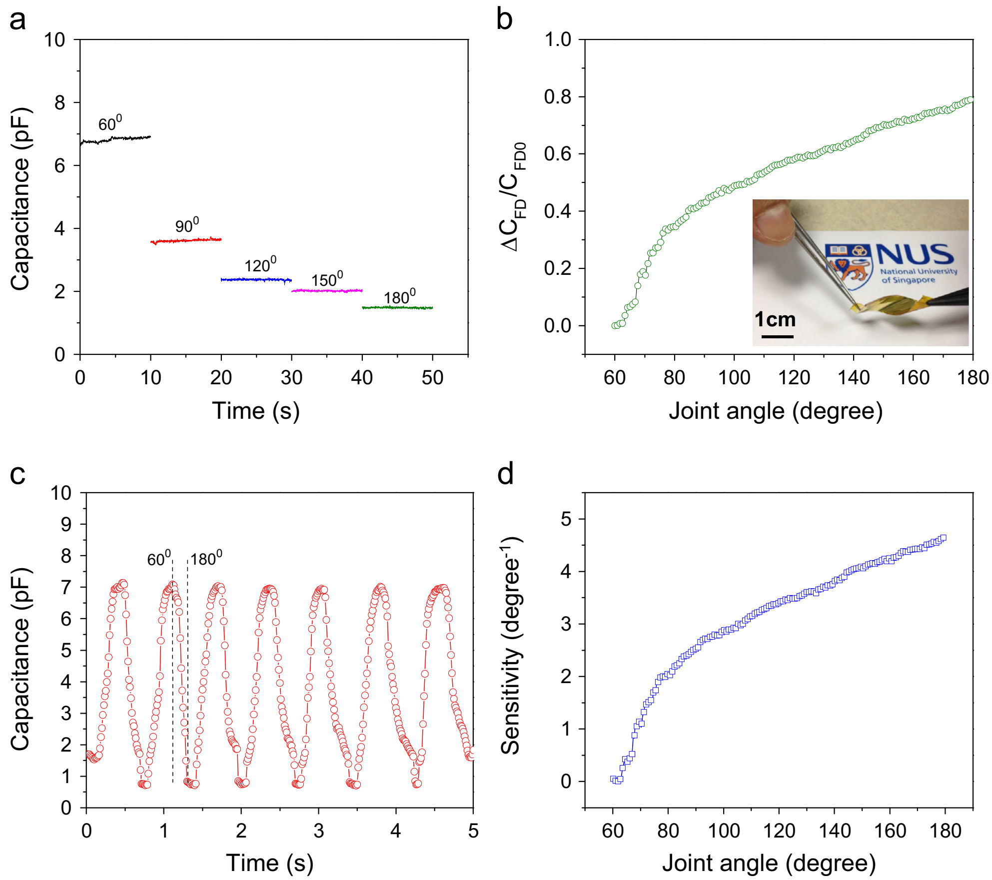

Figure 4 (a) Measurement of capacitance between epidermis and flexible device electrode (C_{FD}) at different finger joint angles, (b) change in capacitance (C_{FD}) as a function of finger joint angle, optical image of the flexible device (inset), (c) time variation of capacitance as the finger joint is moved in cycles from 180°-60°-180° and (d) sensitivity in terms of change in capacitance per unit joint angle ($\delta(\Delta C_{FD}/C_{FD0})/\delta\theta$).

increase in capacitance $C_{FD.}$ Measurements were conducted for capacitance C_{FD} at different joint angles as shown in Figure 4a. The measurements are taken at five difference angles: 60°, 90°, 120°, 150° and 180°. For the capacitance measurements at different joint angles, it was found that the capacitance decreases as the joint angle increases (average gap *d* increases) as predicted by the Eq. (1). The capacitance varied from 6.9 pF at 60° to 1.2 pF at 180°. From the experimental measurements, it is clear that increase in joint angle results in decrease in capacitive coupling between flexible gold electrode and epidermis. Figure 4b shows the change in capacitance as the finger joint angle changes. The measurements were also conducted for dynamic movements of finger moving in cycle from 60°-180°-60° as shown in Figure 4c. The capacitance changes cyclically as the joint angle changes. The sensitivity using capacitance ($\delta(\Delta C_{FD}/C_{FD0})/\delta\theta$) is plotted in Figure 4d which is defined by change in capacitance C_{FD} per unit change in the joint angle θ. The sensitivity was observed to increase with the increasing joint angle.

After capacitive coupling measurements between the epidermis and flexible gold electrode, measurements were conducted for oscillating potential signal due to electric field in environment. We conducted measurements using oscilloscope probes to observe the change in variation of oscillating potential signal amplitude at gold electrode as the capacitive coupling C_{FD} changes. As finger joint angle decreases, the capacitance between the epidermis and gold electrode decreases leading to reduction in capacitive coupling. The oscillating potential signal at electrode is expected to decrease as the coupling between epidermis and gold electrode decreases (simulation results in Supplementary information section 1). Multiple measurements were made to confirm this and it was observed that the acquired signal amplitude decreases as the joint angle decreases as shown in Figure 5a. Normalized signal amplitude values are plotted in Figure 5a for different joint angle values. The normalized signal amplitude continuously decreases as the finger joint angle decreases. All these measurements were conducted for 50 Hz signal due to the electric field created by AC carrying conductors in our lab. Special care was taken during the experiments such that hand did not change the position while conducting a set of experiments for 50 Hz oscillating electric field. To further confirm the working principle of motion sensor, 1 kHz signal was applied to epidermis using a signal generator. The measured signal was processed by passing through a high pass filter of 100 Hz to remove the signal due to 50 Hz electric field. The oscillating potential signal measured for 1 kHz followed the same pattern as measured for 50 Hz signal measurements and confirmed the working principle theory (see Supplementary information section 2). The

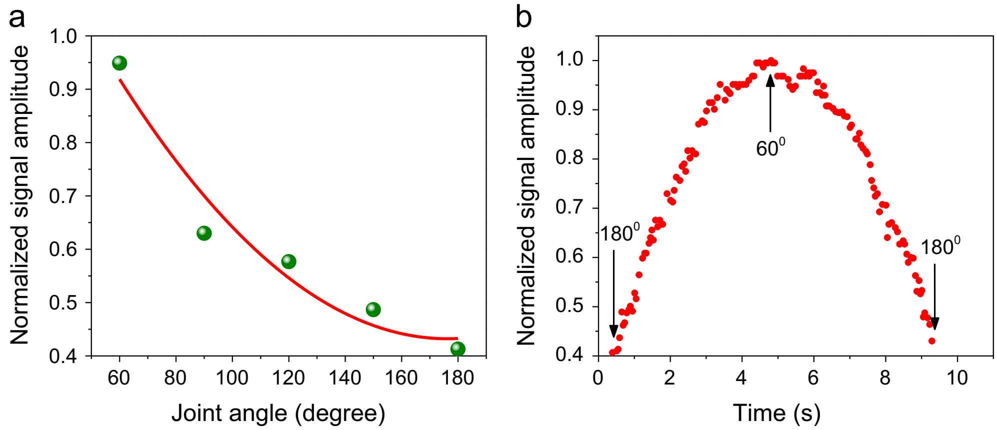

Figure 5 (a) Plot of normalized signal amplitude acquired by flexible device electrode as a function of finger joint angle and (b) variation of normalized signal amplitude as the finger joint angle completes a cycle from 180°-60°-180°.

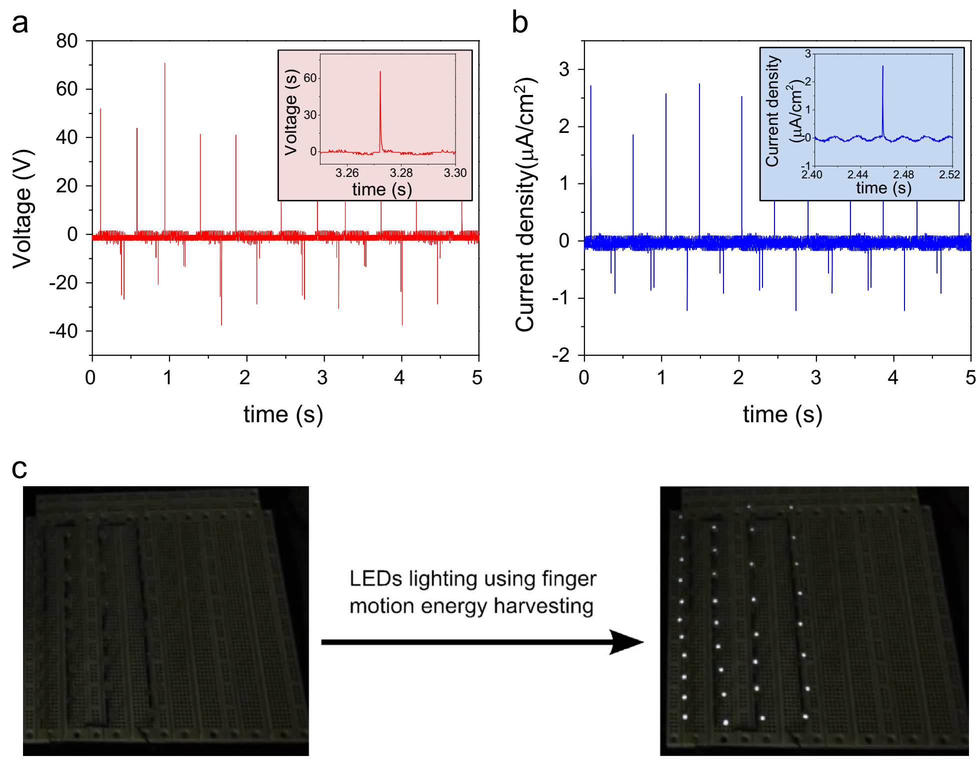

Figure 6 Tribolelectric energy generation characteristics of flexible device. (a) voltage generated, (b) current generated by flexible device due to the index finger movement in full cycles at a load resistance of 5 MΩ and (c) demonstration of LED lighting using the energy generated by flexible device assembled on index finger.

measurements were also conducted for dynamic movement of finger as shown in Figure 5b. The normalized signal amplitude increases from 0.4 at 180° and reached a maximum value of 1 at finger joint angle of 60° and then again drops down as joint angle becomes 180°. The average angular velocity of finger for the motion was calculated to be 0.42 rad/s. One of the limitations of these kind of sensors is that they are highly dependent on the coupling between epidermis and AC carrying conductor which is very sensitive to the position of body in the electric field mesh in the environment. This limitation can be overcome in future by having a controlled electric field at a specific frequency which is dedicated to human motion sensing. This can also be used in robotics for electronic skin applications.

Regarding the energy harvesting testing, the flexible device assembled on index finger was used to harvest biomechanical energy from the motion of finger. Figure 6a shows the voltage generated by the flexible device utilizing biomechanical energy harvesting from finger motion. The peak voltage generated was measured to be about 70 V with a load resistance of 5 MΩ connected in parallel with the device. Figure 5b depicts the current area density generated by the flexible nanogenerator. The peak current area density was measured to be 2.7 μA/cm^2. The power generated by the flexible nanogenerator using finger joint movement was used to power commercially available LEDs as shown in Figure 5c. First part of Figure 5c shows the LEDs in OFF positions and second part shows the LEDs are lighted up using the biomechanical energy harvested by device using triboelectric mechanism. This demonstrates the capability of flexible nanogenerator to power small electronic devices or electronic circuitry from simple finger movement.

Conclusions

We have developed a proof of concept device for a flexible, wearable and self-powered sensor to measure motion characteristics of finger. The novel working mechanism proposed for motion sensor is based on change in oscillating potential signal amplitude as the capacitive coupling between epidermis and device electrode changes. The fabrication process used for the motion sensor is based on molding process which is highly scalable and can be used to realize low-cost polymer based motion sensors. The device is demonstrated to measure the angle at the joints for different positions of finger. The angle data can further be used to measure the angular velocity and acceleration of dynamic finger movement. The flexible wearable device is also demonstrated to have impressive energy harvesting capability using triboelectric mechanism. It uses epidermis as an active triboelectric layer for charge generation which can be used for energy generation to power body wearable sensors using only one fabricated flexible triboelectric layer. It generated peak voltage of 70 V and peak current area density of 2.7 $\mu A/cm^2$ with a load resistance of 5 MΩ using finger motion. We envision that the newly proposed sensing mechanism is very suitable for human body based intelligent wearable sensors and can be utilized in future to realize completely independent self-powered sensors.

Acknowledgments

This work is supported by the NRF2011 NRF-CRP001-057 Program 'Self-powered body sensor for disease management and prevention-orientated healthcare' (R-263-000-A27-281) from the National Research Foundation (NRF), Singapore at the National University of Singapore, Singapore.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2015.04.020.

References

[1] T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, T. Sakurai, Proc. Natl. Acad. Sci. 101 (2004) 9966-9970.
[2] S.C. Mannsfeld, B.C. Tee, R.M. Stoltenberg, C.V.H. Chen, S. Barman, B.V. Muir, A.M. Sokolov, C. Reese, Z. Bao, Nat. Mater. 9 (2010) 859-864.
[3] S. Park, H. Kim, M. Vosgueritchian, S. Cheon, H. Kim, J.H. Koo, T.R. Kim, S. Lee, G. Scwartz, H. Chang, Adv. Mater. 26 (2014) 7324-7332.
[4] J. Chen, K. Karric, D. Chang, J. Luk, R. Bajcsy, Proceedings of the 27th Annual International Conference of the Engineering in Medicine and Biology Society, 2005, pp. 3551-3554.
[5] A. Bourke, J. O'brien, G. Lyons, Gait Posture 26 (2007) 194-199.
[6] C.-C. Lin, M.-J. Chiu, C.-C. Hsiao, R.-G. Lee, Y.-S. Tsai, IEEE Trans. Inf. Technol. Biomed. 10 (2006) 696-704.
[7] J.P. Estes, C. Bochenek, P. Fasler, J. Hand Ther. 13 (2000) 108-123.
[8] A.S. Merians, D. Jack, R. Boian, M. Tremaine, G.C. Burdea, S. V. Adamovich, M. Recce, H. Poizner, Phys. Ther. 82 (2002) 898-915.
[9] T. Yamada, Y. Hayamizu, Y. Yamamoto, Y. Yomogida, A. Izadi-Najafabadi, D.N. Futaba, K. Hata, Nat. Nanotechnol. 6 (2011) 296-301.
[10] D.J. Lipomi, M. Vosgueritchian, B.C. Tee, S.L. Hellstrom, J. A. Lee, C.H. Fox, Z. Bao, Nat. Nanotechnol. 6 (2011) 788-792.
[11] K. Aminian, B. Najafi, Comput. Animat. Virtual Worlds 15 (2004) 79-94.
[12] W. Yang, J. Chen, X. Wen, Q. Jing, J. Yang, Y. Su, G. Zhu, W. Wu, Z.L. Wang, ACS Appl. Mater. Interfaces 6 (2014) 7479-7484.
[13] M.A. Stuchly, T.W. Dawson, Proc. IEEE 88 (2000) 643-664.
[14] T.G. Zimmerman, IBM Syst. J. (1996) 609-617.
[15] T.G. Zimmerman, J.R. Smith, J.A. Paradiso, D. Allport, N. Gershenfeld, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 1995, pp. 280-287.
[16] Y. Qin, X. Wang, Z.L. Wang, Nature 451 (2008) 809-813.
[17] G. Zhu, R. Yang, S. Wang, Z.L. Wang, Nano Lett. 10 (2010) 3151-3155.
[18] Z.L. Wang, J. Song, Science 312 (2006) 242-246.
[19] K.I. Park, M. Lee, Y. Liu, S. Moon, G.T. Hwang, G. Zhu, J. E. Kim, S.O. Kim, D.K. Kim, Z.L. Wang, Adv. Mater. 24 (2012) 2999-3004.
[20] P. Bai, G. Zhu, Z.-H. Lin, Q. Jing, J. Chen, G. Zhang, J. Ma, Z. L. Wang, ACS Nano 7 (2013) 3713-3719.
[21] Y. Yang, H. Zhang, Z.-H. Lin, Y.S. Zhou, Q. Jing, Y. Su, J. Yang, J. Chen, C. Hu, Z.L. Wang, ACS Nano 7 (2013) 9213-9222.
[22] W. Yang, J. Chen, G. Zhu, J. Yang, P. Bai, Y. Su, Q. Jing, X. Cao, Z.L. Wang, ACS Nano 7 (2013) 11317-11324.
[23] Q. Zheng, B. Shi, F. Fan, X. Wang, L. Yan, W. Yuan, S. Wang, H. Liu, Z. Li, Z.L. Wang, Adv. Mater. 26 (2014) 5851-5856.
[24] G. Zhu, Z.-H. Lin, Q. Jing, P. Bai, C. Pan, Y. Yang, Y. Zhou, Z. L. Wang, Nano Lett. 13 (2013) 847-853.
[25] F.-R. Fan, Z.-Q. Tian, Z. Lin Wang, Nano Energy 1 (2012) 328-334.
[26] B. Meng, W. Tang, Z.-H. Too, X. Zhang, M. Han, W. Liu, H. Zhang, Energy Environ. Sci. 6 (2013) 3235-3240.
[27] G. Zhu, Y.S. Zhou, P. Bai, X.S. Meng, Q. Jing, J. Chen, Z. L. Wang, Adv. Mater. 26 (2014) 3788-3796.
[28] B. Meng, W. Tang, X. Zhang, M. Han, W. Liu, H. Zhang, Nano Energy 2 (2013) 1101-1106.
[29] W. Liu, M. Han, X. Sun, B. Meng, X.-S. Zhang, H. Zhang, Nano Energy 9 (2014) 401-407.
[30] M. Han, X.-S. Zhang, B. Meng, W. Liu, W. Tang, X. Sun, W. Wang, Z. Zhang, ACS Nano 7 (2013) 8554-8560.
[31] Y. Yang, H. Zhang, R. Liu, X. Wen, T.C. Hou, Z.L. Wang, Adv. Energy Mater. 3 (2013) 1563-1568.
[32] S. Kim, M.K. Gupta, K.Y. Lee, A. Sohn, T.Y. Kim, K.S. Shin, D. Kim, S.K. Kim, K.H. Leeand, H.-J. Shin, Adv. Mater. 26 (2014) 3918-3925.
[33] F.-R. Fan, L. Lin, G. Zhu, W. Wu, R. Zhang, Z.L. Wang, Nano Lett. 12 (2012) 3109-3114.
[34] P.-K. Yang, Z.-H. Lin, K.C. Pradel, L. Lin, X. Li, X. Wen, J.-H. He, Z.L. Wang, ACS Nano 9 (2015) 901-907.
[35] M. Taghavi, V. Mattoli, A. Sadeghi, B. Mazzolai, L. Beccai, Adv. Energy Mater. 4 (2014) 140002.

[36] X. Cheng, B. Meng, X. Zhang, M. Han, Z. Su, H. Zhang, Nano Energy 12 (2015) 19–25.
[37] B. Meng, X. Cheng, X. Zhang, M. Han, W. Liu, H. Zhang, Appl. Phys. Lett. 104 (2014) 103904.
[38] J. Chen, G. Zhu, W. Yang, Q. Jing, P. Bai, Y. Yang, T.-C. Hou, Z. L. Wang, Adv. Mater. 25 (2013) 6094–6099.
[39] H. Zhang, Y. Yang, Y. Su, J. Chen, K. Adams, S. Lee, C. Hu, Z. L. Wang., Adv. Funct. Mater. 24 (2014) 1401–1407.
[40] Z.H. Lin, G. Zhu, Y.S. Zhou, Y. Yang, P. Bai, J. Chen, Z.L. Wang, Angew. Chem. Int. Ed. 52 (2013) 5065–5069.
[41] D.T. Lykken, P.H. Venables, Psychophysiology 8 (1971) 656–672.
[42] Y. Yang, Y.S. Zhou, H. Zhang, Y. Liu, S. Lee, Z.L. Wang, Adv. Mater. 25 (2013) 6594–6601.
[43] Y. Yang, H. Zhang, J. Chen, Q. Jing, Y.S. Zhou, X. Wen, Z. L. Wang, ACS Nano 7 (2013) 7342–7351.
[44] L. Dhakar, F. Tay, C. Lee, J. Micromech. Microeng. 24 (2014) 104002.
[45] P.E. Shaw, Proc. R. Soc. Lond. Ser. A, Containing Pap. Math. Phys. Character 94 (1917) 16–33.

Lokesh Dhakar received his B.E. (Hons.) degree in Mechanical Engineering from Birla Institute of Technology and Science, Pilani in 2010. He worked in the industry as a design engineer from 2010 to 2011. He is currently working towards his Ph.D. degree from NUS Graduate School of Integrative Sciences and Engineering, National University of Singapore, Singapore. He is also keenly interested in entrepreneurship and technology commercialization. He is currently working on energy harvesting devices aimed at powering wireless wearable sensors for healthcare.

Prakash Pitchappa received his B.Eng. degree in Electronics and Communications from College of Engineering, Guindy, in 2008 and his M.Sc. degree from Department of Electrical and Computer Engineering at National University of Singapore in 2011. He is currently pursuing his Ph.D. from Department of Electrical and Computer Engineering at National University of Singapore and is attached to the Institute of Microelectronics (IME), A*STAR. His research interests include development and fabrication MEMS-based metamaterial devices.

Francis Eng Hock Tay is an Associate Professor with the Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore. He received the Ph.D. degree from the Massachusetts Institute of Technology (MIT), Cambridge, in 1995. Dr. Tay was the founding director of the Microsystems Technology Initiative (MSTI), and had established the Microsystems Technology Specialization. He has also served as the Technical Advisor, in the Micro and Nano Systems Laboratory, Institute of Materials Research Engineering (IMRE). His research areas include MEMS, biotechnology, nanotechnology, wearable devices, fall onset detection, vital signs monitoring, body sensor network, rehabilitation and scoliosis.

Chengkuo Lee received his Ph.D. degree in precision engineering from The University of Tokyo, Tokyo, Japan, in 1996. Currently, he is an Associate Professor in the Department of Electrical and Computer Engineering, National University of Singapore, Singapore. In 2001, he cofounded Asia Pacific Microsystems, Inc., where he was the Vice President. From 2006 to 2009, he was a Senior Member of the Technical Staff at the Institute of Microelectronics, A-STAR, Singapore. He has contributed to more than 250 international conference papers and extended abstracts and 180 peer-reviewed international journal articles. He is co-author of Micro and Nano Energy Harvesting Technologies (Artech House, 2015). He is also the holder of nine U.S. patents.