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Lokesh Dhakar

Triboelectric Devices for Power Generation and Self-Powered Sensing Applications

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Supervisor's Foreword

The progress of humanity has been fueled by the advent of technologies such as steam engine, electricity, transistors and internet. As we move forward, there is a continuous strive towards making our surroundings smarter and intelligent, which means we are looking at a future with myriad of sensors around us. One of the biggest challenges in this aspect to devise a sustainable way of powering these sensors. A potential strategy of achieving this is to design the sensor system in such a way that they are able to capture energy from their surroundings and convert it into usable form, which can be stored into batteries or capacitors. This process of capturing energy from surroundings is known as "Energy Harvesting". The energy available in the environment can be in various forms: solar, heat, acoustic or mechanical. This work specifically focuses on developing energy harvesting devices that convert mechanical energy available in the surroundings to electrical energy using triboelectric mechanism.

Triboelectric mechanism has been known for centuries in the form of static electricity. Recently, researchers have demonstrated a new application for this phenomenon—to convert mechanical energy into electrical energy. Lokesh has been involved in research of triboelectric mechanism since the scientific community began working in this area in 2012. His commitment towards research combined with hard work has resulted into this outstanding thesis. This work has been published in prestigious journals and conferences and has also been covered by many popular science media outlets. A part of this work published as a paper in the Journal of Micromechanics and Microengineering was selected as one of the top highlighted paper in the journal in 2014. He was also the outstanding oral paper award finalist for IEEE International Conference on Micro Electro Mechanical Systems 2015.

One of the most important factors which affect the performance of triboelectric mechanism based devices is the topography of the triboelectric layers. This work systematically studies the effect of micropatterned arrays on the performance of triboelectric devices. This provides important guidelines for researchers to design and pattern devices with the aim of improving their device performance.

Triboelectric mechanism based devices have enormous application in the area of wearable devices due to a wide choice of fabrication materials. The human skin has been proposed and demonstrated as one of the possible materials for biomechanical energy harvesting and sensing applications using triboelectric mechanism. Furthermore, a novel design for triboelectric mechanism based devices that is sensitive to both out-of-plane and in-plane mechanical stimulation has been proposed. Commercial viability of any technology depends on the scalable fabrication and economic production of devices. This work also explores and demonstrates roll-to-roll fabrication process as a method to fabricate triboelectric mechanism based devices in a scalable fashion.

This thesis work will be of interest to graduate students and researchers working in the area of mechanical energy harvesting. It presents a comprehensive literature review in this area, which will be useful for anybody embarking on their research journey in this area. Furthermore, the book provides an in-depth discussion of results obtained as a part of Lokesh's Ph.D. research.

Singapore Associate Professor Francis E.H. Tay
August 2016

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1. L. Dhakar, S. Gudla, X. Shan, Z. Wang, F.E.H. Tay, C.-H. Heng, C. Lee, Large scale triboelectric nanogenerator and self-powered pressure sensor array using low cost roll-to-roll UV embossing. Scientific Reports **6**, 22253 (2016)
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Acronyms

3-MPA	3-mercaptopropionic
AAO	Anodized aluminum oxide
AC	Alternating current
AFM	Atomic force microscope
Al	Aluminum
AlN	Aluminum nitride
Ar	Argon
Cu	Copper
DAQ	Data acquisition
DRIE	Deep reactive ion etching
emf	Electromotive force
FEP	Fluorinated ethylene propylene
Hg	Mercury
HMDS	Hexamethyldisilazane
IoT	Internet of Things
IPA	Isopropyl alcohol
ITO	Indium tin oxide
KOH	Potassium hydroxide
LCP	Liquid crystal polymer
LED	Light emitting diodes
LS-TENG	Large-scale triboelectric nanogenerator
MEMS	Microelectromechanical systems
NaCl	Sodium chloride
O_2	Oxygen
PA	Polyamide
PAN	Personal area network
PCB	Printed circuit board
PDMS	Polydimethylsiloxane
PECVD	Plasma enhanced chemical vapor deposition
PEH	Piezoelectric energy harvester

PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
Pt	Platinum
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
PZT	Lead zirconate titanate
RFID	Radio-frequency identification
RIE	Reactive ion etching
RMS	Root mean square
SEM	Scanning electron microscope
Si	Silicon
SiN	Silicon nitride
SiO_2	Silicon dioxide
TENG	Triboelectric nanogenerators
TiO_2	Titanium dioxide
UV	Ultraviolet
ZnO	Zinc oxide

Symbols

A_{noise}	Amplitude of noise
A_{signal}	Amplitude of required signal
F_0	Amplitude of the sinusoidal excitation force
A_i	Area of the *ith* coil in electromagnetic energy harvester
S	Area of triboelectric layer
F	Average impact force
$v_{av,i}$	Average velocity of the object between P_{i-1} and P_i
$a_{av,i}$	Average velocity of the object between P_{i-1} and P_i
ΔA	Change in area
ΔP	Change in momentum
Δl	Change in the height/length
q	Charge
P	Collective dipole in material
$V_{1/2}$	Contact potential difference of metal 1 against metal 2
C_{FD}	Coupling capacitance between the device electrode and epidermis
C_{B1}	Coupling capacitance of epidermis with current carrying conductor
C_{B2}	Coupling capacitance of epidermis with ground
c	Damping coefficient
Δx	Deformation along x-axis
Δy	Deformation along y-axis
x_{PDMS}	Deformation in PDMS layer
x_{SU-8}	Deformation in SU–8 micropillar
ε_0	Dielectric constant of air
P_k	Dipole created within a molecule
y	Displacement of proof mass
ΔT	Duration of impact
k_{eff}	Effective spring constant of PDMS micropad array
k_{SU-8}	Effective spring constant of the SU–8 micropillar array
d_0	Effective thickness constant
ω	Excitation frequency

F_k	External force applied on the molecule in piezoelectric model
g	Gap between the micropillars
h	Height of the micropillar
C_0	Internal capacitance of oscilloscope
R_0	Internal resistance of oscilloscope
l	Length of the micropillar
B	Magnetic field
σ_{ii}	Normal stress in direction $i = x, y, z$
V_{oc}	Open circuit voltage
Φ	Phase difference
v	Poisson's ratio
V_A	Potential at the current carrying conductor
V_B	Potential at the device electrode
m	Proof mass
M	Proof mass at the end of cantilever
ε_{r1}	Relative dielectric constants of triboelectric layer 1
ε_{r2}	Relative dielectric constants of triboelectric layer 2
$x(t)$	Relative distance between two triboelectric layers
$v(\mathrm{t})$	Relative velocity of triboelectric layers
ω_r	Resonant frequency
I_{sc}	Short circuit current
L	Side length of the array
SNR	Signal to noise ratio
k	Spring constant
$k_{SU\text{–}8\ pillar}$	Spring constant of a single SU–8 micropillar
k_i	Spring constant of an individual PDMS micropad
k_{PDMS}	Spring constant of the PDMS layer
ε_{ii}	Strain in direction $i = x, y, z$
S	Strain in the piezoelectric layer
σ	Surface charge density due to triboelectric effect
v_n	The normal component of velocity for the top part
d_1	Thickness of triboelectric layer 1
d_2	Thickness of triboelectric layer 2
t	Time
Φ	Total magnetic flux
z	Vertical displacement of the cantilever tip
V	Voltage generated across energy harvesting device
w	Width of the micropillar
Φ_1	Work function of metal 1
Φ_2	Work function of metal 2
E	Young's modulus

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Summary

Triboelectric effect has been proposed as a method to harvest mechanical energy from various sources in the environment. It also has applications in the area of sensors including motion sensors, pressure sensors and chemical sensors. This thesis explores the applications of triboelectric effect based contact electrification for mechanical energy harvesting and self-powered sensing. A comprehensive study has been conducted using micropatterned arrays to improve the understanding of device design parameters for triboelectric nanogenerators (TENG) cantilever configuration. Patterned layers were found to have better performance than unpatterned triboelectric layers. In the investigation, it was found that introduction of air voids with an optimum size was necessary to achieve better performance for TENG. It was also concluded that the performance of the TENGs could be significantly improved using smaller sized structures/patterns on the triboelectric layers. The optimum power produced by the device was measured to be 0.91 μW at 1g.

To develop wearable energy harvesting devices, human skin has been proposed and demonstrated as a potential triboelectric layer for biomechanical energy harvesting. The device generated a peak voltage of 70 V and peak current density of 2.7 $\mu A/cm^2$. The skin-based TENG has been demonstrated to capture mechanical energy from various human activities. The design for triboelectric nanogenerator has also been developed into a capacitance based sensor to accurately capture the finger movement. The triboelectric nanogenerator integrated with sensor can be used for osteoarthritis rehabilitation and advanced gesture input devices.

A novel mechanism based on triboelectric effect has been proposed to differentiate between the physical interactions in normal and sliding directions. This design can be used for tactile sensing applications. The device has also been demonstrated to harvest mechanical energy in multiple directions. This small form factor device can be used as a tactile sensor and also an energy harvester to capture energy from keyboard strokes or switches. The device was observed to generate a peak voltage and current of ∼90 V and ∼0.57 μA using normal force, respectively. Through the sliding motion, the peak voltage and current generated were measured to be ∼5 V and ∼0.08 μA, respectively.

For large-scale fabrication of triboelectric sensors and nanogenerators, a scalable fabrication process has been developed. Roll-to-roll UV embossing is used to pattern large-scale polymer films to improve the device performance. The fabricated large-scale nanogenerator produced a peak power density of 62.5 mW m^{-2}. The large-scale fabrication has been demonstrated to fabricate a large size pressure sensor array. The pressure detection sensitivity was observed to be 1.33 V kPa^{-1}. The sensor array has also been characterized and demonstrated for applications in posture monitoring, security systems and patient monitoring.