

Nanogenerators and Self-powered systems

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September 19, 2021

Some Good News

- **No Weekly Homework**
- **No Mid and Final Exams**
- **There is only one Final Project and Presentation**
 - **Format Option:**
 - **Literature Review (No less than 150 papers)**
 - **Technical Report**
- **Thus, Attendance is very important**
 - **One time absence or late = 3 final score less**

Week 1- General Introduction

Energy Harvesting and Sensing for Internet of Things

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Outline

- **Introduction**
- **Energy Harvesting for IoT**
- **Triboelectric Nanogenerators (TENG)**
- **Q&A**

Energy – A Revisit

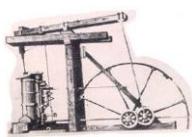
■ World Energy Consumption Trend

- Amount – Increasing

- Type

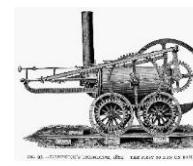
- Centralized to **distributed**
- Ordered to **disordered**

Steam Engine



1763 – first practical steam engine (James Watt)

Railway



1804 – first commercial locomotive train

Electric Power



1821 – principles of mechanical energy to electric power conversion (Michael Faraday)

Telegram, telephone



1876 – first US patent on telephone (Graham Bell)

Automobile, aerospace



1885 – first gasoline automobile (Karl Benz)

1903 – first successful airplane powered heavier than air human flight (Wright Bro.)



1876 – first US patent on telephone (Graham Bell)



Microelectronics, IT & Wireless

AI, IoT ?

What's Next?

Energy: Coal

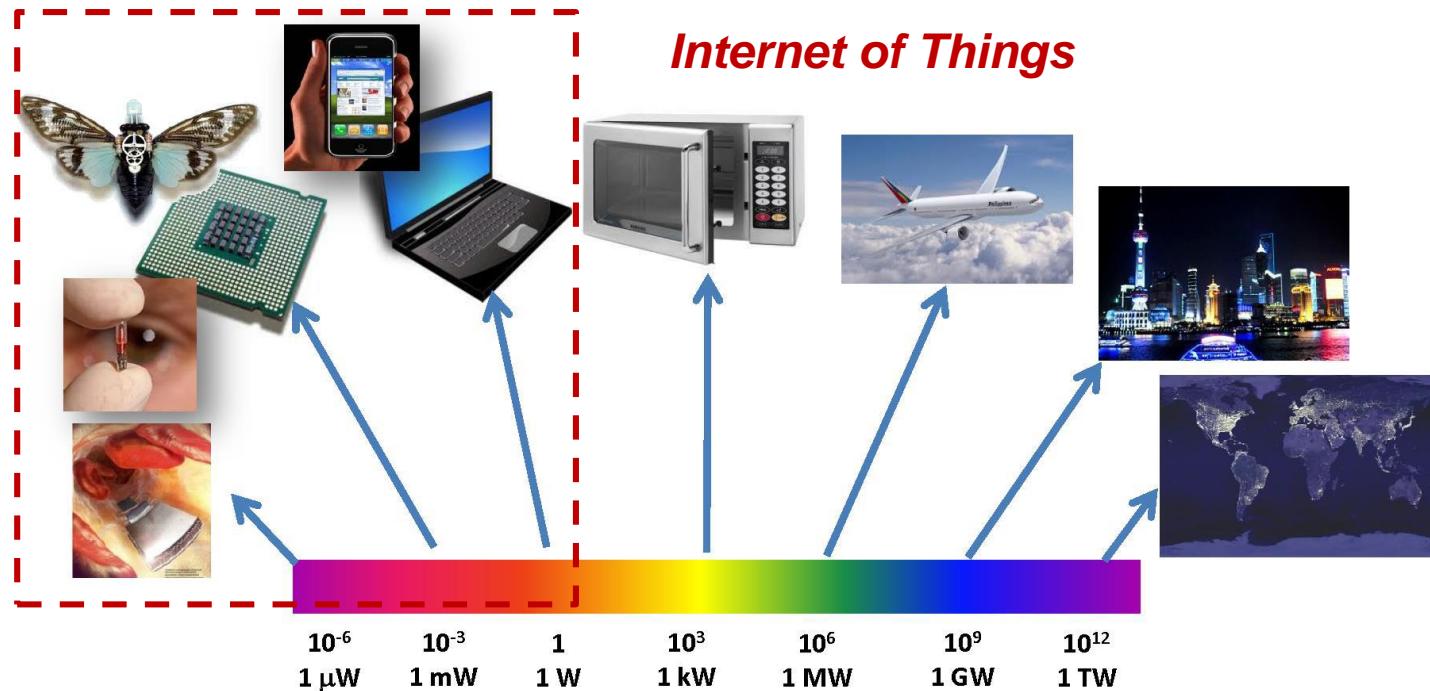
Energy: Oil

Energy: ?

Year

Energy – A Revisit

- Current World Energy Consumption



- 80/20 Principle Applies

A **sustainable power source** is desperately required for both **large scope** (80% devices) and **small scale** (20% energy consumptions) energy needs.

Energy for the Era of IoT

- Distributed Energy Need

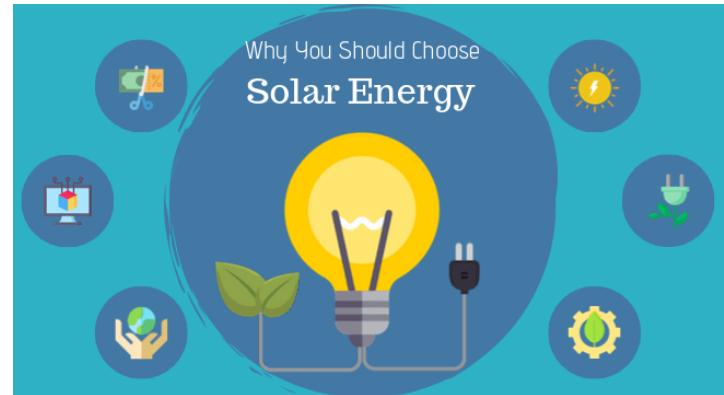


Outline

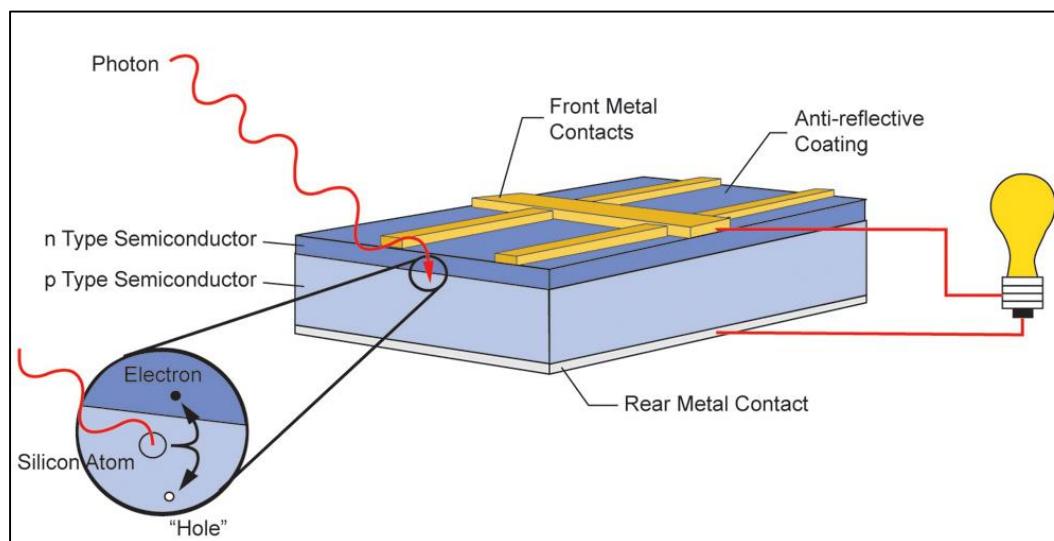
- Introduction
- Energy Harvesting for IoT
- Triboelectric Nanogenerators (TENG)
- Q&A

Solar Cell

- Solar Energy
 - $E = \hbar v$
 - Large Amount
 $10^{15} \text{ W} \sim 5 \text{ M tons of coal}$



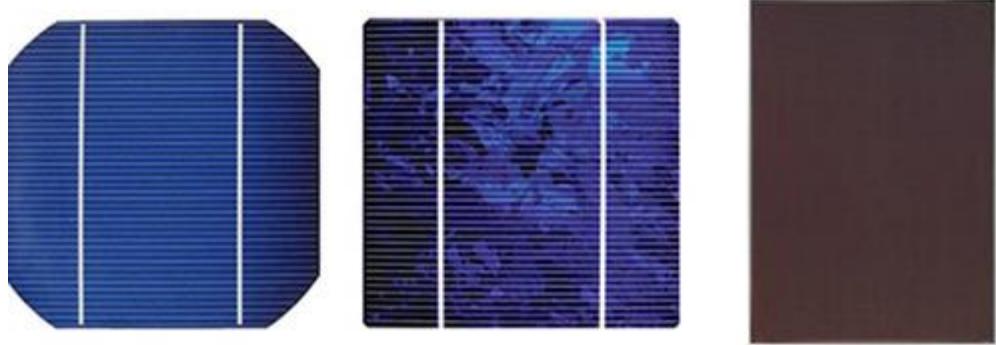
- Solar Cell
 - Photovoltaic Effect



Solar Cell

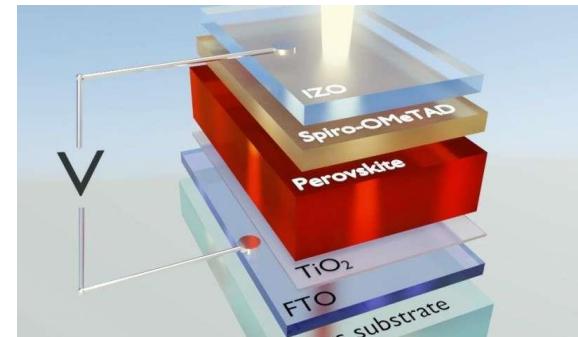
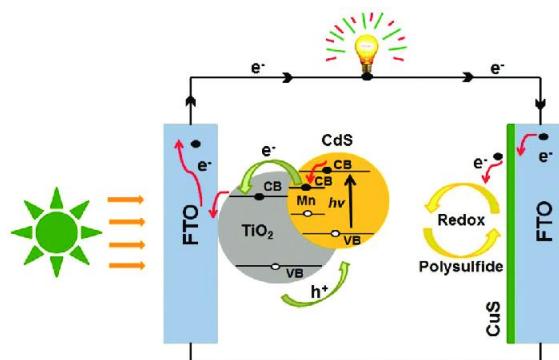
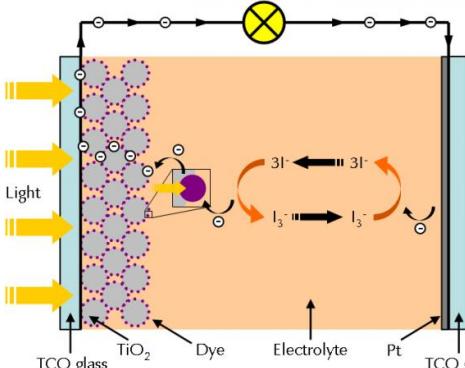
- Silicon-based Solar Cell

- Single-crystal
- Multicrystalline
- Thin-film crystal



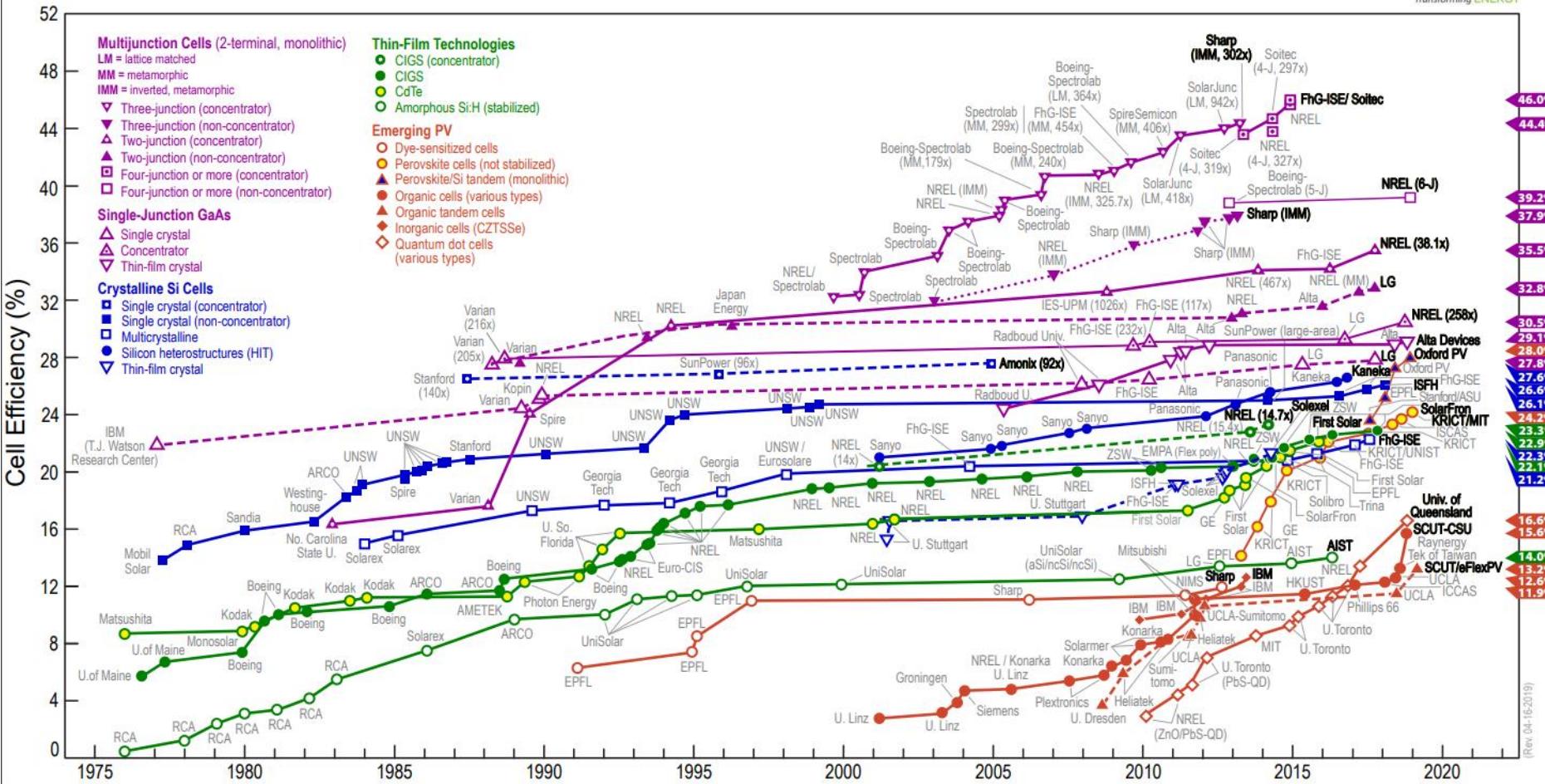
- Emerging Solar Cell

- Dye-sensitized Solar Cell
- Quantum-Dot Solar Cell
- Perovskite Solar Cell



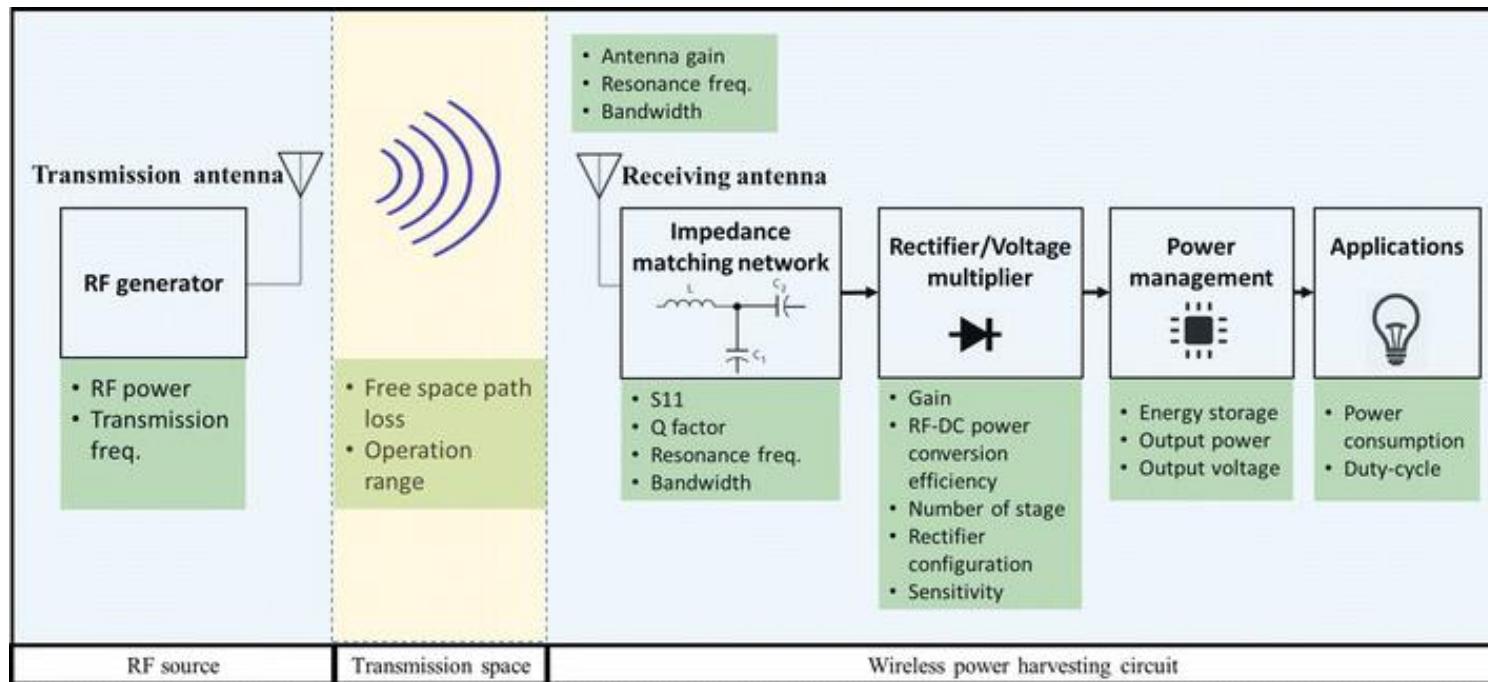
Solar Cell

Best Research-Cell Efficiencies



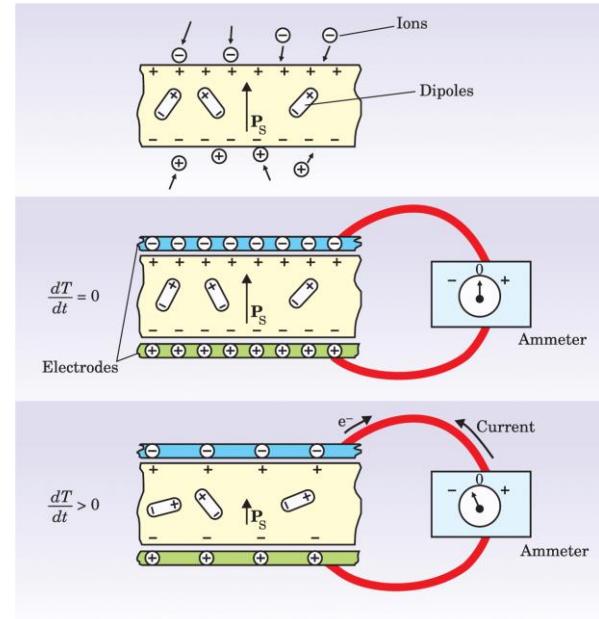
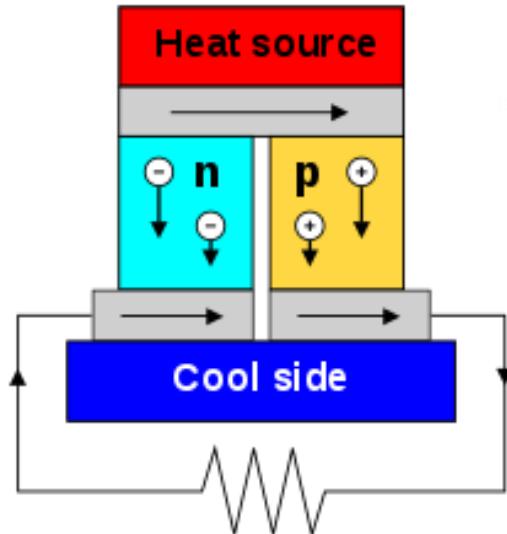
RF Energy Harvesting

- Radio Frequency Energy
 - EM waves $u = \frac{\epsilon_0}{2} E^2 + \frac{1}{2\mu_0} B^2$
- Backscatter Communications
 - Receive the RF power while detecting the signal



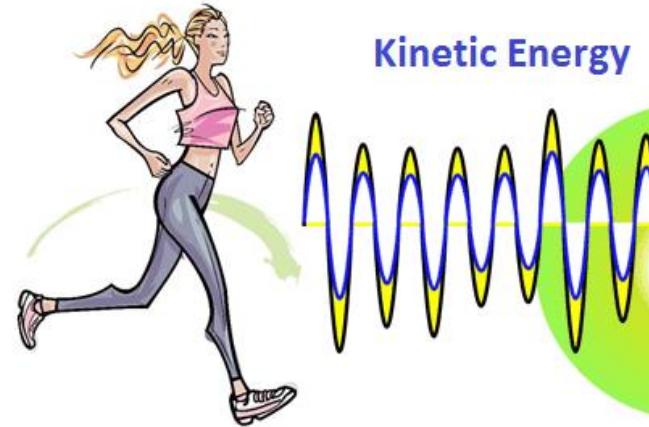
Thermal Energy Harvesting

- Thermal Energy
 - Heat difference, heat transfer
- Thermal Energy Harvesting
 - Thermal electric generator
 - Pyro electric generator



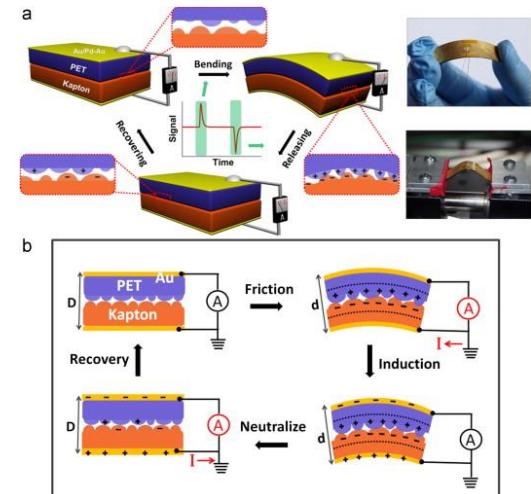
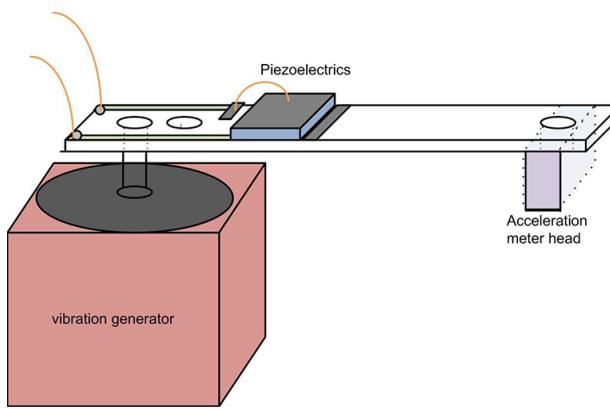
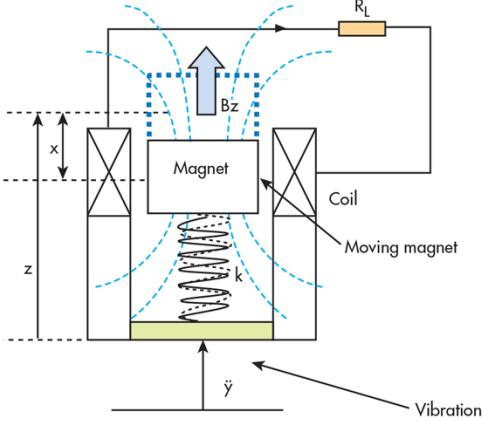
Mechanical Energy Harvesting

- Mechanical Energy
 - Ubiquitous



Mechanical Energy Harvesting

- Mechanical Energy Harvester
 - Electromagnetic generator
 - Piezoelectric generator
 - Triboelectric (nano)generator (TENG)



Energy Sources

- **Traditional Source**

	Availability	Mobility	Stability	Life	Information
Power Grid 	Low	Low	High	High	Low
Battery 	High	High	High	Low	Low

- **Energy Harvesting for IoT**

	Availability	Mobility	Density	Stability	Life	Information
Solar Energy	High	High	1mW/cm ²	Medium	High	Low
Thermal Energy	Medium	Medium	1μW/cm ²	Medium	High	Low
RF Energy	High	High	0.5μW/cm ²	Low	High	High
Mechanical Energy Harvesting	High	High	10μW/cm ²	Medium	High	High



纳米发电机与自驱动系统
2021



该二维码7天内(9月20日前)有效，重新进入将更新



信息收集

扫一扫二维码打开或分享给好友



- 腾讯文档 -
可多人实时在线编辑，权限安全可控

Outline

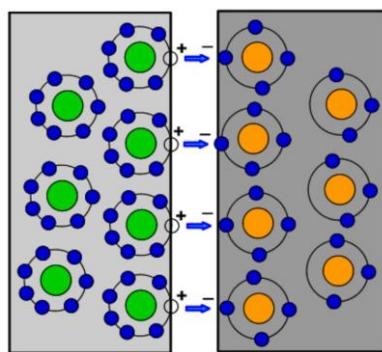
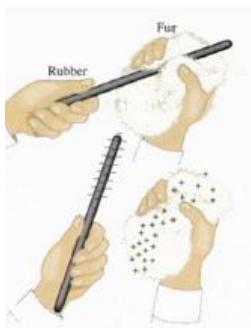
- Introduction
- Energy Harvesting for IoT
- **Triboelectric Nanogenerators (TENG)**
- Q&A

Triboelectric Effect

Contact electrification / Triboelectric effect

Materials become electrically charged after they come in contact with another different material.

Contact electrification



- ❖ A universally observable effect;
- ❖ The in-depth mechanism is still under investigation;
- ❖ Usually considered as negative effect in practical

Benjamin Franklin



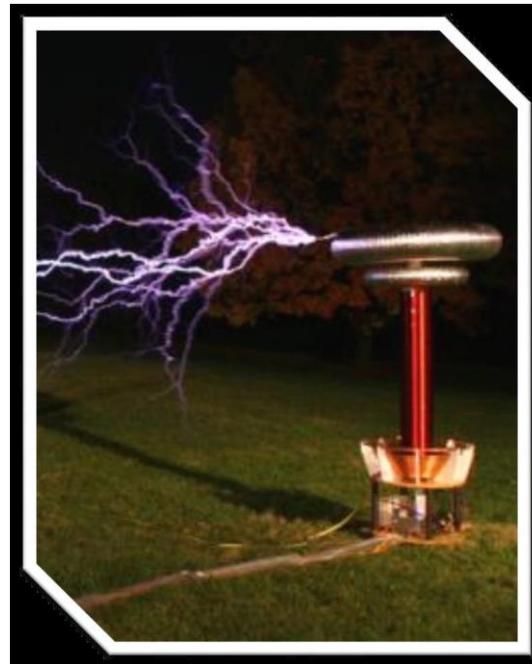
“.....and thereby the Sameness of the Electric Matter with that of Lightning completely demonstrated.”

The Pennsylvania Gazette
Oct. 19, 1752

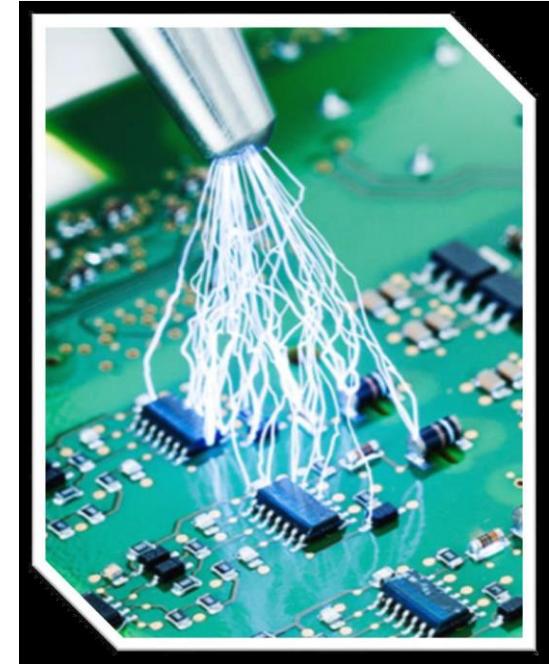
Negative effect?



Dielectric
breakdown

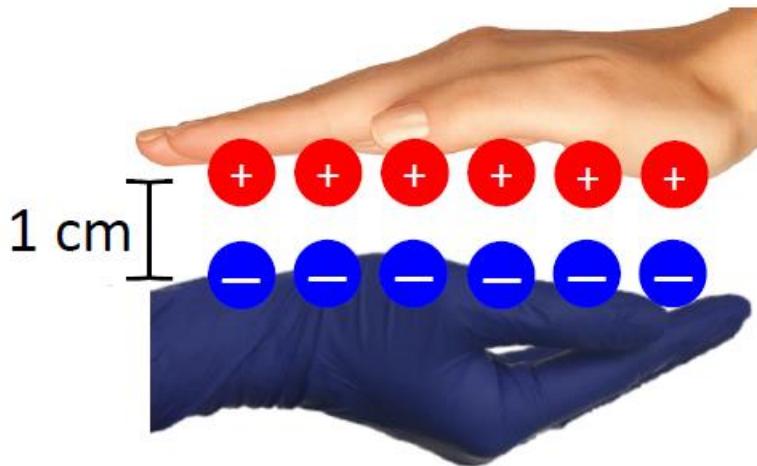


Air
breakdown



Circuits
breakdown

Energy from tribo-charges



Hand-size area, 1 cm apart

Charge density $40 \mu\text{C}/\text{m}^2$

18 mJ

Electric Potential Energy:



Humidity
Meter

~30min



LED

~30min



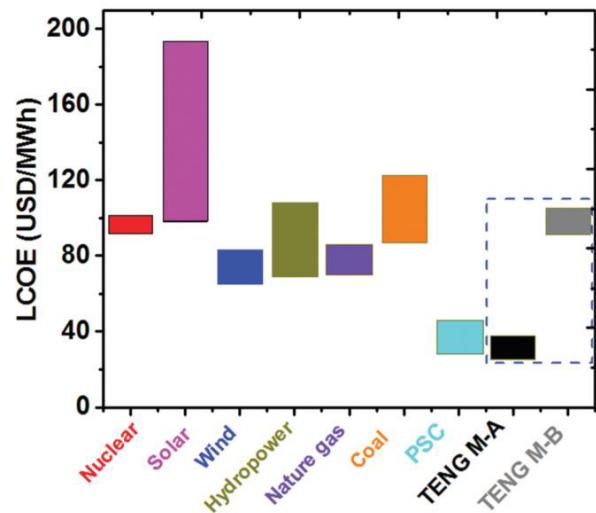
Calculator

~15min

Triboelectric Nanogenerator (TENG)

▪ TENG

- Invented by Prof. Zhong Lin Wang in 2012
 - An electronic device for mechanical to electrical energy conversion via coupling
 - (Step 1) triboelectric effect and
 - (Step 2) electrostatic induction.
- ❖ Convenient and low-cost fabrication
 - ❖ Light weight
 - ❖ Environmentally friendly
 - ❖ Promising output power

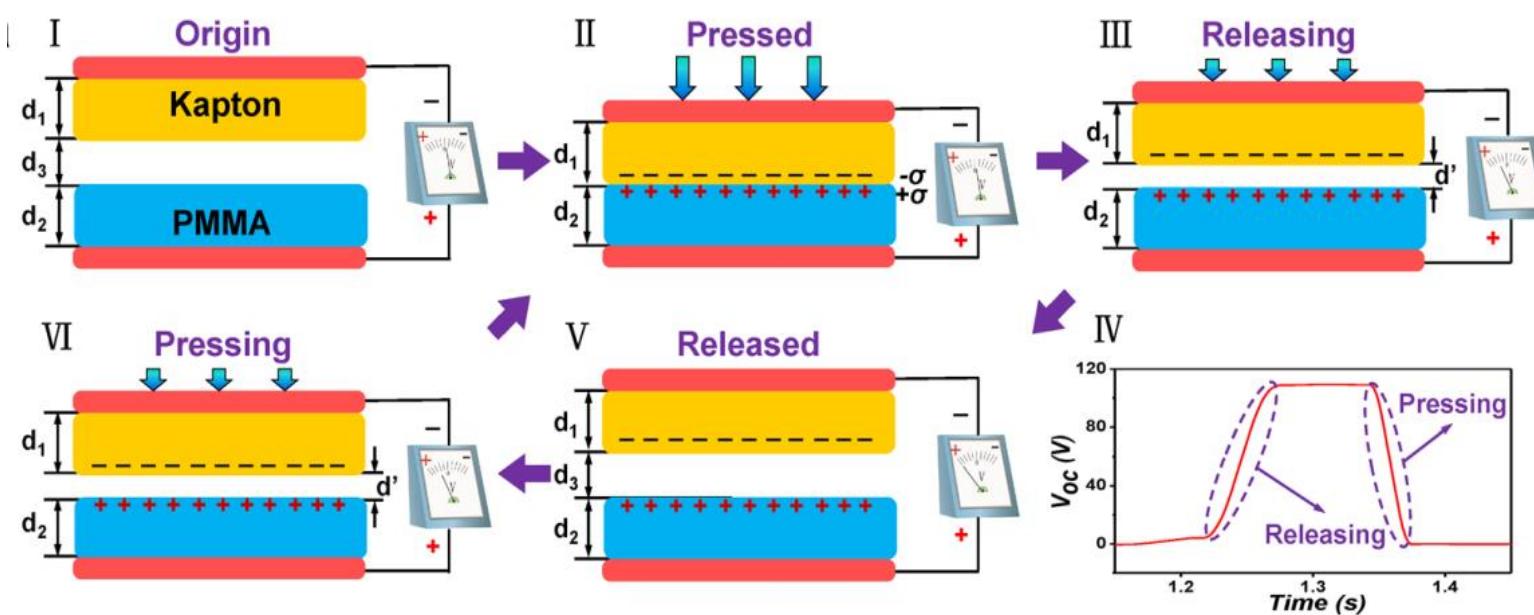


Working Principles

Open-circuit condition

V-Q-x Relationship

$$V = -\frac{Q}{S\epsilon_0}(d_0 + x(t)) + \frac{\sigma x(t)}{\epsilon_0}$$



$$x(t) = d_3$$

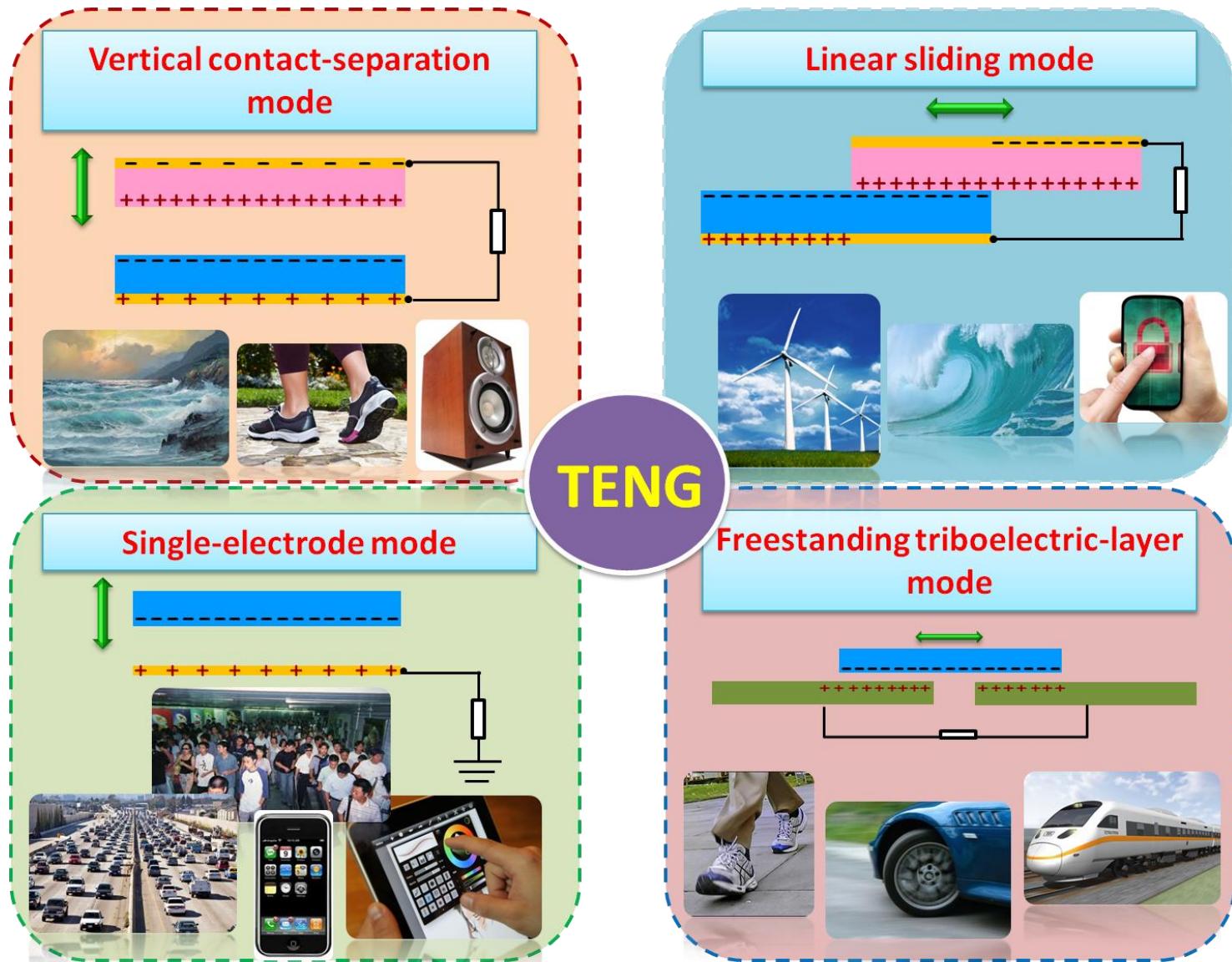
$$d_0 = \frac{d_1}{\epsilon_{r1}} + \frac{d_2}{\epsilon_{r2}}$$

$$Q = 0$$

$$V_{OC} = \frac{\sigma x(t)}{\epsilon_0}$$

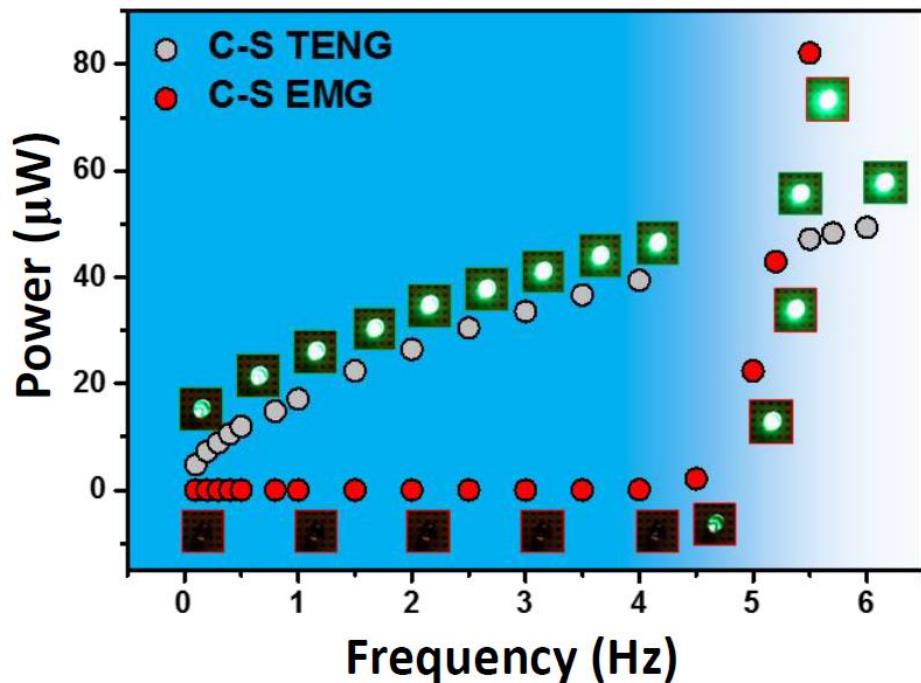
S. Niu et. al., Energy Environ. Sci., 2013, 6, 3576-3583

Basic Working Modes



Capture Low-Frequency Energy

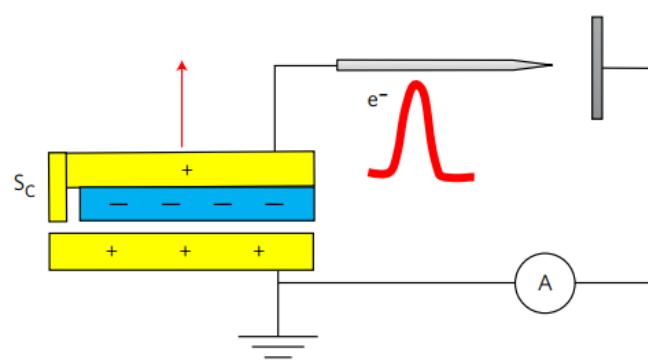
Catch low frequency energy <5Hz



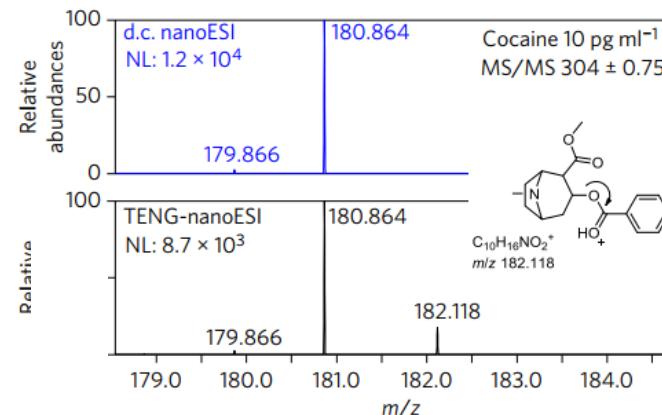
Ultra-high Voltage Output

Effective & Safe High-Voltage (HV) Source

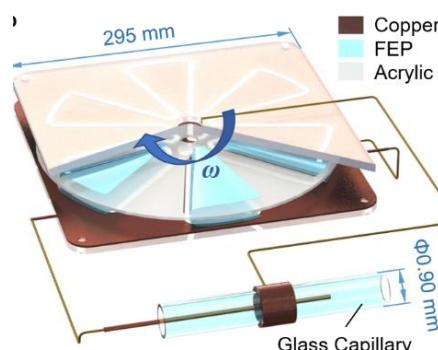
Mass spectrometry



Nature Nanotech. 2017.17



MicroPlasma



Nature Comm. 2018



Photograph without any Photoshop
NIKON D700 @ 70mm, ISO 6400, 30sec, f/2.8

Broad Applications of TENG

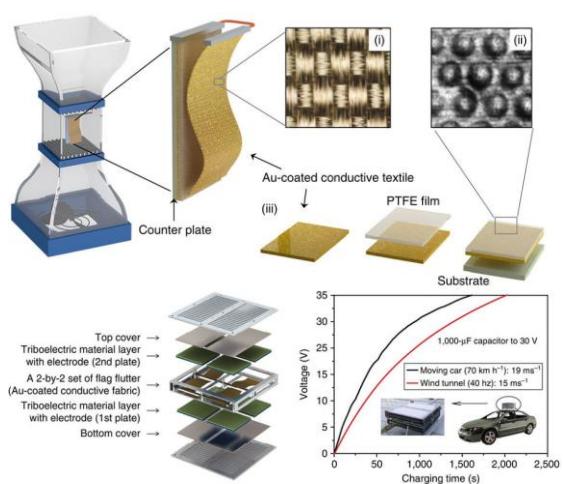
Mechanical Energy Harvesting

Biomechanical energy



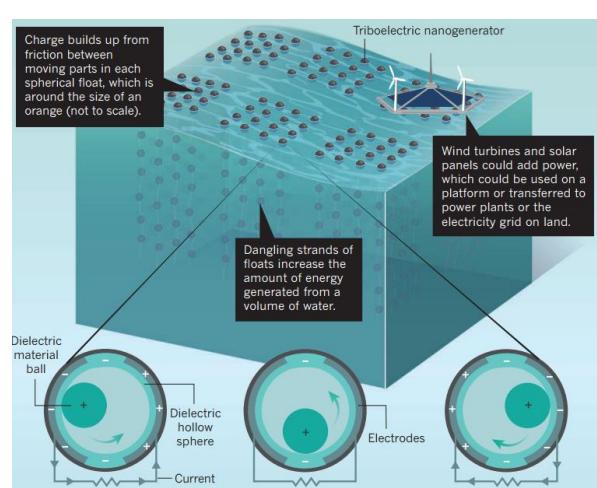
Nat. Commun. 2016, 7, 12744

Wind energy



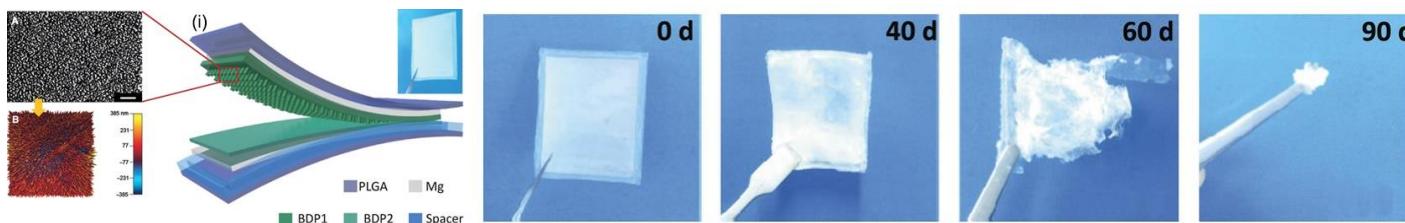
Nat. Commun. 2014, 5, 4929

Blue energy



Nature 2017, 542, 159–160

Biodegradable implantable power source

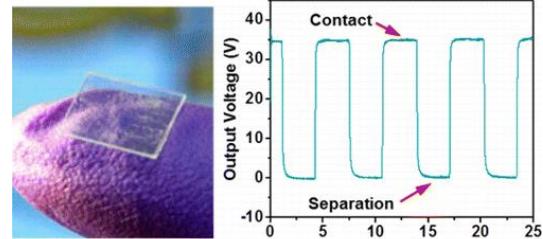


Science Adv. 2016, 2, e1501478

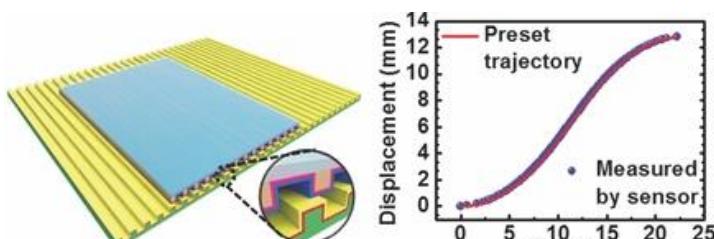
Broad Applications of TENG

▪ Active Mechanosensing

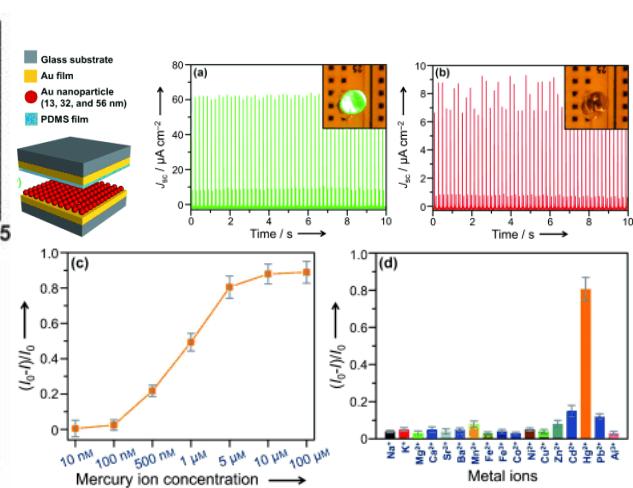
Tactile sensor



Motion sensor



Chemical sensor



Nano Lett. 2014, 14, 3208–3213

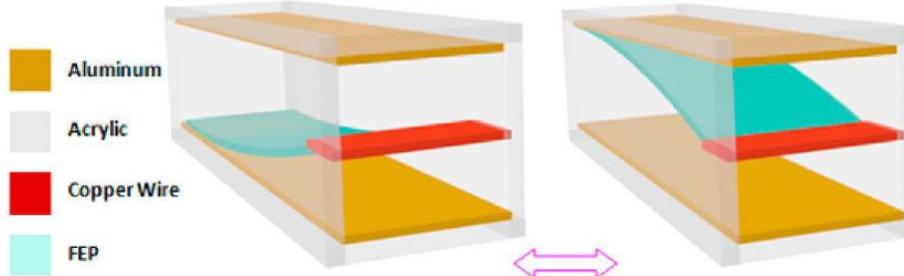
Adv. Mater. 2014, 26, 1719–1724

Angew. Chem. 2013, 52, 5065–5069

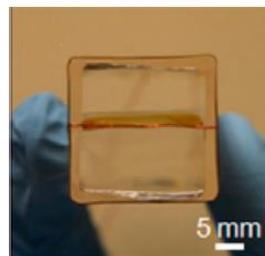
TENG based Mechanical Energy Harvesting

Wind Energy Harvesting

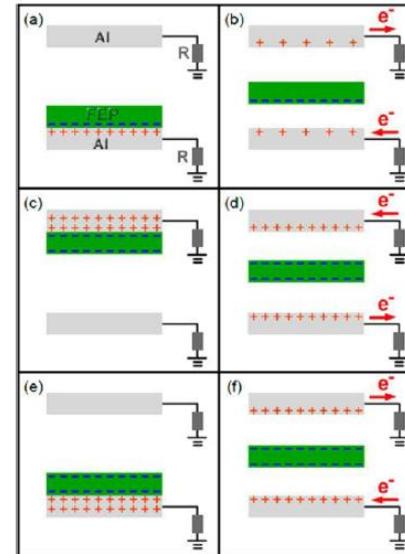
Flutter Structure



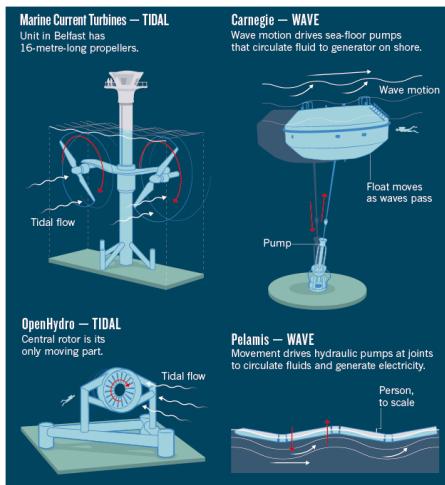
Device



Working Mechanism



Water Energy Harvesting

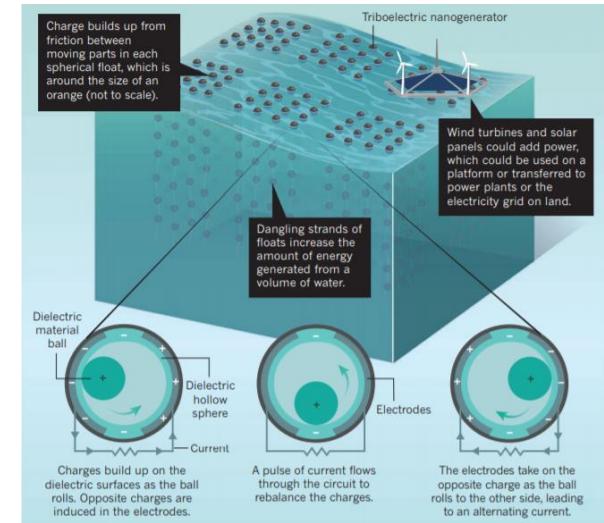


Water Energy

Large



Small



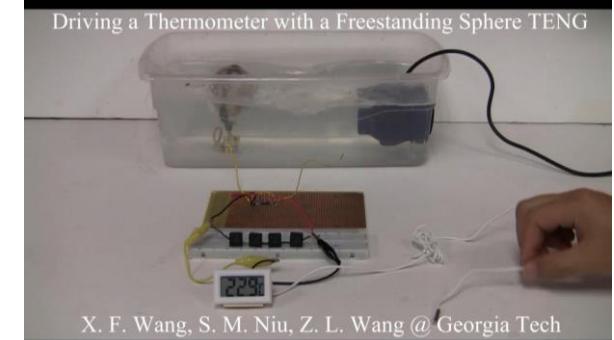
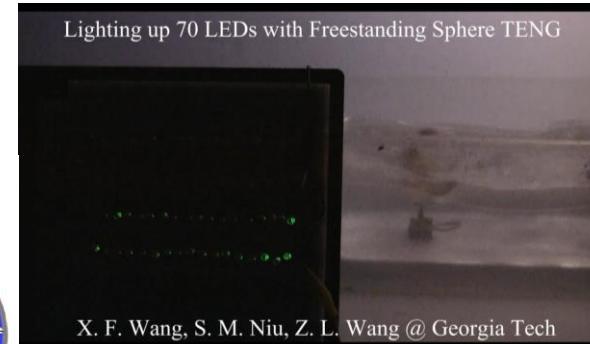
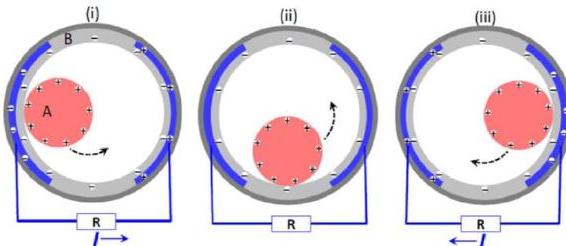
Z.L. Wang, *Nature* 2017, 542, 159–160

Device Structure

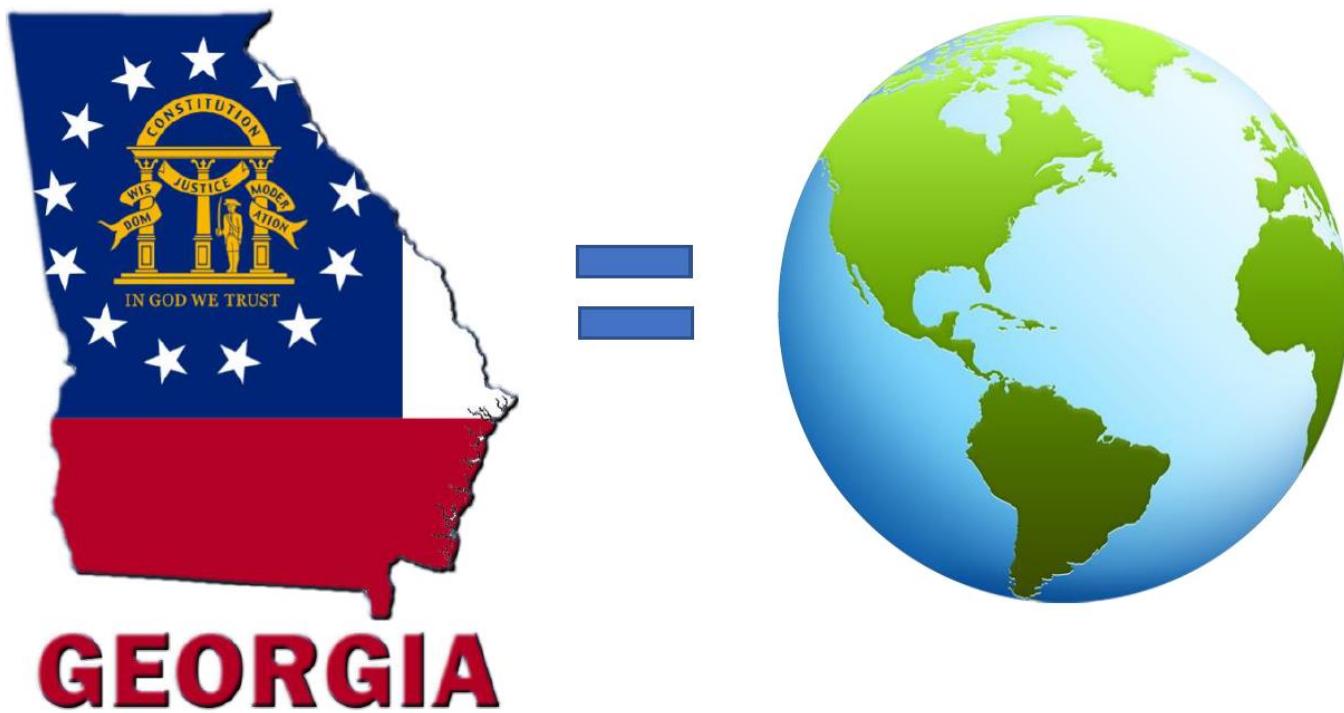
- █ Nylon
- █ Al
- █ Kapton



Working Mechanism



Relax Time

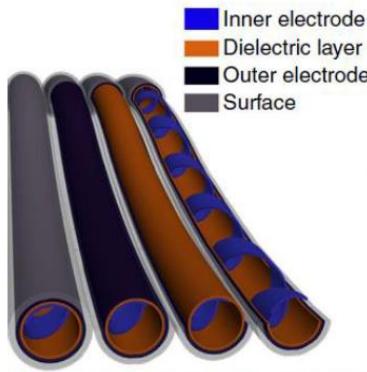


The world's energy consumption today could be met by covering an ocean area the size of the US state of Georgia with a 3D nanogenerator network of devices spaced every 10 cm and stretching 10 meters deep beneath the surface.

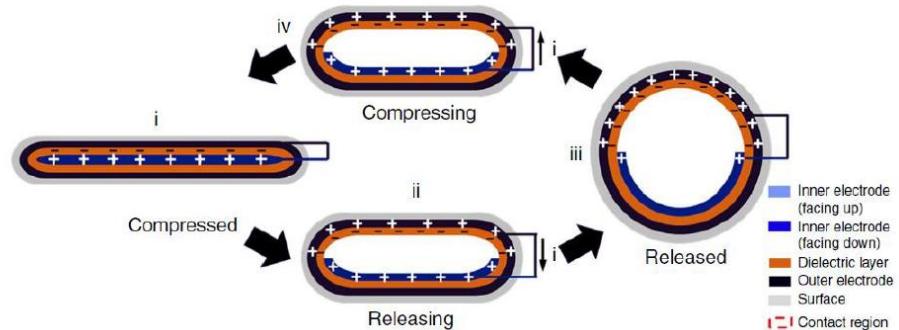
Z.L. Wang, *Nature* 2017, 542, 159–160

Kinetic Energy Harvesting

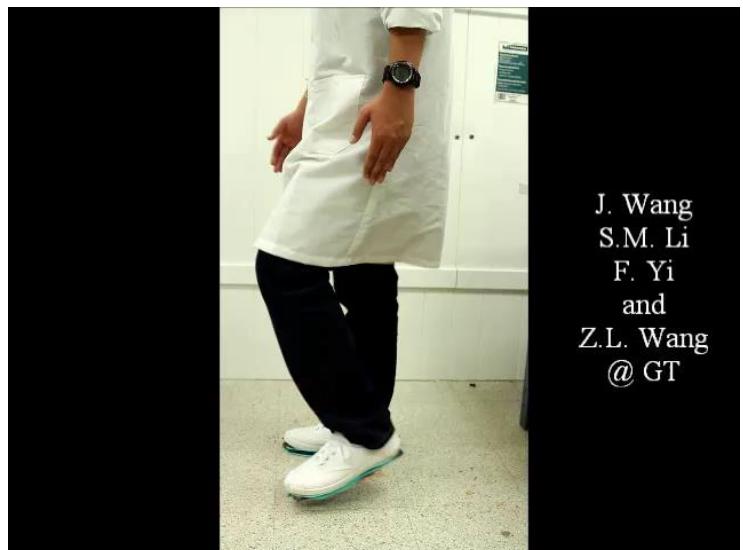
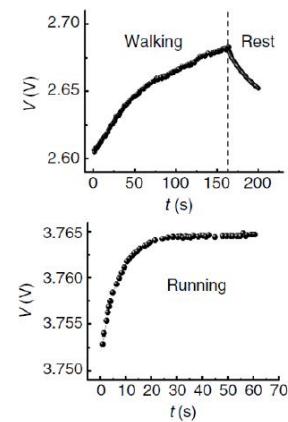
Fiber-like Structure



Working Mechanism



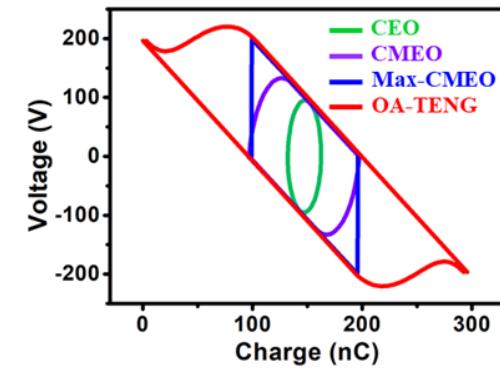
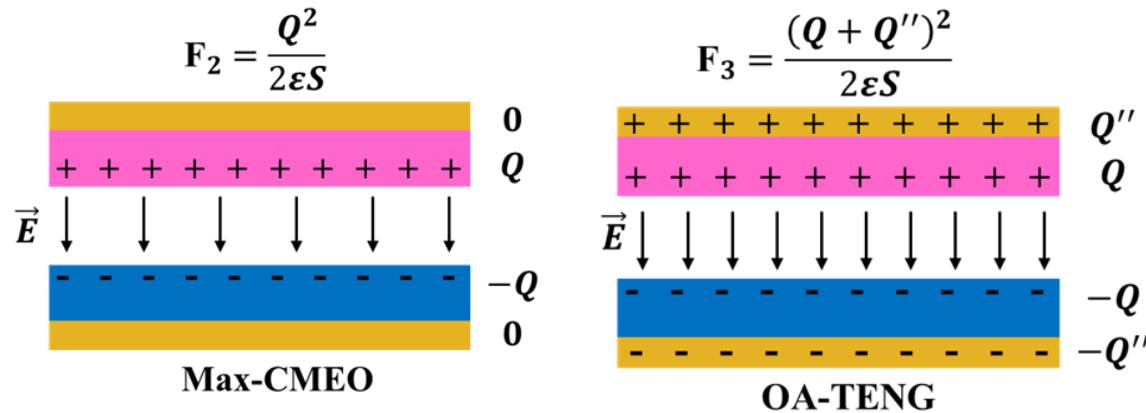
Device and Performance



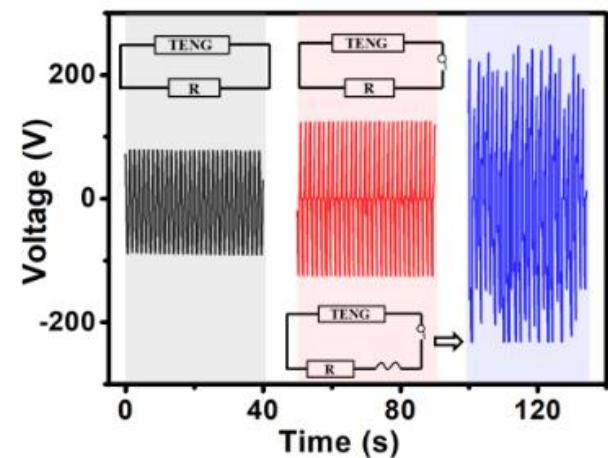
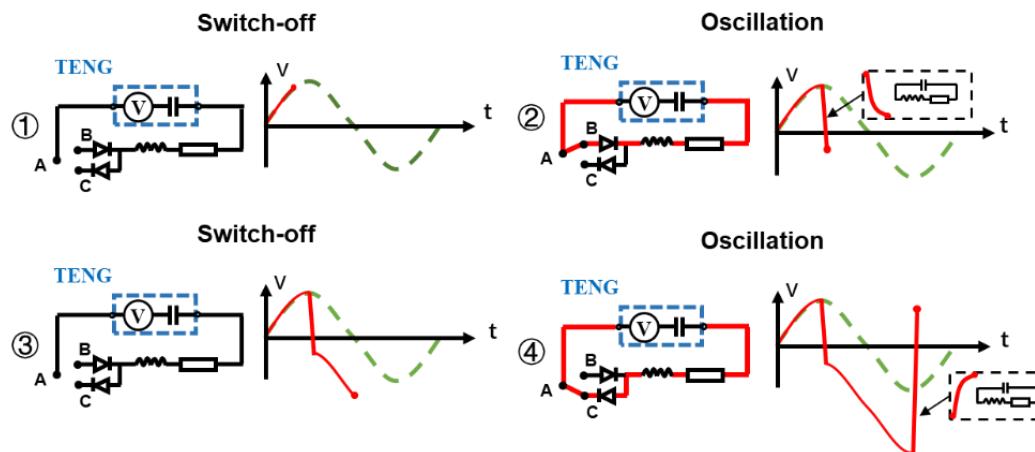
J. Wang
S.M. Li
F. Yi
and
Z.L. Wang
@ GT

Output Power Enhancement

- Output Boost of TENG via Circuit Oscillation
 - Concept

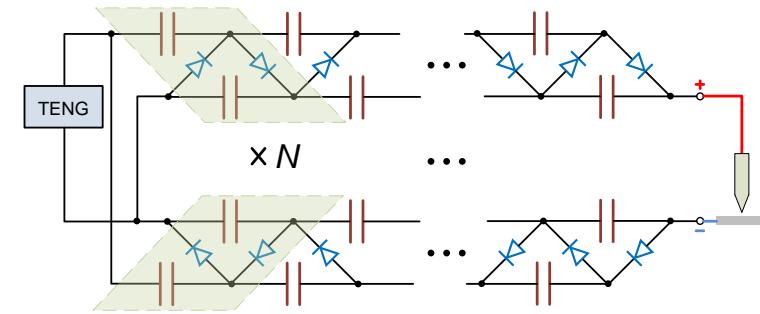
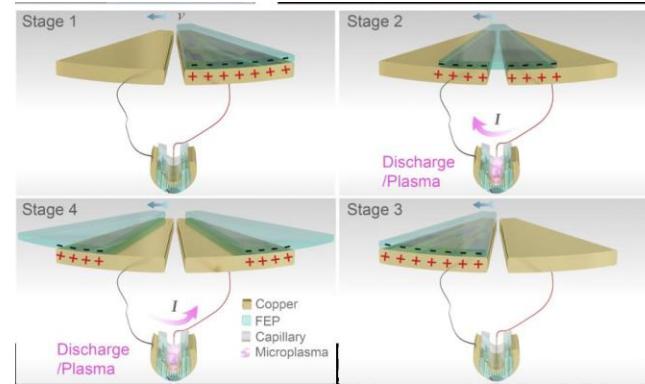


- Method & Performance

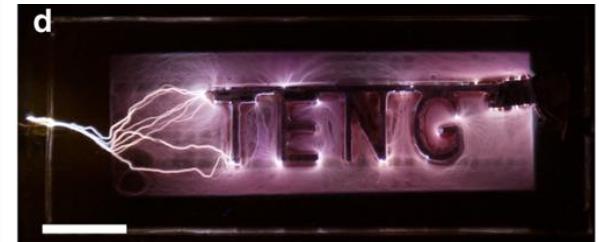
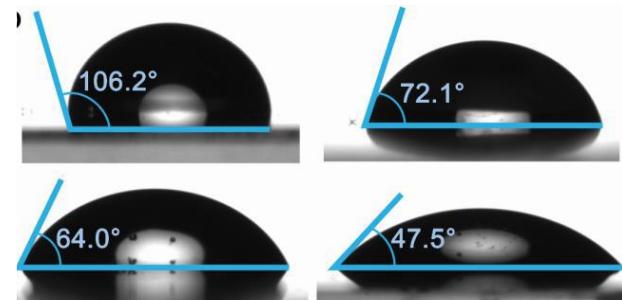
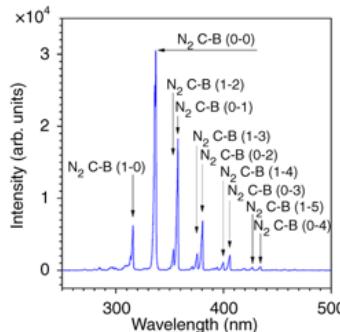


Output Voltage Enhancement

- **Triboelectric Microplasma**
 - TENG as the **safe** high-voltage source

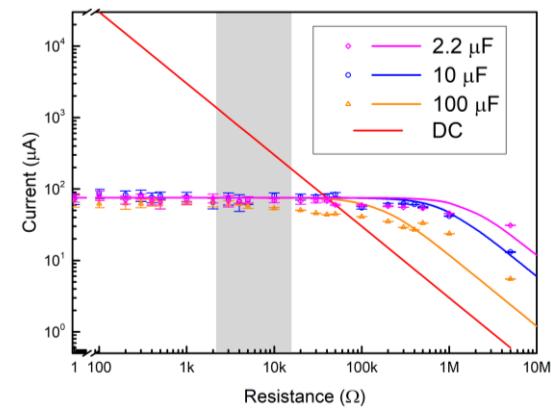
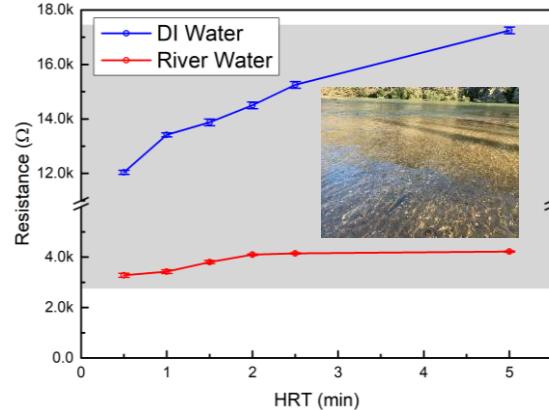
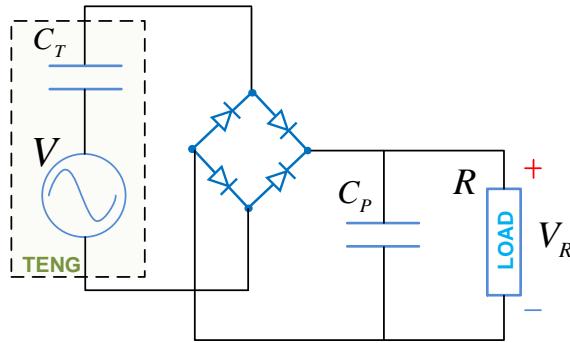


- Results
 - **First** room-temperature and atmospheric-pressure microplasma generator via mechanical stimuli

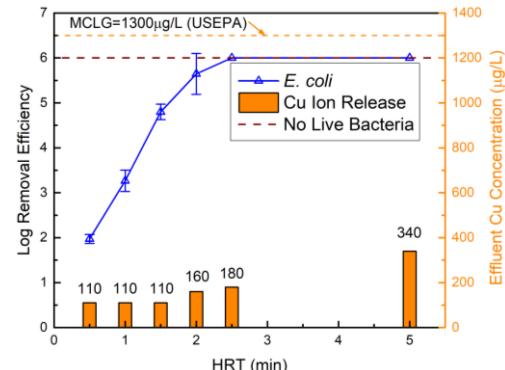
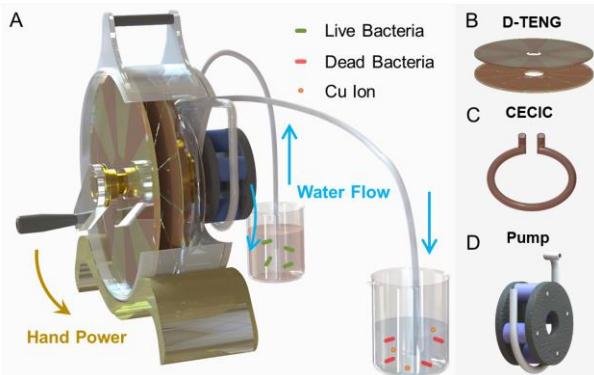


Constant Current Source

- **TriboPump for POU Water Disinfection**
 - TENG as the **constant-current** power source
 - Impedance mismatching → Adaptive to varying resistances



- Design and Performance



Other Works

Kinetic Energy Harvesting Textile



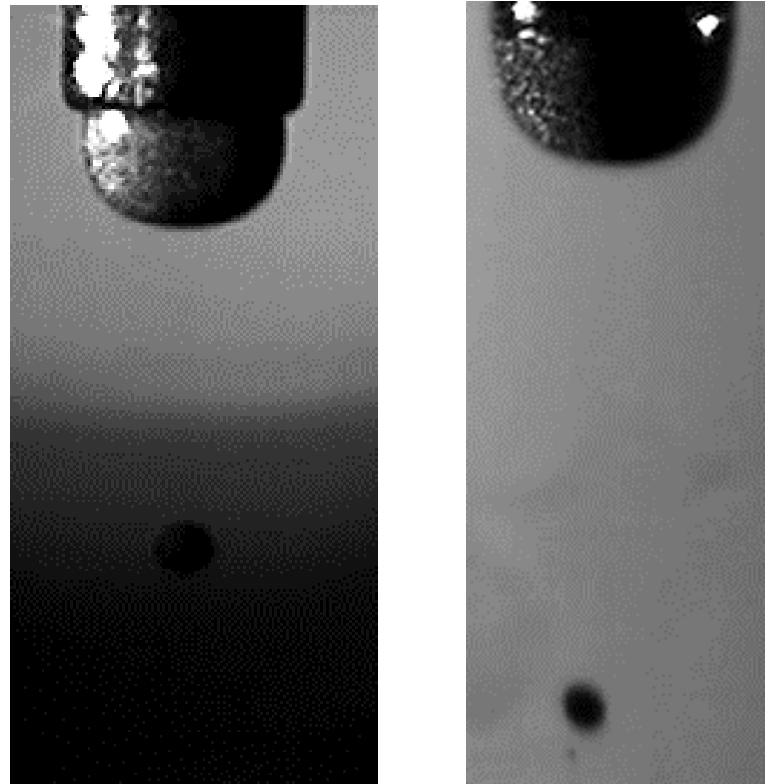
Adv. Mater., 2017, 29, 1702648.

Water Wave Energy Harvesting



ACS Nano, 2019, 13, 2, 2349-2356.

High-Voltage Driven E-Jet Printing

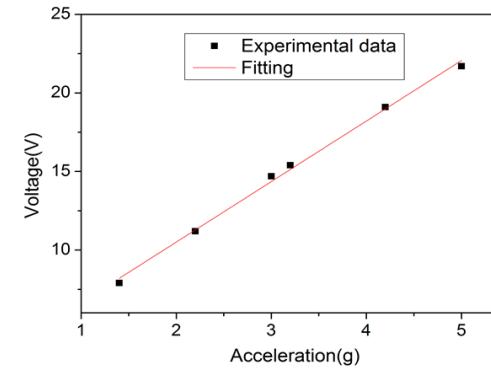
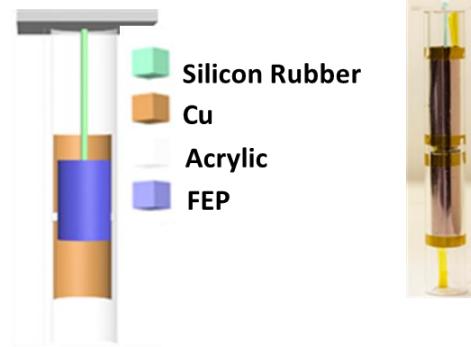


Adv. Func. Mater., 2019, 29, 1901102.

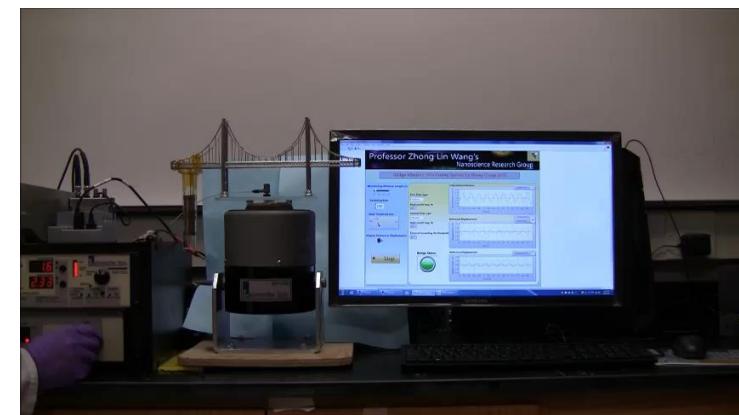
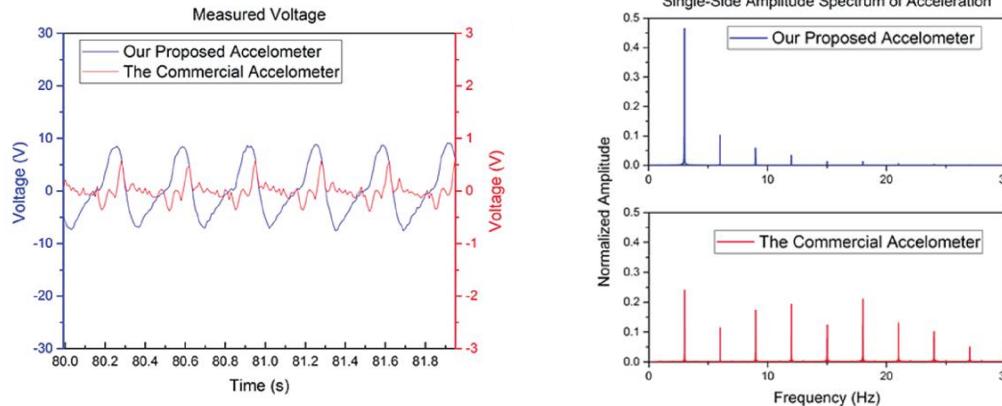
TENG based Mechanical Sensing

Bridge Health Monitoring

- **Low-Frequency Triboelectric Accelerometer**
 - Concept
 - Use TENG inherent Cap. to form natural low-pass filter.
 - Improved algorithm to reduce historical data dependency.



- Performance comparison with commercial one

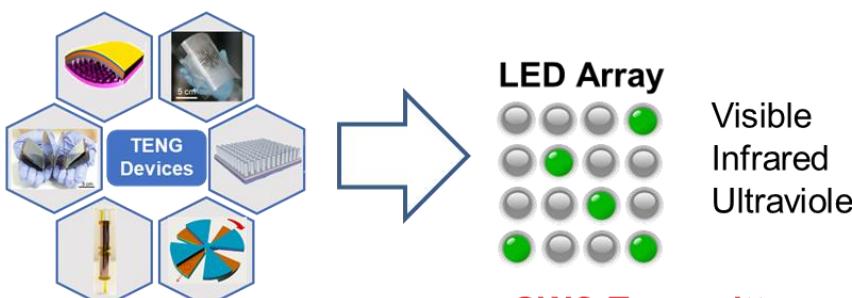


Optical Wireless Communications

- **Self-powered OWC**
 - Concept



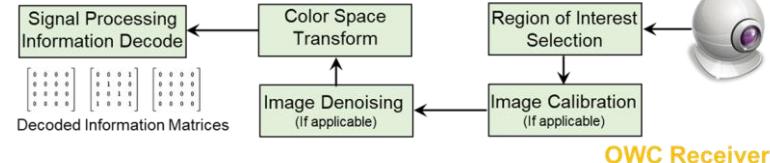
TENG works as both the event trigger and the power source for the OWC transmitter



LED Array

Visible
Infrared
Ultraviolet

OWC Transmitter



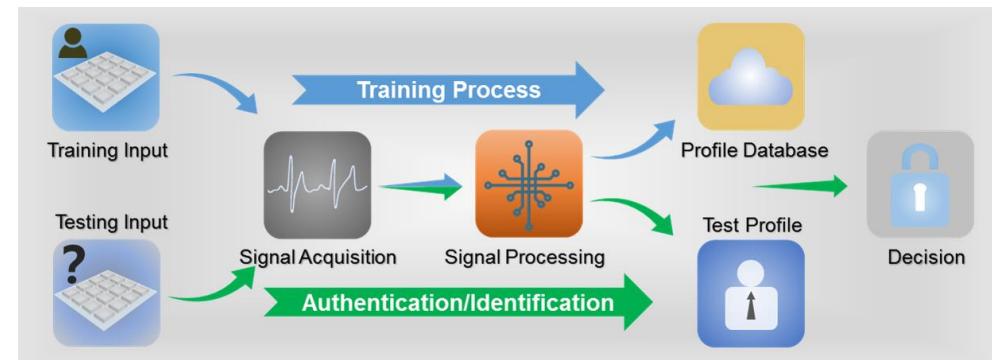
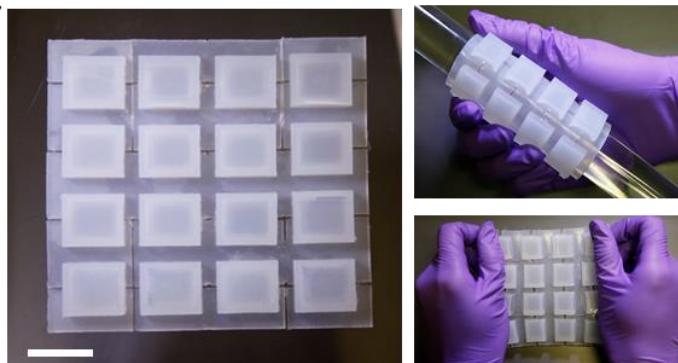
- Results

Demonstration as a self-powered remote control

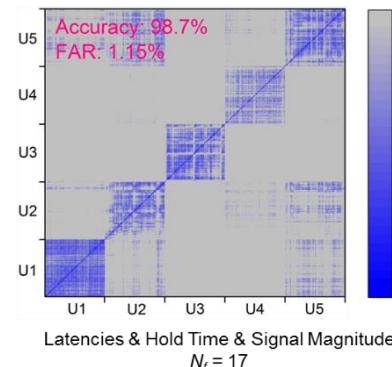
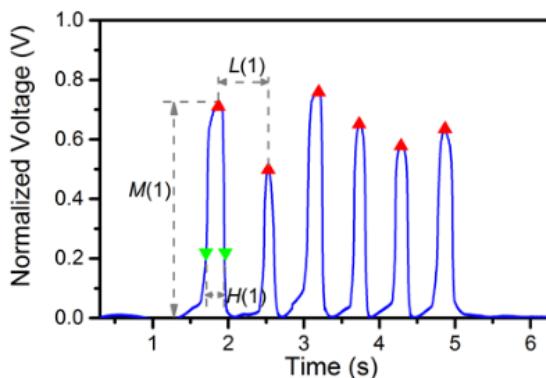
Demonstration for self-powered wireless pressure detection

Cybersecurity

- Keystrokes Dynamics aided Security Keypad
 - Concept and Design



- Results

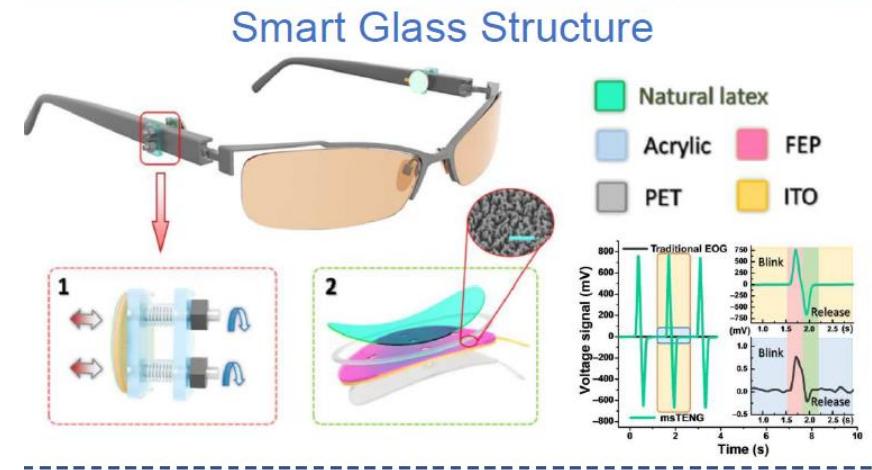


Human-machine Interface

- Eye-motion Triggered Command System**



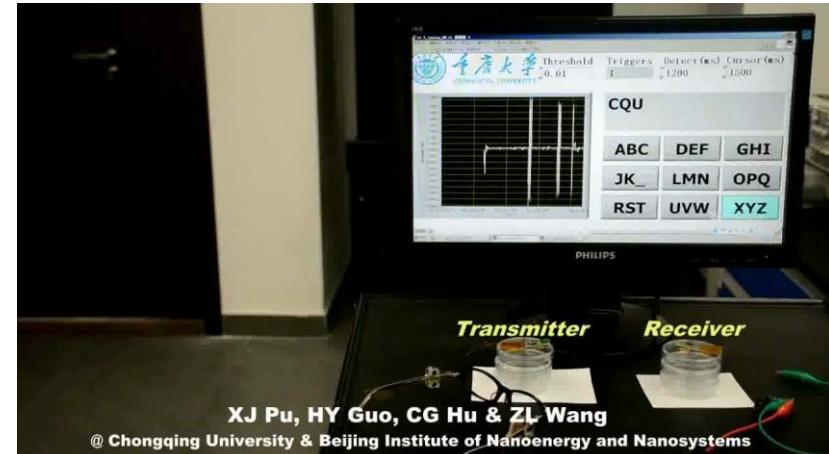
Amyotrophic lateral sclerosis(ALS)



On/Off Control



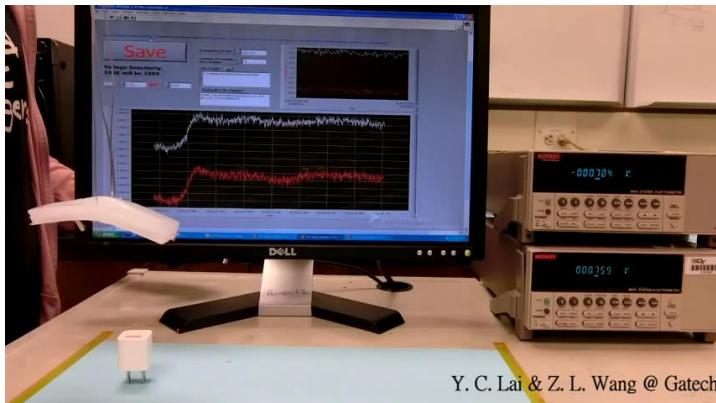
Hands-free Typing System



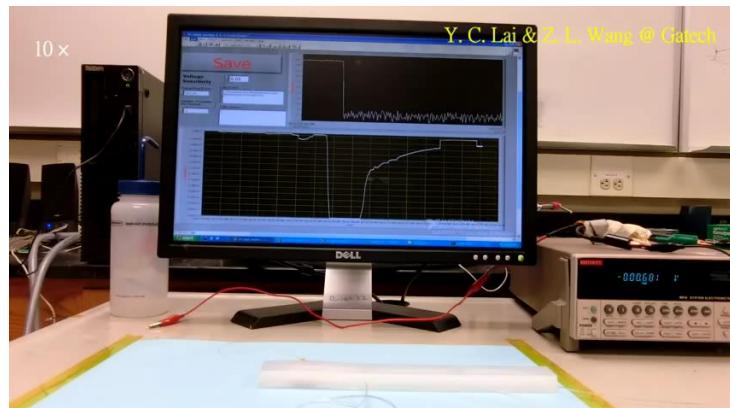
Soft Robotics

▪ Ultra Stretchable Robotics

- Objective sensing



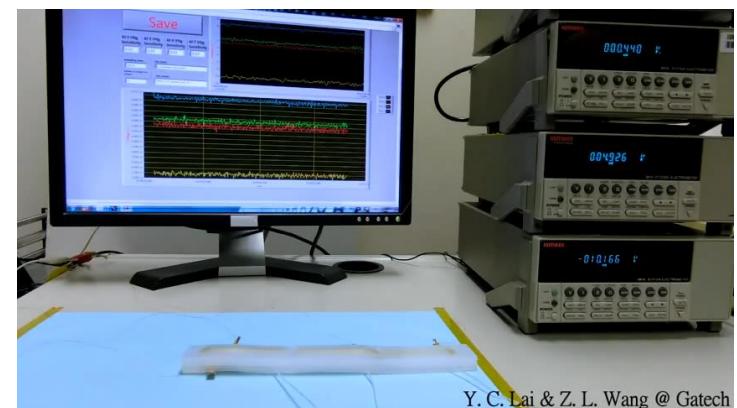
- Self-sensing



Dry-wet sensing



Human-machine interface



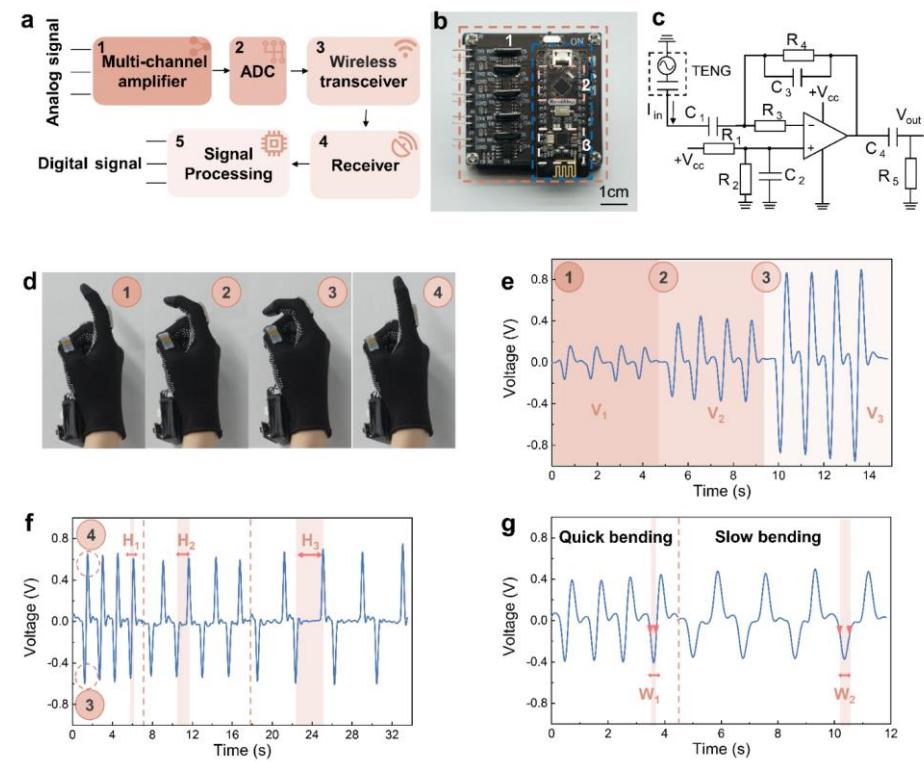
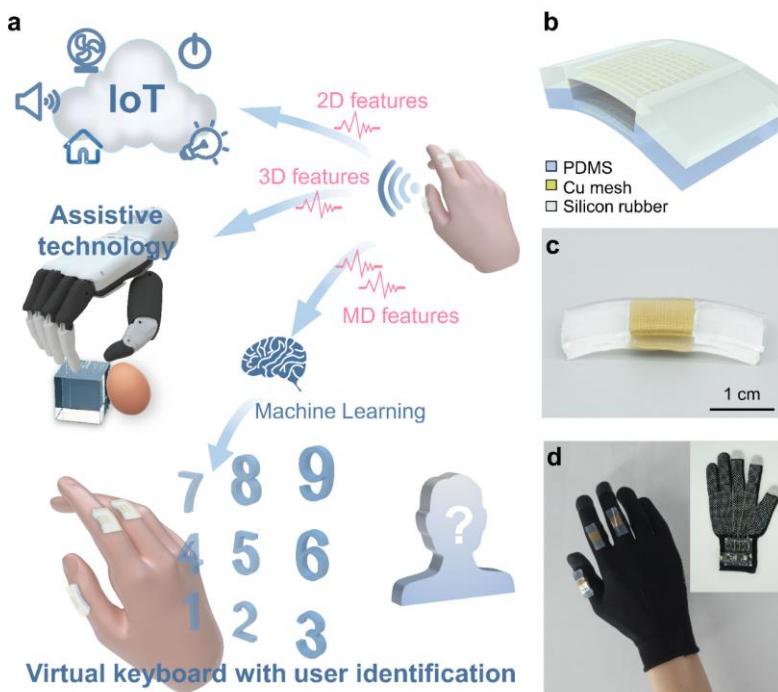
Human Machine Interface

Last Year's Course Final Project.

Published in Nano Energy (IF ~17.8)

Yang Luo, Zihan Wang et al.

Triboelectric bending sensor based smart glove towards intuitive multi-dimensional human-machine interfaces



Human Machine Interface

Intuitive multidimensional human-machine
interfaces using the
triboelectric nanogenerator-based glove

Supplementary Video 1

Advanced robotic hand control

Human Machine Interface

Intuitive multidimensional human-machine
interfaces using the
triboelectric nanogenerator-based glove

Supplementary Video 2

Human Machine Interface

Intuitive multidimensional human-machine
interfaces using the
triboelectric nanogenerator-based glove

Supplementary Video 3

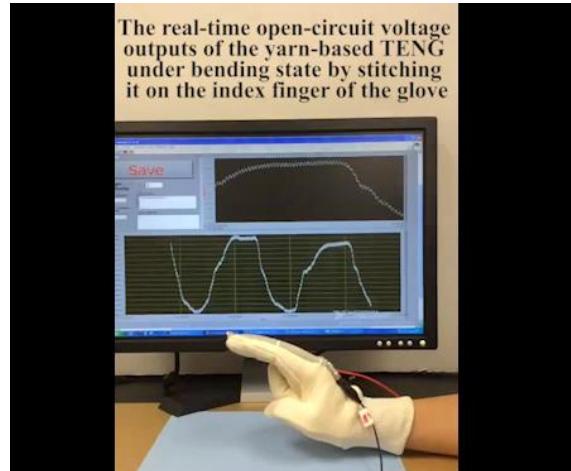
Tactile Sensing

Tactile Sensing

Tactile Sensing

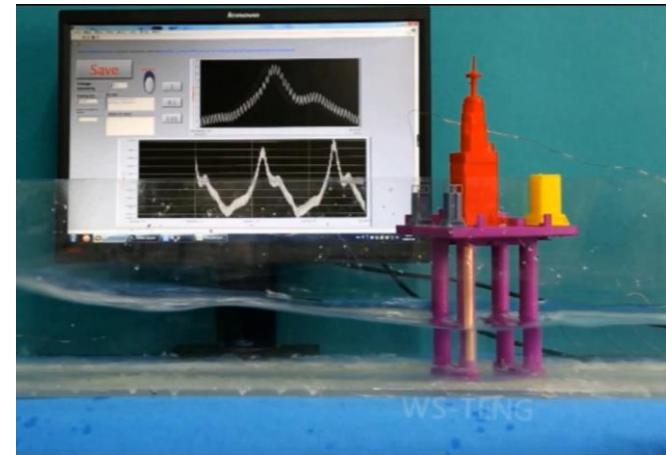
Other Works

Smart Fiber



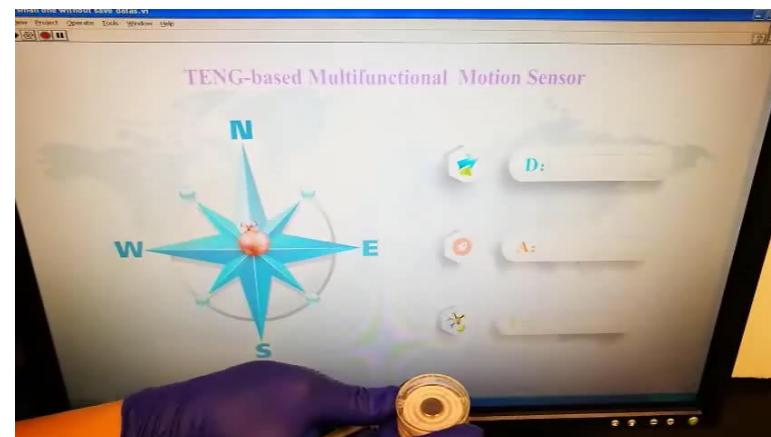
Adv. Energy Mater., 2018, 8, 1801114.

Wave Sensor



Nano Energy, 2019, 57, 574-580.

Direction & Rotation Sensor

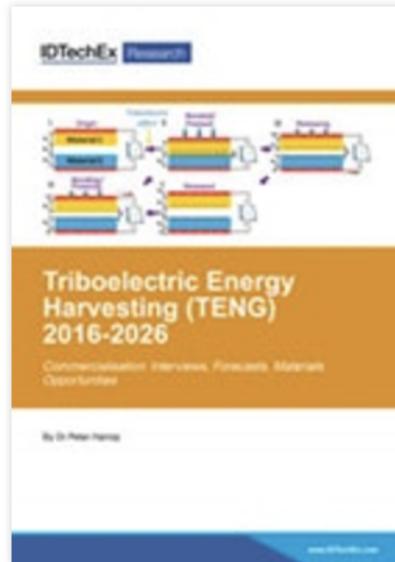


ACS Nano, 2018, 12, 5726-5733.

Outline

- **Introduction**
- **Energy Harvesting for IoT**
- **Triboelectric Nanogenerators (TENG)**
- **Q&A**

Market Forecasting



Triboelectric Energy Harvesting (TENG) 2017-2027

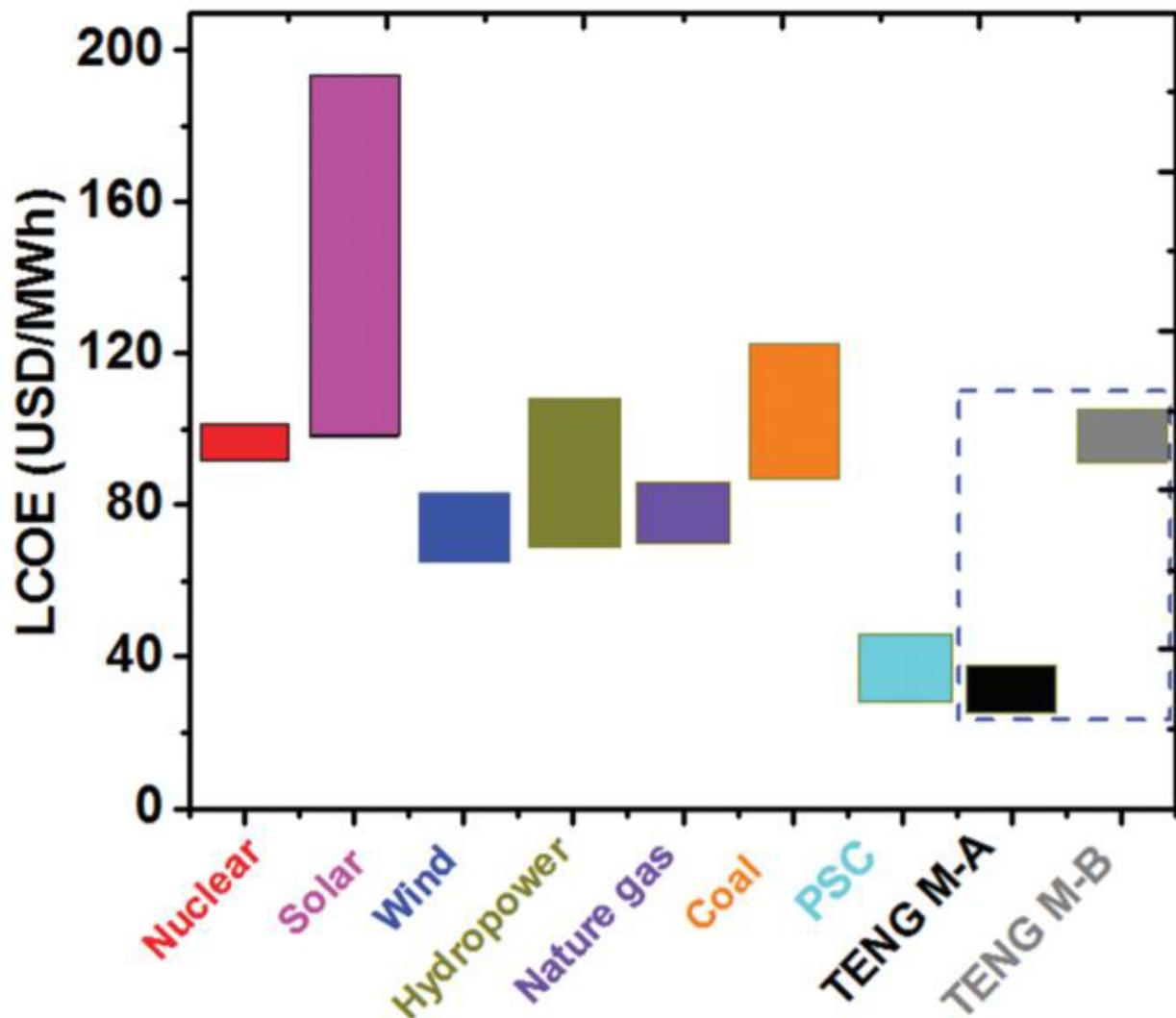
Commercialisation: Interviews, Forecasts,
Materials Opportunities

By [Dr Peter Harrop](#)

Triboelectric energy harvesting transducers will be a \$400 million market in 2027

From IDTechEx

Cost analysis



A TED Video

2020

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北京市科学技术委员会 中国科普博览

Thank you!

