SPECIAL TOPIC:
EMERGING NANOGENERATORS
Guest Editors: Ya Yang, Zhong Lin Wang

Volume 2021 | Issue 2 June
About Research

The journal Research was launched in 2018 as the first journal in the Science Partner Journal (SPJ) program. Research is distributed by the American Association for the Advancement of Science (AAAS) in association with Science and Technology Review Publishing House, the publishing house under the leadership of China Association for Science and Technology (CAST).

Research is a wide-ranging multidisciplinary journal that aims to publish original content reflecting new and innovative discoveries and important issues in engineering and applied sciences. Read more at the Mission and Scope page (spj.sciencemag.org/research/about/#mission-and-scope).

Research content is open access, published under a Creative Commons Attribution License (CC BY). This means that content is freely available to all readers upon publication.

As with all participants in the Science Partner Journal (SPJ) program, Research is editorially independent from the Science family of journals and CAST is responsible for all content published in the journal. To learn more about the Science Partner Journal program, visit the SPJ program homepage (spj.sciencemag.org).

Research is indexed in CAS, CNKI, CSCD, DOAJ, ESCI, Inspec, PubMed Central and Scopus.

Mission and Scope

Research provides an international platform for academic exchange, collaboration and technological advancements. The journal aims to publish high-quality research from any research domain, from any author in the world.

Scope: Research publishes fundamental research in the life and physical sciences as well as important findings or issues in engineering and applied science. The journal publishes primary research, applied research, reviews, editorials and views.

Topics of particular interest include, but are not limited to:

- Advanced Energy
- Advanced Manufacturing
- Advanced Materials
- Artificial Intelligence
- Environmental Science
- Flexible Electronics
- Health Science
- Information Science
- Micro/Nano Technology
- Quantum Information
- Space Science

Read more about Research or review Information for Authors (spj.sciencemag.org/research/guidelines/) to learn more about the different types of content and how to submit your work to Research.
**Article Processing Charges**

The journal *Research* is an open access journal supported by article processing charges (APCs). There are no submission charges.

Beginning in 2021, China Association for Science and Technology (CAST) will partially subsidize APCs, allowing authors to pay the below reduced rates:

- Research Articles: $1500 USD;
- Review Articles: $1500 USD;
- Perspectives: $1200 USD

Additional details can be found on the Article Processing Charges web page (spj.sciencemag.org/research/apc).

**Contact Research**

Editorial and submissions inquiries: research@cast.org.cn

To submit a new manuscript, check the status of a submitted manuscript, or submit a revised manuscript: https://www.editorialmanager.com/research/default.aspx
Editorial board

Editors-In-Chief
Tianhong Cui (International), University of Minnesota, USA
Wei Huang (China), Northwestern Polytechnical University, China

Associate Editors

Advanced Energy
Jun Chen, Nankai University, China
Fangyi Cheng, Nankai University, China
Binghui Ge, Anhui University, China
Chenguo Hu, Chongqing University, China
Yunhui Huang, Huazhong University of Science and Technology, China
Li Ji, Fudan University, China
Jun Lu, Argonne National Laboratory, USA
Xinping Qiu, Tsinghua University, China
Rodney S. Ruoff, University of Texas at Austin, USA
Donald G. Truhlar, University of Minnesota, USA
Oomman K. Varghese, University of Houston, USA
Zhonglin Wang, University of Chinese Academy of Sciences, USA
Rusen Yang, Xidian University, China
Shaik M. Zakeeruddin, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
Qiang Zhang, Tsinghua University, China

Advanced Manufacturing
Christoph J. Brabec, University of Erlangen-Nürnberg, Germany
Huigao Duan, Hunan University, China
Huilin Duan, Peking University, China
Yonggang Huang, Northwestern University, USA
Hanqing Jiang, Arizona State University, USA
Longqiu Li, Harbin Institute of Technology, China
Ning Xi, Michigan State University, USA
Yihui Zhang, Tsinghua University, China

Advanced Materials
H.C. Markus Antonietti, Max Planck Institute of Colloids and Interfaces, Germany
Suryanarayana Challapalli, University of Central Florida, USA
Hui-Ming Cheng, Tsinghua University, China
Tiejun Cui, Southeast University, China
Philippe Dubois, University of Mons, Belgium
Song Gao, South China University of Technology, China
Andreas Greiner, University of Bayreuth, Germany
Jian Ji, Zhejiang University, China
Lei Jiang, Institute of Chemistry, Chinese Academy of Sciences, China
Bingbing Liu, Jilin University, China
Weimin Liu, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, China
Xiaogang Liu, Northwestern Polytechnical University, China
David C. Martin, University of Delaware, USA
Ishwar K. Puri, McMaster University, Canada
Zhifeng Ren, University of Houston, USA
Zhigang Shuai, Tsinghua University, China
Dennis W. Smith, Mississippi State University, USA
Andreas Stein, University of Minnesota, USA
Galen D. Stucky, University of California, Santa Barbara, USA
Jianpu Wang, Nanjing Tech University, China
Xun Wang, Department of Chemistry, Tsinghua University, China
Ningsheng Xu, Fudan University, China
Chunhua Yan, Lanzhou University, China
Dong Hui Zhang, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, China
Ji Zhou, Tsinghua University, China

Artificial Intelligence

Gautam Biswas, Institute for Software Integrated Systems (ISIS), USA
Guangren Duan, Harbin Institute of Technology, China
Wen Gao, Peking University, China
Licheng Jiao, Xidian University, China
Xiang Li, Fudan University, China
Wei Lin, Fudan University, China
Tomaso Poggio, Massachusetts Institute of Technology, USA
Fuji Ren, University of Tokushima, China
Zhi-Hua Zhou, Nanjing University, China

Environmental Science

Charles Thurston Driscoll, Syracuse University, USA
Roy Michael Harrison, University of Birmingham, UK
Michael R. Hoffmann, California Institute of Technology, USA
Derek R. Lovley, University of Massachusetts Amherst, USA
Thalappil Pradeep, Indian Institute of Technology Madras, India
Jianming Xu, Zhejiang University, China
Zhi-Kang Xu, Zhejiang University, China
Hanqing Yu, University of Science & Technology of China, China
Yongguan Zhu, Institute of Urban Environment, Chinese Academy of Sciences, China

Flexible Electronics

Fengwei Huo, Nanjing Tech University, China
Samson A. Jenekhe, University of Washington, USA
Yong Qin, Lanzhou University, China
Shaoxing Qu, Zhejiang University, China
Li Tao, Southeast University, China
Health Science

Xuetao Cao, Nankai University, China
Ye-Guang Chen, Tsinghua University, China
Erdan Dong, Peking University Health Science Center, China
Fu Gao, Institute of Microbiology, Chinese Academy of Sciences, China
Fuchu He, PLA Academy of Military Science, China
Bo Huang, Chinese Academy of Medical Science, China
Lijian Hui, Shanghai Institutes for Biological Sciences, China
Dietmar W. Hutmacher, Queensland University of Technology, Australia
Trey Ideker, University of California, San Diego, USA
Yi Jiang, Institute of Psychology, Chinese Academy of Sciences, China
Eugene V. Koonin, National Institutes of Health (NIH), USA
Ren Lai, Kunming Institute of Zoology, Chinese Academy of Sciences, China
Chenzhong Li, Florida International University, USA
Huiying Li, University of California, Los Angeles, School of Medicine, USA
Lanjuan Li, Zhejiang University, China
Yi Rao, Capital Medical University, China
Zihe Rao, Tsinghua University, China
Yongyong Shi, Shanghai Jiao Tong University, China
Lydia L. Sohn, University of California, Berkeley, USA
Renxiang Tan, Nanjing University, China
Weihong Tan, Hunan University, China
Mi Tian, The Second Hospital of Zhejiang University, China
Daowen Wang, Huazhong University of Science and Technology, China
Fudi Wang, Zhejiang University, China
Wei Wang, Nanjing University, China
Yunfang Wang, Beijing Tsinghua Changgeng Hospital, China
Yuquan Wei, Sichuan University, China
Itamar Willner, The Hebrew University of Jerusalem, Israel
Zhiliu Yang, Southwest Jiaotong University, China
Luxia Zhang, Peking University, China
Jin Zhao, Nanjing University, China
Yuanjin Zhao, Southeast University, China
Hairong Zheng, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, China
Jiankang Zhu, Institute of Plant Physiology and Ecology, Chinese Academy of Sciences, China

Information Science

Ajith Abraham, Scientific Network for Innovation and Research Excellence (SNIRE), USA
Xinlin Chen, Institute of Computing Technology, Chinese Academy of Sciences, China
Xinbo Gao, Chongqing University of Posts and Telecommunications, China
Hai Jin, Huazhong University of Science and Technology, China
Wang-Chien Lee, Pennsylvania State University, USA
Xin (Shane) Li, Louisiana State University, USA
Massoud Pedram, University of Southern California, USA
Tieniu Tan, Institute of Automation, Chinese Academy of Sciences, China
Kun Zhou, Zhejiang University, China
Micro/Nano Technology
Helmut Cölfen, University of Konstanz Physical Chemistry, Germany
Ru Huang, Peking University, China
Charles M. Lieber, Harvard University, USA
Yuehe Lin, Washington State University, USA
Yi-Tao Long, East China University of Science and Technology, China
Zheng Ouyang, Tsinghua University, China
Muthukumaran Packirisamy, Concordia University, Canada
Lianmao Peng, Peking University, China
Martin Pumera, Nanyang Technological University, Singapore
Joseph Wang, University of California, San Diego, USA
Xiaomu Wang, Nanjing University, China
Yong Wang, Pen State University, USA
Kai Wu, Peking University, China
Yadong Yin, University of California, Riverside, USA
Shu-Hong Yu, University of Science and Technology of China, China
Hua Zhang, Department of Chemistry City University of Hong Kong, HK, China
Mingjun Zhang, Ohio State University, USA
Yongsheng Zhao, Institute of Chemistry, Chinese Academy of Sciences, China

Quantum Information
Guilu Long, Tsinghua University, China
Jianwei Pan, University of Science and Technology of China, China

Space Science
Ronggen Cai, Institute of Theoretical Physics, Chinese Academy of Sciences, China
Hongjian He, Tsinghua University, China

Chief Managing Editors
Kangyou Wang, President, Science and Technology Review Publishing House
Yongchao Shi, Vice President, Science and Technology Review Publishing House

Managing Editors
Chengyin Liu, Science and Technology Review Publishing House
Tian Tian, Science and Technology Review Publishing House
Wei Wang, Science and Technology Review Publishing House
Yehua Zhu, Science and Technology Review Publishing House

Email: research@cast.org.cn

Supervised by China Association for Science and Technology
Sponsored and Published by Science and Technology Review Publishing House
Printed by Beijing Jinghuahucai Printing Co, Ltd.
Distributed by the American Association for the Advancement of Science (AAAS)
Print version subscription price China ¥100/issue, ¥400/year. Postal distributing code 82-863.
## Contents

### Special topic: Emerging Nanogenerators

**Guest editors: Ya Yang, Zhong Lin Wang**

**Multieffect Coupled Nanogenerators**
Yun Ji, Yuan Liu, Ya Yang

**Recent Advances in Self-Powered Electrochemical Systems**
Linglin Zhou, Di Liu, Li Liu, Lixia He, Xia Cao, Jie Wang, Zhong Lin Wang
Research, vol. 2021, Article ID 4673028, 15 pages, 2021

**Fully Organic Self-Powered Electronic Skin with Multifunctional and Highly Robust Sensing Capability**
Lijuan Song, Zheng Zhang, Xiaochen Xun, Liangxu Xu, Fangfang Gao, Xuan Zhao, Zhuo Kang, Qingliang Liao, Yue Zhang
Research, vol. 2021, Article ID 9801832, 10 pages, 2021

**A Fully Self-Healing Piezoelectric Nanogenerator for Self-Powered Pressure Sensing Electronic Skin**
Maosen Yang, Jinmei Liu, Dong Liu, Jingyi Jiao, Nuanyang Cui, Shuhai Liu, Qi Xu, Long Gu, Yong Qin
Research, vol. 2021, Article ID 9793458, 9 pages, 2021

**Contrasting Thermoelectric Transport Behaviors of p-Type PbS Caused by Doping Alkali Metals (Li and Na)**
Zhenghao Hou, Dongyang Wang, Jinfeng Wang, Guangtao Wang, Zhiwei Huang, Lidong Zhao
Research, vol. 2020, Article ID 4084532, 11 pages, 2020

**Triboelectric Nanogenerator Enabled Smart Shoes for Wearable Electricity Generation**
Yongjiu Zou, Alberto Libanori, Jing Xu, Ardo Nashalian, Jun Chen

**Understanding the Percolation Effect in Triboelectric Nanogenerator with Conductive Intermediate Layer**
Binbin Zhang, Guo Tian, Da Xiong, Tao Yang, Fengjun Chun, Shen Zhong, Zhiming Lin, Wen Li, Weiqing Yang
Research, vol. 2021, Article ID 7189376, 8 pages, 2021

**A Nonresonant Hybridized Electromagnetic-Triboelectric Nanogenerator for Irregular and Ultralow Frequency Blue Energy Harvesting**
Weibo Xie, Lingxiao Gao, Lingke Wu, Xin Chen, Fayang Wang, Daqiao Tong, Jian Zhang, Jianyu Lan, Xiaobin He, Xiaojing Mu, Ya Yang
Research, vol. 2021, Article ID 5963293, 12 pages, 2021

**Triangulated Cylinder Origami-Based Piezoelectric/Triboelectric Hybrid Generator to Harvest Coupled Axial and Rotational Motion**
Jihoon Chung, Myunghwan Song, Seh-Hoon Chung, Woojin Choi, Sanghyun Lee, Zonghong Lin, Jinkee Hong, Sangmin Lee
Research, vol. 2021, Article ID 7248579, 9 pages, 2021

**Biopolymer Nanofibers for Nanogenerator Development**
Lulu Bai, Qing Li, Ya Yang, Shengjie Ling, Haipeng Yu, Shouxin Liu, Jian Li, Wenshuai Chen
Hybrid Triboelectric Nanogenerators: From Energy Complementation to Integration
Lingjie Xie, Ningning Zhai, Yina Liu, Zhen Wen, Xuhui Sun
Research, vol. 2021, Article ID 9143762, 23 pages, 2021

Thickness-Dependent Piezoelectric Property from Quasi-Two-Dimensional Zinc Oxide Nanosheets with Unit Cell Resolution
Corey Carlos, Yizhan Wang, Jingyu Wang, Jun Li, Xudong Wang
Research, vol. 2021, Article ID 1519340, 7 pages, 2021

Triboelectric Nanogenerators and Hybridized Systems for Enabling Next-Generation IoT Applications
Qiongfeng Shi, Zhongda Sun, Zixuan Zhang, Chengkuo Lee
Research, vol. 2021, Article ID 6849171, 30 pages, 2021

Self-Powered Room-Temperature Ethanol Sensor Based on Brush-Shaped Triboelectric Nanogenerator
Jingwen Tian, Fan Wang, Yafei Ding, Rui Lei, Xiang Sheng, Xinglin Tao, Shuyao Li, Ya Yang, Xiangyu Chen
Research, vol. 2021, Article ID 8564780, 11 pages, 2021

Magnetic Force Enhanced Sustainability and Power of Cam-Based Triboelectric Nanogenerator
Hakjeong Kim, Hee Jae Hwang, Nghia Dinh Huynh, Khanh Duy Pham, Kyungwo Choi, Dahoon Ahn, Dukhyun Choi
Research, vol. 2021, Article ID 6426130, 11 pages, 2021

Self-Powered Intelligent Human-Machine Interaction for Handwriting Recognition
Hang Guo, Ji Wan, Haobin Wang, Hanxiang Wu, Chen Xu, Liming Miao, Mengdi Han, Haixia Zhang
Research, vol. 2021, Article ID 4689869, 9 pages, 2021

Fiber-Shaped Triboiontronic Electrochemical Transistor
Jinran Yu, Shanshan Qin, Huai Zhang, Yichen Wei, Xiaoxiao Zhu, Ya Yang, Qijun Sun
Research, vol. 2021, Article ID 9840918, 10 pages, 2021

General Articles

Centimeter-Deep NIR-II Fluorescence Imaging with Nontoxic AIE Probes in Nonhuman Primates
Zonghai Sheng, Yaxi Li, Dehong Hu, Tianliang Min, Duyang Gao, Jen-Shyang Ni, Pengfei Zhang, Yuenan Wang, Xin Liu, Kai Li, Hairong Zheng, Ben Zhong Tang
Research, vol. 2020, Article ID 4074593, 14 pages, 2020

The Strategies of Pathogen-Oriented Therapy on Circumventing Antimicrobial Resistance
Zifang Shang, Siew Yin Chan, Qing Song, Peng Li, Wei Huang
Research, vol. 2020, Article ID 2016201, 32 pages, 2020

Unveiling the Effects of Interchain Hydrogen Bonds on Solution Gelation and Mechanical Properties of Diarylfluorene-Based Semiconductor Polymers
Lubing Bai, Yamin Han, Chen Sun, Xiang An, Chuanxin Wei, Wei Liu, Man Xu, Lili Sun, Ning Sun, Mengna Yu, He Zhang, Qi Wei, Chunxiang Xu, Yingguo Yang, Tianshi Qin, Linghai Xie, Jinyi Lin, Wei Huang
Research, vol. 2020, Article ID 3405826, 15 pages, 2020

Oxygen-Reconstituted Active Species of Single-Atom Cu Catalysts for Oxygen Reduction Reaction
Liu Yang, Haoxiang Xu, Huibing Liu, Xiaofei Zeng, Daojian Cheng, Yan Huang, Lirong Zheng, Rui Cao, Dopeng Cao
Research, vol. 2020, Article ID 7593023, 12 pages, 2020
Electrodes with Electrodeposited Water-excluding Polymer Coating Enable High-Voltage Aqueous Supercapacitors
Wujie Dong, Tianquan Lin, Jian Huang, Yuan Wang, Zhichao Zhang, Xin Wang, Xiaotao Yuan, Jie Lin, Iwei Chen, Fuqiang Huang
Research, vol. 2020, Article ID 4178179, 13 pages, 2020

Photothermally Responsive Conjugated Polymeric Singlet Oxygen Carrier for Phase Change-Controlled and Sustainable Phototherapy for Hypoxic Tumor
Guo Li, Ruyi Zhou, Weili Zhao, Bo Yu, Jie Zhou, Shujuan Liu, Wei Huang, Qiang Zhao
Research, vol. 2020, Article ID 5351848, 14 pages, 2020

All-in-One Deposition to Synergistically Manipulate Perovskite Growth for High-Performance Solar Cell
Yifan Lv, Hui Zhang, Jinpei Wang, Libao Chen, Lifang Bian, Zhongfu An, Zongyao Qian, Guoqi Ren, Jie Wu, Frank Nüesch, Wei Huang
Research, vol. 2020, Article ID 2763409, 10 pages, 2020

Recent Progress of Biomarker Detection Sensors
Ruitao Liu, Xiongying Ye, Tianhong Cui
Research, vol. 2020, Article ID 7949037, 26 pages, 2020

Electronic Skin from High-Throughput Fabrication of Intrinsically Stretchable Lead Zirconate Titanate Elastomer
Yiming Liu, Huanxi Zheng, Ling Zhao, Shiyuan Liu, Kuanming Yao, Dengfeng Li, Chunki Yiu, Shenghan Gao, Raudel Avila, Pakpong Chirarattananon, Lingqian Chang, Zuankai Wang, Xian Huang, Zhaoqian Xie, Zhengbao Yang, Xinge Yu
Research, vol. 2020, Article ID 1085417, 11 pages, 2020

Zhaoyuan Lyu, Shichao Ding, Nan Zhang, Yang Zhou, Nan Cheng, Maoyu Wang, Mingjie Xu, Zhenxing Feng, Xianghong Niu, Yuan Cheng, Chao Zhang, Dan Du, Yuehe Lin
Research, vol. 2020, Article ID 4724505, 11 pages, 2020

Large-Scale Synthesis of the Stable Co-Free Layered Oxide Cathode by the Synergetic Contribution of Multielement Chemical Substitution for Practical Sodium-Ion Battery
Yao Xiao, Tao Wang, Yan-Fang Zhu, Hai-Yan Hu, Shuangjie Tan, Shi Li, Pengfei Wang, Wei Zhang, Yubin Niu, Enhui Wang, Yujie Guo, Xinan Yang, Lin Liu, Yumei Liu, Hongliang Li, Xiaodong Guo, Yaxia Yin, Yugu Guo
Research, vol. 2020, Article ID 1469301, 16 pages, 2020

Fine-Tuning Pyridinic Nitrogen in Nitrogen-Doped Porous Carbon Nanostructures for Boosted Peroxidase-Like Activity and Sensitive Biosensing
Hongye Yan, Linzhe Wang, Yifeng Chen, Lei Jiao, Yu Wu, Weiqing Xu, Wenling Gu, Weiyu Song, Dan Du, Chengzhuo Zhu
Research, vol. 2020, Article ID 8202584, 11 pages, 2020

Oxygen Reduction Reaction Catalyzed by Carbon-Supported Platinum Few-Atom Clusters: Significant Enhancement by Doping of Atomic Cobalt
Bingzhang Lu, Qiming Liu, Forrest Nichols, Rene Mercado, David Morris, Ning Li, Peng Zhang, Peng Gao, Yuan Ping, Shaowei Chen
Research, vol. 2020, Article ID 9167829, 12 pages, 2020
Selective Dealkenylative Functionalization of Styrenes via C-C Bond Cleavage
Jianzhong Liu, Jun Pan, Xiao Luo, Xu Qiu, Cheng Zhang, Ning Jiao
Research, vol. 2020, Article ID 7947029, 9 pages, 2020

Structure-Enhanced Mechanically Robust Graphite Foam with Ultrahigh MnO₂ Loading for Supercapacitors
Qinghe Cao, Junjie Du, Xiaowan Tang, Xi Xu, Longsheng Huang, Dongming Cai, Xu Long, Xuewen Wang, Jun Ding, Cao Guan, Wei Huang
Research, vol. 2020, Article ID 7304767, 10 pages, 2020

Living Bacterial Microneedles for Fungal Infection Treatment
Fengyuan Wang, Xiaoxuan Zhang, Guopu Chen, Yuanjin Zhao
Research, vol. 2020, Article ID 2760594, 9 pages, 2020

Asymmetric Schottky Contacts in van der Waals Metal-Semiconductor-Metal Structures Based on Two-Dimensional Janus Materials
Jia Liu, Ji-Chang Ren, Tao Shen, Xinyi Liu, Christopher J. Butch, Shuang Li, Wei Liu
Research, vol. 2020, Article ID 6727524, 8 pages, 2020

Near-Infrared-Excitable Organic Ultralong Phosphorescence through Multiphoton Absorption
Ye Tao, Lele Tang, Qi Wei, Jibiao Jin, Wenbo Hu, Runfeng Chen, Qingqing Yang, Huanhuan Li, Ping Li, Guichuan Xing, Quli Fan, Chao Zheng, Wei Huang
Research, vol. 2020, Article ID 2904928, 12 pages, 2020

Wavelength-Tunable Single-Mode Microlasers Based on Photoresponsive Pitch Modulation of Liquid Crystals for Information Encryption
Fafeng Xu, Zhongliang Gong, Yuwu Zhong, Jiannian Yao, Yongsheng Zhao
Research, vol. 2020, Article ID 6539431, 9 pages, 2020

3D Printed Ultrastretchable, Hyper-Antifreezing Conductive Hydrogel for Sensitive Motion and Electrophysiological Signal Monitoring
Zhaozong Wang, Lei Chen, Yiqin Chen, Peng Liu, Huigao Duan, Ping Cheng
Research, vol. 2020, Article ID 1426078, 11 pages, 2020

Electrodeposition of Pt-Decorated Ni(OH)₂/CeO₂ Hybrid as Superior Bifunctional Electrocatalyst for Water Splitting
Huanhuan Liu, Zhenhua Yan, Xiang Chen, Jinhuan Li, Le Zhang, Fangming Liu, Guilan Fan, Fangyi Cheng
Research, vol. 2020, Article ID 9068270, 11 pages, 2020

Smart Microneedles for Therapy and Diagnosis
Xiaoxuan Zhang, Yuetong Wang, Junjie Chi, Yuanjin Zhao
Research, vol. 2020, Article ID 7462915, 26 pages, 2020

Halide Homogenization for High-Performance Blue Perovskite Electroluminescence
Lu Cheng, Chang Yi, Yunfang Tong, Lin Zhu, Gunnar Kusch, Xiaoyu Wang, Xinjiang Wang, Tao Jiang, Hao Zhang, Ju Zhang, Chen Xue, Hong Chen, Wenjie Xu, Dawei Liu, Rachel A. Oliver, Richard H. Friend, Lijun Zhang, Nana Wang, Wei Huang, Jianpu Wang
Research, vol. 2020, Article ID 9017871, 10 pages, 2020

Self-Navigated 3D Acoustic Tweezers in Complex Media Based on Time Reversal
Ye Yang, Teng Ma, Sinan Li, Qi Zhang, Jiqing Huang, Yifei Liu, Jianwei Zhuang, Yongchuan Li, Xuemin Du, Lili Niu, Yang Xiao, Congzhi Wang, Feiyan Cai, Hairong Zheng
Research, vol. 2021, Article ID 9781394, 13 pages, 2021
The LISA-Taiji Network: Precision Localization of Coalescing Massive Black Hole Binaries
Wenhong Ruan, Chang Liu, Zongkuan Guo, Yueliang Wu, Ronggen Cai
Research, vol. 2021, Article ID 6014164, 7 pages, 2021

Hierarchical Network with Label Embedding for Contextual Emotion Recognition
Jiawen Deng, Fuji Ren
Research, vol. 2021, Article ID 3067943, 9 pages, 2021

Interplay between Perovskite Magic-Sized Clusters and Amino Lead Halide Molecular Cluster
Evan T. Vickers, Ziyi Chen, Vivien Cherrette, Tyler Smart, Peng Zhang, Yuan Ping, Jin Z. Zhang
Research, vol. 2021, Article ID 6047971, 7 pages, 2021

*The art that appears on the front cover of this issue was derived from the Zhou et al. paper, “Recent Advances in Self-Powered Electrochemical Systems”. It is being used for the cover with permission from the authors.*

The above articles and the latest content from *Research* can be found at spj.sciencemag.org/research
Preface

Special topic: Emerging Nanogenerators

Guest editors: Ya Yang, Zhong Lin Wang

This special topic is focused on the most forefront research in the subject area of emerging nanogenerators. Nanogenerators that can scavenge energy from the environment as sustainable power sources are newly emerging in the field of nano energy and have extensive potential applications in self-powered systems and active sensors. In the last decade, various emerging nanogenerators have been developed to scavenge different energies and realize other new applications. Authors have contributed original research articles or comprehensive review articles covering fundamental understandings and practical development or applications of emerging nanogenerators enabled by nanomaterials and nanotechnologies. The special topic focuses on the materials, devices, and applications of various nanogenerators. Specific topics of interest include triboelectric nanogenerators, piezoelectric nanogenerators, pyroelectric nanogenerators, hybridized and coupled nanogenerators, from materials to devices as well as various potential applications.
Recent Advances in Self-Powered Electrochemical Systems

Linglin Zhou,1,2 Di Liu,1,2 Li Liu,1,2 Lixia He,1,2 Xia Cao,1,2 Jie Wang1,2 and Zhong Lin Wang1,3

1Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China
2College of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
3School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

Correspondence should be addressed to Xia Cao; caoxia@binn.cas.cn, Jie Wang; wangjie@binn.cas.cn, and Zhong Lin Wang; zhong.wang@mse.gatech.edu

Received 28 December 2020; Accepted 17 February 2021; Published 12 March 2021

Copyright © 2021 Linglin Zhou et al. Exclusive Licensee Science and Technology Review Publishing House. Distributed under a Creative Commons Attribution License (CC BY 4.0).

Electrochemistry, one of the most important research and production technology, has been widely applied in various fields. However, the requirement of external power source is a major challenge to its development. To solve this issue, developing self-powered electrochemical system (SPES) that can work by collecting energy from the environment is highly desired. The invention of triboelectric nanogenerator (TENG), which can transform mechanical energy into electricity, is a promising approach to build SPES by integrating with electrochemistry. In this view, the latest representative achievements of SPES based on TENG are comprehensively reviewed. By harvesting various mechanical energy, five SPESs are built, including electrochemical pollutants treatment, electrochemical synthesis, electrochemical sensor, electrochromic reaction, and anticorrosion system, according to the application domain. Additionally, the perspective for promoting the development of SPES is discussed.

1. Introduction

Electrochemistry, which refers to the interrelation of electrical and chemical effects, has play a crucial part in the sustainable advancement and innovation of industrial processes, including chemical industry, medicine, materials, energy, metal corrosion, and environmental science [1–5]. Electrochemical process highly depends on external power supply, which aggravates the crisis of energy shortage and environmental pollution problems in modern society. To solve these issues, developing a self-powered electrochemical system (SPES), which can operate by integrating electrochemical system with energy harvesting technology for collecting energy form environment [6–10], is one of the promising approaches. On account of the sufficient availability of mechanical energy, converting it from environment to electricity has aroused broad attentions. Recently, many technologies that extract mechanical energy have been reported, such as electromagnetic generator [11] and piezoelectric nanogenerator [6]. However, the low energy conversion efficiency of electromagnetic generator at low frequency and low output power of piezoelectric nanogenerator limit their practical application.

Based on the conjunction of triboelectrification and electrostatic induction, triboelectric nanogenerator (TENG), also known as Wang generators, was invented to extract energy from a variety of ambient mechanical motions, like sound, water waves, and mechanical vibration [12–15]. TENG exhibits many unique advantages including light structural simplicity, diverse materials options, and high conversion efficiency [16]. Moreover, TENG has demonstrates its potential applications in micro/nano power sources [17, 18], self-powered (SP) sensors [19, 20], large-scale blue energy [21, 22], and direct high voltage power sources [22, 23]. To promoting the practical application of TENG, large researches have been focused on improving its output performance via investigating the basic principles [24], enhancing the surface charge density [25–30], and power management [31–33]; thus, 500 W·m⁻² of area power density and >50% of conversion efficiency have been achieved, respectively [34]. In view of these advantages, TENG can be served as a promising alternatively energy harvesting power source to integrate...
with electrochemistry for electrochemical operation. Currently, many SPESs based on TENG have been developed, which will be elaborated in further detail below. Compared with traditional electrochemical systems, SPESs can drive the electrochemical process without the external power supply, which largely promote the sustainable development of electrochemical systems.

Here, the recent progresses and practical applications of SPES based on TENGs are summarized. According to the application, the SPES is classified into five major applications including pollutants treatment, electrochemical synthesis, SP sensors, electrochromic reaction, and anticorrosion system (Figure 1), respectively. Additionally, perspectives and challenges for promoting the development of SPES are proposed.

We would very much like that this paper will significantly advance the development of TENG in the electrochemistry field and offer a direction for future research in SPES.

2. Self-Powered Electrochemical System

SPES is developed from the combination of electrochemistry and TENG technology, where electrochemical process can operate by TENG that produces electrical power from the ambient environment. As a mechanical energy harvester, the recent development of TENG has been reviewed from the mechanism to the potential applications [35, 36]. Classified according to the motion direction and the capacitance change, four basic working modes of TENG were proposed.
since its first invention in 2012 [37–41], which can be divided into two types including contact-separation-type and sliding-type TENG. Driven by external force, repetitive changing of the distance between two planes and the size of contacting area will cause the variation of capacitance of TENG, resulting in the potential difference in two electrodes. For balancing the potential difference, electrons will flow back and forth in external circuit and thus generates an alternative current output. For driving the electrochemical process, a direct current is always employed in the current researches about SPES, where the alternative current output of TENG should be firstly transformed to direct current output by using rectifying device and then drive the electrochemical process.

The fundamental physics mechanism of TENG derives from Maxwell’s displacement current [42, 43], which is defined as

$$ I_D = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t}, \quad (1) $$

where \( I_D \), \( D \), \( P_s \), and \( E \) are the total displacement current density, the electric displacement vector, the polarization field, and the electric field, respectively. The displacement current (\( I_D \)) is a surface integral of \( I_D \):

$$ I_D = \int S \frac{\partial D}{\partial t} dS = \int \frac{\partial D}{\partial t} dS = \frac{\partial}{\partial t} \left[ \nabla \cdot Ddr \right] = \frac{\partial}{\partial t} \left[ \rho dr \right] = \frac{\partial Q}{\partial t} a, \quad (2) $$

where \( S \), \( \rho \), and \( Q \) are the medium surface, the distribution of free charges, and the total free charges on the electrode. According to the equation, the output loop of TENG contains two portions, including the internal circuit in TENG that is controlled by displacement current and the observed current in the external circuit. In summary, the core of physics for current production is the internal driving force of \( \partial P_s/\partial t \), which is named as the Wang term in the displacement current [43], and the external manifestation of displacement is the observed capacitive conduction current in external circuit.

3. Applications of Self-Powered Electrochemical System

3.1. Pollutant Treatment. Owing to the modern industrial activities, an alarming increase of toxic pollutants in the environment caused by human activities has brought to serious environmental issue, such as water pollution and air pollution, which is the most important environmental factor of disease and premature death in the world today [44]. For the growing threat of environmental pollutants, high efficiency pollutant treatment strategy is highly desired to ensure clean environment and human health. Due to high removal efficiency, great versatility, high amenability, and excellent environmental compatibility, electrochemical technology has been extensively developed as a promising method for environmental pollutants treatment [45, 46]. However, the requirement of an external power supply has become the major challenge for the practical application of electrochemical technology. Due to the invention of TENG by collecting mechanical energy from environment, SPES has been proposed as a candidate for environment treatment [47]. Furthermore, with the gradually enhanced output performance of TENG, many efforts have been devoted for removing environmental pollutants from water and air.

Water pollutants are mainly composed of inorganic, organic, and biological contaminants. As one of the most toxic pollutants, heavy metal ions can biologically accumulate upon cumulative exposure, which is not biodegradable, and thus threaten human health via the entire food chain [48]. Aiming to remove heavy metal ions from environment, Li et al. reported a water-driven TENG to extract the kinetic energy from wastewater flow, which used to drive electrochemical reaction for Pb\(^{2+}\) and Cu\(^{2+}\) removal [49]. By using the integrated SP system, 97.4% of the two metal ions was removed from the wastewater in 100 min. Through comparing the electrochemical property of Cr(VI) driven by continuous DC (CDC) and pulsed DC (PDC), Zhou et al. confirmed an enhanced efficiency of removing Cr(VI) under PDC than that of CDC due to the better utilization of ferrous ion, the lower electrode passivation, and the higher ion diffusion rate during the reaction process [50]. Therefore, they proposed an SPES based on TENG with PDC output for improving the electrochemical performance of heavy metal ion treatment. The structures of the rotary TENG and SPES are shown in Figures 2(a) and 2(b). The charge consumption under different power supply is shown in Figure 2(c). Under equal charges consuming with 0.048 C, the removal efficiency driven by PDC was increased by 53.5% compared to that of CDC.

Organic pollutants in water have also drawn wide concern because of the most toxic and potentially carcinogenic; therefore, large efforts have been devoted to removing organic pollutants from wastewater. SP electrooxidation is the common process for organic pollutants treatment by using the produced chlorine and hypochlorite. Li et al. proposed a unique SP electrooxidation system to phenol removal via creatively employing β-cyclodextrin to increase triboelectrification [51]. In the condition of wastewater wave with velocity of 1.4 m s\(^{-1}\) and initial concentration of phenol with 80 mg L\(^{-1}\), 90% of the phenol was removed by the generated power in 320 min. Gao et al. reported a free-standing mode TENG integrated with electrocatalytic technology for degrading 4-aminoazobenzene [52]. With a commercial aluminum panel as stator, the power density reached up to 2.28 W m\(^{-2}\). Driven by the TENG, 4-aminoazobenzene can be electrochemical degradation to small molecule polymers by sensibly adjusting the potentials of electrochemical oxidation. By using the sponge to improve the contact intimacy and precharge injection to increase the surface charges in the dielectric film, Gao et al. improved the power density of a multilayer linkage TENG to 7.4 W m\(^{-2}\), which was used to drive electrochemical catalysis for degrading methyl red [53]. Powered by the multilayer linkage TENG, the degradation percentage of methyl red was almost 100% after 160 min, with a color change from red to colorless. Additionally, Chen et al. fabricated an SP multifunctional system which can
simultaneously realize heavy metal ions and organic pollutant removal driven by a rotary TENG [54]. The illustrations of the rotary TENG and system are shown in Figures 2(d) and 2(e). After rectifying, 100% of rhodamine B and 97.3% cupric ion were removed after 3 hours treatment (Figures 2(f) and 2(g)). Besides, Yang et al. reported an SP electrocatalytic system containing a hybrid energy cell including TENG to degrade methyl orange, which can further achieve a higher performance [55]. In this system, the generated energy can directly power the electro-degradation of methyl orange, or store in an energy storage unit before utilizing for methyl orange treatment, where the removal efficiency of methyl orange reached 80% after 144 h.

Owing to merits of environmentally friendly and particularly efficient, SP electrochemical advanced oxidation system such as SP electro-Fenton process is proposed to removing organic pollutants from the water [56–58]. Feng et al. integrated a rotary TENG with an electrochemical cell to build an SP electro-Fenton system to remove dyes [59]. In this work, a modified graphite felt cathode was used to produce H2O2 along with •OH, and a platinum sheet anode was applied to generate active chlorine, which can be used to oxidize organic pollutants. Through power management, the electric power of integrated rotary TENG improved by 3.5 times for driving electrochemical reaction. Driving by wind flow at the speed of 6.2 m s⁻¹, the SP electro-Fenton system can efficiently degrade dyes without aerating oxygen, and a removal efficiency of 87.5% within 120 min was achieved. Combining with 3D printing techniques, Tian et al. prepared a 3D printed elastic TENG to form an SP electro-Fenton

Figure 2: Self-powered electrochemical pollutant treatment: (a) sketch map of rotary TENG; insert displays the pictures of stator and rotator; (b) SP system for removing Cr(VI) powered by rectified TENG; (c) the comparison of charge consumption for Cr(VI) removal under different conditions [50]; (d) sketch map of the rotary TENG; (e, f) the mechanism image and optical image of SP electrochemical system for cupric ions and rhodamine B removal; (g) removal efficiency of cupric ions and rhodamine B [54]; (h) sketch map of the triboelectric negative air ion generator; (i, j) the contrast photographs of the smog cleaning by the MSNG in stationary conditions (i) and with the FS-TENG conducting at 0.25 Hz (j) [63].
system for removing methylene blue, where 97.0% of methylene blue was removed within 140 min [60]. Biological contaminants such as harmful bacteria and algal blooms caused by uncontrolled discharge of wastewater are the other kinds of water pollutants. Jiang et al. reported an SP electrochemical water treatment system on the basis of an arch-shaped TENG for cleaning sterilization and algae in wastewater [61]. By extracting water wave energy, most of the bactericidal and algae treatment were cleaned by the produced Cl₂ and reduced graphene oxide. By using SPES, high removal efficiencies for three model bacteria and mixed marine algae were achieved.

Air pollution including fine air particulate matter (PM) and gaseous pollutants is a crucial toxicant caused by human activities. Generally, air pollution exposure is related to lots of chronic diseases, such as pulmonary and cardiovascular disease [62]. To clean PM 2.5, Guo et al. reported an SP triboelectric negative air ion generator (MSNG) powered by TENG [63]. Powering by TENG, the voltage of carbon fiber electrodes was over 2 000 V, which can be employed to produce negative air ions in these electrodes (Figure 2h). For demonstrating the ability to clean PM 2.5, 1 × 10¹³ NAI was generated by using a palm-sized MSNG, and PM 2.5 with initial concentration of 999 µg m⁻³ was quickly declined to 0 µg m⁻³ in 80 s at 0.25 Hz. Furthermore, the observable heavy smog purification processes are displayed in Figures 2(i) and 2(j), which demonstrated the high efficiency of the MSNG for air purge.

The primary pollutants of gaseous pollutants result from the original pollutants directly discharged into the atmosphere from the source, mainly including oxysulfide, oxynitride, and organic compounds [64]. For removing sulfur dioxide (SO₂) and dust, Chen et al. reported an SP air cleaning system on the basis of a rotary TENG [65]. Driven by nature wind, rotary TENG produced a high voltage about 300 V, which was applied to power the electrochemical oxidation of SO₂ without the byproducts such as ozone and NOx than conventional electrostatic precipitation. For cleaning oxynitride, Han et al. proposed an SP NOx absorption and degradation system on the basis of a radial-engine-shaped TENG system [66]. By harvesting win energy, the SP system synchronously achieved the removal of NOx. For cleaning formaldehyde in indoor atmosphere, Feng et al. demonstrated an SP electrostatic filter by integrating TENG with photocatalysis technology [67]. In this work, a single electrode TENG was used as power source to produce high electric field on the filtering network. Consequently, the SP electrostatic filter was demonstrated to clean formaldehyde via both electrostatic adsorption effect induced by TENG and enhanced photocatalytic effect by the photocatalyst on the SP filter networks, where the formaldehyde concentration decreased to 60% within 250 min, and a tripled increased efficiency of formaldehyde removal was achieved.

3.2. Self-Powered Electrochemical Synthesis System. Converting energy from environment into easily storable chemical energy such as hydrogen and formic acid has drawn public attention as the alternative technology to ensure a clean and sustainable energy supply [68]. Generally, the process of clean fuel production needs an external input power, where renewable energies such as solar, wind, geothermal, and hydro have been applied along with carbon dioxide and water to generate clean fuels [69]. Owing to the ability of harvesting ambient mechanical energy, TENG-based SP electrochemical system has been demonstrated as a promising technology for clean fuel generation [70–73]. Tang et al. firstly proposed a fully SP water splitting system for producing hydrogen [74], which integrated a rotary TENG with a water splitting unit (Figures 3(a) and 3(b)). Driven by the rotary TENG at 10 Hz, the production ratio of hydrogen was up to 6.25 × 10⁻³ mL min⁻¹ in 30% (w.t.) potassium hydroxide solution. As demonstrating, obvious bubbles were observed in the electrode (Figures 3(c) and 3(d)). To improve the production speed of hydrogen, introducing a hybrid cell to increase the output power of SP water splitting system is a promising strategy [75]. Yang et al. designed an SP water splitting system on the basis of a hybrid energy cell, where the hydrogen production speed had been improved to 4 × 10⁻⁴ mL s⁻¹ [76].

As the other type of clean fuel, formic acid with characteristics of high volumetric capacity, low toxicity, and flammability under ambient condition has drawn wide attention [77]. Leung et al. presented an SP carbon dioxide reduction system that harvests energy from ocean wave for converting carbon dioxide into formic acid (Figure 3(e)) [78]. At an optimal value of discharge voltage (2.4 V) for each cycle, the system realized near 100% faradaic efficiency for shifting carbon dioxide into formic acid. Driven by TENG under a simulated waves with water surface area of 0.04 m², the system generated 2.798 µM of formic acid per day.

Ammonia (NH₃) acts a crucial role in food production, industrial manufacturing, and a predictable ideal energy carrier in the future [79]. In industry, Haber-Bosch process is commonly employed to produce NH₃ with the existence of hydrogen and external energy supply, where the challenge of grueling conditions increases the cost of production [80]. Due to a controllable operation under mild conditions utilizing mechanical energy by TENG, the SP electrocatalytic NH₃ synthesis system based on TENG provides a promising candidate for the conversion of N₂ to NH₃. Gao et al. reported an SP sustainable metal-free NH₃ production system based on a multilayer asway TENG by 3D printing technology, which can efficiently convert N₂ into NH₃ [81]. The maximum power density of 6.7 W m⁻² was realized by the printed TENG, which was used to drive the production of NH₃. By using the carbon materials from melamine sponge as the metal-free electrocatalyst, the assembled SP NH₃ production system can reach NH₃ yield of 36.41 µg h⁻¹ mg⁻¹ cat. By introducing a high-output dual-TENG configuration, Han et al. constructed an SP electrocatalytic NH₃ synthesis system to simultaneously achieve nitrogen fixation and electrocatalytic reduction with air as the N₂ source [82]. The electrocatalytic NH₃ synthesis system mainly consisted of three parts, including TENG-1, a needle-plate, and TENG-2. Specifically, TENG-1 was used to produce high voltage, a needle-plate was utilized to fix nitrogen and produce NOₓ which then flowed into a water receptacle to produce NO₃⁻ and NO₂⁻, and TENG-2 was employed to generate pulsed DC which drove
Figure 3: Self-powered electrochemical synthesis: (a) sketch map of the SP water splitting system; (b) structure of the disk TENG; (c) the SP water splitting system driven by a miniature water turbine; (d) images of the system with bubble producing [74]; (e) sketch map of the SP electrochemical system for CO₂ reduction powered by TENG for harvesting ocean-wave energy [70]; (f) sketch map of the designed TENG; (g) reaction of SP ammonia synthesis system; (h) sketch map of the SP structure driven by exhaust gas; (i, j) concentration of NH₃ in the cathode compartment at different times (i) and the volume of residual solution and the yield of NH₃ (j) by the SP system after ten hours [82].
the reaction for ammonia production (Figures 3(f) and 3(g)). Driven by the gas flow, a high voltage of 7 kV supplied by TENG-1 and the output performance of 3.1 V and 8.9 mA for the cell reaction supplied by TENG-2 were achieved, respectively (Figure 3h). By employing the SP electrosynthetic NH$_3$ synthesis system based on above dual-TENG, 2.4 μg h$^{-1}$ of NH$_3$ was successfully synthesized (Figure 3(i) and 3(j)).

Besides the abovementioned works, some other SPESSs such as SP electrochemical oxidation system and SP electrodeposition system were also developed to electrochemical synthesis [83–86]. Zheng et al. reported an SP electrosynthetic oxidation system on the basis of designed cross-linked TENG for synthesizing polyaniline [85]. As for the cross-linked TENG, the high capability of 69.9 μA and 845.6 V was achieved. By harvesting vibration energy, the SP electrochemical oxidation system was utilized as electricity source for converting aromatic amines to polyaniline. Wang et al. established a self-powered electrodeposition system for poly-pyrrole synthesis, where the polypyrrole as the electrode material of TENG was produced by TENG [86].

3.3. Self-Powered Electrochemical Sensor System. Based on TENG, lots of SP electrochemical sensors have been proposed to detect chemical substances. According to the mechanism of sensing, SP electrochemical sensor can be classified into two types including SP electrochemical passive sensor and SP electrochemical active sensor [47, 87].

SP electrochemical passive sensor is that the conventional sensors are driven by TENG for collecting mechanical energy from environment. Zhang et al. proposed an SP glucose biosensor based on contact-separation type TENG combined with lithium-ion battery [88]. The flexible TENG fabricated by a patterned polydimethylsiloxane (PDMS) film can extract energy from the motion of clapping; thus, the battery with an increased charging voltage from 400 mV to 800 mV was achieved after more than two hours, which was successfully demonstrated to power a glucose biosensor. Aiming to voluntarily supervise the water quality, Bai et al. reported an in situ SP sensing system that can convert the water wave energy to electricity based on tandem disk TENG [89]. Owing to the radial grating disk structure with swinging mass blocks, the tandem disk TENG driven by water waves can realize a conversion from low-frequency water wave motions into high-frequency output; thus, an average power density of 7.3 W m$^{-3}$ was achieved. Through rectification and energy storage, the electricity produced by TENG can be utilized to drive electronics for monitoring the water quality.

As for the SP electrochemical active sensor, a TENG is designed to actively generate electrical signal for responding the stimulation of chemical molecules or environmental factors such as ethanol, phenol, catechin, and pH, where the output performance of TENG and the target shows a linear relationship [51, 90–92]. Zhang et al. demonstrated SP sensors based on the TENGs fabricated by polyamide (PA) film and polypyrrolefluorooethylene (PFTE) film for detecting liquid/gaseous ethanol [90]. The TENG was mainly composed of two plates, where a layer of PA or PFTE film was pasted on a copper foil as back electrode, and a nanopore modified Al foil was used as the triboelectric electrode. Due to the degrees of wettability of the PA and PTFE films to ethanol, the output voltage of the SP sensor logarithmically declined with the concentration of ethanol solutions increasing from 20% to 80%, as well as the output signal decreased with the increase of ethanol gas concentration ranging from 40% to 80%. Lin et al. proposed a contact-separation-type TENG as an SP nanosensor toward catechin detection [91]. For this TENG, PFTE film and a layer of TiO$_2$ nanomaterial (nanowire and nanosheet) array were used as a pair of triboelectric materials. Because of the strong interaction between Ti atoms of TiO$_2$ nanomaterial and enediol group of catechin, a high sensitivity (detection limit of 5 μM) and a linear range from 10 M to 0.5 mM of the SP nanosensor were achieved, demonstrating great potential for the determination of catechin concentrations in real samples. Wu et al. reported an SP triboelectric sensor based on the sliding type TENG for detecting pH value from a periodic contact/separation motion [92]. A fork-finger structure was designed for SP triboelectric sensor, which mainly consisted of fluorinated ethylene-propylene (FEP) film and metal electrodes. The reciprocating motion between SP triboelectric sensor and buffer solution resulted in charge transfer between the adjacent Cu bottom electrodes, generating AC voltage in the external circuit. The output voltage of the SP triboelectric sensor enhanced with increased pH value due to the increased ion concentration. Therefore, the pH value of buffer solution can be actively monitored in real-time by reading the output voltage. Li et al. proposed an SP active sensor to Hg$^{2+}$ ions monitoring based on TENG where 3-mercaptopropionic acid-modified gold nanoparticles was used as recognition element [93]. In this system, a contact-separation-type TENG was employed, which shown a layered structure based on two plates (Figure 4(a)). The output performance of TENG and the concentration of Hg$^{2+}$ ions displayed a linear relationship because the chemical potential difference between the different triboelectric layers defined the triboelectricitation effects. As shown in the inset of Figure 4(b), the output performance of the TENG declined with improving the concentration of Hg$^{2+}$ ions, where the short-circuit current ratio was proportional to the concentration of Hg$^{2+}$ ions in the range of 100 nM-5 000 nM. Due to the high selectivity of 3-mercaptopropionic acid toward Hg$^{2+}$ ions, Hg$^{2+}$ ion can be specifically detected by the proposed sensing system (Figure 4(b)). Jie et al. demonstrated an SP triboelectric sensor for monitoring dopamine in the alkaline condition on the bases of TENG, which was composed of PFTE with nanoparticle arrays and an Al film (Figures 4(c) and 4(d)) [94]. Because the nano-stick PFTE exhibits a strong interaction of dopamine, the output performance of the TENG was inversely proportional to the concentration of dopamine in the range of 10 μM-1 000 μM (Figure 4(e)). In this work, a detection limit of dopamine was 0.5 μM, which suggested an effective means of SP electrochemical sensor for dopamine detection. Wen et al. introduced an SP gas sensor on the basis of a blow-driven TENG, where a rotary TENG was applied as shown in Figure 4(f) [95]. The illustration of the SP breath analyzer is shown in Figure 4(g). Driven by mouth blowing,
the output voltage of the sensor was only proportional to the concentration of alcohol in the air flow (Figure 4(h)). On the basis of blow-driven TENG, the active alcohol breath analyzer exhibited a high detection gas response of ~34 under an optimized condition. Additionally, when the blow-driven TENG was blew by a tester without drinking alcohol, the voltage drop across the sensor was almost zero due to a low sensor resistance (Figure 4(i)). While the air-flow of a tester that had been drank across the sensor, an enhanced voltage would be generated and thus could trigger the warning system (Figure 4(j)), which was caused by the dramatically increased resistance of the sensor in the breathed-out alcohol vapor.

3.4. Self-Powered Electrochromic System. Electrochromic devices can reversibly change their optical properties by the electrochemical redox reaction under an external electric field [96]. Applied TENG as the electricity source to provide a constant voltage, SP electrochromic device has been realized to replace batteries, which provides a promising sustainable power solution [97, 98].
Driven by a dual-mode TENG for harvesting wind and raindrop energy, Yeh et al. realized an SP smart window system [99]. The dual-mode TENG involved a single-electrode TENG on the top of the SP smart window for harvesting the energy from raindrop motions, and a contact-mode TENG assembled by elastic springs below the aforementioned single-electrode-mode TENG for collecting energy from wind energy. Both of the two TENGs consisted of a PDMS thin film adhered to a conducting substrate that were adhered to the electrochromic device with a substrate to fabricate an SP system (Figure 5(a)). The electrochromic device mainly consisted of Prussian blue (PB) nanoparticles and zinc hexacyanoferrate (ZnHCF) nanocubes as the electrochromic material and the ion storage layer. By photolithography and a template molding process, the PDMS film has a micropatterned pyramid array structure for enhancing the hydrophobic property and effect contact area of the surface. Driven by the dual-TENG, the transmittance of the electrochromic exhibited reversible variations. For gaining a more intuitive view of the change of the optical property, the transmittance of the electrochromic device was measured from 400 to 800 nm both before and after the coloring process. As shown in Figure 5(b), the transmittance declined in the full range during the coloring process, and the highest variation was realized at 695 nm, while the transmittance declined from 53.5% to 20.9%. These transmittance changes can be observed by visualization, where the color of the electrochromic device changed from transparent in bleached state to deep blue in colored state (Figure 5(c)). In this work, 32.4% of the maximum transmittance change was achieved at 695 nm, which closed to the value of 32.6% that powered by a conventional electrochemical power source.

Yang et al. reported a WO₃-based electrochromic device integrating with TENG to fabricate an SP electrochromic device [100]. The SP electrochromic device had a multilayered structure, which is displayed in Figure 5(d). Commercial glass was used as the substrate, on which there was a layer of FTO thin films acted as electrodes. The sheet resistance and transmittance of FTO film were 35-45 Ω per sq. and 80%, respectively. Between the two electrodes, there were an array of cells and a layer of WO₃ film (Figure 5(e)), and the distance between the two electrodes was around 20 mm. The cells were filled with polyelectrolyte, and the WO₃ film was about 250 nm which was densely packed nanoparticles. As shown in Figure 5(f), the fully packaged SP electrochromic device still had a transmittance of more
than 70%. As shown in Figure 5(g), powered by TENG, the transmittance of electrochromic cell was drop via coloring process (Figure 5(g), (I)). When the connection of reversible switch was reversed, the electrochromic cell returned to transparency (Figure 5(g), (II)). Compared with the SP electrochromic device, the transmittance of the device greatly dropped, and a relatively stable difference of as much as 17% was maintained for wavelength that ranges from 450 nm to 650 nm (Figure 5(h)), indicating the sensitivity and applicable to a broad range of light wavelength.

To effectively harvest acoustic energy, Qiu et al. integrated a sandwich-like structured TENG with electrochromic device for reversible color changing [101]. The TENG consisted of three layers including Cu foam, polyvinylidene fluoride (PVDF) nanofiber, and a nylon fabric. There was a thick spacer layer between the nylon fabric and PVDF nanofibers to produce more space vibration for the membrane. Driven by sound, high outputs of 25.01 mA m$^{-2}$ and 20.91 $\mu$C s$^{-1}$ were achieved for the designed TENG. The high performance of TENG enabled it to power an electrochromic device. In this system, reversible switches controlled the oxidation and reduction process and thus controlled the color change. Driven by the TENG, the color of electrochromic film changed between the transparent white and dark blue, which were controlled by the switching dot.

3.5. Self-Powered Anticorrosion System. Material corrosion is a long-standing challenge in many engineering applications [102]. The cathodic protection is one of the most durable methods to protect the materials from corrosion, which involves sacrificial anode cathodic protection system (SACPS) and impressed current cathodic protection system (ICCP) [103–105]. Different from SACPS, the ICCPS can protect the steel by cathodic current from a direct current source without any sacrifice of electrode materials [106].
However, the requirement of external electric energy supply limits its practical application. For solving this issue, many works have been focused on the SP anticorrosion system by integrating TENG with chemical anticorrosion protection [107–111].

Wang et al. realized an SP anticorrosion system for iron sheet driven by a high performance TENG [112]. Utilizing the fabricated nanostructures and prior-charge injection method, the charge densities were improved by 48% and 53%, respectively. The schematic image of SP anticorrosion system is depicted in Figure 6(a). Aiming to study the effect of SP anticorrosion system, the iron steel was soaked into 3.5% NaCl solution for 2 h, and the corresponding surface morphology is displayed in Figure 6(b). As displayed, almost no change of the iron sheet was observed by using TENG, while a thin rust film was produced without TENG. This result indicated a good anticorrosion property of the SP system, which exhibited a good prospect to protect materials from rusting with low energy cost.

Considering the metal corrosion is more likely to happen under ocean environmental conditions, Li et al. developed an SP system on the basis of networking TENG and supercapacitor to convert water wave to electricity for metal anticorrosion [113]. To obtain a stable and continuous output, the flexible TENG integrated with a flexible double-layer supercapacitor for harvesting the wave energy and then storing the energy in the supercapacitor. The structure and working mechanism of the SP system displayed in Figure 6(c). Driven by the water wave in the condition of 0.2 m s\(^{-1}\) and 1 Hz, the protected steels injected into electrons stemmed from TENG, leading to a cathodic polarization. In this work, a declined potential of steel electrode from -0.35 V to -0.6 V indicated that the steel become more stable in the protection of designed SP system. Immersing in the solution of sodium chloride with concentration of 0.5 M, there was a thin layer of rust on the steel without the protection of SP system, while there were a few corrosion pits on the steel when the SP system was working (Figure 6(d)). These results demonstrated that the SP system significantly decreased the corrosion rate, which could be adopted in marine corrosion.

Zhu et al. designed an SP cathodic protection system based on a flexible TENG, which can harvest energy from natural rain drops and wind to drive the cathodic protection process [110]. The contact-separation-type TENG was mainly composed of PDMS film and ITO, which were acted as a pair of triboelectric layers (Figure 6(e)). The schematic diagram of the SP metal surface cathodic protection system is shown in Figure 6(f). Under stimulations at a frequency of 1 Hz, the output current of the TENG was over 130 \(\mu\)A, and the voltage reached about 500 V. In this SP cathodic protection system, the protected metal that was immersed into the electrolyte was acted as the cathode, while a carbon rod was used as the anode. The comparison results of the rested specimens with and without SP cathodic protection system are displayed in Figure 6(g). For the specimens protected with SP cathodic protection system, several gray distributing areas appeared on the surface of specimens. These areas enlarge with the increase of corrosion, but no apparent corrosion was observed on these samples. As for the specimen without SP cathodic protection system powered by TENG, numerous corrosion pits were found on the three surfaces of specimens, and more big pits arose on the sample that was corroded in simulated electrolyte for 72 h.

4. Summary and Perspective

Electrochemistry has brought earth-shaking changes to our life, and it has become a technology for production and research in many fields. In order to break the limitation of external powers source for electrochemical operation, integrating electrochemical system with TENG to form SPES is the most promising strategies. According to the latest achievements, SPESs can be summarized into five major fields including pollutants treatment, electrochemical synthesis, electrochemical sensor, electrochromic reaction, and metal anticorrosion, respectively. Although researches into SPES have realized remarkable progresses, the following issues should be addressed for promoting further development of this field:

1. **High Output Power and Durability of TENG.** Output power and durability of TENG are two key points to realize high performance of SPES. To improve the output power of TENG, further improving the surface charge density and integrating existing methods in a large scale are suggested. To enhance the durability of TENG, introducing interface liquid lubrication [114] and developing materials with the most robust mechanical durability and stability might be the promising strategies.

2. **Power Circuit Management of TENG.** TENG has the characteristics of high voltage output and low current output, while the performance of electrochemical process exhibits positive correlation with current density and negative influence such as passive electrode effect and secondary reaction induced by high potential. To achieve a high performance of SPES, the power circuit management of TENG is highly desired to match the corresponding electrochemical process.

3. **Reducing electrode passive is crucial to prolong the lifetime of electrodes, improve the electrochemical efficiency, and ensure a stable activity.** TENG with a pulse output signal has been reported to reduce the electrode passive effect; however, the phase superposition of TENG caused by multiple parallel electrodes makes it hard to realize a full-waveform-pulse-current. Therefore, rational design of the structure of TENG, such as adjusting the rotation center angle ratio between each rotator and stator to obtain a full-waveform-pulse-current, will be a promising strategy to optimize the processes of SPES. It has been reported that alternating current exhibits many virtues such as lower energy consumption, improved mass transfer characteristic, and delayed electrode passivation compared to direct current in the electrochemical system [115]; thus, utilizing the alternating...
current of TENG to build SP electrode system is the other method to reduce the electrode passive and improve the electrochemical performance.

(4) The electrode plays a key role in the electrochemical reaction. Therefore, the electrode materials are the most key factors to determine the properties of electrochemical reaction. Novel electrode materials such as nanoscale electrode materials and metal-organic framework materials with merits of high conductivity, high specific surface areas, high activity, and cycle stability should be prepared to further enhance the performance of SPES.

(5) New Application of SPES. With the improvement performance of TENG, it can be utilized as electricity source to power some new electrochemical reaction such as electrococagulation for removal of oil in water, electrodialysis for desalination and water reuse, and electrophoresis for the separation of protein to build SPES for overcoming the problem of external power supply. Besides traditional electrochemistry based on electrolytic cell that needs high current density, the interrelation of electrical and chemical effect can also be realized by high voltage electrostatic discharge. By utilizing TENG, a high voltage electrostatic is actually quite easy to achieve. Therefore, integrating TENG with electrochemical system to build SP discharge electrochemical system for removing pollutants such as PM [63] provides a new horizon for its application.

Conflicts of Interest
The authors declare no conflict of interest.

Authors’ Contributions
Linglin Zhou and Di Liu contributed equally to this work.

Acknowledgments
This review was supported by the National Key R&D Project from Ministry of Science and Technology (2016YFA0202701), the National Natural Science Foundation of China (Grant Nos. 61774016, 21773009, 51432005, 5151101243, and 51561145021), and the Beijing Municipal Science & Technology Commission (Z171100000317001, Z171100002017017, and Y3993113DF).

References


S. Chen, N. Wang, L. Ma et al., “Triboelectric nanogenerator for sustainable wastewater treatment via a self-powered


[86] J. Wang, Z. Wen, Y. Zi et al., "Self-powered electrochemical synthesis of polypropylene from the pulsed output of a triboelectric nanogenerator as a sustainable energy system,"


[93] H. Zhang, Y. Yang, Y. Su et al., "Self-powered electrochro-

[94] N. W. Y. Jie, X. Cao, Y. Xu, H. Zhang, and Z. L. Wang, "Self-powered triboelectric nanosensor with poly(tetraflu-

[95] Z. H. Lin, G. Zhu, Y. S. Zhou, and D. Wang, "Robust design of unearthed anode, faradaic e-


ABOUT RESEARCH

Join forces to create a first-class worldwide journal. Research is the official journal of the China Association for Science and Technology (CAST) and is published in collaboration with the American Association for the Advancement of Science (AAAS). Launched in 2018, Research is the first Science Partner Journal, a program that connects respected research institutions to the global scientific community.

SCOPE

Research is a multidisciplinary journal that publishes high-quality research reflecting new and innovative discoveries. Disciplines of particular interest include:

- Advanced Energy
- Advanced Manufacturing
- Advanced Materials
- Artificial Intelligence
- Environmental Science
- Flexible Electronics
- Health Science
- Information Science
- Micro/Nano Technology
- Quantum Information
- Space Science

EDITORIAL BOARD

Research’s editorial board consists of distinguished practicing scientists from all over the world, with more than half of its members located outside of China.

Research has two Editors-in-Chief:

Editor-in-Chief (International)
Tianhong Cui
Distinguished McKnight University Professor
University of Minnesota

Editor-in-Chief (China)
Wei Huang
Northwestern Polytechnic University,
academician of the Chinese Academy of Sciences

The editorial board includes numerous well-known international academicians and scholars:

Charles Lieber, Harvard University, (NAS)
Yonggang Huang, Northwestern University (NAE)
Ningsheng Xu, President, Fudan University, (CAS)
Chunhua Yan, President, Lanzhou University, (CAS)
Xuetao Cao, President, Nankai University, (CAE)
Song Gao, President, South China University of Technology (CAS)
Jianwei Pan, Executive Vice President, University of Science and Technology of China (CAS)

AVAILABILITY

Research is updated continuously at spj.sciencemag.org/research and collocated into quarterly printed issues. Each issue features original cover art derived from article content and is produced on the 15th of March, June, September and December.

Print version subscription price:
China ¥ 300/issue, ¥ 1200/year.
Postal code: 82-863

Indexed

CAS, CNKI, CSCD, DOAJ, EI, ESCI, INSPEC, PMC, Scopus

APCs

Research and Review Articles: $1500 USD
Perspectives: $1200 USD
Invited manuscripts are free

Submit your high impact research today!
spj.sciencemag.org/research
PUT YOUR RESEARCH OUT IN FRONT

Submit your research: cts.ScienceMag.org

Science Signaling

Twitter: @SciSignal
Facebook: @ScienceSignaling