中国材料大会 2024

暨第二届世界材料大会

CMC 2024 & WMC 2024

July 8-11, 2024

Guangzhou, China

D15-微纳能源材料与器件

D15- Micro-Nano Energy Materials and Devices

Organized by

Chinese Materials Research Society

Website: https://cmc2024.scimeeting.cn

D15. 微纳能源材料与器件

分会主席：王中林、翟俊宜、訾云龙、董凯

D15. 微纳能源材料与器件-01

Facile and rapid synthesis of MXene-based nanomaterials and heterostructures for energy applications

Jianhua Hao*[1]

1. The Hong Kong Polytechnic University

MXenes have intriguing physical and chemical properties, including high electrical conductivity, functionalized surfaces enabling MXenes hydrophilic. Concentrated HF etching is commonly used to synthesize the MXene in the traditional synthesis route, which raises considerable safety and environmental concerns. In this talk, I will report my group's work on the design and fabrication of HF-free synthesized MXene compounds and MXene-based heterostructures coupled with multiple nanomaterials. We report on a strategy for synthesizing crystal phase-controlled 1 T or 1 T'-MoX_2 (X=S, Se) layers on the synthesized MXene with controlled deposition method. Through our developed HF free-etching and annealing processes, the MXene develops surface point vacancies, allowing the formation of stable metallic 2D materials-based vdW heterostructures. The synthesized MXenes-heterostructures show an exceptionally enhanced capability of hydrogen evolution reaction. Since MXenes are very attractive in sustainable energy applications, including hydrogen/oxygen production and flexible battery, the utilization of the HF-free and facile synthesized MXene for electrocatalyst reaction and flexible devices is beneficial to the environment protection and healthcare. The works are supported by the RGC Grant (PolyU 15303123), and PolyU Projects of RCNN and PRI (1-CE0H and 1-CD6X).

D15. 微纳能源材料与器件-02

基于两相流驱动的摩擦纳米发电设计与应用

王道爱*[1]

1. 中国科学院兰州化学物理研究所

摩擦纳米发电技术（TENG）在能源收集与自供电传感等领域已经展现出广阔的应用前景，但其摩擦电输出较低依然是目前限制其实际应用的关键因素。本报告通过设计两相流驱动的策略，以解决摩擦副在摩擦起电过程中接触分离速度小、接触面积小以及持续接触时间长等问题，实现固-液、固-固 TENG 的高效大功率输出。利用流体的流变学特性和类似文丘里管的结构设计，开发了一种新型的超高功率气-液两相流摩擦发电机，并结合固-液摩擦起电和击穿放电效应，实现了 3789 V 和 867 μA 的超高电压和电流输出，其单位体积输出电荷密度高达 859 mC/m^3，实现了 S-L TENGs 输出性能的新纪录。在试验条件下，从 SEG 喷出的 1.0 mL 液体，可以轻松点亮 1500 个商用 LEDs 灯和一盏 24 W 的商用灯。同时，设计了气-固两相流驱动的 TENG，结合固-固摩擦起电与聚合物表面的尖端放电效应实现较大功率输出，短路电流和输出电压分别可达到 850 μA 和 3500 V。

D15. 微纳能源材料与器件-03

High-Performance Triboelectric Nanogenerator and Tribophotonics

訾云龙*[1]

1. 香港科技大学（广州）

As the development of the Internet of Things (IoT), trillions of widely-distributed devices are integrated for health monitoring, biomedical sensing, environmental protection, infrastructure monitoring, and security, which

require power supplies. To provide a sustainable power solution toward the battery-free IoT, triboelectric nanogenerator (TENG) has been developed since 2012 for high-efficiency mechanical energy harvesting from the ambient environment. The PI's team has made significant contributions to fundamental studies about the triboelectric effect, discharge, and TENG output characteristics. and Multiple strategies to greatly enhance the output performance of TENG has been demonstrated, such as the high-pressure environment and the liquid-solid interface. On the other hand, the PI's team also proposed and developed the concept of tribophotonics: tribo-charge induced tuning or generation of photons toward self-powered wireless sensing, which can be achieved through tunable liquid lens, liquid crystal, optical switch, tribo-induced electroluminescence (TIEL), and discharge. These studies will drive the further development of TENG technology for broad applications in blue energy harvesting, the battery-free IoT, human-machine interface, health & infrastructure monitoring, wearable & implantable electronics, towards high-efficiency self-powered systems.

D15. 微纳能源材料与器件-04

柔性电子器件及其能源系统

衣芳*[1]

1. 中山大学

Wearable technology is changing our life and shaping our future. Wearable electronics are expected to own a huge market share in the next decade. The rapid development of wearable/flexible electronics raises challenges of reliable and sustainable wearable/flexible energy sources. Facing these challenges, researchers have made great efforts to develop various wearable energy sources involving wearable energy harvesters, wearable energy storage devices and wearable power systems. In this presentation, our recent studies on wearable/flexible sensors and their power systems will be presented. The challenges, future directions and potential applications will also be discussed.

D15. 微纳能源材料与器件-05

电润湿辅助电荷注入方法及其在能量收集器中的应用

吴昊*[1]

1. 华南理工大学 物理与光电学院

长久以来，电荷俘获现象一直是电润湿领域面临的问题，至今仍未完全解决，严重制约了相关应用的发展。难以消除的俘获电荷影响了外加电场对界面润湿性的控制，从而影响了电润湿器件的性能和可靠性。然而，我们发现经调控后，由电润湿引起的稳定的俘获电荷可以变废为宝，在基于表/界面电荷的能量收集器件中具有重要应用价值。利用该方法不仅可以提高器件的电输出，还增强了器件的可靠性。本报告将介绍我们对电润湿俘获电荷现象的研究，并进一步介绍其在水滴能量收集，以及我们近期研究的晃动能量收集器件中的应用。

D15. 微纳能源材料与器件-06

面向电力装备自供电传感的微纳能源收集技术

李祎*[1]，肖淞 [1]，唐炬 [1]，张晓星 [2]

1. 武汉大学

2. 湖北工业大学

数智化电网的建设依赖于海量分布式电力装备状态监测传感器，提升传感器的供电可靠性进而实现自

供电感知对拓展设备状态感知系统的深度和广度具有重要意义。近年来，以纳米发电机为代表的微纳能源收集方法与器件被广泛关注，其能够将多元、分散的机械能、热能、电磁能等转化为电能，搭配微能量存储元件与低功耗微纳传感器实现自供电传感。本报告围绕面向电力装备自供电传感的微纳能源收集方法这一主题，首先介绍了电力装备及其运行环境微能量的分布特性；其次，总结了以摩擦纳米发电机、压电纳米发电机、热电纳米发电机、磁场能收集发电机等为代表的微纳能源收集方法原理及特点，分析了其在电力装备场景下的适用性；进一步地，综述了基于微纳能源器件的电力装备微能量收集与自供电传感最新研究进展，并提出了本领域目前发展面临的主要技术难点和潜在解决方案。最后，展望了微纳能源收集方法及器件的发展趋势，有望为电力装备自供电状态监测和数智化发展提供参考与指导。

D15. 微纳能源材料与器件-07

微纳米结构有机/无机复合热电材料及其柔性器件

梁丽荣*[1]

1. 深圳大学

热能作为一种广泛存在的可持续能源尚未被有效利用，尤其是一些废热、余热等低品位热，而热电材料正是一种利用材料内部载流子运动实现热能与电能之间直接相互转换的功能材料。为了进一步实现柔性与可穿戴方面的应用，由热电材料组装而成的热电器件还应具有适应外部机械形变的柔性、可拉伸性与可压缩性等。在此，基于导电聚合物及其复合材料薄膜和气凝胶，制备了高性能微纳米结构的 PEDOT:PSS/SWCNT 复合热电薄膜、PEDOT:PSS/Te/SWCNT 三元复合热电薄膜和 PEDOT:PSS/SWCNT 复合热电气凝胶。然后，基于复合热电薄膜，优化器件结构设计，开发了一种高装配密度和可调面内/面外结构的热电器件，以及一种可拉伸、可压缩、可弯曲和可穿戴的三维螺旋形热电器件。基于三维多孔结构和高弹性的复合热电气凝胶，所设计的器件可实现高温传感、智能火灾预警和高温能量收集。

D15. 微纳能源材料与器件-08

Triboelectric junction: a model for dynamic metal-semiconductor contacts

Zhengbao Yang*[1]

1. Hong Kong University of Science and Technology

Harnessing green energy is an effective solution for addressing the energy crisis. Semiconductor materials have played a significant role in advancing green energy, exemplified by the well-established photovoltaic effect and the emerging tribovoltaic effect. Solar cells, renowned for their remarkable commercial success in the energy sector, employ semiconductors to efficiently convert solar energy into electrical energy through the photovoltaic effect. Similarly, dynamic semiconductor generators harvest mechanical energy through the tribovoltaic effect. However, further investigation is needed to understand the underlying mechanism of the tribovoltaic effect. While many studies have explained this effect based on static junction theories like Schottky junction and PN junction, the effect of triboelectric charge at the contact interface calls for further investigation. To address this issue, we have defined a novel “triboelectric junction” model specifically for analyzing dynamic metal–semiconductor contacts. This work provides a fresh perspective on the mechanism of dynamic metal–semiconductor contacts, paving the way for further fundamental discoveries and potential applications.

D15. 微纳能源材料与器件-09

纤维基高灵敏可呼吸电子皮肤的制备及应用

李召岭*[1]
1. 东华大学

随着人工智能的飞速发展，可穿戴智能电子皮肤在日常生活中起着越来越重要的作用。然而，如何制备兼具优异灵敏度、可拉伸性和可呼吸性的智能电子皮肤仍面临一些挑战。纳米纤维材料具有柔软、透气、轻薄等独特优势，能够满足人体热湿舒适性的生理需求，同时根据需求可以对其进行表面修饰和化学改性，是制备高性能电子皮肤的理想材料。在此报告中，我们基于压电和摩擦电效应制备出纳米纤维基智能电子皮肤，在 0-100 kPa 的检测范围内可以实现 0.18 kPa^{-1} 的力学灵敏度，在最高为 50%的拉伸形变条件下可以保持优异的传感稳定性和机械耐久性。纤维基电子皮肤具备良好的适形性，可以对人体运动姿态进行长期的实时检测，对各种物体的形状和轮廓进行高精度的空间映射，同时具备良好的透气和透湿性能，水蒸气透过率可达 10.26 kg m^{-2} d^{-1}。另外，制备的器件具备自供能特点，无需外部电源供电，并能作为电源使用驱动一些小型电子器件正常工作。该研究工作将为纤维基电子皮肤的发展提高新思路，在智能机器人、交互式设备、人工假肢和运动障碍辅助等领域具有重要的应用前景。

D15. 微纳能源材料与器件-10

界面电子转移与自由基生成

姜鹏*[1]
1. 武汉大学

生物学、化学和物理学中的许多重要过程都在界面上发生，而不是在均相溶液中。最近，我们利用液滴与毛细管内壁构建“固-液”界面，证实“固-液”界面接触起电过程中存在电子转移，并且可以引起界面的水分子发生氧化还原反应，生成·OH 等活性氧（ROS）自由基。此外，我们的研究发现，“液-液”界面接触过程中的也存在电子转移并引起的界面氧化还原反应，产生 ROS 自由基。该研究制备了一种全氟化碳（PFC）纳米乳来构建 PFC-H_2O“液-液”界面体系，通过超声振荡过程中空化气泡的产生和破裂，实现 H_2O 与 PFC 纳米乳之间的高频接触/分离，以研究“液-液”接触过程中的电子转移。该研究首次证实在超声引起的高频“液-液”接触/分离过程中，H_2O 分子中的氧原子会失去电子，生成·OH，而 PFC 分子则得到电子形成带负电的 PFC*。另外，水中的 O_2 可以在超声辅助下从带负电的 PFC*获得电子，产生·O_2^-。最后，我们成功将该 ROS 生成机制应用于肿瘤治疗。

D15. 微纳能源材料与器件-11

复合与耦合纳米发电机

杨亚*[1]
1. 北京纳米能源与系统研究所

提出了通过电磁发电和摩擦发电两种不同的原理来实现同一种机械能到电能转换效率提升的普适性方法，被美国、韩国等 20 多个研究小组广泛采用。首次构筑了基于复合纳米发电机的自供电温度传感器，解决了传统温度传感器需要锂离子电池供电导致寿命有限的难题。提出了利用同一种功能材料的多种物理效应来协同发电增强发电性能的新思路，揭示了多物理耦合效应增强发电性能的机制。首次开发了基于多种物理效应耦合一体式的复合纳米发电机，解决了不同类型纳米发电机的集成度低和成本高的难题。提出了通过界面与能带工程调控光伏器件的新策略，揭示了外部温度对光伏器件的调制规律，建立了温度变化诱导的极化电荷调控界面势垒高度提高光伏器件性能的新方法。

D15. 微纳能源材料与器件-12

高性能纳米摩擦发电机的研究与应用

张楚国*[1]
1. 北京交通大学

摩擦电纳米发电机(TENG)具有高灵敏度和高机电转换效率，广泛应用于自供电传感和机械能收集等研究领域，在未来的智能物联网系统中具有巨大的应用潜力。基于 TENG 技术，通过理论计算、物理模拟和材料选择等，研制出多种高输出性能的 TENG 和高灵敏度的摩擦电传感器。此外，根据不同应用场景的要求，通过巧妙的结构设计，构建了各种用于水波能、风能和人体机械能收集的微纳能源装置。最后，结合电源管理和信息传输技术，开发了具有多种应用领域的自供电无线传感器网络节点。

D15. 微纳能源材料与器件-13

面向聋哑人语音识别的柔性贴肤声学传感器

赵继忠*[1]
1. 中国科学院北京纳米能源与系统研究所

随着物联网技术的飞速发展，语音数据的价值越来越为人们所看重。听力缺失的聋人在社交中常面临困难。好在大多数聋人的声带是完好的，因此根据他们的意图和声带振动之间的对应关系建立语音识别系统有助于克服沟通障碍。与此同时，作为新兴的语音采集手段，贴肤式声学传感器（SAS）与传统空气传导麦克风不同，通过直接采集喉部振动信息并将其转换成电信号来完成语音采集，这使得 SAS 具备优异的抗干扰性能并特别适合于一些特殊人群的交流需求。本文围绕高性能 SAS 的传感材料、响应结构和应用场景，设计了一系列新颖的全柔性、高精度、低成本、抗干扰、长寿命的可穿戴 SAS。成功地实现了聋人的语音交流，初步为克服聋人-健全人-物联网之间的交流障碍提供了解决方法，为聋人与健全人和物联网之间的沟通搭建了方便、有效的沟通渠道。同时也研究了 SAS 对复杂声学环境的抗性，开发出对声源发声质量要求低、不受声传播干扰影响的 SAS 作为声学接收端。

D15. 微纳能源材料与器件-14

适用于皮肤上摩擦电感应的超强韧性二维钛纳米材料

杨勇*[1]
1. 香港城市大学

传统的钛材料（例如块体或薄膜材料）以其相对较高的机械强度、优异的耐腐蚀性和卓越的生物相容性而闻名，适用于生物医学工程和可穿戴设备。然而，传统钛材料的强度通常与其韧性相互抵消，并且它们在可穿戴设备中的应用尚未被探索。在本研究中，我们利用聚合物表面屈曲剥离（PSBEE）方法制备了一系列大尺寸二维钛纳米材料（厚度<50 纳米），其具有独特的异质纳米结构，包含纳米级钛、钛氧化物和类 MXene 相。结果显示，这些二维钛材料在室温下表现出卓越的机械强度（6-13 GPa）和显著的延展性（30%-40%），优于迄今报道的所有其他钛基材料，包括块体钛、钛薄膜和单一 MXene。更有趣的是，除了优异的机械性能外，我们还证明通过 PSBEE 制备的二维钛纳米材料在摩擦电感应方面表现出良好性能，并可用于制造具有良好机械可靠性的自供电皮肤上一致性摩擦电感应传感器。

D15. 微纳能源材料与器件-15

纤维素摩擦电材料的构筑及应用

聂双喜*[1]

1. 广西大学

在低碳经济下化工绿色发展趋势的推动下，先进木质纤维功能材料在分布式能量收集与转化、自驱动传感等新兴领域发挥了重要作用。纤维素具备独特的多尺度结构、优异的机械性能和丰富的化学反应位点，可通过化学改性和结构工程实现纤维素摩擦电材料的定制。本研究通过解析木质纤维微组分微结构，明确了多尺度控制纤维素解离、提取与化学功能化的关键要点，阐明了羟基偶极子调控改善纤维素极化性能的机理，拓展了适用于纤维素极化性能调控的品质因数理论；揭示了纤维素润湿性对其极化性能的影响机制，提出了液-固界面传质的强化策略，构筑了仿生的纤维素功能材料。系列基础研究解决了纤维素材料结构与性能关系不明确的关键科学问题，实现了先进纤维素功能材料的定制与应用，为我国造纸行业可持续发展提供了有力的科学支撑。

D15. 微纳能源材料与器件-16

低维 GaN 功能材料与器件

王幸福*[1]，杨玉青 [1]
1. 华南师范大学

作为信息领域的核心技术，半导体光电子技术在光通信、光存储、光传感、光加工等方面有着重要的应用。现有的光电子器件及系统，无论计算机器件还是激光器，依赖的都是二维的半导体接口，这一现状制约着其小型化和集成化的发展。第三代半导体 GaN 材料具有宽的直接带隙，稳定的物理化学性质、优异的发光效率、高饱和电子漂移速度等性能，是研制高效率光源器件、高速晶体管以及高频通信器件等的理想材料。GaN 材料自身优良性质加上低维材料的特性,使低维 GaN 材料在新颖特性探索及功能器件开发方面有着独特的优势。本报告介绍利用图形化外延生长和电化学衬底剥离方法制备低维 GaN 材料，探索其优异的力、电、光学特性，并在此基础上研制了一系列新型低维电学和光电子器件。

D15. 微纳能源材料与器件-17

透明窗口及其光热管理应用

胡彬*[1]
1. 华中科技大学

透明窗口是连接封闭空间和开放室外环境的界面，是能量与信息互动的重要渠道。通过窗口材料的合理设计，对该界面处的光-电-热交换特性进行有效管理，对于提高众多应用场景的能源利用效率具有重要意义，也是高效光电器件、节能建筑、新能源汽车等领域的平台共同需求。报告从材料微观结构对光谱响应的物理机理入手，重点窗口材料及其在能效相关应用中的研究进展。通过提升透明导电窗口材料的电子迁移率，将光谱的高透射区域扩展到近红外波段，从而显著提高太阳光谱的调制与利用效率。通过优化调制中红外热辐射波段窗户材料的发射率，也实现了不同气候下建筑物的制冷/制热能耗的显著降低，为传统窗材料赋予新的属性，服务我国碳中和战略。

D15. 微纳能源材料与器件-18

可穿戴压电传感器——结构设计与 3D 打印

周欣然*[1]
1. 东华大学

在能源危机和为分布式低能耗传感器供电的挑战日益增加的背景下，自供能传感器在基础研究和商业

应用领域受到了越来越多的关注。压电材料因其固有的晶体结构或分子排列形式，可实现稳定的自供能力学传感。然而其工作形式单一且不可拉伸，难以被广泛应用于可穿戴电子领域。3D 打印是一种先进材料加工方法，它可以赋予材料复杂的结构，从而通过应变工程，通过结构的设计改变材料的机械性质。本汇报将介绍结构设计与 3D 打印是如何改变压电传感器的机械性质、创造新的工作模式，从而使之更加适用于可穿戴电子应用的。

具体来讲，针对按压模式压电纳米发电机，可以通过 3D 打印压电与导电墨水的开发，与有限元仿真辅助 T 切线剪纸结构设计，将传统剪纸结构拉伸时垂直于平面的弯曲形变转换为平面内的旋转形变，极大提高了织物传感器在平面上的可拉伸性，并实现了压电-电极材料全 3D 打印压电器件，用作自供能步态分析传感。针对弯曲模式压电纳米发电机，可利用拉胀弯曲同步变形原理，设计基于拉胀结构的双层图案-基底错配器件结构，以实现弯曲形变中局部垂直方向应力向沿平面方向应力的转化。结合对拉胀结构尺寸对器件应力的影响的研究，突破了压电器件中结构设计引发的压电模式转变与应变的精确控制难题，将弯曲模式压电信号提升 8.3 倍，应用于自供能人体运动监测与软体机器人主动感知。

D15. 微纳能源材料与器件-19

High-performance Coaxial Reversal Rotational Triboelectric Nanogenerator Based on Charge Pumping Strategy Driving Tip High Voltage Breakdown

Congcong Hao*[1], Zekun Wang[1]

1. North University of China

Triboelectric nanogenerator (TENG) is an effective approach for harvesting mechanical energy from the surrounding environment. However, insufficient charge density and wear of friction surface materials greatly limits its practical application. Here, a high-performance self-supplementing coaxial inverse triboelectric nanogenerator (HSCI-TENG) based on charge pump supplementary strategy is presented, which operates in non-contact mode and increases surface charge density with almost no friction loss. The design of coaxial reversal achieves double speed rotation, which greatly improves the output current. In addition, four layers of 0.06 mm thick PET film were innovatively attached to the storage electrode to increase the threshold of electrode charge storage and thus effectively prevent electrode breakdown. At a rotation speed of 300 rpm, the peak-to-peak voltage, peak-to-peak current, and charge transfer of HSCI-TENG are 3340 V, 360 μA and 0.97 μC, respectively. Excellent stability is demonstrated through 10000 cycle tests on the output of HSCI-TENG. In particular, the maximum output power is 770 mW at a load resistance of 8×106 Ω. The high-performance HSCI-TENG has been proven to be a stable energy source driving high voltage breakdown sensor system. The tip high voltage breakdown exhibits high frequency and continuity, with 14 breakdowns occurring within 10 seconds. Besides, HSCI-TENG has potential to serve as an energy source for high-pressure sterilization, high-pressure dust removal, and water electrolysis systems.

D15. 微纳能源材料与器件-20

二维 Bi_2O_2Se 压电纳米发电机与深度学习技术相结合用于部分心血管疾病诊断

孙远虎[1]，毛俊淇[1]，张远征*[1]，崔大祥*[2]，郑海务*[1]

1. 河南大学物理与电子学院

2. 河南大学医学院

压电纳米发电机（PENG）作为新兴的高熵能源捕获器件，其原理是利用外部机械刺激诱导的压电势驱动电路中电荷定向流动，因此具备将人体体表微弱机械能转化为电能的能力，在制备监测人体生理信号的可穿戴器件方面具有独特优势。而 2D 压电材料为设计基于 PENG 的高灵敏度可穿戴生理信号监测器件提供了新的机遇与挑战。本工作通过化学气相沉积（CVD）生长质量优良的 2D Bi_2O_2Se 压电材料，利用压

电响应力显微镜测试了其压电系数 d_{33}=4 pm/V。基于 Bi_2O_2Se 制备的 PENG 在 0.6%应变下的开路电压（VOC）可达 40 mV，器件的灵敏度为 7.989 V/kPa，噪比为 26.6 dB，响应时间为 40 ms，可捕获人体桡动脉处脉搏信号的三个特征峰。通过获取脉搏信号特征参数，如脉搏波速度、僵硬指数和特征 K 值等，可以初步分析人体健康状态。结合深度学习技术对脉搏信号进行分析，可以对常见的 9 种心血管疾病进行诊断，准确率达到 93.75%。这项工作不仅为制备高性能 2D PENG 提供理论指导和实验借鉴，也为发展基于自供电技术的智能医疗器件提供新思路。

D15. 微纳能源材料与器件-21

Theoretical models of triboelectric and tribovoltaic nanogenerators

Jiajia Shao*[1,2]

1. Beijing Institute of Nanoenergy and Nanosystems, CAS

2. University of Chinese Academy of Sciences

Triboelectric nanogenerators (TENGs), using Maxwell's displacement current as the driving force, can effectively convert mechanical energy into electricity. Accurate modeling of a TENG is an indispensable part for revealing the relationships and interactions among physical quantities from different areas. Till now, several theoretical models have been built including the capacitive model, Norton's equivalent circuit model, and mathematical and physical model, which are aimed to improve the overall output and energy conversion efficiency through optimizing the structural design and modifying materials. Importantly, a dynamic field-circuit coupling model and electromechanical coupling model are also built that allows us to elucidate the nature of force, instantaneous power and energy flow during the energy conversion process based on TENGs. In addition, converting mechanical energy into direct-current electric power based on the tribovoltaic effect is a typical characteristic of tribovoltaic nanogenerators (TVNGs). In this talk, we will make a brief description about the theoretical model and physical basis of triboelectric and tribovoltaic nanogenerator.

D15. 微纳能源材料与器件-22

Self-powered agricultural product preservation and wireless monitoring based on dual-functional triboelectric nanogenerator

Jianjun Luo*[1]

1. Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

The global annual vegetable and fruit waste accounts for more than one-fifth of food waste mainly due to deterioration. In addition, agricultural product spoilage can produce foodborne illnesses and threaten public health. Eco-friendly preservation technologies for extending the shelf-life of agricultural products are of great significance to socio-economic development. Here, we report a dual-functional TENG (DF-TENG) that can simultaneously prolong the storage period of vegetables and realize wireless storage condition monitoring by harvesting the rotation energy. Under the illumination of the self-powered high-voltage electric field, the deterioration of vegetables can be effectively slowed down. It can not only decrease the respiration rate and weight loss of pakchoi, but also increase the chlorophyll levels (~33.1%) and superoxide dismutase activity (~11.1%) after preservation for 4 days. Meanwhile, by harvesting the rotation energy, the DF-TENG can be used to drive wireless sensors for monitoring the storage conditions and location information of vegetables during transportation in real time. This work provides a new direction for self-powered systems in cost-effective and eco-friendly agricultural product preservation, which may have far-reaching significance to the construction of sustainable society for reducing food waste.

D15. 微纳能源材料与器件-23

二維互斥顆粒系統在非平坦外勢影響下的相分離過程研究

何明恺*[1]

1. 北京纳米能源与系统研究所

在經典的相分離理論中，某個多組分單相均匀混合物分離為多相共存狀態的過程，通常被認爲是其獨立系統内部自由能降低導致的。這種行爲尤其會在某均匀體系的溫度降低到某臨界溫度時發生，而且會伴隨著許多隨機分佈的新生相。然而，在實際情況下，系統不可避免地與外部場相互作用。當外部效應足夠顯著時，基於自由能變化的經典理論便無法很好地解釋相關相分離行為。本論文聚焦於通過向二维互斥顆粒系統引入外勢，进而引發了一種新型相分離行為。外場的添加被認爲向原本的自由能表達式中添加了與空間分佈相關的項，從而改寫了其表達式，並製造了一種具有全新的具有特定空間分佈規律的相分離行爲。通過一系列實驗和計算研究，我們發現，在一些最初處於平衡狀態的均匀混合系統中，引入外部勢不僅可以引發相分離，還可以決定這些分離區域的空間分布。同樣對一些初態并不穩定的系統也同樣存在類似的空間分佈。另外，值得注意的是該系統的相分離過程同時伴隨著從類液態的非定形結構，到类 HCP 晶體結構的變過程。接著，爲了更進一步的理解這一現象的本質，我們引入了“等效密度”。它被證明是決定系統分離傾向的關鍵參量。同時我們也提到了“内”、“外”勢能降低分別代表著經典自發相分離，和定向相分離的驅動力。最後，我們的工作對定向的相分離動力學提供了一種新的闡述，對以往的理論框架加以了補充，并且拓展了該理論潛在的應用價值。

D15. 微纳能源材料与器件-24

Methods for correctly characterizing the output performance of nanogenerators

Jie An*[1]

1. Tsinghua university

Nanogenerators (NGs) based on triboelectric effect, piezoelectric effect, and pyroelectric effect have rapidly developed in applications of energy harvesting and self-powered sensing. However, a standard output performance characterization system for NG devices is still lacking, which greatly reduces the reference and inheritance of scientific research results, and hinders the development of NG technology. Owing to the mismatch of impedance between the instrument and NG devices, commercial instruments have serious measurement error of up to 77.3%, which causes some experimental phenomena violating the theories. In this work, the influencing factors of measurement error from traditional measurement methods are systematically analyzed through Multiphysics simulations and comparison experiments. Some methods to improve the accuracy are proposed, and a multi-functional and high-precision instrument is designed to improve the measurement accuracy from 22.7% to 64.7%. This discovery points out the shortcomings of the current characterization methods of NG performance, which has important guiding meaning for the development of measurement technology and theoretical research of NGs.

D15. 微纳能源材料与器件-25

梯度诱导湿气发电装置的构筑和应用研究

张学忠*[1]

1. 西南石油大学

利用湿气与活性材料相互作用产生电能的湿气发电装置是绿色能源前沿研究热点。目前，由于设备内部载流子扩散效率不佳，限制了输出功率和稳定性的提升。梯度结构诱导已被证明是提升碳气凝胶湿气发电性能的有效策略，但至今梯度结构的构建方法及其作用机理尚未完全明晰。为此，梯度结构的引入被认

为是优化碳气凝胶湿气发电性能的有效策略。然而，梯度结构的构建方法和作用机理仍需深入研究和阐明。本研究利用芳纶纳米纤维、聚乙烯醇、氧化石墨烯、单壁碳纳米管以及介孔碳等材料，通过梯度结构设计，成功开发了一系列高性能的湿气发电装置。研究表明，梯度结构的出现显著增强了载流子的扩散效率，实现了湿气发电装置的持续高效输出。

D15. 微纳能源材料与器件-26

摩擦纳米发电在海洋蓝色能源的开发应用

洪占勇*[1]

1. 中国科学院北京纳米能源与系统研究所

利用海洋波浪能和洋流能发电，不会消耗燃料与资源，也不会产生污染，合理开发利用波浪能具有重大的实用价值。然而现有波浪能发电装置大多存在转换效率低、成本高昂等缺点，传统的波浪能发电装置多是采用电磁感应发电机发电，但是由于波浪频率低、峰值具有随机性，且发电装置的成本较高，在大规模收集海洋波浪能存在诸多挑战。英国、爱尔兰、美国、加拿大等开发的波浪能发电装置存在启动流速大、造价昂贵、装机容量小、转换效率低、安装布点难等特点，实现大功率商业化发电困难重重。

摩擦纳米发电机（Triboelectric nanogenerator，TENG）是中科院北京纳米能源与系统研究所王中林院士团队 2012 年在国际上率先提出，利用摩擦起电和静电感应效应的耦合把微小的机械能转换为电能的新型技术。相比于传统的基于电磁发电机的技术，该技术在低频下具有显著优势（海洋的波浪频率主要为 0.3-0.7 Hz 的低频频率，纳米发电机在 5 Hz 以下转化效率高于传统电磁发电机），为捕获海洋无序、低频能量提供了一条颠覆性的技术路径。摩擦纳米发电对比风力发电和光伏发电是原创性技术，是基于位移电流将海洋波浪能转换为电能。该技术在海洋开发、海洋环境供电和水面水下监测等领域具有重大的产业应用价值，对提升我国智慧海洋和智慧海上交通管理具有重要作用，具有明显的社会和经济效益。摩擦纳米发电技术可以兼顾收集水面及水下不同深度的波浪能，具有采集设备质轻、结构简单的特点，且受昼夜和天气变化影响较小，是全天候、分布式利用海洋波浪能的新途径。摩擦纳米发电结合光伏发电和风力发电，在海上选取合适的区域建立风光纳立体发电场，充分利用海洋资源和海洋空间具有重要意义。

摩擦纳米发电对海洋波浪能收集转换，主要完成了摩擦纳米发电机集群化设计、微小分布式能源存储技术、多向取能发电浮子制造技术、恶劣工况自驱动自传感技术等难点问题，已成功开发出振球式/扑翼式发电浮子、捕风式发电浮子，相比传统电磁感应发电机发电，可以高效收集各个方向波浪能，将波浪能有效转换成电能。具有装机容量大、制造成本低，多流向取力、模块化组合等显著技术优势，同时具有可在海水任意深度悬浮、受天气和船只等外界干扰低、运行安全可靠等特点。目前研制开发的波浪能摩擦纳米发电机峰值输出功率达到 100 W/m^3，平均功率可达 10-20 W/m^3。摩擦纳米发电作为新兴能源技术，进一步发展潜力巨大，可以在海洋蓝色能源开发上发挥重要作用。

D15. 微纳能源材料与器件-27

基于摩擦纳米发电机的可拉伸自驱动传感阵列

刘瑞远*[1]

1. 苏州大学

大面积可拉伸传感器网络是实现软体机器人、触觉仿生等应用中精确触觉传感的重要保障，基于摩擦纳米发电机的自供电触觉传感器是其中的最佳方案之一。在本次报告中将介绍基于介电功能聚合物的可拉伸摩擦纳米发电机的器件制备及其阵列化，涉及材料开发、器件设计、信号屏蔽和应用探索。

D15. 微纳能源材料与器件-28

兔毛基摩擦纳米发电机用于蓝色能源收集研究

蒋涛[1]，王中林*[1]
1. 中国科学院北京纳米能源与系统研究所

海洋中蕴含着丰富而清洁的可再生蓝色能源，包括波浪能、潮汐能等。海洋能源若实现大规模商业化利用，将极大缓解人类的能源需求，降低二氧化碳排放，带来能源格局的巨大变化。目前波浪能收集与转化主要依赖于电磁发电机，其对于直接转化低频、无序波浪能量的效率很低，而摩擦纳米发电机恰恰在低频、高熵能量收集上具有显著优势，提供了波浪能高效开发利用的一种颠覆性技术路径。当前国内外已完成波浪能摩擦纳米发电的原理验证，然而，在波浪能摩擦纳米发电器件输出性能、能量转化效率、耐久性提升等方面还需要持续的探索。

于此，我们基于柔性兔毛材料制备了高耐久性的摩擦纳米发电机用于海洋蓝色能源的收集，该兔毛材料可显著降低发电机在运动过程中的摩擦阻力，达到器件耐久性和能量转化效率提升的目的。代表性的研究进展如下：

利用自然易得的动物毛皮作为摩擦电材料开发了一种超耐久、低磨损、耐潮湿的发电机，利用兔毛刷的发电机在低力矩下电学输出有 10 倍的提高，0.1 N·m 时 30 万循环后电荷只有 5.6%的衰减，且相对湿度增加到 90%时也能保持较高的输出性能。该工作提供了一种在保证发电机高性能的前提下减少磨损的策略。并且，制备了基于兔毛刷的连杆机构发电机，该结构可充分利用水波的驱动力，从水波中获取更多的能量，且具有很好的耐久性。同时，构建了兔毛刷结构的钟摆发电机，通过摆动组件的栅格结构优化，提出了发电机及其阵列的性能优化方案。进一步地，结合兔毛刷和介电刷结构，提出了一种双重电荷补偿策略，刷新了低磨损工作模式 TENG 的表面电荷密度以及功率密度的记录，且器件连续运行 396 万次循环后性能衰减在 5%以内。在集成能量管理模块后，该发电机可为 3×7 的温湿度计阵列及大功率车载雷达、加速度计模块供电，显示了其稳定且强大的电负载能力。这几种发电机都采用基于毛刷结构的软接触工作模式，为提高 TENG 的功率输出和耐久性提供一种便捷的途径，推动了此类型发电机的实际应用。

D15. 微纳能源材料与器件-29

聚离子凝胶基柔性能量采集及自供电传感

王凌云*[1]
1. 山东大学

聚离子凝胶由于其优异的光学性能、离子导电性、柔性/可拉伸性等特性，可以赋予离子凝胶基可穿戴器件更多的功能性，在能量采集、软机器人、柔性传感、发光显示、生物电子等领域展现了广阔的应用前景。本报告将介绍如何有效调控聚离子凝胶体系的光学性能、离子电导率、介电性能、界面相互作用及给电子能力等，来设计制备离子凝胶基柔性可穿戴器件并展示其在柔性能量（生物力学能、雨滴能）采集、柔性自供电触觉传感及多功能可穿戴器件等方面的应用。

D15. 微纳能源材料与器件-30

生物质基柔性摩擦纳米发电机用于人机交互

马金铭*[1]
1. 燕山大学环境与化学工程学院

柔性摩擦电纳米发电机（TENG）作为一种柔性、便携、可穿戴的器件，在微纳能源和自驱动传感方面具有广阔的应用前景，为可穿戴电子和人机交互提供了新的可能。以天然生物质材料构筑的柔性 TENG 在可穿戴电子领域中拥有巨大优势，这归因于天然生物质材料与生俱来的生物相容性能够缓解长时间佩戴电子设备带来的不适，以及可降解性能够有效减少电子垃圾。在此，我们以蚕丝、鱼鳔、肠衣膜等一系列天

然生物质材料构筑了生物质基 TENGs，用于收集人体运动机械能和实现多模态自驱动传感。得益于生物质膜材料的优化设计，作为摩擦层不仅具有良好的摩擦电性能还展现了优异的机械性能。通过对多个柔性 TENG 输出电信号的收集及处理，开发了基于摩擦电传感的人机交互系统，可实现智能识别、非接触式位移定位等功能。该项工作展示了自驱动摩擦电传感器在人机交互领域的应用价值，为设计柔性可穿戴电子器件提供了一种选择。

D15. 微纳能源材料与器件-31

面向自驱动固氮应用的气体动力摩擦纳米发电机器件探索

韩凯*[1]

1. 香港城市大学

以工业合成氨为代表的人工固氮技术，在化肥等产品的制造中发挥着重要作用。然而，传统合成氨方法需要的高温高压等条件，加剧了能源和环境问题。作为当今的能源技术新宠，摩擦纳米发电机，由于它的高电压输出特性，很容易获得强电场来实现对氮气的固定。基于此，作者设计了两种以气体作为动力源的器件，有叶涡轮双摩擦纳米发电机和无叶特斯拉涡轮摩擦纳米发电机，并结合相应的放电和催化装置，以自驱动方式分别实现了常温常压下空气放电催化固氮和氮气直接放电固氮合成氨。上述器件的探索，对于自驱动固氮应用的发展具有重要的参考意义。

D15. 微纳能源材料与器件-32

Hybrid self-power sensor for ocean wave data collection: Design, Fabrication, and Evaluation

Yunzhong Wang[1], Youhong Tang*[1]

1. Flinders University

With the increment of demand of the fishing industry, high-tech products are being utilized to increase production capability. Information technologies such as big data and AI are making agriculture more efficiency smarter. However, to realize the benefits of these information technologies, massive sensors need to be employed to collect data, which will increase costs significantly. To address this challenge, a hybrid self-power ocean wave sensor has been proposed. It involves a contact-separation mode electromagnetic generator (CS-EMG) and a flexible triboelectric nanogenerator (F-TENG). The CS-EMG consists of a circular-shaped copper coil wounding and a spherical magnet, which serves as a magnetic flux donator. The CS-EMG generates electrical energy through the reciprocal movement between the spherical magnet and the copper winding. This movement produces kinetic energy due to the impact between the magnet and the copper winding. The F-TENG is positioned behind the copper coil to convert vibration energy caused by the CS-EMG generating cycle into electrical energy. The F-TENG includes a PVA-based hydrogel with varying weight ratios of reduced graphene oxide (rGO), silicon rubber and a copper piece serving as two triboelectric materials and the electrode, respectively. Results show the CS-EMG can generate energy at a frequency of only 1.5 Hz and can produce a maximum of 5.2 V at a frequency of 4 Hz and amplitude of 8.6 cm. The F-TENG can also generate 1.4 V at a frequency of 3.0 Hz and amplitude of 8.6 cm as well as producing a 2 W/m^2 output power density. The F-TENG demonstrates feasibility as a sensor for detecting changes in wave amplitude when tested in a water channel system with controllable and repeatably generated waves. The power management system, in cooperation with the CS-EMG, enables the lighting of an LED, even under a 1.5 Hz wave frequency, which demonstrates the hybrid low-frequency energy harvester is capable of sustainable self-power for wave sensing. Hybrid self-power ocean wave sensor show the potential as a cost-effective solution for ocean data collection.

D15. 微纳能源材料与器件-33

Passive Internet of Events Enabled by Broadly Compatible Self-Powered Visualized Platform Toward Real-Time Surveillance

Chaojie Chen[1], Yunlong Zi*[1,2]

1. The chinese university of hong kong

2. The Hong Kong University of Science and Technology (Guang Zhou)

Surveillance is an intricate challenge worldwide especially in those complicated environments such as nuclear plants, banks, crowded areas, barns, etc. Deploying self-powered wireless sensor nodes can increase the system's event detection capabilities by collecting environmental changes, while the incompatibility among components (energy harvesters, sensors, and wireless modules) limits their application. Here, a broadly compatible self-powered visualized platform (SPVP) is reported to construct a passive internet of events (IoE) network for surveillance systems. By encoding electric signals into reference and working LEDs, SPVP can visualize resistance change generated by commercial resistive sensors with a broad working range (<107 Ω) and the transmission distance is up to 30 meters. Visible light signals are captured by surveillance cameras and processed by the cloud to achieve real-time event monitoring and identification, which forms the passive IoE network. It is demonstrated that the passive-IoE-based surveillance system can detect intrusion, theft, fire alarm, and distress signals quickly (30 ms) for 106 cycles. Moreover, the confidential information can be encrypted by SPVPs and accessed through a phone application. This universal scheme may have huge potential for the construction of safe and smart cities.

D15. 微纳能源材料与器件-34

基于 SWCNT/MXene 的新型热电智能火灾预警系统

丁招福 [1]，梁丽荣 [1]，陈光明*[1]

1. 深圳大学

近年来，全球火灾呈现多发的趋势，开发可靠的火灾检测设备对于生命财产、生态环境具有重要意义。热电（TE）材料能够直接进行热能与电能的转换，凭借其自供能特性、良好的重复性以及输出性能与温差之间良好的线性关系，基于热电材料的火灾预警系统正逐渐受到越来越多的关注。本文提出了一种智能自供电热电火灾预警系统，该系统采用了单壁碳纳米管/碳化钛（SWCNT/MXene）的 p 和 n 型复合热电薄膜。通过简单的溶液分散制备的柔性薄膜表现出优异的高温稳定性、阻燃性和 TE（功率因子为 239.7 ± 15.8 μW m^{-1} K^{-2}）性能。组装的 TE 器件（TED）具有可调报警阈值电压（1-10 mV）的快速火灾报警能力。值得一提的是，在 1 mV 的阈值电压下，实现了约 0.1 s 的超快火灾报警行为。此外，该热电火灾警报系统在 50 次重复测试后仍表现出优异的稳定性，即使在暴露于空气 180 天的情况下也满足实际应用所需的稳定性。最后，将该热电器件与无线电子设备耦合，开发了基于 TED 的无线智能火灾报警系统。

D15. 微纳能源材料与器件-35

面向水下能量收集的高性能纳米发电机

Liang Xu*[1]

1. Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

Ocean energy, as a promising clean energy source, has enormous reserves globally, the exploitation of which may contribute greatly to the carbon neutrality and provide a reliable in-situ power source for various instruments in ocean. Compared with the energy harvesting on water surface, the utilization of energy underwater is more challenging yet meaningful to many application scenarios, such as underwater robots, marine observation systems

etc. Here, we will demonstrate a series of our recent studies on developing high-performance nanogenerators for underwater mechanical energy harvesting.

Firstly, a new mechanism by introducing an oil phase into a water–solid interface is demonstrated for energy harvesting based on electric double layer (EDL) capacitance. Through squeezing and releasing oil droplets on a dielectric surface in water environment, charge transfer is observed in the back electrode accompanying the movement of the oil–water–solid three-phase line. The charge transfer is mainly attributed to the effect that the oil phase sweeps away ions near the dielectric surface in the EDL due to the discrepancy of EDL between water–solid and oil–solid interfaces. Under the water environment, the device is shown to be capable of direct energy harvesting and self-powered sensing without costly packaging. As a new working mode relying on EDL, it allows developing nanogenerators adaptive to severe environments underwater with low friction and wear, and narrowing the gap between energy harvesting devices and electro-chemical devices. Through further enhanced EDL, it is reasonable to anticipate devices with an ultrahigh charge density comparable with EDL super capacitors, opening up an avenue toward new nanogenerators with overwhelming performance for practical applications ranging from ocean blue energy harvesting to electro-catalysis.

For effectively harvesting water current energy, we designed high-performance paired triboelectric nanogenerators (P-TENGs) capable of integrating massively into a thin flexible layer as a structured triboelectric surface (STS). Novel gas packet exchange structure and rigid–flexible coupling deformation mechanism are introduced to ensure that the device can work very effectively even in deepwater under high water pressure. The rationally designed TENG array in the STS enables highly efficient power take-off from the flow. Typically, the STS demonstrates a high-frequency output up to 57 Hz, largely superior to current TENG devices, and the power density is improved by over 100 times for triboelectric devices harvesting current energy. The flexible STS is capable of attaching to various surfaces or applying independently for self-powered sensing and underwater power supply, showing great potential for water-current energy utilization. Moreover, the work also initiates universal strategies to fabricate high-frequency devices under large environment pressure, which may profoundly enrich the design of TENGs.

For wave energy harvesting extending underwater, a novel three-dimensional (3D) chiral network of triboelectric nanogenerators (TENGs) is designed. Unlike traditional bulky and rigid machines, the 3D TENG network adopts a distributed architecture with chiral connections between unbalanced units, which imparts the network flexibility, hyper-elasticity in water, and wave-absorption behavior, similar to mechanical chiral metamaterials. The network can be configured to different scales and depths to harvest wave energy in all directions. A comprehensive energy harvesting system integrated with a power management circuit is constructed, with the stored energy enhanced by about 319 times. The novel 3D chiral network shows great potential for blue energy harvesting and self-powered systems based on TENGs, which can be more adaptive to severe ocean environments with flexible and distributed characteristics. This study also presents an insightful paradigm shift from mechanical metamaterial designs to energy harvesting networks, with similarities in mechanical wave energy absorption and conversion, inspiring novel energy harvesting systems and other strongly coupled machinery systems of multiple units based on metamaterials.

D15. 微纳能源材料与器件-36

面向海洋工程装备监测的液固摩擦电传感器研究进展

杜恒旭[1]，席子岳[1]，杨焱[1]，司济仓[1]，徐敏义*[1]

1. 大连海事大学

海洋工程设备的工作环境复杂多变，强烈的海浪和腐蚀等严苛条件给海工设备的监测和维护带来了极大的不便。面对海上设备多而维护人员少的问题，亟需开发多种适合部署且稳定可靠的海工装备监测方式。

传感器的创新设计和应用在提升海洋设备和系统的自动化和可靠性方面具有关键作用。本文从海洋工程领域的监测需求出发，介绍了液固摩擦电传感技术在海洋工程领域的代表性应用示例。液固摩擦电传感器通过液体与固体介电材料之间的摩擦起电效应与静电感应的耦合过程产生灵敏的电信号，实现液体状态的实时感知。具体包括吃水、倾角、波浪检测、设备管道漏水监测、微通道流体运动状态感知等创新传感器设计。液得益于固摩擦电传感器没有运动部件的结构特性，其耐久性与免维护性在海工领域上的优势尤为显著。无源且高灵敏度的信号极大地拓展了液固摩擦电传感器在实际场景中的应用范围。为海上作业及船舶的自动化监测和状态分析提供了坚实可靠的技术支持。

D15. 微纳能源材料与器件-37

高性能海藻多糖基摩擦纳米发电机的构建及应用

逄尧堃*[1]

1. 青岛大学

摩擦电纳米发电机(TENG)作为一种绿色能源收集技术，可以从周围环境和生物中获取能量。利用天然生物材料构建摩擦电纳米发电机对可持续自供电装置的发展具有重要意义。海藻酸钠(SA)是一种具有优异透明性、可再生性、可降解性的海洋生物质材料，在摩擦纳米发电机领域具有独特的优势及应用前景。在这项工作中，我们通过添加环境友好型增塑剂，有效提高 SA 薄膜的力学性能和粘附性，制备了具有优异透光性、柔韧性、降解性和抗菌性的自供电人机交互界面；通过化学接枝改性和金属离子络合的协同作用，制备具有超高电荷密度（205 μC m^{-2}）的生物质正摩擦材料，并构建了一种旋转式摩擦纳米发电机用于收集风能，应用于智慧农业；采用氨基改性 MXene，辅以二氧化钛纳米颗粒，制备具有高输出性能的 SA 基摩擦纳米发电机，并探究其在海洋能收集和金属防腐蚀方面的应用。

D15. 微纳能源材料与器件-38

基于双螺旋折纸弹簧结构的高性能海洋能量收集

姜阳*[1]

1. 北京纳米能源与系统研究所

With the rapid evolution of emerging technologies like artificial intelligence, the Internet of Things (IoT), big data, robotics, and novel materials, the landscape of global ocean science and technology is undergoing significant transformation. Ocean wave energy stands out as one of the most promising clean and renewable energy sources among these advancements. Triboelectric Nanogenerators (TENGs) represent a cutting-edge technology for harnessing this 'random' and ultra-low frequency energy, positioning them as a promising method for blue energy collection. A high-performance triboelectric nanogenerator (TENG) incorporates a novel double spiral spring origami structure engineered to augment continuous sensing and signal transmission in marine environments. Integrating the double spiral spring origami into the TENG system enabling efficient energy harvesting from the ocean's low-frequency, irregular wave motions by converting low-frequency water wave vibrations into high-frequency motions. Under water of 0.8 Hz, the TENG generates maximum peak power density of 55.4 W/m^{-3}.This charge excitation TENG array effectively powered a wireless digital thermometer and signal transmission without an external power supply. The findings of this research contribute to the development of sustainable and renewable energy technologies for oceanic applications and open new pathways for the design of advanced materials and structures in the field of energy harvesting.

D15. 微纳能源材料与器件-39

UV 光波长和强度对水滴-聚合物表面接触带电特性影响

崔楚婷[1]，蔡容容*[1]
1. 华南理工大学化学与化工学院

液-固摩擦纳米发电机（L-S TENG）是新兴的从液体中收集微小机械能的技术，液固界面接触带电（CE）的饱和电荷密度是判断其性能的关键指标。紫外（UV）光的照射能够提高 L-S CE 的饱和电荷密度，在本研究中选取 PTFE、FEP 作为 L-S TENG 中的固体材料，分别对其进行 UV 光照射和无光照处理，通过改变 UV 光的波长及光强进行一系列的实验，探究 UV 光的波长及光强对于 L-S TENG 饱和电荷密度的影响。实验结果表明能够使水滴-PTFE TENG 以及水滴-FEP TENG 饱和电荷密度增大的 UV 光波长范围分别是 275~405 nm 以及 310~405 nm。对于水滴-PTFE，光强增大促进作用增加；对于水滴-FEP，光强减小促进作用增加。我们提出在 UV 光照射水滴-聚合物界面时可能存在以下三个过程：水分子上的电子激发被聚合物表面捕获的电荷积累过程（accumulation）、聚合物表面已捕获的电子被激发离开表面的电荷耗散过程（dissipation）以及聚合物材料本身的电子吸收光子能量被激发而脱离材料的电荷逃逸过程（escape）。同时提出光激发电子转移模型来解释 UV 光波长及光强的改变对 L-S CE 饱和电荷密度的影响。这为进一步优化 L-S TENG 的性能提供了方案。

D15. 微纳能源材料与器件-40

基于摩擦电效应的双模态触觉系统用于材料类型和变形性识别

何少帅[1]，訾云龙*[1]
1. 广州市香港科大霍英东研究院

信息时代下，具有各种功能的传感器发挥重要作用，其中人工触觉传感器可以转换多种环境信息。迄今为止，已经开发出几种人工触觉传感器来测量压力和距离信号。然而，感知物体的材料类型和可变形性仍然具有挑战性。我们受昆虫触角上钟状感觉器的启发，提出了一种基于摩擦电效应的半球形结构的双模智能触觉传感器阵列。该传感器具有软硬度识别、模量量化、材料类型识别等功能。由于不同材料的变形能力不同，摩擦电传感器在不同压力下接触被测物体时会产生独特的摩擦电输出特征。此外，摩擦电传感器阵列还能根据不同的电子亲和力准确识别材料类型，以辅助材料可变形性和弹性模量的识别。该摩擦电效应双模智能触觉传感器有望实现微型化，为人机界面提供实时准确的触觉信息。

D15. 微纳能源材料与器件-41

Dual-mode triboelectric nanogenerator-silicon tandem solar cells towards simultaneously harvesting rain and solar energy

Yuting Xie[1], Jingqiao Zheng[1], Huiyuan Huang[1], Xiya Yang*[1]
1. Jinan University

Rapid economic growth has exacerbated energy demand and resource depletion, prompting a shift towards renewable energy sources such as solar and wind energy. However, the intermittency and power attenuation under weak light or rainy condition of solar cells underscore the necessity for hybrid energy harvesting to extend its power generation. Herein, we develop a dual-mode triboelectric nanogenerator-silicon tandem solar cell (D-TENG / Si TSC) featuring the combination of single-electrode and contact-separation mode TENG that endows the maximum energy conversion of droplet kinetic energy. This design yields an open-circuit voltage of 107.8 V and power density of stimulated by one single droplet. Subsequently, the impact of light intensity on output performances of the D-TENG / Si TSC is systematically investigated, demonstrating the tandem solar cell could break through the bottleneck of low power conversion efficiency (PCE) of individual Si SC under rainy condition. A PCE of 21.71%

can be achieved by the D-TENG / Si TSC, demonstrating a 10.65% enhancement over the bare Si SC with PCE of 19.62%. This work offers insights into the structure design of the TENG / Si tandem solar cell through dual-mode strategy for maximizing the utilization and conversion of droplet kinetic energy, and effectively extends the power generation of solar cell as well as improves the power output under rainy condition.

D15. 微纳能源材料与器件-42

全纤维柔性驱动器及主动感知

熊佳庆*[1]
1. 东华大学

微型软体机器人在低功耗、高响应和多场景适应方面有独特优势，有望实现狭小复杂空间内的智能操控和信息采集。柔性驱动器是开发软体机器人的关键，其驱动性能、响应速度和稳定性决定软体机器人的运动能力和操控灵活度。当前，受限材料形态和结构设计等因素，各类柔性驱动器往往只能对单一环境刺激产生响应和简单变形，缺乏对环境信息的自主感知和采集能力，严重限制了其应用和微型软体机器人的进一步开发。为此，我们提出驱动-传感一体化策略，通过材料合理设计和驱动器开发，实现稳定、可编程驱动性能，同时提出驱动诱导的自能量传感策略，实现驱动器主动感知能力的一体化集成，可感知例如环境温度、湿度、物体特征等信息。这类器件有望以驱动器或电子皮肤形态直接或间接服务于软体机器人的开发，实现结构简化、功能集成和多场景适用，提交人-机-环境交互。

D15. 微纳能源材料与器件-43

双功能柔性 NdFeB/EC 复合材料基摩擦-电磁复合发电机

赵坤*[1]
1. 兰州理工大学

摩擦电-电磁复合纳米发电机（HNG）具有高输出性能，为实现自供电微电子器件的自驱动提供了一个理想的解决方案。然而，传统 HNG 的复杂结构和电磁单元中笨重的磁铁极大影响了器件的可移动性和便携性，限制了其应用范围。在本研究中，课题组创制了双功能的柔性钕铁硼/乙基纤维素（NdFeB/EC）复合膜，其不但可以作为HNG中摩擦纳米发电机（TENG）的摩擦电材料使用，而且可作为电磁发电机（EMG）的磁铁使用，简化了器件结构并显著降低了器件重量。基于其设计了一种旋转结构收集风能的高性能 HNG。在 15.5 m/s 的风速下运行，当叉指电极间隙为 2 mm 时，HNG 的 TENG 单元可以产生 55 V 和 5.4 μA 的开路电压（Voc）和短路电流（Isc），在外部负载电阻为 10 MΩ 条件下，TENG 的最大输出功率可达 99.2 μW。相应的 EMG 单元可以产生大约 0.16 V 和 59.3 μA 的 V_{oc} 和 I_{sc}，其在 2.3 kΩ 的匹配负载电阻下，输出功率为 2.5 μW。与单个 TENG 或 EMG 单元相比，HNG 表现出更好的充电性能，在 600 s 可将 470 μF 的商业电容器电压从 0 V 充电至 3.4 V，并且储存的能量可以成功为商用土壤温湿度计提供连续工作的动力 75 s，并可点亮 30 个并联的蓝色 LED。这项研究对开发摩擦电-电磁双功能材料提供了参考，对设计高集成度、轻量化的 HNG 具有重要的科学意义。

D15. 微纳能源材料与器件-44

近零功耗唤醒式航空航天智能传感系统

许子颉*[1]
1. 中科院北京纳米能源与系统研究所

针对载人/无人飞行器安全飞行参数监测与飞行效率提升需求，研究多物理场环境下自驱动飞行器表面

流态感知机制，发展面向各类飞行器的轻质原位实时气流流场智能感知技术，寻求实现国际领先的飞行器安全传感技术突破，是我国建设航空航天强国的重要标志。同时，面向传统系统待机状态下能耗较高的问题，研究引入低功耗唤醒技术，实现了系统在待机状态下能耗接近零的特性。通过超低功耗设计，项目各类传感系统在航空航天领域具有重要应用潜力，可提供高效的实时监控和数据采集功能。基于摩擦纳米发电技术的自驱动智能传感系统的成功应用将为航空航天领域的智能传感系统发展带来新的突破和创新。

D15. 微纳能源材料与器件-45

高稳定性自保湿燃料电池阴极催化剂设计

祝伟康*[1]，邵元凯 [1]，周冰洁 [1]，李振国 [1]
1. 中国汽车技术研究中心有限公司

燃料电池技术作为“氢能经济”的核心技术之一，其发展受到了越来越多的关注。有关机构预测，全球燃料电池汽车保有量将在 2050 年达到 4 亿辆,这对其核心组件之一的电化学催化剂提出了更高的要求。然而，Pt 基阴极催化剂的催化活性和稳定性仍然面临着很大的挑战，特别是在极端条件下，例如低湿度、冷启动等工况。针对上述问题，本研究提出了一种先进的催化剂碳材料调控方法，获得了具有丰富缺陷位和杂原子掺杂的 Pt 基催化剂载体。具体来说，是利用高温处理过程中 KCl 的插层效应，成功构建了大外表面积、多原子掺杂、微孔丰富的 ZIF 衍生碳载体。该碳载体为稳定的 Pt 纳米颗粒提供了足够的锚定位点。同时，丰富的微孔可以吸收大量的水分，从而使 PEMFC 在低湿度测试中具有较高的性能和稳定性。基于数值模拟、物理吸附和 X 射线微计算机断层扫描（μ-CT）表征结果，本研究为 PEMFC 阴极催化剂层的保水性和稳定性机理提供了多维度的认识，为基于 Pt 金属的 ORR 催化剂设计开辟了新的途径。

D15. 微纳能源材料与器件-46

摩擦伏特效应的理论模型

郭鑫 [1]，尤静 [1]，魏迪 [1]，邵佳佳*[1]，王中林 [1]
1. 中国科学院北京纳米能源与系统研究所

摩擦伏特纳米发电机（TVNGs）能将机械能转化为直流电能。尽管近年来摩擦伏特效应受到了广泛研究，但目前仍然缺乏普遍的理论模型，因此 TVNGs 的工作原理也尚未得到全面的解释。与以往定性的解释不同，本文提出了基于经典半导体物理的理论模型，并推导了 TVNGs 的控制方程，从而揭示了器件内部及外部电路中基本物理量的变化。直流输出源于摩擦伏特效应和接触起电效应的耦合；具体而言，源于非平衡条件下结区/接触界面处过量载流子的准费米能级的移动和重新排列。根据集总参数电路理论，本文建立了 TVNGs 的等效电路模型，该模型等效于与 pn 结二极管相并联的恒流源。此外，本研究引入一个新的概念“机械诱导电场”来描述界面摩擦电荷的影响。最后，利用 COMSOL Multiphysics 软件，构建了 TVNGs 的有限元仿真模型，适用于具有不同几何结构和电荷分布的摩擦伏特效应半导体器件的仿真和计算。

D15. 微纳能源材料与器件-47

基于摩擦电磁复合纳米发电机的高效海水自淡化技术

戴金鸿 [1]，訾云龙*[1]
1. 广州市香港科大霍英东研究院

淡水是当今世界不可或缺的资源，而如何在低能耗甚至零能耗的情况下生产淡水则是一大挑战。因此，提出了一种基于摩擦电磁复合纳米发电机的自供能海水淡化系统。它可以利用水自身的动能去除水中的盐离子，展示了一种“自淡化”的新概念。在 150 rpm 的转速下，该系统可以将 NaCl 盐水从 4000 ppm 稀释

到 145 ppm，脱盐率高达 147.1 μg cm^{-2} min^{-1}，淡水产量为 31.1 L m^{-2} h^{-1}。此外，本系统在不同频率的水动能下都能完成高效的海水淡化过程，并且对于各种初始浓度的盐进料均能处理至饮用水的标准。即便是淡化真实的海水也能达到 99.6%的总离子去除率和 2.7 L m^{-2} h^{-1} 的淡水产率，相比较其他可再生能源驱动的海水淡化系统，基于摩擦电磁复合纳米发电机的自淡化系统展示出更优越的性能。更重要的是，完全自供能的海水淡化过程可以通过手动转动和水能冲击来实现，两者均能够将 1000 ppm 的盐饲料处理至饮用水标准。总而言之，此复合系统不仅具有优异的海水淡化性能，而且解决了目前海水淡化事业中的能耗和脱盐容量有限的难题，提供了一种全新的“自淡化”模式。

D15. 微纳能源材料与器件-48

3D Printing of PEDOT: PSS/ Graphene Composites for High-resolution, Stretchable Piezoresistive Pressure Sensor Array

Wenrui Zhang[1], Zeji Sun[1], Kai Zhuang[1], Mei Zhou[1], Mojun Chen*[1]

1. The Hong Kong University of Science and Technology (Guangzhou)

Piezoresistive pressure sensors have been considered significant for monitoring physical health. For achieving high-performance detection, flexible pressure sensor arrays with high-resolution are required. In this work, a cost-effective 3D printing method was applied to fabricate the flexible pressure sensor array by printing PEDOT: PSS/ graphene composites array onto poly (ethylene terephthalate) (PET) films. The morphology of the printed patterns is investigated, showing a resolution of ~ 20 μm. Furthermore, for testing the potential to be applied as pressure sensing, the electrical property and the flexibility of the sensor is demonstrated. The resistance of printed line showed stable response as the applied pressure changes in the range of 0 ~ 4 kPa and it retains excellent electric performance after stretching and bending test. The printed PEDOT: PSS/graphene array are encapsulated on double-layered substrates, forming a sandwich structured sensing pad, which is capable of positioning 25 pressure sites in an area of approximately 4 mm^2.

D15. 微纳能源材料与器件-49

面向人体舒适性管理的摩擦电纤维织物

龚维*[1]

1. 安徽农业大学

纺织品是各种新兴可穿戴设备的常见载体，通过纺织品的湿热管理可以调节人体的生理舒适度、预防疾病并降低由负面情绪引起的决策错误。尤其是在闷热潮湿的环境中，人体表面的服装限制了汗液的传输和蒸发，进一步加剧了上述问题。近年来，虽然研究人员为改善纺织品的汗液传输开展了一系列工作，但仍有一些核心问题尚未解决。为了保证衣物的干爽性和人体的舒适感，提高纺织品的水分蒸发速率是非常有意义的。本文探索了铁电纳米纤维在金属和聚合物接触起电过程中的增强机制，并根据润湿性梯度和孔径差异设计了一种定向吸湿排汗织物，该织物可以让汗液快速渗透，然后在亲水层中迅速扩散蒸发。在整个吸湿排汗过程中，疏水层与皮肤接触的一侧水分含量始终为 0（从测试的第一秒开始），从而保持体表绝对干燥。这种新型的摩擦电纺织品在速干运动服、凉爽面料、无线运动监测鞋垫等领域显示出广阔的应用前景。

D15. 微纳能源材料与器件-50

具有低等效阻抗的液滴摩擦纳米发电机

郑明理*[1]

1. 河南大学

基于液滴的摩擦电纳米发电机（D-TENG）由于其高能量转换效率而被认为是收集液滴能量的重要技术。等效阻抗是 D-TENG 等效的重要参数，较低的等效阻抗将有利于构建具有高储能效率的自供电传感系统。尽管目前的工作已经报道了数千欧姆的等效阻抗，但影响等效阻抗的因素仍然不清楚。目前发表的文献将液滴与顶部电极接触的过程视为开关，其电荷转移过程与具有开关结构的 TENG（TENG-SS）非常相似。理论上，两者应当有类似的电输出特性，但在 TENG-SS 的等效阻抗为 0 Ω。本文构建了一系列由不同厚度的 SiO_2 经疏水处理制备的器件，系统地研究了电荷转移过程和等效阻抗的来源。讨论了 D-TENG 和 TENG-SS 的不同电荷转移过程和电输出。我们提出了电荷空间效应可以限制电荷转移的速率并产生额外的电阻，增大 D-TENG 的等效阻抗。在实验中，系统地分析和阐明了影响等效阻抗的因素：本征电容和液滴浓度。最后，实现了约 5000 Ω 的较低等效阻抗。这些研究为 D-TENG 的基础研究和应用提供了新的视角。

D15. 微纳能源材料与器件-51

有机-无机杂化卤化物钙钛矿的摩擦电性能调控及其应用

焦勇[1]，常晶晶*[1]

1. 西安电子科技大学

近年来，基于摩擦起电和静电感应的摩擦电纳米发电机（TENG）可以将自然环境中广泛分布的不规则低频机械能转化为电能。卤化铅钙钛矿由于其优异的介电性能，。在光电子学领域中广泛使用的卤化铅钙钛矿材料($APbX_3$，A=MA^+，FA^+，Cs^+；X=Cl^-，Br^-，I^-）由于其$[PbX_6]^{4-}$八面体的非中心对称晶体结构和高介电常数被认为是 TENG 的一种有前途的候选材料。我们从制备方法和组分调控方面研究了有机-无机杂化卤化物钙钛矿的摩擦电输出性能，研究发现：

1. 通过改变薄膜的制备方法提升了有机-无机杂化 TENG 的摩擦电输出性能。最优输出性能为：200 V、16.3 μA、88.2 nC 和 11.32W/m^2。

2. 通过调控薄膜的组分提升了有机-无机杂化 TENG 的摩擦电输出性能。最优输出性能为：245 V 、23.9 μA、80.2 nC 和 11.23W/m^2。

D15. 微纳能源材料与器件-52

基于摩擦放电的小型全自供电无线流量计

万冬[1]，訾云龙*[1]

1. 广州市香港科大霍英东研究院

流量传感技术在工业监测、资源管理和环境保护等领域具有重要的应用价值。尽管如此，开发一种能够独立于外部电源、实现实时全向无线气体或液体流量监测的紧凑型设备，一直是一个巨大挑战。本研究成功推出了一种直径不足 50 毫米的紧凑型全自驱动无线感应流量计（CSWF），该设备能够利用旋转摩擦电纳米发电机（R-TENG）自主产生动力，并发送实时全向的无线信号。R-TENG 激发气体放电管（GDT）的击穿放电，通过其发射的电磁波来无线感知流量。至关重要的是，CSWF 的性能不会因 R-TENG 输出的波动而受影响，且其信号传输距离超过 10 米。我们已成功实现了风速和水流量的实时无线远程监测。此项研究为构建一个具有广泛应用前景的无线、自驱动环境监测系统提供了新途径，其潜在应用包括持续的气象观测、海洋环境监测、自然灾害预警以及远程生态系统监控等。

D15. 微纳能源材料与器件-53

Study of the Electrocatalytic Performance of Two-dimensional Transition Metal Phosphides by On-chip Electrocatalytic Microdevices

Wenbin Wang*[1]
1. City University of Hong Kong

Transition metal phosphides (TMPs) have drawn extensive attention in electrocatalysis owing to their distinct physochemical properties, efficient charge transport and abundant earth reserves. However, most TMPs intrinsically possess a three-dimensional (3D) nonlayered crystal lattice, making it extremely challenging to synthesize TMPs with two-dimensional (2D) morphology. In this talk, I will introduce the synthesis of 2D TMPs via gas-phase transformation and their electrocatalytic hydrogen evolution performance explored by the emerging on-chip electrocatalytic microdevices (OCEMs). First, by using 2D precursors (transition metal dichalcogenides, TMDs) with gas-phase phosphorization, 2D TMPs were successfully synthesized. Then, the obtained 2D TMPs were comprehensively characterized, including their chemical compositions, crystal structures and electrical properties. Second, a protocol describing the critical concept, experimental standardization, operational principles and data analysis of the emerging OCEM platform was established, focusing on the investigation of nanocatalysts at the microscopic level. The OCEMs not only allow high-precision electrochemical measurements at the individual nanomaterials level but also provide unique perspectives inaccessible to conventional electrochemical methods. Third, I applied the developed OCEM platform to explore the electrocatalytic properties of the as-prepared 2D TMPs. 2D TMPs were demonstrated to possess excellent electrocatalytic hydrogen evolution performance in both acidic and neutral electrolytes. By using the spatial-resolved measurements of the OCEMs, it was found that the nonlayered 2D TMPs are catalytically active at both the basal plane and the edge sites, while layered 2D materials (with defects) have higher catalytic activity at the edge sites than the basal plane.

D15. 微纳能源材料与器件-54

通过电压抬升策略实现高性能摩擦纳米发电机

王前旺[1]，胡东阳[1]，陈赦*[1]，徐思行[1]
1. 湖南大学

Triboelectric nanogenerator (TENG) has received significant attention as an energy harvesting technology capable of converting mechanical energy from the environment into electrical power. However, due to its inherent high impedance and low charge transfer output characteristics, the output of TENG is often relatively small. Current research typically focuses on switching on and off under intrinsic voltage for performance management. Therefore, in this study, we propose an energy management strategy aimed at voltage boosting. This strategy ingeniously designs the discharge sequence of two discharge switches to adjust the connection between the intrinsic capacitor and the matched capacitor, thereby facilitating instantaneous charge transfer under voltages surpassing the intrinsic voltage and significantly enhancing the power density. Combining this strategy with a power converter has significantly enhanced the energy storage efficiency of capacitors, thereby enabling improved power supply for sensor devices. Moreover, experimental results show a power density of 324.8 kW/m², indicating a 100% increase compared to the direct discharge strategy. With such high output power, five parallel 10-watt commercial lamps can be illuminated. This strategy introduces a novel idea for achieving high performance output from TENG.

墙报

D15. 微纳能源材料与器件-P01

A Highoutput PDMS-MXene/Gelatin Triboelectric Nanogenerator Inspired by Petal Surface-Microstructure

Zekun Wang[1], Congcong Hao[1]
1. North University of China

Triboelectric nanogenerator (TENG) have a promising future in the field of energy harvesting and self-powered sensing due to their simplicity in structure, low cost, and efficient energy harvesting from the surrounding environment. The output electrical performance of TENG can be improved by doping the friction material with functional materials and modifying the surface of the friction material. However, the current method of adding functional materials to friction materials is costly and wasteful, and the method of modifying the surface structure of friction materials is cumbersome and not easy to operate. In this work, we present a PDMS-MXene/Gelatin triboelectric nanogenerator (PMMG-TENG) based on petal surface-microstructures, which has the advantages of low cost, simple preparation, high output performance, and ecological friendliness. By doping 0.03wt% of MXene in PDMS, the output electrical performance of TENG can be significantly improved, with an output current increase of up to 139.7%. Four different petals are used as natural molds to prepare PMMG-TENG. The results show that PMMG-TENG with peony petal surface microstructure has the best electrical performance, and the output current increase of up to 228.17% compared with PMMG-TENG without structure. The PMMG-TENG with peony petal surface-microstructure exhibits excellent electrical performance, demonstrating a maximum open-circuit voltage of 417.39 V and a maximum short-circuit current of 12.01 μA at a size of 3 cm ×3 cm, and a maximum power density of 170 $\mu W/cm^2$ at a load resistance of 107Ω. Gelatin film exhibits excellent degradation performance, with complete degradation time of only 150s in water at a constant temperature of 75°C. PMMG-TENG not only shows excellent performance in the field of energy harvesting, but also has a broad application prospect in the field of self-powered sensing. This work provides a simple, low cost, natural and green method to significantly improve the output electrical performance of TENG.

D15. 微纳能源材料与器件-P02

Humidity-resistant, breathable, waterproof, and bionic triboelectric electronic skins for self-powered haptic sensing and human motion recognition

Xia Liu[1,2], Aifang Yu[1,2], Lingyu Wan[1], Junyi Zhai[*1,2]
1. School of Physical Science and Technology, Guangxi University
2. Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

Researchers have been striving for a long time to create an electronic skin (E-skin) that can rival or surpass human skin in functionality. Herein, inspired by human skin, we developed a bionic triboelectric E-skin (BTE-skin) via a cost-effective method with superior humidity-resistance, breathability and waterproofness. Benefiting from introducing HKUST-1 into silicone rubber as the triboelectric layer significantly enhances the humidity resistance of the triboelectric E-skin, and the output is increased by a factor of 2.15 at 90% relative humidity. The construction of a fully enclosed electrode structure and a three-dimensional microporous array structure promises BTE-skin excellent breathability (water vapor transmission of 500 g/m2/d and air permeability of 293 mm/s) and waterproofness. In addition, the BTE-skin exhibits a wide sensing range (up to 100 kPa), ultra-high pressure response sensitivity in the low-pressure region (504.60 nA/kPa), fast response time (42 ms), and excellent cycling stability over 10,000 cycles. Furthermore, based on the BTE-skin, a self-powered smart home control system and a visual leg motion recognition system have been successfully developed. This work proposes a new strategy for tracking electronic human skin and manifests great potential in the intelligent wearable sensing field, which can help human life move toward a more convenient and intelligent future.

D15. 微纳能源材料与器件-P03

用于时空灵活性行为干预的太阳能自清洁气体感应神经调制器

金先淳[1,2]，钟天延[2]，雷林[1]，薛欣宇[2]，赵晓冲*[1]

1. 中国工程物理研究院材料研究所

2. 电子科技大学

将高灵敏度气体传感器与神经电刺激技术相结合，是在低浓度有害气体环境下诱发行为反应的一种令人信服的解决方案。使用电池供电或基于线圈的配置会带来时空限制，包括因电池寿命或必须将受试者限制在特定地点以进行无线电力传输而造成的实验持续时间限制。在这项研究中，我们展示了一种先进的无线神经调制器，它经过精心设计，可在不受限制的环境中进行行为干预。该设备集成了太阳能供电装置、气体传感器、脑刺激信号管理系统和神经刺激电极。太阳能的利用消除了电池更换的必要性和局部范围的限制。太阳能电池的表面经过超疏水涂层处理，减轻了传统太阳能电池固有的表面污染问题，从而提高了在户外环境中的性能。这一创新保证了持续、长期、按需运行的能力，确保了系统的不间断供电。实验显示，通过刺激小鼠的脑导水管周围灰质（PAG）区域，可以延长小鼠的运动活动时间长达 30 分钟。这些结果凸显了我们的技术在不受空间和时间限制的神经调节应用方面的巨大潜力，为减轻有害气体暴露对生理功能的不利影响提供了一种可行的策略。

D15. 微纳能源材料与器件-P04

基于电荷俘获密闭型能量收集器

赵也[1]，李果[1]，王磊阳[1]，潘予琦[1]，陈柏荣[1]，吴昊*[1]

1. 华南理工大学

由于固-液界面的低摩擦，基于流体的能量收集器被认为是利用清洁能源的一种有前景的工具。然而，传统固-液界面摩擦电纳米发电机受到摩擦电荷不稳定和低密度的限制。这里，提出了一种基于电荷俘获的封闭式发电机（CTEEG），用于从环境机械能中被动收集能量，具有卓越的体积电荷密度输出。通过均匀电润湿辅助电荷注入的方法对含氟聚合物膜进行预充电，然后将水封装到氟化乙丙管中，开发了一种通用、高性能、水管基 CTEEG。它表现出 19.1 $mC\,m^{-3}$ 的出色体积电荷密度输出，超过了以前的所有报告。另外，由于电荷是俘获在聚合物薄膜内的，CTEEG 设备在收集环境机械能方面表现出色的稳定性，在六个月的间歇测试中没有明显衰减。此外，得益于水的高灵活性，CTEEG 可以在各种模式下运行，并从多种机械能中发电。CTEEG 已成功演示为 LCD 屏幕和 LED 灯供电，显示出在户外环境中的能量采集和自供电传感领域的巨大潜力。

D15. 微纳能源材料与器件-P05

微型超级电容器用 PANI/MXene 复合电极的 3D 打印

张岸忆[1]，张亚斌*[1]

1. 广西大学

可穿戴和便携式电子产品的大规模普及和应用对储能器件提出了高能量密度、高功率密度、体积微小等需求。其中，微型超级电容器（MSCs）因功率密度高、使用寿命长、充放电速度快、安全稳定等优点吸引了大量研究。然而，传统方法制备的 MSCs 为平面电极，活性物质负载量低，能量密度低，难以满足微型电子产品需求。因此，亟需寻找能够制备出高能量密度 MSC 的新方法。3D 打印作为新兴技术，可在有限的面积内制备高精度、高活性物质负载的三维厚电极，有效解决了 MSC 能量密度低的问题。另一方面

是电极材料，MXene 作为新兴的二维材料，具有高导电性、大比表面积、丰富的官能团等优点，因此被大量用作 MSC 电极材料。然而，采用单一 MXene 制备的 MSC 电化学性能一般，因此需要与其他纳米材料复合。导电聚合物中苯胺（Aniline）由于成本低廉，具有高导电性和高比电容而被视为与 MXene 复合的良好候选者。在这里，我们采用点胶的 3D 打印方法制备了两种结构的 PANI/MXene 基复合 MSC。首先，我们采用 MILD 方法刻蚀 Ti3AlC2 MAX 相制备了 Ti3C2Tx MXene，制备的 Ti3C2Tx MXene 呈现蓬松的气溶胶状，具有大比表面积和=O,-F,-OH 等丰富的表面官能团。首先制备了第一种复合结构，以 Ti3C2Tx MXene 为分散体，采用苯胺单体低温化学氧化聚合的方法制备了 PANI/MXene 复合物，其溶液呈翠绿色，冷干后呈粉末状，通过 SEM 图像可观察到 MXene 单层片上均匀生长了许多小突起，即聚苯胺。苯胺在 MXene 表面聚合形成的聚苯胺可以充当保护层抑制 MXene 的氧化和重新堆积，还会产生协同效应，形成赝电容，增强其电化学性能。将复合物制备成墨水，采用点胶打印方法逐层打印 3D 微型叉指电极（面积 0.45 cm^2, 打印高度约为 2 mm）并封装制备成 MSC。其次是另一种结构，采用点胶方法将纯 MXene 打印成尺寸一致的 3D 微型叉指电极，随后采用同样方法在 MXene 微电极表面复合 PANI 得到复合电极并封装制备成 MSC。两种结构的 MSC 具有比纯 MXene 基 MSC 更优秀的电化学性能，为制备高能量密度和高功率密度的 MSC 提供了高效可行的解决方案。

D15. 微纳能源材料与器件-P06

Optimizing Energy Storage and Conversion through MXene Engineering

Sin Yi Pang[1,2], Jianhua Hao*[1,2]

1. The Hong Kong Polytechnic University
2. Shenzhen Research Institute of The Hong Kong Polytechnic University

Supported metallic nanoparticles can impart highly tunable physical and chemical properties to mix-dimensionality materials used in electrocatalysts. However, some support materials are susceptible to dissolution in acidic solutions or unstable in ambient air. The development of high-performance catalysts has faced significant challenges, such as sluggish activity in alkaline solutions and the need for high energy inputs to stabilize the nanoparticles on the supports, which hampers the pH-universality and applicability of the supported metallic nanoparticles. In this talk, I will report our work on the design of a one-step strategy to modulate the growth of platinum (Pt) nanoparticles (NPs) on HF-free MXene at the atomic level using a low-temperature metal-support interaction reaction. By controllably tailoring the morphology and strain induced by surface terminations, we have grown Pt (111) NPs with a sub-nanoscale size of 1.15 nm as a 0D/1D heterostructure, overcoming the restrictions of employing reduction gas and high annealing temperature. Benefiting from the pH-universal MXene support and the highly reactive Pt NPs, the high-performance catalyst exhibits a low overpotential of 33.3 mV for an acidic solution and 65.1 mV for an alkaline solution at a current density of 10 mA cm^{-2}. This study not only provides a scalable pathway to develop a cost-efficient catalyst under moderate conditions, but also demonstrates an effective surface modulation strategy for engineering 0D/1D heterostructures. This work was supported by RGC Grant (PolyU 15303123), HKPDFS (Ref. No. PDFS2324-5S09), and PolyU Projects of PRI and RCNN (1-CD6X and 1-CE0H).

D15. 微纳能源材料与器件-P07

A Water Evaporation-Induced Triboelectric Nanogenerator for Low-Grade Heat Harvesting

Hang Qu[1], Lingyu Wan*[1], Zhiqun Tian[1], Gaunlin Liu[1], Zhong Lin Wang[2]

1. Guangxi University
2. Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

The mounting challenges posed by climate change and environmental pollution, fueled by the extensive utilization of depleting fossil fuels, have propelled investigations into renewable and cleaner energy technologies. Research into emerging technologies mitigating the drawbacks of traditional energy sources emerges as a significant avenue. Water, abundantly and perpetually recycled in the atmospheric water cycle, inherently possesses the capacity to evaporate at any temperature and air pressure, propelled by the fundamental principle of entropy increase. Exploring the utilization of the widespread natural phenomenon of evaporation for power generation is a topic warranting thorough investigation. Presently, two primary devices capture energy associated with evaporation. One utilizes sunlight to augment steam production, liberating heat energy with the aid of thermoelectric or pyroelectric nanogenerators. The other technology, water-evaporation-induced electricity, depends on Coulomb interactions at the solid/liquid interface. Vapor-induced ion motion propels charge carriers, generating electricity. Nevertheless, electricity generation driven by evaporation and the heat absorption process remains limited. Our research introduces an innovative technology—the Water Evaporation-Induced Triboelectric Nanogenerator (WE-TENG). WE-TENG employs the spatially heterogeneous heat source generated during natural evaporation to drive a heat engine, conducting external work. Coupled with the triboelectric nanogenerator (TENG), the device efficiently converts the widely distributed low-grade heat energy in the environment into electrical energy. The WE-TENG, the first triboelectric nanogenerator (TENG) propelled solely by natural evaporation, exhibits robust adaptability, heightened stability, and outstanding output performance. This technology proves efficient in powering two commercial 2 W LED lights and wearable devices, offering a providing solution for decentralized energy generation. Additionally, it impedes the spontaneous corrosion of carbon steel materials in NaCl solution, highlighting its potential in materials protection. This study not only enhances the fundamental principles of existing evaporation-power generation technologies by integrating a heat engine but also offers conceptual guidance for advancing both TENG and evaporation-power generation technologies. The capability of WE-TENG to capture low-grade heat energy in the environment broadens the application scope of heat energy harvesting, making a valuable contribution to the field of energy collection.

仅发表论文

D15. 微纳能源材料与器件-PO01

Piezopotential-Gated MoS_2 Ferroelectric Field-Effect Transistors

Shidai Tian[1], Haiming Zhang[2], Junyi Zhai*[2,3]

1. University of Electronic Science and Technology of China

2. Beijing Key Laboratory of Micro-Nano Energy and Sensor, Center for High-Entropy Energy and Systems, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

3. School of Nanoscience and Engineering, University of Chinese Academy of Science

The modulation of charge carrier transport behavior in field-effect transistors (FETs) by strain-induced piezo-potential has been significantly developed in recent years. Ferroelectric materials, as a type of piezoelectric material, possess piezoelectric coefficients that are significantly larger than those found in conventional piezoelectric materials. Here, a composite ferroelectric field-effect transistor (St-FeFET) based on laminate composites is proposed, which consists of two pieces of ferroelectric single crystal (PMN-PT) and a MoS_2 flake. Utilizing external strain instead of gate voltage to achieve piezo-potential modulation, the St-FeFET achieves a maximum on-off current ratio of 1250% and realizes a gauge factor (GF) of 1.19×10^6 under a very small strain (0.01%), much higher than that of conventional strain sensors. This work presents innovative approaches to the operation methods of FETs and proposes potential application directions for their coupling with strain sensors and various devices across different fields.

D15. 微纳能源材料与器件-PO02

Core-shell interlocking coaxial fibers for wearable electronics

Yulong Wang[1,2], Aifang Yu[2,3], Junyi Zhai*[1,2,3]

1. Center on Nanoenergy Research, School of Physical Science and Technology, Guangxi University

2. School of Physical Science and Technology, Guangxi University

3. School of Nanoscience and Technology, University of Chinese, Academy of Sciences

Flexibility, stretchable, and conductive smart fibers have received significant attention due to their possibility of being utilized in wearable and foldable electronics for health and movement monitoring, human–machine interfaces (HMI) and energy harvesting. However, the accustomed approaches for constructing fibrous device based on the core-spun-yarn and multistep fabrication processes still encounter persistent limitations in terms of scalability, fabrication procedure, and mechanical durability. Herein, a fully flexible core-shell interlocking coaxial fiber was achieved by one-step direct wet spinning coherent solutions. Benefiting from the strong topological structure at the fiber interface of the inner and outer layers and the similar modulus of both layers, it successfully overcomes issues like delamination during long-term use. Additionally, this coaxial fiber, as a strain sensor, exhibits excellent conductivity and stability, with a wider operational range (strain range from 0 to 398.3%), high sensitivity (GF=6713 at 398.3%), fast response time (248 ms), and good durability (1300 cycles at 100% strain). Therefore, coaxial fibers can be utilized in various human motion monitoring applications. With the assistance of machine learning, high-accuracy recognition of gait and American Sign Language (95% and 100%, respectively) can be achieved. Coaxial fibers can also serve as fiber triboelectric nanogenerators (F-TENG) and textile triboelectric nanogenerators (T-TENG) for self-powered sensors and mechanical energy harvesting. This work further explores the development of multifunctional micro-wearable electronic devices. Medical sensing and energy harvesting have enormous potential in the fields of smart wearable electronics, human-computer interaction, and artificial intelligence.

D15. 微纳能源材料与器件-PO03

二維互斥顆粒系統在非平坦外勢影響下的相分離過程研究

何明恺*[1]

1. 北京纳米能源与系统研究所

在經典的相分離理論中，某個多組分單相均匀混合物分離為多相共存狀態的過程，通常被認爲是其獨立系統内部自由能降低導致的。這種行爲尤其會在某均匀體系的溫度降低到某臨界溫度時發生，而且會伴隨著許多隨機分佈的新生相。然而，在實際情況下，系統不可避免地與外部場相互作用。當外部效應足夠顯著時，基於自由能變化的經典理論便無法很好地解釋相關相分離行為。本論文聚焦於通過向二维互斥顆粒系統引入外勢，进而引發了一種新型相分離行為。外場的添加被認爲向原本的自由能表達式中添加了與空間分佈相關的項，從而改寫了其表達式，並製造了一種具有全新的具有特定空間分佈規律的相分離行爲。通過一系列實驗和計算研究，我們發現，在一些最初處於平衡狀態的均匀混合系統中，引入外部勢不僅可以引發相分離，還可以決定這些分離區域的空間分布。同樣對一些初態并不穩定的系統也同樣存在類似的空間分佈。另外，值得注意的是該系統的相分離過程同時伴隨著從類液態的非定形結構，到类 HCP 晶體結構的變過程。接著，爲了更進一步的理解這一現象的本質，我們引入了“等效密度”。它被證明是決定系統分離傾向的關鍵參量。同時我們也提到了“内”、“外”勢能降低分別代表著經典自發相分離，和定向相分離的驅動力。最後，我們的工作對定向的相分離動力學提供了一種新的闡述，對以往的理論框架加以了補充，并且拓展了該理論潛在的應用價值。

D15. 微纳能源材料与器件-PO04

一种柔性的 PI/Gr 异质结光电突触

郭俊猛*[1]
1. 河南大学

人工神经视觉电子设备在低功率和高效模式识别领域引起了极大的研究兴趣。然而，由于半导体中固有的光电效应，模仿视锥和视杆细胞的超极化行为以及进一步发展的图像识别功能遇到了巨大的挑战。在这里，我们提出了基于聚酰亚胺（PI）/石墨烯异质结的柔性光电突触器件，以有效地模仿人类的视觉功能。PI 不仅可以用作柔性底物，而且表现出显著的紫外光吸收能力。此外，石墨烯沟道的电导可以通过紫外光照射和摩擦纳米发电机（TENG）诱导的气体离子吸附调控，分别对应于抑制性和兴奋行为。负光电效应是由于 PI 中的光生电子与石墨烯中的空穴的复合，它赋予视锥和视杆细胞的超极化行为的模拟。而调节光脉冲参数来实现各种突触行为。此外，TENG 诱导的气离子吸附在石墨烯表面上作为浮栅，导致石墨烯电导的增加。通过电晕放电的连续脉冲刺激可以在突触装置中长期兴奋行为。最终，将光电耦合权重更新与人工神经网络算法相结合，可以实时手写数字识别。这项工作为构建简单的灵活人造视觉电子系统提供了新的途径。

D15. 微纳能源材料与器件-PO05

Lanthanide metal-organic frameworks with isotropic metal ions for enhanced triboelectric nanogenerator

Rongmei Wen*[1]
1. North University of China

Two new isostructural lanthanide MOFs based on anisotropic Dy(III) ions and isotropic Gd(III) ions were constructed to study the impact of different lanthanide metals on triboelectric nanogenerator for the first time. The triboelectric performance shows that the triboelectric performance of TENG improves to 171 V, 25 μA, and 21.79 nC, which are increased by 3.55, 4.23, and 2.70 times when the center metal ion is changed from Dy(III) ions to Gd(III) ions. The underlying mechanism involving magnetism has also been studied in detail through experimental analysis. This work proves a novel strategy to improve the output performance by judicious selection of MOFs with isotropic metal ions.