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D32-Piezotronics and Self-power Intelligent

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D32. 压电电子学材料及自驱动系统

分会主席：王中林、杨如森、文震、王杰、胡卫国

最终交流类型：邀请报告

D32-01

静电击穿效应在 TENG 中的利用与优化

戴叶婧*

Sun Yat-sen University

摩擦纳米发电机（TENG）由于高电压、轻质、以及对低频响应等优点被认为是一种十分具有希望的新型能源技术，并在近些年来被人们所广泛关注。TENG 的输出受到表面电荷密度的明显影响，然而摩擦介质层表面电荷密度的增加将会在介质层之间诱导出较高的静电场，从而使摩擦层与电极之间发生空气击穿，并释放摩擦层表面的部分电荷。正是由于这一问题的存在，使得 TENG 在空气中的有效电荷密度受到限制。在我们的工作中，我们通过优化电极结构，引入介电材料的自发极化等方法，有效提高了 TENG 表面电荷密度的上限，并合理的利用空气击穿现象以实现击穿电荷的收集，通过这些方法，TENG 的输出性能被大幅提高，实现了 5.40 mC m^{-2} 的表面电荷密度，通过优选摩擦介质层材料，进而实现了 8.80 mC m^{-2} 的超高表面电荷密度。这些策略为今后 TENG 的设计与应用提供了理论指导与技术支持。

最终交流类型：邀请报告

D32-02

自供能生物材料和生物电子器件

李琳琳 [1, 2]

1. 中国科学院北京纳米能源与系统研究所
2. 中国科学院大学，纳米科学与技术学院

人体的各项生理活动都离不开生物电的支持，它在胚胎发育、细胞增殖分化、组织器官再生与修复等过程中发挥着重要的调控作用。电刺激作用于细胞和生物系统，能够实现对细胞/组织功能的调控，在再生医学、恶性肿瘤治疗等方向具有重要的研究意义和应用价值。本报告将介绍具有仿生结构和自供能特性的生物材料和生物电子器件的设计思路及对细胞功能、细胞氧化应激、药物递送等的调控方法，实现在干细胞分化与组织再生、生物传感及恶性肿瘤和感染性疾病治疗等方面应用的工作。

最终交流类型：邀请报告

D32-03

Bending Measurement and control in super-resolution imaging

Qing Yang

1. State Key Laboratory of Extreme Photonics and Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China
2. ZJU-Hangzhou Global Scientific and Technological Innovation Center, Hangzhou 311215, China
3. Research Centre for Frontier Fundamental Studies, Zhejiang Lab, Hangzhou 311121, China
4. Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, China

Super-resolution in a lumen is a multi-interdisciplinary challenge. The major blocker of optics application in a lumen is the dependency of: classical super-resolution on specific fluorescent markers, large-size objective lenses, and static environments for internal cavity in vivo super-resolution (object: high scattering tissue, environment: dynamic narrow space, imaging goal: fast super-resolution). Multimode fiber (MMF) is a good candidate for super-resolution in a lumen. The main block in MMF imaging is mechanical deformation and the difficulties in obtaining correct transformation matrix under dynamic deformation. In

this presentation, we present recent progress on in vivo super-resolution imaging based on single MMF. Spatial-frequency tracking adaptive beacon combined with spatial frequency engineering was proposed to ensure KHz fast tracking high stable super-resolution multimode fiber endoscopy imaging. Sub-diffraction-limited resolution about 250 nm (λ/3NA) is achieved. Multimode fiber has been integrated in a white-light endoscopy (WLE) to achieve cross-scale in vivo imaging inside the lumen. The high resolution and robust observation in a minimally invasive manner will provide an exciting new modality to endoscopy with wide applications in basic biology and clinic research.

最终交流类型: 邀请报告

D32-04

Piezo-Phototronic Effect in Multi-Layer Structured Optoelectronic: Bilateral Piezoelectric Charge Modulation

Wenbo Peng*

Xi'an Jiaotong University

Piezo-phototronic effect utilizes the strain induced piezoelectric charges inside the piezoelectric semiconductors to modulate the local energy band diagram at the interface of junctions, thus controlling the photo-generated carriers' behaviors and the performance of optoelectronic devices. Since its invention in 2010, piezo-phototronic effect is vastly demonstrated in photodetectors, light-emitting diodes, and solar cells, where only one interface is modulated by piezoelectric charges. In 2018, we first propose to construct multi-layered structure for efficient utilization of piezoelectric charges with both polarities and obtain better performance optimization by piezo-phototronic effect, which we recently name as Bilateral Piezoelectric Charge Modulation. Here, we summarize the recent progresses of our researches on bilateral piezoelectric charge modulation, including both experimental results and analytical theories.

An n-ZnO/p-Si/n-ZnO double heterojunction bipolar phototransistor is designed, and the regulation of bilateral piezoelectric charges on bipolar phototransistor's performances is studied from the perspectives of theoretical derivation and experimental research simultaneously. A theoretical model of n-ZnO/p-Si/n-ZnO double heterojunction bipolar phototransistor is established, and the influence of four polar combinations of piezoelectric charges induced by different strains formed at the interface of two heterojunctions on the characteristics of phototransistor is carefully studied. The theoretical calculation results show that, when positive piezoelectric charges are generated at both two interfaces, the regulation of strain on the phototransistor is a superposition of two positive effects, which can significantly improve the performances of phototransistor. Then an n-ZnO/p-Si/n-ZnO double heterojunction bipolar phototransistor is experimentally prepared. By rationally designing the device structure, positive piezoelectric charges could be simultaneously generated at the two heterojunction interfaces when an external compressive strain is applied. The saturation current of phototransistor is significantly improved, and the photoresponsivity is also improved to a certain extent by the applied compressive strain. To further optimize the performances, the effects of interdigitated electrode's size, substrate and ZnO layer on the strain regulation of device performance are carefully studied. The experimental results show that when the p-Si substrate is used, the size of interdigitated electrodes is chosen as channel width W0 = 80 μm, the channel length L = 5 μm, and the number of electrodes N = 14, and the ZnO nanowires layer prepared by low temperature hydrothermal growth method is used as both emitter and collector, the strain induced bilateral piezoelectric charges regulation of the obtained bipolar phototransistor is the best. At a compressive strain of -1.37%, the photoresponsivity is enhanced about 2000%, indicating the significant modulation of applied strain on the performances of heterojunction bipolar phototransistor.

最终交流类型：邀请报告

D32-05

基于应力分级结构的摩擦电人工机械感受器及其在人机交互中的应用

雷浩[1]、赵春*[2]、文震[3]

1. 利物浦大学

2. 西交利物浦大学

3. 苏州大学

Triboelectrification-based artificial mechanoreceptors (TBAMs) can convert mechanical stimuli directly into electrical signals, realizing self-adaptive protection and human–machine interactions of robots. However, traditional contact-electrification interfaces are prone to reaching their deformation limits under large pressures, resulting in a relatively narrow linear range. Here, we fabricated mechano-graded microstructures to modulate the strain behavior of contact-electrification interfaces, simultaneously endowing the TBAMs with high sensitivity and a wide linear detection range. The presence of step regions within the mechanically graded microstructures helps contact-electrification interfaces resist fast compressive deformation. The highly sensitive linear region of TBAM with 1.18 V/kPa can be effectively extended to four times that of devices with traditional interfaces. In addition, the device is able to maintain a high sensitivity of 0.44 V/kPa even under a large pressure from 40 kPa to 600 kPa. TBAM has been successfully used as an e-skin to realize self-adaptive protection and grip strength perception for a commercial robot arm. Finally, a high angle resolution of 2° and excellent linearity of 99.78% for joint bending detection were also achieved. With the aid of a CNN algorithm, a data glove based on TBAMs realizes a high accuracy rate of 95.5% for gesture recognition in a dark environment.

最终交流类型：口头报告

D32-06

面向医疗康复和智能体育的织物基 TENG

于爱芳[1, 2]、程美妃[1]、王伟[1, 2]、贺梦[1]、刘霞[1]、王玉龙[1]、翟俊宜[1]，[2*]

1. 中科院北京纳米能源与系统研究所

2. 中国科学院大学

织物基 TENG 因其柔软性和可穿戴性以及能量采集能力等优势，在医疗康复和智能体育领域具有广泛的应用前景。本为主要从设计、制备到最后的应用方面，介绍了三种类型的 TENG 织物。 第一类织物为由导电不锈钢丝 (SS) 组成的芯壳纱作为电极，以及具有抗菌性能 (UV/OM-CY) 的抗紫外线棉纱与紧密缠绕在芯 SS 纤维周围的聚乙烯 (PE) 纱线相结合作为基本构建块 (PE/UV/OM-CY)的具有抗菌、紫外线 (UV) 防护和辐射冷却性能等高级功能的 TENG 织物，并展示了在为自供电运动传感器的出色能力，可以帮助患者修改他们的锻炼程序。第二类织物为由螺旋弹簧为电极和支撑层，以力致发光材料 ZnS:Cu/PDMS 作为支撑层和内芯，设计并制备了一种柔性可拉伸的同轴纤维摩擦电纳米发电机。基于此纤维的可穿戴织物 TENG 作为全身传感器，能够实时、可视化、无创、自供电、双模式传感监测关节运动。第三类织物为由一种基于 1D 纱线的摩擦电编织物（t-braid）用于自供电智能运动设施和可穿戴设备，其中编织的包芯纱（mantle）相互交织并紧密缠绕轴向弹性纤维（kern）。5.5 毫米/32 股（直径/股数）t-braid 表现出高达 ~10 MPa (256.4 N) 的显着拉伸强度和 ~227% 的轴向断裂应变。出色的强度和弹性使 T-braid 不仅成功地用于高强度蹦床比赛指导运动和比赛裁判，还可以作为实时自供电跳绳计数系统。此外，我们证明 t-braid 可以用作可穿戴设备来监测运动过程中的呼吸。

最终交流类型：邀请报告

D32-07

宏量 MXene 的超临界剥离及其微型能源信息多功能一体化集成器件与应用

杨维清
西南交通大学前沿科学研究院

空间受限特殊环境下高速列车转向架、特殊战略装备、航空发动机关键部件等系统的状态监测与故障诊断，对保障智能系统的安全可靠至关重要。而空间受限特殊环境关键部件运行多参量监测的微能源供给是一项世界性技术难题。近年来，以微型多功能一体化集成器件为代表的智能微传感技术获得快速发展，有望解决这一项关键技术难题。相比传统功能单一、大体积监测器件，微型多功能一体化集成器件具有微型化、智能化和多功能化的特点，兼具多参数监测、适用领域广等优势，有望实现受限空间的健康状态实时监测。本报告提出全 MXene 能源信息多功能一体化集成器件的“一材多能，工艺兼容”新策略，利用 CO_2 超临界剥离技术，在 5 小时内成功蚀刻制备超过 10 种 MXene，同时实现单次 Ti_3AlC_2 的公斤级刻蚀；其次，以高能超临界 CO2 为物理催化剂，亚临界 H_2O 为化学催化剂，利用超临界 CO_2 耦合亚临界 H_2O 成功在 1h 内刻蚀制备 Nb4C3Tx，得到兼具能量采集、能量存储、压力传感、光电探测等能源信息多功能的“一材多能”MXene 公斤级制备，开发“工艺兼容”MXene 油墨的流变学调控技术，采用电流体 3D 喷墨打印、激光雕刻等技术，集成一体化无线自供能微传感器，实现 MXene 基能源信息多功能一体化集成器件在受限空间智能传感领域的长期可靠应用，为空间受限特殊装备长寿命健康实时监测的战略需求提供科学与技术支撑。

最终交流类型：邀请报告

D32-08

低频低幅水波能采集与自驱动海洋无线传感系统构建

万玲玉
广西大学

海洋波浪能分布广泛，储能丰富，具有全天时全天候能量采集、零碳排放等优点，但低频低幅水波能的采集一直是难题。在对北部湾的海浪特性进行统计分析的基础上，发展了不同结构的高灵敏电磁-摩擦复合纳米发电机，系统研究了复合纳米发电机从实验室模拟到真实海浪等不同激励水平下的加速度特性和电气性能。提出的穿梭式模块化复合纳米发电机高灵敏响应各种低幅值运动，无论在实验室还是在真实海浪条件下都表现出色。在模拟水波条件下，最大峰值功率密度为 250.2W/m³。在常规海况的海洋实验中，器件处于较低的激励水平，其最概然加速度幅值约为实验室直线电机模拟运动最大加速度幅值的 24%和模拟水波运动最大加速度幅值的 57%。由于高灵敏响应的优点，最概然输出频率达到 0.83Hz，约为海洋波浪主频率（0.1-0.2Hz）的四倍。12 个模块集成的系统高性能收集海洋水波能实现自驱动的水质检测。此外，类摩天轮结构的复合纳米发电机也表现出了优异的低频低幅水波能采集特性。最后，通过原位的水波能收集，实验了海上的远距离自驱动无线传感数据传输。

最终交流类型：邀请报告

D32-09

基于摩擦电智能鼠标与机器学习的自驱动安全识别系统

任泽伟
西安电子科技大学

摩擦纳米发电机（TENG）技术基于摩擦起电和静电感应效应，可将环境中的高熵能源有效转化为电能，在当前物联网时代展现出巨大应用前景，为构建自驱动系统提供了潜在解决方案。本报告将报道一种用于人机界面交互的自驱动安全识别系统，基于摩擦电智能鼠标的开发与机器学习算法，我们给出了一种计算机操作人员的身份试别系统。通过信号处理、特征提取、模型训练等过程，实现了对不同个体的高精度识别。所提出的新型计算机安全识别策略可应用于网络和信息安全。本报告将同时介绍基于摩擦电能量采集器件与能源管理设计的自驱动能量系统，给出新型自驱动能源包的设计策略与应用方案。

最终交流类型：邀请报告

D32-10

自恢复应力发光智能材料及其自驱动传感与显示应用

彭登峰

深圳大学，物理与光电工程学院

应力发光是指发光体在机械力作用下产生的发光现象。应力发光材料与普通发光材料不同，具有“力”激励发光特性。由于无需光照和通电，部分应力发光材料在清洁光源和可视化应力探测方面具有独特优势。自恢复性（Self-recovery）应力发光特性半导体材料与有机弹性体复合后，例如 ZnS:Mn/Cu/PDMS 复合材料在数 10 万次反复动态压强下保持可重复的发光，在可视化应力传感和智能无源显示器件领域表现出极为重要的应用前景。本报告介绍通过合成条件优化和材料结构组合设计，在 ZnS 半导体及 CaZnOS 和 ZnS/CaZnOS 异质结复合材料中实现了数十种稀土离子、过渡金属离子的有效掺杂和高亮度应力发光，极大拓宽发光光谱范围，同时提高了发光强度，还降低合成成本。基于所合成的应力发光材料，我们阐明机理的同时，展示了其在应力分布可视化成像、电子签名笔、防伪标签和荧光棒等新型应用，并结合无机+有机应力发光复合材料在自驱动柔性传感与显示器件领域应用方向做适当展望。

最终交流类型：邀请报告

D32-11

接触分离式摩擦纳米发电机的动态电荷模型研究

刘伊娜*

西交利物浦大学

随着物联网时代的来临，分布式多功能传感器网络正成为智能设备和控制终端之间信息交换的核心节点。考虑到大量离散型传感器的移动性供电需求，寻找合适的自驱动供能方式是实现这一目标的有效策略。近年来诞生的摩擦纳米发电机（TENG）在收集环境低频机械能方面有着独特的优势，配合恰当的储能及电源管理技术，能够实现传感系统连续工作时间的有效延长。然而，TENG 存在电荷密度低、稳定性差和能量转换效率低的问题，这严重阻碍了其实际应用。为了克服这些问题，我们构建 TENG 全局动态电荷模型，从而系统地讨论 TENG 动态电荷行为，增加电荷贮存，减少耗散，实现对摩擦电荷的有效调控。

最终交流类型：邀请报告

D32-12

基于压电电子学隧道结的高灵敏度应变传感器

于秋红，刘书海*

1. 河南科技大学物理工程学院

2. 兰州大学材料与能源学院

压电电子学因能够实现功能器件与机械环境之间的无缝自适应交互而成为新兴研究热点。作为该领域的关键器件，压电电子学晶体管利用界面处的压电极化调控界面势垒高度，从而有效调控电子器件中载流子的输运特性，展现出在压力/应变触发的电子器件、传感器、人机通信等诸多领域中的广阔应用前景。本文设计了一种具有金属/绝缘体/压电半导体异质结构的压电电子学隧道结晶体管，实现了压电极化电荷对隧道结势垒高度和宽度的并行调控。这种协同调控机制使基于压电电子学隧道结（Ag/HfO_2/n-ZnO）的应变传感器在 0.10%的应变下表现出高达 4.8 × 105 的超高应变灵敏度系数，比基于传统肖特基结（Ag/n-ZnO）的应变传感器高出 17.8 倍以上。进一步研究表明，压电极化调控的超敏区域出现在超低应变（<0.01%）

下。在 0.01%的应变下，其等效的肖特基势垒高度变化可高达 150 meV。这种独特特性使压电电子学隧道结晶体管特别适用于微小应变检测，拓展了其在高灵敏度应变传感领域的应用潜力。

最终交流类型: 口头报告

D32-13

3D 柔性结构在微型多功能能量收集电子设备中的应用

豆维新

西安电子科技大学

微型发电机的开发对于可穿戴设备和便携式设备的发展至关重要。摩擦纳米发电机已成为一种前景广阔的解决方案，但其微型化和宽带能量采集仍具有挑战性。为了应对这一挑战，本研究利用屈曲自组装技术开发了一种具有三维结构的多功能装置。我们设计并将平面前驱体布局转化为微型纳米发电机所需的三维结构，而无需使用额外的连接部件。通过屈曲技术将二维结构的几何图形转换为扩展的三维布局，可以创建一个小型化、高性能输出的纳米发电机。改变三维结构的拓扑结构和尺寸，可扩展设备的功能和适应性。这种结构小巧的装置可用于传感和发电，具有出色的周期稳定性和宽带能量转换能力。利用 PVDF 产生电荷和利用 PI 存储电荷的协同作用提高了器件的性能。基于三维结构的微型装置为推进可穿戴和自供电传感技术提供了一种战略性方法。

最终交流类型：口头报告

D32-14

氨基酸基 MOFs 压电材料构筑及压电性能调控

王咏梅、刘存顺、杨如森*

西安电子科技大学

金属有机框架材料（MOFs）是由金属离子和有机配体自组装配位形成的长程有序的晶体多孔材料。由于金属离子和有机配体的广泛选择性，理论上 MOFs 的种类有无限种可能，且可以同步集成金属和有机构筑单元的性质，因此 MOFs 具有结构多样、性质多样及功能可设计性强等特点。本报告主要介绍在氨基 MOFs 上通过后修饰氨基酸的方法引入手性，构筑并调控氨基酸 MOFs 压电性；通过以氨基酸为手性配体构筑氨基酸基 MOFs 并通过外电场调控其晶体生长及压电性等方面取得的一些进展。

最终交流类型：口头报告

D32-15

软离子导体在柔性传感中的应用

龙勇，赵冰奇

北京纳米能源与系统研究所

近年来，随着物联网的迅速崛起，柔性电子器件和可穿戴电子器件引起了人们的极大关注。作为有前途的离子导电柔性材料之一，水凝胶因其透明、可拉伸和离子导电的优点而被广泛研究。然而，传统水凝胶不可避免地面临着由于暴露在环境中时内部水分流失而失去柔性和导电性的问题，这严重限制了其在柔性电子领域的应用。因此，本报道设计了一种可拉伸的多功能有机凝胶离子导体（MOIC）。这种有机凝胶不仅具有出色的导电性、柔性、保水性和热稳定性，还表现出超强的应变能力（高达 9000%）和防冻能力（低至-30℃），还能在 600%的应变下交替加载/卸载 1800 次循环后，仍保持高的机械稳定性。基于这种 MOIC，作者构建了高性能的摩擦纳米发电机（MOIC-TENG），以采集机械能。此外，作者还用其实现了多功能柔性可穿戴传感器，包括应变传感器、压阻传感器和触觉传感器。该 MOIC 展现了在小型能量采集的 TENG 和小型人体运动监测的应变/触觉传感器方面的应用前景。

最终交流类型：邀请报告

D32-16

人工“微闪电”：直流摩擦纳米发电机

王杰*

北京纳米能源与系统研究所

作为一种分布式电源供给新技术，摩擦纳米发电机(TENG)在最近几年受到了全世界广泛的关注。传统的 TENG 依靠摩擦起电和静电感应原理，通常提供交流(AC)输出【1-2】，而我们利用摩擦起电与静电击穿效应，实现了直流输出的 TENG (DC-TENG) 【3】。DC-TENG 不仅可以直接驱动电子器件，并能避免了 AC-TENG 的空气击穿问题和摩擦介质层击穿问题，有望进一步提升 TENG 的输出性能。这里将简要介绍 DC-TENG 的基本原理，讨论提高其输出性能的方法【4-6】，并对其潜在的应用前景进行简要评述。

最终交流类型：邀请报告

D32-17

How to fabricate large-scale, low-cost, green, and bio-compatible piezoelectric materials?

Zhengbao Yang

The Hong Kong University of Science and Technology

Piezoelectric biomaterials have attracted great attention owing to the recent recognition of the impact of piezoelectricity on biological systems and their potential applications in implantable sensors, actuators, and energy harvesters. However, their practical use is hindered by the weak piezoelectric effect caused by the random polarization of biomaterials and the challenges of large-scale alignment of domains. Here, we present an active self-assembly strategy to tailor piezoelectric biomaterial thin films. The nanoconfinement-induced homogeneous nucleation overcomes the interfacial dependency and allows the electric field applied in-situ to align crystal grains across the entire film. The β-glycine films exhibit an enhanced piezoelectric strain coefficient of $11.2\,\mathrm{pm\,V^{-1}}$ and an exceptional piezoelectric voltage coefficient of $252\times10^{-3}\,\mathrm{Vm\ N^{-1}}$. Of particular significance is that the nanoconfinement effect greatly improves the thermostability before melting (192^{o}C). We further developed a fast and versatile electrostatic disc microprinting for fabricating nanoparticles, films, and micro-patterns. Printing diversified functional materials, ranging from suspensions of dielectric ceramic and metal nanoparticles, to insulating polymers, to solutions of biological molecules, demonstrates its great potential in electronics, biotechnology and beyond.

最终交流类型：邀请报告

D32-18

Triboelectric Potential Driven FETs for Interactive Neuromorphic Synaptic Devices and Systems

Qijun Sun[1]

[1]Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

Fully imitating functions of biological synapses or afferents is critical to the evolution of neuromorphic computation and artificial intelligence. Benefiting from recent progress in bioinspired sensors, artificial synapses and interactive systems, more intelligent neuromorphic devices (or systems) capable of processing sensing signals and delivering interactive feedback are urgent to be developed and have been rapidly emerging recently. Different types of electronic devices (e.g., memristor, ionic devices, floating-gate transistor) have been demonstrated to successfully mimic synaptic functions assisted with electrical, optical and mechanical plasticization. Integration

with sensory, processing, and actuating components further endows the traditional neuromorphic devices with more complete bionic somatosensory ability. The seamless and adaptive interactions between neuromorphic synaptic devices and external environment is believed to be essential in establishing future brain-like computers and artificial intelligent systems. This presentation will introduce interactive neuromorphic synaptic devices and systems based on our recent research work of artificial afferents, bioinspired analogous nerves, myoelectric-mechanical interface, etc.

This talk will mainly cover the significant progress concerning on artificial synapses correlated with mechanical, optical, pressure and strain trigger-signals. Based on our researches of artificial afferent, mechanoplastic neuromorphic devices, and bioinspired mechano-photonic synapses, “interactive neuromorphic device” will be the core in this presentation. This talk will start from the principle of neurosynaptic devices activated by different sensing signals and introduce the influence of external signals on synaptic plasticity. It will also introduce the research progress of interactive neuromorphic synaptic devices/systems inspired by pressure, touch, displacement, light, heat, and mixed signals, and look forward to the future applications of interactive neuromorphic synaptic devices/systems. The interactive neuromorphic synaptic device will involve electronic devices, neuromorphic computation, sensors, and human-machine interactions, which is highly promising for revolutionary artificial synapse and neuromorphic systems.

最终交流类型：邀请报告

D32-19

基于摩擦纳米发电机的自驱动传感器

郑莉*

上海电力大学

Triboelectric nanogenerator (TENG) can convert mechanical energy in the environment into electrical energy, such as waves, sounds, muscle contractions, mechanical vibrations, which is based on the principle of triboelectrification and charge induction. Due to its excellent durability and plasticity, TENG can be easily combined with other functional devices. Therefore, TENG has wide applications in various areas. Here we will discuss some applications of TENG in different areas, such as electrostatic manipulations, flexible robots, flexible wearable sensor, self-powered driving sensor, sensor in voice and gesture recognition, sensor in security, sensor in remote transmission lines and so on. For example, based on the coupling of vapor responsive PDMS film and TENG, a flexible actuator for object transport and a double-finger gripper for loading small objects is designed and demonstrated, and an object of 6 g can be easily clamped by the gripper. The study on self-powered sensors in various areas will greatly expand the applications of TENG.

最终交流类型：邀请报告

D32-20

高性能自供电电化学系统的构建及应用

周灵琳、王杰*

北京纳米能源与系统研究所

基于摩擦电纳米发电机（Triboelectric nanogenerator，TENG）的自供电电化学系统能够将环境中的机械能转化为电能以驱动电化学反应，为解决传统电化学方法在水污染处理中能耗高、成本大等问题提供了新的策略。为提高自供电电化学系统的去除效率和使用寿命，首要的是增强 TENG 的功率密度和耐久性。为了同时实现功率密度和耐久性“双高”的 TENG 器件，提出了界面电荷和接触状态双重调控方法，以同时提高 TENG 的功率输出和耐久性，从而实现了 3.45 W m−2 Hz−1 的功率密度和长达 1,000,000 工作循环的超长耐久性。基于报道的高性能 TENG，设计了自供电电化学系统，以有效去除水中的重金属离子和有机

污染物。此外，还系统地研究了电流形式对电化学性能的影响。结果表明，交流电（AC）作为 TENG 的典型输出，在提高反应效率和降低电化学方法能耗方面具有优势。我们的工作将为设计一种零能耗、低成本、高效率的废水处理新电化学方法提供坚实基础。

最终交流类型：邀请报告

D32-21

碳基柔性传感材料与器件

张莹莹
清华大学

近年来，柔性可穿戴智能器件与系统的发展引起了人们广泛关注。探索高性能柔性和可穿戴电子器件的低成本、大规模制备方法具有重要意义。新型柔性可穿戴材料的开发是发展柔性可穿戴器件的重要基础。具有碳原子 sp2 杂化结构的纳米碳材料具有导电、轻质、稳定等优势，是一类很有潜力的柔性可穿戴功能材料。我们基于纳米碳材料与蚕丝蛋白材料优势结合和功能转化的研究思路，发展了针对柔性可穿戴应用的系列材料，例如，导电功能油墨、电子纤维材料和导电织物材料等，并在此基础上研制了系列纤维与织物基新型柔性可穿戴式传感器件，构建了感知-反馈一体化智能系统，展示其在运动监测、呼吸监测、人机交互、早期医疗诊断方面的应用前景。相关研究为高性能、多功能柔性可穿戴材料与器件的制备与应用提供了新思路。

最终交流类型：邀请报告

D32-22

基于第三代半导体异质结传感器

孟建平
北京纳米能源与系统研究所

开发具有高灵敏度、快速响应回复和低功耗（自驱动）传感器以满足物联网的需求推动着传感器发展。传感器的性能依赖于传感材料，其中，具有半导体、压电和热释电多种特性的第三代半导体是理想材料之一。本报告围绕第三代半导体异质结，通过耦合势垒调节、局域表面等离子体激元共振（LSPR）、热释光电子效应、压电光电子效应、能带工程和铁电极化，开发高灵敏光传感器、气体传感器和生物传感器。

最终交流类型：邀请报告

D32-23

摩擦纳米发电机中静电击穿现象的调控和利用

赵志浩、王杰*
北京纳米能源与系统研究所

开发可持续的和移动的分布式能源供应器件是解决新时代物联网能源供给的重要方法。作为一种新型而有效的分布式能源收集策略，摩擦纳米发电机可以实现环境中微小机械能的收集并转换成电能，但是摩擦纳米发电机的输出性能受到其表面电荷密度的限制。虽然现阶段有诸多方法可以提高摩擦纳米发电机的表面电荷密度，但随着表面电荷密度的提升，静电击穿现象对其的限制作用进一步突出。本报告将从摩擦纳米发电机中静电击穿现象的产生机制出发，讨论调控或者利用静电击穿以提高摩擦纳米发电机电荷密度的方法。

最终交流类型：口头报告

D32-24

智能机器人的“感官进化”：摩擦电式传感在物体辨识的创新探索

魏雪莲*
中国科学院北京纳米能源与系统研究所

机器人身上携带的各种传感器犹如人类的感知器官，是机器人感知世界的重要媒介。物体特性是机器人和周围环境进行有效交流所需要的重要信息之一，不同种类的传感器侧重于捕获不同状态物体的信息。先进的触觉传感器能够捕捉触摸固体材料的特征信息，而味觉传感器则可以分析液体成分并识别液体类型。为了推动智能机器人技术的质的飞跃，完善机器人的感知系统，引入创新技术无疑是一项充满挑战的尝试和突破。摩擦纳米发电机技术的兴起，为各种感知类传感器在物体辨识功能上的应用开辟了全新的视角。随着摩擦电式传感器研究的快速发展，一系列研究成果充分证明了这一新思路的可行性和巨大潜力。本报告聚焦于机器人的智能感知与识别领域，以不同状态物体的识别为主要导向，致力于深入探索基于摩擦纳米发电机技术的传感器在物体辨识功能上的研究与应用。通过相关研究，旨在提升智能机器人的感知能力，并进一步推动相关技术在实际应用中的创新与发展。

最终交流类型: 口头报告

D32-25

Investigation of the self-assembled behavior of amino acid on Au (111) surface: A molecular dynamics study

Pei Du,Dan Tan,Rusen Yang*
Xidian University

Understanding and controlling the growth of organic crystals deposited from the vapor phase is important for fundamental materials science and applications in wearable or implantable electronic devices. Herein, inspired by experiments, the growth kinetics of three aliphatic amino acids on Au (111) substrate were studied by molecular dynamics (MD) simulation. The effects of temperature and external electric field on the self-assembly process of amino acid molecules were investigated. The dynamics of amino acid molecular self-assembly into crystals are characterized by different parameters, such as root mean square deviation (RMSD), potential energy, hydrogen bond formation, calculated X-ray diffraction (XRD) and dipole moments. The optimum temperature of three amino acids self-assembling into crystal were obtained, whose XRD patterns calculated are in good agreement with the experimental results. It was found that the presence of an electric field promotes the arrangement of the dipole moments of individual molecules, thereby accelerating the ordered arrangement and crystallization of amino acid molecules. These observations contribute to future research on the controlled formation of amino acid self-assembly crystals and understanding their electromechanical properties.

最终交流类型：口头报告

D32-26

通过电荷反向过程构建高效摩擦纳米发电机

郭紫婷[1,2]、赵志浩[1,2]、王杰*[1,2]
1. 北京纳米能源与系统研究所
2. 中国科学院大学纳米科学与工程学院

摩擦纳米发电机（TENG）作为物联网时代的新能源，其输出性能和能量利用效率备受关注。其中，空气击穿效应被普遍认为是限制 TENG 输出的关键因素，与其伴生的电荷反向现象更被认为不利于 TENG 性能的提升。在此，我们提出了一种新的见解与策略——基于静电击穿效应和电荷反向过程构建了高效 TENG。由于电荷产生于静电击穿过程，而不受材料初始接触效率的限制，TENG 的表面电荷密度（SCD）实现了显著提升。以聚四氟乙烯（PTFE）为摩擦层，TENG 的 SCD 从初始的 97 μC m^2 增加到 780 μC m^2，提升超 8 倍，甚至超越了 Paschen 定律给出的理论上限。同时，由于简化的电路，TENG 在能量管理后表现出显著提升的能量利用性能。尤其在低压区（约 5 V），与不使用能量管理系统（PMS）相比，TENG 的

平均功率密度提高超 22 倍。此外，还提出一种改进的电介质电容模型，以理解高 SCD 状态下 TENG 的表面电荷转移行为，解释电荷反向现象的产生。更进一步，材料表面电荷的动态演变过程也被深入探究。理论推导和实验结果都证明，电荷反向在高压下普遍存在，其源于电荷迁移行为，而非静电击穿。且基于该动态演变过程，有望实现材料表面电荷状态的可控调节，推动众多静电领域应用的发展。本研究不仅提出了一种构建高效 TENG 的新策略，建立了改进的电介质电容模型来理解高 SCD 状态下 TENG 的表面电荷转移行为，更进一步对材料表面电荷的动态演变进行了深入探究，这些发现对于推进 TENG 的发展及促进静电领域的实际应用具有重要意义。

最终交流类型：口头报告

D32-27

基于摩擦伏特效应的自驱动传感系统

乔文艳[1,2]、王杰*[1,2]

1. 中国科学院大学北京纳米能源与系统研究所

2. 中国科学院大学纳米科学与工程学院

摩擦伏特纳米发电机（TVNG）以其高电流密度、低匹配阻抗和直流电输出的特性，为小型电子器件的供电提供了新的解决方案。然而，摩擦界面的磨损现象显著制约了其电流密度的稳定性和使用寿命。针对该问题，本研究提出了一种创新策略，即在 TVNG 的摩擦界面引入水性润滑液：一方面，利用水溶液提高载流子的传递效率，进而增强电流密度；另一方面，通过水溶液的润滑性能有效减少界面磨损，从而在提升 TVNG 直流电密度的同时，显著延长其使用寿命。该策略有效地解决了 TVNG 输出性能和稳定性难以“双高”的问题，实现了高达 754 mA m^{-2} 的电流密度和超过 90,000 次循环的超长耐久性。此外，基于这一高稳定性的 TVNG，我们进一步实现了振动传感器阈值监测和智能工厂生产线中重量监测的自驱动传感。对比使用润滑策略前后的 TVNG 传感器响应灵敏度，我们发现润滑策略显著减少了硬摩擦的影响，使得在 1N、2N、5N 和 10N 不同负载下，重量监测的自驱动传感器灵敏度分别提高了 2.8、3.9、15.3 和 17 倍。本研究不仅为设计低成本、长寿命的自供电 TVNG 传感技术提供了坚实基础，同时也为相关领域的研究和应用提供了新的视角。

最终交流类型: 口头报告

D32-28

单根导线高效收集动态界面静电能

何礼霞

中国科学院大学

自发发生的静电击穿释放出巨大的能量，但由于其即时性、非均匀性、不规则性和非指向性等固有特点，如何调控和利用其能量仍然是一项挑战。本报告提出了一种革命性的方法，通过简单地在介电材料下嵌入一根导线（直径为 25 微米），有效地收集动态界面静电击穿的能量，将接触带电产生的原本混乱和分布的静电能量调节成聚集状态，有效地将机械能转化为电能。同时，提出了一个点电荷物理模型来解释其发电过程和输出特性，指导结构设计，提高输出性能。在此基础上，建立了包含 72 对介电材料对的摩擦电序列，用于材料的选择和优化。此外，使用聚四氟乙烯和聚对苯二甲酸乙二醇酯为材料对可实现超过 10 千伏的高电压。这项工作为有效利用静电能量提供了新思路，在新型高压电源、智能服装和物联网等领域提供了有前途的应用。相关成果以“Dynamic interfacial electrostatic energy harvesting via a single wire”为题发表在 Science Advances 期刊。

最终交流类型: 口头报告

D32-29

通过自建立反向电场提升库伦效率以增强摩擦纳米发电机的性能

高毅奎
中国科学院北京纳米能源与系统研究所

摩擦纳米发电机（TENG）性能提升一直是一个巨大的挑战，尤其是考虑到其固有的高压特性所造成的静电击穿的问题。传统策略通过高真空，高气压或高电气绝缘气体提高 TENG 所处环境域的临界击穿电场，来提高 TENG 的性能。然而，这种策略所需的严格封装的条件剥夺了 TENG 结构简单、成本低、灵活性强的优势。此外，在性能优化方面，人们一直致力于提高短路输出电荷，忽略了在负载条件下的输出电荷才是表征 TENG 性能的关键。这在一定程度上误导了 TENG 性能优化的方向，尤其是考虑到静电击穿使得 TENG 理想 *V-Q* 曲线塌缩的情况下。在这里，我们提出了一种简单且高效的策略，通过在 TENG 的电极和摩擦层之间构建反向电场，来将击穿域的电场强度调控至临界击穿电场以下。最终从短路电荷、开路电压以及库伦效率三个方面共同提升了 TENG 的性能，并分别在直流 TENG 器件和交流 TENG 器件中实现了 2.3 W m^{-2} Hz^{-1} 和 6.15 W m^{-2} Hz^{-1} 的高平均功率密度，同时，针对负载条件下 *V-Q* 曲线向内塌缩的问题，我们引入了一个新的性能评价指标-库仑效率（TENG 在固定电压下的电荷利用效率）来正确评估 TENG 的实际性能，并用于指导 TENG 的性能优化。

最终交流类型：口头报告

D32-30

受触觉启发摩擦电调控的基于可重构 p-n 结的人工突触

贾萌萌[1,2]、翟俊宜*[1,2]
1. 中科院北京纳米能源与系统研究所
2. 中国科学院大学

模拟具有学习记忆功能和可塑性的生物突触对神经形态计算系统的发展至关重要。目前，实现低功耗、高效率且可以主动式驱动的人工突触仍然面临着挑战。本文提出了一种摩擦电势调控下可重构的 p-n 结以实现低功耗、自驱动的触觉传感系统。该器件集成了摩擦纳米发电机和基于石墨烯/氮化硼/二硒化钨范德瓦尔斯异质结的半浮栅晶体管，通过施加机械脉冲使晶体管在 p-n 结和 n+-n 结两个工作状态之间切换并表现出相应的整流行为，通过摩擦电势的调制作用和半浮栅层中载流子捕获和脱陷过程，提出了一种简单且不引入杂质的制备同质 p-n 结的方法。在此基础上，本文利用机械脉冲作为突触前电压尖峰，实现了人工突触权重的大范围调节，并成功模拟了典型的突触可塑性，例如短时/长时记忆、双脉冲抑制/易化以及学习经验行为。同时这种设计还可以大幅度地降低突触事件能耗至与生物可比拟的飞焦水平。这种可重构性和机械塑性的特征有望为未来低功耗、实时交互的人工智能系统提供新的策略。

最终交流类型：邀请报告

D32-31

材料基因多级序构策略与自驱动生理监测技术

苏元捷
电子科技大学

材料基因组计划是材料科学与工程的“圣杯”。针对压电复合材料结晶度低和自发极化弱等瓶颈问题，利用高通量相场模拟结合机器学习系统阐释了换能材料微观形态与宏观材料特性构效关系，提出了一种基于 Ti3C2Tx MXene 锚定效应的聚合物基质全反式分子构型操控策略，结合分子动力学计算和相场模拟，从微观和介观两个尺度阐释并验证了 Ti3C2Tx 表面羟基与含氟聚合物间氢键牵引电畴演化机制，使压电响应提高 196%，可全方位、零功耗地进行人体运动监测、步态识别与跖痛症早期筛查，为个性化移动医疗提供了一种低廉、轻便、可靠的方法。

最终交流类型：邀请报告

D32-32

半导体材料中的挠曲电电子学效应

翟俊宜*

中国科学院大学

多功能微/纳米设备和系统在智能电子产品和半导体材料中的挠曲电电子学效应人机交互系统中具有重要的应用，比如医疗保健，人机界面，基础设施监控和安全性。挠曲电电子学提供了一种新的方法通过施加可控的应力/应变来显着改善/调节半导体器件的电子学和光电子学性能。其原理是通过调节由外部施加的应变产生的挠曲电电势来调节在异质结/界面处的载流子产生，传输，分离和/或重组。本次演讲总结了 (1) 挠曲电电子学的原型器件的设计和原理，(2) 基于超薄二维半导体材料的超低功耗的挠曲电电子学器件和光突触，以及（3）宏观尺度硅基的挠曲电电子学效应和硅基挠曲电晶体管。

最终交流类型：邀请报告

D32-33

压电光电子学效应增强局域表面等离激元热电子注入特性研究

王幸福*、杨玉青

华南师范大学

基于局域表面等离激元修饰的光电器件性能主要受到金属-半导体异质结处热载流子注入效率的限制。本报告围绕电化学剥离制备自支撑的 GaN 薄膜的基础上，系统研究 Au NPs/GaN 界面处热电子输运行为，并通过 GaN 材料的压电光电效应和自发极化效应调节异质结界面肖特基势垒的高度以提高热电子的注入效率，优化了紫外-红外光电器件的光响应性能。这项研究是针对等离激元驱动器件界面热电子注入效率低这一关键技术瓶颈和界面转移机制不清晰而提出的新型研究思路和解决方案，对最终实现高光响应器件具有重要研究价值。

最终交流类型: 邀请报告

D32-34

Study from dielectric material to the electromechanical conversion models of TENG

Yi Xi*

Chongqing University

Most of the proposed high performance of devices based on triboelectric nanogenerator (TENG) face the challenge of stability and low conversion efficiency. Here, based on the performance improvement of TENG, the key parameter of triboelectric dielectric materials has been systematically studied. The relative experimental results are explained theoretically by quantum tunneling effect, material matching, quasi-piezoelectric model and leakage current. Moreover, TENG guided by the theory of fluid dynamics needs further exploration. Herein, a dynamic model is proposed to study the intrinsic interaction between the electrical properties of TENG and fluid dynamics of gas and liquid. These works can provide a direction for in-depth understanding of the electromechanical conversion mechanism, and enhancing the performance for TENG.

最终交流类型：邀请报告

D32-35

二维铁电的相变调控及类脑器件应用

薛飞[1]

浙江大学, 杭州 311200

随着人工智能、物联网和大数据的到来，海量数据需要在极短时间内处理并保存。数据不停地穿梭于计算与存储单元，给主流的冯诺依曼架构计算机带来严峻的速度与能耗挑战。为解决此问题，新的计算范式应运而生，例如类脑计算 (Neuromorphic Computing) 和存算一体 (In-memory Computing), 这些技术能够模拟人类大脑的工作模式，在同一器件中实现计算与存储的完美融合，能大幅度降低运行功耗并提高计算速度。新兴的二维铁电存储器件给类脑计算和存算一体的硬件实施，提供了全新的希望与方向，因为它们有出众的极限缩微、多功能传感、超快运行速度、稳定阻变等特性。本报告将介绍我们在面向类脑计算的二维铁电相变晶体管和相变铁电存储器方面的持续探索。.

最终交流类型: 口头报告

D32-36

用于偏振敏感柔性光电探测器的具有高拉伸性的少层紫磷中各向异性声子的单轴应变工程

张建斌

西安电子科技大学

量子材料的机械现象在宏观层面上的表现与其晶格内明显的电子-电子相互作用密切相关，这种关系在具有降维特征的材料中尤为明显。紫磷（VP）是一种新兴的二维材料，以其独特的跨层垂直排列管状结构而著称，由于其特定层的电子带隙可变性、优异的载流子迁移率和强大的空气稳定性而备受关注。在此，我们对沿 a、b 和 <110> 方向受到面内单轴拉伸应变的少层 VP 进行了全面的拉曼光谱分析。观察到的拉曼模式显示了与施加应变方向有关的明显不同的转变。计算得出的格吕奈森参数约为 2.4，超过了其他有据可查的二维材料，显示出更大程度的非谐波性。密度泛函理论（DFT）计算表明，外加应变不仅会改变 VP 的键长和键角，还会使两根管子在平面上旋转，从而产生明显的各向异性拉曼响应。此外，利用柔性 VP 开发的偏振敏感光电探测器显示出 18.2 毫秒的快速响应时间和 2.26 的各向异性比。这项研究不仅证实了交叉结构 VP 具有优异的拉伸性和抗冲击性，而且为探索 VP 固有的应变诱导各向异性导电特性奠定了基础。

最终交流类型: 邀请报告

D32-37

Extending the piezotronics to flexotronics

Longfei Wang*

Chinese Academy of Sciences

Semiconductor is the basis of modern industry and information technology. The strain-induced interface polarization is one of the core scientific issues in the physical properties of semiconductor materials and device design and development, which has important applications in new energy, information and other fields. Meanwhile, the interfacial polarization engineering can adapt and seamlessly connect mechanical signals with electronic device, which has important application prospects in the field of tactile sensing and human-computer interaction. The strain-induced piezoelectric polarization-electronic/phototronic coupling has triggered many new physical phenomena such as piezotronics and piezo-phototronics, which is expected to break through the bottleneck of semiconductor device performance. Moreover, Non-uniform strain-induced flexoelectric polarization is widely present in various materials, which can effectively solve the limitations of the crystal structure requirements of piezoelectricity. This report will introduce the progress of mechano-electronic/phototronic coupling effect in semiconductor and their applications.

最终交流类型：邀请报告

D32-38

从 GaN 到接触起电诱导的界面光谱

李丁*
中国科学院北京纳米能源与系统研究所

本报告将以 GaN 材料作为载体，重点介绍多相原子间电子转移及其在压电光电子、摩擦伏特效应和接触起电诱导界面光谱（CEIIS）方面的发展，涵盖从基本原理到典型的应用场景。首先，我将介绍基于 GaN 的压电光电子效应及其应用。接下来，我将介绍摩擦伏特效应及其应用。最后，我将重点介绍一个新兴领域——CEIIS。我们首次观测到两种固体材料在接触起电（CE）过程中的原子特征光子发射光谱。光子发射是 CE 过程中电子在界面上从一种材料中的一个原子转移到另一种材料的另一个原子的证据。它传递了关于界面处能量结构的丰富信息，并自然地为对应于界面处接触起电的光谱学铺平了道路，这可能对理解固体、液体和气体之间的相互作用产生根本影响。尽管我们在本研究中只关注固体-固体情况下 CE 中的光子发射，但对于一般情况，它可以扩展到 CE 中的俄歇电子激发、X 射线发射和电子发射，这还有待探索。

最终交流类型：邀请报告

D32-39

高性能固-液界面摩擦纳米发电机的构建及其能量转换研究

李潇逸*
中国海洋大学

人类社会面临着化石能源短缺及其利用带来的环境污染问题，因此，推动能源转型升级是当今世界的重大任务之一。此外，随着人工智能、物联网以及大数据时代的到来，人们开始愈发关注发展分布式能源。其中，包含降雨、波浪和河流等多样形式的水能作为可再生清洁能源，因其储量巨大，分布广泛等特点，极具开发价值。摩擦纳米发电机（TENG）作为一种新型能源技术，不仅在收集水能等可再生能源方面具有广阔的前景，而且也为物联网探测器的分布式能源发展提供可能性。TENG 种类多样，其中，基于固-液接触起电的 TENG 具有结构简单、使用范围广泛以及输出性能高的特点，特别适用于分布式水能收集领域。然而，固-液接触型 TENG 仍存在很多亟待解决的问题。首先，固-液界面的电荷极易耗散，导致 TENG 输出低；其次，目前适用于液体环境的摩擦材料种类较为单一；再次，固-液界面摩擦起电机理尚未明确，电子转移缺乏定量化标准；最后，尚未建立统一的 TENG 能量定量化模型，缺乏对 TENG 器件及集成系统设计的理论指导。

报告主要围绕固-液接触起电的水能收集 TENG，通过修饰摩擦材料表面、设计中间层结构以及瞬时结构，成功构筑了面向小尺度液滴能量收集和大尺度蓝色能源收集的高性能 TENG 器件；并同步构建了能量定量分析方法，计算了 TENG 的能量转换过程；最后分析了液体中离子浓度对不同结构 TENG 的影响，并展示了 TENG 在盐水环境中的应用，为高性能海洋 TENG 的发展提供参考价值。

最终交流类型：邀请报告

D32-40

Self-Powered Triboelectric Buoys and Applications in Marine IoT

Xiya Yang,* Shouchuang Jia, Weizhao Feng, Liqiang Liu, Hongxin Hong
Institute of New Energy Technology, Jinan University, Guangzhou

The rapid development of Internet of Things brings increasing attention on the harvesting of distributed sustainable energy. Recently, study on triboelectric nanogenerators (TENG) in collecting low-frequency and irregular amplitude ocean wave energy has become increasingly mature.

However, attaining stable and long-lasting power supply from conventional commercial batteries still remains challenging, which significantly restricts the development of blue economic toward intelligent and diversified. Combining TENG with electromagnetic generator (EMG) through flexible structural design can not only retain the advantages of TENG of high-voltage output in low-frequency, but also make use of the characteristic of EMG to work in high-frequency. Herein, several self-powered triboelectric-electromagnetic hybrid nanogenerators combining various working modes will be presented towards wide frequency wave energy harvesting and applications in smart ocean including the seesaw-structured spherical buoy, nodding duck structured multi-layer buoy and gyroscope-structured spherical buoy. Electrical output performances are systematically investigated and optimized via studying the effects of the configuration parameters, including various structure parameters, oscillation frequency, and swing amplitude of each module and the entire device. The instantaneous maximum output power density can reach up from 4 W/m^3 of individual TENG, to17 and 30 W/m^3 of hybrid TENG-EMG device. Finally, self-powered applications in smart ocean including sea surface wireless positioning, smart marine farming and ocean current monitoring are presented. These studies provide an ingenious design of realizing the synchronized movements among hybrid effects / modes-based generators, and achieve self-powered buoy in smart ocean applications, which renders a practicable strategy and generic energy solution for efficient ocean wave energy scavenging and enabling future development marine Internet of Things.

最终交流类型：邀请报告

D32-41

基于 TENG 的自驱动传感系统及性能调控机制研究

谢欣凯*

东南大学

随着智能化物联网的迅猛发展，其对大规模、多功能的传感网络要求越来越高，摩擦纳米发电机的诞生为解决分布式能源供电及自驱动传感提供了有效的解决方案。因此，本文从摩擦纳米发电机的本征电容特性出发，建立基于摩擦纳米发电机负载匹配效应的自驱动传感机制，选取线性响应范围，构建自驱动量化传感演示，实现无需外部监测电路的完全自驱动传感系统。其次，融合基于突触晶体管器件参数的神经形态网络算法，分析识别复杂的摩擦电输出信号，并通过界面终端进行人机交互应用，拓宽自驱动摩擦电传感在人工智能物联网领域的应用。同时，基于摩擦层表面电荷的产生、积累与转移动力学过程，构建中间层结构摩擦纳米发电机，通过界面能带理论深入研究电荷阻挡机制，延长表面电荷贮存时间，提升摩擦电传感器件的表面电荷密度和应用稳定性，对类人机器人、智能传感、物联网等多学科交叉融合的前沿发展领域具有重要的科学意义。

最终交流类型: 邀请报告

D32-42

Micro/nano energy harvesting and self-powered sensing based on triboelectric nanogenerator

Hengyu Li,Tinghai Cheng*

BEIJING INSTITUDE OF NANOENERGY AND NANOSYSTEMS, CHINESE ACADEMY OF SCIENCES

Triboelectric nanogenerator (TENG) was first invented by Professor Zhong Lin Wang in 2012 and has become

a promising technical development in the field of scientific instruments and devices due to their ability to harness random, high-entropy environmental energy into electricity. It plays an essential role in the field of self-powered sensors, high-voltage energy devices, blue energy devices, micro/nano-energy devices, and solid-liquid interface probes. In this review, we will start with the internal model and performance improvement methods, and elaborate on the mechanical energy harvesting structure of wind energy, wave energy, and vibration energy. After modulating the output signal through the power management circuit (PMC), the construction and application of the self-powered sensing system are finally realized. Firstly, research on the output performance of TENG has been extensively and systematically conducted. Therefore, a universal first-order equivalent circuit model of the TENG is established to analyze the internal circuit and evaluate the power source. In addition, a series of TENGs based on the charge excitation method is deeply explored to enhance the output performance. Natural environmental energy has low frequency, intermittent and irregular characteristics. Therefore, mechanical design TENG, such as frequency pumped, intermittent energy harvesting, and mechanical regulation are proposed. These studies have achieved high-efficiency harvesting of low-frequency energy, long-time harvesting of intermittent excitations, and steady harvesting of random energy, respectively. At present, the majority of sensors employ the mobile battery as the energy supply, which limits the applications in the industries. The triboelectric sensor based on the TENG does not need to be driven by the external power supply. Therefore, our team proposes a self-powered mechanical sensing method for the intelligent machinery industry. Especially for mechanical motion, vibration, and fluid condition sensing in the field of modern industry, our team has carried out in-depth research work. In addition, with the assistance of PMC, an almost constant current output is generated, which provides a guarantee for the stable energy supply of the self-powered sensing system. This research provides essential guidance for improving output performance, harvesting natural energy, and promoting the development of the self-powered sensing system.

最终交流类型：口头报告

D32-43

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

Yuting Xie, Jingqiao Zheng, Huiyuan Huang, Xiya Yang*

Institute of New Energy Technology, Jinan University, Guangzhou

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 $1.72\,\mathrm{W/m^2}$ 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.

最终交流类型：口头报告

D32-44

Zeolitic imidazolate framework/Prussian blue analogue derived $CoSe_2/FeSe_2$ heterostructure for long-cycle aluminum-ion batteries

Tianming Liu[a], Meng Liu[b], Juchen Guo[cd], Changchun Zhao*[a], Hao Liu[a], Xiaowei Li[b], Libing Liao[b] and Guocheng Lv*[b]

1. School of Science, China University of Geosciences, Beijing, 100083, China.
2. School of Materials Science and Technology, China University of Geosciences (Beijing), 100083, China.
3. Department of Chemical and Environmental Engineering, University of California, Riverside, California 92521, USA
4. Materials Science and Engineering Program, University of California, Riverside, California 92521, USA

Aluminum-ion batteries (AIBs) have been considered a low-cost, safe and high energy density candidate for large-scale electrochemical energy storage systems. Here, we utilize the concept of interface engineering to synthesize a $CoSe_2/FeSe_2$ heterostructure cathode through MOF-on-MOF heteroepitaxial growth. The presence of an internal electric field between the $CoSe_2$ and $FeSe_2$ phases induces a synergistic effect to achieve rapid charge transfer and ion diffusion, which enables a facile conversion reaction based on Co^{2+}/Co^0 and Fe^{2+}/Fe^0. The $CoSe_2/FeSe_2$ heterostructure displays an initial discharge capacity of 356.9 mA h g^{-1} at 100 mA g^{-1}. After 1600 cycles at 200 mA g^{-1}, the reversible capacity is 133.7 mA h g^{-1}. Theoretical calculation also demonstrates that the designed $CoSe_2/FeSe_2$ heterostructure can significantly promote the directional electron transfer and reduce the aluminum-ion migration barrier energy. Therefore, the concept of heterostructure cathodes provides a strategy to develop long-cycle life AIBs.

最终交流类型：口头报告

D32-45

挠曲电电子学调控的硅基半导体器件

郭迪[1,2]、翟俊宜*[1,2]

1. 中国科学院北京纳米能源与系统研究所
2. 中国科学院大学

在可调谐电子、人机界面和微/纳机电系统中，实现机械触发和当前硅技术之间的自适应和无缝交互具有较高的挑战性。压电电子学被认为是应力/应变对电子传输调控的有效机电耦合。然而，这种压电效应受限于非中心对称半导体和特定方向。针对中心对称半导体硅的机电交互需求，我们开发了 Si 基挠曲电电子学晶体管（SFT），它可以创新地将机械驱动转换为电控制信号，并直接实现硅基机电功能。利用 Si 中的应变梯度诱导的挠曲电极化场作为“门控”，可以对宏观硅基晶体管中的金属-半导体界面肖特基势垒的高度和 SFT 的沟道宽度进行大幅调制，进而实现载流子输运的调控；并且，在不同的受力模式下具有特定的可调谐电子输运特性。基于此，进一步开发了硅基触觉感知系统，根据器件在不同调控模式下特定的电学输运特性能够识别触觉感知力的位置。基于 SFT 的应变传感器具有 2189 的高应变灵敏度（Gauge factor，GF），比大多数压阻/压电纳米器件（2~2000）大得多。这些发现不仅在硅基电子器件中实现了具有高灵敏度的机电交互作用，也是压电电子学在硅基电子中的进一步拓展，同时对半导体挠曲电效应提供了深入的认识，对构建下一代硅基机电纳米器件和纳米系统的发展具有重要意义。

最终交流类型：墙报

D32-P01

Bulk transfer of μLED for contact lens display

Jianan Niu,Jiangwen Wang,Yong Long*

University of Chinese Academy of Sciences

Human-computer interaction skin-emitting display technology has unique and attractive properties as a future display. However, due to material and manufacturing technology limitations, flexible displays are still one of the reasons hindering the development of wearable and virtual reality devices. Here, we report an efficient, neat, and lossless transfer of InGaN/GaN multiple quantum well micro-light-emitting diodes (μLED) from rigid silicon-based substrates to flexible, stretchable substrates by vapor-phase bulk transfer. The transferred μLEDs are observed to have stable luminescence characteristics, and the piezoelectric photoelectric effect is the basic theory guiding the design of flexible optoelectronic devices. The flexible μLED array is used for contact lens display. Therefore, this will facilitate the application of simple, low-cost, and flexible μLED devices, especially in virtual, wearable, and skin displays.

最终交流类型：墙报

D32-P02

Flexible, transparent, and hydrophobic organogel elastomer for organogel sensor underwater and energy harvesting applications

Zhaowei Cui[1],Yuanhong Shi[2],Zilong Dong[2],Jianan Niu[2],Yong Long*[2]

1. Guangxi University

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

The fabrication of stretchable, flexible, multifunctional electronic device that can be used in various application scenarios can enable transformative applications in different novel fields. In this study, PBALi triboelectric nanogenerator (PBALi-TENG), organogel sensor, and liquid solid TENG (LS-TENG) were successfully fabricated based on BA raw materials, which are used in different application scenarios respectively, including harvesting human motion energy and detecting human motion underwater, personal communication and water level monitoring. The PBALi-TENG was employed to gather the impact energy from human motion under the contact separation mode. The out performance of the PBALi-TENG will be enhanced by optimizing parameters. The human motion can generate a voltage of up to ~63 V and a current of about ~0.8μA. The motion of fingers, wrists and elbows and the personal communication by morse code can be measured by organogel sensors underwater. The water level of rivers and lakes is demonstrated to be detected by LS-TENG for the early warning of disasters without extra power sources. Therefore, we demonstrated the facile preparation process of PBALi-TENG, Organogel sensor, and LS-TENG for different functional application scenarios.

最终交流类型：墙报

D32-P03

Neuro-inspired Thermoresponsive Nociceptor for Intelligent Sensory Systems

Yuanhong Shi[1], Qilin Hua[2]*

1. Guangxi University, Nanning, China

2. Beijing Institute of Technology, Beijing, China

Artificial nociceptors with biologically complex sensory functions show intriguing potential in the growing fields of humanoid robotics and intelligent prosthetics. However, conventional artificial sensory systems with separation

of sensors, memory, and processing units pose serious challenges in terms of device integration, efficiency, and power consumption. Here we demonstrate a neuro-inspired artificial electronic receptor prototype based on a bismuth selenide (Bi_2Se_3) memristor for a highly efficient artificial thermal nociception system. Bi_2Se_3 thermoelectric films as functional materials enable the memristor to have in-situ temperature sensing, internal storage, and computing capabilities. Ag/PMMA/Bi_2Se_3/ITO memristor-based electronic receptors can reproduce the 'threshold', 'relaxation', and 'no adaptation' behaviors of human nociceptors according to the intensity, duration, and repetitions of external stimuli. Further combining this artificial receptor with a robotic manipulator can be used to construct an artificial thermal nociception system and successfully demonstrate the nerve reflex action under thermal stimulation. The designed and realized highly efficient artificial nociceptors will enable novel sensing paradigms in biomimetic applications and neuromorphic engineering.

最终交流类型：墙报

D32-P04

The Modulation of Flexible InGaN/GaN Multiple Quantum Wells on Fabric by Piezo-Phototronic Effect

Bingjun Wang[1], Wei Sha[1,*]

Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 101400, P. R. China

Fabric-based wearable electronics are showing advantages in emerging applications in wearable devices, Internet of everything, and artificial intelligence. Compared to the one with organic materials, devices based on inorganic semiconductors (e.g., GaN) commonly show advantages of superior characteristics and high stability. Upon the transfer of GaN-based heterogeneous films from their rigid substrates onto flexible/fabric substrates, changes in strain would influence the device performance. Here, we demonstrate InGaN/GaN multiple quantum wells (MQWs) films transferred onto flexible/fabric substrates with an effective lift-off technique. The physical properties of InGaN/GaN MQWs film are characterized by atomic force microscopy and high-resolution X-ray diffraction, indicating that the transferred film does not suffer from huge damage. In the transferred film on fabric, excellent flexible properties are observed, and the photoluminescence (PL) intensity is enhanced by piezo-phototronic effect, which shows an increase of about 10% by applying external strain with increasing film curvature to 6.25 mm-1. Moreover, energy band diagrams of GaN/InGaN/GaN heterojunction at different strains are illustrated to clarify internal modulation mechanism by the piezo-phototronic effect. This work would facilitate the guidance of constructing high-performance devices on fabrics, and also push forward the rapid development of flexible and wearable electronics.

最终交流类型：墙报

D32-P05

悬臂结构

刘昱秀 [1]，胡卫国 [1]*

中国科学院大学

With the explosive development of artificial intelligence, power devices integrated with real-time sensing functions have attracted tremendous attention and will play an important role in intelligent control applications. In this work, a cantilever-structured AlGaN/AlN/GaN high electron mobility transistor integrated with ultrahigh sensitivity and large output power modulation is fabricated through a low-damage anisotropic and isotropic etching process, and achieves excellent electrical performance with a maximal output current of 236 mA mm−1 at a gate bias of 1 V. Due to the facile structure of the cantilever, the device is capable of sensing external stimuli, e.g., gentle wind, and in turn controlling the power output. Significantly, the device exhibits an extraordinarily large output power modulation (ΔP: 1.68 × 103 W cm−2) under external stimuli in the saturation region, and

obtains an ultrahigh strain sensitivity (gauge factor: 1472) under gate voltage in the linear region. Moreover, the wind-evoked mutational behavior of crickets is emulated by the device to demonstrate the capability of autonomous motor control. Such wind-evoked power devices ingeniously coupled with the dynamic piezotronic effect will have great significance in real-time sensing and actuation applications in artificial intelligence, autonomous driving, and aerospace

最终交流类型：墙报

D32-P06

Ultrafast and Low-Power 2D Bi_2O_2Se Memristors and Artificial Synapse

Zilong Dong[1]

Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, China

Artificial synapse with synaptic plasticity is a building block for opening a new era of energy-efficient neuromorphic computing architecture, which will overcome the limitation of the von Neumann bottleneck with the physical separation of memory and computation units. Bi_2O_2Se is an emerging material platform for next-generation electronics, which is of great significance in improving the efficiency and performance of emerging memristive devices, enabling low operation voltage, high switching speed, and ultra-dense integration. In this work, a single heat source growth method is designed, which has the advantages of simple conditions and stable growth. Then, 2D Bi_2O_2Se memristors are fabricated with excellent memristor stability and excellent performance including ultrafast switching speed (<5 ns) and low power consumption (<3.02 pJ). Moreover, synaptic plasticities, such as long-term potentiation (LTP), long-term depression (LTD), paired-pulse facilitation (PPF), and spike-timing-dependent plasticity (STDP), are demonstrated in the as-fabricated Bi_2O_2Se memristor, showing its potential as an artificial synapse. Furthermore, with the excellent synaptic plasticity of the artificial synapse, the MNIST dataset recognition rate with the simulated artificial neural networks (ANN) based on the LTP/LTD of the device could reach a high accuracy of 91% in the confusion matrix. This work provides one way for memristors to attain ultrafast and low-power attributes, showing great potential in neuromorphic computing applications.

最终交流类型: 墙报

D32-P07

Low-resistance $TiAl_3$/Au ohmic contact and enhanced performance on AlGaN/GaN HEMT

Te Xu, Weiguo Hu*, Junyi Zhai*

Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

The advent of an era characterized by intelligent, interconnected systems of AlGaN/GaN High Electron Mobility Transistors (HEMTs) electronic devices is underway. Within this context, the performance of ohmic contacts in HEMTs bears substantive influence on the electrical characteristics of power devices, notably impacting parameters such as on-resistance and output current. Therefore, the improvement of ohmic contacts attributes in AlGaN/GaN HEMT devices has perennially constituted a focal point of considerable industry. Based on the AlGaN/GaN heterostructure, a novel $TiAl_3$/Au ohmic contact has been successfully developed for HEMTs. A low contact resistance of 0.23 Ω·mm (2.33×10^{-6} Ω·cm^2) is obtained, which proposes a new interface contact for AlGaN/GaN heterojunction. Transmission electron microscope (TEM) illustrates that the contact mechanism for low resistance is direct contact with two-dimensional electron gas (2DEG) through the substitution of the TiN compound with a smaller area Au dominated penetration. Concurrently, in contrast to TiN, Au exhibits a diminished capacity for Ga dissolution, thereby substantiating its efficacy in preserving the structural integrity of the crystal lattice. In addition, the reduction of Al can impede the diffusion notably, further showing the smooth surface morphology of the electrode with atomic force microscope (AFM) and scanning electron microscopy (SEM) measurements. The ohmic contacts of HEMTs are individually fabricated with Ti/Al/Ni/Au and $TiAl_3$/Au configurations. The HEMTs with $TiAl_3$/Au ohmic contacts demonstrate superior DC characteristics.

Key Words: High Electron Mobility Transistors (HEMTs); Ohmic contact; TiAl alloy; Surface morphology;

Current-voltage characteristic

最终交流类型: 墙报

D32-P08

Maximizing the Energy Conversion of Triboelectric Nanogenerator Through the Synergistic Effect of High Coupling and Dual-track Circuit for Marine Monitoring

Ying Lou , Mengfan Li , Aifang Yu , Junyi Zhai *

Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

The wave energy harvesting efficiency (EHE) and electrical energy storage efficiency (ESE) significantly impact ocean power at the front-end and back-end stages, respectively. In this work, to maximize the overall energy conversion affected by these two factors, a clip-like structured pendulum coupled nanogenerator (CP-CNG) integrated with a dual-track circuit (DTC) is elaborately designed to address poor energy conversion of the TENGs for marine monitoring. The optimized EHE was realized through coupling one freestanding triboelectric nanogenerator (FR-TENG) unit and two electromagnetic generator (EMG) units into two contact-separation triboelectric nanogenerator (CS-TENG) units. The space utilization rate of CP-CNG can be as high as 91.9%. Meanwhile, increased ESE is achieved by integrating DTC as voltage regulators, which perform backend energy management for CS-TENG and EMG, respectively. It is worth noting that for a 1 mF capacitor, the stored energy via the cooperation of CP-CNG and DTC can reach 60.7 mJ in 110 s, which is about 164 times that of CS-TENG (0.37 mJ) coupling with FR-TENG and EMG and 1.6 times that of CS-TENG (36.8 mJ) with buck circuit, demonstrating excellent synergistic effects. Owing to the synergistic effect, one CP-CNG can continuously drive four thermohygrometers under simulated water wave conditions. In additional, a hazard alarm system, including an immersion sensor, Bluetooth and gateway support, can also be powered by one CP-CNG successfully. This work develops a state-of-the-art concept for maximum energy conversion of TENGs, which should have a profound impact on the design of high-performance TENGs in the future.

最终交流类型: 墙报

D32-P09

基于材料改性与电荷泵浦的超高输出摩擦纳米发电机

李泽坤，翟俊宜

北京纳米能源与系统研究所，北京，101400

在实现摩擦纳米发电机(TENG)大规模工业化制造的路上，进一步提升 TENG 的输出是永恒的追求。受到自然界中广泛存在的协同效应的启发，一种基于材料内部改性和外部电荷泵浦模块集成协同效应的超高输出纳米发电机被提出。精心选择的聚(偏二氟乙烯-co-六氟丙烯)(P(VDF- HFP))薄膜因其具有强极化和高介电常数，因此具备优异的摩擦发电性能并且其电学性能可以进一步被掺杂的钛酸钡纳米颗粒($BaTiO_3$)所增强。同时，精心设计和优化的电荷泵浦模块可以泵浦充足的电荷。作为结果，使用 8 微米厚的复合薄膜所制备的电荷泵增强的 TENG 可以输出 3.5 mC/m^2 的电荷密度。与使用复合薄膜制造的普通 TENG 和纯 P(VDF- HFP)薄膜制造的电荷泵增强 TENG 相比，复合薄膜电荷泵增强 TENG 的输出远超二者之和，进一步说明了了基于协同效应制备高性能发电机是合情合理且成功的。除此之外，一个基于协同效应的电荷转移模式被提出用于说明内部材料改性和外部泵浦模块的角色。这项工作提出了一个用于设计高性能 TENG 的前沿概念，为高输出 TENG 的制备提供新见解。

最终交流类型: 墙报

D32-P010

High-Coupled Magnetic-Levitation Hybrid Nanogenerator with Frequency Multiplication Effect for

Wireless Water Level Alarm

Mengfan Li , Ying Lou , Aifang Yu , Junyi Zhai *
Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

Hybrid nanogenerators (HNGs) represent a promising avenue for water energy harvesting, yet their commercial viability faces hurdles such as limited power output, poor coupling, and constrained operational lifespans. Here, this paper introduces a highly coupled triboelectric-electromagnetic magnetic-levitation hybrid nanogenerator (ML-HNG) that shows great potential for water energy harvesting. The ML-HNG fulfills the challenges of high power output, strong coupling, and long operational lifespans. Based on the principle of like-pole repulsion of permanent magnets, the ML-HNG is designed to maximize the energy harvesting efficiency. During the contact-separation process of the triboelectric nanogenerator (TENG), the changing magnetic flux in the electromagnetic generator (EMG)'s coils generates a potential difference between the coils and Cu electrodes. The unique design of the ML-HNG employs a shared coil electrode configuration, which enhances the coupling without adding extra volume. This integration allows the ML-HNG to achieve multifrequency vibrations and multiple output cycles per external longitudinal movement, a phenomenon known as the frequency multiplication effect. As a result, the ML-HNG produces a total energy output of 0.60 mJ, which is 1.7 times greater than the fundamental frequency energy. With an average power density of 1.69 W m^{-3} in water, the ML-HNG provides continuous power for thermo-hygrometer and can quickly drive a wireless water level alarm system within a minute. This groundbreaking hybrid nanogenerator design holds significant promise for the efficient and consistent harvesting of low-frequency ocean wave energy, marking a substantial advancement in blue energy technology.

最终交流类型: 墙报
D32-P011

压电和磁双栅控铁电半导体晶体管

池梦霜
北京纳米能源与系统研究所，北京，101400

压电电子学是金属-半导体或半导体-半导体异质结界面上的压电极化与半导体特性之间的耦合效应。在压电半导体材料中，如第三代半导体 GaN、ZnO 和 SiC，以及二维过渡金属二硫族化合物（MoS_2, WSe_2）已经得到了很好的研究。得益于机械刺激和半导体特性的直接耦合，压电电子学不仅可以用于高灵敏度测量应变/应力，而且还可以通过施加的力提高电子设备的性能。然而，这些传统压电半导体的压电系数相对较小，从而阻碍了器件的实际应用。二维铁电半导体α-In_2Se_3 因其在室温下具有互锁的面内（IP）和面外（OOP）偶极子，可以将铁电性维持在几个原子层而引起了人们的关注。α-In_2Se_3 具有合适的带隙（≈1.39 eV）和较大的压电系数，被认为是一种很有前途的压电电子学材料。基于此，我们采用 Terfenol-D、氧化铝（Al_2O_3）和铁电半导体α-In_2Se_3 制备了一种压电和磁双栅铁电半导体晶体管（PM-FEST）。Terfenol-D 具有极大的磁致伸缩系数，在外磁场作用下可提供连续可调的拉伸或压缩应变。当磁场作用于 PM-FEST 时，Terfenol-D 的磁致伸缩被转移到粘附在其表面的通道层，可以利用铁电半导体中的极化电荷来调制局部肖特基接触。在低磁场（< 200 mT）下，基于α-In_2Se_3 的 PM-FEST 的最大电流开/关比高达 1700%。与传统的压电器件相比，PM-FEST 具有比压电半导体更高的 GF 值（2.3×10^4）。通过设计复合材料器件，在室温下利用压电和磁致伸缩合金的耦合在半导体中实现磁调制电子学的可能性。

最终交流类型: 墙报
D32-P012

Zn ionophores to suppress hydrogen evolution and promote uniform Zn deposition in aqueous Zn batteries

Xue Bai,Xiong Pu*

University of Chinese Academy of Sciences

Zn dendrites and side reactions such as Zn self-corrosion and hydrogen evolution reaction (HER) remain major challenges for the further development of aqueous Zn batteries (AZBs). In this work, macrolide antibiotics are proposed to be added in aqueous electrolyte, serving as Zn ionophores to modulate Zn solvation structure, regulate Zn electrodeposition and suppress undesirable parasitic reactions. Azithromycin (Azi) is demonstrated to undergo bidentate coordination with Zn ions and remodel the solvation structure. Meanwhile, the self-corrosion and HER at the Zn anode side are significantly suppressed, evidenced quantitatively by the on-line hydrogen production monitoring. Furthermore, the promotion of dense and uniform Zn electrodeposition by the ionophores is also confirmed. The repeated Zn plating/stripping test with 0.1 M Azi in electrolyte reaches a high cumulative capacity of 10 Ah at a current of 10 mA . Moreover, the corresponding pouch cell achieves stable operation for 100 cycles without bulging caused by gas evolution. Thus, our electrolyte engineering approach presents a practically viable strategy for the development of AZBs.

最终交流类型: 墙报

D32-P013

Self-adaptive and soft-contact ellipsoidal pendulum-structured triboelectric nanogenerator for harvesting water wave energy

Bingqi zhao,Yong Long,Weiguo Hu*

Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences

The growing global energy shortage has spurred extensive research into harnessing environmentally friendly clean energy sources. Water wave energy stands out as one of the most promising candidates in this endeavor. To effectively capture this abundant energy resource, highly efficient harvesting techniques are essential. Triboelectric nanogenerators (TENGs) have emerged as a notable solution for capturing low-frequency, large-scale, and random energy, drawing significant interest. However, traditional TENGs designed for wave energy harvesting face limitations due to their small contact area and incomplete separation. In this study, we propose a novel approach: a soft-contact and self-adaptive ellipsoidal-pendular-structured TENG (SSEP-TENG) specifically tailored for water wave energy harvesting. Unlike conventional spherical TENGs, the SSEP-TENG features a spring-actuated soft contact mechanism. This innovation not only enhances the contact area and reduces wear on the TENG but also facilitates a rapid and complete contact-separation process, thereby improving the device's overall performance. Furthermore, the synergy resulting from the two solid-solid contact-separations further enhances the SSEP-TENG's output performance. Importantly, we demonstrate the practical application of SSEP-TENG in maritime IoT, successfully powering a Global Positioning System (GPS) wireless positioning and tracking system. This includes accurately determining the longitude, latitude, altitude, and other location information of the tracked target. In summary, our research underscores the advantages of SSEP-TENG in efficiently harvesting wave energy and its potential for practical applications in renewable energy technology.

最终交流类型: 墙报

D32-P014

压电能带工程和柔性 AlGaN/GaN HEMT

胡卫国 *

中国科学院大学

AlGaN/GaN HEMT 是备受关注的新一代功率器件，在电力电子、功率射频等领域有着重要应用价值。自发/压电极化效应是 AlGaN/GaN HEMT 形成高浓度、高迁移率的二维电子气的关键因素。王中林院士指

出极化电场能有效调制器件能带结构，影响着量子跃迁、复合、载流子输运等关键物理过程，从而制约着电子、光电子器件的性能[1]。随着近年来人机交互技术和可穿戴电子设备的迅猛发展，压电极化效应也提供了微纳电子/光电子器件与外界机械应变实现有效、灵活、无缝交互的新途径，在智能传感、环境监控、物联网、人机交互等领域有潜在应用价值。

我们耦合压电本构方程-泊松-薛定谔方程，进一步发展了氮化镓压电能带理论；采用金属有机物化学气相沉积和湿法刻蚀技术，研制了柔性 AlGaN/GaN 高电子迁移率晶体管（HEMT）阵列；研制了 HfZrO 新型钝化层，降低漏电流，提高开关比；开发基于异向/同向的复合刻蚀技术，一次成型 AlGaN/GaN HEMT 微悬臂，借鉴生物的条件-非条件反射层级控制系统，实现微弱机械信号对大功率密度电力的直接、实时、可编程调控[2]。这些研究加深了我们对压电电子学的理解和认识，为优化 GaN 电力电子器件性能提供新途径，有望开拓其在自动驾驶、仿生机器人、自动控制等新应用。

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最终交流类型: 墙报

D32-P015

摩擦伏特纳米发电机的理论模型

郭鑫, 尤静, 魏迪, 邵佳佳*, 王中林

中国科学院北京纳米能源与系统研究所

基于摩擦伏特效应的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。