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D15. 微纳能源材料与器件

分会主席：王中林、翟俊宜、胡卫国、范凤茹、董凯

D15-01

基于碳管三维组装体的高性能滤波超级电容器

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高质量电子产品，需将交流转为稳定的直流电后供电。在此过程中，滤波电容不可或缺，它能滤除整流后电路中的纹波、平滑输出电压，确保高/精/尖电子器件的平稳运行，对一定频率交流电，器件容量越大，滤波效果越好。目前的滤波电容器是以铝电解电容为主。其比容量小、体积大，占据了电路板中的极大空间，制约了电子设备的小型化。所以，研制小型 滤波电容器，是人们追求的目标。超级电容器的比容量大，有望成为小型滤波电容器。它是通过电极与电解液的接触表面 存储电荷的。因此，常用表面积大的多孔碳基材料作电极，其比容量大。但离子在弯曲小孔中迁移慢，导致响应频率很低，不能滤波。如果能其提高响应频率，将是滤波电容器小型化的重要途径。

我们经过长期攻关，发明了垂直孔与横向孔相互连接的三维有序多孔阳极氧化铝模板，开创了用模板孔限域方法批量可控制备三维互连碳管组装体网格膜的新方法。以三维互连碳管网格膜作电极构筑了双电层超级电容器，不仅其响应频率与高性能的铝电解电容相当，而且比电容比铝电解电容高出两个数量级，同时其面比电容比国际同类器件的最高值高 25%，进而发现其滤波性能优于日本松下和尼康铝电解电容器，不仅解决了超级电容器不能滤波的国际难题，而且其体积仅是铝电解电容器的 1/25，因其能为集成电路与芯片等提供小型供电方案而入选 Chip 2022 中国芯片科学十大进展。

D15-02

基于界面摩擦起电的润滑状态监测与磨损失效预警设计

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在现代工业装备的运行中，摩擦磨损现象广泛存在并严重影响着关键部件的性能与寿命，对摩擦副的摩擦运动状态进行实时监测十分重要。然而，这在实际操作中十分困难。特别是在一些严苛环境和极端工况下，传统检测或监测方法往往无法及时发现摩擦副的微小损伤，导致无法进行及时干预，进而增加了设备的维护成本和故障风险。基于此，本报告提出了一种基于界面摩擦起电设计的润滑监测与失效预警新技术。摩擦过程伴随的摩擦起电现象，源于表面物质间电子转移，会积累电荷并产生电流信号。这种信号的变化于材料表面磨损的程度和磨损过程的动态特征息息相关。通过实时监测摩擦副在摩擦过程中的电流变化，可为机械装备的摩擦磨损提供一种便捷、快速、无损的检测手段。本研究利用摩擦起电跟摩擦界面的关系，构建了几种具有自感知特性的摩擦电智能润滑监测与预警系统。该技术通过实时捕获摩擦界面电荷变化情况，建立摩擦状态与摩擦电信号响应的对应关系，实现摩擦副磨损的在线预警。同时，结合自修复技术，为解决机械设备系统状态监测与自主修复一体化的难题提供了全新的解决思路。

D15-03

机电纤维材料及自供能可穿戴器件

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基于摩擦电效应机电转化纤维材料是新型机械能收集利用技术——摩擦纳米发电技术与传统纺织材料的无缝结合，不仅赋予了传统纺织以自主式供电和自驱动传感功能，而且保持了服装原有的透气、舒适和健康安全属性。针对基于摩擦电效应机电转化纤维材料的起电机制不清、电输出性能不高、自驱动传感品质不高和智能化应用场景有限等诸多关键科学技术问题，我们探究了基于特定聚合物纤维材料及其结构

的摩擦/接触起电机制，通过表界面材料改性、界面微结构调控、三维织物结构设计、直流发电模式设计、自充电技术等策略，提升了摩擦电效应机电转化纤维材料的输出功率密度和压力传感品质。借助于缠绕、涂覆、纺纱等纤维制备手段和机织、针织、编织等织物织造工艺，探索了高性能摩擦电效应机电转化纤维材料的规模化制备方案。通过电路管理、程序开发和界面设计，研究了摩擦电效应机电转化纤维材料在多种场合下的应用，包括可穿戴自充电发电衣、复杂人体运动识别、水下超声定位与追踪、生理信号监测与个性化健康诊断、智能安防系统、人机交互设备等，并积极推进摩擦电效应机电转化纤维材料的产业化应用。

D15-04

挠曲电电子学调控的 Si 基机电交互器件

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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。

D15-05

激光诱导石墨烯自供电器件的研究

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以湿度环境能源收集为代表的自供电器件，即是户外柔性高端电子装备开发的共性需求，又可成为重要的能源储备与能源供应器件。激光加工诱导石墨烯技术可通过光热光化学反应加工机理迅捷制备石墨碳/少层石墨烯，具有样品多样化、集成化定制化的特点，广泛的应用于石墨烯器件的开发过程当中。近年来，随着可穿戴设备、柔性机器人等高端装备的发展，具有湿度吸收能力的高导电性激光诱导石墨烯材料对于开发高性能、长续航的自供电器件方面具有明显的促进作用，并获得突破性成果。

本文主要研究内容如下：

（1）提出激光诱导石墨烯多维度加工工艺及石墨烯一体融合复合材料的成型方法：通过高能激光辐照带来的光热效应、光化学效应引起聚合物内部化学键的断裂及重排，揭示了可调控高精度（10~100 μm）、宽幅面（500×500 mm）的激光诱导多维度材料转化过程，为激光诱导石墨烯一维/二维柔性电子器件的开发打下技术基础。

（2）提出采用吸湿激光诱导石墨烯电极的自供电器件开发方法：针对湿度电能获取器件电学性能衰减这一共性问题，开展适用于 LIG 湿度电能获取设备的电能转化机制研究。通过数值仿真、材料半导体物理研究与器件性能调控相结合的方法，解决 LIG 湿度电能获取器件电学性能衰减的问题，提供高稳定性 LIG 湿度电能获取器件的开发方案，满足高端装备的定制化、自供电、长续航的湿度微能源器件的开发需求。

（3）提出激光诱导石墨烯折纸结构下的摩擦纳米发电机 TENG 设备开发方法：激光诱导石墨烯的多孔结构、跨尺度定制化电极加工以及石墨烯纸可折叠基底是开发集成 TENG 的优选方案之一，通过设计折

纸结构可实现赋予 TENG 优异的折叠性能、发电性能和传感能力，对于研究仿生结构自供电设备具有研究参考价值。

D15-06

从接触起电到生物医学：接触电动力疗法（CEDT）和摩擦电免疫疗法（TIT）的创建

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接触起电现象在各种界面上广泛存在。前期研究证实，在固/固、固/液界面的接触起电过程中会发生电子转移，从而诱发接触电催化（contact-electro-catalysis, CEC）生成活性氧（ROS）自由基。最近，我们在 CEC 反应机理研究方面取得以下进展：（1）建立了不依赖超声诱导的固/液 CEC 体系，证实了 CEC 反应的根本驱动力是接触起电诱导的界面电子转移机制，而非传统认识的水声分解机制，解决了 CEC 中自由基生成路径的争议；（2）开发了基于全氟碳（PFC）纳米乳的液/液 CEC 体系，证明了液/液接触起电也可诱导 CEC 反应，扩展了 CEC 催化剂的筛选范围，并且建立了一种全新的肿瘤治疗策略——接触电动力疗法（contact-electro-dynamic therapy, CEDT），将 CEC 催化技术拓展到生物医学领域。该疗法利用 PFC 纳米乳在超声波条件下生成的 ROS 自由基，实现肿瘤消融；（3）将摩擦起电理论与免疫治疗结合，创立了可穿戴自驱动无药物治疗策略——摩擦电免疫疗法(triboelectric immunotherapy, TIT)。该疗法利用直流摩擦纳米发电机(TENG)产生的静电击穿脉冲电流，诱导肿瘤细胞发生免疫原性细胞死亡，激活机体 T 细胞介导的抗肿瘤免疫反应，可以实现实体瘤的非药物消融。

D15-07

固液起电界面的电荷转移机制及催化效应

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固液带电界面广泛存在，常见于非均相催化中催化剂与溶液界面，电化学能源中电极与电解液界面等，对催化学科、能源化工产业等都具有重要意义。事实上固体与液体接触时，界面处会自发接触起电（又名摩擦起电），导致电子在固液界面转移产生带电界面，简称固液起电界面。该界面受机械力作用引起固液两相间发生电子转移，同时，还可能伴随相应的化学反应。本报告将分析固液起电界面的电子转移及催化机制，并从材料、激发方式和应用基础研究角度探讨这类新型的催化方法——接触电致催化。

D15-08

柔性自供电声学传感器用于语音识别

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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。与此同时，作为新兴的语音采集手段，柔性自供电声学传感器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。本文围绕高性能柔性自供电声学传感器的传感材料、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、长寿命的可穿戴柔性自供电声学传感器，成功地实现了聋人的语音交流和对复杂声学环境的抗性，为克服听障人群-健全人-物联网之间的交流障碍提供了初步的解决方法。

D15-09

High Energy Density Non-Contact Bidirectional Spinning Oscillating Float-type Triboelectric Nanogenerators for Energy Extraction from Irregular Waves

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The pursuit of sustainable and self-sufficient energy solutions has become critical for the advancement of marine Internet of Things (IoT) technologies. While triboelectric nanogenerators (TENGs) have shown great potential in harnessing high-entropy, low-frequency wave energy, their practical applications are hindered by low power output and issues related to frictional wear. Hence, this research presents a novel non-contact bidirectional spinning oscillating float-type triboelectric nanogenerator (OF-TENG) for efficient wave energy harvesting. Utilizing a planetary gear and bidirectional rotation structural design, low-frequency vertical wave energy with random and multi-directional conditions can be converted into high-frequency rotational energy. At a frequency of 0.5 Hz, the OF-TENG achieves a peak output power of 93.48 mW, and an average output volumetric power density of 31.3 W m^{-3}. Furthermore, the non-contact working mode ensures robust output stability, with no significant performance degradation observed after 5,680,000 working cycles. An intelligent self-powered marine ranching system for automatic feeding and water quality monitoring is further developed based on the OF-TENG. This work not only provides an effective solution for harvesting low-frequency wave energy, but also promotes the development of smart marine IoT technologies and marine agriculture.

D15-10

Tribo-induced Wireless Sensing, Visualized Sensing, and Tactile Sensing toward Embodied Intelligence

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Embodied intelligence involves AI systems that have a physical presence, such as robots, which must perceive their surroundings to make decisions and take actions. Sensors serve as the “eyes,” “ears,” and “skin” of these systems, allowing them to capture diverse sensory data from the environment. Tribo-induced sensing solution provides novel methods to convert the high-voltage electric signals to be wireless or optical signals, delivering the new method of wireless sensing through the optical way. As triggered by triboelectricity, such wireless sensing can be conducted in fully-self-powered manner through triboelectric discharge, and optical sensing can be done through triboelectrification-induced electroluminescence. In the meanwhile, triboelectricity can play as a new method in tactile sensing and tactile feedback as a fundamental phenomenon during touching. These studies will pave the road for tribo-induced sensing toward embodied intelligence.

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D15-11

基于仿生微纳孔材料的离子能量体系

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在自然界中，细胞膜上离子通道和离子泵中的精妙智能传输过程与信号传递，电位调控，能量转换与存储等多种生命活动息息相关。相关仿生体系的研究不仅对于我们理解生命体传质过程，而且对解决盐差能转换等相关应用领域中的关键瓶颈都有着重要意义。受生命体离子通道的结构与功能启发，我们构筑了基于仿生微纳孔材料的纳流离子传输膜，总结出了利用结构、电荷、以及界面浸润性协同作用调控离子传输进而实现功能性增强的新策略，并进一步将生命体以蛋白质离子通道为核心的能量机制引入到人工微纳米通道，构筑了多种高性能离子能量体系。

D15-12

摩擦电全向声学传感器：噪声环境下的高精度人机交互解决方案

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语音传感器在人机交互（HMI）系统中发挥着关键作用，但噪声环境下的全向声源识别仍具挑战性。本研究开发了一种自供电摩擦电立体声语音传感器（SVS），采用三维结构设计，具备出色的全向声源识别与追踪能力。该传感器的核心创新在于采用具有高电子亲和力和低杨氏模量的多孔振动膜材料，实现了 3172.9 mV Pa^{-1}的高灵敏度和 56.37 dB 的信噪比（SNR），频率响应范围覆盖 100~20,000 Hz。得益于其全向识别特性和可调谐共振频率设计，SVS 能在噪声环境中精确提取目标音频信号。实际应用测试表明，该传感器可同时识别会议系统中的多个说话者，并在自动驾驶场景中有效区分背景音乐和语音指令，展现了其在复杂声学环境中的卓越性能，为人机交互技术提供了新的解决方案。

D15-13

柔性单晶热电薄膜及器件

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热电技术是一种可以实现热能和电能之间直接相互转换的绿色能源转换技术。近年来，可穿戴电子设备和传感器迅速发展，对供能方式也有了更多的要求，柔性热电发电机可以利用人体与环境的温差进行发电，为穿戴电子设备的自供电提供有效的解决方案。Bi-Te 合金是低品位热量收集的理想候选材料，然而，无机材料固有的刚性和脆性阻碍了它们在新兴应用领域的适用性。因此，发展高性能 Bi_2Te_3 基柔性热电薄膜和器件是拓展热电技术新规模化应用的关键。

本研究采用传统的布里奇曼法和区熔法生长 p 型及 n 型 Bi_2Te_3 单晶，从相应单晶剥离出来的 Bi2Te3 薄膜在 1000 次弯曲周期内的良好柔韧性，且室温功率因子达到 4.2（p 型）和 4.6（n 型）mW m^{-1} K^{-2}。这种前所未有的可弯曲性归因于原位观察到的交错层结构，该结构在薄膜制备过程中自发形成，可在保持良好导电性的同时促进应力传播。此外，类施主交错层结构极少影响薄膜的载流子传输，从而保持了其卓越的热电性能。本研究的柔性发电机在 60 K 温差下显示出 321 W m^{-2} 的高归一化功率密度。研究结果为理解和推进传统无机电子学中的结构-性能相关性铺平了道路，同时为柔性电子设备的自供电提供了有用范例。

D15-14

基于黑磷光热效应构建多功能摩擦纳米发电机与传感系统

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物联网和 5G 技术的兴起推动了柔性可穿戴智能设备和柔性传感器件的快速发展。材料选择、组装机理以及结构设计是构建鲁棒性多功能微纳能源和传感器的重要环节。黑磷作为新兴的二维材料，具有出色的生物相容性和光热性能，被广泛应用于催化和生物医药等领域。拓宽黑磷基柔性传感器的多功能性具有重要意义。基于此，分别设计了单宁酸修饰黑磷纳米片（TAPB）参与的聚丙烯酰胺-琼脂糖基复合水凝胶和有机凝胶。其中，水凝胶表现出优异的导电性、拉伸性和透明度，作为柔性应变传感器应变灵敏因数为 1.97。该水凝胶作为柔性电极材料构建了多功能摩擦纳米发电机，输出功率密度为 149.8 mW m^{-2}，并在近红外光诱导下验证了其在保密通讯和信息防伪应用的可行性。制备的黑磷参与的丙烯酰胺-琼脂糖基复合有机凝胶，展现出优异的光热性能，和环境耐受性，基于其光热效应构建了光热非接触式传感器件。以上工作拓宽了黑磷基复合凝胶材料在柔性传感器和柔性摩擦纳米发电机领域的应用价值，为设计柔性可穿戴电子器件提供了一种选择。

D15-15

智能纤维材料及其可穿戴应用

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纤维材料在人类社会中扮演着重要的角色，从医疗保健到航空航天，从装备制造到休闲用品都有纤维的身影。随着科技的飞速发展，新型智能纤维在材料、纺织、电子等领域掀起了一场创新浪潮，吸引了大量研究人员致力于开发全新的功能纤维与智能织物。本报告将在纤维和织物层面引入新颖的功能性设计，以开拓更广泛的应用场景。基于本研究团队在智能纤维领域的研究基础，从加工性、舒适性以及功能性三个角度来探讨未来智能纤维的发展与现有技术之间的联系。通过在纤维加工与设计过程中，借助现有的熔融、湿法、静电纺丝等技术制备形态、功能各异的智能纤维。探讨体表微环境温湿度对人体舒适性的作用机制，解析纤维在人体与环境交互期间的演变规律。

D15-16

Triboelectric Nanogenerators Powered Hydrogen Production System Using MoS_2/Ti_3C_2 as Catalysts

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Hydrogen energy is an alternative to carbon-based fuels due to its zero pollution and high energy density. The electrolysis of water, driven by triboelectric nanogenerators (TENGs), is considered as a promising green method for hydrogen production. Two-dimensional transition metal carbides/nitrides can be used as catalyst carriers, through interface engineering to prepare molybdenum disulfide/titanium dioxide (MoS_2/Ti_3C_2) composites for accelerating the kinetics of hydrogen evolution reaction (HER). In this work, a multilayered rotating TENG (MR-TENG) was designed to convert rotating mechanical energy into electrical energy for constructing a self-powered hydrogen production system. MoS_2/Ti_3C_2 composites were utilized as electrodes for electrolyzing water, which can enhance the catalytic activity in the HER. The output performance of the MR-TENG and its managed charging performance when integrating with a constant voltage power management module were investigated. Besides the application demonstrations of powering a digital thermometer, an anemometer, and a commercial incandescent lamp, the power-managed MR-TENG was applied to generate electricity for water electrolysis, and realize a hydrogen evolution rate of 7.1 mL min^{-1} at the rotation speed of 90 rpm. This work provides an effective approach to the self-powered production of high-purity green hydrogen based on renewable blue energy utilization with important industrial application prospects.

D15-17

In-situ Turbulent Flow Sensing System for Aircraft Based on Airflow Induced Vibration Mechanism

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The national demand for intelligent manufacturing in the aviation industry drives technological innovation in key engineering materials. The era, driven by the dual engines of “domestic large aircraft” and “low-altitude economy,” has arrived, ushering in the independent innovation and development of China’s aircraft. Compared to various aircraft sensors that have reached high commercial maturity, research on surface turbulence flow sensing systems remains a global challenge: the stall issue resulting from indirect/non-in-situ monitoring currently stands as the primary cause of air disasters. This project addresses the need for monitoring aircraft safety flight parameters and enhancing flight efficiency, exploring the self-powered sensing mechanism of aircraft surface turbulence flow in a multi-physics open environment. It innovatively establishes a signal conversion and transmission model, developing lightweight, in-situ, near-zero power consumption wake-up technology for intelligent sensing of surface turbulence flow, suitable for various aircraft. By adjusting the secondary structure of positively charged silk fibroin materials, the modified electrodes attain high intrinsic surface charge density, ensuring continuous operation in high-altitude open environments. The sensing system enables near-zero power consumption operation and high signal-to-noise ratio signals for turbulence sensing arrays.

D15-18

采集热能的摩擦纳米发电机研究

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作为采集高熵能源的新兴技术，摩擦纳米发电机（TENG）近年来受到广泛关注。基于摩擦起电和静电感应原理，TENG 可高效采集周围环境中的各类低质量能源，如振动能、人体动能、风能、海洋波浪能等。当前，TENG 多为直接利用机械能，对于自然环境中存在的各种形式的低质量热能，还有待开发利用。针对周围环境低品位热能的采集，分别设计了基于水蒸发现象与环境温差驱动的摩擦纳米发电机，构建了热-力-电的自驱动能源系统，拓展了 TENG 的能量来源。采用“饮水鸟”结构，构建了一种通过水自然蒸发驱动的摩擦纳米发电机，可采集周围环境的热能转化为电能。通过结构优化、蒸发材料优化等策略，在自然蒸发条件下 TENG 的开路电压和短路电流分别达到 380 V 和 1.2 μA，并可实现持续输出。其次，利用热磁效应，发展了气-液界面自然温差驱动的热磁 TENG，通过温度梯度到机械运动的自动响应，实现热能向机械能的高效转化。将发电系统与热释电传感器结合，实现了自驱动环境感知与预警功能。

D15-19

面向人体健康管理的柔性可穿戴/可口服器件

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柔性可穿戴/可植入器件是一种针对人体健康管理的技术，具有轻便、柔性、舒适等可穿戴性特征，并能够实时准确地监测和评估人体生理和健康状态。在近年来，汗液发电备受关注，但该技术在为健康监测电子设备供电方面存在一定的挑战。为了解决这个问题，我们开发了一种基于汗液的发电机（SEG），该发电机可以通过汗液和电极之间的氧化还原反应生成电流和功率，而且使用单壁碳纳米管修饰电极可以提高其性能，并可实现无线心率传感和汗液乳酸的检测功能。除此之外，我们还研究出了基于无创胆结石治疗的新方案，使用柔性医疗微机器人来粉碎胆结石，为胆结石疾病的非侵入性治疗提供了新的方向。第三个工作，我们利用石墨烯基热电复合材料开发出了一种能够实现高灵敏度的应变和温度检测的传感器。这项技术对口腔保健和饮食习惯方面有着重要的判断和指导意义。总的来说，柔性可穿戴/可口服器件技术为健康监测电子设备、胆结石治疗及智能电子产品的发展提供了新的思路和方向。

D15-20

摩擦表界面行为对界面起电的影响机制研究及展望

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界面摩擦起电与表界面性质密切相关，有望作为新的摩擦学探针并发展新型的摩擦电传感技术。本报告介绍了黏附、摩擦、磨损、材料转移、润滑、双电层等表界面行为对摩擦起电的影响，揭示了二者之间的内在联系，并介绍了通过表面活性剂调控界面起电的方法。最后，对摩擦起电在未来摩擦学设计、监测、摩擦调控等研究的应用前景及发展趋势进行了展望。

D15-21

摩擦纳米发电机中静电击穿现象的调控和利用

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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。

D15-22

Synergistically Designed Carbon-based Hybrid Non-Contact Triboelectric-and-electromagnetic Nanogenerator with Ultralong Charge Retention for Wearable and Ambient Electromagnetic-waste Energy Harvesting and Self-powered Sensing

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Deformable triboelectric nanogenerators (TENGs) show great promise for wearables and human-machine interfaces, but limited output and friction losses constrain their practical application. Here, we present a highly efficient untethered carbon-based non-contact hybrid nanogenerator that combines triboelectric and electromagnetic (EM) induction to convert biomechanical and ambient EM-waste energy into available electricity while enabling self-powered non-contact sensing. It uses graphite-like powder to capture and transport tribo-charges, and graphite-like textiles as tribo-charge reservoirs and stretchable conductors for EM induction. Notably, the use of recycled cotton fabric as a starting material underscores a sustainable and eco-friendly approach to material sourcing. The synergistic designs significantly enhance triboelectricity output (288 V, ±1.23 μA, 4 Hz) and extend tribo-charge retention time beyond 10,000 min, achieving EM-induced electrification (±15 V, ±2.4 μA, 60 Hz). Even in non-contact condition, outputs remain 186.5 V (triboelectricity) and ±9 V (EM waste) at a 1-mm distance, effectively enabling the powering of electronic devices. To the best of our knowledge, this is the first reported non-contact stretchable nanogenerator that can simultaneously harvest both energy types. Moreover, the performance and tribo-charge retention time are superior to those of reported carbon (graphene, graphene oxide, C60)-functionalized non-contact TENGs. Last, a multiplexing self-powered touchless gesture-sensing system is demonstrated. These advancements hold significant potential for real-world applications, such as energy-efficient wearables for health monitoring, touchless human-machine interfaces in robotics, and sustainable self-powered sensors for environmental monitoring, offering efficient material and structural strategies for hybrid energy harvesting and sensing in next-generation devices.

D15-23

In-Situ Precipitation 3D Printing of Hierarchical Piezoelectric Nanogenerators with Tunable Porosity for Wearable Electronics

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Piezoelectric nanogenerators (PENGs) are highly desirable for sensing and monitoring biological signals in complex environments due to their superior performance, deformability, and facile fabrication.[1-3] However, conventional fabrication methods face challenges in simultaneously achieving macroscopic 3D architectures and microscale porosity, both of which are critical for maximizing local stress concentration and electrical output in PENGs. Here, we present an in-situ precipitation 3D printing (ISP3DP) technique to fabricate hierarchical polyvinylidene fluoride/barium titanate (PVDF/BTO) nanocomposites in a single step. This approach leverages a universal polymer-solvent-nonsolvent system, inducing phase separation through solvent exchange followed by in-situ ink solidification. By adjusting the ink concentration, 3D microarchitectural PENGs with tunable porosity can be readily fabricated. Finite element simulations and experimental results demonstrate that the interconnected air-filled pores locally concentrate stress at piezoactive sites, significantly enhancing electrical output. The optimized porous PENGs achieve a maximum peak-to-peak voltage of 50.2 V and a power density of 43.7 μW cm^{-2}. Furthermore, hollow cylinder PENG architectures printed via ISP3DP exhibit excellent flexibility and sensitivity, enabling real-time monitoring of human motion and automotive vibrations. This cost-effective and versatile printing strategy establishes a new paradigm for the scalable fabrication of 3D structured piezoelectric nanogenerators, advancing their integration into next-generation wearable electronics.

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D15-24

电荷自恢复驻极体多孔膜制备及其在摩擦纳米发电机中的应用

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驻极体材料近年来由于高电荷密度和应用范围广泛而成为学术热点。然而，驻极体材料的环境稳定性仍然是限制其应用中的一个重要问题。本研究制备了一种复合多孔驻极体薄膜（porous composite electret material film，简称 PCEM），该材料在浸水后表现出良好的电荷自恢复性能。PCEM 采用双层设计，下层为 PTFE 薄膜，上层为以 PTFE 纳米颗粒为填料、PDMS 为基体、乙醇为造孔剂的复合多孔膜。电晕充电后的 PCEM 电荷稳定性良好。PCEM 在水中浸泡后取出，其表面电位在 2 h 后恢复为其初始值的 94%；此外，PCEM 在相对湿度为 80%的环境下放置 6 h 仍能保持 83%的初始电位。为探究 PCEM 的结构和性能影响因素，我们针对 PCEM 的制备工艺进行了多组实验变量的探索，并结合等温电荷衰减模型探究了 PCEM 的电荷自恢复机理。最后，将 PCEM 组装成纳米摩擦发电机（TENG）时，能产生稳定周期性的电荷输出，并且该 TENG 在水浸泡后取出，输出性能也能在 2 h 后恢复到原来的 84%。该研究提供了一种制备简单、环境稳定性良好的复合多孔驻极体薄膜，为纳米摩擦发电机在高湿环境下的应用提供了新的思路。

D15-25

Fully Stretchable Microbial Fuel Cell with 75% Stretchability

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A decent stretchability is of paramount significance to operate microbial fuel cell (MFC) under mechanically dynamic conditions. However, it remains a grand challenge to fabricate fully stretchable MFC without compromising its power output. Here, using Shewanella oneidensis MR-1 as the model electrogenic bacteria, we demonstrate a prototype fully stretchable MFC device which can operate with a stretchability of up to 75%. Our design takes advantage of a stretchable and ion-conductive thermoplastic polyurethane membrane, which encapsulates the rGO-bacteria biohybrids on the PDMS anodic current collector for synchronous stretching. We discover that the living biohybrids can respond to the stretching/releasing stimulation by sustaining an adaptive bio-current output. Our design also employs a stretchable air cathode, which is fabricated by embedding Ag-Pt core-shell nanowires on PDMS substrate. The stabilized peak power density of the fully stretchable MFC device follows a slight increasing trend with the applied strain, and reaches 5.0 ± 0.7, 5.9 ± 0.9, 6.2 ± 1.1, 6.6 ± 1.4 W cm^{-2} at strains of 0%, 25%, 50% and 75%, respectively. Our results provide insights to design stretchable MFCs for future practical use.

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D15-P01

A Self-Adaptive Pendulum TENG for High-Efficiency Wave Energy Harvesting and Marine IoT Applications

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With growing global energy demands, water wave energy has emerged as a promising renewable solution. This study presents a soft-contact, self-adaptive ellipsoidal pendulum-structured TENG (SSEP-TENG) designed to overcome the limitations of conventional wave energy harvesters. Unlike rigid spherical TENGs, its spring-actuated soft-contact mechanism significantly enlarges the triboelectric interface while minimizing wear, enabling rapid and complete contact-separation cycles for enhanced power output. The dual solid-solid contact-separation synergy further boosts performance. As a practical demonstration, the SSEP-TENG successfully powers a self-contained maritime IoT system capable of real-time GPS positioning, transmitting longitude, latitude, and altitude data without external power. This work highlights the SSEP-TENG's superior wave energy conversion efficiency and its potential for autonomous marine monitoring applications.

D15-P02

Ultrafast and Low-Power 2D Bi_2O_2Se Memristors for Neuromorphic Computing Applications

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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.

D15-P03

摩擦电复合风轮发电性能与流动控制研究

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风致扭转颤振会严重影响桥梁的结构稳定性。改善桥梁表面的气动特性对于抑制这种扭转颤振具有重要的研究意义。通过研究具有宽厚比（B:D=5:1）的理想化矩形板模型，结合摩擦电发电理论，本文提出了一种将流动控制与能量收集特性相结合的多功能摩擦电风轮。实验结果表明，该摩擦电风轮不仅有效地抑制了矩形板颤振，这验证了摩擦电风轮在工程桥梁中作为降低风荷载气动控制件的应用潜力。同时摩擦电风轮将流场动能转化为电能，经过电路转换后，我们成果实现了摩擦电风轮为电容器储存能量，并为温度和湿度传感器持续供电。多功能摩擦电风力发电机为未来工程桥梁的振动抑制和智能维护提供了一种创新方法。

D15-P04

The Application of Gallium Nitride Power Devices in the Direction of Force-Electric Regulation

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As a typical high-power device, the core of GaN high electron mobility transistors (HEMTs) is that a quantum well is formed at the AlGaN/GaN heterojunction interface, which attracts and confines electrons, thereby creating a two-dimensional electron gas (2DEG) with high concentration and high electron mobility. Applying stress to GaN HEMT devices can change the polarization charge distribution at the AlGaN/GaN heterojunction interface through the piezoelectric effect, thereby improving the electrical output performance of GaN HEMT devices. Here, dry etching process is adopted to etch the microcantilever to minimize damage to the device. When external stress is applied to the HEMT device microcantilever, the electrical output performance of the microcantilever device is improved by approximately 10%. Therefore, external stress regulation can be used to control soft robots based on artificial muscles, achieving deformation processes at the millisecond level, providing a new idea for simulating the movement of biological organisms.

D15-P05

Effect of Barrier Layer Thickness on ScAlN/GaN High Electron Mobility Transistors on Silicon Substrate

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We report on DC performance of ScAlN/GaN high-electron-mobility transistors (HEMTs). The ScAlN/GaN heterostructures was epitaxially grown on a GaN template on a 4-in Si substrate by molecular beam epitaxy. The effect of ScAlN barrier thickness is investigated, and compared it with AlGaN/GaN HEMTs with similar structure. The thickness of ScAlN barrier layers is 10 nm and 20 nm. The fabricated ScAlN/GaN HEMTs showed clockwise hysteretic transfer curves with a wide threshold voltage tuning range of -3.21 V and -3.88 V, respectively. Due to the pronounced polarization gradient at the ScAlN/GaN heterojunction interface, the two-dimensional electron gas density is relatively increased by 40% and 44.8%, respectively. The results provide a basis for the research of rare earth element doped power electronic device.

D15-P06

基于 GaN HEMT 机械-热-电耦合机制的压电效应调制温度

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Gallium nitride (GaN) based high electron mobility transistors (HEMTs) are crucial candidates for high-power devices, exhibiting advanced properties such as high-voltage, large-current, and high-frequency. Nonetheless, the self-heating effect in GaN HEMT severely deteriorates its electrical performance, manifesting as the significant decline of saturation current and the diminution of device’s lifetime and long-term reliability. Piezotronics, an emerging domain within mechanical-electric coupling, offers innovative strategies for thermal modulation in GaN HEMT. However, the temperature regulation with piezotronics and mechanical-thermal-electric multi-physical field coupling mechanism remain unelucidated. Herein, we systematically delineate the modulation of device temperature characteristics introduced by piezotronic effect. Firstly, the steady/transient thermal processes were examined, revealing that the peak temperature occurs near the gate, primarily due to the carrier depletion effect of electric-field engendered by abrupt change in electric-potential. Subsequently, the application of external stress successfully reduces the device temperature, demonstrating the efficacy of temperature modulation through piezotronic effect. Furthermore, building upon piezotronics theory and simulations, the mechanism of electric and thermal field regulated by external stress is delved. The piezotronics modulates the device temperature by altering the two-dimensional electron gas (2DEG) concentration, and based on this, the mechanical-thermal-electric coupling mechanism model is constructed. This work integrates piezotronics theory with the thermal coupling field and provides novel perspectives and guidance for mitigating operational temperature and confronting power device dissipation challenges.

D15-P07

MXene-Graphene Oxide Hybrid Aerogel Microspheres Reinforced Coated Source Electrode for Droplet Energy Harvesting

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Energy harvesting technologies at the nanoscale based on the principles of friction initiation and electrostatic induction show great potential for energy distribution at low frequencies and low densities. Nevertheless, the choice of materials for the electrode layer is still largely limited to metals/metal oxides, and there is a need to develop electrode structures to achieve performance breakthroughs and expand the range of applications. Interestingly, multiple application scenarios (e.g., building-integrated rainwater energy harvesting through architectural coatings) require support for coating harvesting technologies and special material choices to directly reduce dependence on conventional fossil fuels. A flexible coated electrode has been designed that employs MXene-graphene oxide (GO) 2D nanostructured self-assembled composites with interlayer-reinforced microsphere lamellar structures with favorable performance characteristics similar to those of metallic electrode layers. Dielectric material polytetrafluoroethylene (PTFE) and coated source electrodes (SE) for droplet energy generating membranes (DEGMs) achieved a short-circuit current (I_{sc}) of 960 μA and a peak power density of 108 W m^{-2}. Development of the coated SE provides surface-coated droplet energy harvesting for deployment in green buildings and distributed Internet of Things (IoT) systems.

D15-P08

一种具有阳离子-π 相互作用的坚韧、高导电性和耐溶剂的多功能离子凝胶用于柔性可穿戴传感器

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Iongels have great potential in the field of flexible electronic devices due to their excellent ionic conductivity and flexibility. However, it remains the challenge to improve mechanical strength and conductivity simultaneously. Here, an iongel with cation-πinteractions are prepared via one-step photoinitiated polymerization of 2,2,3,4,4,4-hexafluorobutyl acrylate (HFBA) and acrylamide (AAm) in a hydrophobic ionic liquid [EMIM][TFSI] doped with polystyrene microsphere (PS). The abundant noncovalent interactions including hydrogen bonding, ion-dipole interactions and cation-π interactions endow the ionogels with excellent mechanical strength, high conductivity, and solvent-resistant capability. The cation-π interactions between the PS and the cation in ionic liquid ([EMIM]+) acts as a dynamic physical crosslinking point in the gel network, which can effectively improve the mechanical properties and conductivity of the iongel and optimize the ion transport channel at the same time. It is believed that the designed iongel has great application potential in wearable devices and ionotronics.

D15-P09

A Self-Powered Body Motion Sensing Network Integrated with Multiple Triboelectric Fabrics for Biometric Gait Recognition and Auxiliary Rehabilitation Training

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Gait analysis provides a convenient strategy for the diagnosis and rehabilitation assessment of diseases of skeletal, muscular, and neurological systems. However, challenges remain in current gait recognition methods due to the drawbacks of complex systems, high cost, affecting natural gait, and one-size-fits-all model. Here, a highly integrated gait recognition system composed of a self-powered multi-point body motion sensing network (SMN) based on full textile structure is demonstrated. By combining of newly developed energy harvesting technology of triboelectric nanogenerator (TENG) and traditional textile manufacturing process, SMN not only ensures high pressure response sensitivity up to 1.5 V kPa^{-1}, but also is endowed with several good properties, such as full flexibility, excellent breathability, and good moisture permeability. By using machine learning to analyze periodic signals and dynamic parameters of limbs swing, the gait recognition system exhibits a high accuracy of 96.7% of five pathological gaits. In addition, a customizable auxiliary rehabilitation exercise system that monitors the extent of the patient’s rehabilitation exercise is developed to observe the patient’s condition and instruct timely recovery training. The machine learning-assisted SMN can provide a feasible solution for disease diagnosis and personalized rehabilitation of the patients.

D15-P10

Microfiber-Based Triboelectric Acoustic Sensors Enable Self-Powered Ultrasonic Localization and Tracking Underwater

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Underwater ultrasonic detection is critical for marine security, playing a vital role in resource development, environmental protection, and national defense. However, existing detection systems, which primarily rely on active scanning technologies, are hindered by high costs, significant energy demands, and challenges in achieving large-scale deployment. Here, we introduce a microfiber-based triboelectric acoustic sensor (MTAS) featuring a core-shell hierarchical structure, offering a self-powered solution for precise measurement of underwater ultrasound source distance. By leveraging the principles of contact electrification/triboelectrification and electrostatic induction, the MTAS efficiently converts complex ultrasonic vibrations into real-time electrical signals. The MTAS demonstrates rapid response times as low as 8.6 μs, a high signal-to-noise ratio of 29.8 dB, and the capability to detect ultrasonic sources with power levels above 1.6 W via time-difference-of-arrival analysis. To address large-scale sea applications, we further propose a distributed network that integrates multiple MTAS units capable of precise ultrasonic source localization and real-time motion trajectory visualization. This innovation represents a transformative approach, combining self-powered operation, ease of deployment, and high imperceptibility, paving the way for large-area, energy-efficient submarine security systems. Such advancements redefine the paradigm of underwater target detection, aligning technological innovation with the pressing demands of marine safety and environmental sustainability.

D15-P11

Unveiling the Contact Electrification of Triboelectric Fibers by Exploring Their Unique Micro- and Macroscale Structural Properties

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The emerging triboelectric fibers or textiles have recently attracted widespread attention due to their unique wearable energy supply and self-powered sensing functions. However, the unique micro- and macrostructural effects of triboelectric fibers on contact-electrificaion (CE) have not been systematically studied, which result in the lower charge output compared to conventional film structure. Here, in order to provide theoretical guidance for designing high-performance triboelectric fibers with optimized structural designs, a systematic experimental measurement and theoretical analysis method is developed to explore the influence laws and potential mechanisms of the surface microstructural defects and overall macrostructural compositions of triboelectric fibers on their CE behaviors. It can be found that the surface microstructure defects contribute to increasing the total charge transfer, due to the increase in effective interface contact area. In addition, triboelectric fibers with core-shell coaxial structure prepared by uniform coating method have higher electrical output performance, which can ensure maximum contact between the conductive layer and the dielectric layer. This work provides a new research paradigm for studying the CE behavior and quantifying surface charges of complex structures, and suggests a multiscale structural design strategy for high-performance triboelectric fibers.

D15-P12

Highly Stretchable Kirigami-Patterned Nanofiber-Based Nanogenerators for Harvesting Human Motion Energy to Power Wearable Electronics

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Wearable electronics are advancing towards miniaturization and flexibility. However, traditional energy supply methods have largely hindered their development. An effective solution to this problem is to convert human mechanical energy into electricity to power wearable electronic devices. Therefore, it is greatly attractive to design flexible, foldable and even stretchable energy harvesting devices. Herein, we use the electrospinning and kirigami approach to develop a type of highly stretchable kirigami-patterned nanofiber-based triboelectric nanogenerator (K-TENG). Due to its innovative structural design, the K-TENG can achieve a tensile strain of 220%, independent of the tensile properties of the material itself. When a person swings their arms, the K-TENG fixed to the clothing can convert mechanical energy from human movement into electrical energy. The produced electricity can directly drive 50 LED lights and a digital watch, or be stored in a lithium battery to charge the smartwatch and smartphone, respectively. This study employs a new method to fabricate a stretchable triboelectric nanogenerator and demonstrates its promising applications in wearable power technology.

D15-P13

From One-Dimensional to Three-Dimensional, the Criss-Crossed Fiber Materials Forge High-Performance Lithium-Sulfur Batteries

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Lithium-sulfur batteries are considered the preferred system for high-performance batteries due to their high theoretical energy capacity density, environmental friendliness, and wide range of available sources of the active substance sulfur. However, the challenges inherent in lithium-sulfur batteries, such as polysulfide shuttling, sulfur insulation, lithium dendrites, and volume changes, have greatly impeded their progress towards commercialization. Fortunately, the inherent flexibility, lightweight nature, expansive surface area, and cost-effectiveness of fiber materials offer significant potential to tackle these challenges. In cathode, the layered structure formed by stacking fiber materials can effectively inhibit polysulfides and mitigate volume changes, thereby maintaining the stability of the cathode. In separator, fibers can help distribute lithium ions evenly, which can prevent the formation of dendrites and reduce the risk of puncture. In anode, the three-dimensional structure of the fiber materials can effectively guide the uniform distribution of lithium and also enhance the mechanical properties. The fiber-based interlayer is also present to inhibit the shuttling of polysulfides or guide the distribution of lithium ions. In this paper, fibers are categorized based on their conductivity, and the paper elaborates in detail on the effects of fiber types (such as carbon, metal, aramid, and glass fibers), structural designs (porous, hollow, core-shell, etc.), and modifications (elemental doping, metal-compound modification, and synergistic modification by elemental doping and metal compounds) on the electrochemical performance of batteries, as well as the mechanism of their effects in various position. Finally, an outlook on the evolution direction and existing troubles of flexible batteries are also given.

D15-P14

A Moisture-Proof, Anti-Fouling, and Low Signal Attenuation All-Nanofiber Triboelectric Sensor for Self-Powered Respiratory Health Monitoring

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Breathing is an important physiological health indicator of the human body. Real time and long-term monitoring with low attenuation of human respiratory health status is of great significance. However, the working performance of respiratory sensors typically placed at the mouth and nose of the human body is greatly affected by exhaled moisture and small pollutants. Here, an all-nanofiber self-powered respiratory sensor (ASRS) with a multi-layer stacking structure is developed based on contact electrification or triboelectrification effect. By spraying method to chemically graft low surface energy octadecyltrichlorosilane (OTS) small molecules onto the surface of nanofibers, the ASRS is endowed with excellent superhydrophobicity and self-cleaning properties, making it free from the influence of high humidity and small particle pollutants in exhaled gas. Due to the gradient variation of contact interface with increasing pressure, the ASRS exhibits a multi-stage linear sensitivity response trend, which has high pressure response sensitivity of 0.048 kPa^{-1}. In addition, the ASRS is further integrated on a smart mask for real-time and long-term monitoring of respiratory health status, including age and gender of subjects, physical activity status, and sleep apnea syndrome. This work provides an effective self-powered sensing strategy for daily physiological monitoring, proactive healthcare, and early disease warning.

D15-P15

An Intelligent Self-Powered Life Jacket System Integrating Multiple Triboelectric Fiber Sensors for Drowning Rescue

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The inherent unpredictability of the maritime environment leads to low rates of survival during accidents. Life jackets serve as a crucial safety measure in underwater environments. Nonetheless, most conventional life jackets lack the capability to monitor the wearer’s underwater body movements, impeding their effectiveness in rescue operations. Here, we present an intelligent self-powered life jacket system (SPLJ) composed of a wireless body area sensing network, a set of deep learning analytics, and a human condition detection platform. Six coaxial core-shell structure triboelectric fiber sensors with high sensitivity, stretchability, and flexibility are integrated into this system. Additionally, a portable integrated circuit module is incorporated into the SPLJ to facilitate real-time monitoring of the wearer’s movement. Moreover, by leveraging the deep-learning-assisted data analytics and establishing a robust correlation between the wearer’s movements and condition, we have developed a comprehensive system for monitoring drowning individuals, achieving an outstanding recognition accuracy of 100%. This groundbreaking work introduces a fresh approach to underwater intelligent survival devices, offering promising prospects for advancing underwater smart wearable devices in rescue operations and the development of ocean industry.

D15-P16

All-Fabric Direct-Current Triboelectric Nanogenerators Based on the Tribovoltaic Effect as Power Textiles

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The tribovoltaic effect is the direct-current (DC) output that results from sliding a p-type semiconductor on top of an n-type semiconductor, and it is caused by the electron-hole pairs generated. However, the rigid structure of traditional semiconductor limits its potential application in wearable fields. Here, p-type and n-type fabric with semiconductor properties are prepared by doping small organic molecules of cetyltrimethylammonium bromide and sodium dodecylbenzene sulfonate on the carbon atoms of single-wall carbon nanotubes (SWCNTs), and three all-fabric direct-current triboelectric nanogenerators based on the tribovoltaic effect (AFDC-TENG) are developed, which exhibit high flexibility, satisfactory comfort, and stable DC output. In addition, the effects of structural parameters and environmental factors on the electrical output of AFDC-TENG are systematically discussed. The output voltage, current, and power density of p-type AFDC-TENG can reach 0.2 V, 0.29 μA, and 45.5 mV m^{-2} at a maximum speed of 0.2 m s^{-1} and a sliding frequency of 1 Hz, respectively. This work proposes a simple and scalable design form for all-fabric DC power supply devices, which has potential applications in the future micro/nano energy or self-powered flexible sensors.