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纸基压力传感器的研究进展与应用前景

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摘 要

本篇综述主要介绍了纸基压力传感器的研究进展与应用前景。纸基压力传感器作为一种新兴的柔性传感器，因其低成本、可降解、柔韧性好等优点而受到广泛关注。本文首先介绍了纸基压力传感器的基本概念和工作原理，然后详细阐述了纸基压力传感器的制备方法，包括材料选择、结构设计和制造工艺三个方面。接着，探讨了纸基压力传感器在可穿戴设备、医疗健康和环境监测等领域的应用。最后，分析了当前面临的挑战，并展望了未来的发展方向。研究表明，纸基压力传感器在柔性电子领域具有广阔的应用前景，但仍需在灵敏度、稳定性和大规模生产等方面进行进一步研究。

关键词

纸基压力传感器，柔性电子，可穿戴设备，医疗健康，环境监测

Research Progress and Application Prospect of Paper-Based Pressure Sensor

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Abstract

This paper reviews the research progress and application prospects of paper-based pressure sensors. As an emerging type of flexible sensor, paper-based pressure sensors have attracted widespread attention due to their advantages such as low cost, degradability, and good flexibility. The article first introduces the basic concepts and working principles of paper-based pressure sensors, then elaborates on their preparation methods, including material selection, structural design, and manufacturing processes. Subsequently, it discusses the applications of paper-based pressure sensors in areas such as wearable devices, healthcare, and environmental monitoring. Finally, it analyzes the current challenges and looks forward to future development directions. Research indicates that paper-based

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pressure sensors have broad application prospects in the field of flexible electronics, but further research is needed in terms of sensitivity, stability, and large-scale production.

Keywords

Paper-Based Pressure Sensors, Flexible Electronics, Wearable Devices, Healthcare, Environmental Monitoring

1. 引言

随着物联网和智能设备的快速发展，柔性电子技术受到了广泛关注[1]-[3]。作为柔性电子领域的重要组成部分，压力传感器在可穿戴设备、医疗健康和环境监测等方面发挥着重要作用[4]-[9]。传统的压力传感器通常基于硅基材料，虽然具有高灵敏度和稳定性，但存在成本高、柔韧性差、不可降解等缺点。近年来，纸基压力传感器作为一种新兴的柔性传感器，因其低成本、可降解、柔韧性好等优点而备受关注[1] [10] [11]。

纸基压力传感器以纸为基底材料，结合功能性材料制备而成。它不仅继承了传统压力传感器的优点，还具有独特的优势。首先，纸是一种低成本、可大规模生产的材料，有利于降低传感器成本[1]；其次，纸具有良好的柔韧性和可折叠性，适合用于可穿戴设备[10]；再次，纸是可降解材料，符合环保要求[6]；最后，纸的多孔结构有利于提高传感器的灵敏度[11]。因此，纸基压力传感器在柔性电子领域具有广阔的应用前景[4] [5]。

本文旨在综述纸基压力传感器的研究进展，包括其工作原理、制备方法、应用领域以及面临的挑战和未来发展方向。通过系统梳理相关研究成果，为纸基压力传感器的进一步研究和应用提供参考。

2. 纸基压力传感器的基本原理

纸基压力传感器的工作原理主要基于压阻效应、电容效应和压电效应。根据不同的压阻机制，将压力传感器分为：压阻式、电容式和压电式压力传感器[12]-[14]。每种类型的传感器都有其独特的优点和局限性，适用于不同的应用场景。以下是对这三种类型纸基压力传感器的详细介绍：

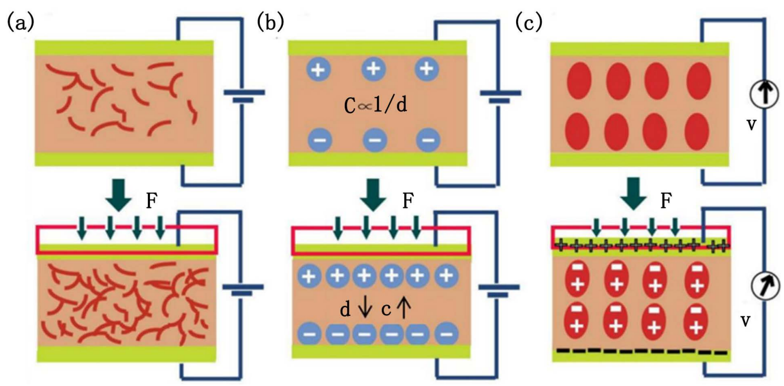

Figure 1. Types of flexible pressure sensors: (a) Piezoresistive; (b) Capacitive; (c) Piezoelectric
图 1. 柔性压力传感器的类型[12]-[14]：(a) 压阻式；(b) 电容式；(c) 压电式

压阻式纸基传感器利用材料的电阻随压力变化而改变的特性来检测压力，工作原理示意图如图 1(a)所示。在纸基压阻式传感器中，通常将导电材料(如碳纳米管[15] [16]，、石墨烯[17]等)涂覆或嵌入纸基中，当施加压力时，导电材料之间的接触面积或距离发生变化，从而导致电阻改变[18]。它的优点是对压力变化非常敏感，能够检测到微小的压力变化；结构相对简单，易于制备和集成；材料和制备工艺成本较低，适合大规模生产。但缺点是在长期的使用中，导电材料的电阻可能会发生变化，影响传感器的稳定性。压阻式传感器经常用于可穿戴领域(如监测人体运动和姿势)和医疗健康检测(如脉搏、呼吸频率)等领域[19]-[24]

电容式纸基传感器则是基于电容随极板间距和介电常数变化的原理。电容通过存储电荷来保持电能。它主要由两个平行的平板电极以及夹在它们之间的介电层构成。当受到外力(如拉力、压力等)作用时，电极之间的距离或者有效面积会发生改变，从而导致电容值发生变化。其工作原理示意图如图 1(b)所示。纸基电容式传感器通常采用纸作为介电层，在纸的两面涂覆导电材料作为电极。当施加压力时，纸的厚度发生变化，导致电容改变。压电式传感器利用某些材料在受到机械应力时产生电荷的特性来检测压力。在纸基压电式传感器中，通常将压电材料(如聚偏氟乙烯)与纸基结合，当施加压力时产生电荷，从而检测压力信号。该传感器具有高的分辨率和低功耗性，能够检测到非常小的压力变化，适合高精度测量，并且在工作过程中消耗的能量较少，适合电池供电的应用。局限性表现在需要多层结构，制备工艺相对复杂，而且灵敏度受到介电层材料和厚度的影响，难以实现高灵敏度和宽检测范围。对于应用领域方面，主要用于人机交互(如电子皮肤)和环境监测等领域[25]-[29]。

压电式纸基压力传感器主要由压电敏感材料组成，能将机械能和电能相互转换。它们的转导机理可以描述如下：当材料在外部压力下变形时，功能材料内部发生正负电荷分离。在材料的两个相对表面上，会出现相反方向排列的正负电荷，内部会形成电位差[30]，其工作原理如图 1(c)所示。它的优点是能够快速响应压力的变化，适合动态压力检测。缺点是压电材料的成本较高制备工艺复杂，并且不合适检测静态或缓慢变化的压力。对于三类纸基压力传感器的具体比较如表 1 所示

Table 1. Compares the advantages and disadvantages of different types of sensors
表 1. 不同类型传感器的优缺点比较

类型	灵敏度	稳定性	响应速度	成本	适用场景
压阻式	高	较差	中等	低	可穿戴设备、医疗健康监测
电容式	高	较好	中等	中等	人机交互、环境监测
压电式	高	中等	快	高	动态压力检测、能量收集

纸基压力传感器的性能指标主要包括灵敏度、响应时间、检测范围和稳定性。灵敏度是指传感器输出信号随输入压力变化的程度，通常用单位压力下的电阻或电容变化率表示。响应时间是指传感器从受到压力到输出稳定信号所需的时间，反映了传感器的动态响应能力。检测范围是指传感器能够准确测量的压力范围。稳定性是指传感器在长期使用过程中保持性能不变的能力。这些性能指标直接影响传感器的实际应用效果，因此是纸基压力传感器研究的重要内容。

3. 纸基压力传感器的制备方法

纸基压力传感器的制备方法主要包括材料选择、结构设计和制造工艺三个方面。在材料选择方面，纸基材料通常选用普通打印纸、滤纸或特种纸，这些材料具有多孔结构、良好的柔韧性和可降解性。功能性材料的选择则取决于传感器的工作原理，常用的材料包括碳纳米管、石墨烯、金属纳米线等导电材料，以及聚偏氟乙烯等压电材料。如图 2 所示，Yun T [31]等人创新性地采用羧甲基纤维素钠(CMC)离子

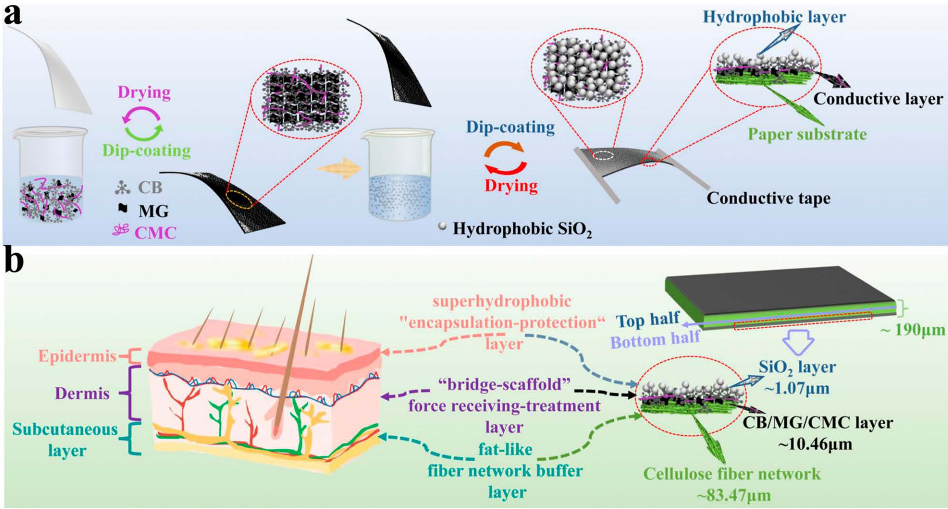

Figure 2. (a) Schematic illustration of fabricating superhydrophobic PB strain sensor and (b) the design concept inspired from the structure of human skin [31]
图 2. (a) 制作超疏水 PB 应变传感器的示意图和(b)受人类皮肤结构启发的设计概念[31]

作为桥连剂，增强炭黑(CB)与多层石墨烯(MG)之间的界面作用，并以 SiO_2 纳米粒子作为超疏水层，制备了一种具有超疏水性的纤维素纸(图 3)。所得到的纸基(PB)传感器显示出优异的应变感测行为、宽的工作范围(−1.0%至 1.0%)、超高灵敏度(GF = 70.2)和好的耐久性(>10,000 次循环)。

在结构设计方面，纸基压力传感器通常采用多层结构，包括电极层、敏感层和基底层。电极层用于收集和传输电信号，通常由导电材料制成。敏感层是传感器的核心部分，负责将压力信号转换为电信号。基底层则提供机械支撑和保护作用。为了提高传感器的性能，研究人员还设计了各种微结构，如金字塔形、圆柱形等，以增加传感器的灵敏度和检测范围。如图 3 所示，Han 等人[32]开发了一种基于 PDMS/Ag 微结构和粗糙 PI/Au 叉指电极的电阻式可穿戴压力传感器，该传感器基于低成本炭黑空气辅助纸复合材料，具有曲面和纤维网络设计。压力传感器具有高灵敏度(0~2.5 kPa 范围内为 259.32 kPa^{-1})、宽动态响应范围(0~54 kPa)、快速响应(≤200 μs)和低检测限(0.36 Pa)。

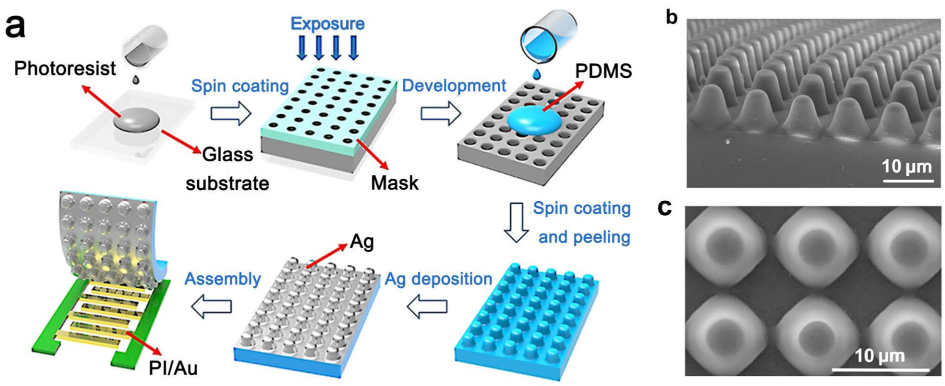

Figure 3. Pressure sensor with a roughened structural design. (a) Schematic illustration of the fabrication process of the rough-rough pressure sensors. (b, c) Cross-sectional and top-view SEM images of the conical frustum-like PDMS microstructures [32]
图 3. 具有粗糙结构设计的压力传感器。(a) Rough-Rough 压力传感器制造工艺示意图。(b, c)圆锥状 PDMS 微观结构的横截面和俯视扫描电子显微镜图像[32]

另外，Wang C 等人[33]提出了一种软硬结合设计策略来提高纸基压力传感器的传感性能，并将仿生

Figure 4. The main preparation processes of the paper-based pressure sensor
图 4. 纸基压力传感器的主要制备过程[33]

微结构引入传感器架构中以进一步改进，如图 4 所示。因此，制备的纸基压力传感器具有更快的响应/恢复速度(<50 ms)、较宽的触发感应范围(1 MPa)和频率响应带宽(0.05~1000 Hz)以及出色的循环稳定性(5000 次循环)。另外，基于出色的传感性能和防水性，该传感器在未来水下救援中显示出巨大的潜力。

制造工艺方面，纸基压力传感器的制备方法主要包括涂覆法、印刷法和浸渍法。涂覆法[34] [35]是将功能性材料溶液涂覆在纸基表面，然后通过干燥或热处理形成敏感层。印刷法[36] [37]则是利用丝网印刷或喷墨印刷技术将功能性材料图案化地沉积在纸基上。Jung M 等人[38]使用纸平台和喷墨打印的方式提出了一种高灵敏度，灵活，双峰纸基传感器，该传感器纸平台上构建了微金字塔结构和热电电路。浸渍法[39]是将纸基浸入功能性材料溶液中，使材料渗透到纸基的多孔结构中。Li A 等人[40]将得到的高耐湿性的封装纸浸渍了 MXene 悬浮液，得到具有微凸结构的传感器层，从而制造了一种具有高耐湿性和透气性的全纸基压力传感器。这些方法各有优缺点，研究人员需要根据具体应用需求选择合适的制备方法。

4. 纸基压力传感器的应用领域

纸基压力传感器在多个领域展现出广阔的应用前景。在可穿戴设备方面，纸基压力传感器可用于智能手环、智能服装等，实时监测人体运动状态和生理信号[41] [42]。例如，将纸基压力传感器集成到鞋垫中，可以监测步态和足底压力分布，为运动分析和康复训练提供数据支持[43]。在智能服装中，纸基压力传感器可以检测呼吸、心跳等生理信号，实现健康监测[44]。

在医疗健康领域，纸基压力传感器可用于电子皮肤、健康监测设备等。电子皮肤是一种模仿人类皮肤功能的柔性传感器阵列，可以检测压力、温度等多种刺激。纸基压力传感器因其柔韧性和生物相容性，是制备电子皮肤的理想材料。在健康监测方面，纸基压力传感器可用于脉搏检测和血压监测等，为疾病诊断和健康管理提供便利[45] [46]。

在环境监测领域，纸基压力传感器可用于智能包装、结构健康监测等。在智能包装中，纸基压力传感器可以检测包装内部的压力变化，实时监控食品或药品的保存状态。在结构健康监测方面，纸基压力传感器可以嵌入建筑物或桥梁中，监测结构的应力分布和变形情况，为结构安全评估提供数据支持。

此外，纸基压力传感器还可应用于人机交互、机器人等领域。例如，将纸基压力传感器集成到触摸屏或键盘中，可以实现更自然、更灵敏的人机交互。在机器人领域，纸基压力传感器可用于机器人皮肤的制备，提高机器人的环境感知能力。

5. 纸基压力传感器的挑战与展望

尽管纸基压力传感器展现出巨大的应用潜力，但仍面临一些挑战。首先，在性能方面，如何提高传感器的灵敏度、响应速度和稳定性是亟待解决的问题。目前，许多纸基压力传感器的性能仍落后于传统硅基传感器，限制了其在高精度测量领域的应用。其次，在大规模生产方面，如何实现纸基压力传感器的低成本、高效率制造仍是一个挑战。现有的制备方法大多局限于实验室规模，难以满足工业化生产的需求。

未来，纸基压力传感器的研究可以从以下几个方面展开：第一，开发新型功能性材料，如高性能导电材料、压电材料等，以提高传感器的性能；第二，优化传感器结构设计，如引入微纳米结构、多层结构等，以增强传感器的灵敏度和检测范围；第三，探索新的制造工艺，如丝网印刷、3D 打印等，以实现传感器的大规模生产；第四，拓展传感器的应用领域，如将其与人工智能、物联网等技术结合，开发智能感知系统。

此外，纸基压力传感器的环境友好特性也值得进一步研究。例如，开发完全可降解的纸基压力传感器，探索其在一次性医疗设备、环境监测等领域的应用。同时，研究纸基压力传感器的回收和再利用方法，以最大限度地减少电子废弃物对环境的影响。

6. 结论

纸基压力传感器作为一种新兴的柔性传感器，因其低成本、可降解、柔韧性好等优点，在可穿戴设备、医疗健康和环境监测等领域展现出广阔的应用前景。本文综述了纸基压力传感器的基本原理、制备方法、应用领域以及面临的挑战和未来发展方向。研究表明，尽管纸基压力传感器在性能和大规模生产方面仍面临一些挑战，但通过材料创新、结构优化和工艺改进，有望实现性能提升和工业化生产。未来，纸基压力传感器有望在柔性电子领域发挥更重要的作用，为智能感知和物联网技术的发展提供新的解决方案。

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