

激光与光电子学进展

基于光电子技术的智能可穿戴纺织品

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摘要 近年来光电子技术飞速发展,在各领域发挥重要作用,尤其在能源和传感领域有较大突破。与此同时,智能可穿戴作为智能终端产业下一个热点已被市场广泛认同,将光电子技术应用于纺织领域制备智能可穿戴设备是一个必然的趋势。纺织材料的柔性、可穿戴性及成熟的加工技术使其成为了智能电子设备的优良载体,结合光电子技术,智能纺织品可具备多种附加功能,包括传感、集能、交互等。重点讨论和总结基于光电子技术的智能可穿戴纺织品的分类、发展及应用,以便更好地与传统纺织结构或技术融合,推进智能纺织品在各个领域的发展。

关键词 光电子技术; 可穿戴纺织品; 传感; 集能

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Wearable Smart Textiles Using Optoelectronic Techniques

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Abstract Optoelectronic techniques have developed rapidly in recent years and play a crucial role in various fields, particularly energy harvesting and sensing. The smart wearable device has also gained widespread acceptance by the market as the next hotspot of smart terminal industry. In order to fabricate intelligent wearable devices, optoelectronic techniques will inevitably become more prevalent in textile industry. The advantages of textile material, including flexibility, wearability, and mature processing technology, make it an excellent carrier of intelligent electronic devices. Based on optoelectronic techniques, intelligent textiles can achieve a variety of additional functions, such as sensing, energy harvesting, and interaction. Therefore, this paper summarizes the classification, development, and application of smart wearable textiles based on optoelectronic techniques, which can better integrate with traditional textile structure and technology, thereby promoting the development of smart textiles in various fields.

Key words optoelectronic technique; wearable textile; sensing; energy harvesting

1 引言

随着人类进入信息时代,人们对可穿戴电子产品的舒适性、多功能性和审美价值的要求越来越高,而传统的可穿戴电子产品缺乏灵活性、柔软性和透气性,并不适合长期使用。为了适应时代的要求,智能纺织品发展迅速,成功将功能性、智能化、信息化结合起来以丰富人们的生活^[1-6]。可穿戴电子设备是智能纺织中一个发展方向,其电子功能可以通过附加或内置技术无缝集成到纺织架构中,将纤维、纱线、织物作为载体,该类纺织品具有柔软、舒适、耐磨等特点,是人机交互设备理想的材料之一,并不会给正常的人类行为带来

额外的负担^[7-11]。

近年来在国家宏观经济调控的作用下,我国纺织行业发展迅速,《纺织工业“十三五”科技进步纲要》提出研究智能纺织材料多重结构设计和调控机理,开发可穿戴柔性电子元件,加快研发智能纺织品,突破柔性导电纺织材料关键技术,建立示范生产线。所以未来纺织工业材料必然往新型环保、可持续、智能化方向发展。

智能纤维、纱线、织物是能对环境中的光、热、电等产生感应的纺织品^[11-18],比如光纤对光学信号具有传导功能和良好的响应特性,广泛用于信号通讯探测领

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域。导电智能纺织材料由于具有优良的导电性能和导热性能,可应用于防静电服、防电磁辐射服、智能纺织品及军工纺织品等领域^[19-22],其中可触屏手套即是通过在面料中植入导电智能纤维实现的^[23-25]。

智能可穿戴纺织品目前存在多信号源干扰、传感响应效率低、复合成型技术不成熟等问题,限制了相关产品的推广使用,如果以上瓶颈得以突破,社会效益和经济效益不可估量。本文从光和电两个方向介绍了基于柔性光电子技术^[26-29]的智能可穿戴纺织品的相关研究,包括电致发光纤维、光敏变色纤维、光导纤维及智能发电纺织材料在超级电容器、传感器及光伏织物领域的应用和发展,以便更好地与传统纺织结构或技术融合,推进智能纺织品在各个领域的发展。

2 电致发光纤维

电致发光(EL)是通过加在两电极的电压产生电场,被电场激发的电子碰击发光中心,以致电子在能级发生跃迁、变化、复合从而导致发光的一种物理现象。电致发光物料的例子包括掺杂了铜和银的硫化锌和蓝色钻石。目前电致发光的研究方向主要为有机材料的应用^[30-36],也逐渐应用到纺织领域^[37-42]。显示器是现代电子学的基本组成部分。将显示器集成到纺织品中为智能纺织品提供了一个改变人与电子设备交互方式的机会。纺织品可以作为电子显示器与人机交互的桥梁,为有声音或语言障碍的人提供实时交流工具^[43-44]。

2017年,Zhang等^[45]开发了一种新型的轻质可拉伸电致发光织物,如图1(a)所示,其最高亮度超过 $70\text{ cd}\cdot\text{m}^{-2}$ 。

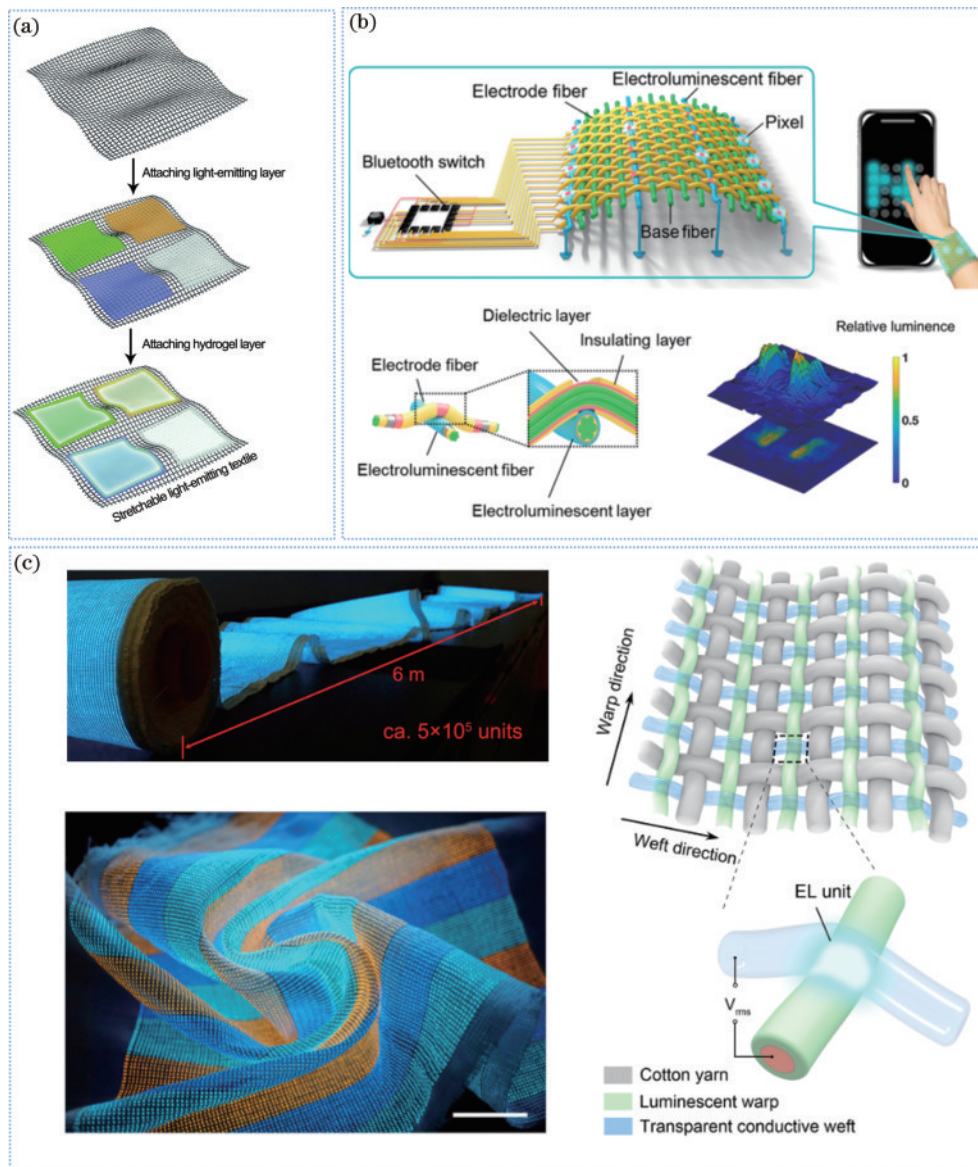


图1 电致发光纤维。(a)可拉伸发光织物的制备流程及示意图^[45]; (b)可伸缩发光织物的制备流程及结构示意图^[46]; (c)发光织物的实物图及结构示意图^[47]

Fig. 1 EL fibres. (a) Fabricating process and schematic diagram of stretchable luminescent fabric^[45]; (b) fabricating process and structural schematic diagram of stretchable luminescent fabric^[46]; (c) photograph and structural schematic diagram of luminescent fabric^[47]

在每秒 100% 应变、10% 应变拉伸速度下拉伸 100 次后,可拉伸发光织物的亮度仍可保持为原本的 98.5%。该可拉伸发光织物进一步集成了不同颜色的发光模块。它还能够检测外部刺激,如压力,伴随着这种检测的视觉反馈。2021 年, Mi 等^[46]报道了一种由超伸缩纤维(伸缩率为 400% 的电致发光纤维,伸缩率为 250% 的电极纤维)编织的电致发光织物,其可以通过手机应用程序实现基于像素的任意可控图案显示,如图 1(b)所示。为了实现超延展性,研究者将液态金属包裹在聚氨酯芯(高弹性)上制成这些纤维。为了实现任意控制,设计了由 ZnS 基电致发光纤维和垂直电极纤维组成的平纹编织结构。电致发光光纤与电极光纤之间的交叉点形成可独立开关的像素,进一步形成基于像素的任意可控图案显示。通过掺杂不同的元素, ZnS 基电致发光纤维可以发出绿色、蓝色或黄色的光。同时,这些纤维的制造采用了浸渍涂层,这是一种可扩展的制造方法,不需要高温或真空条件。2021 年,复旦大学高分子科学系教授彭慧胜领衔的研究团队^[47]成功将显示器件的制备与织物编织的过程融合起来,在 高分子复合纤维交织点集成多功能微型发光器件,揭示了纤维电极之间电场分布的独特规律,实现了大面积柔性显示织物和智能集成系统。该团队着眼于研制两种功能纤维,包括负载有发光活性材料的高分子复合纤维和透明导电的高分子凝胶纤维,两者在编织过程中的经纬交织形成电致发光单元,并通过有效的电

路控制实现新型柔性显示织物,如图 1(c)所示。

目前,电致发光纤维已在信息交互、智能穿戴、潮流装饰等领域发挥重要作用,但是大部分研究都集中于将电致发光纤维直接用于织物的制备,或者采用涂层方式将电致发光材料附着于织物表面获得发光功能,制备方式较为局限,且工艺复杂,成本较高,难以量产。因此,基于发光原理,借助纺织成熟工艺、新型纺丝技术及纺织材料,简化制备工艺流程、降低成本、提高穿戴舒适性是推进电致发光可穿戴纺织品产业化的重要需求。

3 光敏变色纤维

光敏变色纤维^[48-54]指在特定波长的光辐射作用下,纤维中一种热力学相对稳定的物质会转变成另一种物质,而在另一特定波长的光辐射作用下,这种物质又能恢复为初始物质,这个过程中由于物质的改变纤维颜色发生可逆变化的纤维^[55-59],也称为光致变色纤维。光敏变色纤维可对不同强度或波长的光辐射产生响应,因此可用于防护材料、辐射监测等领域。目前市场上光敏纤维主要用来制作防晒衣、眼镜等防护材料。

Shen 等^[60]报道了一种简单的一步湿纺丝方法,通过将红色发光的 $Y_2O_2S: Eu^{3+}, Mg^{2+}, Ti^{4+}$ 荧光粉和螺旋体聚糖染料集成到醋酸纤维素(CA)基体(LPCA)中,制备具有可逆光致变色性能的红色持久发光纤维,该纤维具有良好的抗循环疲劳性能,如图 2(a)所示。此外,该纤维在激发后表现出优异的红色持续发

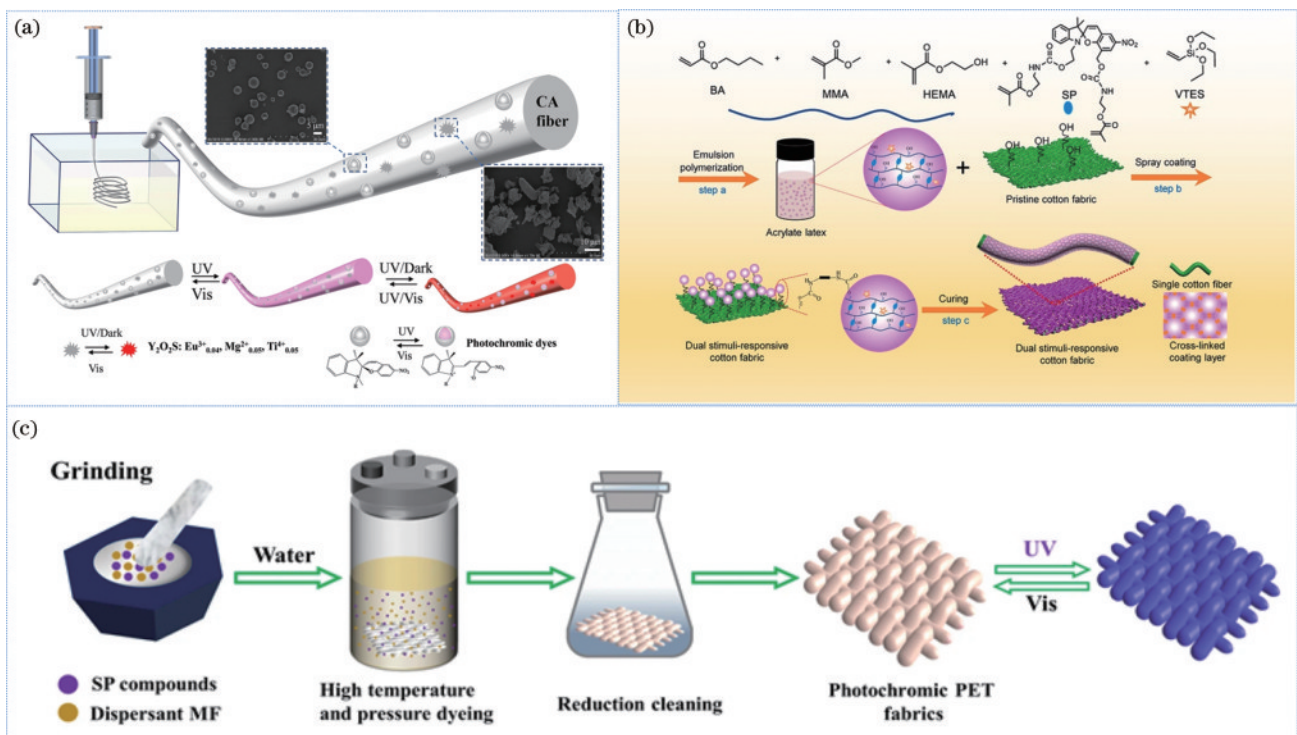


图 2 光敏变色纤维。(a) 光敏变色纤维的制备流程^[60]; (b) 光敏变色和机械致变色双刺激响应织物的制备流程^[61]; (c) 光敏变色织物的制备流程^[62]

Fig. 2 Photosensitive color changing fibres. (a) Fabricating process of photochromic fibre^[60]; (b) fabricating process of a dual-stimuli responsive (photochromic and mechanochromic) fabric^[61]; (c) fabricating process of the photochromic fabric^[62]

光性能,可以用简单的方法制造,并且在智能纺织品和信息加密领域具有良好的发展前景。Wang 等^[61]开发了一种光致变色和机械致变色双刺激响应织物,并将其作为柔性可重写介质或显示衬底,在棉织物上喷涂不同成分和添加率的乳胶,如图 2(b)所示。经 50 次皂洗和 20 次光照射后,功能化棉织物在无墨书写下仍能变色。即使经过多次洗涤,该柔性棉织物也可以作为高效、稳定的柔性显示基板使用。Zheng 等^[62]通过引入柔性间隔剂,设计并合成了一系列具有不同自由体积基的含螺吡喃光致变色分子,使得烷基链较长的分子的光致变色平衡时间由 330 s 缩短至 60 s,恢复平衡时间由 480 s 缩短至 40 s,如图 2(c)所示。将所设计的光致变色分子应用于涤纶织物,该涤纶织物获得了良好的光敏性和可逆性,在智能纺织品、光学器件、防伪等领域具有潜在的应用前景。

光敏变色纤维可满足人们对服装高档化、个性化的需求,具备较高的附加值和高效益,近年来发展迅速。其主要制备方法包括对织物进行印花、染色,或者采用溶液纺丝与熔融纺丝。虽仍然面临稳定性、耐久性与响应速度难以平衡的困境,随着高新技术的出现,光敏变色纤维会继续发展并改善目前的缺陷,广泛应用于装饰材料、时尚服装、防伪技术及军用纺织品等领域。

4 光导纤维

光导纤维简称光纤,是一种把光能闭合在纤维中而产生导光作用的光学复合材料,具有感知和单向传输功能,实际指由透明材料制成纤芯,在它周围采用比纤芯的折射率稍低材料制成包层将其包覆,射入纤芯的光信号经包层界面反射,使光信号在纤芯中传播前进的媒体,而透明状的电极材料是制备这些光电子器件的关键材料^[63-67]。

光纤从 20 世纪 60 年代进入工业生产以来,理论研究和生产工艺都迅速发展。光纤具备通信容量大、成本低、绝缘、抗干扰、耐腐蚀、柔性等优势,相当适用于易燃易爆、高温高压和辐射等领域,具有广阔的应用前景^[68-69]。同时,光纤因灵敏度高、响应速度快等优点,成为智能可穿戴传感器制备的新解决方案^[70]。与电子传感器类似,光纤传感器也可用于检测人体运动和生理信号,如心跳和呼吸。然而,大部分研究均将光纤传感器集成到服装中用于照明或加热,较少应用到聚合物纤维传感器上直接与人体相连进行身体运动监测或健康监测等^[71-75]。

2017 年,Quandt 等^[76]报道了一种基于光纤织物的反射式连续心跳和血流监测传感器,如图 3(a)所示。通过在纺织品上绣入熔融聚合物纤维,优化了纤维的

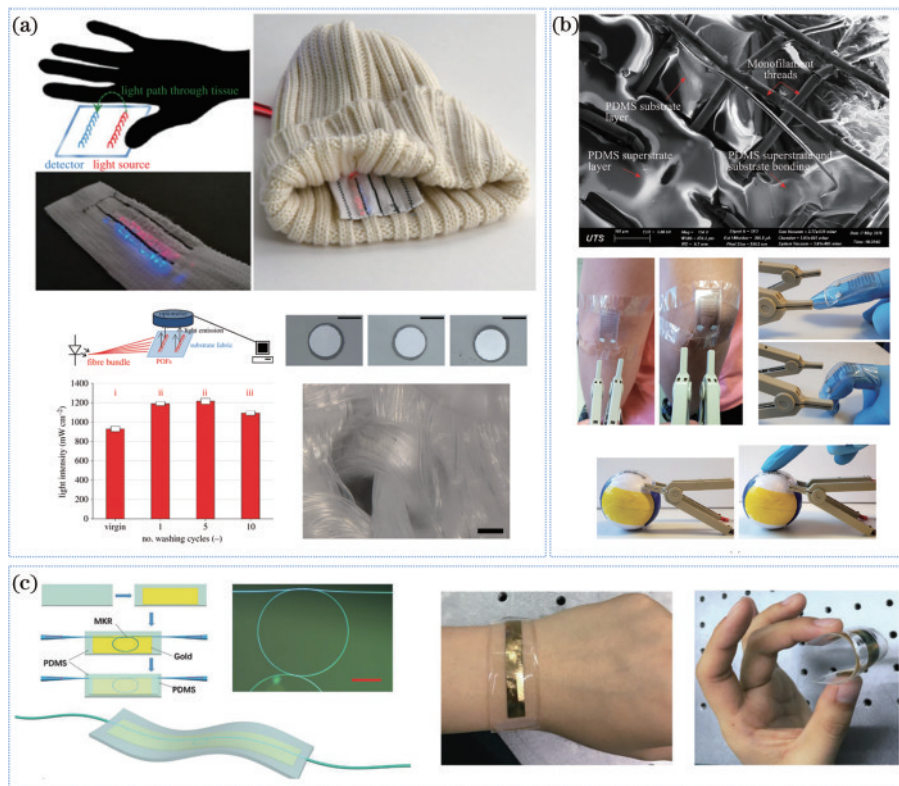


图 3 光导纤维。(a) 反射模式下的传感器原理图、照明时的传感器实物图、抗洗涤性能及光纤的三维显微镜图像^[76]; (b) 透明导电织物的扫描电镜图和传感器作为可穿戴应变传感器的应用^[77]; (c) 可穿戴传感器的制作工艺、显微镜图像、示意图及其柔性^[78]
Fig. 3 Optical conductive fibre. (a) Schematic diagram of the sensor in reflection mode, photograph of the sensor under illuminating state, anti-washing performance, and three-dimensional microscope image of the optic fiber^[76]; (b) SEM of transparent conductive fabric and the application of the wearable strain sensor^[77]; (c) fabricating process, SEM, schematic diagram, and flexibility of the wearable sensor^[78]

一系列参数,保证纤维的可靠性和均匀性。在干燥和出汗的条件下,与皮肤模型相比,该传感器纺织品显示出比传统使用的床单更低的静态摩擦系数,也可用于敏感皮肤状况和有压疮风险的患者的一般长期监测。2018年,Nag等^[77]提出了一种实现柔性透明应变传感器的新方法。它结合了透明导电织物与聚二甲基硅氧烷(PDMS),通过简单直接的逐层组装过程,采用导电织物实现透明电极的制备,采用PDMS作为衬底和封装层。作为概念演示,利用该方法设计和制造了一个数字电容式传感器。然后根据其透明度和机电性质来表征所制备的传感器。除了具有较高的光学透明度(70%)外,该传感器显示出较为精确的传感结果,这验证了所提出的方法在可穿戴传感应用中的适用性,如图3(b)所示。2018年,Li等^[78]报告了一种可穿戴光纤传感器的简单架构,它能够用于医疗保健的应变和压力检测,如图3(c)所示。所提出的传感器由嵌入在聚二甲基硅氧烷膜中的混合等离子体微光纤结谐振器组成,机械灵敏度比传统的电子器件或其他光纤器件高1个数量级以上。此外,还对腕部脉搏、呼吸和手指脉搏的传感进行了实验验证,结果表明该器件可以用于个性化诊断和生理监测,并为可穿戴传感器提供新的基础。由于具有嵌入智能服装网络和患者远程健康监测的潜力,这些具有良好生物相容性的传感器将在军事、航空航天和医疗应用中具有显著优势,特别是在高磁场环境中,例如磁共振成像。

相比传统的电子传感器,光纤传感器具备较高的

安全系数、不发热等优势,因此逐渐受到研究者的关注。当光在光纤中传播时,容易受到外界环境因素影响,如压力、位移、温度等外界条件的变化会引起光纤光强、频率、波长等参数的变化,参数的变化即为人机交互中传感的信号来源,可用于人体生理监测,具备较高的灵敏度。但如何实现光纤传感与纺织材料的一体成型,同时具备高效的传感性能与织物的机械稳定性和可穿戴舒适性,是光纤传感在智能制造中面临的一大难题。

5 智能发电纺织材料的研究现状

5.1 纺织基超级电容器

对智能电子产品日益增长的需求激发了安全可靠的储能设备的发展。在各种候选材料中,超级电容器(SCs)^[79-81]因具有更高的功率密度和快速的充放电速率得到了广泛的研究。同时,基于柔性纺织品的超级电容器由于具有高灵活性、轻质量和易于集成到纺织材料中的优点,在电子纺织系统中显示出巨大的应用潜力^[82-84]。由于独特的纺织结构柔韧性、高面积或体积电容、与纺织材料的无缝集成,纺织超级电容器一直是研究热点^[85-87]。

2019年,Zhou等^[88]利用可控化学沉积方法在镍织物和镍刷上成功合成了镍纳米半球。镍纳米半球电极的比面积显著扩大,电刷电极在电流密度为 $5\text{ mA}\cdot\text{cm}^{-2}$ 时表现出 $6.82\text{ F}\cdot\text{cm}^{-2}$ 的优异比电容,如图4(a)所示。更重要的是,当电流密度从 $3\text{ mA}\cdot\text{cm}^{-2}$ 增加到

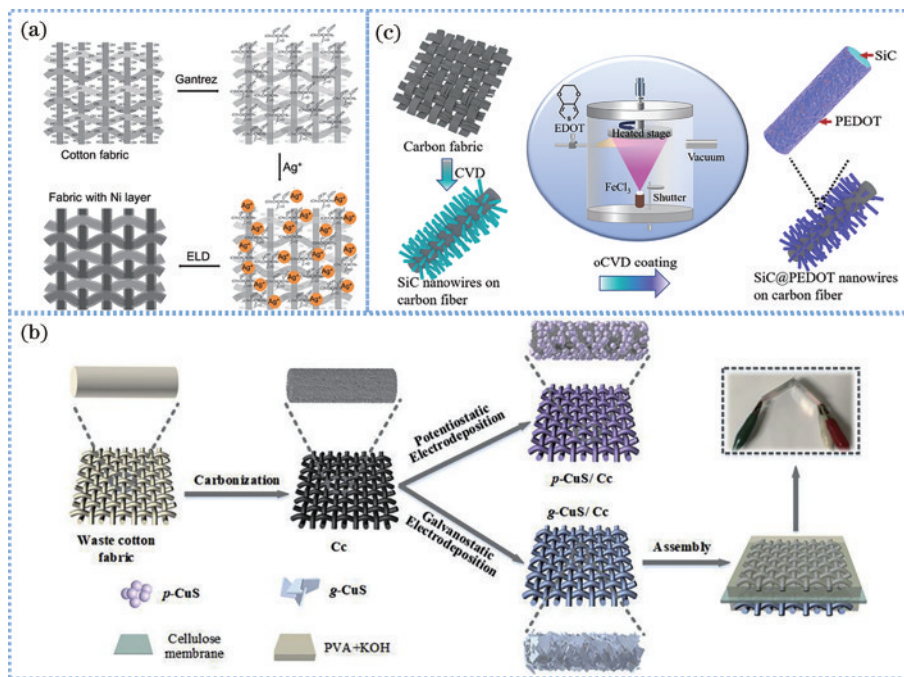


图4 纺织基超级电容器。(a)在棉布表面沉积镍的方法^[88]; (b)基于导电介孔碳化织物的柔性织物电极的制备流程^[89]; (c)碳织物纳米线阵列的制备原理^[90]

Fig. 4 Textile-based supercapacitors. (a) Method of depositing nickel on the surface of the cotton cloth^[88]; (b) fabricating process of the flexible fabric electrode based on electroconductive mesoporous carbonized clothes^[89]; (c) fabricating process of the carbon fabric with SiC nanowires^[90]

20 mA·cm⁻²时,比电容仅下降了 8%,表明性能良好。这种增强可归因于镍独特的纳米半球形结构,它将体积变化的应力分散到更广泛的区域,而不是沿着活性材料和电极之间的狭窄界面,从而最大限度地减少了体积变化的影响,并在长期充放电电化学反应中保持高比电容。2019 年, Jin 等^[89]提出了一种基于导电介孔碳化织物的柔性织物电极,利用恒流电沉积方法将 CuS 纳米片沉积到织物上,如图 4(b)所示。CuS 纳米片的高比面积(450.76 m²·g⁻¹)和碳材料与 CuS 之间的协同作用使复合电极具有 4676 mF·cm⁻²的高比电容。复合电极还表现出优异的循环性能,表明 CuS 具有快速的电子传递和良好的电荷转移能力。此外,将该材料与 PVA/KOH 凝胶电解质组装成对称的织物基超级电容后,该器件具有 1333 mF·cm⁻²的高比电容和 0.96 Wh·cm⁻²的超高能量密度。2022 年, Liu 等^[90]采用全干氧化化学气相沉积方法,在 SiC 纳米线周围镀上导电 PEDOT,如图 4(c)所示。值得一提的是, SiC 纳米线的致密结构显著提高了电极的表面积,并提供了额外的活性位点。PEDOT 的无黏结剂生长也促进了界面处的电子传递,降低了电极电阻。所有这些特性赋予了器件出色的电化学性能,包括 26.53 mF/cm²的高比电容和 10000 次循环后 104% 的容量保持率。

超级电容器不同于传统的储能器件,其较高的功率密度、较好的柔性可满足可穿戴能源储存设备的发展需求,性能主要由电极材料决定,包括电极材料的机械性能、导电性能、比表面积等。但超级电容器仍面临制备效率低下、机械性能较差、循环寿命低等问题,也是这些问题的存在阻碍了超级电容器在实际生活中的应用。纺织材料柔软、结构多变,是超级电容器的良好载体,结合成熟的纺织工艺,可大大提高纺织基超级电容器的制备效率。同时新型电极材料得到发展,并逐渐应用于纺织基超级电容器,可在超级电容器领域发挥重要作用。

5.2 纺织基传感器

随着科学技术的发展,物联网系统可应用于日常生活的各个方面,包括生物医药、医疗保健、汽车工业等诸多领域,其发展离不开各种新型传感器的发明和制造。特别是近年来,智能纺织品、可穿戴电子产品和软机器人进入我们的视野,引起了研究者的极大兴趣^[91-95]。将智能柔性纤维或织物用于可穿戴传感,将被测量的信息按一定规律转换为电信号的纺织基传感器具有良好的柔韧性、延展性,甚至可以自由弯曲或折叠,可根据测量条件的要求任意布置^[96-97]。纺织基传感器可以很容易地以透气和舒适的方式融入现代服装中,主要包括压电式、电容式^[98]、压阻式和摩擦电式^[99-102]柔性传感器,按照感知信息分类为应变传感器、压力传感器、温度传感器、湿度传感器等,大量应用于电子皮肤、医疗康复、医疗器械、运动器材、纺织、航空

航天、环境监测、人体运动捕捉、生理活动监测和人机交互等领域^[103-106]。

2017 年, Shuai 等^[107]展示了一种基于弹性体电极和微阵列结构的高灵敏度柔性压力传感器,涂有银纳米线(AgNWs)的聚二甲基硅氧烷(PDMS)衬底作为顶部电极,聚偏氟乙烯(PVDF)作为介电层,如图 5(a)所示。在微阵列结构的 PDMS 薄膜中嵌入 AgNWs 制备底电极的过程中,采用了几种转移工艺寻求简便的策略。柔性压力传感器将顶电极、介电层和微阵列电极集成在三明治结构中。结果表明,该传感器具有灵敏度高、响应时间短(50 ms)、柔性好和周期稳定性好等优点。这种传感器制备简单,可以很容易地扩大规模,以构建用于检测负载压力的强度和分布的压力传感器阵列。此外,这种柔性压力传感器即使在非接触方式下也表现出良好的性能,例如能检测声音振动和空气流动。由于优越的性能,这种设计的柔性压力传感器在电子皮肤和可穿戴医疗监护仪的应用中具有很大的潜力。柔性压力传感器由于在可穿戴人体健康监测和护理系统中的潜在应用而受到越来越多的关注。2020 年, Lian 等^[108]提出了一种用集成银纳米线涂层织物制造全纺织压阻压力传感器的简便方法,首先合成了 AgNWs 溶液,然后采用浸涂法将棉片浸入 AgNW 分散体中制备导电织物,如图 5(b)所示。主动传感元件包含双层镀银钨的棉花和棉花网间隔物,以确保它们之间的初始接触。压力传感的原理是外部压力下层与层之间的接触引起的电流变化。这种基于全纺织品的压阻式压力传感器充分利用了纤维/纱线/织物多层次接触的协同效应,在 0~10 kPa 和 10~100 kPa 下分别获得 3.24×10^5 kPa⁻¹ 和 2.16×10^4 kPa⁻¹ 的超高灵敏度。此外,该器件实现了快速响应和高稳定性。因此,这种高性能的全纺织压力传感器有望应用于智能服装、活动监测、医疗器械等领域。2021 年, Lee 等^[109]报道了一种实现可拉伸多模态器件的方法,该器件基于压电、摩擦电和压阻的各种电学特性,具有超出了人类触觉感知的能力,如图 5(c)所示。所制备的电子皮肤由皱褶图案的硅弹性体、银纳米线和氧化锌纳米线的杂化纳米材料、覆盖在杂化纳米材料上的薄弹性体介电层组成,其中介电层具有模仿人类指纹的高表面粗糙度。这种多功能装置不仅可以识别和区分来自单一刺激(如压力、拉伸应变或振动)的机械应力,还可以识别和区分来自多种刺激组合的机械应力。通过同时感知和分析综合刺激,当多功能电子皮肤应用于机械人手时,该方法可以实现对仿生假体的材料识别和纹理识别。2022 年, Chen 等^[98]报道了一种电容式应变传感器,该传感器由包芯纺丝的压力传感纱线编织而成。该纱线由棉纤维包绕金属丝构成,并喷涂聚氨酯胶黏剂形成稳定的结构。根据不同的设计,用包芯纺纱压敏纱线和普通纱线编织成不同的重复触感矩阵。对于触摸矩阵的设计,采用了一种具有螺旋通道分布的交

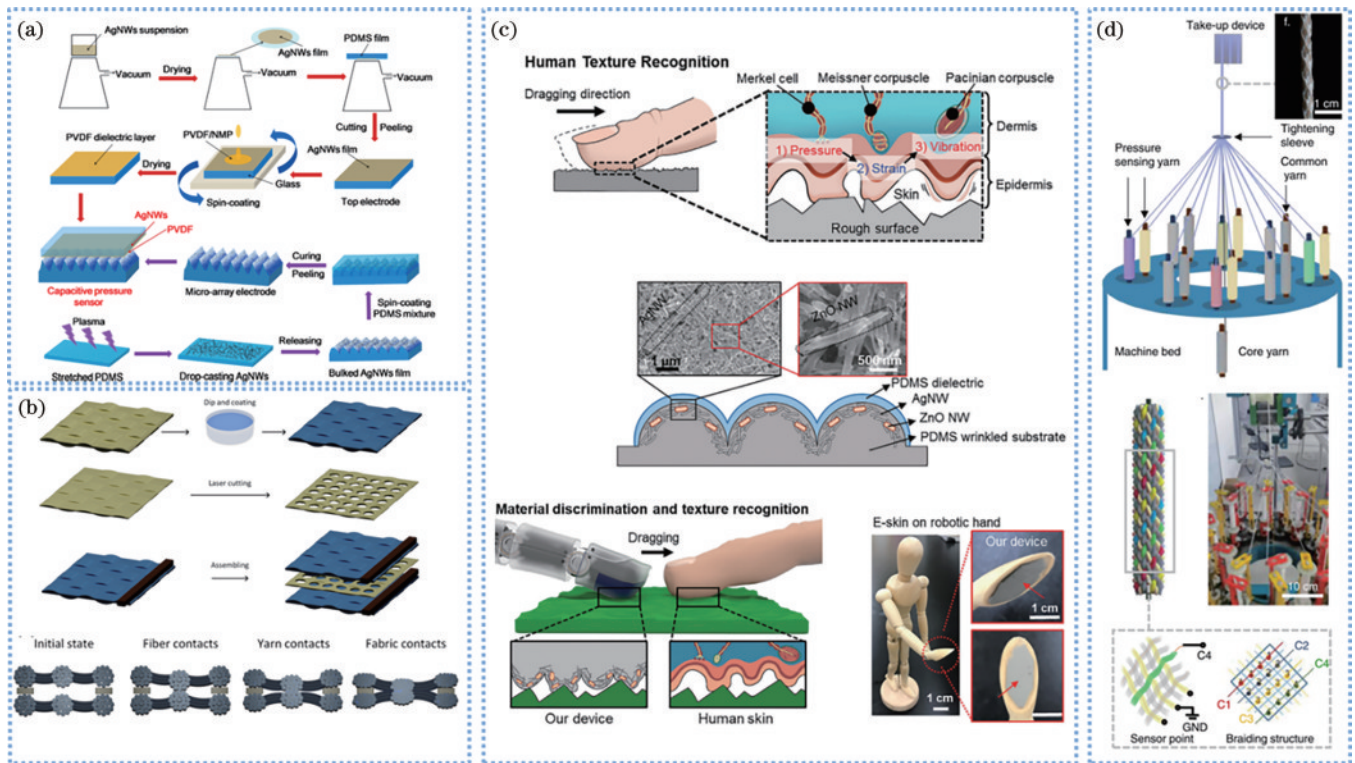


图5 纺织基传感器。(a) 电容式柔性压力传感器的制备流程^[107]；(b) 压阻式压力传感器的制备流程和工作原理^[108]；(c) 基于压电、摩擦电和压阻的电子皮肤结构示意图和工作原理^[109]；(d) 电容式应变传感器的制备流程和结构示意图^[98]

Fig. 5 Textile-based sensors. (a) Fabricating process of capacitive flexible pressure sensor^[107]; (b) fabricating process and working mechanism of the piezoresistive pressure sensor^[108]; (c) fabricating process and working mechanism of the electronic skin based on the piezoelectric, triboelectric, and piezoresistive theory^[109]; (d) fabricating process and the schematic diagram of the capacitive strain sensor^[98]

互式纺织绳,其可以区分不同的位置、不同的接触区域和不同的运动,此外基于多种编织技术,可以包含更多的触摸矩阵。无需大面积覆盖,这种小型化的界面可以用少量的通道实现多种交互方式。

纺织基传感器保证了器件的透气性、柔性及环境友好性,其根据输出信号,包括电阻、电容及电压,来响应外部刺激,具备较高的灵敏度。随着纺织基传感器的发展,仍有几大问题需要突破。首先是电极材料的耐水洗性和耐久性,其导电涂层的厚度或均匀性会影响电极材料的制作成本、使用寿命和导电性能;其次是纺织基传感器的灵敏度虽高,但传感结果易受外界环境因素的影响,传感精确度有待提高;第三是降低成本提高制备效率,能在保证高性能的前提下批量制造,推进纺织基传感器的产业化,促进其在各个领域的应用和发展。

5.3 光伏织物

柔性太阳能电池是现代人体电子设备中最重要的电源之一^[110]。基于光生伏特效应的太阳能电池可将太阳能转换为电能并存储,绿色环保节能,但其能量接收完全取决于环境。近年来,光纤型或织物型光伏器件越来越受到人们的关注^[111-115]。与平面结构的传统太阳能电池相比,纤维或织物结构的太阳能电池具有显

著的柔韧性和可变形性,可以编织成任何形状,可以与任何便携式电子设备组装为可持续电源^[116-120]。服装即纺织品作为人的第二层皮肤,具有优异的机械变形性、良好的透气性和丰富的花样,非常适合作为人与机器之间的界面平台。传统的纺织工艺将柔性纤维太阳能电池编织到织物中的能力催生了基于纺织品的电源的出现,例如为人体保持温暖、为手机供电或为其他便携式电子设备提供能量;还可以照亮建筑外墙、遮阳篷和窗帘;或为加热的汽车座椅供电等。然而,智能能源纺织品的开发仍面临如何实现大容量、耐久性、设计美观及可批量化生产等问题^[121]。

2018年,Liu等^[122]提出了一种纺织经纬纱交错结构,来制造聚合物太阳能电池纺织品,使电路连接更加容易,首次在工业织机上实现了预期的适用于米尺度的有机光伏纺织品,其能有效地连接大量扭曲的纤维电极,如图6(a)所示。这种光伏织物可以在三维上变形,同时具备较好的透气性。这种新颖的结构成功地将器件制造、纺织编织和电路连接集成为一个过程中,大大提高了有机光伏纺织品的性能。聚合物太阳能电池纺织品薄、轻、灵活,工作稳定性高,与日常服装材料非常接近,在可穿戴电子产品、生物医学电子产品和人工智能等各种新兴应用领域具有潜力。2023年,

Saravanapavanantham 等^[123]使用了一种可打印电子墨水形式的纳米材料,如图 6(b)所示。这些材料与可打印的电极一起沉积在厚度仅为 3 μm 的塑料基材上,形成一个太阳能模块。然后,将超薄模块集成到复合纤维织物上,该基底提供了防止撕裂所需的机械强度,使这些纤维-光伏系统即使在 500 次卷起循环后也能保持性能,同时增加的质量又能做到最小。最终,成品是

一种极具柔性而且超轻的太阳能电池,质量只有传统太阳能电池板的百分之一,但每千克发电能力是传统太阳能电池板的 18 倍。在测试中,研究小组发现,当太阳能电池附着在织物上时,每千克可以产生 370 W 的功率,而单独放置时,可以产生 730 W 的功率。这种将光伏制造和集成分离的方法为无处不在的能源生产提供了新的机会。

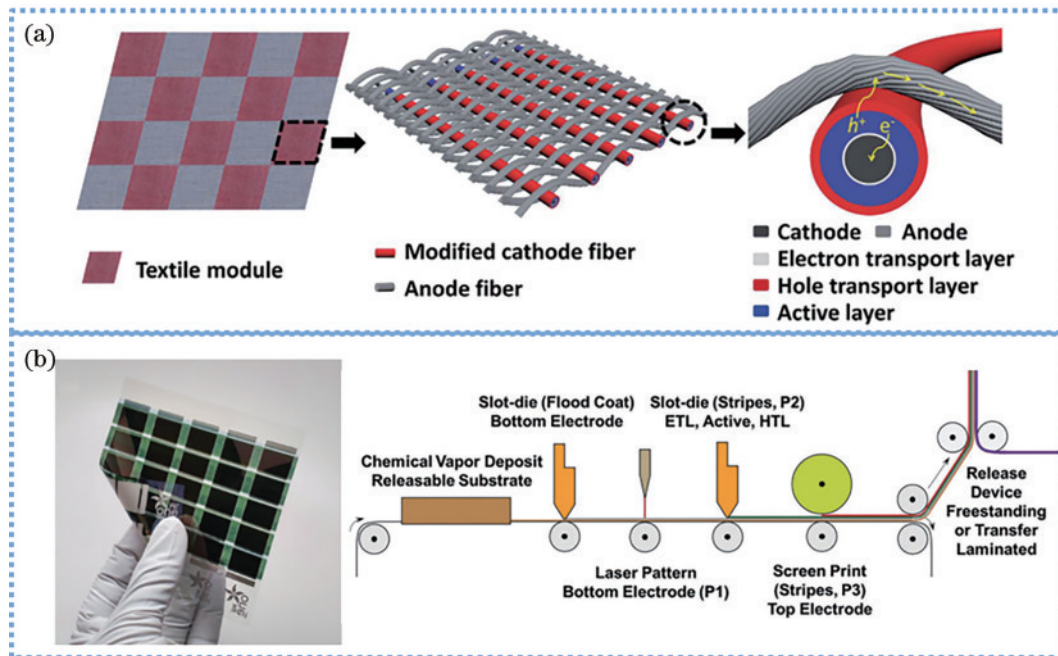


图 6 光伏织物。(a) 基于纺织平纹机织结构的聚合物太阳能电池纺织品的结构示意图^[122]; (b) 光伏织物的实物图及太阳能模块的制作流程^[123]

Fig. 6 Photovoltaic fabric. (a) Schematic diagram of the polymer solar cell textile with plain woven structure^[122]; (b) photograph of the photovoltaic fabric and fabricating process of the solar module^[123]

光伏织物作为智能可穿戴纺织品的电源,可与任意纺织基底组装,或直接与纺织材料进行一体化制备,与传统的光伏电池相比,其生产成本低、绿色环保、轻质,且具备较高的穿着舒适性和柔性。但光伏织物的研究也面临较多困境,首先,如何通过优化电极材料和结构来提高光电转换效率;其次,部分光伏织物采用纤维状太阳能电池制备,机械性能较差,属于脆性结构,拉伸易断裂,因此,设计可拉伸结构的光伏纤维以制备光伏织物是解决这一困境的方法之一;另一个难题是提高光伏织物的储存效率,保持较高的稳定性和耐久性,而将超级电容器与光伏织物的优势结合,采用纺织技术进行一体化制备,也许会是一个较好的突破点。

6 结 语

综述了光电子技术在纺织领域近几年的主要研究和发展,包括电致发光纤维、光敏变色纤维、光导纤维、智能发电纺织材料在纺织基超级电容器、传感器及光伏织物上的应用和发展前景,并详细列举了各器件的

制备及工作原理。

基于纤维和织物的可穿戴纺织品对电子功能的完整性、结构的舒适性、使用过程中的稳定性和精确性等方面有较高需求,尽管基于光电子技术的可穿戴纺织品取得较大进步,但是也面临诸多挑战。与传统的电子器件相比,智能纺织品虽具备较高的穿着舒适性和柔性,但电学性能相对较差,在电极材料方面,导电纤维的电导率远低于薄膜电极,且反复洗涤过程中,纤维表面导电材料的涂层很容易剥落,因此在提高导电纤维的导电性能的同时,如何实现纺织器件在不同变形下的机械稳定性和电学稳定性是目前面临的主要挑战。除此之外,目前实验室规模的人工编织仍是制备智能纺织品的主要方法,为了促进智能可穿戴纺织品的产业化,关键是要在确保各项性能满足实际应用要求的前提下,能实现大规模低成本的高效生产,因此开发新的高效纺织技术来生产智能可穿戴纺织品是必不可少的。第三,可穿戴纺织品目前缺乏统一的评价标准,采用不同方法制备的纺织电子器件的材料及结构参数的差异较大,且算法多样,导致智能纺织品的性能

难以得到比较。

综上所述,目前基于光电子技术的智能可穿戴纺织品在可穿戴电子领域取得了很大的发展和巨大的应用前景。未来,智能纺织品不仅可以满足日常穿着的需求,还可以应用于生活娱乐、运动监测、健康监测、军事和航空等重要的检测领域,还有人机交互、人工智能等新兴领域,改变人们的生活方式。尽管这一领域面临着巨大的挑战,但在不同领域研究人员的不断努力下,新材料、新结构、新原理将不断产生,促进可穿戴纺织品的产业化应用。

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