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基于聚二甲基硅氧烷柔性传感器的研究进展

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摘要：与传统应变传感器相比，柔性传感器的柔韧性、可穿戴性和实时监测是独特的优点，近年来柔性传感器快速发展并应用于医疗检测、可穿戴设备等多方面，由于聚二甲基硅氧烷(PDMS)的优异理化性质，常作为柔性传感器基底。文中总结了近年来用PDMS作为柔性传感器基底的研究工作，首先对PDMS纳米复合材料的传感机理进行详细的介绍，包括压阻式、电容式与压电式传感机制；然后对以碳纳米管(CNT)、石墨烯与纳米银等为纳米填料的PDMS基柔性传感器进行了详细综述；最后，对PDMS基柔性传感器的研究现状及存在的问题进行了总结并做出展望。

关键词：聚二甲基硅氧烷；柔性；传感器；纳米复合材料
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传感器作为一种检测并传递信息的设备，开发其在增强或替代人工来对设备进行干预的应用至关重要。传统传感器主要是由金属、半导体等材料来制备，其质重、测量范围较窄，灵敏度有限[1]。柔性传感器类似人类的听觉、触觉、嗅觉、视觉和味觉，通过刺激使柔性传感器响应或有所动作，从而实现其与环境互动[2]。柔性传感器具有轻质、柔性、高灵敏度和宽应变等特点，在个性化健康监测、电子皮肤、机器人等方面发挥着重要的作用[3]，如Fig.1所示。

目前，柔性传感器的柔性基底材料主要有聚二甲基硅氧烷(PDMS)、热塑性聚氨酯(TPU)、聚酰亚胺(PI)、聚对苯二甲酸乙二醇酯(PET)、聚乙烯醇(PVA)等。如Lin等[4]以高弹性TPU为基体，在TPU纳米纤维膜表面依次组装一维CNTs网络和二维银纳米纤维层网络制备了压阻式应变传感器(Fig.1(a))。由于不同维度导电网络的协同作用赋予了其1.36×10^5的高灵敏度，可以用来监测身体运动。Zhu等[5]将导电炭黑分散在绝缘的PI中，制备了一种检测三维力的PI柔性压阻传感器(Fig.1(b))，其具有良好的线性响应，且在测量三维力上的灵敏度最高可达到1.739 kΩ/N。Khurana等[6]通过在PET片材上面绘制石墨轨迹制备了一种应变传感器，这种制备方法简单、易行且成本较低，但是其应变检测的范围较窄(0.80%~0.96%)。Wang等[7]用PVA和聚醚酰亚胺复合水凝胶掺杂氯化锂制备了应变传感器，这种传感器弹性较好，生物安全性好，可以用于检测人体运动(Fig.1(c))。Shi等[8]通过在医用胶带上机械挤压石墨烯再嵌入到柔性PDMS基底中制备了可拉伸的导电薄膜，这种薄膜对微小的压力和应变具有高灵敏度，可以瞬间检测到蟋蟀的微小运动和手机扬声器的音乐(Fig.1(d))。

PDMS由于具有良好的柔性、可拉伸性、低弹性模量、较稳定的理化性质、耐腐蚀性和光学透明性，同时因其与电子结合能力较好，而被广泛用作柔性可穿戴传感器的基底材料。目前，以PDMS为柔性基底制备的传感器综述并不完善，因此本文综述了近年来PDMS作为柔性传感器基底材料的研究工作，介绍了PDMS基柔性传感器的传感机理、种类、研究现状以及发展趋势。

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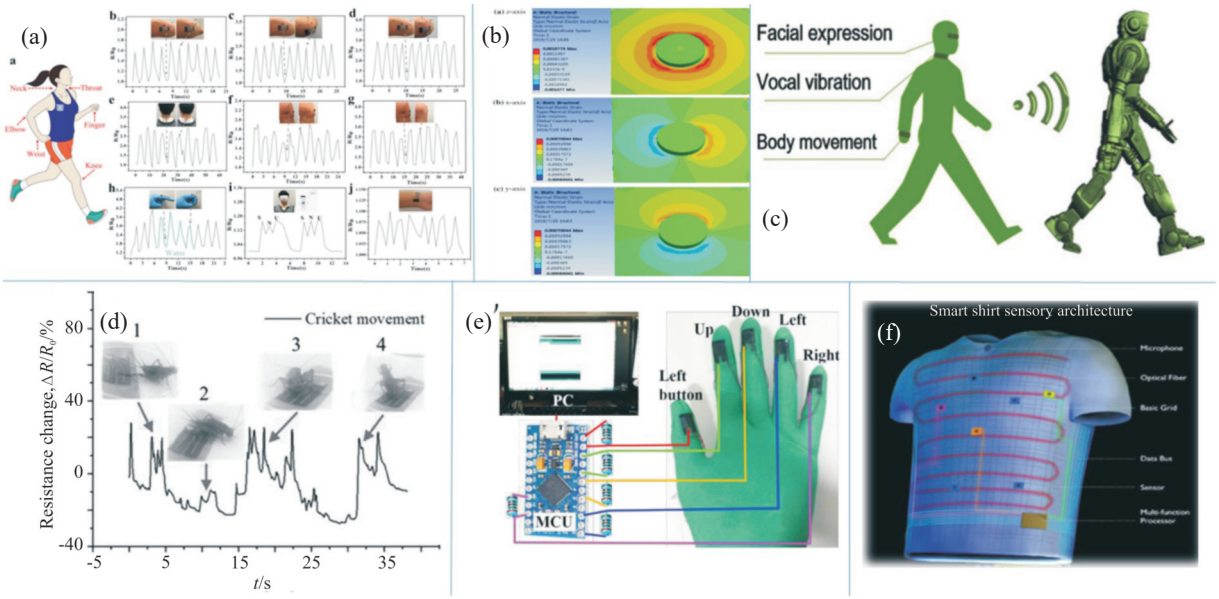


Fig. 1　(a) Application scenario of flexible sensor and schematic diagram of monitoring body motion[4]; (b) strain distribution of sensor chip when force is applied along *x*, *y*, *z* directions[5]; (c) schematic diagram of sensor attached to different parts [7];(d) real-time monitoring of cricket movement[8]; (e) human-computer interaction fixed on glove fingers[9];(f) smart shirt and its sensing structure[10]

1　聚二甲基硅氧烷柔性传感器传感机理

目前柔性传感器的分类方法较多，按照用途分类有压力传感器、气体传感器、湿度传感器、温度传感器、应变传感器、磁阻抗传感器和热流量传感器等；按照感知机理分类有电阻式传感器、电容式传感器和压电式传感器等。下面就电阻式、电容式和压电式传感器机理进行介绍。

1.1　压阻式传感器的传感机理

压阻式传感器主要是通过监测电阻变化来探测外力或者变形(Fig.2(a1))。压阻式传感器具备结构简单、能耗低、测量简便、检测范围广等特点。为了实现柔性压阻式传感器在应用上所需的柔性和高压力灵敏性，因此多用柔性高分子材料作为基底，进而解决了传统材料贴合差引起的测量难问题。Mu 等[11]通过成孔剂制备了多孔 PDMS，继而分别将氧化石墨烯和 CNTs 覆盖于上面构建了三维导电网络(Fig.2(a2))，不仅可以检测拉伸弯曲等形变，还可以对羽毛发出的极其轻微的滴答声产生明显的响应，甚至可以实时监控人类的呼吸和音乐节奏。Vashist 等[13]采用模塑工艺将石墨烯喷涂在环氧树脂和 PDMS 表面制备了柔性压阻压力传感器，具有 0~25 kPa 的监测范围和 1.2 kPa^{-1} 的灵敏度并且有出色的稳定性。

1.2　电容式传感器的传感机理

电容式传感器主要基于电容器原理，通过测量电容的变化来探测不同的力，如压力、剪切力等，如 Fig.2(b1)所示。电容式传感器具备高灵敏度及低功耗的特点，柔性电容式传感器以导电纤维、纱线、织物等柔性导电材料作为极板，以泡沫、间隔织物、橡胶等弹性材料为电介质层，应用在医疗保健、运动监测以及安全防护等领域。但这种可穿戴的材料容易受到干扰导致稳定性较差，其重复拉伸性、耐水洗、耐摩擦、可折叠性等耐用性能也有待提高。目前，实现电容式传感器的改进方法主要是通过改变介质、对介质进行修饰或对其结构的改变。Ham 等[12]用碳纤维填充的 PDMS 充当介电层和纯 PDMS 充当电极层，制备了柔性电容式传感器。通过喷涂工艺将粗糙衬底的表面微观结构转移到 PDMS 表面，研究了基底表面粗糙程度对压缩载荷的敏感性，并通过手指的不同组合替代鼠标指令实现了简单的人机交互(Fig.2(b2))。

1.3　压电式传感器的传感机理

压电式传感器主要是利用压电材料在外力作用下可以产生电荷的特性，探测机械力的变化，如 Fig.2(c1)所示。常用的压电复合材料有陶瓷纤维、偏聚氟乙烯薄膜[14]以及填充了导电颗粒的复合导电薄膜等。压电传感器具有灵敏度高、频带宽、动态特性良好与可自供电等优点，但是存在柔性和拉伸性能有限、不够稳定、结构与制备过程相对复杂的缺点。Ham 等[12]使用(K，Na)NbO_3(KNN)压电粒子

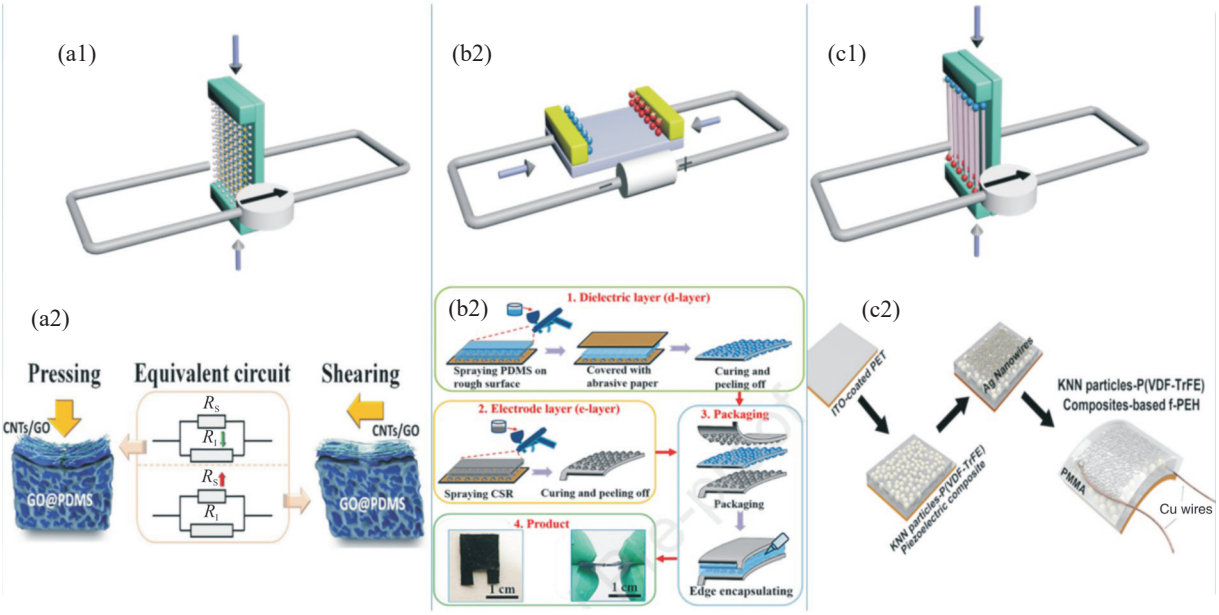


Fig. 2 (a1) Schematic diagram of a piezoresistive sensor; (a2) schematic diagram of the shape deformation of the contact point of the sensor and the corresponding resistance change under the action of normal pressure and lateral shear force[11]; (b1) schematic diagram of a capacitive sensor; (b2) capacitive material with surface microstructure[9]; (c1) schematic diagram of piezoelectric senor; (c2) schematic diagram of assembly of piezoelectric material[12]

和聚偏氟乙烯三氟乙烯基体制备了一种基于混合压电复合材料的柔性能量采集器，并用其制造了运动传感器，该传感器在人类手指上产生了可靠的传感信号，可以在无需供电的条件下监测微小的生物力学运动和各种手势，如Fig.2(c2)所示。

2 聚二甲基硅氧烷柔性传感器的种类

2.1 碳纳米管/聚二甲基硅氧烷复合材料柔性传感器

一维碳纳米材料CNT具有优异的导电性和力学性能。目前，柔性传感器多选择孔隙结构来保证灵敏性，Sun等[15]研究出了一种基于CNTs/PDMS的压阻纳米复合材料，其具有双面粗糙多孔结构，可应用于检测3D接触力，通过将1个单元中4个单元的电阻与预先校准的数据相结合来计算每个轴力分量，在各个方向均具有灵敏性(Fig.3(a))。Li等[16]使用羧化CNTs与PDMS进行混合制备了柔性应变传感器(Fig.3(b))，其具有高导电率与灵敏度（*GF*值为7.22）。Taissa等[17]采用CNTs和PDMS通过糖模板法制备了具有多孔结构的支架材料，该复合材料具有较好的可变形性，但该材料应用于传感器中可能由于孔隙的塌陷，导致的传感性能相对下降，目前还没有更好的解决方案。

由于使用环境的特殊要求，兼具透光性、电容器功能、超疏水性、耐酸碱性等性能的柔性传感器也是研究热点。Chen等[18]通过简单的喷涂沉积和转移方法制备了PDMS/CNTs/PDMS应变传感器，在550 nm处具有53.1%的透光性。Zhang等[19]将起皱的CNTs组装在PDMS膜上，制备了对各种变形具有灵敏性的电阻响应型应变传感器。在180°弯曲100个循环后其仍具有98%的电容保持率，这表明微结构固定的褶皱碳纳米管电极的设计有利于优异的电化学性能(Fig.3(c))。Wang等[20]使用超声诱导的方法将CNTs装饰在电纺TPU纳米纤维表面，制备出TPU/CNTs/PDMS的超疏水应变传感器，且在酸碱条件下可进行监测工作。

2.2 石墨烯/聚二甲基硅氧烷复合材料柔性传感器

石墨烯是目前世界上最薄且强度最高的材料，具有优异的力学、热学、电学和光学性能，应用前景十分广阔。石墨烯传感器主要的刺激类型有压力、应变、剪切和振动等，且通常具有较好的性能[20,21]。PDMS基石墨烯复合传感材料同样以制备多孔材料和具有多种应用性能为趋势。Jung等[22]使用糖模板工艺和浸涂法制备出具有三维微孔的石墨烯/PDMS海绵涂层，经过测试该传感器具有稳定的力学性能与高传感性能，如Fig.4(a)所示。3D打印技术制造传感器是一种简便的方法，Shi等[23]将电化学衍生的氧化石墨烯（EGO）与PDMS微珠的水性纳米复合油墨应用于3D打印技术，实现了迄今为止报道的最

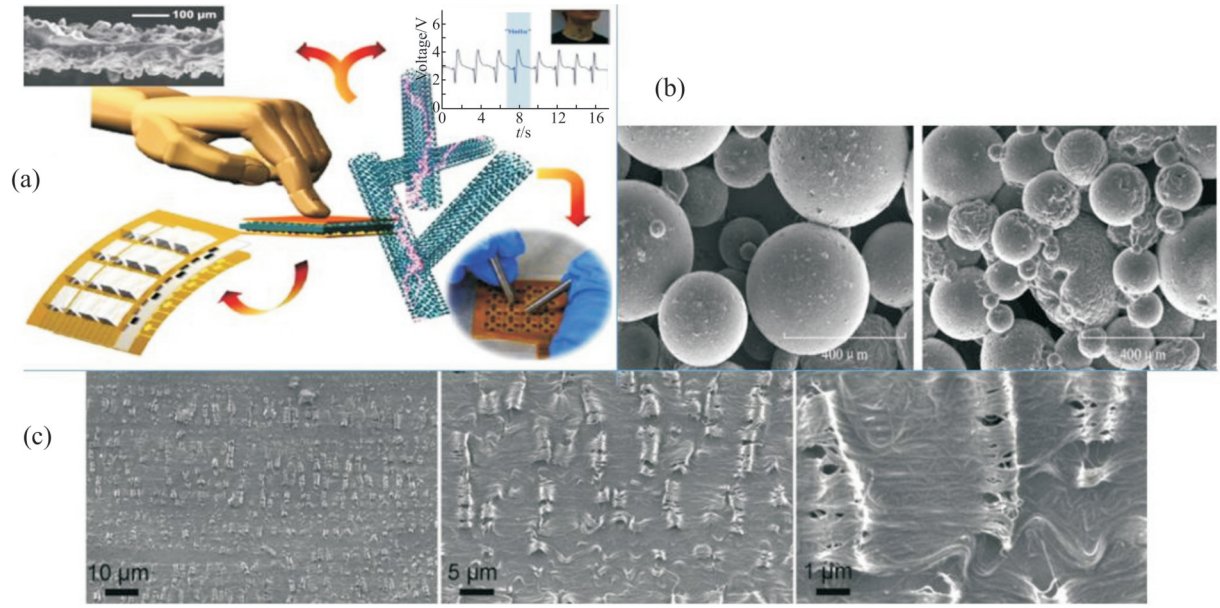


Fig. 3 (a) Schematic diagram of CNTs/PDMS sensor[15]; (b) SEM images of carboxylated CNTs/PDMS emulsion[16]; (c) SEM images of wrinkled CNTs on PDMS film[19]

高分辨率的 PDMS 基直接墨水书写器件（DIW），如 Fig.4(b)。但对于其内在结构的表征不足，还需要进一步的研究。许多学者也针对传统石墨烯传感器的聚集问题进行改性和研究，Zhao 等[24]通过一步化学还原法合成了银/氧化石墨烯（Ag/rGO）复合材料，并制备了高度灵敏的 Ag/rGO/PDMS 海绵传感器，如 Fig.4(c)，其最大压力敏感度为 8.86 kPa^{-1}。石墨烯纳米片可以提高 Ag/rGO/PDMS 海绵的柔性和稳定性，促进电子传递。此外，Ag/rGO/PDMS 海绵在压缩和膨胀测量中表现出良好的重复性和非滞后行为，银和石墨烯的结合为压阻传感器的发展提供新的视角。Nguyen 等[25]使用由 Fe_3O_4 纳米颗粒插层 $Ti_3C_2T_x$ 纳米片修饰的石墨烯泡沫（GF）与 PDMS 基体共混制备出兼具屏蔽性能的传感器，其在 8.2~12.4 GHz 具有 80 dB 的电磁干扰屏蔽效能。Xu 等[26]制备了一种双模式传感器，它基于附着在微图案弹性体上的 rGO/PDMS 膜，能够同时检测人体的细微和较大运动。其中胶体晶体薄膜与 rGO/PDMS 膜可以分别检测不同应变范围，微小形变和大形变均可检测。

石墨烯在电容式传感器中同样也受到了研究人员的关注。Xia 等[27]通过在丙烯酸基板上旋涂制备了取向的石墨烯片/PDMS 复合材料，并研究了石墨烯片的有序性对石墨烯片/PDMS 复合材料的电容与介电损耗特性。Kou 等[28]用微图案化的石墨烯与 PDMS 为介电层，研究不同浓度石墨烯对传感器灵敏度的影响，如 Fig.4(d)所示。同样，Luo 等[29]利用石墨烯电极和具有不同间距的 PDMS 电介质层制作了电容式压力传感器，模拟了不同间距的 PDMS 棱锥与灵敏度的关系曲线，发现棱锥间距是影响电容式压力传感器灵敏度的主要因素。王瑞荣[30]以石墨烯与 PDMS 为介质层，采用电极-介质-电极 3 层的方法完成了可检测 0～20 kPa 压力的传感器制备。Sergio 等[31]设计了一款电容式织物压力传感器，此传感器是在可压缩弹性泡沫两侧垂直相交排列多根导电纱，多组导电纱两两相互垂直相交，交叉点所组成的阵列即为电容阵列。Filippidou 等[32]为了使石墨烯分散的更均匀，用 FT-IR 光谱表征了石墨烯在各种溶剂中的分散状态，以此为指导并采用逐层旋涂的简便方式，制备了用于柔性电容式应变传感器的 PDMS/石墨烯复合材料，如 Fig.4(e)所示。

2.3　纳米银/聚二甲基硅氧烷复合材料柔性传感器

由于金属银纳米颗粒与银纳米线（AgNW）具有优异的导电性和高稳定性，同时还具有优异的透光性和耐曲挠性，也成为了传感器的研究热点。Zhou 等[33]基于 AgNWs 与 PDMS 制备了具有三层结构的传感器，通过相关的扫描电源电路和数据采集系统，证明该系统能够成功地捕获由不同形状物体诱发的触觉图像，如 Fig.5(a)所示。Lee 等[34]基于 PDMS 和 AgNWs，设计了一种新型空气间隙柔性压力传感器。在制备过程中，通过刮刀在底部 PDMS 层上制备叉指型 Ag 电极，并且 AgNWs 嵌入在顶部 PDMS

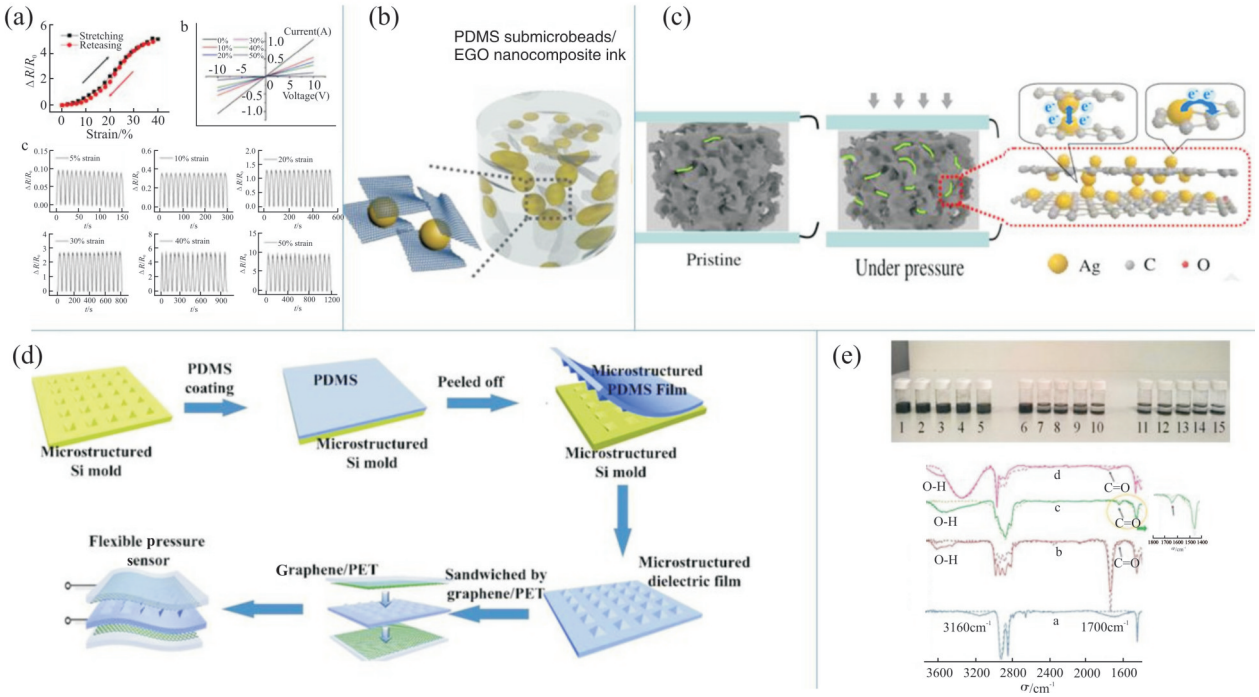


Fig. 4 (a) Sensing property of PDMS sponge coated with graphene[22]; (b) schematic diagram of PDMS submicron beads/EGO nanocomposite ink[23]; (c) schematic diagram of Ag/rGO-PDMS sensing mechanism[24]; (d) preparation process of PDMS dielectric layer with micro-pyramid structure and graphene electrode based on pressure sensor[29]; (e) FT-IR showing the dispersion state of graphene in solvent[32]

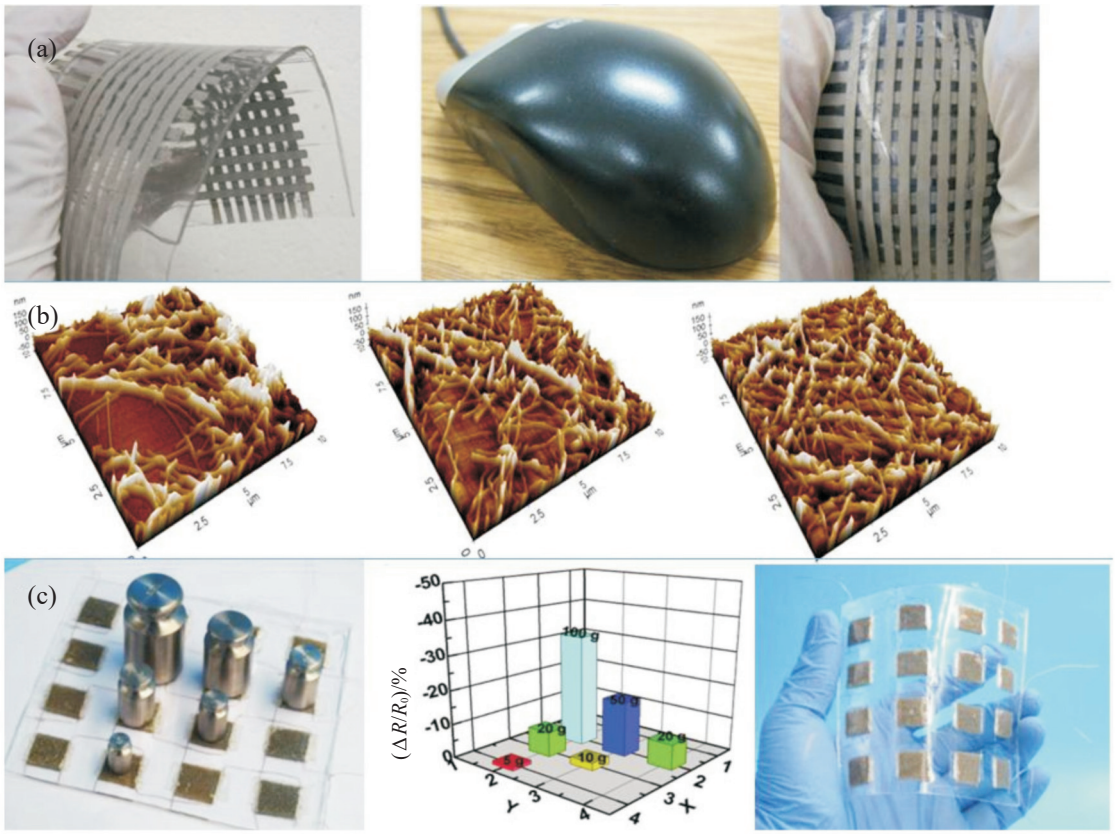


Fig. 5 (a) Photographs of AgNWs and PDMS tactile sensor arrays and proof of flexibility and stretchability[33]; (b) atomic force microscope measurement images of AgNW thin films prepared by single-layer, double-layer, and three-layer spraying on glass substrate[36]; (c) sensor schematic diagram of force-sensitive sensor array[37]

Tab. 1 Sensors based on PDMS composites and their sensing performance comparison

Sensing mechanism	Nanocomposites	Sensitivity/kPa^{-1}	Detection limit /kPa	Response or recovery time /ms	Reference
Piezoresistive sensor	CNTs/PDMS	12.1	6	6.8	[23]
Piezoresistive sensor	CNTs/PDMS	1.71	5	6	[20]
Piezoresistive sensor	CNTs/PDMS	7.22	/	/	[16]
Piezoresistive sensor	CNTs/PDMS	/	/	95.4	[18]
Piezoresistive sensor	Graphene/PDMS	/	80.9	/	[22]
Piezoresistive sensor	Graphene/PDMS	0.31	500	83	[15]
Piezoresistive sensor	Ag/rGO-PDMS	8.86	10	/	[24]
Capacitive sensor	Graphene/PDMS	0.24	100	67	[28]
Capacitive sensor	Graphene/PDMS	/	20	/	[30]
Piezoresistive sensor	AgNWs/PDMS	/	250	/	[33]
Piezoresistive sensor	AgNWs/PDMS	16.1	42	/	[34]
Piezoresistive sensor	AgNWs/PDMS	0.93	/	/	[35]
Piezoresistive sensor	AgNWs/PDMS	/	/	90	[37]

层中,AgNWs层和叉指型电极之间自然形成气隙。由此形成的气隙由AgNWs层的数量控制,所获得的柔性压力传感器在正常工作条件下具有相当高的灵敏度和机械稳定性。Heo等[35]在弹性体上引入多种浮雕结构,通过调控沟槽数量与高度比引起不均匀和复杂的应变,从而使其在拉伸时产生不同的AgNWs裂纹密度分布,即可调节灵敏度。对传感层和力学性能的研究表明,较低的高度比和较大数量的沟槽明显可提高传感器的灵敏度。

但是金属与有机材料的相容性是个难以解决的问题。为了解决金属材料与基材的结合问题,由于独立的AgNWs薄膜在拉伸应变下表现出不稳定的电阻,Lee等[36]在未固化的PDMS上直接喷涂AgNWs,使AgNWs渗透到未固化的PDMS中,从而增强AgNW电极的表面形态和黏附性能。并用聚(3,4-亚乙基二氧噻吩):聚(苯乙烯磺酸盐)(PEDOT:PSS)涂覆在AgNW薄膜的顶部,PEDOT:PSS的覆盖层能有效地抑制了AgNWs从PDMS中的突出(Fig.5(b)),这种双层结构确保了应变下电阻的稳定。Li等[37]实现了基于半嵌入的AgNWs与PDMS的一种3D互联的中空微结构,由于半嵌入的AgNWs不会剥落,这种独特的结构保证了高的力学性能,如Fig.5(c)所示。Hu等[38]用TPU、AgNWs、羰基铁与PDMS复合制备了具有电磁传感特性的PDMS弹性体材料,并研究了导电磁流变液的机械-电-磁耦合性能,这种电磁传感器有望应用到人造皮肤中。Zhao等[39]采用浸渍的方法将银纳米粒子修饰的还原氧化石墨烯(Ag/rGO)复合材料填充到PDMS海绵中制备了柔性高压敏传感器。包覆在石墨烯纳米片表面的Ag纳米粒子提高了Ag/rGO复合材料的导电性,降低了石墨烯纳米片的接触电阻。石墨烯提高了Ag/rGO/PDMS的柔性稳定性,促进电子传输。但这类传感器中金属容易氧化、制造成本相对较高,且金属与聚合物的相容性差,这些仍是待解决的问题。

2.4 氧化锌/聚二甲基硅氧烷复合材料柔性传感器

纳米氧化锌(ZnO)是一种非常重要的半导体材料,由于其压电特性、生物相容性和较好的力学性能,多应用于光、电、半导体等材料中。Marschner等[40]制备了具有压电效应的ZnO/PDMS复合材料,较高含量的ZnO会在PDMS基体中产生连续排列的压电颗粒,明显增加了复合材料的介电常数和压电性能。Zhang等[41]进一步探究了结构化ZnO/PDMS复合材料的压电效应,通过介电电泳效应诱导ZnO定向排布,使该复合材料的介电和压电性能得到了显著改善(Fig.6(a))。这种技术增加了ZnO/ZnO界面之间的连接性,允许在聚合物基体内产生连续的定向压电粒子,因此压电效应大大增强。Edmission等[42]基于压电传感器的机理,设计了一个可以作为键盘的电子手套,用以感知手的弯曲和轻敲动作,

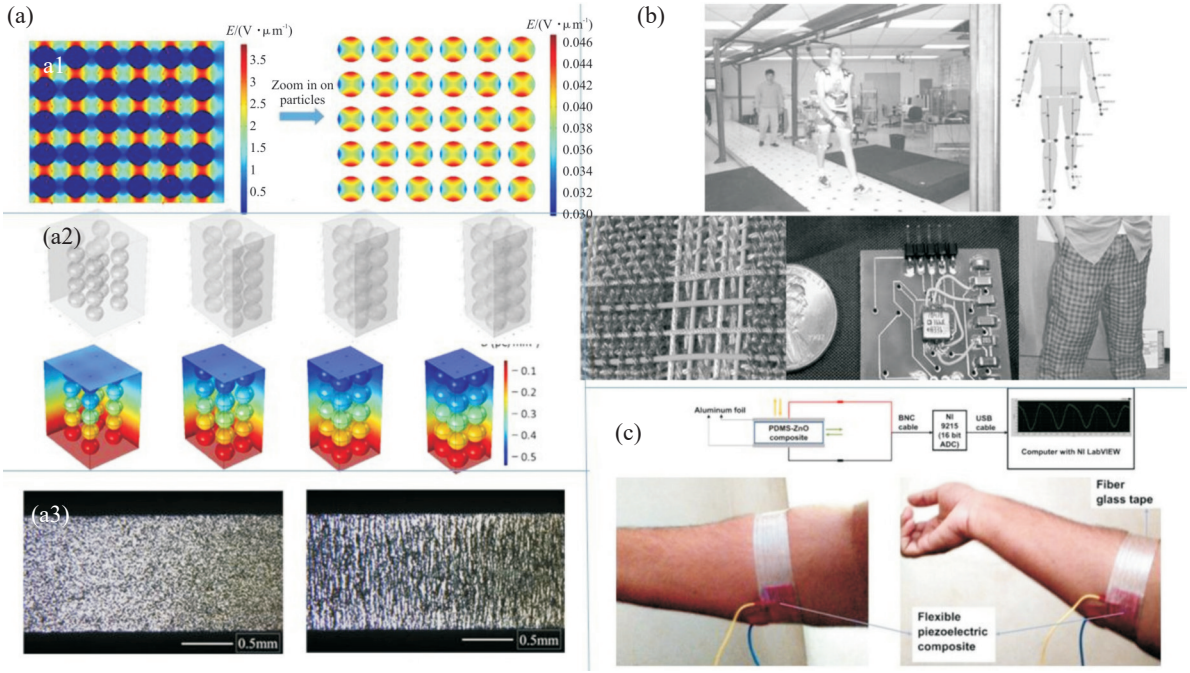


Fig. 6 (a1) 3D model of zinc oxide/PDMS composite material, schematic diagram of corresponding charge density under a compressive stress of 1 MPa in the vertical direction; (a2) electric field distribution in composite materials with different ZnO volume fractions and close-up view of particles; (a3) microscopic images after electric field[41]; (b) a typical gait analysis instrument[42]; (c) flexible piezoelectric composite material wraps the wrist flexor muscle for muscle activity measurement[43]

如Fig.6(b)所示。Filippidou等[43]开发了PDMS基体和ZnO填料的柔性压电复合材料，将该柔性压电复合材料包裹腕屈肌用于测量肌肉的活动，如Fig.6(c)所示。传感器输出电压的变化与肱二头肌和腕屈肌的弹性模量呈线性变化，且ZnO的加入没有明显增加复合材料的硬度和弹性模量，从而确保传感器的高柔软性和灵活性。

3 总结和展望

本文介绍了近年来PDMS基柔性传感器的最新研究进展，包括碳纳米管、石墨烯、纳米银和氧化锌等PDMS基柔性传感器在压阻、电容、压电3种信号转换机制下的传感机理和制造方法，以及在温度、脉搏、表情识别和运动监测等方面的性能与应用。最后总结了多种PDMS纳米复合材料柔性传感器的传感性能，如Tab.1所示。柔性传感器应该在保证提高传感性能的同时注重穿戴的舒适性以及安全性，就目前来说，传感器的灵敏度、监测范围、稳定性以及响应时间等指标还有待进一步提升，多功能、实用性与成本问题也是待解决的问题。如何设计简单与稳定的结构并减少纳米填料的使用量，是解决灵敏度、稳定性与成本等问题的关键，这样才能使之广泛应用到医疗健康、人工智能、可穿戴电子等方面。相信随着科学技术的发展，特别是纳米材料和纳米技术的研究不断深入，柔性传感器将展现出更为广阔的应用前景。

参考文献：

[1] Shi J D, Wang L, Dai Z H, *et al*. Multiscale hierarchical design of a flexible piezoresistive pressure sensor with high sensitivity and wide linearity range[J]. Small, 2018, 14: 1800819-1800826.

[2] Sekitani T, Someya T. Stretchable, large-area organic electronics [J]. Advanced Materials, 2010, 22: 2228-2246.

[3] Yuan W, Qu X Y, Lu Y, *et al*. MXene-composited highly stretchable, sensitive and durable hydrogel for flexible strain sensors[J]. Chinese Chemical Letters, 2021, 32: 1904758-1904767.

[4] Lin L W, Choi Y J, Chen T Y, *et al*. Superhydrophobic and wearable TPU based nanofiber strain sensor with outstanding sensitivity for high-quality body motion monitoring[J]. Chemical Engineering Journal, 2021, 419: 129513-129523.

[5] Zhu Y Y, Jiang S W, Xiao Y, *et al*. A flexible three-dimensional force sensor based on PI piezoresistive film[J]. Journal of Materials Science: Materials in Electronics, 2018, 29: 19830-19839.

[6] Khurana V, Kaur M, Kumar S, *et al*. Multifunctional graphitic

tracks on flexible polymer sheet as strain, acoustic vibration and human motion sensor[J]. Measurement, 2019, 146: 9-14.

[7] Wang C, Hu K, Zhao C C, *et al*. Customization of conductive elastomer based on PVA/PEI for stretchable sensors[J]. Small, 2020, 16: 1904758-1904767.

[8] Shi G, Zhao Z H, Pai J H, *et al*. Highly sensitive, wearable, durable strain sensors and stretchable conductors using graphene/ silicon rubber composites[J]. Advanced Functional Materials, 2016, 26: 7614-7625.

[9] Wang X L, Xia Z D, Zhao C, *et al*. Microstructured flexible capacitive sensor with high sensitivity based on carbon fiber-filled conductive silicon rubber[J]. Sensors and Actuators A: Physical, 2020, 312: 112147-112182.

[10] Rasel M S, Maharjan P, Salauddin M, *et al*. An impedance tunable and highly efficient triboelectric nanogenerator for large-scale, ultra- sensitive pressure sensing applications[J]. Nano Energy, 2018, 49: 603-613.

[11] Mu C H, Song Y Q, Huang W T, *et al*. Flexible normal-tangential force sensor with opposite resistance responding for highly sensitive artificial skin[J]. Advanced Functional Materials, 2018, 28: 1707503-1707511.

[12] Ham S S, Lee G J, Hyeon D Y, *et al*. Kinetic motion sensors based on flexible and lead- free hybrid piezoelectric composite energy harvesters with nanowires- embedded electrodes for detecting articular movements[J]. Composites Part B, 2021, 212: 108705-108715.

[13] Vashist S K, Luong J H T. Recent advances in electrochemical biosensing schemes using graphene and graphene- based nanocomposites[J]. Carbon, 2015, 84: 519-550.

[14] 王庆锋, 吴斌, 宋吟蔚, 等. PVDF 压电传感器信号调理电路的设计[J]. 仪器仪表学报, 2006, 27(6): 1652-1655.
Wang Q F, Wu B, Song Y W, *et al*. Design of signal conditioning circuit of PVDF piezoelectric sensor[J]. Chinese Journal of Scientific Instrument, 2006, 27(6): 1652-1655.

[15] Sun X G, Sun J H, Li T, *et al*. Flexible tactile electronic skin sensor with 3D force detection based on porous CNTs/PDMS nanocomposites[J]. Nano-Micro Letters, 2019, 11: 1-14.

[16] Li T, Li J H, Zhong A, *et al*. A Flexible strain sensor based on CNTs/PDMS microspheres for human motion detection[J]. Sensors and Actuators A: Physical, 2020, 306: 111959-111959.

[17] Taissa R M, Michael J C, Muhammet E C, *et al*. Evaluation of porous polydimethylsiloxane/carbon nanotubes (PDMS/CNTs) nanocomposites as piezoresistive sensor materials[J]. Microsystem Technologies-Micro-and Nanosystems Information Storage and Processing Systems, 2020, 26: 1101-1112.

[18] Chen J W, Zhu Y T, Jiang W. A stretchable and transparent strain sensor based on sandwich- like PDMS/CNTs/PDMS composite containing an ultrathin conductive CNT layer[J]. Composites Science and Technology, 2020, 186: 107938-107946.

[19] Zhang C J, Li H, Huang A, *et al*. Rational design of a flexible CNTs@PDMS film patterned by bio - inspired templates as a strain sensor and supercapacitor[J]. Small, 2019, 15: 1805493-1805501.

[20] Wang L, Chen Y, Lin L W, *et al*. Highly stretchable, anti-corrosive and wearable strain sensors based on the PDMS/CNTs decorated elastomer nanofiber composite[J]. Chemical Engineering Journal, 2019, 362: 89-98.

[21] Tian H, Shu Y, Cui Y L, *et al*. Scalable fabrication of high-performance and flexible graphene strain sensors[J]. Nanoscale, 2014, 6: 699-705.

[22] Jung Y, Jung K, Park B, *et al*. Wearable piezoresistive strain sensor based on graphene- coated three- dimensional micro-porous PDMS sponge[J]. Micro and Nano Systems Letters, 2019, 7: 1-9.

[23] Shi G, Lowe S E, Teo A J T, *et al*. A versatile PDMS submicrobead/graphene oxide nanocomposite ink for the direct ink writing of wearable micron- scale tactile sensors[J]. Applied Materials Today, 2019, 16: 482-492.

[24] Zhao X H, Xu W, Yi W M, *et al*. A flexible and highly pressure-sensitive PDMS sponge based on silver nanoparticles decorated reduced graphene oxide composite[J]. Sensors & Actuators: A. Physical, 2019, 291: 23-31.

[25] Nguyen V T, Ki M B, Yi Y, *et al*. MXene($Ti_3C_2T_X$/graphene/ PDMS composites for multifunctional broadband electromagnetic interference shielding skins[J]. Chemical Engineering Journal, 2020, 393: 124608-124642.

[26] Xu H, Zhang K, Lu Y F, *et al*. Dual-mode wearable strain sensor based on graphene/colloidal crystal films for simultaneously detection of subtle and large human motions[J]. Advanced Materials Technologies, 2020, 5: 1901056 -1901064.

[27] Xia X N, Chen J, Liu G L, *et al*. Aligning graphene sheets in PDMS for improving output performance of triboelectric nanogenerator[J]. Carbon, 2017, 111: 569-576.

[28] Kou H R, Zhang L, Tan Q L, *et al*. Wireless flexible pressure sensor based on micro- patterned Graphene/PDMS composite[J]. Sensors and Actuators A: Physical, 2018, 277: 150-156.

[29] Luo S, Yang J, Song X F, *et al*. Tunable- Sensitivity flexible pressure sensor based on graphene transparent electrode[J]. Solid State Electronics, 2018, 145: 29-33.

[30] 王瑞荣. 基于石墨烯/PDMS 介质层的柔性压力传感器[J]. 电子元件与材料, 2019, 38(8): 72-75.
Wang R R. Flexible pressure sensor based on graphene/PDMS dielectric layer[J]. Electronic Components and Materials, 2019, 38(8): 72-75.

[31] Sergio M, Manaresin N, Targagni M. A textile based capacitive pressure sensor[J]. Proceedings of IEEE Sensors, 2002, 2: 45-52.

[32] Filippidou M K, Tegou E, Tsouti V, *et al*. A flexible strain sensor made of graphene nanoplatelets/polydimethylsiloxane nanocomposite[J]. Microelectronic Engineering, 2015, 142: 7-11.

[33] Zhou D B, Wang H P. Design and evaluation of a skin-like sensor with high stretchability for contact pressure measurement[J]. Sensors & Actuators A: Physical, 2013, 204: 114-121.

[34] Jeong H, Noh Y,Ko S H, *et al*. Flexible resistive pressure sensor with silver nanowire networks embedded in polymer using natural formation of air gap[J]. Composites Science and Technology, 2019, 174: 50-57.

[35] Heo Y, Hwang Y, Jung H S, *et al*. Sensors: secondary sensitivity control of silver-nanowire-based resistive-type strain sensors by geometric modulation of the elastomer substrate [J]. Small, 2017, 13: 1700070-1700078.

[36] Lee J Y, Shin D, Park J. Fabrication of silver nanowire-based stretchable electrodes using spray coating[J]. Thin Solid Films, 2016, 608: 34-43.

[37] Li Y X, Han D Y, Jiang C J, *et al*. A facile realization scheme for tactile sensing with a structured silver nanowire - PDMS composite[J]. Advanced Materials Technologies, 2019, 4: 1800504-1800514.

[38] Hu T, Xuan S H, Ding L, *et al*. Stretchable and magneto-sensitive strain sensor based on silver nanowire- polyurethane sponge enhanced magnetorheological elastomer[J]. Materials & Design, 2018, 156: 528-537.

[39] Zhao X H, Xu W, Yi W M, *et al*. A flexible and highly pressure-sensitive PDMS sponge based on silver nanoparticles decorated reduced graphene oxide composite[J]. Sensors & Actuators A: Physical, 2019, 291: 23-31.

[40] Marschner U, Nima Mahmoodi S, Collet M. The 2016 ASME Conference on smart materials, adaptive structures and intelligent systems: symposium on modeling, simulation, and control of adaptive systems[J]. Journal of Intelligent Material Systems and Structures, 2019, 30: 1366-1367.

[41] Zhang X T, Le M Q, Zahhaf O, *et al*. Enhancing dielectric and piezoelectric properties of micro- ZnO/PDMS composite- based dielectrophoresis[J]. Materials & Design, 2020, 192: 108783-108798.

[42] Edmison J, Jones M, Lockhart T, *et al*. An e-textile system for motion analysis[J]. Studies in Health Technology and Informatics, 2004,10:292-301.

[43] Filippidou M K, Tegou E, Tsouti S, *et al*. A flexible strain sensor made of graphene nanoplatelets/polydimethylsiloxane nanocomposite[J]. Microelectronic Engineering, 2015, 142: 7-11.

Development of Flexible Sensors Based on Polydimethylsiloxane

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ABSTRACT: Compared with traditional strain sensors, the flexibility, wearability, and real-time monitoring of flexible sensors are unique advantages. In recent years, flexible sensors have developed rapidly and are applied to medical detection, wearable devices, and many other aspects. Due to the excellent physical and chemical properties of polydimethylsiloxane (PDMS), it is often used as flexible sensor substrate. This article summarized the recent research work on the use of polydimethylsiloxane as flexible sensor substrate. Firstly, the sensing mechanism of PDMS nanocomposites was introduced in detail, including piezoresistive, capacitive and piezoelectric sensing mechanisms. Then the PDMS-based flexible sensors with carbon nanotube (CNT), graphene or nano-silver as nano-particles were reviewed. Finally, the research status and existing problems of PDMS-based flexible sensors were summarized and prospected.

Keywords: polydimethylsiloxane; flexible; sensor; nanocomposite