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掺杂具有 POSS 结构的单体及纳米复合材料 对聚合物分散液晶薄膜电光性能的影响

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摘要: 聚合物分散液晶(PDLC)作为一种无需偏振片、具有独特微相分离形貌的光电复合材料,克服了传统液晶器件依赖严格盒式结构的局限。针对当前 PDLC 面临的驱动电压高与电光损耗大等问题,本文系统综述了笼型聚倍半硅氧烷(POSS)基单体(POSS-SH、KH570-POSS)及纳米复合掺杂体系对 PDLC 性能的调控机制与最新进展,重点分析了 POSS 单体及纳米掺杂剂的引入对 PDLC 相分离过程、聚合物网络形貌、液晶微滴尺寸与取向及界面锚定作用的调控规律,阐明了微观结构演变与 PDLC 驱动电压、对比度、电光损耗等关键性能之间的构效关系。结果表明,POSS 笼状结构的引入能有效优化相分离网络结构,显著降低驱动电压并提升对比度。本文从微观形貌演变与界面相互作用层面深化了 PDLC 的性能调控理论,为高性能柔性智能窗及光电器件的设计提供了重要参考。

关键词: 聚合物分散液晶;多面体低聚倍半硅氧烷 POSS;驱动电压;对比度

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Influences of monomer with POSS structure and nanocomposites on electro-optical properties of polymer dispersed liquid crystal films

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Abstract: As innovative photoelectric composites characterized by unique microphase-separated morphologies, polymer-dispersed liquid crystals (PDLCs) eliminate the need for polarizers and overcome the inherent reliance of traditional liquid crystal devices on rigid cell structures. To address the critical challenges of

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high driving voltages and substantial electro-optical losses in current PDLCs, this review systematically summarizes the recent advances and underlying regulatory mechanisms of PDLCs incorporating polyhedral oligomeric silsesquioxane (POSS)-based monomers (POSS-SH and KH570-POSS) and their nanocomposite doping systems. Particular attention is devoted to elucidating how the incorporation of POSS monomers and nanofillers modulates the phase separation process, polymer network morphology, liquid crystal droplet size/orientation, and interfacial anchoring. Furthermore, the intrinsic structure-property correlations between these microscopic structural evolutions and macroscopic electro-optical performances—specifically driving voltage, contrast ratio, and optical loss—are comprehensively established. The findings demonstrate that the introduction of the unique cage-like POSS structure effectively optimizes the phase-separated polymer network, thereby significantly reducing the driving voltage and enhancing the contrast ratio. By deepening the theoretical understanding of performance modulation from the perspectives of microscopic morphological evolution and interfacial interactions, this review provides critical insights for the future design of high-performance flexible smart windows and advanced optoelectronic devices.

Key words: polymer dispersion liquid crystal; polyhedral oligosiloxane; driving voltage; contrast ratio

1 引 言

现代光学材料和器件的开发为人类的生活带来了许多便利,但是传统的光学器件需要偏振片和取向层来实现功能,限制了其性能和应用^[1]。近年来,液晶/聚合物复合材料作为新型的光学器件,因其高效的光学响应特性得到了越来越广泛的应用^[2]。根据聚合物质量分数和相分离网络形貌的差异,液晶/聚合物复合材料主要划分为聚合物分散液晶(PDLC)和聚合物稳定液晶(PSLC)两种体系^[2-3]。从微观形貌来看,二者存在本质区别:PDLC呈现“聚合物连续相、液晶分散相”的典型结构,液晶以微米级液滴形式被聚合物基体包裹;而PSLC则以液晶为连续相,少量聚合物(质量分数1%~10%)仅形成稀疏的三维网络骨架以稳定液晶取向,无明显液滴结构^[4-5]。这种形貌差异直接决定了二者的力学与电光性能。PSLC稀疏的网络导致其剪切强度较弱,难以制备柔性薄膜,但其高透过率使其在全息光栅、空间光调制器等精密光学器件中占据不可替代的地位^[7]。相反,PDLC较高的聚合物含量(质量分数通常大于20%,甚至达40%)赋予了其优异的机械强度与成膜柔韧性,使其具备了卷对卷大面积批量制备的先天优势^[6-8]。

对于具备柔性量产优势的PDLC而言,其核心机制在于液晶微滴的电控光散射特性。无电场时,微滴内液晶分子随机取向导致折射率失配,

薄膜呈光散射态;施加电场后,液晶分子沿电场方向重排实现折射率匹配,薄膜转为透明态^[9-12]。与传统的纯液晶显示器相比,PDLC彻底摆脱了对偏振片和精密取向层的依赖,不仅大幅简化了工艺、降低了能耗,还真正实现了器件的柔性化^[10]。特别是近年来,随着物联网与绿色建筑理念的深入,智能窗正从单一的透雾切换向隔热、自供电等多功能集成方向快速演进。PDLC兼具良好的介电、光学各向异性与高机械稳定性的特点,完美契合了这一产业升级需求,因而在大面积调光智能窗、柔性显示器、防伪等领域展现出巨大的应用潜力^[13-19]。

电光性能是衡量PDLC薄膜性能的一个重要指标,主要包括阈值电压(V_{th})、饱和电压(V_{sat})、关态透过率(T_{off})、开态响应时间(t_{on})、关态响应时间(t_{off})和对比度(CR)等^[20-21]。 V_{th} 和 V_{sat} 分别是指薄膜透过率达到最大值的10%和90%时的外加电压。关态透过率(T_{off})是指关闭电场后薄膜的透过率。 t_{on} 是施加电场后,薄膜透过率由最大透过率10%上升到90%所需的时间。 t_{off} 是关闭电场后,薄膜透过率由90%下降到10%时所需的时间。CR是薄膜的开态透过率(T_{on})与关态透过率之比。

PDLC的电光性能受如LC畴的形状和尺寸、聚合物基体组分、制备工艺及薄膜的厚度等多种因素的影响^[22-28]。然而,由于聚合物与液晶微滴界面处存在强烈的锚定作用,通常需要较高的外

加电场才能克服界面壁垒,使液晶分子沿电场方向重新排列^[24]。高阈值电压不仅显著增加了器件的运行能耗,更严重制约了其在智能窗领域及低功耗柔性设备中的实际应用。

为此,开发低电压驱动、高对比度的PDLC体系已成为当前研究的核心热点。其中,纳米复合掺杂策略因其在界面工程中的独特优势备受瞩目^[29]。近年来,研究人员将半导体纳米粒子、金属氧化物、纳米纤维等引入PDLC体系^[30-34]。尽管传统纳米填料取得了一定成效,但该领域仍面临严峻挑战:纳米粒子的引入往往会导致体系相容性变差甚至团聚;更为棘手的是,降低薄膜驱动电压与提升对比度之间往往存在固有的“此消彼长”效应,难以实现多维度性能的协同优化。

近年来,多面体低聚倍半硅氧烷(POSS)纳米材料因其优异的特性吸引了研究人员的关注^[35-36]。依托其独特的笼状结构,POSS基聚合物已被用于制备纳米级结构设计的新型复合材料,能够通过调控聚合物网络结构显著改善复合材料的机械性

能,提升其热稳定性,展现出良好的应用前景^[37-40]。不同于传统纳米填料易团聚的缺陷,POSS分子级别的无机-有机杂化笼状结构在调控聚合物网络拓扑形貌和界面相互作用方面展现出极高的可控性^[37]。研究表明,POSS基复合材料不仅能通过干预相分离动力学有效降低体系的驱动电压,还能通过其特殊的纳米级界面效应同步提升对比度,为打破PDLC中降低电压与提高对比度相互制约的瓶颈提供了全新的解决方案^[41-43]。基于此前沿背景,本文综述了POSS基单体对PDLC聚合物网络形貌及电光性能的调控机制,探讨了其他纳米粒子以及POSS作为可聚合单体与其他纳米材料协同掺杂时对PDLC电-光性能的提升规律。

2 POSS微结构及SiO₂纳米材料掺杂PDLC

各纳米粒子对PDLC电光性能的影响如表1所示。

表1 各掺杂体系参数对比表

Tab. 1 Comparison of parameters for various doping systems

液晶	单体	纳米粒子	紫外光强/ (mW·cm ⁻²)	研究发现	年份	文献 编号
SLC1717	PEGDA400/IBMA/ HPMA/CHMA	POSS-SH	5.0	V _{th} 从42.9 V降至23.8 V, V _{sat} 从84.8 V降至32.9 V, CR由约45提高至110(20 μm)	2021	[41]
E8	DET	POSS- KH570	5.0	V _{th} 从约35 V降至约15 V, V _{sat} 从91 V降至42 V, CR由约15提高至约60(20 μm)	2022	[54]
E7	TMPTA/EP828	CQDs		V _{th} 由30.1 V降低至24.1 V, V _{sat} 由70.6 V降低至62.3 V; t _{on} 和 t _{off} 分别由32 ms和50 ms降低至10 ms	2026	[60]
E7	PCDH	GO	3.0	V _{sat} 从125 V降至11.5 V(6 μm)	2024	[63]
TEB50+CB15	NVP/TweenTM80/ ebecryl8301	MWCNT		V _{sat} 从5.11 V/μm降至1.77 V/μm, V _{th} 从1.64 V/μm降至0.68 V/μm(20 μm)	2020	[65]
GXP-6011	HPMA/PFPMA/Bis- EMA15/PEGDA600	WO ₃ /Ag ₂ O	12	V _{sat} 从24.8 V降至15.2 V, V _{th} 从12.7 V降至9.8 V, CR由81提高至132(20 μm)	2024	[66]
E8	IBMA/CHMA/ HPMA/PEGDA400	POSS-SH、 Cs ₂ WO ₃	5	V _{th} 从约60 V降至9 V, V _{sat} 从大于100 V降至12 V, CR从<10提高至183(20 μm)	2023	[68]
E8	PEGDA400/IBMA/ HPMA/CHMA	POSS-SH、 IBMA		V _{sat} 从58.3 V降至14 V, V _{th} 从46.2 V降至10.5 V(20 μm)	2023	[70]

据D. Berouguiaa团队报道,掺杂少量的SiO₂即可对PDLC的电光性能有所改善,响应时间有

所减少^[44]。Yaroshchuk等人研究了不同掺杂量的SiO₂纳米粒子的聚合物分散液晶的电光性能和

微观结构。研究表明, SiO₂ 纳米粒子的掺杂会使光散射效应增强, 导致对比度显著增加^[45]。尺寸范围在 1~3 nm 的 POSS 分子被认为是粒径最小的 SiO₂ 纳米颗粒^[36]。其分子结构是由 Si—O—Si 键组成的纳米笼状结构, 因其具有低介电常数、良好的溶解性及在可见波长范围内的透明度高等特点, 成为一种具有吸引力的有机-无机纳米材料^[39-40]。由于 POSS 可以用作单官能团、接枝单体或多官能团交联剂来形成聚合物^[46], 因此可将其引入聚合物基体中, 探索改善 PDLC 电光性能的可能性。He 等人(2021年)合成了巯基修饰的多面体倍半硅氧烷(POSS-SH), 首次将 POSS 微结构引入到 PDLC 聚合物基体中^[41]。如图 1 所示, PDLC 样品的驱动电压随着 POSS-SH 的引入由 85 V 显著降低至 36 V 以下, 且薄膜的对比度迅速提升至 200 以上。在 PDLC 薄膜制备过程中, 随着固化反应的进行, 预聚物的分子量逐渐变大, 导致体系的溶解度降低, 进而实现液晶微滴的相分离。在紫外光固化过程中, POSS-SH 与丙

烯酸酯单体发生巯基-丙烯酸酯加成反应, 形成硫醇-烯网络与丙烯酸酯自聚长链揉在一起的杂化网络。同时 POSS 的笼状纳米结构较大的空间位阻会降低基体的交联密度^[47-48]。因此聚合物网孔的尺寸随着 POSS-SH 掺杂量的增加而逐渐增大(图 2)。在扫描电子显微镜(SEM)图像中, 聚合物网孔的结构对应液晶微滴的位置。较大的聚合物网孔意味着 PDLC 中存在较大尺寸的液晶微滴, 进而需要较低的驱动电压。当 PDLC 处于电场环境时, 液晶一方面受到来自聚合物的锚定力作用, 使其保持原来状态, 另一方面受到电场作用力的驱动, 使其沿电场方向排列。水接触角测试结果表明, 随着 POSS-SH 的掺杂量逐渐增大, 聚合物表面能逐渐降低, 导致聚合物对液晶产生的锚定力减小。POSS-SH 的引入使微观网孔增大和聚合物表面能降低, 二者协同作用使 PDLC 薄膜的驱动电压降低, 对比度增大^[41]。

在 PDLC 中分别掺杂 POSS-SH 和 SiO₂ 纳米材料的研究表明, 由于 POSS 纳米笼状结构的空

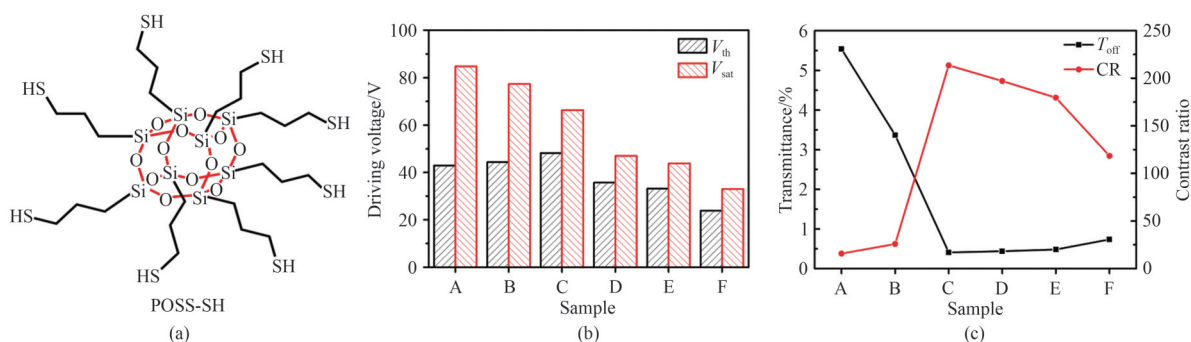


图 1 (a) POSS-SH 化学结构; (b) 阈值电压 (V_{th}) 和饱和电压 (V_{sat}); (c) 对比度 (Contrast Ratio, CR) 和关态透射率 (T_{off})^[41]。
Fig. 1 (a) Chemical structures of the POSS-SH; (b) Threshold voltage (V_{th}) and saturation voltage (V_{sat}); (c) Contrast ratio (CR) and off-state transmittance (T_{off})^[41].

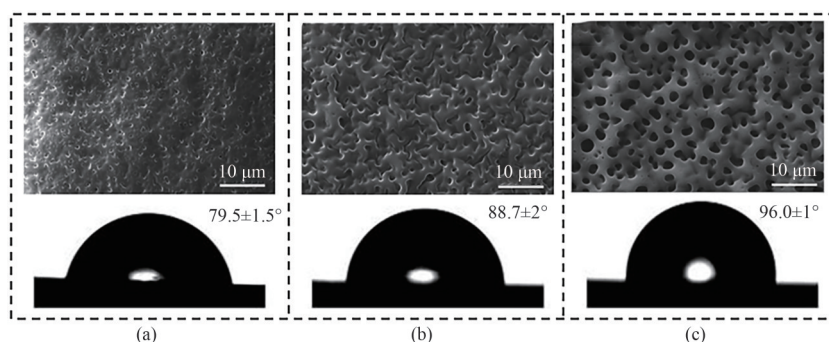


图 2 含有不同 POSS-SH 质量分数的聚合物网络形貌和去离子水接触角测量结果。(a) 0%; (b) 3%; (c) 5%^[41]。
Fig. 2 Morphologies and deionized water contact angles of polymer with different POSS-SH mass fractions. (a) 0%; (b) 3%; (c) 5%^[41].

间位阻以及表面官能团的可聚合性,掺杂 POSS-SH 可以获得均匀多孔的聚合物网状结构,而掺杂 SiO_2 纳米颗粒在聚合物基体中发生团聚,仅得到疏松的非均相聚合物结构^[42]。这就导致 SiO_2 纳米材料对 PDLC 电光性能的改善不理想,而 POSS-SH 材料有效提升了 PDLC 的电光性能,使薄膜驱动电压降低了近 80%^[42]。此外,在紫外聚合过程中,由于制备条件的变化,PDLC 薄膜的电光性能也会受到影响^[49]。Yu 等人的研究表明,聚合温度和紫外光强度均会影响丙烯酸酯和 POSS-SH 单体的聚合速率。较低的紫外光强度以及适当的聚合温度会形成较低的自由基聚合速率,使微观相

分离充分,从而得到较大的液晶微滴,实现更优异的电光性能^[43]。

在上述研究基础上,可进一步将聚乙烯醇 (PVA) 纳米纤维通过静电纺丝的方法涂覆在氧化铟锡 (ITO) 表面来调节 POSS-SH 掺杂的 PDLC 样品的关态透过率 (T_{off}) 和对比度 (CR)^[50]。如图 3 所示, PVA 纳米纤维与缝隙中空气的折射率不匹配,这使得含有纳米纤维的 PDLC 样品相比传统的 PDLC 样品具有更低的 T_{off} 和更大的 CR。选取的纳米纤维层与聚合物基体之间的折射率匹配性,使 PDLC 样品在电场作用下可以切换为透明态^[51]。

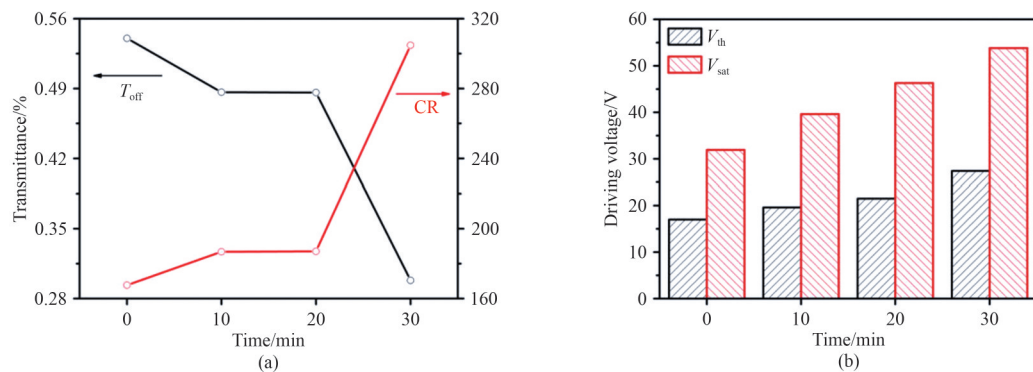


图 3 (a) 对比度 (CR) 和关态透射率 (T_{off}); (b) 在不同紫外光强度下制备的含有纳米纤维的样品的阈值电压 (V_{th}) 和饱和电压 (V_{sat})^[50]。

Fig. 3 (a) Contrast ratio (CR) and the off-state transmittance (T_{off}); (b) Threshold voltage (V_{th}) and the saturation voltage (V_{sat}) of the samples in nanofiber cell prepared under different UV light intensities^[50].

用丙烯酸酯对 POSS 表面进行改性接枝,可以得到 KH570-POSS。如图 4 所示, POSS-SH 和 KH570-POSS 的尺寸相近,均为 200 nm 左右,形貌相近,且在有机溶剂中均能较好地分布^[41,52]。研究表明,将 KH570-POSS 掺杂到 PDLC 时,随着掺杂量的增加,纳米结构增强的光散射效应增强了体系的 CR (>100),但驱动电压的变化趋势与 POSS-SH 掺杂不同,表现为先下降后上升。一方面,POSS 笼状纳米结构的引入会削弱聚合物网络的锚定效应^[41];另一方面, KH570-POSS 表面的丙烯酸酯基团发挥交联剂的作用,与体系中的单体发生反应,从而形成较为致密的聚合物网络结构,增强聚合物基体对液晶分子的总锚定效果^[52]。当 KH570-POSS 作为掺杂剂时, PDLC 的电光性能的变化趋势源于二者的竞争作用^[52]。

亲核试剂引发的点击化学反应可在无紫外光

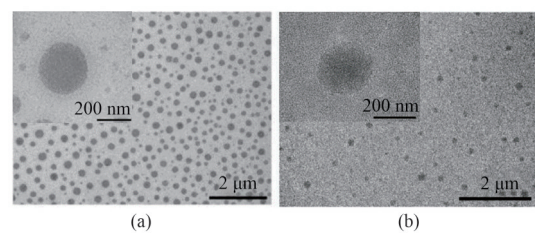


图 4 POSS-SH (a) 和 KH570-POSS (b) 的透射电子显微镜 (TEM) 形貌图^[41,52]。

Fig. 4 Transmission electron microscope (TEM) images of (a) POSS-SH and (b) KH570-POSS^[41,52].

照的条件下发生,是近年来制备 PDLC 的研究热点^[53]。通常, PDLC 通过链式自由基聚合制备,通过硫醇-烯点击反应制备 PDLC 的报道较少。选择 DET(2,20-(乙二氧基)二乙基硫醇)作为 PDLC 的反应单体,并向其中添加丙烯酸酯修饰的 KH570-POSS 和 KH570- SiO_2 两种纳米结构,经聚合形成

复合薄膜^[54]。DET的加入导致KH570-POSS中丙烯酸基团之间的交联减少,聚合物网络密度降低,对LC微滴的界面锚定能减弱,从而更容易驱动LC分子的运动以降低驱动电压。而KH570-SiO₂可以取代部分KH570-POSS,通过硫醇-烯点击反应形成聚合物网络,提高SiO₂纳米粒子在膜中的兼容性。当KH570-SiO₂含量(质量分数)接近5%时,可实现薄膜驱动电压低于安全电压36V,且对比度值为165的良好性能^[51]。不同含量的DET也会对PDLC电光性能产生影响。Zhang等人的研究表明,DET含量的增加,会导致聚合物网络尺寸增大,从而降低了LC和聚合物基质之间的表面能,有效提升PDLC的电光性能^[55]。通过调节UV强度可将驱动电压保持在相对较低的水平,同时提高薄膜对比度^[56]。通过硫醇-烯点击反应进一步优化了具有POSS结构的PDLC薄膜的电光性能,为PDLC材料的应用带来更多的机会和可能性。

3 其他纳米粒子掺杂PDLC

半导体纳米颗粒(NPs)因其尺寸与形貌的高度可调性,展现出独特的光电与磁学特性,也因此被广泛应用于发光器件、太阳能电池、光电二极管、场效应晶体管、显示器等诸多技术领域^[57]。有研究证实,将ZnO纳米粒子掺杂到PDLC中将导致液晶微滴尺寸增大,阈值和驱动电压降低,响应时间增加^[56]。Gülsüm Kocakulah等人向聚合物分散液晶(PDLC)中掺杂CdSeS/ZnS量子点(QDs),有效改善了薄膜的电光与介电性能^[58-59]。一方面,QDs的引入显著降低了器件的阈值电压^[59];另一方面,得益于量子点的硫基壳层结构,掺杂体系的响应时间也明显缩短^[58]。聚合物、液晶分子与量子点间的界面相互作用,也使得PDLC的介电参数显著增强^[58-59]。碳量子点(CQDs)的掺杂可调控PDLC微观结构与介电环境^[60],同步实现电光性能优化与荧光强度的大幅提升。碳量子点(CQDs)掺杂可延缓PDLC聚合,优化其微观结构,增大液晶微滴尺寸,从而降低界面锚定能并增强内部有效电场。在0.2%最优掺杂量(质量分数)下,器件阈值与饱和电压分别降低19.9%和11.8%,同时开关态响应时间均同步降低至10ms^[60]。通过介电环境调控与光程优化,荧光

强度最高提升约130%。

通过在环氧-硫醇聚合物分散液晶(PDLC)中掺杂蒽醌染料,可实现彩色高对比度PDLC的制备^[61]。研究发现,染料种类和浓度可协同调控材料性能:分散橙能提升透过率与力学强度,但会增加驱动电压;溶剂绿28和溶剂蓝104可降低驱动电压。通过优化染料配方,可以实现光电性能与力学性能的协同优化。

氧化石墨烯(GO)是一类具有典型二维蜂窝结构的材料,兼具优异的机械性能与光电特性,如良好的柔韧性、较高的机械强度以及因表面含氧官能团^[62]带来的高极化率等突出光电响应。提高氧化石墨烯的氧化程度,有利于其在极性溶剂中实现稳定分散,并可与液晶分子形成较强的 π - π 堆积作用^[62-63]。已有研究表明,氧化石墨烯可有效应用于液晶基智能窗器件中。Malik团队通过优化氧化石墨烯的掺杂浓度,提升了GO-PDLC复合体系智能窗的节能性能^[63]。研究发现,在无电场条件下,氧化石墨烯片层倾向于沿ITO导电基底取向排布,并与液晶分子取向保持一致,受液晶苯环与石墨烯蜂窝结构间强锚定作用影响,近GO片层的液晶分子更易沿其表面有序排布。当施加足够电场时,石墨烯片随电场取向并进一步诱导液晶分子同向排列,使GO-PDLC的驱动电压低于纯PDLC。二维纳米粒子的引入通常会造成器件开态透过率的下降。碳纳米管(CNTs)具有与液晶分子相似的细长棒状结构,更易与液晶分子取向相匹配,从而避免器件透过率的降低^[64]。已有研究证实,在PDLC中掺入CNTs能显著降低器件阈值电压,同时保持较高的对比度^[65]。

北京科技大学与北京大学杨槐团队联合开发了一种基于WO₃/Ag₂O p-n异质结光电效应的新型PDLC智能窗,通过引入异质结纳米粒子与红外发射型单体,同步实现了电光性能与热管理的双重优化^[66]。该p-n异质结能有效分离光生载流子,其光电效应增强了薄膜内部的电场,从而将驱动电压(饱和电压)大幅降低了约41%,同时通过增加散射中心提高了对比度。通过在聚合物基质中引入具有高红外发射率的可聚合单体,可在大气窗口波段高效辐射热量,实现被动降温。该多功能集成方案为低功耗节能智能窗的设计提供了新思路^[67]。

4 POSS 与其他结构共掺杂 PDLC

在 PDLC 中掺杂 POSS 纳米笼状结构,可以有效地改变聚合物基体的物理性质,如分子间相互作用、力学性质、热稳定性等,显著调节 PDLC 薄膜的电光性能。因此,将 POSS-SH 作为可聚合单体加入 PDLC 中,并添加其他种类的纳米材料来强化薄膜的功能性,是一种可行的设计思路^[68-72]。铯钨青铜(Cs_xWO_3)的局域表面等离子效应赋予了该纳米粒子强的近红外光(NIR)屏蔽效果和高可见光透过等优点^[71]。He 等人将 Cs_xWO_3 纳米粒

子引入到以 POSS-SH 为基体的 PDLC 薄膜中^[68]。如图 5 所示,随着 Cs_xWO_3 掺杂浓度的增加,薄膜在近红外光波段透过率逐渐降低,有效屏蔽近红外光。POSS-SH 可有效降低薄膜的驱动电压, Cs_xWO_3 的引入可以有效遮挡近红外光,提高薄膜的温度调节能力,二者的协同作用使薄膜具有优异电光性能的同时有效阻隔近红外光^[68]。Gao 等人将二茂铁引入到含有 POSS 结构的薄膜中,赋予了薄膜紫外屏蔽性能,得到了具有优异电光性能的紫外屏蔽薄膜^[69]。因此,POSS 作为单体与功能性纳米粒子共掺杂的策略,为 PDLC 薄膜在节能智能窗方面的应用提供了更多的可能性。

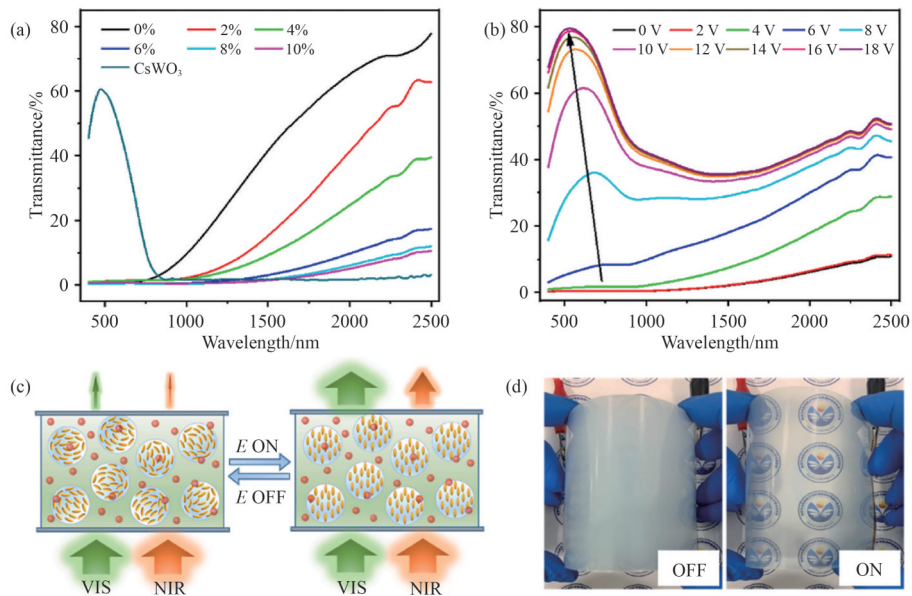


图 5 (a) 不含液晶的 Cs_xWO_3 薄膜和含有不同浓度 Cs_xWO_3 的 PDLC 薄膜透射光谱; (b) 含有 8% (质量分数) 的 Cs_xWO_3 薄膜在不同电压下的透射谱; (c) 不同状态下可见光(VIS)和近红外光(NIR)透射率调制示意图; (d) 在 OFF 和 ON 状态下薄膜的显示照片^[68]。

Fig. 5 Transmission spectra for (a) Cs_xWO_3 film without liquid crystal and PDLC films with different concentrations of Cs_xWO_3 and (b) PDLC film with 8% (mass fraction) Cs_xWO_3 under different voltages; (c) Schematic illustration of the modulation of visible light (VIS) and near infrared (NIR) light transmittance at different states; (d) Photographs of the hybrid film at OFF and ON states^[68].

据报道,两性离子在提升液晶器件性能的同时,可以有效减少单一阳离子或阴离子引发的离子积累从而损害器件稳定性问题^[70-72]。将两性离子化合物 SBMA 掺杂到 POSS 基 PDLC 薄膜,可进一步提升薄膜电光性能。离子化合物的浓度和聚合工艺均会影响 PDLC 的电光性能。采用直接涂覆不进行热处理的方式,SBMA 与单体的交联发生在靠近 ITO 的表面,驱动电压下

降 20 V^[70]。在紫外光聚合前通过预加热的方式可加速两性离子扩散,可诱导 SBMA 进入 POSS 基 PDLC 预聚物的内部,产生交联反应,改变聚合物基体的微观形貌。9% 的含量(质量分数)可使薄膜的驱动电压从 58.3 V 降低到 14.0 V, CR 值大于 200,开关状态下的雾度也表现出良好的性能。如图 6 所示,两性离子不仅会提高离子电导率,降低聚合物电阻率,还会影响液晶分子

取向,同时其双偶极矩产生的内建电场会降低液晶分子受到的锚定力。该研究进一步拓宽

了PDLC薄膜在可穿戴设备和智能窗领域的应用^[70]。

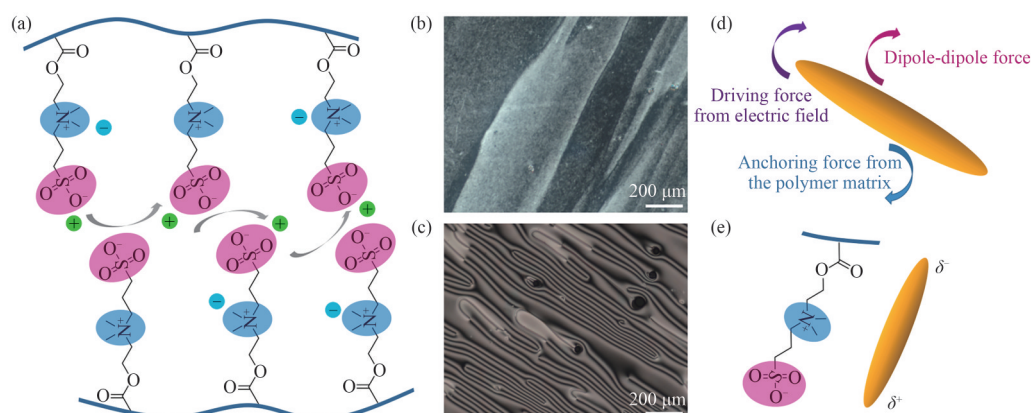


图6 (a)两性离子处理的PDLC中聚合物基体内离子杂质迁移机理示意图;(b)传统液晶盒和(c) SBMA处理的液晶盒中E8的偏光显微镜图像(溶液中SBMA浓度(质量分数)为7.0%);(d)电场作用下两性离子处理的PDLC样品中液晶分子受力情况示意图;(e)两性离子基团与液晶分子之间分子间相互作用示意图^[70]。

Fig. 6 (a) Schematic diagram of a proposed migration mechanism for the ionic impurities in the polymer matrix of the zwitterion-treated PDLCs; POM images of E8 in (b) a conventional LC cell and (c) an SBMA-treated LC cell (the SBMA concentration (mass fraction) in the solution is 7.0%); (d) Schematics of the force condition on the LC molecule in the zwitterion-treated PDLC sample under an electric field; (e) Schematic diagram of the intermolecular interaction between the zwitterionic moieties and LC molecules^[70].

5 结论与展望

本文主要介绍了POSS-SH、KH570-POSS、以及POSS-SH共掺杂其他纳米粒子对PDLC薄膜电光性能的影响。当前单纯地提升PDLC电光性能的一个方面已不能满足现实需求,需要在提升单个性能的同时最大程度地优化其他性能,包括PDLC样品的稳定性、可切换性、响应速度以及制备成本等,以此探索新的PDLC调控途径,满足不同应用场景的需求。通过引入POSS笼状结构以及其他纳米粒子,可有效降低PDLC薄膜的驱动电压,提升对比度,拓宽复合薄膜在智能窗、传感器柔性显示器等

领域的应用。因此,POSS笼状结构的引入对进一步优化PDLC薄膜性能具有重要的研究意义。

未来,随着智能建筑和智能交通等领域的发展,PDLC薄膜的应用场景将会更加广泛和多样化。在探索新的聚合物分散液晶调控途径的同时,我们需要加强对PDLC薄膜在复杂环境下的性能表现、可持续性和环境友好性等方面的系统研究。此外,针对不同应用场景的需求,还需进一步降低PDLC薄膜制备成本并提高其制备效率。只有通过不断探索和创新,才能进一步提高PDLC薄膜的应用价值和市场需求,推动相关领域智能化和绿色化发展。

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