

改性蒙脱石对聚醚酰亚胺复合电介质高温储能性能的影响

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摘 要: 高温聚合物电介质材料的研究对于电子电力设备的高热稳定性和小型化发展尤为重要, 但大漏导电流极大限制了其规模化应用。以聚醚酰亚胺为基体, 蒙脱石纳米片为填料, 探讨了聚乙烯亚胺改性蒙脱石纳米片对聚醚酰亚胺复合电介质在高温强电场下储能性能的影响规律。结果表明, 采用聚乙烯亚胺修饰蒙脱石能够显著提高蒙脱石与聚醚酰亚胺基体的相容性, 使其能够均匀分散在有机相中; 适量掺杂的蒙脱石纳米片能够有效抑制复合薄膜泄漏电流, 降低电导损耗; 在 150 °C 和 500 MV/m 场强下, 复合薄膜表现出最窄的充放电曲线, 最大放电能量密度高达 3.54 J/cm³, 充放电效率保持在 86.7%。该复合薄膜在高温介电聚合物应用领域具有良好的潜力。

关键词: 聚醚酰亚胺; 蒙脱石; 聚乙烯亚胺; 能量密度; 充放电效率

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聚合物电介质电容器通过电介质在静电场下的极化和去极化过程储能, 与电池和超级电容器相比, 电介质电容器具有超快的充放电速率和超高的功率密度, 尤其在先进电力和电子器件的脉冲功率系统中不可或缺^[1-4]。此外, 电介质电容器还具有工作电压高、介质损耗低、自愈性强和稳定性高等优点, 广泛应用于电动汽车、新能源并网以及先进激光武器等领域^[5-6]。然而, 聚合物电介质电容器在高温性能上存在不足。例如, 双向拉伸聚丙烯薄膜(BOPP)是商业化最成功的电介质材料之一, 其最高使用温度为 105 °C, 长期使用则温度需低于 85 °C^[7-8]。随着电动汽车、光伏发电、油气勘探等的快速发展, 其并对高温介电聚合物材料的需求日益增加。

聚醚酰亚胺因其高玻璃化温度(217 °C)和高熔点(247 °C), 成为最具应用潜力的高温电介质材料之一^[9-11]。但其苯环的 π - π 共轭结构导致其在高温高电场下电导损耗急剧增加, 造成效率和储能密度大幅降低。在 150 °C 和效率超过 90% 时, 储能密度仅为 0.4 J/cm³^[12], 电导损耗产生的焦耳热还会引发发热失控及电容器失效的风险。

蒙脱石具有天然的二维层状纳米片结构, 且其资源丰富、禁带宽度大及绝缘性能良好^[13-15]。将蒙脱石纳米片引入聚合物基体中, 能够提高载流子跃迁势垒并在面内方向耗散载流子^[16-18], 从而抑制传导电流, 提高聚合物的高温储能性能。Tomer 等^[19]研究发现, 取向排列的蒙脱石纳米片垂直于电场方向时, 能够显著提高聚烯烃纳米复合材料的击穿强度和储能密度。Wang 等^[20]将剥离的蒙脱石纳米片涂覆于聚酰胺薄膜表面, 能够抑制电极电荷注入, 降低泄漏电流, 在 150 °C 和 500 MV/m 时, 储能密度提升到 2.9 J/cm³。Wu 等^[21]采用聚乙烯醇和蒙脱石纳米片混合制备成自组装涂层, 能够提高电极电荷的注入势垒, 减少泄漏电流, 在 150 °C 和 400 MV/m 时, 储能密度达到 2.48 J/cm³。然而, 将蒙脱石制备成聚合物电介质的涂层虽能抑制电极电荷的注入, 但并未改变电介质体相的能垒, 当有热电子激发时, 依然存在泄漏电流和热失控的风险。

将蒙脱石纳米片分散在聚醚酰亚胺体相中有望解决上述问题, 但基体(柔性)和无机填料(刚性)之间的显著差异使提高有机-无机界面的相容性成为挑战。

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为此, 采用聚乙烯亚胺对蒙脱石纳米片进行表面修饰, 提高了其与聚醚酰亚胺的界面相容性, 使其均匀分散于有机相基体中, 降低了介质内的泄漏电流, 抑制了聚醚酰亚胺在高温高电场下的电导损耗, 使得复合材料在 150 °C 和 450 MV/m 时储能效率维持在 90.1%, 放电储能密度高达 3.15 J/cm³; 在 150 °C 和 500 MV/m 时, 最大放电能量密度达到 3.53 J/cm³; 储能效率维持在 86.7%。通过表面修饰提高蒙脱石纳米片与聚合物基体的相容性, 为提高高温介电聚合物的高温储能性能提供了新的途径。

1 实验

1.1 原料

原料包括: 聚醚酰亚胺(PEI, 玻璃化温度 217 °C), 从 PolyK Technologies 公司购买; 钠基蒙脱石(阳离子交换量为 1.31 mmol/g), 从古丈县山麟石语矿产品有限公司购买; 聚乙烯亚胺(分子量为 300)和聚甲基吡咯烷酮(NMP), 从上海阿拉丁生化科技股份有限公司购买; 去离子水, 为实验室自制。

1.2 蒙脱石的改性

将 1 g 蒙脱石超声分散于 200 mL 去离子水中, 加入 0.6 g 聚乙烯亚胺, 磁力搅拌 4 h。在此过程中, 聚乙烯亚胺分子置换蒙脱石表面的钠离子。将所得悬浮液以 4000 r/min 的速度离心, 取沉淀, 加入 100 mL 去离子水。重复上述过程 3 次, 以清洗过量的聚乙烯亚胺分子。将离心后的蒙脱石冷冻干燥 24 h, 得到聚乙烯亚胺修饰的蒙脱石纳米片。

1.3 蒙脱石/PEI 复合薄膜的制备

称取 1.5 g 的 PEI 颗粒溶解于 10 mL NMP 中, 在 50 °C 加热搅拌 6 h。待 PEI 颗粒完全溶解后, 称取 30 mg 改性蒙脱石超声分散于 1 mL NMP 中; 按质量分数(0.1%、0.2%、0.3%)用移液枪分别量取 50、100、200 μL 的蒙脱石悬浮液, 加入 PEI 溶液中, 继续超声 0.5 h。将所得悬浮液用刮刀在干净的玻璃板上流延, 在真空干燥箱中以 80 °C 干燥 12 h, 然后将温度提高到 200 °C 继续干燥 4 h, 以彻底去除 NMP 溶剂。将玻璃基板置于去离子水中静置 10 min, 复合薄膜脱离玻璃基板, 得到厚度约 10 μm 的复合薄膜。

1.4 样品表征

采用扫描电子显微镜(SEM)观察改性前后蒙脱石的表面形貌, 放大倍数为 3000 倍和 15 000 倍。采用 X 射线衍射仪(XRD)分析蒙脱石的晶体结构, 测试条件为 Cu 靶, 管压为 40 kV, 管流为 100 mA,

扫描角度为 3°~70°(2θ), 扫描速率为 5 (°)/min。采用傅里叶变换红外光谱(FTIR)对蒙脱石表面分子官能团进行表征, 测试范围为 400~4000 cm⁻¹。采用 X 射线光电子能谱(XPS)分析蒙脱石表面的元素组成。采用同步热重-热差(TG-DSC)热分析仪分析复合薄膜的玻璃化温度, 测试温度范围为 30~240 °C, 升降温速率为 5 °C/min, 测试气氛为氩气。

1.5 储能性能测试

采用磁控溅射镀膜仪将薄膜两面镀上直径为 3 mm 的金电极。使用英国稳科的 WK6500B 型阻抗分析仪测试复合薄膜的介电常数, 介电谱的测试频率为 10²~10⁶ Hz, 介电谱的温度区间为 30~200 °C, 测试频率为 1000 Hz; 使用美国 polyK Technologies 的铁电分析仪测试复合薄膜的击穿场强, 测试夹具采用硅油加热至 150 °C; 使用美国 polyK Technologies 的铁电分析仪测试复合薄膜的极化曲线, 测试温度为 150 °C, 测试频率为 100 Hz。

2 结果与讨论

图 1a 为蒙脱石表面改性的示意图。聚乙烯亚胺分子在水溶液中电离为聚合阳离子^[22-23], 当其浓度较高时, 会置换蒙脱石表面的钠离子, 并吸附于蒙脱石层间和表面, 生成聚乙烯亚胺改性的蒙脱石纳米片。聚乙烯亚胺改性提高了蒙脱石在 NMP 溶剂中的分散性, 使蒙脱石纳米片均匀分散在 PEI 基体中, 同时增强了有机相和无机相的相容性。为了验证聚乙烯亚胺的改性过程, 我们对改性前后的蒙脱石进行了红外光谱和 X 射线光电子能谱表征。图 1b 为傅里叶变换红外光谱。改性后的蒙脱石出现了 CH₃ 和 CH₂ 的伸缩振动(分别为 2946 cm⁻¹ 和 1435 cm⁻¹)和弯曲振动峰(分别为 2906 cm⁻¹ 和 1421 cm⁻¹), 同时也观察到 NH₂ 的伸缩振动峰(3290 cm⁻¹)和摇摆振动峰(795 cm⁻¹)^[23-24], 这些峰的存在表明聚乙烯亚胺成功负载在蒙脱石表面。图 1c 和图 1d 是 X 射线光电子能谱, 经 C 1s 峰校正后, 改性后蒙脱石的谱图中出现了 N 1s 的峰, 也进一步验证了聚乙烯亚胺的成功负载。

XRD 不仅能够表征蒙脱石的晶体结构, 而且根据衍射峰(001)的角度能够计算层间距, 从而判断是否有分子嵌入蒙脱石的层间^[25-26]。图 2 是蒙脱石在改性前后的 XRD 谱。从图 2 可以看出, 样品的衍射峰主要是蒙脱石的峰(JCPDS 13-0259), 且有较弱的石英的衍射峰(JCPDS 46-1045), 这是因为购买的蒙脱石样品中含有少量的石英杂质。改性后蒙脱石的 *d*₍₀₀₁₎ 峰由 2θ = 7.04° 位移至 2θ = 6.45°, 说明蒙脱石的层间距增大。

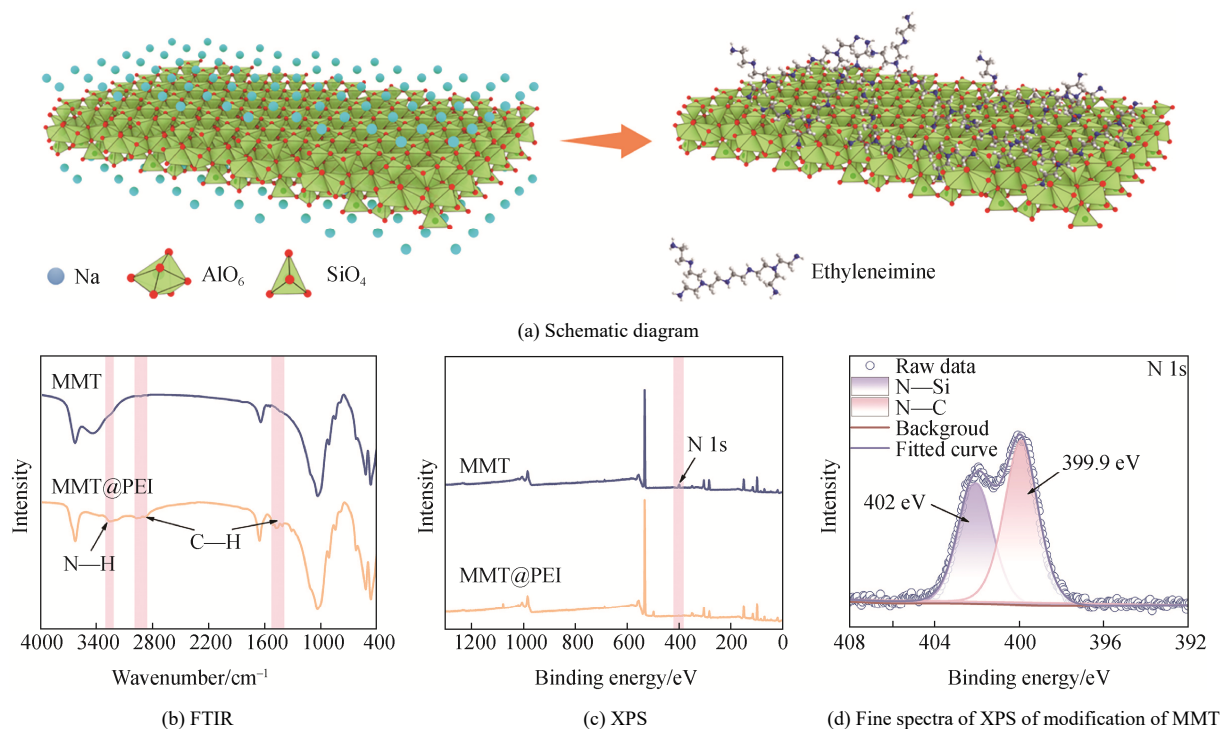


图1 蒙脱石表面改性示意图, 以及傅里叶变换红外光谱和 X 射线光电子能谱

Fig. 1 Schematic diagram, FTIR and XPS spectra of surface modification of montmorillonite (MMT)

根据布拉格衍射方程 $2d\sin\theta=n\lambda$, ($\lambda=0.154\ 06\ \text{nm}$, n 取 1)^[27], 计算结果显示改性后蒙脱石的层间距由 $1.255\ \text{nm}$ 增加到 $1.369\ \text{nm}$ 。层间距的增大表明聚乙烯亚胺分子不仅负载在蒙脱石的表面, 而且嵌入到层间, 使得蒙脱石片层得到有效剥离。

呈现花状排列。

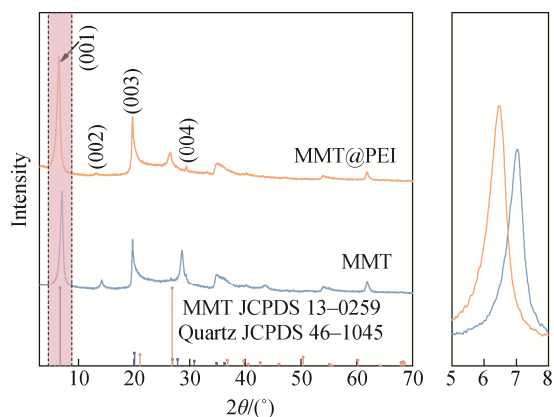


图2 蒙脱石改性前后的 XRD 谱

Fig. 2 XRD patterns of MMT before and after modification

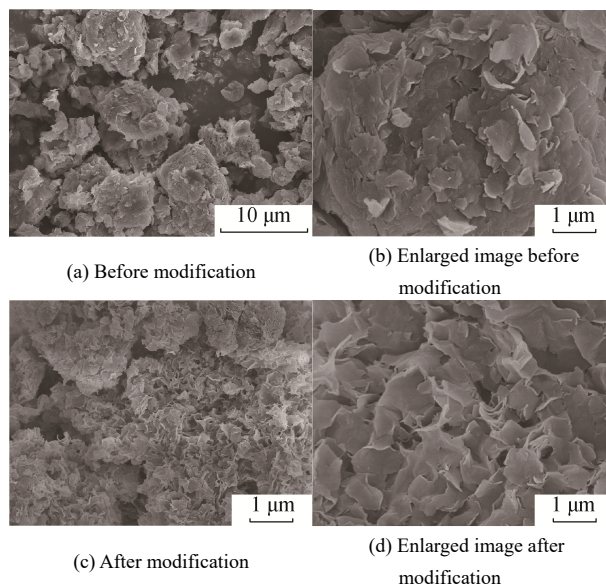


图3 蒙脱石改性前后的 SEM 照片

Fig. 3 SEM images of MMT before and after modification

图3为蒙脱石改性前后的 SEM 照片。由于蒙脱石片层呈电负性, 表面吸附有钠离子, 改性前, 蒙脱石片层间静电引力作用力较强, 层间距较小, 片层平行排布, 堆积成数微米的大颗粒; 而改性后, 聚乙烯亚胺嵌入层间, 使得蒙脱石片层剥离, 片层

将改性后的蒙脱石纳米片掺杂到 PEI 基体中制备成复合薄膜, 通过同步热分析仪对复合薄膜的玻璃化温度进行研究, 测试温度范围为 $30\sim 240\ ^\circ\text{C}$, 升降温速率为 $5\ ^\circ\text{C}/\text{min}$, 测试气氛为氩气。图4为 PEI 复合薄膜的热容曲线随蒙脱石掺杂比例的变化。随

随着蒙脱石掺杂量的增加, 复合薄膜的玻璃化温度 T_g 由 216 °C 提高到 221 °C, 这表明引入蒙脱石纳米片能够提高聚醚酰亚胺的耐高温性能^[28]。

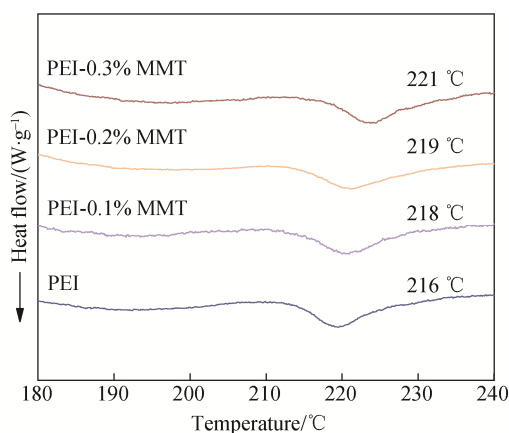
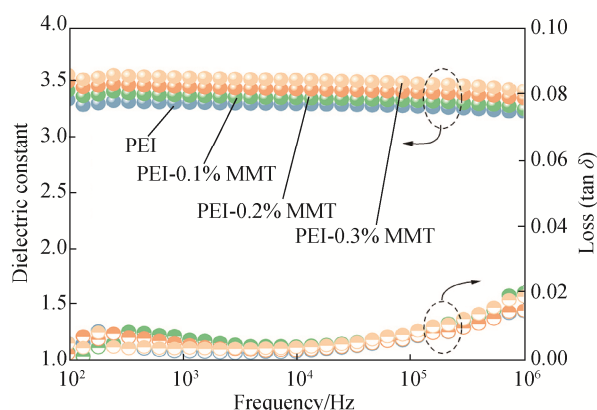


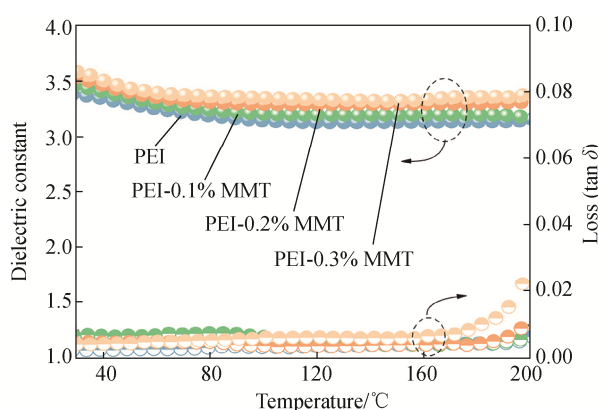
图 4 复合薄膜的热分析曲线
Fig. 4 DSC curves of PEI composites

为了研究蒙脱石对聚醚酰亚胺介电性能的影响, 该研究分别测试了复合薄膜的介电常数随频率和温度的变化。由图 5a 可看出, 复合薄膜在 $10^2 \sim$



(a) Frequency dependence of dielectric constant

10^6 Hz 频率区间内的介电常数仅有轻微的衰减(小于 2%), 表明其具有良好的频率稳定性。随着蒙脱石掺杂量的增加, 复合薄膜在 1000 Hz 频率下的介电常数由原始 PEI 的 3.25 提高至 3.54, 且介电损耗在整个频率区间内均低于 0.02, 保持在较低水平。图 5b 则展示了在 30~200 °C 范围内, 复合薄膜的介电常数在 1000 Hz 频率下的变化规律。在 30~60 °C 温度区间内, 介电常数明显降低, 而在 60~200 °C 温度区间内几乎没有衰减, 显示出良好的温度稳定性。在 150 °C 和 1000 Hz 频率下, 复合薄膜的介电常数随着蒙脱石掺杂量的增加从 3.13 提高至 3.32, 且介电损耗维持在较低水平, 但当掺杂量增加到 0.3% 时, 介电损耗在 160 °C 有明显增加。以上结果表明, 通过引入蒙脱石纳米片, 能够有效提高 PEI 复合材料的介电常数, 且随着掺杂量的提高, 复合材料的介电常数也有所提高, 这得益于蒙脱石的大比表面积能够增大复合材料的界面极化强度。此外, 蒙脱石纳米片分散在 PEI 基体中能够阻挡载流子在介质内的迁移, 降低介质损耗, 使得复合材料在整个频率、温度范围内保持较低的损耗。



(b) Temperature dependence of dielectric constant

图 5 PEI 复合材料在 $10^2 \sim 10^6$ Hz 和 30~200 °C 的介电常数和损耗
Fig. 5 Dielectric constant and loss of the PEI composites from $10^2 \sim 10^6$ Hz and from 30~200 °C

该研究采用威布尔(Weibull)分布统计法分析复合薄膜的介电击穿性能, Weibull 分布公式为

$$P(E) = 1 - \exp(-(E/E_b)^\beta) \quad (1)$$

其中: E_b 为累积失效概率为 63.2% 时的 Weibull 击穿强度; β 为反映数据分散程度的形状参数^[29-30]。如图 6a 所示, 在 150 °C 时, 原始 PEI 的击穿强度为 435.4 MV/m。引入改性蒙脱石后, 复合薄膜的击穿强度呈先上升后下降的趋势。当掺杂量为 0.1% 时, 击穿强度提高到 487.2 MV/m; 当掺杂量为 0.2% 时, 击穿强度进一步提升至 507.5 MV/m。然而, 当掺杂

量继续增加时, 击穿强度下降至 459.5 MV/m。这表明适量的蒙脱石纳米片能够有效提升复合材料的介电击穿性能。此外, 介电聚合物复合材料的储能密度与电场的平方呈正相关, 因此, 击穿强度越高, 储能密度越高。这表明通过优化蒙脱石的掺杂量, 能够有效提高介电聚合物复合材料的击穿强度和储能密度。

图 7 为 PEI 及其复合薄膜在 150 °C 的电滞回线。由图 7 可见, 掺杂 0.2% 蒙脱石的复合薄膜具有较窄的电滞回线, 这表明其电导损耗得到了有

效抑制^[31], 能量损失较低。在 150 °C 和 500 MV/m 场强下, 复合材料表现出最窄的充放电曲线, 其效率最高可达 86.7%。相比之下, 原始 PEI 在 150 °C 和 450 MV/m 场强下的储能效率仅为 72.5%, 这表

明蒙脱石的掺杂显著提升了复合材料的储能效率。以上结果表明, 通过优化掺杂量, 能够显著改善复合材料的电滞回线, 从而提高其储能性能和储能效率。

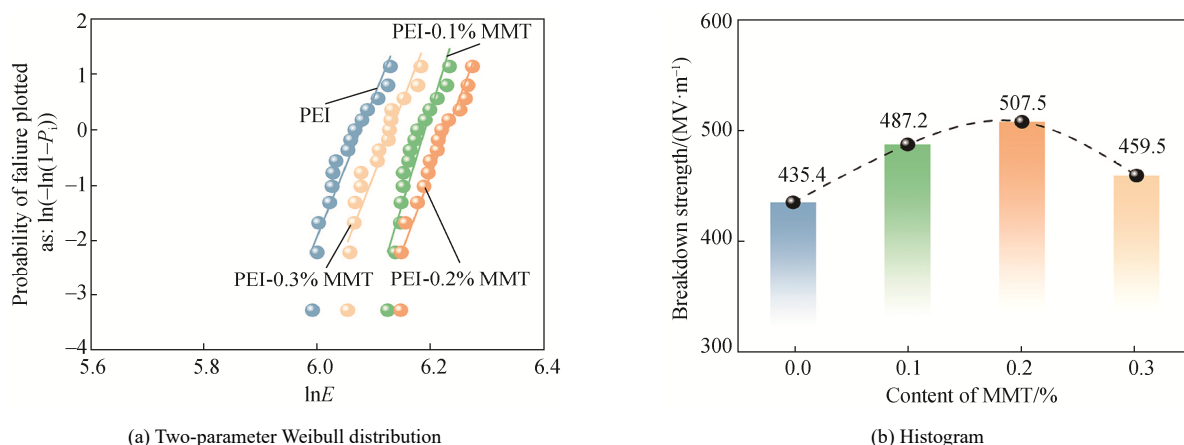


图 6 PEI 复合材料在 150 °C 击穿场强的 Weibull 分布和直方统计图

Fig. 6 Two-parameter Weibull distribution and histogram of the dielectric breakdown strength of PEI composites at 150 °C

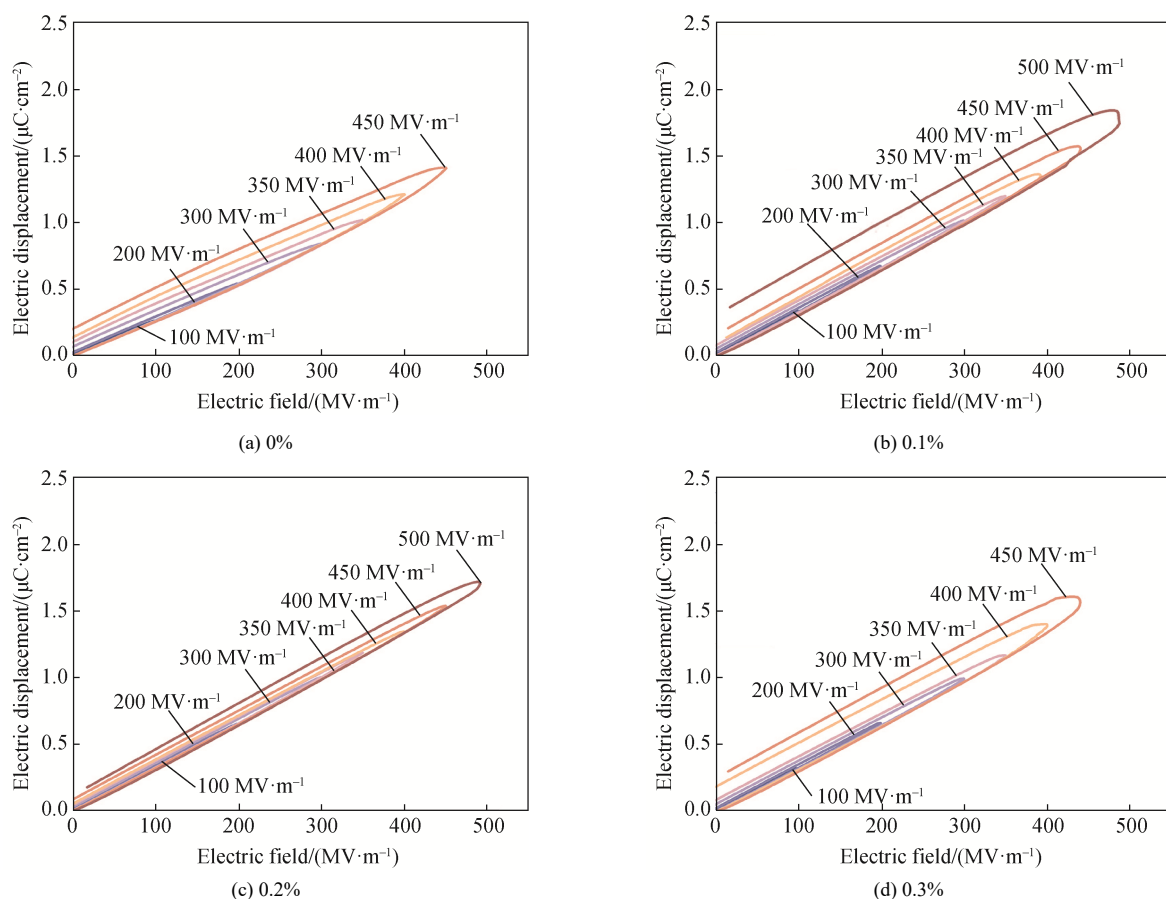


图 7 不同掺杂比例蒙脱石 PEI 复合材料在 150 °C 的电滞回曲线

Fig. 7 P - E loops of PEI composites with different dosage of MMT at 150 °C

由于能量损耗, 放电能量密度通常低于充电能量密度, 这一比例被定义为充放电效率。在实现较

高放电能量密度的同时, 保持高效率(大于 90%)对于避免设备故障和热失控至关重要^[32]。如图 8 所示,

原始 PEI 在 150 °C 和 450 MV/m 场强下的放电能量密度为 2.56 J/cm^3 , 而效率仅为 72.5%, 远低于聚合物薄膜电容的使用标准。引入蒙脱石纳米片后, 复合薄膜的击穿强度和介电常数同步增强, 电荷存储能力显著提升。具体地, 掺杂 0.1% 蒙脱石时, 在 150 °C 和 500 MV/m 场强下, 最大放电能量密度提高到 3.17 J/cm^3 , 但效率仅为 77.8%。当掺杂量增加至 0.2% 时, 最大放电能量密度在 150 °C 和 450 MV/m 场强下达到了 3.15 J/cm^3 , 此时效率提高至 90.1%, 满足薄膜电容的标准工况要求。在 150 °C 和 500 MV/m 场强下, 放电能量密度进一步提高至 3.54 J/cm^3 , 效率保持在 86.7%。然而, 当掺杂量提高至 0.3% 时, 最大放电能量密度和效率均有所降低。这表明适量的蒙脱石掺杂能够有效提升复合材料的放电能量密度和效率, 但掺杂量过多会导致储能性能下降。

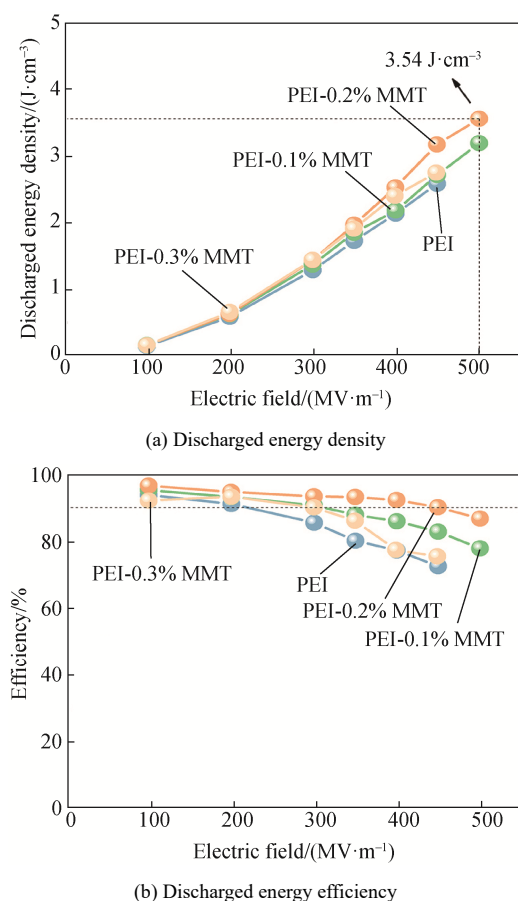


图 8 PEI 复合材料在 150 °C 的储能密度和储能效率

Fig. 8 Discharged energy density and efficiency of the PEI composites at 150 °C

图 9 为 PEI/蒙脱石复合材料的储能密度和充放电效率与先前报道复合材料的比较, 储能密度和效率是衡量介电聚合物储能性能的重要参数。通过表

面改性, 提高了蒙脱石与 PEI 基体的界面相容性, 良好分散的蒙脱石纳米片能够抑制载流子在介质中的传输, 降低介质损耗, 使得该 PEI 复合材料能够在 150 °C 保持较高效率(86.7%)的同时获得高储能密度(3.54 J/cm^3)。

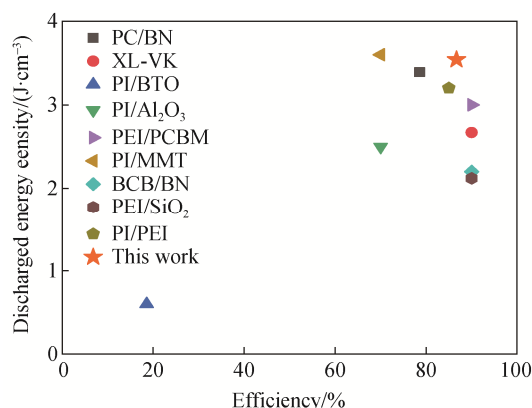


图 9 先前报道的聚合物基高温介电储能性能与本工作的比较^[12, 16, 33-39]

Fig. 9 Comparison of previous reported high-temperature energy storage performance of polymer-based dielectrics and this work^[12, 16, 33-39]

3 结论

通过阳离子交换, 本工作成功将聚乙烯亚胺分子负载在蒙脱石纳米片的表面和层间, 这一过程使得蒙脱石片层得到有效剥离, 并提高了蒙脱石纳米片在溶剂中的分散性及与聚醚酰亚胺基体的相容性, 从而确保了复合材料的结构均匀性。掺杂改性蒙脱石后, 复合材料的储能性能呈现出先提升后降低的趋势, 其中 0.2% 掺杂量时表现最佳, 在 150 °C 和 1000 Hz 频率下的介电常数为 3.45, 击穿强度为 507.5 MV/m。在 450 MV/m 电场强度下, 充放电效率达到 90.1%, 放电储能密度为 3.15 J/cm^3 ; 在 500 MV/m 电场强度下, 充放电效率为 86.7%, 最大放电能量密度达到 3.54 J/cm^3 。这项工作表明, 蒙脱石纳米片的掺杂是提升聚醚酰亚胺高温储能性能的有效策略, 为开发高强度、高性能的高温介电聚合物开辟了新途径。

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Influences of Modified Montmorillonite on the High-Temperature Energy Storage Performance of Polyetherimide Dielectric Composites

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Extended Abstract

Introduction Polyetherimide with its high glass transition temperature (*i.e.*, 217 °C) and melting point (*i.e.*, 247 °C) is considered as a promising high-temperature dielectric material. However, the π - π conjugated structure of its benzene rings leads to a sharp increase in conductivity loss at high temperatures and electric fields, thus reducing efficiency and energy storage density. Montmorillonite possesses a large bandgap and good insulation properties. Incorporating montmorillonite nanosheets into the polymer matrix is an effective approach to enhance the carrier transition barrier and dissipate carriers in the in-plane direction, thereby suppressing conduction current and improving the high-temperature energy storage performance of the polymer. However, the significant differences between the flexible matrix and the rigid inorganic filler pose some challenges for the compatibility at the organic-inorganic interface. In this paper, polyethylenimine was modified onto the surface of montmorillonite nanosheets to improve their interface compatibility with polyetherimide, allowing for uniform dispersion within the organic matrix. In addition, the impact of modified montmorillonite on the dielectric constant, breakdown strength and energy storage performance of polyetherimide composites was also investigated.

Methods The modified montmorillonite was prepared *via* cation exchanging with polyethylenimine, and MMT/PEI composites were prepared by a tape casting method. PEI particles were firstly dissolved in NMP solvent under heating and stirring at 50 °C for 6 h. Once the PEI particles were completely dissolved, modified montmorillonite with a target content were firstly dispersed in the solvent under ultrasonication for 0.5 h. The resulting suspension was then cast onto a clean glass plate with a scraper and dried in a vacuum oven at 80 °C for 12 h. Afterwards, the material was dried at 200 °C for 4 h to completely remove the NMP solvent. The glass substrate was then placed in deionized water and left to stand for 10 min, allowing for the composites film to detach from the glass substrate, resulting in a composite film with a thickness of approximately 10 μ m.

Results and Discussion The relative dielectric constant of the composites exhibits only a slight decrease in the frequency range of 10^2 Hz to 10^6 Hz, indicating a good stability. The dielectric constant of the composites at 1000 Hz increases from 3.25 for pure PEI to 3.54, while the dielectric loss remains below 0.02 in the entire frequency range as the amount of montmorillonite increases. Moreover, the dielectric constant of the composites increases from 3.13 to 3.32 with the addition of montmorillonite at 150 °C and 1000 Hz. The dielectric loss remains at a low level. Thus, the dielectric breakdown strength of pure PEI at 150 °C is 429 MV/m. After introducing modified montmorillonite, the breakdown strength of the composites initially increases and then decreases. At a doping modified montmorillonite amount of 0.1%, the breakdown strength increases to 487.2 MV/m, and with a doping modified montmorillonite amount of 0.2%, it further increases to 507.5 MV/m. However, the breakdown strength decreases to 459.5 MV/m when the doping modified montmorillonite amount continues to increase. The discharge energy density of pure PEI at 150 °C and at 450 MV/m is 2.56 J/cm³, with an efficiency of only 72.5%. After introducing the modified montmorillonite nanosheets, the breakdown strength and dielectric constant of the composites both are enhanced, leading to an improvement in charge storage capability. At 0.1% of modified montmorillonite doping amount, the maximum discharge energy density increases to 3.17 J/cm³ at 150 °C and 500 MV/m, although the efficiency remains low at 77.8%. When the doping modified montmorillonite amount increases to 0.2%, the maximum discharge energy density reaches 3.15 J/cm³ at 150 °C and 450 MV/m, with the efficiency improving to 90.1%, thus meeting the standard operational requirements for film capacitors. At 150 °C and 500 MV/m, the discharge energy density further increases to 3.54 J/cm³, while the efficiency stabilizes at 86.7%. However, when the doping modified montmorillonite amount increases to 0.3%, the maximum discharge energy density and efficiency both decline. This indicates that an appropriate amount of montmorillonite nanosheets can effectively enhance the energy storage properties of PEI-based composites. The excessive doping can lead to a negative effect on the energy storage performance of composites, likely due to aggregation or suboptimal

dispersion of the nanosheets.

Conclusions Polyethyleneimine molecules were effectively loaded onto the surface and interlayers of montmorillonite nanosheets through cation exchange. This process improved the dispersibility of the montmorillonite nanosheets in solvents and their compatibility with the polyetherimide matrix, ensuring the structural uniformity of the composite materials. After doping with modified montmorillonite, the energy storage performance of the composites exhibited the optimum performance observed at a doping modified montmorillonite amount of 0.2%. At this doping amount, the dielectric constant was 3.45 at 1000 Hz and 150 °C, while the breakdown strength reached 507.5 MV/m. At an electric field strength of 450 MV/m, the charge-discharge efficiency achieved 90.1%, with a discharge energy density of 3.15 J/cm³; at 500 MV/m, the charge-discharge efficiency was 86.7%, and the maximum discharge energy density reached 3.54 J/cm³. The results of this work indicated that doping with montmorillonite nanosheets could be an effective strategy for enhancing the high-temperature energy storage performance of polyetherimide, paving a way for the development of high-strength, high-performance high-temperature dielectric polymers.

Keywords polyetherimide; montmorillonite; polyethylenimine; energy density; charge–discharge energy efficiency