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Advances in organic field-effect transistors with polymeric gate dielectrics: A short review

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Organic field-effect transistors (OFETs) have emerged as promising components in flexible and low-cost electronic applications due to their mechanical flexibility, compatibility with solution processing, and the ability to tune electrical properties. A critical element in OFET performance is the gate dielectric, with polymeric dielectrics such as PMMA, PVP, and polystyrene offering notable advantages in terms of processability, dielectric strength, and interface engineering. This review presents a comprehensive analysis of OFETs utilizing polymeric gate dielectrics, with a focus on the deposition of organic semiconductors by spin-coating and thermal evaporation methods. The review discusses how the interaction between polymer dielectrics and semiconductors affects charge transport, interface traps, threshold voltage, and overall device stability. Key device architectures including bottom-gate and top-gate configurations are evaluated, highlighting performance trends and material selection strategies. Finally, new designs such as bilayer dielectrics, organic–inorganic hybrid systems, and low-voltage organic field-effect transistors are considered to address issues related to environmental sensitivity and lifetime. This review aims to guide future research in optimizing material combinations and fabrication techniques to advance the practical application of polymeric-gated OFETs in next-generation electronics.

Keywords: organic semiconductors, organic field-effect transistors, organic gate, transistor characteristics

Досягнення в органічних польових транзисторах з полімерними діелектриками затвора: короткий огляд. *K. R. Rajesh, C. S. Menon, C. R. Indulal.*

Органічні польові транзистори (OFET) стали перспективними компонентами в гнучких та недорогих електронних пристроях завдяки своїй механічній гнучкості, сумісності з обробкою розчинів та можливості налаштування електричних властивостей. Критичним елементом у продуктивності OFET є діелектрик затвора, причому полімерні діелектрики, такі як ПММА, ПВП та полістирол, пропонують помітні переваги з точки зору технологічності, діелектричної міцності та інженерії інтерфейсу. У цьому огляді представлено комплексний аналіз OFET, що використовують полімерні діелектрики затвора, з акцентом на осадження органічних напівпровідників шляхом спінінгового покриття та термічного випаровування. В огляді обговорюється, як взаємодія між полімерними діелектриками та напівпровідниками впливає на перенос заряду, пастки на інтерфейсі, граничну напругу та загальну стабільність пристрою. Оцінено ключові архітектури пристроїв, включаючи конфігурації з нижнім та верхнім затворами, з акцентом на тенденції продуктивності та стратегії вибору матеріалів. Нарешті, розглянуто нові конструкції, такі як двошарові діелектрики, гібридні органічнонеорганічні системи та низьковольтні органічні польові транзистори, для вирішення проблем, пов'язаних з чутливістю до навколишнього середовища та довговічністю експлуатації. Цей огляд має на меті спрямувати майбутні дослідження в оптимізації комбінацій матеріалів та методів виготовлення для просування практичного застосування полімерних OFET в електроніці наступного покоління.

1. Introduction

Organic field-effect transistors (OFETs) have garnered significant attention as core components of flexible, lightweight, and low-power electronic devices. Their integration into large-area applications such as wearable electronics, biosensors, and flexible displays is enabled by their compatibility with solution processing and mechanically compliant materials. A key factor determining OFET performance is the gate dielectric, which influences the threshold voltage, charge carrier mobility, and operational stability of the device. Among various dielectric materials, polymeric gate dielectrics—such as PMMA, polystyrene (PS), and polyvinylphenol (PVP) – have shown great promise due to their chemical tunability, process simplicity, and ability to form ultra-smooth films [1, 2]. Recent advances have focused on improving the charge carrier mobility and stability of polymer-gated OFETs. Cross-linked polymer dielectrics and high-k composites have demonstrated improved interfacial characteristics and dielectric strengths, enabling field-effect mobility exceeding 1 $cm^2 V^{-1} s^{-1}$ in some systems [3, 4]. For instance, novel high-k polymers with cyclic carbonate functionality have achieved enhanced mobility and air stability simultaneously [5]. These developments are often accompanied by interface engineering strategies such as self-assembled monolayers and surface passivation, which reduce trap densities and bias stress effects [6, 7].

In terms of stability, the incorporation of fluorinated polymers and amorphous perfluoropolymers anchored to dielectric surfaces has significantly mitigated hysteresis and threshold voltage drift under ambient conditions [8, 9]. Moreover, dielectric designs that facilitate low-voltage operation and minimize gate leakage have improved long-term device reliability [5]. These innovations collectively highlight the critical role of polymeric gate dielectric engineering in unlocking next-generation OFET technologies with improved electrical performance and environmental durability [10]. Meanwhile, fabrication of organic semiconductors in OFETs has advanced with deposition techniques such as spin-coating and thermal evaporation, enabling highly controlled and reproducible organic thin films. The spin-coating method produces uniform solution-processed films, enabling scalable fabrication, while thermal evaporation provides high-purity, crystalline semiconductor layers. This review discusses the advances in organic field-effect transistors (OFETs) using polymer gate dielectrics with semiconductors deposited by these two methods

2. Polymeric Gate Dielectrics: Materials and Advantages

Common polymeric gate dielectric materials include polymethyl methacrylate (PMMA), polyvinylphenol (PVP), polystyrene (PS), and cross-linked fluoropolymers. These materials can be processed from solution at low temperatures and enable large-area deposition [11]. Furthermore, their low leakage currents, wide band gaps, and moderate dielectric constants make them suitable for flexible OFETs [12, 13].

Ultra-thin polymer gate dielectrics improve gate coupling and reduce operating voltages. Noh and Sirringhaus demonstrated that ultra-thin layers (<30 nm) of polymer dielectrics enhance mobility and reduce subthreshold swing [11]. Another crucial aspect is the polymer–semiconductor interface. Polymer surface roughness, polarity, and chemical composition affect semiconductor morphology and carrier transport [14].

3. Organic Semiconductor Deposition by Spin-Coating

The spin-coating method is widely employed to prepare solution-processed organic semiconductors such as P3HT, TIPS-pentacene, and diketopyrrolopyrrole (DPP) derivatives. The film thickness and morphology can be controlled by changing the rotation speed, the solvent evaporation rate, and its concentration [15-17]. Importantly, spin-coating enables vertical phase separation in semiconductor–insulator blends, which can promote ordered interfaces beneficial for charge transport [18]. Similarly, Jung et al. reported that spin-deposited blends form single-crystal-like domains at the

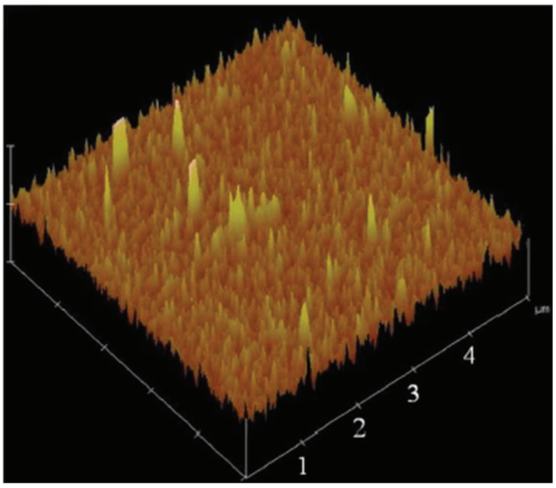

Fig. 1 Morphology of thermally evaporated Zinc Phthalocyanine over the organic gate

dielectric interface, which significantly enhances the mobility [17]. Interface modifications, such as surface functionalization with self-assembled monolayers (SAMs), have also been reported to enhance semiconductor ordering and reduce trap states [20].

However, spin-coating may lead to problems such as coffee-ring effects, film inhomogeneity, and solvent interdiffusion with polymer dielectrics [21, 22]. To address these issues, strategies such as solvent modification, surface tension control, and post-deposition annealing have been used [23].

4. Thermal Evaporation of Organic Semiconductors

Thermal evaporation is especially effective for small-molecule organic semiconductors such as pentacene and rubrene. It offers superior film uniformity, high purity, and precise thickness control. Eccher et al. compared spin-coated and thermally evaporated semiconductors, finding that vacuum-deposited films often display better crystallinity and mobility [1]. Polymeric gate dielectrics produced by thermal evaporation must withstand mild thermal processing. Materials like PMMA and PVP are commonly used due to their thermal stability and processability. Liu et al. fabricated devices with crystalline pentacene films thermally evaporated on polymeric dielectrics, and obtained high-performance OFETs with stable operation [24]. Fig 1 shows morphology of thermally evaporated Zinc Phthalocyanine (ZnPc) over the organic gate [25].

However, the main challenges include vacuum damage to soft polymeric substrates and charge trapping at the interface. Surface treatment and buffer layers like polyethyleneimine (PEI) or polyethyleneglycol (PEG) have been used to improve adhesion and reduce interface defects [26, 27].

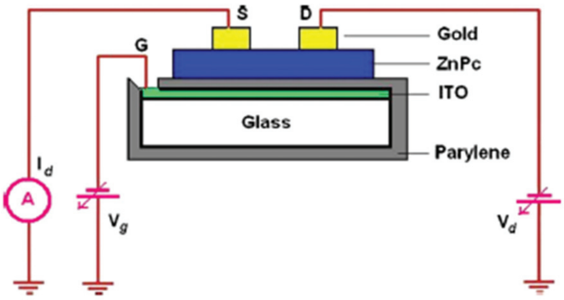

Fig. 2 Schematic of bottom gate − top contact OFET using ZnPc and parylene–C gate

5. Performance Trends and Device Architectures

The performance of organic field-effect transistors (OFETs) is highly dependent on their device architecture and gate dielectric characteristics. Typically, OFETs have one of four geometric configurations: bottom gate – bottom contact (BGBC), bottom gate – top contact (BGTC), top gate – bottom contact (TGBC), and top gate – top contact (TGTC), each of which affects the charge injection and transport paths [28]. Top-gate architectures, in particular, allow for superior dielectric encapsulation, minimizing environmental degradation [29]. Polymeric gate dielectrics such as PMMA, PVP, and polystyrene continue to be widely used due to their low leakage current, flexibility, and compatibility with low-temperature solution processing [29, 30]. Fig. 2 shows the schematic of bottom gate − top contact OFET using ZnPc and organic parylene–C gate [25]

Fig 3 shows the output characteristics of the quaterthiophene OFETs fabricated using different dielectrics: PMMA, CyEP, Parylene-C [26]. Device performance is evaluated based on the mobility (μ), threshold voltage (V_{th}), subthreshold swing (SS), and on/off ratio (I_{on}/I_{off}). Facchetti et al. demonstrated that modifying the dielectric surface chemistry can tune V_{th} and SS [1]. Roichman and Tessler reported numerical simulations supporting the critical role of gate dielectric–semiconductor interfaces [21]. Table 1 shows the mobility and on/off ratio of various organic FETs fabricated with organic gates. Recent developments emphasize dielectric surface modification and mo-

Table 1. Mobility and on/off ratio of various organic FETs with organic gates

Sl. No.	Organic Semiconductor	Gate Dielectric Material	Mobility (cm2/ V·s)	I on/I off	Ref. No.
1	Diketopyrrolopyrrole–based polymer	Crosslinked poly(vinylphenol) (PVP)	1.25	1×10^6	[5]
2	P3HT	PMMA	0.20	5×10^5	[10]
3	TIPS-pentacene	Polystyrene (PS)	2.10	1×10^6	[9]
4	Conjugated donor–acceptor copolymer	High-k fluoropolymer blend	1.50	8×10^5	[28]
5	Ambipolar conjugated polymer	Poly(methyl methacrylate) (PMMA)	0.85 (hole)	2×10^5	[30]
6	2D organic–inorganic hybrid perovskite	PVP	0.60	1×10^4	[12]
7	Small-molecule semiconductor blend	Hydrophobic fluoropolymer	1.80	5×10^5	[32]

lecular engineering to control semiconductor morphology and interface trap density. This approach has led to improved subthreshold swings and mobilities [31, 33]. Furthermore, ultra-thin polymer layers with controlled wettability have been shown to reduce hysteresis and improve the operational stability of OFETs under ambient conditions [33, 34]. Cui et al. demonstrated poly(3,4-ethylenedioxythiophene) (PEDOT)-based OFETs fabricated entirely by spin-coating [35]. In some configurations, dual-gate and bilayer polymer dielectrics allow for enhanced charge modulation and threshold voltage tuning, which are particularly advantageous for logic circuits and memory integration [36].

Another promising direction involves polymer electrets and ion-gel layers, which offer non-volatile behaviour and ultralow voltage operation. These innovations support the trend toward printable, flexible, and transparent OFETs for applications in wearable and biosensor technologies [7]. Importantly, devices using high-*k* fluorinated polymer dielectrics or polymer-inorganic nanocomposites have exhibited enhanced capacitance, improved interface energy alignment, and reduced gate leakage [1]. As OFETs approach commercial viability, the interplay of device geometry, dielectric engineering, and semiconductor deposition (spin-coating or thermal evaporation) remains central to optimizing performance and scalability over large areas. Recent works reported mobilities >1 cm^2/Vs using P3HT and TIPS-pentacene over cross-linked PVP and PMMA dielectrics [37, 38]. Moreover, the use of bilayer or hybrid

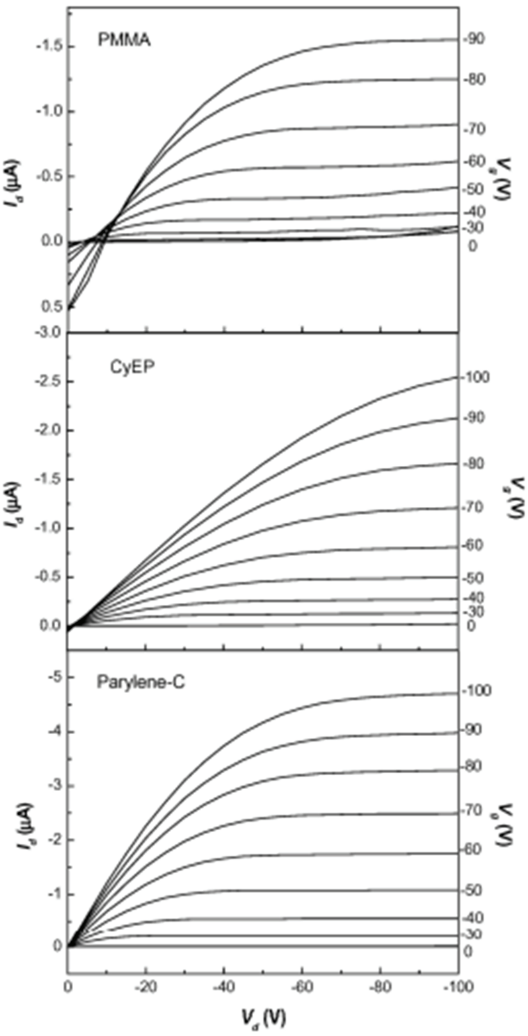

Fig 3 Output characteristics of the quaterthiophene OFETs using dielectrics: PMMA, CyEP, Parylene-C

dielectric structures further improves charge transport and reduces hysteresis [17].

6. Challenges and Future Prospects

Although polymeric gate dielectrics are promising, several challenges remain. These include:

- Interfacial charge trapping due to impurities or surface roughness,
- Dielectric swelling during solvent evaporation of spin-coated semiconductors,
- Thermal limitations during vacuum evaporation,
- Moisture and oxygen sensitivity under ambient conditions.

Recent research is shifting toward hybrid organic–inorganic dielectrics, nanocomposite polymer dielectrics, and low-voltage OFETs for energy-efficient applications [37–40]. Future OFETs will likely exploit multifunctional gate dielectrics that offer mechanical compliance, ionic conduction, or sensing capabilities.

Conclusions

Organic field-effect transistors (OFETs) featuring polymeric gate dielectrics continue to show strong promise in advancing flexible, lightweight, and solution-processable electronics. This review examines their design principles, performance parameters, and fabrication strategies, with particular emphasis on organic semiconductor deposition through spin-coating and thermal evaporation. Polymeric dielectrics, such as PMMA, PVP, and their cross-linked counterparts, offer significant advantages in terms of mechanical flexibility, process compatibility, and interface tunability. Their pairing with spin-coated semiconductors allows for scalable, low-temperature processing; whereas thermal evaporation remains an effective technique for achieving highly ordered, small-molecule semiconductor films with superior crystallinity. The interplay between dielectric characteristics, interface quality, and deposition methods remains the cornerstone for optimizing OFET performance metrics, such as carrier mobility, threshold voltage, and operational stability. New device architectures including bilayer dielectrics, top-gate geometries and dual-gate configurations, offer additional opportunities to tailor electrostatic control and enhance environmental robustness. Furthermore, innovations in dielectric engineering – such as hybrid organic–inorganic layers and high-k nanocomposites – are addressing key limitations including gate leakage, interfacial trap densities, and long-term stability under ambient conditions.

Looking forward, OFETs are poised to contribute significantly to next-generation electronic applications, ranging from flexible displays to wearable biosensors and low-power neuromorphic devices. Future research should focus on novel multifunctional dielectric materials, advanced surface treatments, and eco-friendly fabrication techniques. A holistic approach involving material innovation, interface engineering, and scalable processing will be vital to unlocking the full commercial potential of polymeric-gated OFET technologies.

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