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Polycrystalline Organic Semiconductors for Low-Power AI-Integrated Devices: Fabrication and Characterization

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Abstract

Polycrystalline organic semiconductors constitute a promising class of functional materials, combining architectural flexibility, compatibility with low-temperature processing, and tunable electronic properties. Owing to their ability to form ordered morphologies with defined crystallinity, these materials can be seamlessly integrated into energy-efficient intelligent systems—such as neuromorphic components, sensing nodes, and photo-analytical elements. In the context of rapidly growing interest in edge computing and Internet-of-Things infrastructures, they offer advantages over silicon counterparts, including mechanical robustness, spectral sensitivity, and the capacity for on-site primary signal processing. This study reviews methods for producing polycrystalline films, examines how fabrication parameters influence morphological and electrical structure, and surveys quality-control techniques at both micro- and structural levels. Organic semiconductors thus fulfil a strategic role in the design of adaptive, miniaturized, and self-learning devices operating under unstable conditions, forming the basis for subsequent advances in intelligent organic electronics.

Keywords: organic semiconductors; polycrystalline films; neuromorphic devices; edge computing; intelligent electronics; sensing systems.

1.Introduction

The evolution of modern electronics increasingly focuses on the design of flexible, ultra-low-power systems endowed with advanced computational capabilities, capable of operating in highly unstable and non-standardized environments. A central challenge lies in simultaneously achieving energy efficiency, adaptability to external conditions, and a reduced form factor, all while preserving reliable computational performance. In this light, polycrystalline organic semiconductors (POSCs) gain particular importance due to their ability to form ordered structural states under mild processing conditions, their pronounced responsiveness to external stimuli, and their compatibility with scalable printing techniques.

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Taken together, these attributes render POSCs a versatile foundation for next-generation hardware solutions intended for integration into artificial-intelligence architectures.This work is dedicated to exploring fabrication strategies, structural-organization parameters, and the functional viability of organic semiconductors when employed in neuromorphic modules, sensing arrays, and localized signal-processing nodes.

2.Methods and Materials

Polycrystalline organic semiconductor materials have gained increasing prominence in the scientific pursuit of energy-efficient, flexible, and adaptive next-generation interfaces for artificial-intelligence systems. Their distinctive advantages—low-temperature processing, biocompatibility, and compatibility with flexible substrates—position them as a promising foundation for low-power edge modules in modern computational architectures.

Amid a surge of interest in neuromorphic hardware solutions and organic bioelectronics, there is a growing demand for rigorous evaluation of both the fabrication characteristics and functional parameters of these materials. Z. Guo and his colleagues [1] demonstrate the potential of organic heterostructures—combining semiconductors and halide perovskites—for synaptic photodetectors, paving the way toward highly sensitive AI sensory interfaces. M. Hosseini and R. Nawrocki [2] focus on advances in thin-film transistors, underscoring the importance of organic architectures for flexible electronics and edge-AI devices. S. Jiang and his colleagues [3] provide a detailed review of in situ and operando characterization techniques for organic semiconductors—atomic force microscopy, X-ray structural analysis, and UV spectroscopy—that are essential for correlating morphology with electrical performance.Y. Kim and his colleagues [4] summarise the latest developments in neuromorphic sensory nodes, highlighting organic components as key elements that replicate biological sensory principles. The dissertation by I. Krauhausen [5] and its collaborative publication [6] spotlight organic neuromorphic electronics tailored to biosignal interpretation and adaptive functions, including conductive polymer implementations. K. Liu and his colleagues [7] examine technological breakthroughs in organic field-effect transistors—scalability, low-temperature processing, and flexible-substrate integration—while J. Y. Na and his colleagues [8] explore how spin-coating parameters influence the morphology of poly(thiophene) films, which is critical for controlling crystallinity and film-to-film consistency.

D. Pathak and his colleagues [9] survey emerging applications of novel organic semiconductors in optoelectronic devices, with an emphasis on linking thin-film structural features to functional behaviour. T. Someya and his colleagues [10] contribute a foundational framework for “plastic bioelectronics” as a platform for flexible medical sensors and wearable AI components. A. Stoddart’s work [11] elucidates pore-formation mechanisms in organic layers, connecting deposition conditions with semiconductor properties, and Y. Xie and his colleagues [12] present integrated organic-transistor architectures that enable compact, autonomous intelligent systems. M. Zhang and his colleagues [13] review progress in stretchable sensor platforms based on organic field-effect transistors, advancing the development of next-generation electronic skins and biocompatible interfaces.

However, a critical review of this extensive body of literature reveals that prior studies often focus on discrete aspects of the field. Research tends to concentrate on either novel material synthesis, specific device applications like neuromorphic electronics, or advanced characterization methods in isolation. A noticeable gap exists in work that provides a holistic synthesis, systematically connecting the key fabrication parameters, the multi-level characterization methodologies required for quality control, and the functional requirements of low-power AI-integrated devices. This paper seeks to address this gap by creating an integrated overview that bridges these disparate domains, providing a comprehensive framework for understanding and developing these materials for intelligent systems.

This research utilises comparative-analysis methods, a structural-functional approach, and systematic synthesis of data from current scientific literature. These methodologies facilitate a comprehensive assessment of fabrication parameters, organic-semiconductor film properties, and the applicability of resulting solutions to low-power AI devices.

3.Results and Discussion

Polycrystalline organic semiconducting materials constitute a class of compounds capable of conducting electrical current via charge-carrier delocalisation across molecular orbitals. This behaviour arises from the structure of aromatic conjugated systems—such as pentacene, poly(3-hexylthiophene) or DNTT—whose molecules tend to self-organise into ordered aggregates with preferred orientation, yielding polycrystalline films with pronounced inter-grain boundaries that govern charge transport characteristics [1]. Thanks to their compatibility with printing techniques, ability to be deposited on flexible substrates, and tunable morphological and electronic parameters, these materials exhibit high potential for wearable electronics, biosensing devices, display technologies, and, in particular, low-power systems integrated with artificial-intelligence architectures [3].

In the context of rapid AI-environment expansion, there is growing demand for compact, resource-efficient hardware solutions—especially under edge-computing, Internet-of-Things, and autonomous-sensor paradigms—where silicon components often prove excessively power-hungry. In contrast, organic semiconductors, with their structural flexibility and low-temperature fabrication processes, demonstrate promise as a foundation for next-generation adaptive AI interfaces [5].

Table 1 presents a comparative evaluation of the principal properties of silicon components and organic semiconductors with regard to their suitability for integration into AI-enabled devices (compiled by the author on the basis of [10]).

Table 1: Comparative evaluation of silicon and organic semiconductors for AI-device integration

Criterion	**Silicon Components**	**Organic Semiconductors**
Technological maturity	High; industrial-scale production	Emerging; under active research
Processing temperature	High (400–1000 °C)	Low (≤ 150 °C); compatible with temperature-sensitive substrates
Structural flexibility	Rigid substrates	Can be deposited on flexible, elastic, and biocompatible supports
Scalability and cost	Expensive equipment; lithographic processes	Inexpensive printing and solution-based techniques
Energy consumption	Relatively high in edge applications	Low, particularly in passive and neuromorphic circuits
Edge-AI suitability	Limited; suboptimal for resource-constrained environments	Well suited, especially for autonomous sensors and distributed networks
Biocompatibility	Limited	High; potential use in bio-interfaces and electronic skin (e-skin)
Application in AI interfaces	Requires additional signal-conversion stages	Direct implementation of recognition and adaptation functions
Typical application areas	Centralised computing; server platforms	IoT, wearable electronics, flexible sensors, local AI solutions

Polycrystalline organic semiconductors offer substantial scientific advantages—chiefly in energy efficiency, structural adaptability, and intrinsic functionality—positioning them as a promising platform for adaptive AI interfaces that operate at the computational edge with minimal power requirements and maintain stable performance under atypical operating conditions [2].

Integration of these materials into low-power intelligent devices unfolds across several avenues. One is the development of neuromorphic components, such as organic transistors and memristors that replicate synaptic functions. Another involves sensor platforms that combine primary signal acquisition with on-site analog preprocessing. A third focuses on machine-vision elements capable of local optical data analysis, leveraging the material's high photosensitivity [4]. Fabrication of polycrystalline structures employs methods that precisely control crystal orientation and film morphology: from spin coating, which ensures uniform deposition by centrifuging a solution, to directed-deposition techniques (zone casting, blade coating), thermal evaporation, and zone melting. These processes yield highly ordered textures suitable for scalable printing methods, including inkjet and roll-to-roll technologies [6].

The drive toward energy-efficient, flexibly configurable, and extensible microelectronic architectures has intensified interest in organic semiconductors as next-generation functional materials. Their exceptional properties—mechanical flexibility; compatibility with low-temperature, solution-based processing; pronounced light sensitivity; and the ability to undergo molecular-scale structural reconfiguration—open new opportunities for low-power intelligent systems that must function under tight energy budgets and within unconventional form factors [7].

Implementation of organic semiconductors in device architectures concentrates on three principal areas. First, neuromorphic elements: organic transistors and memristors emulate neural-synaptic activity and provide both short- and long-term plasticity, forming the hardware foundation of artificial neural networks and configurable computing nodes. Second, next-generation sensor systems: these combine detection of mechanical, chemical, thermal, or optical signals with analog preprocessing at the sensor level, reducing digital-circuit workloads and markedly improving energy efficiency. Third, machine-vision components: here, organic photosensitive materials perform local image processing with high sensitivity and spectral selectivity, enabling operation in low-light or infrared conditions and carrying out primary visual-data analysis directly at the sensor stage [8].

Controlled fabrication of semiconductor films with precisely defined morphological and structural characteristics is the decisive factor in successfully realising the directions outlined above. The formation of polycrystalline layers relies on a suite of techniques that allow variation of crystallinity, orientation, and textural order: from spin-coating—which produces a uniform coating by centrifuging a solution—to directed deposition methods (blade-coating, zone-casting), thermal evaporation, and zone-melting. The latter generate highly ordered structures with pronounced anisotropy, which is crucial for enhancing charge-carrier mobility and device stability. These technologies also integrate seamlessly with industry-scale printing techniques, including inkjet and roll-to-roll processes—lending organic components genuine manufacturing potential [6].

Process parameters—such as substrate temperature, deposition rate, solvent choice, and drying/annealing conditions—require meticulous optimisation because they ultimately determine the film’s final morphology, mechanical strength, charge-transport characteristics, moisture and UV resistance, leakage currents, and energy-level alignment with electrodes at the HOMO/LUMO interfaces [2]. Optimising these variables is critical for the stable, reproducible performance of organic electronic components within intelligent devices (see Table 2).

Table 2: Key process parameters for forming organic semiconductor films and their influence on device properties (compiled by the author based on [8])

Parameter	**Impact on Film Properties**
Substrate temperature(controls crystallisation rate and molecular orientation)	Morphology; crystallinity; resistance to degradation
Deposition rate(determines film thickness and uniformity)	Grain size; defect density; electronic homogeneity
Solvent choice(governs material solubility and evaporation kinetics)	Formation of ordered domains; degree of phase purity
Drying/annealing conditions(control solvent removal and complete recrystallisation)	Film texture; reduction of charge traps; stability under environmental stress
Deposition method(spin-coating, blade-coating, evaporation, zone-melting, etc.)	Degree of structural order; scalability; reproducibility
Energy-level alignment (HOMO/LUMO)(matching material and electrode energy levels)	Charge-injection/extraction efficiency; leakage currents; operational stability

Integration of organic semiconductors into the architecture of energy-efficient intelligent systems represents a highly promising avenue for modern microelectronics—one that emphasises flexibility, structural adaptability, and high functional integration. Employing these materials in neuromorphic components, sensor platforms with on-sensor analog preprocessing, and machine-vision elements establishes a foundation for compact, customisable, and accessible next-generation devices [1]. The critical condition influencing the success of this integration remains the controlled fabrication of semiconductor layers with predefined morphological and structural traits—demanding precise adjustment of deposition and thermal-processing regimes, where exact control of temperature profiles, solution chemistry, and deposition dynamics is paramount [4].

Progress in scalable printing methods, combined with thoughtful engineering of materials and interfaces, establishes a robust foundation for advancing organic electronics into intelligent devices, sensor infrastructures, and neuromorphic data-processing systems [5].

Among the key characteristics determining the suitability of polycrystalline organic semiconductors for artificial-intelligence environments, their pronounced mechanical flexibility—accompanied by resilience to cyclic deformation—stands out. This combination of properties renders organic materials exceptionally valuable in the design of wearable electronics, soft sensor platforms, and flexible robotic systems, where components inevitably endure repeated stretching, bending, and compression. Unlike brittle inorganic counterparts, organic coatings retain stable electrical parameters even under significant mechanical deformation, thereby extending their operational envelope to conditions in which traditional materials fail [8].

Equally significant is the high capacity of organic semiconductors for structural tuning, evident in the ability to perform precise engineering at both molecular and supramolecular scales. This approach enables the fabrication of materials with defined energy levels, crystalline order, and morphological architecture, allowing active device regions to function reliably amid variable external conditions—temperature fluctuations, changes in humidity or illumination, and mechanical stresses [9]. Such adaptive capability is fundamental for AI systems operating in open or loosely constrained environments, including distributed sensor networks and autonomous intelligent modules [11].

Achieving reproducible, stable performance of organic functional elements demands comprehensive characterization of their morphological, structural, and electrical states. Atomic-force microscopy and scanning-electron microscopy reveal surface topography, grain size, and film uniformity; X-ray diffraction analysis determines crystallinity and structural orientation, which directly affect charge-carrier mobility [12]; ultraviolet-visible spectroscopy provides insight into bandgap width, excited states, and photon interactions [13]; and current–voltage measurements serve as a primary tool for assessing conductivity, leakage currents, operational reliability, and resilience to external destabilising influences [13].

Polycrystalline organic semiconductors are increasingly assuming prominent roles in the development of intelligent, low-power systems. Their architectural flexibility, capacity for self-organisation, pronounced sensitivity to external stimuli, and the ability to perform elementary computing tasks—such as signal filtering, spiking learning, and local processing—at the material level make them fully fledged functional blocks for future AI-oriented architectures [3]. Analysis shows that organic electronics provides a robust foundation for a new class of intelligent platforms in which the traditional boundaries between sensor, logic, and actuator blur: information processing occurs directly within the material, bypassing conventional signal-transmission and conversion schemes. Achieving stable, reproducible performance of organic semiconductors in these smart platforms requires precise control over their morphological, structural, and electronic states, necessitating a suite of high-precision analytical techniques, each of which probes a specific quality parameter of the organic film—from micro-topography and grain distribution to energy-level alignment and conductivity [13].

Table 3: Methods for characterising organic-semiconductor films and their corresponding monitored parameters (compiled by the author based on [3], [9])

Analysis Method	**Purpose and Monitored Parameters**
Atomic-force microscopy (AFM)	Nanoscale surface topography; roughness, morphology, grain size, surface defects
Scanning-electron microscopy (SEM)	Surface structure and relief imaging; film uniformity, grain boundaries, porosity, macroscopic defects
X-ray diffraction (XRD)	Degree and nature of crystallinity; crystal size and orientation, ordering, interplanar spacings
Optical spectroscopy (UV-Vis)	Optical and electronic properties; bandgap width, absorption spectra, electronic transitions
Current–voltage measurements (I–V)	Electrical diagnostics; carrier mobility, leakage current, threshold voltage, operational stability under bias
Impedance spectroscopy (optional)	Frequency-dependent circuit analysis; capacitance, resistance, interfacial parameters, AC response characteristics

Ultimately, the analysis of fabrication methods and characterization techniques (Tables 1-3) culminates in a critical insight: a successful transition from laboratory potential to reliable AI-integrated devices depends on an integrated, cyclical approach. The characterization results are not merely a final quality check; they must serve as a direct feedback mechanism to iteratively refine the fabrication parameters. For instance, detecting high defect density (SEM) or poor crystallinity (XRD) should directly inform adjustments in substrate temperature or solvent choice. This holistic framework, which tightly couples synthesis with multi-level diagnostics, is what bridges the gap between the theoretical promise of organic materials and the practical demands of stable, reproducible, and functionally efficient neuromorphic and sensory systems. This interdependent relationship elevates the process from simple material deposition to true device engineering.

4.Conclusion

Polycrystalline organic semiconductors demonstrate significant potential in the design of low-power intelligent systems that integrate structural flexibility, scalable manufacturing processes, and an inherent capacity for computation. Their ability to self-organize, resilience under repeated mechanical stress, and the tunability of electronic properties at the molecular-architecture level establish the foundation for adaptive hardware solutions in which sensing, analysis, and response are all embedded within a single functional medium. The promise of these materials lies not only in their physicochemical characteristics but also in their compatibility with roll-to-roll printing and thermolabile processing methods—enabling mass-production of cost-effective flexible electronics tailored to artificial-intelligence applications.

To provide a balanced perspective, it is important to define the scope and limitations of this study. The work is structured as a systematic review and synthesis of existing literature; therefore, it does not include the generation of new primary experimental data. Consequently, while the proposed framework is robustly grounded in established research, its validation through direct experimental application or specific case studies represents a logical next step for future work. Additionally, the discussion is focused on the foundational technological principles rather than the specific economic and industrial challenges of commercialization, such as long-term device stability and batch-to-batch reproducibility, which are extensive research areas in their own right. Finally, as with any rapidly advancing field, the specific materials and techniques discussed represent a snapshot in time.

Continued fundamental study of film morphology, interface engineering, and the scalability of processing techniques will open the door to a new class of devices in which traditional distinctions between sensors, logic elements, and actuators dissolve, making computational functionality an intrinsic property of the material itself.

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