Organic Semiconductors as Neural Matter: The Potential for Brain-Inspired Computing

Executive Summary

The relentless progress of artificial intelligence has exposed the fundamental limitations of conventional computing architectures, creating an urgent need for hardware that can process vast amounts of data with greater efficiency. Neuromorphic engineering, which seeks to emulate the brain's massively parallel and low-power computational paradigm, offers a compelling solution. While silicon has been the cornerstone of the digital revolution, its rigid nature and energy-intensive fabrication processes present barriers to creating the next generation of intelligent systems, particularly those designed to interface with the biological world. This report examines the burgeoning field of organic neuromorphic computing, which leverages the unique properties of carbon-based semiconductors to build brain-inspired hardware.

Organic materials, exemplified by the technology in Organic Light-Emitting Diode (OLED) displays, offer a distinct set of advantages over silicon, including mechanical flexibility, inherent biocompatibility, and the potential for low-cost, large-area manufacturing via printing techniques. These properties make them an ideal substrate for emulating the soft, complex, and ion-rich environment of the brain. This analysis details the development of key organic neuromorphic devices, such as organic synaptic transistors (OSTs) and memristors, which can physically replicate the learning mechanisms of biological synapses. A central focus is placed on iono-electronic materials like PEDOT:PSS, whose ability to conduct both electrons and ions provides a direct bridge between synthetic electronics and biological signaling. Groundbreaking research has demonstrated that these devices can achieve computational accuracy on par with software-based neural networks while operating at energy levels rivaling biological synapses—a critical milestone for creating autonomous, low-power systems. The most transformative potential of this technology lies in its ability to create seamless bio-integrated electronics. By matching the mechanical and chemical properties of living tissue, organic neuromorphic systems are paving the way for advanced brain-computer interfaces, intelligent neuroprosthetics, and closed-loop therapeutic devices that can listen to and act upon biological signals in real time.

Despite this profound potential, significant challenges remain. Issues of device-to-device variability, long-term stability, and the complex task of integrating these novel organic systems with conventional silicon control circuitry must be overcome. The path to commercialization will require a concerted, interdisciplinary effort in materials science, manufacturing engineering, and algorithm co-design. The first successful applications are likely to emerge not in direct competition with high-speed silicon, but in niche, high-value domains such as implantable medical devices, where the unique benefits of organic materials provide an unparalleled advantage. As this technology matures, it will not only redefine the boundaries of computing but also necessitate the development of robust ethical frameworks to guide its responsible integration with human biology.

Section 1: The Foundation: Organic Semiconductors versus Silicon

The exploration of organic materials as a substrate for computation requires a foundational understanding of their properties in contrast to silicon, the element that has defined the electronic landscape for over half a century. The central thesis is not that organic electronics will supplant silicon, but rather that they offer a complementary set of attributes—flexibility, biocompatibility, and novel manufacturing pathways—that enable new technological paradigms inaccessible to rigid, inorganic materials. This section establishes the materials science context, dissecting the fundamental advantages and limitations of organic semiconductors to rationalize their pursuit for brain-inspired computing.

1.1 Defining Organic Electronics

Organic electronics is a field of materials science centered on the design, synthesis, and application of carbon-based molecules and polymers that exhibit useful electronic properties, such as conductivity or semiconductivity. Unlike conventional inorganic semiconductors such as crystalline silicon (Si) or gallium arsenide (GaAs), these materials are constructed from organic molecules using the versatile toolkit of synthetic chemistry. It is critical to distinguish elemental **silicon (Si)**, the semiconductor at the heart of modern microchips, from **silicone**, a class of rubbery, silicon-containing polymers often used as sealants or for encapsulation in electronics. The electronic behavior of organic semiconductors is governed by delocalized \pi-electrons within their molecular structures, forming energy levels analogous to the valence and conduction bands in inorganic crystals, known as the Highest Occupied Molecular Orbital (HOMO) and the Lowest Unoccupied Molecular Orbital (LUMO). A key feature of these materials is that their electronic properties, including the band gap and charge carrier mobility, are highly tunable. This tuning can be achieved through precise chemical synthesis, modifying the molecular structure, or through a process known as "doping," where small quantities of other chemicals are introduced to increase the concentration of charge carriers (electrons or holes), thereby modulating conductivity. This inherent chemical tailorability provides a degree of design freedom that is a core advantage over the more constrained crystalline structures of inorganic materials.

1.2 The Case for Organic Materials: A Paradigm of Advantages

The investigation into organic materials for advanced computing is motivated by a unique combination of properties that are either absent or difficult to achieve with traditional silicon-based technologies.

Mechanical Flexibility and Form Factor

Perhaps the most visually striking advantage of organic semiconductors is their mechanical flexibility. They can be processed into thin, lightweight, and pliable films, enabling a host of innovative applications such as flexible and foldable displays, wearable sensors, and conformal medical implants. This property stands in sharp contrast to the inherent rigidity and brittleness of silicon wafers, which confines them to planar, rigid form factors. This flexibility is not merely an aesthetic feature; it is a critical functional requirement for the burgeoning field of bio-integrated electronics, where devices must conform to the soft, dynamic surfaces of the human body.

Low-Cost and Scalable Manufacturing

The fabrication of silicon chips is a highly complex, capital-intensive process involving high-temperature, high-vacuum photolithography in specialized facilities known as foundries. Organic materials, conversely, can often be dissolved to create functional "inks," making them compatible with large-area, high-throughput additive manufacturing techniques like inkjet printing, screen printing, and roll-to-roll processing. These methods are potentially far less costly and consume significantly less energy than silicon fabrication. This opens the possibility of producing electronics on vast, flexible substrates, paving the way for applications like intelligent packaging, smart textiles, and sensor-covered surfaces that are economically and practically infeasible with silicon.

Biocompatibility

The carbon-based composition and mechanical softness (low Young's modulus) of many organic electronic materials make them inherently more compatible with biological tissue than hard, rigid inorganic materials. This biocompatibility is the cornerstone for developing the next generation of medical implants and brain-computer interfaces. When rigid devices are implanted in soft tissue like the brain, the mechanical mismatch leads to chronic inflammation and the formation of scar tissue (gliosis), which degrades signal quality and ultimately leads to device failure. Soft organic devices can mitigate this foreign body response, enabling more stable, long-term, and intimate integration with biological systems.

Tunable Optoelectronic Properties

Organic materials exhibit a remarkable efficiency in the interconversion of electricity and light, a property famously leveraged in Organic Light-Emitting Diode (OLED) displays. By chemically modifying the structure of the organic molecules, researchers can precisely tune the color of emitted light or the spectral sensitivity of a photodetector. This optoelectronic versatility is now being harnessed to create novel neuromorphic devices that can be stimulated or "programmed" with light, opening up new avenues for parallel information processing.

1.3 The Silicon Incumbent: Challenges and Limitations of Organic Electronics

Despite their compelling advantages, organic semiconductors face significant challenges when compared to the mature and highly optimized technology of silicon.

Performance Deficits

Silicon's dominance is built on a foundation of exceptional performance and reliability. It boasts high chemical and thermal stability and, most critically, a high intrinsic charge carrier mobility (around 1400 $cm^2/(V \cdot s)$), which is a direct determinant of transistor switching speed and, consequently, processing power. Organic semiconductors generally exhibit significantly lower carrier mobilities, with high-performance materials typically in the range of 1-40 $cm^2/(V \cdot s)$. Furthermore, many organic materials are susceptible to degradation when exposed to ambient oxygen and humidity, posing challenges for long-term operational stability without robust encapsulation.

Manufacturing and Miniaturization Hurdles

While the promise of printed electronics is vast, the manufacturing processes are far less mature than those for silicon. The inherent randomness in the morphology of polymer films and the relatively large size of the molecules themselves make it extremely difficult to pattern them into the densely packed, nanometer-scale transistors that define modern microprocessors. The transistor density achievable with current organic fabrication is often compared to that of silicon technology from one or two decades ago. Moreover, the solvents required for traditional high-resolution photolithography are often incompatible with organic materials, as they can dissolve the active layers, necessitating the use of alternative, and often less precise, patterning techniques.

Stability and Lifetime

The operational lifetime of organic electronic devices remains a significant concern. This is particularly evident in OLED technology, where blue-emitting organic materials have a notoriously shorter lifespan than their red and green counterparts, leading to color shifts over time. This susceptibility to degradation from environmental factors like water and heat, as well as from electrical stress during operation, is a critical challenge that must be addressed to create robust and reliable computing hardware.

The comparison between organic and silicon electronics is therefore not a simple contest of which is "better," but rather a nuanced evaluation of technological trade-offs. Silicon provides unparalleled computational speed, density, and reliability, making it the undisputed material of choice for centralized processing units like CPUs and GPUs. Organic materials, on the other hand, offer a suite of unique properties—flexibility, biocompatibility, printability—that are not intended to replace silicon in its established domains but to create entirely new classes of electronic systems. This suggests that the future is not a matter of "organic versus silicon," but rather a hybrid technological ecosystem where each material is deployed in the application for which its properties are best suited. Consequently, the domain of organic neuromorphic computing is most likely to find its niche in applications like distributed intelligent sensor networks, edge computing devices, and, most profoundly, in direct interfaces with biological systems, where silicon's fundamental properties render it unsuitable.

This landscape also reveals that one of the most significant rate-limiting steps for the advancement of high-performance organic computing lies in manufacturing engineering. The very processes, such as inkjet printing, that make organic electronics attractive for low-cost, large-area applications like solar cells are the same ones that currently lack the nanoscale precision required for high-density logic circuits. This creates a technological paradox: the key to unlocking the full potential of organic neuromorphic computing lies not only in discovering new materials but in inventing new high-resolution, high-yield methods for patterning them at scale.

Property	Silicon Semiconductors	Organic Semiconductors
Carrier Mobility	High (e.g., ~1400 $cm^2/(V \cdot s)$ for Si)	Low to Moderate (e.g., ~1-40 $cm^2/(V \cdot s)$)
Manufacturing Process	Complex, high-vacuum, high-temperature	Simpler, solution-based processes (e.g., inkjet printing,

Property	Silicon Semiconductors	Organic Semiconductors
	photolithography	roll-to-roll)
Cost	High capital investment for foundries; low cost per transistor due to massive scale	Potentially low material and processing costs, especially for large areas
Mechanical Properties	Rigid, brittle crystalline wafer	Flexible, stretchable, lightweight films
Biocompatibility	Poor due to mechanical mismatch and rigid nature	Generally good due to carbon-based nature and mechanical softness
Stability	Excellent chemical and thermal stability	Variable; often sensitive to oxygen, humidity, and heat
Device Density	Extremely high (billions of transistors per chip)	Low; limited by manufacturing precision and material properties
Power Consumption	High for complex computations; leakage current is a challenge at small scales	Potential for very low power operation, especially in electrochemical devices

Section 2: The Neuromorphic Paradigm: Emulating the Brain's Efficiency

The transition from materials science to computational architecture is pivotal. Understanding the potential of organic semiconductors as "brain matter" requires an appreciation for the computational paradigm they are intended to serve: neuromorphic engineering. This section introduces the core concepts of brain-inspired computing by first examining the architectural limitations of conventional computers. It then contrasts this with the brain's remarkably efficient blueprint for processing information, establishing the computational goals that organic materials are being uniquely engineered to achieve.

2.1 The von Neumann Bottleneck: The Limits of Conventional Computing

Virtually all modern digital computers, from smartphones to supercomputers, are based on the von Neumann architecture, a design conceived in the 1940s. A defining feature of this architecture is the physical separation of the central processing unit (CPU), where calculations are performed, and the memory unit (RAM), where data and instructions are stored. While this design has been extraordinarily successful, it creates an inherent inefficiency known as the "memory wall" or "von Neumann bottleneck".

For any computation to occur, data must be constantly shuttled back and forth between the memory and the processor over a data bus of limited bandwidth. In an era of "big data" and complex artificial intelligence algorithms, this constant data transfer consumes a substantial fraction of the total time and energy of a computation, becoming the primary limiting factor for performance. Specialized processors like Graphics Processing Units (GPUs) and Tensor Processing Units (TPUs) have mitigated this bottleneck for the specific parallel operations common in AI, but they are fundamentally still von Neumann machines and are notoriously power-hungry, making them unsuitable for many energy-constrained applications.

2.2 The Brain's Blueprint: A Masterclass in Efficiency

In stark contrast to the von Neumann architecture, the human brain represents a masterclass in computational efficiency. It performs highly complex tasks, such as pattern recognition and learning, while consuming only about 20 watts of power—orders of magnitude more efficiently than the most advanced supercomputers attempting similar tasks. This remarkable efficiency is not due to faster components but to a fundamentally different architecture.

The brain is a massively parallel network of approximately 86 billion neurons, interconnected by trillions of synapses. Crucially, in this biological network, the functions of processing and memory are not physically separate; they are co-located and deeply intertwined at the synaptic level. The core mechanism of learning and memory in the brain is **synaptic plasticity**, the ability of a synapse's connection strength, or "weight," to change over time based on the activity of the neurons it connects. This principle, often summarized by the Hebbian maxim "neurons that fire together, wire together," allows the brain to learn from experience, adapt, and store information directly within the structure of its network. This plasticity manifests in different forms, including short-term plasticity (STP), which lasts for seconds to minutes, and long-term plasticity (LTP), which can persist for hours or longer and is believed to be the basis of long-term memory.

2.3 Neuromorphic Engineering: From Simulation to Emulation

The goal of neuromorphic engineering is to move beyond merely *simulating* neural networks in software on conventional computers and to instead build hardware that physically *emulates* the brain's structure and function. This involves designing and fabricating physical devices that can act as artificial neurons and, most importantly, artificial synapses.

These hardware components are designed to operate in a parallel, event-driven manner, communicating via "spikes" (brief electrical pulses) much like biological neurons. The central component is the artificial synapse, a device whose physical properties (such as its electrical conductance or resistance) can be modified in an analog fashion to represent and retain a synaptic weight. By building large arrays of these components, neuromorphic systems aim to perform computation directly within the memory substrate, thereby circumventing the von Neumann bottleneck entirely. This approach holds the promise of creating a new class of highly efficient, specialized hardware for AI, robotics, and real-time sensory processing.

2.4 Clarifying Terminology: "Organic Neuromorphic" vs. "Organic Computing" and "Wetware"

The term "organic" in the context of computing can be a source of confusion, as it is used in several distinct fields. It is essential to clarify these definitions:

- **Organic Neuromorphic Computing:** This is the primary focus of this report. It refers to the use of synthetic, carbon-based organic semiconductor *materials* to build physical, brain-inspired hardware components like artificial synapses and neurons. The material is synthetic, but the architecture is biologically inspired.
- **Organic Computing:** This is a distinct paradigm within computer science and software engineering. It focuses on designing complex *software systems* that exhibit life-like properties such as self-organization, self-configuration, self-healing, and adaptation.

These are architectural principles inspired by biological organisms but are typically implemented as algorithms running on conventional silicon hardware.

- **Wetware Computing:** This is a futuristic and still largely conceptual field that aims to use *living biological matter*, such as cultured neurons or other cells, as the fundamental components of a computer. In this paradigm, the computational substrate is literally "wet" and alive, as opposed to the synthetic, solid-state materials used in organic neuromorphic computing.

The current technological landscape is defined by a convergence of factors. The explosive growth in the complexity and scale of AI models has created a powerful "demand-pull" for new hardware architectures that can break free from the energy and performance constraints of the von Neumann model. At the same time, decades of research in materials science have led to a "technology-push" from the field of organic electronics, which now offers a class of materials whose intrinsic properties are uniquely suited to the analog, parallel, and low-power nature of neuromorphic computation. The ability of organic electronic devices, particularly those based on the movement of ions, to exhibit a history-dependent change in their electrical resistance or conductance allows them to mimic synaptic plasticity within a single, simple device structure. This confluence of AI's needs and material science's capabilities marks a critical inflection point, suggesting that the time is ripe for the development of a new hardware substrate for intelligence.

This pursuit also represents a fundamental philosophical shift in the nature of computation. Conventional digital computing is built on a foundation of binary logic (0s and 1s) and deterministic, perfectly repeatable operations. The brain, in contrast, achieves its remarkable robustness and cognitive power using "noisy," imperfect components that operate in an analog and probabilistic fashion. It compensates for the unreliability of individual components through massive parallelism and constant adaptation. From the perspective of digital logic, the inherent material variability and "soft" switching characteristics of many organic materials might be seen as defects. However, from a neuromorphic perspective, these very properties can be advantageous. Neuromorphic systems can be designed to tolerate, and in some cases even leverage, this variability, much as the brain does. This requires engineers to move beyond the pursuit of perfect digital switches and embrace the principles of analog computation, where a large ensemble of "good enough" components working in concert can outperform a small number of perfect ones for complex, real-world tasks like pattern recognition and sensory perception.

Section 3: The Building Blocks of an Artificial Brain: Organic Neuromorphic Devices

At the heart of organic neuromorphic computing are the physical devices engineered to emulate the fundamental components of the brain's neural circuitry. This section transitions from the abstract concept of an artificial synapse to the concrete physics of transistors and memristors built from organic semiconductor materials. The focus here is on the device-level mechanisms—*how* these materials are structured and operated to store and process information in a manner analogous to biological synapses and neurons.

3.1 Organic Synaptic Transistors (OSTs): The Three-Terminal Synapse

Organic Synaptic Transistors are among the most widely studied devices for neuromorphic applications. They are typically three-terminal devices, comprising a source, a drain, and a gate, analogous to a standard field-effect transistor.

Structure and Function

In an OST, a channel made of an organic semiconductor connects the source and drain electrodes. The flow of current through this channel—the postsynaptic current—is modulated by a voltage applied to the gate electrode, which represents the presynaptic input. Unlike a simple switch, the effect of the gate pulse is designed to be non-volatile or quasi-non-volatile. This means that a change in the channel's conductance persists even after the gate voltage is removed, allowing the conductance state to represent and retain a synaptic weight.

Mimicking Plasticity

The emulation of synaptic plasticity is the key function of an OST. By applying a train of voltage pulses to the gate, the channel conductance can be incrementally and controllably increased (a process called potentiation) or decreased (depression). This directly mimics the long-term potentiation (LTP) and long-term depression (LTD) that are the cellular basis of learning and memory in the brain. Researchers have successfully demonstrated OSTs that can be tuned to hundreds of distinct, stable conductance states, providing the high-precision analog control needed for accurate neural network computation.

Material Systems

A diverse array of organic semiconductors has been explored for use as the active channel material in OSTs. These include small molecules like pentacene and rubrene, which can form well-ordered crystalline films with relatively high carrier mobility, and a wide range of semiconducting polymers such as PDPP4T and P3HT. The specific choice of material, along with the dielectric and electrode materials, critically determines the device's performance characteristics, including its switching speed, energy consumption, and memory retention time.

3.2 Organic Memristors: The Two-Terminal Memory Resistor

An alternative and structurally simpler approach to creating an artificial synapse is the memristor, or memory resistor.

Concept

First theorized in 1971 and physically realized decades later, a memristor is a two-terminal passive electronic component whose electrical resistance is not constant but is a function of the history of the voltage applied across it or the current passed through it. This intrinsic "memory of resistance" makes memristive devices natural candidates for implementing synaptic weights.

Switching Mechanisms

In organic memristors, the change in resistance is governed by various physical mechanisms. Common examples include electrochemical doping, where mobile ions are driven into or out of the organic material by an electric field, changing its conductivity; charge trapping, where electrons or holes become localized at specific sites within the material, such as embedded nanoparticles; or the formation and rupture of nanoscale conductive filaments that bridge the two electrodes.

Advantages for Density

The primary advantage of the two-terminal memristor structure is its simplicity, which allows for the fabrication of extremely dense crossbar arrays. In such an architecture, memristors are placed at each intersection of a grid of perpendicular wires. This high density is crucial for building the large-scale artificial neural networks needed for complex tasks. Furthermore, this architecture is ideally suited for "in-memory computing," a paradigm where logic operations are performed directly within the memory array itself, completely bypassing the von Neumann bottleneck.

3.3 A Case Study in Iono-Electronics: The Role of PEDOT:PSS

Among the many materials used in organic neuromorphics, one has emerged as a particularly important benchmark: poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate), or PEDOT:PSS. Its utility stems from a unique property that makes it exceptionally well-suited for emulating biological processes.

The Benchmark Material

PEDOT:PSS is a conductive polymer dispersion in water that is prized for its combination of good electronic conductivity, processability from solution, and, crucially, its biocompatibility. This has made it a workhorse material in the broader field of organic bioelectronics.

Mixed Conduction

The key to PEDOT:PSS's success in neuromorphics is its nature as a mixed ionic-electronic conductor (MIEC). This means it can transport not only electronic charge carriers (holes) like a conventional semiconductor but also ions from a surrounding electrolyte. This dual-conduction mechanism is the fundamental property that allows synthetic devices to "speak the language" of biology, which itself operates on the flow of ions (e.g., Na^+, K^+, Ca^{2+}) and chemical neurotransmitters. While conventional electronics are limited to electrons and holes, creating a fundamental mismatch at the bio-electronic interface, MIECs can directly transduce between the ionic signals of biology and the electronic signals of computation.

Organic Electrochemical Transistor (OECT) Operation

This property is leveraged in the Organic Electrochemical Transistor (OECT). In a typical PEDOT:PSS-based OECT, the semiconductor channel is in direct contact with an electrolyte (which can be as simple as saline solution) that also contains the gate electrode. When a voltage is applied to the gate, it drives ions from the electrolyte to penetrate the entire volume of the polymer channel. This injection or extraction of ions changes the doping level (oxidation state) of the PEDOT:PSS, which in turn dramatically modulates its electronic conductivity. This volumetric electrochemical process is remarkably analogous to the way neurotransmitters modulate ion channels in a biological synapse and allows for very large changes in current with very low operating voltages.

Neuromorphic Functions

Researchers have successfully used PEDOT:PSS OECTs to demonstrate a wide range of synaptic functions, including both short-term and long-term plasticity, with high fidelity and low power consumption. Recent advances have focused on chemically modifying the PEDOT:PSS formulation to improve performance, for example, by using acid treatments to enhance conductivity or by adjusting additives to switch between volatile (short-term memory) and non-volatile (long-term memory) operational modes.

3.4 Novel Modalities: Optoelectronic and All-Photonic Synapses

Leveraging the strong light-matter interactions in organic materials, researchers are developing new classes of synaptic devices that use light as a primary signal.

Light as a Stimulus

Organic Synaptic Phototransistors (OSPs) are devices where the synaptic weight (channel conductance) is modulated by pulses of light, either instead of or in conjunction with electrical gate signals. This approach takes advantage of the excellent and highly tunable optoelectronic properties of organic semiconductors. The benefits include the potential for non-contact programming of synaptic weights, high bandwidth, and massive parallelism, as a patterned light source could potentially modulate an entire array of synapses simultaneously. Recent work on OSPs based on organic semiconductor heterojunctions has demonstrated their efficacy within an artificial neural network, achieving a high recognition accuracy of approximately 93% on standard classification tasks.

All-Photonic Synapses

Pushing this concept to its limit is the development of all-photonic synapses, a frontier technology where both the input signal (the stimulus) and the output signal (the readout of the synaptic state) are purely optical. In a groundbreaking demonstration, researchers found an organic molecule whose fluorescence intensity changes based on its history of light exposure. The intensity of light emitted at one wavelength could be potentiated by repeated exposure to light at another wavelength, directly mimicking synaptic behavior without any flow of electrical current. This opens a path toward ultra-fast, low-power neuromorphic systems where information is processed entirely with photons.
The choice between these different device architectures—two-terminal memristor versus three-terminal transistor—is not trivial; it represents a core design trade-off between the density of a neural network and the integrity of its signals. The simplicity of memristors allows them to be packed into extremely dense crossbar arrays, which is ideal for maximizing the number of synapses in a given area. However, this density comes at the cost of potential "sneak path" currents, where signals can leak through unintended routes in the array, causing crosstalk and making precise programming and readout difficult. Transistors, with their third (gate) terminal, provide crucial signal isolation. The gate input is electrically separated from the channel's output current, which prevents crosstalk and allows for the construction of more complex, multi-input logic. The trade-off is that transistors are physically larger and more complex to fabricate,

resulting in lower network density. This suggests that mature, large-scale organic neuromorphic systems will likely employ hybrid architectures, using dense memristor arrays for the bulk storage of synaptic weights, which are then controlled and read out by less dense but more precise transistor-based peripheral circuits.

Device Type	Structure	Operating Principle	Key Materials	Key Performance Metrics
Organic Field-Effect Synaptic Transistor	3-Terminal	Charge Trapping / Ferroelectric Gating	Pentacene, Rubrene, Copolymers	Energy/Event: pJ to fJ; States: >100; Retention: minutes to hours
Organic Electrochemical Transistor (OECT)	3-Terminal	Electrochemical Doping (Ion Migration)	PEDOT:PSS, p(g2T-TT)	Energy/Event: <10 pJ; Low Voltage (<1V); High Transconductance
Organic Memristor	2-Terminal	Filament Formation / Electrochemical Doping	Conductive Polymers, Small Molecules in a Matrix	High Density; States: >100; Switching Speed: ns-range
Organic Synaptic Phototransistor (OSP)	3-Terminal	Photoelectric Effect / Charge Trapping	PDPP4T/NTCDI-F15 Heterojunctions	Light-programmable; 93% ANN Accuracy; >800 States
All-Photonic Organic Synapse	N/A (Material-based)	Anti-Stokes Photoluminescence Modulation	S2OC (Carbazole derivative)	Non-contact operation; Optical I/O; High spatiotemporal resolution

Section 4: The Bio-Integration Frontier: From Neuromorphic Computing to Bioelectronics

The most profound and potentially transformative application of organic neuromorphic materials lies beyond simply building more efficient computers. It is their unique capacity to create a safe, stable, and functional interface with living biological systems. This section explores this frontier, moving from brain-*inspired* architectures to brain-*integrated* systems. It details the material properties that enable this seamless connection and reviews the pioneering experiments that are beginning to erase the boundary between synthetic electronics and living tissue.

4.1 The Imperative of Biocompatibility

The long-term success of any implantable electronic device, particularly in the brain, hinges on its biocompatibility. Traditional neural interfaces, built from silicon, platinum, and other rigid inorganic materials, face a fundamental challenge at the tissue interface.

Mechanical Mismatch

Brain tissue is extremely soft, with a Young's modulus (a measure of stiffness) in the kilopascal range. In contrast, rigid electrode materials are orders of magnitude stiffer. This severe mechanical mismatch causes micromotion between the implant and the surrounding tissue, leading to chronic inflammation and the formation of a dense sheath of glial scar tissue around the device. This process, known as gliosis, effectively insulates the electrode from the neurons it is trying to record from or stimulate, leading to a gradual degradation of signal quality and eventual device failure.

The Soft Materials Solution

Organic electronics offer a direct solution to this problem. Conductive polymers and hydrogels can be engineered to have mechanical properties that closely mimic those of biological tissue. By creating devices that are soft, flexible, and can conform to the intricate, curved surfaces of the brain or peripheral nerves, the mechanical stress on the tissue is minimized. This leads to a significantly reduced inflammatory response, less scarring, and the potential for stable, high-fidelity communication with the nervous system over much longer periods.

Chemical and Ionic Compatibility

Beyond mechanics, functional bio-integration requires chemical and ionic compatibility. As detailed in the previous section, the ability of Organic Electrochemical Transistors (OECTs) to operate in an aqueous, ion-rich environment and to directly transduce ionic and chemical signals is a key enabling property. These devices can "listen" to the chemical language of the nervous system (i.e., neurotransmitters and ion fluxes) and translate it into electronic signals, providing a far more intimate and direct interface than is possible with conventional electrodes that only measure electrical potential.

4.2 Biohybrid Systems: Bridging the Synthetic-Living Divide

The ultimate test of biocompatibility is the creation of functional biohybrid systems where synthetic and living components work in concert.

Proof-of-Concept

Landmark experiments have successfully demonstrated this principle. In one key study, researchers cultured neuroendocrine cells from a rat, which are known to release the neurotransmitter dopamine, directly onto one of the soft polymer electrodes of an organic synaptic device. When the living cells were stimulated to release dopamine, the neurotransmitter molecules underwent an electrochemical reaction at the electrode surface. This reaction caused a direct and permanent change in the conductance of the artificial synapse, effectively "transmitting" a chemical signal from the living cell to the synthetic device.

Towards a Closed Loop

This demonstration represents a critical first step toward a closed-loop bio-machine interface. It proves that an organic device can "listen" to the chemical signals of neurons. The next frontier is to create systems that can also "speak" back to the cells, for instance by using an electrical signal from the device to trigger the release of specific ions or biomolecules to stimulate the cells in a controlled manner. Researchers are also developing more sophisticated interfaces, such as Enzymatic Neuromorphic Organic Devices (ENODes), which incorporate artificial cell membranes (supported lipid bilayers) onto PEDOT:PSS channels to create even more biologically realistic hybrid synapses capable of emulating complex memory effects.

4.3 Toward Advanced Brain-Computer Interfaces (BCIs) and Neuroprosthetics

The unique properties of organic neuromorphic materials are poised to revolutionize the field of brain-computer interfaces and neuroprosthetics.

Current BCI Limitations

While existing BCI technologies, such as the Utah array used in clinical research and the flexible threads being developed by companies like Neuralink, have shown remarkable promise, they are still largely based on metallic electrodes that suffer from the long-term biocompatibility issues of mechanical mismatch and gliosis.

The Organic Advantage

Soft, conformal, conductive polymer-based interfaces promise to overcome these limitations, offering the potential for higher signal quality, significantly reduced tissue damage, and much longer functional implant lifetimes. Their ability to be fabricated in large, flexible sheets or as form-fitting cuffs for peripheral nerves opens up a vast design space for new types of interfaces. This technological shift enables a move from passive recording electrodes that simply stream raw data to an external computer, towards intelligent interfaces that perform local, low-power data processing directly at the tissue site. Current BCIs generate enormous streams of data that must be transmitted and processed externally, a power-intensive process that creates a significant data bottleneck, especially for wireless implants. Organic artificial nerves, constructed from arrays of synaptic transistors, can preprocess complex sensory information on-device, mimicking the hierarchical processing of the human nervous system. This local, or "edge," computation can extract relevant features, filter out noise, and compress the data before transmission, drastically reducing the power and bandwidth requirements. The true revolution offered by organic neuromorphics in the BCI space is therefore not just a better electrode material, but the fusion of sensing and computation into a single, biocompatible, intelligent platform. This will be the key to creating fully autonomous bioelectronic systems that can make decisions and initiate actions locally.

Future Applications

This integrated sensing and processing capability could enable revolutionary advances across medicine and neuroscience:

- **Neuroprosthetics:** The creation of truly biomimetic artificial nerves that can interface with muscles or the brain to restore lost sensory or motor function. Intelligent implants could learn to adapt to a patient's specific neural patterns to treat disorders like Parkinson's, epilepsy, or chronic pain with unprecedented precision.
- **Medical Diagnostics:** Smart, wearable, or implantable sensors that do not just passively monitor physiological signals but actively analyze them in real-time to detect disease

signatures, predict adverse events, or provide personalized therapeutic feedback.
- **Neuroscience Tools:** The development of advanced, long-term tools for neuroscientists to monitor and modulate neural circuits with high fidelity in behaving animals, providing profound new insights into the workings of the brain.

Section 5: Performance, Progress, and Practicality

While the conceptual promise of organic neuromorphic computing is immense, its practical realization depends on achieving robust performance and overcoming significant engineering challenges. This final section provides a pragmatic assessment of the technology's current state, benchmarking key performance metrics against meaningful targets and soberly addressing the primary hurdles that lie on the path from laboratory demonstration to commercial and clinical application.

5.1 Benchmarking the State-of-the-Art

The field has made remarkable progress in recent years, moving from simple proofs-of-concept to devices and small-scale systems that demonstrate genuine computational capability.

Energy Efficiency

A critical benchmark for any neuromorphic technology is its energy consumption per synaptic operation. Biological synapses are incredibly efficient, operating with an estimated energy cost of around 10 femtojoules (10×10^{-15} J) per event. Early artificial synapses consumed orders of magnitude more energy, typically in the picojoule range. However, a major milestone has been achieved with the demonstration of organic nanowire synaptic transistors that, due to their highly confined channel geometry, reached an energy consumption of approximately 1.23 fJ per synaptic event. This landmark result proves that it is physically possible for synthetic organic devices to operate at the same fundamental energy scale as biology, validating the promise of ultra-low-power computing for applications in edge AI and long-term implantable devices.

Computational Accuracy

The ultimate purpose of these devices is to compute. To this end, researchers have built small artificial neural networks using arrays of organic synaptic devices and tested them on standard machine learning benchmark tasks. These hardware-based networks have demonstrated high classification accuracy, for example, in recognizing handwritten digits from the widely used MNIST dataset. Reported accuracies are often in the range of 90-97%, even when the input data is corrupted with noise. This level of performance confirms that arrays of these analog devices are not merely theoretical curiosities but can effectively execute complex computational tasks.

Device Performance Metrics

Beyond system-level benchmarks, there has been steady progress in the fundamental performance of individual devices:

- **Switching Speed:** While early electrochemical devices were slow, recent organic memristors and electrochemical RAM (ECRAM) cells have demonstrated programming with voltage pulses as short as 20-300 nanoseconds, bringing their speed into a range relevant for many real-time processing tasks.
- **Dynamic Range and Linearity:** The performance of an analog neural network is highly dependent on the quality of its synaptic weights. Researchers have developed new polymer materials, such as p(g2T-TT), that provide a larger dynamic range (the ratio between the highest and lowest achievable conductance states) and more linear, symmetric updates in response to programming pulses. These characteristics are crucial for achieving high accuracy during the neural network training process.
- **Retention:** A key requirement for a memory device is the ability to retain its programmed state over time. While short-term plasticity is a useful feature for some types of computation, long-term memory is essential for learning. Researchers have demonstrated organic neuromorphic devices where the programmed conductance states remain stable for at least two months, indicating excellent potential for non-volatile memory applications.

5.2 The Road to Commercialization: Overcoming Key Hurdles

Despite these impressive advances, the transition from academic research to widespread commercial technology is fraught with challenges. The focus of the field is now shifting from demonstrating that a single device *can* work to engineering systems where millions of devices *do* work reliably and efficiently in concert.

Device-to-Device Variability and Reliability

A persistent challenge for nearly all emerging memory and computing technologies, and particularly for those based on solution-processed organic materials, is device-to-device variability. The inherent randomness in the molecular assembly of these materials means that two devices, even when fabricated side-by-side, may not have identical electrical characteristics. This variability can severely degrade the performance of a large-scale neural network, which relies on the collective behavior of thousands or millions of synapses. Achieving the high yields and low variability required for commercial manufacturing remains a primary obstacle.

Endurance and Long-Term Stability

While the retention of a static memory state can be excellent, the endurance of a device—its ability to withstand a large number of write/erase cycles without degrading—is another critical metric. Furthermore, the long-term chemical and physical stability of organic materials, especially when operating in ambient air or, more challengingly, within the warm, saline environment of the human body, is a major area of ongoing research and development.

Scaling and CMOS Integration

To be practically useful in a larger system, arrays of organic neuromorphic devices must be controlled and read out by conventional silicon-based Complementary Metal-Oxide-Semiconductor (CMOS) circuits. This hybrid integration of two fundamentally different material systems and fabrication technologies is a formidable manufacturing challenge.

Developing processes that can deposit and pattern delicate organic materials onto a finished silicon wafer without damaging either component is a key step toward building functional neuromorphic systems-on-a-chip.

Algorithm and Hardware Co-Design

The unique physical behaviors and inherent imperfections of organic neuromorphic devices mean that algorithms developed for ideal, software-based neural networks may not perform optimally on this new hardware. Achieving the best results will require a holistic co-design approach, where training algorithms are specifically developed to be aware of, and even compensate for, the physical characteristics of the hardware they are running on.

Ethical Considerations

As this technology matures and the prospect of high-bandwidth, intelligent brain-computer interfaces becomes more realistic, it brings to the forefront profound ethical questions. Issues of cognitive privacy, consent for the use of neural data, the potential for misuse of neuro-modulation technologies, and the risk of exacerbating social inequalities through cognitive enhancement must be proactively addressed. The development of this technology must proceed in parallel with the establishment of robust neuro-ethical frameworks and open systems of governance to ensure its benefits are realized responsibly and equitably.

The trajectory of this field suggests that the first commercially viable products will likely emerge not in the high-performance, general-purpose computing market dominated by silicon, but in niche, high-value applications where the unique advantages of organic materials provide an overwhelming value proposition. The most promising of these are in the medical and bio-interfacing domains. Applications such as intelligent neuroprosthetics, closed-loop therapeutic implants, and advanced diagnostic biosensors place a premium on biocompatibility, mechanical flexibility, and extreme low-power operation—precisely the areas where organic neuromorphics excel. These specialized, high-margin markets can tolerate the higher initial costs and less mature manufacturing infrastructure of an emerging technology, providing a crucial foothold from which it can mature before potentially expanding into higher-volume consumer applications like smart wearables.

Conclusion and Future Outlook

The inquiry into the potential for organic materials, such as those found in OLEDs, to function as "brain matter" opens a window into one of the most exciting frontiers in materials science and computer engineering. The analysis reveals that while OLEDs provide a familiar entry point, the true potential lies in a broader class of organic semiconductors whose unique properties are enabling a paradigm shift in how we conceive of and construct intelligent systems. These materials offer a pathway to move beyond the rigid, binary, and energy-intensive world of silicon-based computing toward a future of soft, analog, and bio-integrated intelligence.

The journey from fundamental material properties to functional neuromorphic systems is built on a series of key advancements. The inherent advantages of organic semiconductors—mechanical flexibility, solution processability, and tunable electronic properties—provide the foundational toolkit. When applied within the neuromorphic computing paradigm, which emulates the brain's efficient, in-memory processing architecture, these materials find their ideal application. Devices like organic synaptic transistors and memristors have successfully demonstrated the ability to physically emulate synaptic plasticity, the building block of learning and memory, with some achieving an energy efficiency that rivals their biological counterparts.

Perhaps the most compelling aspect of this technology is its profound biocompatibility. The ability of iono-electronic materials like PEDOT:PSS to "speak the language" of biology by transducing between ionic and electronic signals, combined with their soft mechanical nature, is paving the way for a new era of bioelectronics. The successful demonstration of biohybrid synapses that can communicate directly with living cells marks the dawn of truly integrated brain-computer interfaces, advanced neuroprosthetics, and autonomous therapeutic devices.

However, the path forward is laden with significant engineering challenges. The successful transition from laboratory curiosities to robust, scalable technologies will depend on solving the critical issues of device variability, long-term operational stability, and the complex integration of these novel organic components with the established silicon CMOS platform. This will require a deeply interdisciplinary effort, fostering a co-design approach where materials scientists, device physicists, circuit designers, and computer scientists work in concert to develop hardware and algorithms in tandem.

The future outlook for organic neuromorphic computing is one of immense possibility, guided by several key research directions:

1. **Materials Discovery:** A continued search for new organic materials with improved carrier mobility, enhanced environmental stability, and greater endurance is paramount.
2. **Scalable Manufacturing:** The development of high-resolution, high-yield printing and patterning techniques is essential for fabricating the large, dense arrays needed for complex neural networks.
3. **Hybrid System Integration:** Pioneering robust methods for integrating organic neuromorphic arrays with silicon CMOS control and readout circuitry will be the key to building practical, powerful systems.
4. **Ethical Frameworks:** A parallel and equally critical effort must be dedicated to establishing comprehensive ethical guidelines to navigate the societal implications of advanced bio-integrated technologies.

In conclusion, organic semiconductors are not positioned to replace silicon but to augment it, creating new possibilities where silicon cannot go. They are the leading candidates to form the material basis of a new class of computation—one that is not only inspired by the brain's efficiency but is also physically and chemically compatible with its living environment. The continued exploration of this field promises to redefine the boundaries between electronics and biology, unlocking transformative technologies for medicine, robotics, and artificial intelligence.

Works cited

1. Organic electronics - Wikipedia, https://en.wikipedia.org/wiki/Organic_electronics 2. Organic vs Inorganic Semiconductors: Which Has More Potential? - Patsnap Eureka, https://eureka.patsnap.com/article/organic-vs-inorganic-semiconductors-which-has-more-potential 3. ELI5: Why is sillicone used in electronics over organic semiconductors? - Reddit, https://www.reddit.com/r/explainlikeimfive/comments/s23vkd/eli5_why_is_sillicone_used_in_electronics_over/ 4. eli5: What exactly is silicone and why is it so essential to making electronics - Reddit, https://www.reddit.com/r/explainlikeimfive/comments/16wzwfd/eli5_what_exactly_is_silicone_and_why_is_it_so/ 5. Organic vs Silicon Semiconductors - Shin-Etsu MicroSi,

https://www.microsi.com/blog/organic-vs-silicon-semiconductors/ 6. OLED Advantages and Disadvantages - Electronics | HowStuffWorks, https://electronics.howstuffworks.com/oled5.htm 7. OLED Display Technology: Advantages, Applications, and the Future - Riverdi, https://riverdi.com/blog/exploring-oled-display-advantages-and-applications 8. Soft bioelectronic materials for brain computer interface - Bohrium, https://www.bohrium.com/paper-details/soft-bioelectronic-materials-for-brain-computer-interface/1081508188634742826-130107 9. (PDF) Soft bioelectronic materials for brain computer interface - ResearchGate, https://www.researchgate.net/publication/386055178_Soft_bioelectronic_materials_for_brain_computer_interface 10. Printable and environmentally friendlier: the potential benefits of organic semiconductors, https://hellofuture.orange.com/en/organic-semiconductors-open-up-new-possibilities-in-electronics/ 11. What is an OLED? | Ossila, https://www.ossila.com/pages/what-is-an-oled 12. Organic electronics for neuromorphic computing Yoeri van de Burgt1, Armantas Melianas2, Scott Tom Keene2, George Malliaras3, Alb - University of Cambridge, https://www.repository.cam.ac.uk/bitstreams/803664eb-7890-43fd-82bc-7e545c822140/download 13. Biocompatible organic transistors - Advanced Science News, https://www.advancedsciencenews.com/biocompatible-organic-transistors/ 14. PEDOT:PSS Interfaces Support the Development of Neuronal Synaptic Networks with Reduced Neuroglia Response In vitro, https://pmc.ncbi.nlm.nih.gov/articles/PMC4712304/ 15. Organic Synaptic Transistors Based on a Semiconductor ..., https://pubs.acs.org/doi/10.1021/acs.nanolett.4c05809 16. Recent Progress in Organic Optoelectronic Synaptic Devices - MDPI, https://www.mdpi.com/2304-6732/12/5/435 17. Organic Memristor with Synaptic Plasticity for Neuromorphic ... - MDPI, https://www.mdpi.com/2079-4991/13/5/803 18. Emerging Artificial Synaptic Devices Based on Organic Semiconductors: Molecular Design, Structure and Applications | ACS Applied Materials & Interfaces, https://pubs.acs.org/doi/abs/10.1021/acsami.4c17455 19. The neuromorphic computing for biointegrated electronics - OAE Publishing Inc., https://www.oaepublish.com/articles/ss.2024.12 20. Organic All-Photonic Artificial Synapses Enabled by Anti-Stokes Photoluminescence | Journal of the American Chemical Society, https://pubs.acs.org/doi/10.1021/jacs.2c13471 21. Temperature-resilient solid-state organic artificial synapses for neuromorphic computing, https://pmc.ncbi.nlm.nih.gov/articles/PMC7458436/ 22. Organic neuromorphic devices: Past, present, and future challenges | MRS Bulletin, https://www.cambridge.org/core/journals/mrs-bulletin/article/organic-neuromorphic-devices-past-present-and-future-challenges/A641A09A984E4D18AED39AD90B70CA3F 23. Scientists Develop Artificial Neurons That Mimic Human Perception - SciTechDaily, https://scitechdaily.com/scientists-develop-artificial-neurons-that-mimic-human-perception/ 24. Recent progress of organic artificial synapses in biomimetic sensory neural systems, https://pubs.rsc.org/en/content/articlehtml/2024/tc/d4tc00704b 25. MRS Bulletin: Volume 45 - Organic Semiconductors for Brain-Inspired Computing | Cambridge Core, https://www.cambridge.org/core/journals/mrs-bulletin/issue/organic-semiconductors-for-braininspired-computing/2244656B14A1F66927D948BE082E0161 26. The road to commercial success for neuromorphic technologies - ResearchGate, https://www.researchgate.net/publication/390804245_The_road_to_commercial_success_for_neuromorphic_technologies 27. Organic electronics for neuromorphic computing - Apollo - University of Cambridge, https://www.repository.cam.ac.uk/items/466b4130-09ea-4d27-844e-be84ef7f0a00 28.

Multifunctional Organic Materials, Devices, and Mechanisms for ..., https://communities.springernature.com/posts/multifunctional-organic-materials-devices-and-mechanisms-for-neuroscience-neuromorphic-computing-and-bioelectronics 29. Organic neuromorphic devices - ECE Research - NC State University, https://research.ece.ncsu.edu/gkoupidenis/research/organic-neuromorphic-devices/ 30. Organic Computing - am Institut für Datentechnik und Kommunikationsnetze - Technische Universität Braunschweig, https://www.ida.ing.tu-bs.de/en/organic0-1 31. Design and construction of organic computing systems - ResearchGate, https://www.researchgate.net/publication/224301981_Design_and_construction_of_organic_computing_systems 32. Organic Computing - Research, https://groups.csail.mit.edu/cag/raw/documents/Agarwal-Harrod-organic-2006.pdf 33. Wetware computer - Wikipedia, https://en.wikipedia.org/wiki/Wetware_computer 34. Introduction to Organic Computing | by Aayush Patel - Medium, https://medium.com/@aayushvp0/introduction-to-organic-computing-7d0576f57cd7 35. Organic Artificial Nerves: Neuromorphic Robotics and Bioelectronics ..., https://pubs.acs.org/doi/abs/10.1021/acs.chemrev.4c00571 36. Recent Advances in Flexible Organic Synaptic Transistors - ResearchGate, https://www.researchgate.net/publication/353468351_Recent_Advances_in_Flexible_Organic_Synaptic_Transistors 37. Organic core-sheath nanowire artificial synapses with femtojoule energy consumption - PMC - PubMed Central, https://pmc.ncbi.nlm.nih.gov/articles/PMC4928881/ 38. A review of memristor: material and structure design, device performance, applications and prospects - PMC, https://pmc.ncbi.nlm.nih.gov/articles/PMC9980037/ 39. Materials aspects of PEDOT:PSS for neuromorphic organic electrochemical transistors, https://www.researchgate.net/publication/378534462_Materials_aspects_of_PEDOTPSS_for_neuromorphic_organic_electrochemical_transistors 40. Perspective: Organic electronic materials and devices for neuromorphic engineering | Journal of Applied Physics | AIP Publishing, https://pubs.aip.org/aip/jap/article/124/15/151902/348082/Perspective-Organic-electronic-materials-and 41. Transient modeling of PEDOT:PSS based organic electrochemical transistors, https://acs.digitellinc.com/p/s/transient-modeling-of-pedotpss-based-organic-electrochemical-transistors-54241 42. High-Endurance Long-Term Potentiation in Neuromorphic Organic Electrochemical Transistors by PEDOT:PSS Electrochemical Polymerization on the Gate Electrode | ACS Applied Materials & Interfaces - ACS Publications, https://pubs.acs.org/doi/10.1021/acsami.3c10576 43. Neuromorphic Functions in PEDOT:PSS Organic Electrochemical Transistors - PubMed, https://pubmed.ncbi.nlm.nih.gov/26456708/ 44. Beyond acid treatment of PEDOT:PSS: decoding mechanisms of electrical conductivity enhancement - Materials Advances (RSC Publishing), https://pubs.rsc.org/en/content/articlelanding/2024/ma/d4ma00078a 45. Brain-computer interfaces and the future of bioelectronics - CAS, https://www.cas.org/resources/cas-insights/brain-computer-interfaces-and-the-future-of-bioelectronics 46. One surprising fact about the human brain | Stanford Report, https://news.stanford.edu/stories/2025/08/surprising-fact-human-brain-artificial-synapses-research 47. Artificial synapse works with living cells | Stanford Report, https://news.stanford.edu/stories/2020/06/artificial-synapse-works-living-cells 48. An organic brain-inspired platform with neurotransmitter closed-loop control, actuation and reinforcement learning - PMC, https://pmc.ncbi.nlm.nih.gov/articles/PMC11182378/ 49. Concealing Organic Neuromorphic Devices with Neuronal-Inspired Supported Lipid Bilayers - PMC, https://pmc.ncbi.nlm.nih.gov/articles/PMC11251551/ 50. A Review of Organic and Inorganic Biomaterials for Neural Interfaces - PMC, https://pmc.ncbi.nlm.nih.gov/articles/PMC4373558/

51. Spiers Memorial Lecture: Challenges and prospects in organic photonics and electronics, https://pubs.rsc.org/en/content/articlehtml/2024/fd/d3fd00152k 52. Organic neuromorphic computing - TUE Research portal - Eindhoven University of Technology, https://research.tue.nl/files/296757352/20230525_Doremaele_van_st.pdf 53. Organic materials and devices for brain-inspired computing: From artificial implementation to biophysical realism | MRS Bulletin - Cambridge University Press & Assessment, https://www.cambridge.org/core/journals/mrs-bulletin/article/organic-materials-and-devices-for-brаininspired-computing-from-artificial-implementation-to-biophysical-realism/F907554D6706D272EA5ECEF05416B274