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Role of Solid-State Materials in the Development of Devices for the Internet of Medical Things

Anantham Srujana Jyothi[1,*], K.V.V. Subba Rao[2], Manas Kumar Yogi[3]

Abstract

The Internet of Medical Things (IoMT) represents a transformative paradigm in healthcare delivery, integrating connected medical devices, sensors, and wearable technologies to enable real-time patient monitoring and personalized treatment. Solid-state materials form the foundational infrastructure of IoMT systems, encompassing semiconductors, energy storage materials, sensing materials, and flexible electronics. This article explores the critical role of advanced solid-state materials in enabling miniaturization, energy efficiency, biocompatibility, and enhanced sensing capabilities essential for IoMT applications. The discussion encompasses semiconductor materials for processing and communication, energy storage solutions including solid-state batteries and supercapacitors, sensing materials for bio signal detection, and flexible substrates for wearable devices. Integration challenges, including biocompatibility, power management, and data security, are examined alongside emerging material innovations such as two-dimensional materials, perovskites, and biodegradable electronics. The convergence of materials science and healthcare technology promises unprecedented opportunities for continuous health monitoring, early disease detection, and improved patient outcomes in the era of connected medicine.

Keywords: IoMT, sensor, solid, polymer, crystal, nanomaterials

INTRODUCTION

The Internet of Medical Things (IoMT) represents a revolutionary convergence of healthcare and information technology, creating an interconnected ecosystem of medical devices, sensors, wearable technologies, and healthcare information systems [1]. This emerging paradigm enables continuous patient monitoring, real-time data analytics, personalized treatment protocols, and remote healthcare delivery, fundamentally transforming traditional medical practice. The global IoMT market has experienced exponential growth, projected to reach over $250 billion by 2028, driven by aging populations, chronic disease prevalence, and demand for cost-effective healthcare solutions [2].

At the core of this technological revolution lies the indispensable role of solid-state materials—the physical foundation upon which IoMT devices are constructed and operated [3]. Solid-state materials encompass a diverse range of substances, including semiconductors, dielectrics, conductors, energy storage materials, and sensing materials, each of which has unique properties that are essential for IoMT functionality. These materials enable device miniaturization, enhance energy efficiency, provide biocompatibility for direct body contact, and deliver the sensing capabilities necessary for accurate physiological monitoring [4].

The integration of advanced solid-state materials addresses fundamental challenges in IoMT

***Author for Correspondence**
Anantham Srujana Jyothi
E-mail: srujanajyothi.cse586@gmail.com

[1]Assistant Professor, Department of Computer Science and Engineering (Artificial Intelligence and Machine Learning), Pragati Engineering College (A), Surampalem, Andhra Pradesh, India
[2,3]Assistant Professor, Department of Computer Science and Engineering, Pragati Engineering College (A), Surampalem, Andhra Pradesh, India

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development, including power consumption constraints, device longevity, signal processing capabilities, wireless communication requirements, and mechanical flexibility for wearable applications. Silicon-based semiconductors have traditionally dominated electronic device manufacturing, but emerging materials such as gallium nitride, organic semiconductors, two-dimensional materials such as graphene, and perovskites are expanding their possibilities for IoMT applications. Furthermore, solid-state energy storage technologies, particularly lithium-based batteries and supercapacitors, provide the power density and charging characteristics required for autonomous medical device operation [5].

The biomedical sensing revolution depends heavily on materials that can transduce physiological signals (electrochemical, optical, mechanical, or thermal) into measurable electrical outputs. Electroactive polymers, nanomaterials, metal oxides, and composite materials serve as sensing interfaces to detect biomarkers, monitor vital signs, and identify disease indicators with unprecedented sensitivity and specificity. In addition, the development of flexible and stretchable electronics relies on novel substrate materials and conductive composites that maintain electrical functionality while conforming to human body contours and movements.

This study examines the multifaceted role of solid-state materials in IoMT development and analyzes their contributions to device architecture, performance optimization, and clinical applicability. The discussion encompasses semiconductor technologies, energy storage systems, sensing materials, flexible electronics, and emerging material innovations that promise to further advance the IoMT capabilities. Understanding the material science foundation of IoMT is essential for researchers, engineers, and healthcare professionals working to realize the full potential of connected medical technologies in improving patient care and health outcomes [6].

SEMICONDUCTOR MATERIALS IN IoMT DEVICES

Silicon-Based Technologies

Silicon remains the predominant semiconductor material in IoMT device fabrication owing to its well-established processing techniques, excellent electrical properties, and mature manufacturing infrastructure. Complementary metal-oxide-semiconductor (CMOS) technology, based on silicon, enables the integration of millions of transistors on microchips smaller than a fingernail, providing the computational power necessary for on-device signal processing, data encryption, and intelligent decision-making in medical devices [7]. Modern IoMT devices utilize system-on-chip (SoC) architectures that incorporate processors, memory, wireless communication modules, and sensor interfaces on a single silicon substrate, dramatically reducing the device size and power consumption.

The continuous scaling of silicon transistors following Moore's law has enabled increasingly sophisticated medical devices with enhanced functionality. However, fundamental physical limitations drive the exploration of alternative semiconductor materials and device architectures. Three-dimensional integrated circuits and silicon-on-insulator technologies represent evolutionary approaches that extend the viability of silicon for future IoMT applications by improving the performance and reducing parasitic capacitance [8].

Wide Bandgap Semiconductors

Wide bandgap semiconductors, particularly gallium nitride (GaN) and silicon carbide (SiC), offer superior performance characteristics for specific IoMT applications requiring high-frequency operation, elevated temperature tolerance, and high-power efficiency [9]. GaN-based power amplifiers enable efficient wireless power transfer and wireless communication in implantable medical devices, extend battery life, and reduce the frequency of surgical interventions for device replacement. The high electron mobility and breakdown voltage of GaN make it particularly suitable for radio frequency identification (RFID) systems and near-field communication (NFC) modules used in IoMT infrastructure [10–12] (Table 1).

Table 1. Comparison of semiconductor materials for IoMT applications.

Material	Bandgap (eV)	Electron mobility ($cm^2/V \cdot s$)	Thermal conductivity ($W/m \cdot K$)	Primary IoMT applications	Key advantages
Silicon (Si)	1.12	1,400	150	Processors, sensors, Radio-Frequency Identification (RFID)	Mature technology, low cost, established manufacturing
Gallium nitride (GaN)	3.4	2,000	130	Power amplifiers, wireless charging	High-frequency operation, power efficiency
Silicon carbide (SiC)	3.26	900	490	High-temperature sensors	Temperature stability, radiation hardness
Gallium arsenide (GaAs)	1.43	8,500	55	Optical sensors, photodetectors	High electron mobility, optical properties
Organic semiconductors	1.5–3.5	1–10	0.1–1	Flexible sensors, displays	Mechanical flexibility, low-temperature processing

Organic and Flexible Semiconductors

Organic semiconductors represent a paradigm shift in IoMT device design, enabling the fabrication of flexible, lightweight, and biocompatible electronics that conform to body surfaces and seamlessly integrate with biological tissues. Conjugated polymers and small-molecule organic semiconductors can be processed from solutions at low temperatures, facilitating large-area deposition on flexible plastic substrates such as polyethylene terephthalate (PET) or polyimide. Organic thin-film transistors (OTFTs) form the basis of flexible biosensor arrays, electronic skin, and conformable health-monitoring patches that maintain functionality during mechanical deformation [13].

The development of n- and p-type organic semiconductors with balanced charge transport properties has enabled complementary organic circuits with improved noise margins and lower power consumption, which are critical requirements for battery-powered IoMT devices. Recent advances in molecular engineering have produced organic semiconductors with electron mobilities exceeding 10 $cm^2/V \cdot s$, approaching that of amorphous silicon while retaining mechanical flexibility. Encapsulation technologies using thin-film barriers protect organic semiconductors from moisture and oxygen degradation and extend operational lifetimes to meet medical device reliability standards.

ENERGY STORAGE MATERIALS FOR IoMT SYSTEMS

Solid-State Lithium Batteries

Energy storage represents a critical bottleneck in IoMT device development because miniature medical sensors and wearable devices require reliable, long-lasting power sources in severely constrained volumes. Solid-state lithium batteries utilizing ceramic or polymer electrolytes offer significant advantages over conventional liquid electrolyte batteries, including enhanced safety through the elimination of flammable organic solvents, improved energy density, wider operating temperature ranges, and reduced self-discharge rates. Lithium-ion conducting ceramics such as NASICON-type materials, garnet-structured oxides like $Li_7La_3Zr_2O_{12}$ (LLZO), and sulfide-based electrolytes provide ionic conductivities approaching 10^{-2} S/cm at room temperature, enabling practical solid-state battery operation [13].

The interface between solid electrolytes and electrode materials presents both opportunities and challenges for IoMT applications [13]. Thin-film solid-state batteries fabricated using physical vapor deposition or atomic layer deposition techniques achieve excellent interfacial contacts and can be integrated directly onto semiconductor substrates or flexible polymer supports. These batteries exhibit exceptional cycle lives exceeding 10,000 charge-discharge cycles, which are essential for implantable medical devices designed for multi-year operation without replacement [14, 15] (Table 2).

Table 2. Energy storage technologies for IoMT devices.

Technology	Energy density (Wh/L)	Power density (W/L)	Cycle life	Charging time	IoMT suitability	Limitations
Solid-state Li battery	300–500	50–200	>10,000	1–4 hours	Implantable, long-term wearables	High cost, interface resistance
Conventional Li-ion	250–700	200–500	500–2,000	1–3 hours	Portable devices, smartwatches	Safety concerns, limited flexibility
Supercapacitors	5–15	1,000–10,000	>100,000	Seconds-minutes	Energy harvesting, pulse power	Low energy density
Flexible batteries	100–300	50–150	1,000–5,000	2–5 hours	Wearable patches, smart textiles	Lower performance, durability issues
Biofuel cells	0.1–1	0.01–0.1	Continuous	N/A (continuous)	Implantable with body fluid access	Very low power output

Supercapacitors and Hybrid Systems

Supercapacitors, also known as electrochemical capacitors, store energy through electrostatic charge accumulation at electrode-electrolyte interfaces rather than through chemical reactions. This charge storage mechanism enables extremely rapid charging and discharging, power densities orders of magnitude higher than those of batteries, and virtually unlimited cycle life. Carbon-based electrode materials, including activated carbon, carbon nanotubes, and graphene, provide high surface areas (>1,000 m^2/g) that maximize capacitance while maintaining electrical conductivity.

For IoMT applications requiring both high energy for sustained operation and high power for intermittent wireless data transmission, energy storage systems combining batteries and supercapacitors offer optimal performance. The supercapacitor handles peak power demands during radio transmission or sensor activation, whereas the battery provides steady baseline power, extending the overall system lifetime and enabling miniaturization. Pseudocapacitive materials such as manganese dioxide, ruthenium oxide, and conducting polymers enhance supercapacitor energy density through Faradaic charge transfer reactions while maintaining high-power capability [15].

Energy Harvesting Materials

Ambient energy-harvesting technologies reduce or eliminate the need for battery replacement in IoMT devices by converting environmental energy sources into electrical power. Piezoelectric materials generate electricity from mechanical vibrations and deformations, making them ideal for harvesting energy from body motion, cardiac contractions, and respiratory movements. Lead zirconate titanate (PZT), zinc oxide nanowires, and polyvinylidene fluoride (PVDF) polymers serve as piezoelectric transducers in self-powered medical sensors [16].

Thermoelectric materials convert temperature gradients between the body and environment into electrical energy through the Seebeck effect [17]. Bismuth telluride alloys and organic thermoelectric materials with high Seebeck coefficients and low thermal conductivities can generate microwatts to milliwatts from the typical 5–10°C temperature difference between the skin and ambient air. Photovoltaic cells using organic semiconductors or dye-sensitized nanostructured titanium dioxide can harvest indoor lighting for wearable devices, whereas radio frequency energy harvesting captures ambient electromagnetic radiation from Wi-Fi, cellular, or dedicated transmitters [16].

SENSING MATERIALS AND BIOINTERFACE TECHNOLOGIES

Electrochemical Sensing Materials

Electrochemical sensors form the cornerstone of continuous glucose monitoring, lactate detection, electrolyte analysis, and various other analyte measurements in IoMT systems [16]. These sensors transduce chemical information into electrical signals through redox reactions occurring at electrode surfaces [16]. Noble metals such as platinum, gold, and their alloys serve as electrode materials owing to their chemical stability, biocompatibility, and electrocatalytic properties [17–19]. However, the high cost and limited selectivity of bare metal electrodes have driven the development of modified electrodes that incorporate nanomaterials, enzymes, and molecular recognition elements.

Carbon-based nanomaterials, particularly carbon nanotubes and graphene, enhance the electrochemical sensor performance through their high surface area, excellent electrical conductivity, and ability to facilitate electron transfer. Graphene field-effect transistors (GFETs) enable the label-free detection of biomarkers, proteins, and nucleic acids with femtomolar sensitivity, approaching the theoretical limits for electrical biosensing. Metal oxide nanoparticles, including zinc oxide, titanium dioxide, and cerium oxide, provide catalytic sites and biocompatible scaffolds for enzyme immobilization in biosensors.

Optical and Photonic Materials

Optical sensing technologies offer noninvasive monitoring capabilities with immunity to electromagnetic interference, making them attractive for IoMT applications. Photoplethysmography (PPG) sensors utilizing light-emitting diodes (LEDs) and photodetectors measure blood volume changes to determine the heart rate, blood oxygen saturation, and blood pressure. Gallium nitride and indium gallium nitride quantum wells produce efficient green, blue, and ultraviolet LEDs, whereas silicon photodiodes or avalanche photodiodes detect reflected or transmitted light.

Fiber optic sensors incorporating Bragg gratings written into silica or polymer optical fibers enable the distributed sensing of strain, temperature, and pressure along a single fiber strand. These sensors can be woven into smart textiles or embedded in bandages for the continuous monitoring of wound healing, limb swelling, or respiratory patterns. Plasmonic nanostructures exploiting surface plasmon resonance in gold or silver nanoparticles provide an extremely sensitive detection of molecular binding events for point-of-care diagnostics.

Flexible and Stretchable Conductors

Mechanical flexibility and stretchability are essential characteristics of wearable and implantable IoMT devices that must conform to curved body surfaces and accommodate tissue movement. Intrinsically stretchable conductors based on conducting polymers such as poly(3,4-ethylenedioxythiophene)polystyrene sulfonate (PEDOT:PSS) maintain electrical conductivity under strain through their interpenetrating network of conductive and elastic domains. Composite materials incorporating conductive fillers, such as silver nanowires, carbon nanotubes, or metal nanoparticles, in elastomeric matrices create percolation networks that sustain conductivity during deformation (Table 3).

Table 3. Sensing materials for IoMT biosensors.

Material type	Examples	Transduction mechanism	Detected parameters	Sensitivity range	Advantages	Challenges
Noble metals	Pt, Au, Ag	Electrochemical redox	Glucose, lactate, H_2O_2	µM to mM	High conductivity, stability	Cost, limited selectivity
Carbon nanomaterials	Graphene, CNTs	Electrochemical/FET	Multiple biomarkers	fM to µM	High surface area, sensitivity	Fabrication complexity
Metal oxides	ZnO, TiO_2, CeO_2	Electrochemical/optical	pH, glucose, H_2O_2	nM to mM	Biocompatibility, catalytic	Stability in physiological conditions
Conducting polymers	PEDOT:PSS, Polypyrrole (PPy)	Electrochemical/resistive	Ions, biomolecules, pressure	nM to mM	Flexibility, biocompatibility	Long-term stability
Quantum dots	CdSe, CdTe, carbon dots	Optical fluorescence	Biomarkers, cells, pH	pM to nM	High sensitivity, multiplexing	Toxicity concerns (Cd-based)

CNTs, carbon nanotubes; EDOT:PSS, poly(3,4-ethylenedioxythiophene)polystyrene sulfonate;

Liquid metal alloys, particularly eutectic gallium-indium (EGaIn), offer intrinsic stretchability, self-healing properties, and conductivities approaching those of bulk metals [18]. Encapsulated in elastomeric microchannels, liquid metals form flexible interconnects, antennas, and electrodes that maintain their functionality during extreme deformations exceeding 400% strain. Microstructured metal films employing serpentine, fractal, or Kirigami patterns distribute strain across the structure, enabling rigid conductive materials, such as gold, to achieve apparent stretchability suitable for electronic skin and conformable sensors.

Biocompatible Interface Materials

The biointerface between IoMT devices and biological tissues critically influences device performance, longevity, and safety [19]. Foreign body responses to implanted materials can lead to fibrous encapsulation, reducing sensor sensitivity, or blocking drug delivery [18]. Biocompatible polymers such as polyethylene glycol (PEG), polyurethanes, and silicones minimize protein adsorption and cellular adhesion, thereby creating more benign interfaces [17]. Hydrogel coatings with high water content mimic natural tissue mechanics and reduce inflammatory responses, thereby improving the integration of chronic implants [20–24] (Tables 4 and 5).

Table 4. Biocompatible materials for IoMT device interfaces.

Material category	Specific materials	Key properties	IoMT applications	Biocompatibility mechanism	Degradation behavior
Biocompatible Polymers	PEG, silicone, polyurethane	Low protein adhesion, flexibility	Coatings, encapsulation	Hydrophilic surface, minimal immune response	Non-degradable (long-term)
Hydrogels	Polyvinyl alcohol (PVA), alginate, chitosan	High water content, soft mechanics	Soft electrodes, drug delivery	Tissue-like mechanics, low friction	Tunable degradation
Conducting Polymers	PEDOT:PSS, Polypyrrole	Electrical conductivity, softness	Neural interfaces, biosensors	Soft interface, drug incorporation	Slowly degradable
Biodegradable Polymers	PLGA, Polycaprolactone (PCL), Polylactic Acid (PLA)	Controlled degradation	Transient electronics, scaffolds	Degradation to biocompatible products	Days to months
Biodegradable Metals	Mg, Zn, Fe alloys	Electrical conductivity, degradability	Transient conductors, electrodes	Natural minerals, controlled dissolution	Weeks to months

PEG, polyethylene glycol; PET, polyethylene terephthalate; PEDOT:PSS, poly(3,4-ethylenedioxythiophene)polystyrene sulfonate; PLGA, poly(lactic-co-glycolic acid)

Table 5. Emerging solid-state materials for next-generation IoMT.

Material innovation	Composition	Unique properties	Potential IoMT applications	Development stage	Key challenges
2D Materials	Graphene, MoS_2, BP	Atomic thickness, high mobility	Ultra-sensitive biosensors, transparent electrodes	Laboratory/early prototype	Large-scale synthesis, stability
Halide Perovskites	$CH_3NH_3PbI_3$, $CsPbBr_3$	High optical absorption, tunable bandgap	Photodetectors, optical sensors	Laboratory research	Stability, lead toxicity
Organic Thermoelectrics	PEDOT, P3HT composites	Mechanical flexibility, low cost	Body heat energy harvesting	Early prototype	Low efficiency ($ZT < 0.5$)
Self-Healing Materials	Dynamic polymers, liquid metals	Autonomous repair after damage	Durable wearables, robust implants	Laboratory demonstration	Limited conductivity, response time
Transient Electronics	Biodegradable Si, Mg, PLGA	Controlled dissolution in body fluids	Temporary implants, monitoring devices	Clinical trials (limited)	Balancing functionality with degradation rate

Functional biointerfaces can actively promote tissue integration and provide stimuli-responsive behaviors. Conducting polymers doped with bioactive molecules enable simultaneous electrical recording and local drug delivery for neural interfaces. Biodegradable materials, including poly(lactic-co-glycolic acid) (PLGA) and magnesium alloys, enable transient electronics that function for a defined period before safely dissolving, eliminating the need for surgical removal.

CONCLUSION

Solid-state materials constitute the essential foundation upon which the IoMT is built, enabling the transformation of healthcare through connected intelligent medical devices. The convergence of semiconductor technologies, advanced energy-storage systems, sophisticated sensing materials, and flexible electronics has created unprecedented opportunities for continuous health monitoring, early disease detection, and personalized treatment strategies. Silicon-based semiconductors continue to provide the computational backbone for IoMT devices, while emerging materials such as organic semiconductors, two-dimensional materials, and wide bandgap compounds expand the functional possibilities for flexible, efficient, and specialized medical sensors.

Energy storage remains a critical challenge in IoMT development, with solid-state batteries, supercapacitors, and hybrid systems offering improved safety, longevity, and power density that are essential for autonomous device operation. Energy-harvesting technologies utilizing piezoelectric, thermoelectric, and photovoltaic materials promise to reduce or eliminate battery replacement requirements, which are particularly valuable for implantable devices. The sensing revolution enabled by nanomaterials, conducting polymers, and advanced optical materials provides the sensitivity and selectivity necessary for detecting minute physiological changes and molecular biomarkers that are indicative of disease states.

The mechanical interface between rigid electronic components and soft biological tissues presents a fundamental challenge for flexible and stretchable materials to be addressed through innovations in conductive polymers, composite materials, liquid metals, and microstructured metal films. Biocompatibility considerations drive material selection and surface modification strategies to minimize foreign body responses and promote long-term device integration. Biodegradable materials are emerging as transformative technologies for transient medical devices that eliminate surgical removal, while maintaining functionality during critical monitoring or treatment periods.

The continued evolution of solid-state materials will expand IoMT capabilities through enhanced miniaturization, improved energy efficiency, multimodal sensing, and seamless integration with human physiology. Challenges remain in manufacturing scalability, long-term reliability, regulatory pathways, and data security, but the foundation of materials science is rapidly advancing to address these obstacles. Interdisciplinary collaboration between materials scientists, electrical engineers, biomedical researchers, and healthcare professionals will accelerate the translation of material innovations into clinical applications that improve patient outcomes and transform healthcare delivery into the connected medical ecosystem.

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