

Emerging nanomaterial and microfabrication techniques for wearable and implantable bioelectronics: Comprehensive review



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ARTICLE INFO

Keywords:

Biosensor
Bioelectronics
Encapsulation
Flexible electronics
Nanomaterials
Implantable devices
Wearable electronics
Health monitoring

ABSTRACT

Wearable and implantable nanoelectronics demand the heterogeneous integration of transducers, analogue front-ends, wireless power and data links, and hermetic encapsulation on substrates that remain mechanically compliant and biostable *in vivo*. Progress in wearable and implantable bioelectronics has been enabled by co-optimisation of material systems, process windows and packaging architectures with the capability to maintain stability under coupled mechanical, electrochemical, and thermal stresses. Nanoscale and two-dimensional semiconductors expand the design space for low-power transduction, but they impose stringent requirements on defect density, contact resistance, and encapsulation-induced strain after transfer to elastomeric substrates. This present work surveys nanomaterials and microfabrication strategies that address this systems-level requirement and complement existing material-class surveys organising the field along co-design axis of material, fabrication process, encapsulation and tissue interface. Additionally, the review presents a novel cross-material performance benchmark that compares carrier mobility, tensile-strain limit, limit of detection, encapsulation WVTR, fabrication-to-application suitability and regulatory pathway. The scope of this review is restricted to skin-mounted, intracutaneous, and intracorporeal medical devices reported between 2018 and 2026.

1. Introduction

The continuous proliferation of miniaturised integrated circuits (ICs) and micromachining have transformed microelectronics in the two decades [1,2]. The integration of miniaturised ICs and micromachining with artificial intelligence, Internet of Things, materials science, sensing and actuator technologies has driven innovation in flexible, implantable, and wearable electronic devices targeted at medical and healthcare applications [3,4]. The need to integrate these devices seamlessly with the human body across cutaneous curvature under repeated body movement and over long deployment periods imposes stringent mechanical and biological requirements on device materials and fabrication techniques. Multi-functional design within a low-profile substrate area [5] as found in consumer-grade systems including smartwatches [6,7], augmented and virtual reality headsets [8–10], fitness trackers [11,12], and comparable requirements is established to drive bioelectronic systems such as medical wearables and implants. However, to satisfy the mechanical and biological requirements of bioelectronic systems, intense research has converged on

nanomaterials, which exploit size and interface-dominated properties at the nanoscale [3,13]. Existing works in the literature on wearable and implantable systems demonstrated the use of graphene [14], silicon nanomembranes [15,16], carbon nanotubes [17,18], liquid-metal alloys [19,20], and other organic and inorganic nanomaterials [21,22]. The use of nanomaterials in wearable electronics and devices have significantly evolved from single-material to heterogeneously integrated systems.

Wearables are devices worn on the skin or integrated into clothing to monitor physical and physiological parameters continuously, using biosensing modalities selected for analyte of interest including Na⁺ activity in sweat or saliva for dietary-sodium tracking and SARS-CoV-2 antigen or RNA assays for COVID-19 detection [21–27]. Beyond passive monitoring, wearables are increasingly used for screening, detection, and prediction. A dry-electrode system screens patients for sleep apnoea and differentiating apnoea subtypes during routine use [28]. For example, a wearable electrochemical glove-based sensor achieves a methamphetamine limit of detection (LoD) of 0.1 µg mL⁻¹ with a 60-day shelf life demonstrating the wider sensing capability of skin-mounted

Peer review under responsibility of Shanghai Jiao Tong University.

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<https://doi.org/10.1016/j.nbe.2026.100079>

Received 15 July 2026; Received in revised form 22 August 2026; Accepted 29 August 2026

electrochemistry [29]. Abdelrazik et al. demonstrated the efficacy of wearable devices support arrhythmia detection via early identification and remote monitoring [30]. Stehlik et al. developed an analytical platform using continuous physiological data streams from multi-sensor patch to predict heart-failure readmission with 76%–88% sensitivity and 85% specificity [31] and wearable telemonitoring effectively predicted post-pancreatectomy complications more accurately than the American College of Surgeons National Surgical Quality Improvement Program risk calculator based on machine learning models [32].

Implantables are devices and tissue constructs placed within the body temporarily or permanently to support physiological functionalities but their operation is often constrained by limited communication bandwidth and onboard power management [33]. However, different power management strategies including enzymic and microbial bio-fuel cells have been used to activate self-powered implants that draw energy from biochemical fuels in interstitial fluid [34–36]. Implantable drug-delivery platforms span oncology, contraception, and other gynaecological application [37]. Wearable and implantable bioelectronic systems comprises four functional layers: transducer layer, analogue front-end, wireless power and data interface, and encapsulation layer on a mechanically compliant substrate with each layer coupled to one or more system-level integration constraints such as mechanical deformation, ionic ingress, foreign-body response and available energy budget. According to the author's knowledge, several reviews on wearable and implantable bioelectronics between the period 2024 – 2026 including dedicated surveys of MXene bioelectronics, gallium-based liquid metals and hydrogel bioelectronics focused around single material family or device modality [38–40]. However, the present review is focused along co-design axis of material, fabrication process, encapsulation and tissue interface in comparison to material family only. In addition, the review presents novel cross-material performance benchmark that place carrier mobility, tensile-strain limit, limit of detection, water vapour transmission rate (WVTR) in encapsulation, fabrication-to-application suitability and regulatory pathway on a common axis.

The review is organised as follows: Section 2 presents the various nanomaterial families within the transducer, interconnect, encapsulation and bio-interface layers. Section 3 discussed the electrochemical sensing subsystem and address the solid-contact ion-selective electrode (SC-ISE) stability, anti-biofouling and multi-channel signal decoupling. Section 4 surveys the bottom-up, top-down, and hybrid microfabrication routes and maps each to skin-mounted or long-term implantable service. Section 5 integrates the material and process analyses at the system level, addressing percolation mechanics, encapsulation and long-term reliability, clinical translation, and manufacturing-scale variability. The conclusion drawn from the review is presented in Section 6.

2. Nanomaterials fundamentals in wearable and implantable devices

Nanomaterials as materials with external dimension and surface structure on the nanoscale, typically within the 1–100 nm geometry, classified by morphology, dimensionality, source material and fabrication route [41–43]. This section presents a comprehensive classification of nanomaterials by device-layer functionalities including transducer semiconductor, conjugated polymer, stretchable interconnect, encapsulation stack and bio-interface. Additionally, the section discusses conventional nanomaterial-based taxonomy such as carbon allotropes, hydrogels, inorganic nanoparticles, ceramics and quantum dots.

2.1. Transducer-layer materials

Transition-metal dichalcogenides (TMDs) such as molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), tungsten diselenide (WSe_2)

and molybdenum ditelluride (MoTe_2) are 2-dimensional layered semiconductor whose monolayers combine direct bandgap within the 1–2 eV range with sub-nanometre thickness to enhance low-voltage sub-threshold operation on flexible substrates. Field-effect carrier mobilities of 200–500 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ have been demonstrated for CVD-grown monolayer MoS_2 on polyimide after high- κ gating and picomolar-level LoD has been demonstrated for MoS_2 ion-sensitive FETs targeting cortisol, cardiac troponin and DNA [44,45]. Monolayer TMDs require strain-decoupling encapsulation stack to prevent interference of mechanical and electrochemical signals since monolayer TMDs are strain-tunable with bandgap shift $\approx 50 \text{ meV}$ per strain (%). Nanocrystalline oxide semiconductors such as indium-gallium-zinc oxide (IGZO) and zinc-tin oxide are amorphous, soluble at temperatures compatible with parylene and polyimide, and patternable by area-selective atomic layer deposition (AS-ALD) but possess lower carrier mobilities typically $\approx 10 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, which are essential for analogue front-end design of wearable patches where wafer-scale uniformity is more critical than peak mobility [46,47].

2.2. Conjugated polymer and mixed ionic materials

Conjugated polymers such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS), PEDOT: PSS-hydrogel blends and polyaniline are organic flexible bio-interfaces that conduct both ions and electrons and are printable at room temperature. Solution-cast PEDOT: PSS coatings reduce the contact impedance of bare metal microelectrode by one to two orders of magnitude, reaching $< 1 \text{ k}\Omega$ at 1 kHz for 100 μm -diameter contacts [48,49]. In the organic electrochemical transistors (OECTs), the polymer channel amplifies analyte-driven ionic modulation into a drain current resulting in transconductances of 10–100 mS at sub-1V operation which is compatible with the energy budget of a near-field communication (NFC)-harvested wearable [48,50]. The blending of OECTs with polyacrylic-acid networks would result in toughness required for cyclic on-skin application [51]. However, PEDOT: PSS exhibits key limitations including hydrolytic doping drift and de-doping under repeated redox cycling.

2.3. Stretchable materials

Stretchable materials interconnects for epidermal and implantable electronics employ percolating nanowire networks, eutectic liquid metals, and strain-accommodating metallic thin-film architectures. The interconnect maintains the electrical continuity under repeated multi-directional skin deformation, which can involve strains of several tens of percent at highly mobile anatomical sites, while implanted leads must additionally accommodate the smaller but persistent deformations associated with soft-tissue micromotion. Percolating silver-nanowire (AgNW) networks deposited on elastomeric substrates can provide low sheet resistances, with values on the order of 10–20 Ωsq^{-1} reported for relatively dense and well-connected networks, while their mechanical tolerance depends strongly on nanowire dimensions, areal density, junction resistance, substrate properties, and network architecture. Junction welding, including thermal, photonic, or plasmonic approaches, can substantially reduce inter-wire contact resistance and improve resistance stability under cyclic deformation; nevertheless, the strain at which electrical degradation or percolation-network failure is architecture- and test-condition-dependent, with highly engineered networks capable of sustaining strains of several tens of percent or more. Eutectic gallium–indium (EGaIn) offers substantially greater intrinsic deformability because electrical conduction is maintained through a liquid-metal phase; its spontaneous formation of a thin Ga_2O_3 -rich oxide skin in air imparts a finite interfacial yield stress, suppresses uncontrolled spreading, and enables patterned traces to retain their geometry while accommodating strains exceeding 200% in appropriately designed architectures. This oxide layer, however, also influences wetting, interfacial adhesion, flow and electrical-mechanical

stability. Metallic thin films, particularly Au- and Pt-based films on compliant substrates such as PDMS, can likewise achieve large effective stretchability through controlled cracking, buckling, delamination and/or formation of island-bridge morphologies. Following mechanical conditioning, these structures can preserve electrical continuity over large strains, but their resistance evolution and cyclic lifetime depend strongly on metal thickness, adhesion, pre-strain, substrate modulus, crack morphology and loading history. Consequently, their long-term performance is generally governed by the coupled evolution of cracks, interfaces and conductive pathways under cyclic loading rather than by the monotonic fracture strain alone.

2.4. ALD nanolaminates and hybrid over-layers

Encapsulation is the primary determinant of chronic implant lifetime, and no single material simultaneously satisfies the requirements of low water-vapour transmission rate (WVTR), mechanical compliance, and biostability; a multilayer stack is therefore standard. An ALD inorganic diffusion barrier — typically $\text{Al}_2\text{O}_3/\text{HfO}_2$ nanolaminates of 25–100 nm total thickness — provides WVTR of 10^{-6} – 10^{-5} g m $^{-2}$ day $^{-1}$. Al_2O_3 alone hydrolyses in phosphate-buffered saline at 37 °C; interleaving with HfO_2 suppresses this reaction by an order of magnitude and stabilises the barrier over months in vivo [46,47,52]. A 3–10 μm parylene-C over-layer and, for skin-facing devices, a 100–500 μm silicone elastomer add mechanical robustness and abrasion resistance without dominating the moisture path. Where a sensor must transport analyte in one region and reject water elsewhere, patterned openings in the ALD barrier are protected by a hydrogel or track-etched membrane.

2.5. Bio-interface contact impedance

The tissue interface acts as a low-pass electrochemical filter whose impedance governs signal-to-noise in recording and stimulation. The accepted target for cortical recording is sub-k Ω contact impedance at 1 kHz for a 100 μm -diameter microelectrode. Three coating classes achieve this target: (i) electrodeposited PEDOT:PSS or PEDOT:tosylate, providing the volumetric ionic–electronic capacitance; (ii) iridium oxide (IrOx) grown by activated sputtering or electroplating, combining faradaic charge storage with clinical-grade biocompatibility and used in marketed cochlear and deep-brain stimulators; and (iii) nanoporous Pt or Pt-black, which raises the effective electrode area by up to two orders of magnitude but may delaminate under aggressive stimulation. Coating–foreign-body interactions.

2.6. Carbon nanomaterials

Carbon-based nanomaterials are treated here as a family because they share sp^2 -hybridised bonding and, in most device deployments,

occupy the transducer or bio-interface layer rather than the interconnect or encapsulation layer. Where earlier taxonomies classify graphene as an “organic” nanomaterial, the term is used here only in the descriptive sense of a carbon-only material, not as an organic compound. Representative carbon-nanomaterial morphologies as illustrated in Fig. 1.

2.6.1. Graphene

Graphene is a two-dimensional hexagonal allotrope of sp^2 -hybridised carbon in a honeycomb lattice. Fig. 1 illustrates the structural representation of graphene field-effect-transistor (FET) biosensor. Suspended monolayer graphene exhibits a thermal conductivity of ≈ 3000 – 5000 W m $^{-1}$ K $^{-1}$, an intrinsic in-plane electrical conductivity of 10^6 – 10^8 S m $^{-1}$, and carrier mobilities up to $\approx 2 \times 10^5$ cm 2 V $^{-1}$ s $^{-1}$ in low-disorder samples, with the integer quantum Hall effect observable at room temperature [54–59]. The monolayer has an in-plane Young's modulus of ≈ 1 TPa and an intrinsic strength of ≈ 130 GPa, and its sub-nanometre thickness of ≈ 0.34 nm per layer gives low bending stiffness which preserve flexibility at device scale. High specific surface area, high carrier mobility, and mechanical robustness together yield low limits of detection and tolerance to long-term on-skin deployment. Existing works reported graphene FET biosensor for real-time interleukin-6 detection over 10 pM–100 nM [53], graphene micro-needle array for continuous glucose and ketone monitoring with a sensitivity of 234.18 μA mM $^{-1}$ cm $^{-2}$ and a limit of detection of 1.21 μM [60].

2.6.2. Fullerenes

Fullerenes are closed-cage carbon allotropes of sp^2 -hybridised atoms in fused hexagonal and pentagonal rings [61,62], of which C_{60} is the most studied. Substitution and curvature modulate solubility, polarisability, and energy density, producing nucleophilic and electrophilic sites [63]. The resulting spherical aromaticity supports nucleophilic addition, redox, and encapsulation reactions, enabling use as carriers in biological media [64]. A graphene-oxide/fullerene fabric sensor discriminated ionic species in artificial sweat [65], and a Mg-doped fullerene sensor detected γ -butyrolactone with high adsorption-driven sensitivity and conductivity [66].

2.6.3. Carbon nanotubes

Carbon nanotubes (CNTs) are one-dimensional cylindrical variants of graphene with diameters of 0.4–50 nm and lengths up to micrometres structures above ≈ 50 nm diameter are classified as carbon nanofibers [67–70]. The mechanical, surface, and electronic properties of single-, double-, and multi-walled CNTs depend on wall count and chirality: chirality governs electronic behaviour, whereas wall count governs mechanical and transport properties. The nanostructures of single- and multi-walled CNTs are shown in Fig. 2. CNTs combine high tensile strength, high Young's modulus, and elastic recovery; their high

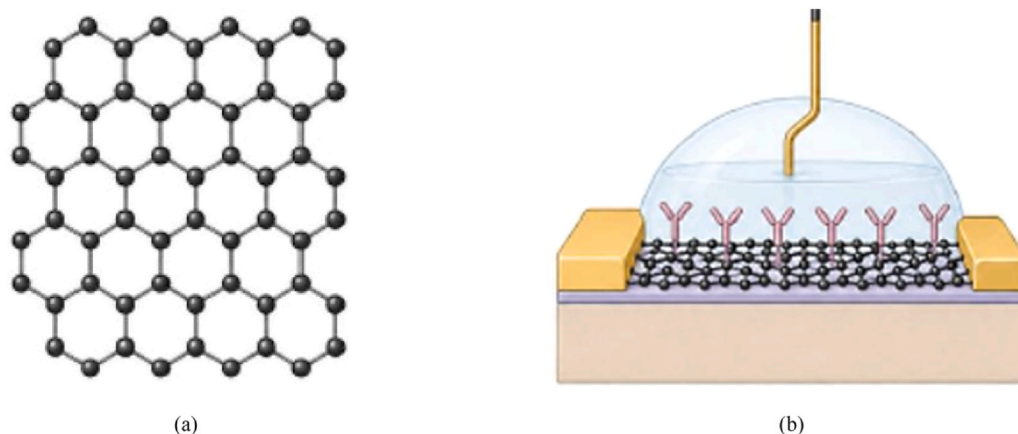


Fig. 1. Graphene structure and wearable-biosensor performance. (a) Honeycomb lattice and band structure showing the sp^2 -hybridised carbon network and corresponding band structure near the K point; (b) Schematic of graphene FET biosensor for cytokine detection [53].

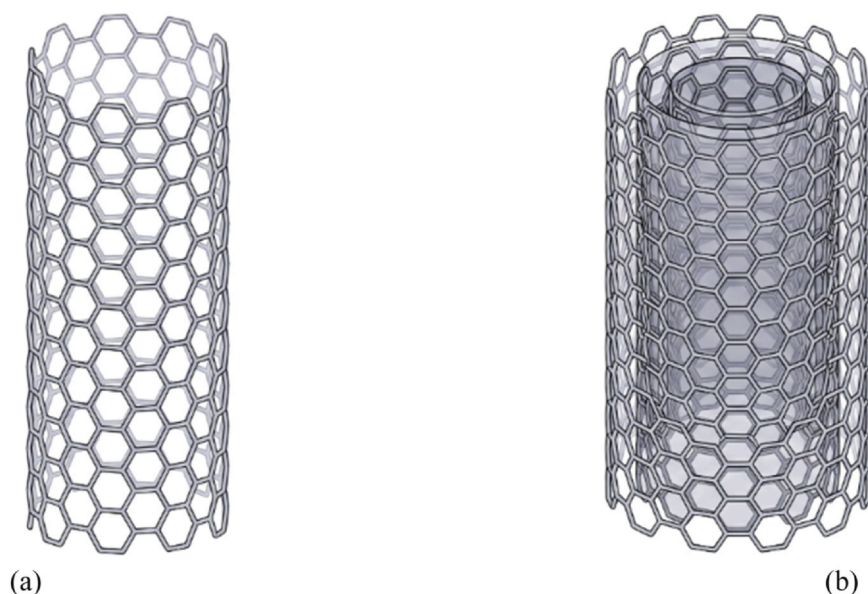


Fig. 2. Nanostructures of CNT geometry with chirality Indices for (a) Single-walled (b) multi-walled. Created in BioRender. Oguntala, G. (2026) <https://BioRender.com/bevazzx>.

aspect ratio yields porous, high-surface-area networks, and their surfaces functionalise covalently or non-covalently to host biomolecules [67–70]. A wrinkled CNT capacitive strain sensor exceeded the theoretical gauge factor of 1.0 for parallel-plate geometries by a factor of two, with high response speed and low hysteresis [71]. A CNT/polyaniline thermoelectric yarn reached an electrical conductivity of 3651 S cm^{-1} and a power factor of $1294 \mu\text{W m}^{-1} \text{ K}^{-2}$ [72]. Carbon-infiltrated CNT coatings on titanium reduced *Staphylococcus aureus* adhesion by ≈ 2.5 -fold at a 150 nm tube diameter, indicating a passive antibacterial pathway for orthopaedic implants [73].

2.7. Hydrogels and nanogels

Hydrogels are crosslinked three-dimensional polymer networks that absorb large water volumes while remaining insoluble [74–77]. Nanogels are hydrogel particles with at least one nanoscale dimension. They combine biocompatibility, biodegradability, and mechanical adaptability with chemically tuneable stimuli-responsive behaviour, making them effective carriers for targeted drug delivery [77,78]. A physically crosslinked nanogel-based cotton bionic skin responds to multiple physical stimuli with a colour-coded readout [79]. Photopolymerisation of a choline chloride/acrylic-acid deep-eutectic solvent incorporating PEDOT:PSS produced a stretchable electronic skin whose conductivity increased after sulfuric-acid post-treatment [51]. A self-powered, tumour-microenvironment-activated core-shell nanogel of Fe^{3+} -stabilised sodium alginate/tannic acid encapsulating CaO_2 /L-arginine induced apoptosis *in vitro* and *in vivo* and was systemically eliminated, supporting combined chemo-dynamic and gas therapy [80]. Hydrogels also provide the selectively permeable region over sensing electrodes.

2.8. Inorganic nanomaterials

Inorganic nanomaterials — elemental metals, metal oxides, ceramics, and semiconductors — generally provide higher electrical conductivity, greater chemical stability, and stronger optical and magnetic responses than organic nanomaterials [81]. Their functionality depends strongly on size and shape: smaller particles exhibit greater cellular internal functionalities, bioactivity, and redox activity [82]. Nanorods, nanotubes, and spherical particles differ in conductivity, reactivity, and spectroscopic accessibility, with spherical morphologies serving as a

common reference [83]. Representative inorganic nanoparticle morphologies by materials class including metal, metal-oxide, ceramic, and quantum dots are shown in Fig. 3.

2.8.1. Metal nanoparticles

Metal nanoparticles of silver, gold, copper, and iron and their alloys exhibit high surface-to-volume ratio, high thermal and electrical conductivity, and localised surface plasmon resonance [87]. Silver nanoparticles have been reported to exhibit broad-spectrum antimicrobial activity, encompassing antibacterial, antifungal, and antiviral effects. [88]. A silver-nanoparticle/multi-walled-CNT ink with a PEDOT:PSS binder achieved a film conductivity of $\approx 29 \text{ S cm}^{-1}$, a gauge factor of 142 at 5% strain, cyclic stability over 10^4 cycles, and low surface roughness at $9.5 \mu\text{m}$ thickness [89]. To mitigate silver-induced cytotoxicity in load-bearing implants, a multilayer surface treatment combining biomimetic micro-grooves, alkaline-heat-treated sodium titanate, and a chitosan/silver coating improved wear resistance, bioactivity, and stability [84]. Gold nanoparticles are bio-inert and oxidation-resistant [90,91], supporting applications in drug delivery, precision oncology, and diagnostics [92]. A template-printed gold-

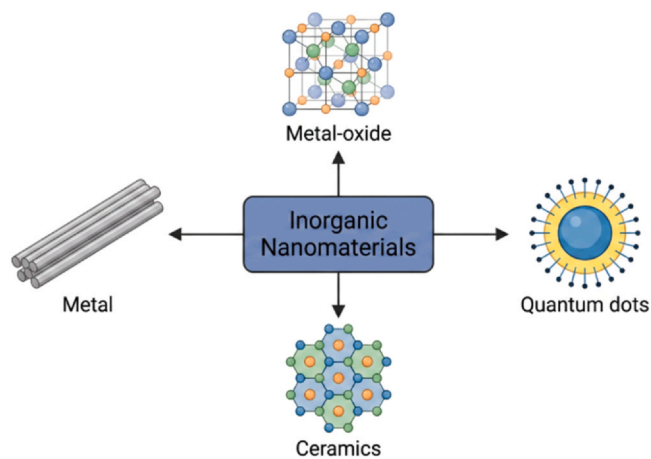


Fig. 3. Inorganic nanoparticle morphology by materials class: Metal [84], Metal-oxide [85], Ceramic [86] and Quantum dots. Created in BioRender. Oguntala, G. (2026) <https://BioRender.com/qxzpzuf>.

nanoparticle superlattice film with sub-fracture-threshold domain size remained mechanically intact while enhancing surface-enhanced Raman scattering in wearable sensors [93], and a polydopamine-coupled gold/curcumin nanohybrid achieved anti-biofilm and antibacterial efficiencies of 99% and 98% against *Staphylococcus aureus* [94].

2.8.2. Metal-oxide nanomaterials

Metal-oxide nanomaterial properties depend on size, shape, surface chemistry, metal cation, target analyte, stoichiometry, and bonding environment [95,96]. Common oxides include TiO_2 , ZnO , Co_3O_4 , Fe_2O_3 , and SiO_2 [97]. TiO_2 combines a Young's modulus of ≈ 244 GPa, a Mohs hardness of 5.5–7, high thermal stability (melting point ≈ 1843 °C), and photocatalytic and photovoltaic activity [98,99]. A non-fluorinated piezoresistive fabric sensor of octadecyl-isocyanate-modified TiO_2 retained hydrophobicity with a sensitivity loss below 0.02 kPa^{-1} under water, milk, saline, sweat, and humidity [100]. A quartz-crystal-microbalance humidity sensor coated with a nanoflower-textured TiO_2 /ethyl-cellulose composite exhibited fast, repeatable, analyte-selective response for respiration monitoring [101]. Layer-by-layer chitosan/alginate/ TiO_2 coatings on porous titanium suppressed *Staphylococcus aureus* biofilm formation with lower cytotoxicity than equivalent silver coatings [102]. A hydrothermally grown TiO_2 nanoneedle architecture on titanium, decorated with silver nanoparticles and polydopamine, combined antibacterial action with promotion of bone-marrow mesenchymal stem-cell osteogenesis, indicating a route to integrated infection control and osseointegration [103].

2.8.3. Ceramic nanomaterials

Ceramic nanomaterials, obtained from natural sources or by heat-and-cool routes, include nano-carbides, nano-carbonates, nano-phosphates, nano-nitrides, and nano-oxides [104,105] and combine low density, high hardness, corrosion resistance, chemical stability, biocompatibility, and low cost [106,107]. Nanohydroxyapatite (nHAP), a calcium-phosphate ceramic, provides mechanical robustness, hydrophilicity, low electrical conductivity, high surface area, osteoconductivity and a porous bone-mimetic morphology [86,108–111]. Nacre-mimetic ribbon fibres wet-spun from layered nHAP nanowires and sodium polyacrylate reached a tensile strength of ≈ 204 MPa and a Young's modulus of ≈ 25 GPa while remaining knittable [112]. nHAP coatings on cellulose-paper triboelectric nanogenerators (TENGs) increased peak voltage and current by $5.8 \times$ and $4.2 \times$, respectively, and retained 59% of dry-state output at 71.7% relative humidity versus 45% for uncoated devices [113]. Twin-screw-extruded poly(L,DL-lactide)/nHAP composites yielded 3D-printed implants with bone-like density, bioactivity, and biodegradability [114], and non-clogging nHAP coatings on graded-porosity electron-beam-melted titanium achieved deep osseointegration relative to surface-only fixation on uncoated controls [115].

2.8.4. Silicon carbide

Silicon carbide (SiC) is a wide-bandgap semiconductor with biocompatibility, hemocompatibility, and biostability suited to chronic implants, together with high hardness, fracture toughness, and thermal conductivity, a low thermal-expansion coefficient, corrosion and oxidation resistance, and high electron drift velocity [116–119]. Under appropriate excitation it supports single-photon emission from defect colour centres and broadband ensemble luminescence. A photodetector formed by electrophoretic deposition of aerogel-derived SiC nanowires with high-temperature bonding showed enhanced sensitivity, gain, and stability [120]. A direct-write humidity sensor based on a SiC/magnetite polymer-matrix nanocomposite ink exhibited a monotonic conductivity decrease with increasing relative humidity [121]. A flexible system based on crystalline SiC nanomembranes transferred onto polyimide showed no hydrolysis or measurable Na^+ or H_2O ingress in PBS over several weeks and retained its faradaic interface for long-term multimodal *in vivo* sensing [122]. A wafer-scale dual-phase dry-etch

process that selectively removes silicon from an Si/SiC/polyimide stack produced flexible, electrically stable SiC devices that accelerated stimulated cell migration, supporting long-term electrostimulation [123].

2.8.5. Quantum dots

Quantum dots (QD) are zero-dimensional core-shell semiconductor nanoparticles of 2–10 nm diameter whose properties are governed by quantum confinement [124,125]. Quantum dots combine large molar extinction coefficients, broad absorption with size-tuneable narrow emission, high photoluminescence yield, photostability, and above ≈ 2 –3 of the bandgap photon energy and multiple-exciton generation [126–128]. In surface engineering, cadmium (Cd)-free indium phosphide (InP)/zinc sulfide (ZnS) or copper indium disulfide (CuInS_2)/ZnS shell QD tailors biocompatibility and antibacterial activity, whereas unprotected Cd-based cores remain cytotoxic [124]. CdSe QDs encapsulated in poly(styrene-co-methyl methacrylate) by solution polymerisation and electrospinning yielded fibres with temperature-dependent fluorescence quenching that retained their optical signature under salt, humidity, and heat, indicating potential for wearable thermometry [129]. A streptavidin-functionalised QD-antibody biochip detected the stress biomarkers Hsp70 and Hsp90 in artificial serum with limits of detection of ≈ 96 nM and ≈ 50 nM, respectively [130]. Cd-free CuInSe/Al -doped ZnS near-infrared QD patterns delivered intradermally with a vaccine by dissolvable microneedles remained readable under a NIR-imaging smartphone for nine months while inducing protective antibody titres, enabling combined record-keeping and immunisation [131]. An InP/ZnS QD thin film on ITO seeded with hippocampal neurons modulated post-synaptic currents under 450 nm photostimulation, which demonstrate photo-faradaic plasticity for neuro-morphic interfaces.

2.9. Composite and other nanostructures

Composite nanomaterials combine two or more nanoscale phases, either with a bulk matrix (nanocomposites) or with another nanomaterial, deriving their utility from the combined constituent properties - the principal motivation for hybrid fabrication. Additional nanostructures include nanodiamonds, dendrimers, liposomes, nitrides, and MXenes, were tabulated in the initial submission. Among these, MXenes are particularly notable: they provide solution-processable transducer layers with metallic conductivity, termination-tuneable work functions, and demonstrated capabilities for sweat glucose and lactate sensing [132,133]. A detailed cross-material performance benchmark for wearable/and implantable bioelectronic materials under various conditions including carrier mobility, tensile-strain limit at 10 % conductance loss, biosensor limit of detection and encapsulation water-vapour transmission rate is presented in Fig. 4.

3. Electrochemical sensing and system-level integration

This section addresses three coupled determinants of long-duration biofluid sensing: interfacial stability of solid-contact ion-selective electrodes (SC-ISEs), anti-biofouling strategies, and multi-channel signal decoupling.

3.1. Solid contact ion-selective electrodes

Continuous ion monitoring in sweat, tears, and interstitial fluid employs SC-ISEs rather than liquid-junction electrodes because SC-ISEs are miniaturisable and require no internal filling solution. Their principal failure mode is potential drift, caused by an uncontrolled water layer forming between the ion-selective membrane and the electronic conductor; the solid-contact transducer must therefore be simultaneously ionically permeable, electrically conductive, redox-stable, and hydrophobic. Three transducer families dominate: PEDOT doped with poly(styrene sulfonate) or hydrophobic counter-ions (perchlorate, tosylate) provides a redox-active mixed-ionic-electronic buffer, with

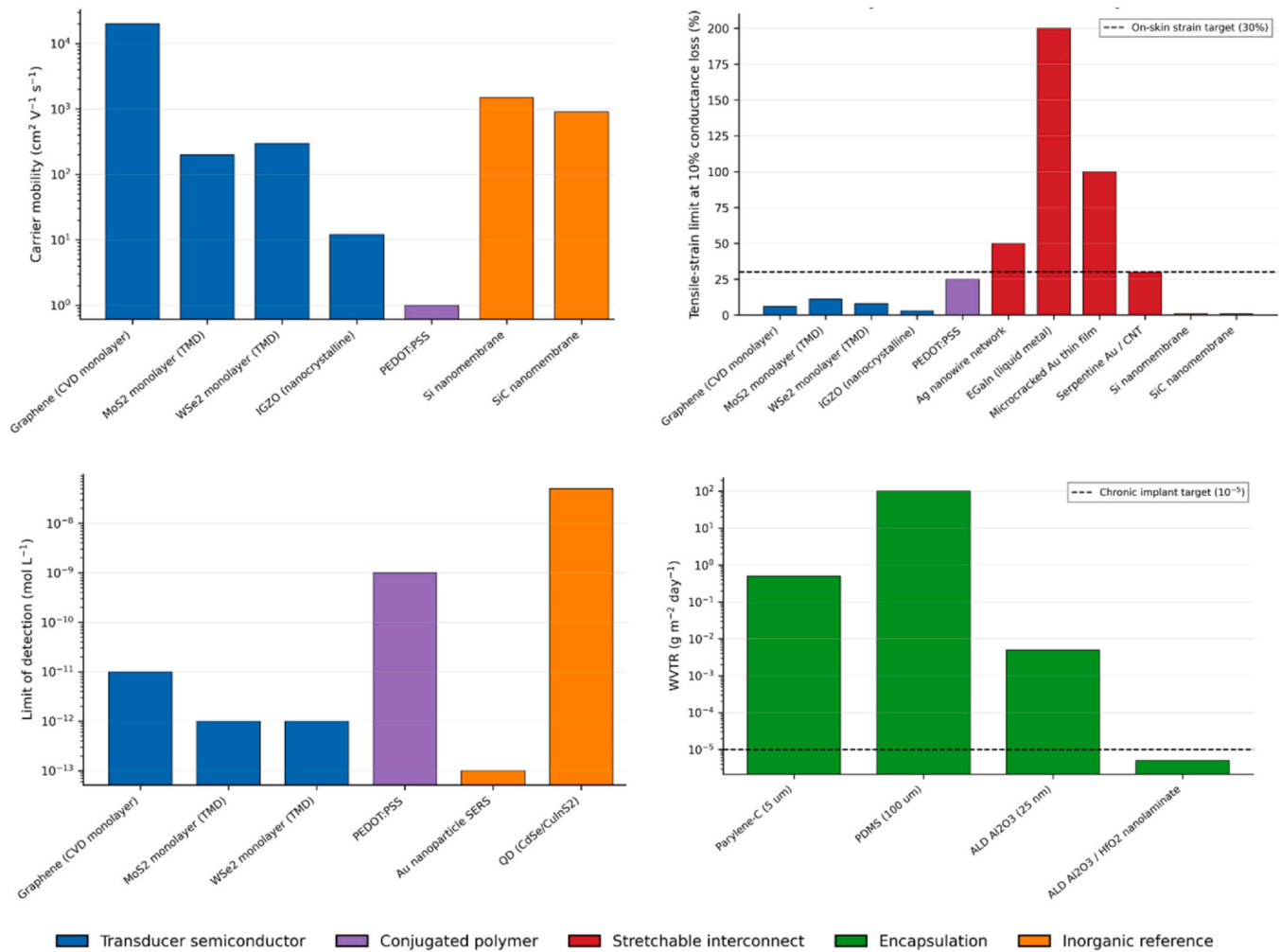


Fig. 4. Cross-material performance benchmark for wearable/and implantable bioelectronic materials. (a) carrier mobility (b) tensile-strain limit at 10% conductance loss (c) biosensor limit of detection; (d) Encapsulation water-vapour transmission rate.

potential drift below 0.1 mV h^{-1} reported over multi-day sweat exposure for tosylate-doped PEDOT [134,135]. Carbon-black and graphene-oxide transducers provide large double-layer capacitance without redox chemistry, minimising drift at the cost of slower response. Gold-nanocluster and Prussian-blue transducers are used where a defined redox couple is beneficial, as in Na^+ and K^+ electrodes for exercise physiology. In all cases the SC-ISE must be encapsulated per Section 2.4 so that only the ion-selective membrane contacts the biofluid; unencapsulated back-contacts drift within hours.

3.2. Anti-biofouling

Biofouling by proteins, cells, and biofilms is the second dominant cause of chronic sensor drift. Four surface strategies constitute current best practice: (i) zwitterionic coatings such as poly(sulfobetaine methacrylate) or phosphorylcholine polymers, which suppress non-specific protein adsorption by more than an order of magnitude relative to bare PDMS; (ii) polyethylene-glycol brushes grafted via silane or dopamine anchors, equally effective but more susceptible to oxidative degradation over multi-week deployment; (iii) molecularly imprinted polymer (MIP) over-layers, combining analyte selectivity with rejection of larger fouling species; and (iv) self-cleaning hydrogel skins that shed the fouling layer by shear-induced swelling. These strategies are complementary: a typical implantable continuous glucose or lactate sensor combines a MIP or enzyme layer on the electrode, a zwitterionic protein-rejecting top coat, and a cell-rejecting hydrogel skin [136,137].

3.3. Multi channel signal decoupling

System-level continuous biofluid monitoring rarely uses a single electrode: a modern sweat patch or transdermal microneedle array carries 5–20 electrochemical channels, several potentiometric ISEs, and one or more physical sensors sharing a common reference. Three decoupling techniques dominate. Differential ISE arrays with matched pseudo-reference electrodes remove common-mode drift and skin-potential offsets, with residual drift bounded by ISE mismatch. Adaptive digital filtering (Kalman, recursive least squares) and blind-source separation (independent component analysis) separate co-modulated signals such as glucose and lactate that share redox partners. Calibration-free potentiometry uses in-line reference calibration with on-body temperature and pH correction to eliminate impractical per-sensor calibration. The engineering trade-off is between algorithmic complexity and analogue-front-end quality: a differential architecture with a clean pseudo-reference outperforms a single-ended architecture with an elaborate ICA back-end at equal power budget and should be preferred where the analogue bill-of-materials permits [137].

4. Fabrication techniques

Nanomaterial fabrication is conventionally classified as bottom-up, top-down, or hybrid [138–142] via different complementary schemes including medium phase such as solid, liquid, vapour [143], material synthesis from molecular precursors from existing material. With

various material properties due to scale, morphology control, defect density, environmental footprint, and cost trade-off, one or more fabrication techniques are hybridised to support emerging advanced wearable and implantable systems techniques [139].

4.1. Bottom-up methods

Bottom-up techniques assemble nanomaterials from molecular or atomic precursors via chemical or biological pathways [138,141]. Covalent or non-covalent aggregation of building blocks affords tight structural control at low defect density at the expense of scalability, yield, and byproduct removal [142]. The class comprises vapour-phase routes such as chemical vapour synthesis, arc discharge, chemical vapour deposition, atomic layer deposition, pyrolysis, liquid-phase routes sol-gel, solvothermal/hydrothermal, thermal decomposition, micro-emulsion, polyol, reverse micelle, chemical reduction; and molecular-assembly methods including self-assembly, π - π stacking, hydrophobic interaction, structural-modification methods such as grafting-from, spinning, capping; and biosynthesis [138,139,141–143].

4.1.1. Vapour-phase synthesis and deposition

Vapour-phase synthesis maintains precursors in the gas phase, where they react and crystallise into nanoparticles on cooling [143]. Chemical vapour synthesis (CVS), distinct from the deposition variant, thermally decomposes precursors at high temperature and high-energy atomic collisions to drive homogeneous nucleation and rapid coagulation [144–147]. Arc discharge sublimates electrode material under high current arc and re-deposit as nanoparticles on cooling [148–151]. Arc discharge is simple and inexpensive but yields heterogeneous, low-selectivity products, and mainly used for CNTs, fullerenes, and graphene [149,152]. Chemical vapour deposition (CVD) forms thin crystalline nanostructures by transporting volatile precursors over a heated, plasma-activated, or photo-activated substrate for conformal reaction [153,154]. CVD films are uniform, pure, and scalable, but require high temperature, can generate toxic byproducts, and are difficult for nanocomposites. Atomic-layer deposition (ALD) uses alternating self-limiting reactant pulses to produce sub-nanometre-resolution conformal films [155–159] offering excellent step coverage on temperature-sensitive substrates. However, ALD is effective for moisture-barrier oxides in wearable and implantable encapsulation and is limited by low throughput, precursor cost and toxicity and reactant utilisation.

4.1.2. Liquid-phase synthesis and biosynthesis

Liquid-phase methods use dissolved precursors, surfactants and stabilisers to control morphology at low cost and high throughput [160]. Chemical reduction generates zero-valent metal atoms from precursor salts using a reductant such as hydrogen, with the process being fast, inexpensive and morphologically controllable but prone to aggregation and parametric sensitivity [161–164]. Biosynthesis uses organic templates or living systems such as plants, microbes, DNA scaffolds, actin, amino acids to drive redox chemistry and self-assembly under ambient conditions which results in biocompatible, environmentally benign products that require control of biological contamination and downstream separation [165,166].

4.2. Top-down methods

Top-down methods break, pattern, or transform bulk material into nanomaterials via subtractive routes including attrition, milling, grinding or additive routes such as lithography, which are typically in solid or liquid media [140,141,160]. Top-down methods often yield high crystallinity, source-defined purity, low environmental burden, scalability, and low cost, which is offset by surface, shape, and size defects. Different strategies are employed in top-down methods including mechanical methods such as high-energy ball milling, grinding, attrition; thermal methods such as laser ablation, pyrolysis, nano-

spraying, inert-gas condensation; lithographic methods such as photolithography, electron-beam lithography, nanoimprint lithography, and physical vapour deposition [104,142]. High-energy ball milling deforms, welds, fractures, and mechanochemically transforms precursor powders by repeated collision in hard, non-reactive vessels [167–170]. Laser ablation focuses pulsed beam onto a precursor to form plasma plume that recondenses into nanoparticles in liquid or gas media [171]. Laser ablation is fast, versatile and modular and is often ineffective on spherical particles with low yield, high cost, and inner-filter heating at high concentration [172–174]. Nanoimprint lithography (NIL) is a standard tool for wafer-scale nanostructure replication, as it replicates master pattern by mechanical embossing of thermoplastic or UV-curable resist followed by curing and demoulding, as it combines high resolution, high aspect ratio, throughput, and low cost, limited by mould wear and demoulding defects [175–178].

4.3. Hybrid methods

Hybrid approaches combine two or more techniques to mitigate the limitations of any single method or to add functionality unattainable by one route.

4.4. Fabrication-to-application mapping

Fabrication-route selection for wearable and implantable devices is governed by three constraints: process temperature (compatible with the compliant substrate), residual chemistry (no cytotoxic leaching after implantation), and defect density (below the maximum tolerable failure rate for the target lifetime). The mapping, developed in Tables 1 and 2, is summarised as follows. Bottom-up ALD and low-temperature CVD dominate encapsulation for both skin-mounted and implantable devices because they deposit conformal sub-nanometre films at ≤ 200 °C. Liquid-phase and biosynthesis routes suit short-lived skin-mounted sensors but require rigorous purification for implantable service. Top-down lithography and imprint routes serve both categories, subject to photoresist-residue and lift-off-solvent removal for implants. Mechanical top-down routes (ball milling, high-energy grinding) are largely restricted to bulk precursor preparation upstream of the device stack. Table 2 summarises the process parameters and application suitability of the principal bottom-up and top-down families. In Table 2, the process temperature(*T*) represents the substrate temperature during patterning, the feature resolution is described as the minimum reliably patterned feature size; suitability is scored as Improved clinical use, translational-ready, research demonstration, or not recommended.

5. Discussion

Top-down lithographic and etching processes introduce residual crystallographic defects, whereas bottom-up chemical and biological syntheses yield incompletely removed organic byproducts; neither approach alone satisfies the concurrent requirements of sub-10 nm structural precision, chemical purity below parts-per-million thresholds, and throughputs exceeding 10^4 devices per batch demanded by clinical-grade bioelectronic manufacturing. Hybridised fabrication sequences resolve this impasse by assigning each unit operation to the length scale and material system for which it offers the lowest defect density. Sequential high-energy ball milling followed by chemical vapour deposition (CVD) of graphite-encapsulated Fe nanoparticle achieves specific surface area $> 200 \text{ m}^2\text{g}^{-1}$, a crystallographically ordered core-shell architecture, residual oxide content $< 3 \text{ wt}\%$, and electrochemical stability windows exceeding 1.2 V [192]. Analogously, partitioned lithographic hierarchies — electron-beam definition of sub-100 nm features combined with nanoimprint lithography (NIL) replication of micrometre-scale reservoirs within the same UV-curable resist layer resulting in microfluidic chips with defect densities below 0.1 cm^{-2} at wafer-scale throughput [193]. Hybridisation should

Table 1
Device-metric Benchmark across various Nanomaterials used in Wearable and Implantable Bioelectronics.

Material	Representative morphology	Substrate compatibility	Sensitivity	Gauge factor	LoD	Cyclic stability	Use Cases	References
Graphene	CVD monolayer, laser-induced foam	PI, PDMS, parylene-C	234.18 $\mu\text{A mm}^{-1} \text{cm}^{-2}$ (glucose)	1.5–10 (piezoresistive)	10 pM IL-6; 1.21 μM glucose	$> 10^5$ at 10% strain	Wearable dominant; implantable emerging	[53,60]
MoS_2/WS_2 (TMDs)	Monolayer, CVD or exfoliated	PI, parylene-C after transfer	10–100 mV dec^{-1} (ISFET)	-	1 pM (troponin); 1 fM (DNA)	$> 10^4$ at 5% strain	Both; requires ALD encapsulation	[45,46]
PEDOT:PSS	Spin- or ink-coated film/OECT channel	PDMS, Hydrogel, parylene-C, PI	Transconductance 10–100 mS (OECT)	0.5–5	1 nM (dopamine); 10 nM (K ⁺)	$> 10^4$ at 20% strain	Both; primary bio-interface coating	[49–52]
Ag nanowire network	Percolating spun-cast film	PDMS, PU, elastomer laminate	n/a (interconnect)	50–150 at 5% strain	-	$> 10^4$ at 30% strain	Wearable dominant	[89,179]
EGaIn liquid metal	Direct-write, injection, sinter-activated composite	PDMS, Silicone	n/a (interconnect)	≤ 0.05 (strain-insensitive)	-	$> 10^5$ at $> 100\%$ strain	Wearable dominant; implantable emerging	[19,20,180]
Microcracked Au thin film	Evaporated on pre-strained PDMS	PDMS, parylene	n/a (interconnect)	≤ 0.1 (island-bridge)	-	$> 10^5$ at 30–100% strain	Wearable dominant	[181]
ALD Al_2O_3 / HfO_2 nanolaminate	25–100 nm conformal film	PI, parylene, SiC nanomembrane	$\text{WVTR} < 10^{-5} \text{ g m}^{-2} \text{ day}^{-1}$	-	-	> 6 months in PBS at 37 °C	Implantable dominant	[47,48]
Parylene-C	CVD-deposited 3–10 μm film	Almost any substrate	$\text{WVTR} \approx 0.1\text{--}1 \text{ g m}^{-2} \text{ day}^{-1}$	-	-	> 5 years for cochlear implants	Both; clinical-grade	[54,134]
SiC nanomembrane	Crystalline monolayer / thin film	PI	n/a (encapsulation + electrode)	-	-	> 8 weeks in PBS (no hydrolysis)	Implantable dominant	[122,123]
Silicon nanomembrane	Transferred single-crystal thin film	PI, parylene-C	$\approx 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (FET)	-	-	Bioresorbable variants; 2–12 Weeks	Implantable / bioresorbable	[15,16,182]
Carbon nanotube (SW/MW)	Aligned or random network/yarn	PDMS, PI, textile	$\approx 29 \text{ S cm}^{-1}$ composite ink	142 at 5% strain (network)	10–100 nM (dopamine)	$> 10^4$ at 30% strain	Both; implantable requires purification	[72–74]
IrOx	Activated-sputtered or electroplated coating	Pt, Au, Ti electrodes	Charge storage 25 mC cm^{-2}	-	-	$> 10^9$ stimulation pulses	Implantable clinical (DBS, CI)	[183,184]
Nanohydroxyapatite (nHAP)	Electron-beam-melt coating; wet-spun fibre	Ti, PLA, cellulose	$\approx 204 \text{ MPa}$ tensile fibre	-	-	Osseointegration	Implantable	[112–115]
CuInS_2 / InP quantum dots	Core-shell 2–10 nm	ITO, elastomer, microneedle	50–96 nM (Hsp70, Hsp90)	-	50–96 nM (biomarker)	> 12 weeks in vivo 9 months intradermal	orthopaedic clinical Both; Cd-free variants only	[130,131,185]
MXene ($\text{Ti}_3\text{C}_2\text{T}_x$)	Solution-processable 2-D flake	PI, parylene, hydrogel	$\approx 10^4 \text{ S cm}^{-1}$ film; $\leq 20 \mu\text{M}$ glucose	50–200 at 5% strain	$\leq 20 \mu\text{M}$ glucose; $\leq 100 \text{ nM}$ lactate	readout $> 10^4$ at 30% strain	Wearable dominant; MRI-compatible variants explored	[132–134]

In Table, sensitivity and gauge factor are reported at the strain or analyte concentration; limit of detection (LoD) is analyte-normalised cyclic stability is cycles to 90 % signal retention.

Table 2
Fabrication Techniques to Application Mapping for Wearable and Implantable Devices.

Technique	Class	Process <i>T</i> (°C)	Substrate Compatibility	Feature Resolution	Throughput	Skin-mounted	Long-term implantable	Key failure mode	Reference
Atomic layer deposition (ALD)	Bottom-up, vapour	80–250	PI, parylene, SiC, elastomer	≤ 1 nm (thickness)	Low	Improved clinical use	Improved clinical use	Pinhole nucleation, precursor cost	[168–173]
Chemical vapour deposition (CVD)	Bottom-up, vapour	400–1000	Refractory (Si, quartz) then transfer	≈ 10 nm	Medium	translational-ready	translational-ready	Transfer defects, high <i>T</i>	[149–152,166,167]
Chemical vapour synthesis (CVS)	Bottom-up, vapour	600–1400	particle synthesis		Low-to-Medium	research	research demonstration	Overgrowth, aggregation	[153,155–158]
Arc discharge	Bottom-up, vapour	> 3000	particle synthesis		Medium	research	not recommended	Heterogeneous product	[160–165]
Pyrolysis	Bottom-up, vapour	300–900	Non-flammable substrates	≈ 100 nm	Medium	research	research demonstration	Residual carbon impurity	[186]
Sol-gel	Bottom-up, liquid	20–300	Broad	≈ 50 nm	High	translational-ready	research demonstration	Solvent residue	[187]
Solvothermal/ hydrothermal	Bottom-up, liquid	100–300	particle synthesis		Medium	research	research demonstration	Sealed-vessel batch limit	[188]
Polyol	Bottom-up, liquid	100–200	particle synthesis		Medium	demonstration	research demonstration	Polyol residue	[189]
Reverse micelle	Bottom-up, liquid	20–100	particle synthesis		Low	translational-ready	research demonstration	Surfactant residue	[190]
Chemical reduction	Bottom-up, liquid	20–100	particle synthesis		High	translational-ready	research demonstration	Aggregation	[176–178]
Biosynthesis	Bottom-up, biological	20–40	particle synthesis		Low–Medium	translational-ready	research demonstration	Pathogenic contamination	[186,187]
Self-assembly/ π - π stacking	Bottom-up, molecular	20–100	Broad	≈ 5 nm	Medium	translational-ready	research demonstration	Defect propagation	[191,192]
High-energy ball milling	Top-down, mechanical	20–200	bulk-to-particle		High	research	not recommended	Milling-media contamination	[188–193]
Laser ablation	Top-down, thermal	> 3000 (local)	Broad	≈ 100 nm	Medium	research	research demonstration	Spherical-bias, low yield	[194–197]
Photolithography	Top-down, lithographic	20–150	PI, parylene, Si	≈ 100 nm	High	Improved clinical use	Improved clinical use	Photoresist residue	[193]
Electron-beam lithography	Top-down, lithographic	20–100	PI, parylene, Si	≈ 5 nm	Low	research	translational-ready	Throughput	[193]
Nanoimprint lithography (NIL)	Top-down, lithographic	20–150	Polymers, PI	≈ 10 nm	High	translational-ready	translational-ready	Mould wear, demoulding defects	[177,178]
Physical vapour deposition	Top-down, thin-film	20–300	Broad	≈ 1 nm (thickness)	High	Improved clinical use	translational-ready	Adhesion on elastomer	[193]
Transfer printing of CMOS islands	Hybrid, top-down + bottom-up	20–200	Elastomer + Si chiplet	≈ 1 μ m	Medium	translational-ready	research demonstration	Interfacial delamination	[182,193]
Roll-to-roll ink patterning	Hybrid, additive	20–200	PI, PET, elastomer web	≈ 10 μ m	Very high	Improved clinical use	research demonstration	Particulate contamination	[146,147]
Area-selective ALD	Hybrid, vapour	80–250	PI, parylene	≈ 20 nm	Low	translational-ready	translational-ready	Precursor cost, low throughput	[48,49]

Table 3
Encapsulation Stack WVTR Flexural Performance and Chronic Stability.

Stack	Thickness	WVTR ($\text{g m}^{-2} \text{day}^{-1}$)	Flexural performance	Chronic stability	Failure mode	References
Parylene-C	3–10 μm	≈ 0.1 –1	$> 10^5$ bends at $r = 5 \text{ mm}$	> 5 years (cochlear implants)	Pinhole nucleation, silicone delamination	[54,134]
PDMS	50–500 μm	$\approx 10^2$	$> 100\%$ strain	> 90 days for skin patches	Water diffusion, plasticiser leach	[134]
ALD Al_2O_3 (25 nm)	25 nm	$\approx 10^{-2}$	$\leq 5\%$ strain	2–4 weeks in PBS at 37°C	Hydrolysis	[47,54]
ALD Al_2O_3 / HfO_2 nanolaminate	25–100 nm	$\leq 10^{-5}$	$\leq 5\%$ strain (bare); $> 30\%$ with parylene overlay	> 6 months in PBS at 37°C	Pinhole nucleation; HfO_2 rate-limiting	[47,48]
ALD nanolaminate + parylene-C + silicone	25–100 nm + 3–10 μm + 100–500 μm	$\leq 10^{-5}$	$> 30\%$ biaxial strain	> 12 months (retinal-implant trials)	Silicone–parylene delamination	[48,54,134]
SiC nanomembrane (transferred)	$\approx 100 \text{ nm}$	Chemical rather than diffusive barrier	$> 10^4$ bends at $r = 5 \text{ mm}$	> 8 weeks in PBS; no hydrolysis	Adhesion to PI	[126,127]
Bioresorbable Mg / SiO_2	Design-dependent	Transient by design	$> 10^4$ bends	2–12 weeks (by design)	Programmed dissolution	[15,16,136]

therefore constitute an explicit first-order design decision in device fabrication workflows.

The operational lifetime of any conformal bioelectronic device is governed by interconnect reliability under repetitive mechanical deformation. For random networks of high-aspect-ratio conductive fillers, sheet conductance obeys the percolation scaling relation $\sigma \propto (\rho - \rho_c)^t$, where ρ_c denotes the critical percolation threshold determined by the filler aspect ratio and t is the universal conductivity exponent (≈ 1.3 in two dimensions). For Ag nanowires (AgNWs) of aspect ratio 50–100, ρ_c corresponds to areal densities of 0.1 – $0.3 \mu\text{g cm}^{-2}$; post-deposition thermal or plasmonic welding reduces inter-wire junction resistance by one to two orders of magnitude. Fatigue under cyclic uniaxial strain proceeds predominantly via junction debonding rather than individual wire fracture: beyond approximately 10^4 cycles at 30% applied strain, the network undergoes topological fragmentation into electrically isolated clusters, and macroscopic conductance decays precipitously once mean cluster connectivity falls below ρ_c . In eutectic gallium–indium (EGaIn) architectures, continuous traces fail when the native Ga_2O_3 skin fractures at regions of high local curvature or at electrode-landing interfaces, enabling metallic gallium to redistribute by capillary-driven thinning. Particulate liquid-metal–elastomer composites additionally exhibit failure by re-oxidation at inter-particle crack surfaces and electromigration-induced voiding under sustained DC bias. Microcracked Au thin films on polydimethylsiloxane (PDMS) substrates fail by fatigue-crack propagation from the initial pre-existing crack network; once mean crack density surpasses approximately one crack per micrometre, sheet resistance increases supra-linearly with continued cycling. Consequently, interconnect reliability must be characterised by cycled-to-failure metrics under physiologically representative strain profiles rather than by monotonic ultimate-strain values, which systematically overestimate chronic-use performance.

The predominant barrier to translating laboratory bioelectronic prototypes into chronic implantable systems is the coupled encapsulation–tissue-interface problem: the device architecture must simultaneously satisfy hermetic moisture exclusion (water-vapour transmission rate, $\text{WVTR} \leq 10^{-5} \text{ g m}^{-2} \text{day}^{-1}$) over inactive regions, ionic permeability at the electrochemical sensing window, and minimisation of the foreign-body response at the tissue–device boundary. In physiological saline, Al_2O_3 barrier degradation proceeds via surface-dominated hydrolytic dissolution rather than Fickian bulk diffusion; interposition of HfO_2 sub-layers within an atomic-layer-deposited (ALD) nanolaminate reduces the effective dissolution rate by approximately one order of magnitude and shifts the predominant failure mechanism from catastrophic monolithic barrier collapse to rate-limited pinhole nucleation at grain-boundary triple junctions [48,49]. Accelerated lifetime estimation requires dual-modality aging: temperature–humidity exposure ($85^\circ\text{C}/85\% \text{ RH}$, Arrhenius-extrapolated) probes bulk barrier integrity, whereas isothermal phosphate-buffered-saline (PBS) immersion at 37°C probes surface dissolution kinetics; neither protocol alone captures the coupled degradation pathway operative *in vivo*. Chronic implant duration data > 90 days, remain limited to cochlear prostheses, deep-brain-stimulation leads and epiretinal arrays. In wearable designs, the dominant failure mode is interfacial delamination at silicone–parylene boundaries under combined thermal and mechanical cycling, mitigated by organosilane coupling agents (e.g., 3-methacryloxypropyltrimethoxysilane). Concurrently, the foreign-body response attenuates transducer sensitivity by 50%–80% within 4–6 weeks for uncoated implants through progressive fibrous encapsulation; zwitterionic polymer brushes and poly(ethylene glycol) antifouling coatings retard macrophage adhesion and fibroblast proliferation, while substrate compliance matching — maintaining Young’s modulus within a factor of three of the target tissue — suppresses micromotion-driven capsule thickening. The reconciliation of hermetic encapsulation with electrochemical accessibility is achieved through spatially patterned architectures: ALD nanolaminates deposited over non-sensing regions, with selectively defined openings exposing hydrogel or track-etched polycarbonate membranes at the transduction interface. Table 3 presents the

Table 4
Regulatory pathways and translational status of each nanomaterial families.

Nanomaterial family	Archetypal product	US FDA pathway	EU CE-MDR class	Sterilisation compatibility	Clinical status	Principal obstacle
Iridium oxide (IrO ₂)	DBS / cochlear implant electrode coating	PMA (Class III)	Class III (implantable)	EtO, gamma, autoclave	Marketed	Adhesion under high current density
Parylene-C	Chronic implant encapsulation	PMA (as component)	Class III (implantable)	EtO, gamma, VHP	Marketed	Delamination from silicone
Silicone / PDMS	Skin-mounted patch, catheter	510(k) or PMA (context)	Class IIa / III	EtO, gamma, autoclave (bulk)	Marketed	Plasticiser leaching
Nanohydroxyapatite (nHAP)	Orthopaedic implant coating	510(k) (Class II)	Class IIb / III	Gamma, autoclave	Marketed	Batch composition variability
Graphene / graphene oxide	Wearable biosensor patch	510(k) or De Novo	Class IIa	Gamma (defects) EtO (residues)	Trial / research	Chronic biocompatibility data
TMDs (MoS ₂ , WSe ₂)	Wearable / implanted biosensor	De Novo	Class IIa-IIb	VHP; gamma partial	Pre-clinical	Air stability, GMP scale-up
PEDOT:PSS	Neural electrode coating; OEET	PMA (as component)	Class III	EtO, gamma (drift), VHP	Trial / limited market	Long-term redox drift
Ag nanowires	Wearable dry electrode / heater	510(k) or De Novo	Class I / IIa	EtO, VHP	Marketed (skin-mounted)	Silver ion leach at electrode landings
EGaIn liquid metal	Stretchable interconnect	De Novo	Class IIa-IIb	EtO, VHP (autoclave: NO)	Trial / research	Ga cytotoxicity, cracking of oxide skin
Cd-based QDs	Bioimaging / thermometry patch	De Novo / PMA	Class IIb / III	VHP	Research	Cd toxicity
Cd-free QDs (InP, CuInS ₂)	Vaccine record-keeping microneedle	De Novo	Class IIa	VHP; gamma partial	Trial	Batch-to-batch fluorescence variance
MXenes	Sweat biosensor patch	De Novo	Class IIa	VHP; EtO partial	Pre-clinical	Oxidation under storage
SiC nanomembrane	Chronic neural interface	PMA	Class III	EtO, gamma, autoclave	Trial	Wafer-scale manufacturing yield
Bioresorbable Si / Mg	Transient bioelectronic implant	De Novo / PMA	Class III	EtO, gamma	Trial	Programmed-degradation reproducibility

WVTR, mechanical compliance, chronic longevity, and dominant degradation pathway for representative encapsulation stacks.

Process refinements address agglomeration and cytotoxicity in terms of atmospheric-pressure spatial ALD which eliminates vacuum constraints via inert-gas curtain separation [193], while biogenic reduction such as Ficus carica-mediated ZrFeO synthesis, 2.0–2.5 nm crystallites coupled with supercritical-fluid purification eliminates cytotoxic reductants and endotoxin contamination [194–196]. Surface engineering with Ni–Co/SiC/MoS₂ multilayer nanocomposites (HV ≈ 632, μ = 0.05) demonstrates the principle of co-patterned hard–soft graded interfaces for chronic durability [197,198]. Clinical translation is rate-limited by sterilisation and material incompatibilities: EtO chemisorption on high-surface-area nanomaterials, γ -induced sp²-lattice defects shifting V_{th} by 50–200 mV, and autoclave-induced Ga₂O₃ fracture at 121 °C. VHP emerges as the low-temperature compromise. Marketed nanomaterials remain limited to IrO_x, Pt, parylene-C, silicone, and nHAP; graphene, TMDs, MXenes, and liquid metals remain preclinical, constrained by insufficient chronic biocompatibility data, GMP batch variability and absence of regulatory predicates. Table 4 maps each material family to its applicable regulatory pathway, sterilisation compatibility, translational status, and rate-limiting obstacle.

Bayesian-optimisation-driven closed-loop autonomous experimentation and ML surrogate models offer the most efficient route to reproducible wafer-scale manufacturing [199]. However, regulatory submissions must report defect-density distributions and B10 reliability metrics rather than best-batch values. Material, process, encapsulation, interface, and regulatory pathway constitute a coupled multi-objective decision space requiring concurrent co-design not sequential optimisation to advance nanomaterial-enabled bioelectronics from proof-of-concept to chronic clinical deployment.

6. Conclusion

The progress in wearable and implantable bioelectronics has been less enabled by peak device-level performance but by co-optimisation of material systems, process windows and packaging architectures with the capability to maintain stability under coupled mechanical, electrochemical, and thermal stresses. Nanoscale and two-dimensional semiconductors are contributing to the design space for low-power transduction but impose stringent requirements on defect density, contact resistance, and encapsulation-induced strain after transfer to elastomeric substrates. Percolating nanowire networks and liquid-metal interconnects partially decouple electrical conductivity from bulk strain. However, these nanomaterial-based systems introduce conductance fluctuations near the percolation threshold, as well as oxidation- and electromigration-driven failure modes that must be addressed at the system level. From sensing perspective, the key *in vivo* limitations are interfacial such as ionic double-layer dynamics, biofouling and impedance drift in sweat, interstitial fluid and cerebrospinal environments. Consequently, microfabrication processes need to be co-designed with bio-interface chemistry, with surface-functionalisation layers, antifouling coating, and permselective membranes integrated and co-patterned with transducers than introduced post-hoc. Emerging additive and hybrid manufacturing methods improve areal throughput and enable multi-material integration on non-planar substrates; however, variability in nanoparticle sintering, residual solvent content, and adhesion to soft substrates increases threshold-voltage variation and sensor sensitivity, thereby complicating calibration and regulatory qualification.

Bridging laboratory demonstrations and clinical deployment require standardised accelerated-aging protocols under physiologically relevant biofluid conditions, validated multi-physics reliability models and design rules that explicitly balance hermeticity against analyte transport. In addition, with rigorous manufacturing controls and authenticated cyber-physical update pathways, these advances would enable

nanoelectronics-enabled wearable and implantable systems to support longitudinal, closed-loop physiological monitoring and therapy with target-specific performance comparable to wafer-scale CMOS, while satisfying the mechanical compliance and biocompatibility requirements imposed by the human body.

CRediT authorship contribution statement

Mazen Muhammad: Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ahmed Yinusa:** Methodology, Writing – review & editing. **George Oguntala:** Writing – review & editing, Visualization, Supervision, Project administration, Conceptualization.

Funding

Not applicable.

Declaration of Generative AI and AI-Assisted technologies in the writing process

Not applicable.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] C. Jia, Z. Lin, Y. Huang, X. Duan, Nanowire electronics: from nanoscale to macroscale, *Chem. Rev.* 119 (15) (2019) 9074–9135, <https://doi.org/10.1021/acs.chemrev.9b00164>.
- [2] D. Zhong, et al., High-speed and large-scale intrinsically stretchable integrated circuits, *Nature* 627 (8003) (2024) 313–320, <https://doi.org/10.1038/s41586-024-07096-7>.
- [3] M. Yang, Z. Ye, Y. Ren, M. Farhat, and P.-Y. Chen, Recent Advances in Nanomaterials Used for Wearable Electronics, *Micromachines*, vol. 14, no. 3, p. 603doi: 10.3390/mi14030603.
- [4] R. Wei, H. Li, Z. Chen, Q. Hua, G. Shen, K. Jiang, Revolutionizing wearable technology: advanced fabrication techniques for body-conformable electronics, *npj Flex. Electron.* 8 (1) (2024) 83, <https://doi.org/10.1038/s41528-024-00370-8>.
- [5] K. Kang, Y. Cho, and K.J. Yu, Novel Nano-Materials and Nano-Fabrication Techniques for Flexible Electronic Systems, *Micromachines*, vol. 9, no. 6, p. 263doi: 10.3390/mi9060263.
- [6] B. Reeder, A. David, Health at hand: A systematic review of smart watch uses for health and wellness, 10/01/ 2016, *J. Biomed. Inform.* 63 (2016) 269–276, <https://doi.org/10.1016/j.jbi.2016.09.001>.
- [7] T.C. Lu, C.M. Fu, M.H. Ma, C.C. Fang, A.M. Turner, Healthcare Applications of Smart Watches. A Systematic Review (in eng), *Appl. Clin. Inform.* 7 (3) (Sep 14 2016) 850–869, <https://doi.org/10.4338/aci-2016-03-r-0042>.
- [8] P.A. Rauschnabel, Y.K. Ro, Augmented reality smart glasses: an investigation of technology acceptance drivers, *Int. J. Technol. Mark.* 11 (2) (2016) 123–148, <https://doi.org/10.1504/IJTMKT.2016.075690>.
- [9] H. Kim, Y.-T. Kwon, H.-R. Lim, J.-H. Kim, Y.-S. Kim, W.-H. Yeo, Recent Advances in Wearable Sensors and Integrated Functional Devices for Virtual and Augmented Reality Applications, *Adv. Funct. Mater.* 31 (39) (2021) 2005692, <https://doi.org/10.1002/adfm.202005692>.
- [10] X. Yu, et al., Skin-integrated wireless haptic interfaces for virtual and augmented reality, *Nature* 575 (7783) (2019) 473–479, <https://doi.org/10.1038/s41586-019-1687-0>.
- [11] K. Kaewkannate, S. Kim, A comparison of wearable fitness devices, *BMC Public. Health* 16 (1) (2016) 433, <https://doi.org/10.1186/s12889-016-3059-0>.
- [12] J. Xie, D. Wen, L. Liang, Y. Jia, L. Gao, J. Lei, Evaluating the Validity of Current Mainstream Wearable Devices in Fitness Tracking Under Various Physical Activities: Comparative Study, *JMIR Mhealth Uhealth* 6 (4) (2018) e94, <https://doi.org/10.2196/mhealth.9754>.
- [13] L. Wang, et al., Application Challenges in Fiber and Textile Electronics (in eng), *Adv. Mater.* 32 (5) (Feb 2020) e1901971, <https://doi.org/10.1002/adma.201901971>.
- [14] N. Karim, S. Afroz, S. Tan, K.S. Novoselov, S.G. Yeates, All Inkjet-Printed Graphene-Silver Composite Ink on Textiles for Highly Conductive Wearable Electronics Applications, *Sci. Rep.* 9 (1) (2019) 8035, <https://doi.org/10.1038/s41598-019-44420-y>.
- [15] Z. Ma, X. Xiang, L. Shao, Y. Zhang, J. Gu, Multifunctional Wearable Silver Nanowire Decorated Leather Nanocomposites for Joule Heating, Electromagnetic Interference Shielding and Piezoresistive Sensing, *Angew. Chem. Int. Ed.* 61 (15) (2022) e202200705, <https://doi.org/10.1002/anie.202200705>.
- [16] M. Sang, et al., Ultrahigh Sensitive Au-Doped Silicon Nanomembrane Based Wearable Sensor Arrays for Continuous Skin Temperature Monitoring with High Precision, *Adv. Mater.* 34 (4) (2022) 2105865, <https://doi.org/10.1002/adma.202105865>.
- [17] S. Shajari, M. Mahmoodi, M. Rajabian, K. Karan, U. Sundararaj, L.J. Sudak, Highly Sensitive and Stretchable Carbon Nanotube/Fluoroelastomer Nanocomposite with a Double-Percolated Network for Wearable Electronics, *Adv. Electron. Mater.* 6 (2) (2020) 1901067, <https://doi.org/10.1002/aeml.201901067>.
- [18] X. Liang, et al., Stable and Biocompatible Carbon Nanotube Ink Mediated by Silk Protein for Printed Electronics, *Adv. Mater.* 32 (31) (2020) 2000165, <https://doi.org/10.1002/adma.202000165>.
- [19] Y. Yu, J. Guo, B. Ma, D. Zhang, Y. Zhao, Liquid metal-integrated ultra-elastic conductive microfibers from microfluidics for wearable electronics, *Sci. Bull.* 65 (20) (2020) 1752–1759, <https://doi.org/10.1016/j.scib.2020.06.002>.
- [20] P. Won, S. Jeong, C. Majidi, S.H. Ko, Recent advances in liquid-metal-based wearable electronics and materials, *iScience* 24 (7) (2021) 102698, <https://doi.org/10.1016/j.isci.2021.102698>.
- [21] W. Gao, et al., Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis, *Nature* 529 (7587) (2016) 509–514, <https://doi.org/10.1038/nature16521>.
- [22] M. Haghi, K. Thurow, R. Stoll, Wearable Devices in Medical Internet of Things: Scientific Research and Commercially Available Devices (in eng), *Healthc. Inform. Res.* 23 (1) (Jan 2017) 4–15, <https://doi.org/10.4258/hir.2017.23.1.4>.
- [23] S. Seneviratne, et al., A Survey of Wearable Devices and Challenges, *IEEE Commun. Surv. & Tutor.* 19 (4) (2017) 2573–2620, <https://doi.org/10.1109/COMST.2017.2731979>.
- [24] J. Xie, Q. Chen, H. Shen, G. Li, Wearable graphene devices for sensing, *J. Electrochem. Soc.* 167 (3) (2020) 037541.
- [25] S.M.A. Iqbal, I. Mahgoub, E. Du, M.A. Leavitt, W. Asghar, Advances in healthcare wearable devices, *npj Flex. Electron.* 5 (1) (2021) 9, <https://doi.org/10.1038/s41528-021-00107-x>.
- [26] X. Chen, D.-H. Kim, N. Lu, Introduction: Wearable Devices, *Chem. Rev.* 124 (10) (2024) 6145–6147, <https://doi.org/10.1021/acs.chemrev.4c00271>.
- [27] M. Tan, et al., Recent Advances in Intelligent Wearable Medical Devices Integrating Biosensing and Drug Delivery, *Adv. Mater.* 34 (27) (2022) 2108491, <https://doi.org/10.1002/adma.202108491>.
- [28] M. Contini, et al., Validation of a new wearable device for type 3 sleep test without flowmeter (in eng), *PLoS. One* 16 (4) (2021) e0249470, <https://doi.org/10.1371/journal.pone.0249470>.
- [29] N. Anzar et al., Wearable Electrochemical Glove-Based Analytical Device (eGAD) for the Detection of Methamphetamine Employing Silver Nanoparticles, *Biosensors*, vol. 13, no. 10, p. 934doi: 10.3390/bios13100934.
- [30] A. Abdelrazik et al., Wearable Devices for Arrhythmia Detection: Advancements and Clinical Implications, *Sensors*, vol. 25, no. 9, p. 2848doi: 10.3390/s25092848.
- [31] J. Stehlik, et al., Continuous Wearable Monitoring Analytics Predict Heart Failure Hospitalization: The LINK-HF Multicenter Study (in eng), *Circ. Heart Fail.* 13 (3) (Mar 2020) e006513, <https://doi.org/10.1161/circheartfailure.119.006513>.
- [32] H. Cos, et al., Predicting Outcomes in Patients Undergoing Pancreatectomy Using Wearable Technology and Machine Learning: Prospective Cohort Study (in eng), *J. Med. Internet Res.* 23 (3) (Mar 18 2021) e23595, <https://doi.org/10.2196/23595>.
- [33] B.D. Nelson, S.S. Kariptott, Y. Wang, and K.G. Ong, Wireless Technologies for Implantable Devices, *Sensors*, vol. 20, no. 16, p. 4604doi: 10.3390/s20164604.
- [34] A. Zebda, et al., Challenges for successful implantation of biofuel cells, *Bioelectrochemistry* 124 (2018) 57–72, <https://doi.org/10.1016/j.bioelechem.2018.05.011>.
- [35] P. Bollella, I. Lee, D. Blaauw, E. Katz, A Microelectronic Sensor Device Powered by a Small Implantable Biofuel Cell, *ChemPhysChem* 21 (1) (2020) 120–128, <https://doi.org/10.1002/cphc.201900700>.
- [36] R. Singh, M.J. Bathaei, E. Istif, L. Beker, A Review of Bioresorbable Implantable Medical Devices: Materials, Fabrication, and Implementation, *Adv. Healthc. Mater.* 9 (18) (2020) 2000790, <https://doi.org/10.1002/adhm.202000790>.
- [37] E. Magill, et al., Solid implantable devices for sustained drug delivery, *Adv. Drug. Deliv. Rev.* 199 (2023) 114950, <https://doi.org/10.1016/j.addr.2023.114950>.
- [38] S. Oh, et al., Liquid Metals for Reconfigurable Bioelectronics, *Adv. Mater.* 38 (38) (2026) e21174, <https://doi.org/10.1002/adma.202521174>.
- [39] N.S. Rupanti, et al., Advances in Wearable Technology: MXene-Based Multifunctional and Biomedical Smart Textiles, *ACS Omega* 11 (1) (2025) 197–228, <https://doi.org/10.1021/acsomega.5c08488>.
- [40] H. Yuk, B. Lu, X. Zhao, Hydrogel bioelectronics, *Chem. Soc. Rev.* 48 (6) (2019) 1642–1667, <https://doi.org/10.1039/c8cs00595h>.
- [41] T.A. Saleh, Nanomaterials: Classification, properties, and environmental toxicities, 11/01/ 2020, *Environ. Technol. & Innov.* 20 (2020) 101067, <https://doi.org/10.1016/j.eti.2020.101067>.
- [42] M. Pirzada and Z. Altintas, Nanomaterials for Healthcare Biosensing Applications, *Sensors*, vol. 19, no. 23, p. 5311doi: 10.3390/s19235311.
- [43] H. Gleiter, Nanostructured materials: basic concepts and microstructure, *Acta Mater.* 48 (1) (2000) 1–29, [https://doi.org/10.1016/S1359-6454\(99\)00285-2](https://doi.org/10.1016/S1359-6454(99)00285-2).

- [44] J. Tang, et al., Low power flexible monolayer MoS₂ integrated circuits, *Nat. Commun.* 14 (1) (2023) 3633, <https://doi.org/10.1038/s41467-023-39390-9>.
- [45] I.M. Datye, A. Daus, R.W. Grady, K. Brenner, S. Vaziri, E. Pop, Strain-Enhanced Mobility of Monolayer MoS₂, *Nano Lett.* 22 (20) (2022) 8052–8059, <https://doi.org/10.1021/acs.nanolett.2c01707>.
- [46] J. Meyer, et al., Al₂O₃/ZrO₂ Nanolaminates as Ultrahigh Gas-Diffusion Barriers—A Strategy for Reliable Encapsulation of Organic Electronics, *Adv. Mater.* 21 (18) (2009) 1845–1849, <https://doi.org/10.1002/adma.200803440>.
- [47] H. Kim, A.K. Singh, C.Y. Wang, C. Fuentes-Hernandez, B. Kippelen, S. Graham, Experimental investigation of defect-assisted and intrinsic water vapor permeation through ultrabARRIER films (in eng), *Rev. Sci. Instrum.* 87 (3) (Mar 2016) 033902, <https://doi.org/10.1063/1.4942510>.
- [48] D. Khodagholy, et al., In vivo recordings of brain activity using organic transistors, *Nat. Commun.* 4 (1) (2013) 1575, <https://doi.org/10.1038/ncomms2573>.
- [49] M.J. Donahue, et al., Tailoring PEDOT properties for applications in bioelectronics, *Mater. Sci. Eng. R Rep.* 140 (2020) 100546, <https://doi.org/10.1016/j.mser.2020.100546>.
- [50] J. Rivnay, S. Inal, A. Salleo, R.M. Owens, M. Berggren, G.G. Malliaras, Organic electrochemical transistors, *Nat. Rev. Mater.* 3 (2) (2018) 17086, <https://doi.org/10.1038/natrevmats.2017.86>.
- [51] J.H. Lim, M.J. Kim, H.G. Yoon, S.W. Kim, Highly sensitive and long-term stretchable eutectic nanogel conductor with conducting interpenetrating nanogel networks for monitoring human motions, *Compos. Part B Eng.* 247 (2022) 110299, <https://doi.org/10.1016/j.compositesb.2022.110299>.
- [52] X. Xie, et al., Long-term reliability of Al₂O₃ and Parylene C bilayer encapsulated Utah electrode array based neural interfaces for chronic implantation (in eng), *J. Neural Eng.* 11 (2) (Apr 2014) 026016, <https://doi.org/10.1088/1741-2560/11/2/026016>.
- [53] K.E. Laliberte, P. Scott, N.I. Khan, M.S. Mahmud, E. Song, A wearable graphene transistor-based biosensor for monitoring IL-6 biomarker, *Microelectron. Eng.* 262 (2022) 111835, <https://doi.org/10.1016/j.mee.2022.111835>.
- [54] M. Rizwan, A. Shoukat, A. Ayub, B. Razaq, M.B. Tahir, Chapter 3 - Types and classification of nanomaterials, in: M.B. Tahir, M. Sagir, A.M. Asiri (Eds.), *Nanomaterials: Synthesis, Characterization, Hazards and Safety*, Elsevier, 2021, pp. 31–54.
- [55] P.V. Nagime, V.S. Chandak, A comprehensive review of nanomaterials synthesis: Physical, chemical, and biological approaches and emerging challenges, *Biocatal. Agric. Biotechnol.* 62 (2024) 103458, <https://doi.org/10.1016/j.bcab.2024.103458>.
- [56] M. Sajid, Nanomaterials: types, properties, recent advances, and toxicity concerns, *Curr. Opin. Environ. Sci. Health* 25 (2022) 100319, <https://doi.org/10.1016/j.coesh.2021.100319>.
- [57] A. Géczy, C. Farkas, R. Kovács, D. Froš, P. Veselý, A. Bonyár, Biodegradable and Nanocomposite Materials as Printed Circuit Substrates: A Mini-Review, *IEEE Open. J. Nanotechnol.* 3 (2022) 182–190, <https://doi.org/10.1109/OJNANO.2022.3221273>.
- [58] J. Hu, M. Dong, Recent advances in two-dimensional nanomaterials for sustainable wearable electronic devices, *J. Nanobiotechnol.* 22 (1) (2024) 63.
- [59] S. Choi, S.I. Han, D. Kim, T. Hyeon, D.-H. Kim, High-performance stretchable conductive nanocomposites: materials, processes, and device applications, *Chem. Soc. Rev.* 48 (6) (2019) 1566–1595, <https://doi.org/10.1039/c8cs00706c>.
- [60] Q. Wang, Q. Liu, G. Zhong, T. Xu, X. Zhang, Wearable Vertical Graphene-Based Microneedle Biosensor for Real-Time Ketogenic Diet Management, *Anal. Chem.* 96 (21) (2024) 8713–8720, <https://doi.org/10.1021/acs.analchem.4c00960>.
- [61] N.P. Shetti, A. Mishra, S. Basu, T.M. Aminabhavi, Versatile fullerenes as sensor materials, *Mater. Today Chem.* 20 (2021) 100454.
- [62] P. Bhakta, B. Barthunia, Fullerene and its applications: A review, *J. Indian. Acad. Oral. Med. Radiol.* 32 (2) (2020) 159–163.
- [63] C. Pesado-Gómez, et al., Fullerenes: historical background, novel biological activities versus possible health risks, *Coord. Chem. Rev.* 501 (2024) 215550.
- [64] X. Chang, Y. Xu, M. von Delius, Recent advances in supramolecular fullerene chemistry, *Chem. Soc. Rev.* 53 (1) (2024) 47–83, <https://doi.org/10.1039/d2cs00937d>.
- [65] J. Zhang, et al., Flexible textile ion sensors based on reduced graphene oxide/fullerene and their potential applications of sweat characterization, *Cellulose* 28 (5) (2021) 3123–3133, <https://doi.org/10.1007/s10570-021-03730-z>.
- [66] B. Huwaimel, S. Alqarni, Design of C₂₄ fullerene-based sensors for gamma-butyrolactone detection as advanced tools for biomedical and pharmaceutical applications, *Sci. Rep.* 15 (1) (2025) 13799.
- [67] N. Gupta, S.M. Gupta, S. Sharma, Carbon nanotubes: synthesis, properties and engineering applications, *Carbon Lett.* 29 (5) (2019) 419–447.
- [68] M.N. Norizan, et al., Carbon nanotubes: Functionalisation and their application in chemical sensors, *RSC Adv.* 10 (71) (2020) 43704–43732.
- [69] S. Parameshwar, et al., A green and sustainable biodiesel production from *Chlorella vulgaris* microalgae using functionalized carbon nanotube heterogeneous catalysts derived from rice husk and mixed fruit waste, *Green. Technol. Sustain.* (2026) 100392.
- [70] M.A. Castro-Rojas, Y.I. Vega-Cantu, G.A. Cordell, A. Rodriguez-Garcia, Dental applications of carbon nanotubes, *Molecules* 26 (15) (2021) 4423.
- [71] X. Hu, et al., A super-stretchable and highly sensitive carbon nanotube capacitive strain sensor for wearable applications and soft robotics, *Adv. Mater. Technol.* 7 (3) (2022) 2100769.
- [72] H. Li, et al., High-performance polyaniline-coated carbon nanotube yarns for wearable thermoelectric generators, *ACS Appl. Mater. Interfaces* 16 (14) (2024) 17598–17606.
- [73] L.C. Bowden, et al., Carbon-infiltrated carbon nanotubes inhibit the development of *Staphylococcus aureus* biofilms, *Sci. Rep.* 13 (1) (2023) 19398, <https://doi.org/10.1038/s41598-023-46748-y>.
- [74] T.-C. Ho, et al., Hydrogels: properties and applications in biomedicine, *Molecules* 27 (9) (2022) 2902.
- [75] D. Yang, Recent advances in hydrogels, *ed ACS Publ.* 34 (2022) 1987–1989.
- [76] Y.S. Zhang, A. Khademhosseini, Advances in engineering hydrogels, *p. eaf3627*, *Science* 356 (6337) (2017) p. eaf3627.
- [77] S. Correa, et al., Translational applications of hydrogels, *Chem. Rev.* 121 (18) (2021) 11385–11457.
- [78] M.H. Ayoubi-Joshaghani, et al., Potential applications of advanced nano/hydrogels in biomedicine: static, dynamic, multi-stage, and bioinspired, *Adv. Funct. Mater.* 30 (45) (2020) 2004098.
- [79] C. Zheng, M. Ju, X. Zhang, K. Xie, A. Hou, A. Gao, A multi-stimulus responsive nanogel actuator with the π - π stacking interaction self-assembly and application for bioinspired smart skin with light, heat and humidity responses and superb UV resistance, *Chem. Eng. J.* 499 (2024) 156092.
- [80] M. Zhao, H. Zhou, Z. Lai, Y. Cui, C. Wang, Tumor microenvironment-triggered H₂O₂ self-powered theranostic nanogels for magnetic resonance imaging and chemodynamic/gas synergistic therapy, *Mater. Today Chem.* 52 (2026) 103435.
- [81] B.H. Alshammari, et al., Organic and inorganic nanomaterials: fabrication, properties and applications, *RSC Adv.* 13 (20) (2023) 13735–13785.
- [82] J. Mussin, G. Giusiano, Biogenic silver nanoparticles as antifungal agents, *Front. Chem.* 10 (2022) 1023542.
- [83] R. Dhir, et al., Plant-mediated synthesis of silver nanoparticles: unlocking their pharmacological potential—a comprehensive review, *Front. Bioeng. Biotechnol.* 11 (2024) 1324805.
- [84] J. Liang, et al., A shellfish-inspired bionic microstructure design for biological implants: Enhancing protection of antibacterial silver-loaded coatings and promoting osseointegration, *J. Mech. Behav. Biomed. Mater.* 167 (2025) 106963.
- [85] M.S. Waghmode, A.B. Gunjal, J.A. Mulla, N.N. Patil, N.N. Nawani, Studies on the titanium dioxide nanoparticles: biosynthesis, applications and remediation, *SN Appl. Sci.* 1 (4) (2019) 310, <https://doi.org/10.1007/s42452-019-0337-3>.
- [86] C. Pushpalatha, et al., Nanohydroxyapatite in dentistry: A comprehensive review, *Saudi Dent. J.* 35 (6) (2023) 741–752, <https://doi.org/10.1016/j.sdentj.2023.05.018>.
- [87] R. Ajib, K. Shanmugaraj, R.M. Yadav, T.P. Brito, D.P. Singh, Metallic nanoparticles: from biosynthesis to biomedical applications, current scenarios and prospects, *Nanoscale Adv.* 8 (8) (2026) 2482–2511, <https://doi.org/10.1039/d4na01054>.
- [88] H. Duman, F. Eker, E. Akdaşçı, A.M. Witkowska, M. Bechelany, S. Karav, Silver nanoparticles: A comprehensive review of synthesis methods and chemical and physical properties, *Nanomaterials* 14 (18) (2024) 1527.
- [89] A. Sivan Pillai, A. Chandran, S. Kuzhichalil Peethambharan, Silver nanoparticle-decorated multiwalled carbon nanotube ink for advanced wearable devices, *ACS Appl. Mater. Interfaces* 14 (41) (2022) 46775–46788.
- [90] M. Janik, K. Khachatryan, G. Khachatryan, M. Krystjan, Z. Oszczęda, Comparison of physicochemical properties of silver and gold nanocomposites based on potato starch in distilled and cold plasma-treated water, *Int. J. Mol. Sci.* 24 (3) (2023) 2200.
- [91] X. Bai, et al., The basic properties of gold nanoparticles and their applications in tumor diagnosis and treatment, *Int. J. Mol. Sci.* 21 (7) (2020) 2480.
- [92] G. Pasparakis, Recent developments in the use of gold and silver nanoparticles in biomedicine, *Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol.* 14 (5) (2022) e1817.
- [93] H. Ye, et al., Patterned gold nanoparticle superlattice film for wearable sweat sensors, *Nano Lett.* 24 (35) (2024) 11082–11089.
- [94] P. Faghani-Eskandarkolaei, H. Heli, N. Akbari, O. Koohi-Hosseinabadi, F.S. Aslani, N. Sattarhamady, Antibacterial and anti-biofilm activities of gold-curcumin nanohybrids and its polydopamine form upon phototherapy of *Staphylococcus aureus* infected implants: In vitro and animal model studies, *Int. J. Biol. Macromol.* 282 (2024) 137430.
- [95] M.P. Nikolova, M.S. Chavali, Metal oxide nanoparticles as biomedical materials, *Biomimetics* 5 (2) (2020) 27.
- [96] S.C. Baral, P. Maneesha, S. Sen, S. Sen, S. Sen, An introduction to metal oxides, *Optical Properties of Metal Oxide Nanostructures*, Springer, 2023, pp. 1–34.
- [97] M. Khalil, B.M. Jan, C.W. Tong, M.A. Berawi, Advanced nanomaterials in oil and gas industry: Design, application and challenges, *Appl. Energy* 191 (2017) 287–310.
- [98] M. Mhadhbi, H. Abderazzak, B. Avar, Synthesis and properties of titanium dioxide nanoparticles, *Updates Titan. Dioxide* (2023).
- [99] R. Javed, N. ul Ain, A. Gul, et al., Diverse biotechnological applications of multifunctional titanium dioxide nanoparticles: an up-to-date review, *IET Nanobiotechnol.* 16 (5) (2022) 171–189, <https://doi.org/10.1049/nbt.2.12085>.
- [100] L. Yang, et al., Highly accurate fabric piezoresistive sensor with anti-interference from both high humidity and sweat based on hydrophobic non-fluoride titanium dioxide nanoparticles, *J. Mater. Chem. C* 9 (15) (2021) 5217–5226, <https://doi.org/10.1039/d0tc05881e>.
- [101] Y. Zhang, et al., Nanoflower-like titanium dioxide modified ethyl cellulose-based QCM humidity sensor with low-hysteresis for wearable respiratory monitoring, */11/15/ 2025, Sens. Actuators B Chem.* 443 (2025) 138286, <https://doi.org/10.1016/j.snb.2025.138286>.
- [102] M. Rothpan et al., Titanium-Dioxide-Nanoparticle-Embedded Polyelectrolyte Multilayer as an Osteoconductive and Antimicrobial Surface Coating, *Materials*, vol. 16, no. 21, p. 7026doi: 10.3390/ma16217026.

- [103] Y. Chen, et al., Multifunctionally disordered TiO₂ nanoneedles prevent peri-prosthetic infection and enhance osteointegration by killing bacteria and modulating the osteoimmune microenvironment (in eng), *Theranostics* 14 (15) (2024) 6016–6035, <https://doi.org/10.7150/tno.98219>.
- [104] B. Mekuye, B. Abera, *Nanomaterials: An overview of synthesis, classification, characterization, and applications*, *Nano Sel.* 4 (8) (2023) 486–501, <https://doi.org/10.1002/nano.202300038>.
- [105] T. Foster, et al., Exploring delivery systems for targeted nanotechnology-based gene therapy in the inner ear, *Ther. Deliv.* 15 (10) (2024) 801–818, <https://doi.org/10.1080/20415990.2024.2389032>.
- [106] W.H.-Y. Clarissa, C.H. Chia, S. Zakaria, Y.C.-Y. Eryan, Recent advancement in 3-D printing: nanocomposites with added functionality, *Progress. Addit. Manuf.* 7 (2) (2022) 325–350, <https://doi.org/10.1007/s40964-021-00232-z>.
- [107] M.Z. Nizami, V.W. Xu, I.X. Yin, C.Y. Lung, J.Y. Niu, and C.H. Chu, Ceramic Nanomaterials in Caries Prevention: A Narrative Review, *Nanomaterials*, vol. 12, no. 24, p. 4416doi: 10.3390/nano12244416.
- [108] A. Anil, W.I. Ibraheem, A.A. Meshni, R.S. Preethanath, and S. Anil, Nano-Hydroxyapatite (nHAp) in the Remineralization of Early Dental Caries: A Scoping Review, *International Journal of Environmental Research and Public Health*, vol. 19, no. 9, p. 5629doi: 10.3390/ijerph19095629.
- [109] S. Lara-Ochoa, W. Ortega-Lara, and C.E. Guerrero-Beltrán, Hydroxyapatite Nanoparticles in Drug Delivery: Physicochemistry and Applications, *Pharmaceutics*, vol. 13, no. 10, p. 1642doi: 10.3390/pharmaceutics13101642.
- [110] A.M. Rheima, et al., Nano bioceramics: Properties, applications, hydroxyapatite, nanohydroxyapatite and drug delivery, *Case Stud. Chem. Environ. Eng.* 10 (2024) 100869, <https://doi.org/10.1016/j.csee.2024.100869>.
- [111] S.-C. Wu, H.-C. Hsu, W.-H. Wu, and W.-F. Ho, Enhancing Bioactivity and Mechanical Properties of Nano-Hydroxyapatite Derived from Oyster Shells through Hydrothermal Synthesis, *Nanomaterials*, vol. 14, no. 15, p. 1281doi: 10.3390/nano14151281.
- [112] R.-L. Yang, Y.-J. Zhu, F.-F. Chen, D.-D. Qin, Z.-C. Xiong, Bioinspired Macroscopic Ribbon Fibers with a Nacre-Mimetic Architecture Based on Highly Ordered Alignment of Ultralong Hydroxyapatite Nanowires, *ACS Nano* 12 (12) (2018) 12284–12295, <https://doi.org/10.1021/acsnano.8b06096>.
- [113] S. Liu, W. Tong, C. Gao, X. Wang, Y. Liu, Y. Zhang, Hygroscopic paper enhanced using hydroxyapatite coating for wearable TENG sensors, *Chem. Eng. J.* 493 (2024) 152597, <https://doi.org/10.1016/j.cej.2024.152597>.
- [114] S. Targonska, et al., New way to obtain the poly(L-lactide-co-D,L-lactide) blend filled with nanohydroxyapatite as biomaterial for 3D-printed bone-reconstruction implants, *Eur. Polym. J.* 165 (2022) 110997, <https://doi.org/10.1016/j.eurpolymj.2022.110997>.
- [115] R. Watanabe, et al., Novel nano-hydroxyapatite coating of additively manufactured three-dimensional porous implants improves bone ingrowth and initial fixation, *J. Biomed. Mater. Res. Part B Appl. Biomater.* 111 (2) (2023) 453–462, <https://doi.org/10.1002/jbm.b.35165>.
- [116] K. Daviau and K.K.M. Lee, High-Pressure, High-Temperature Behavior of Silicon Carbide: A Review, *Crystals*, vol. 8, no. 5, p. 217doi: 10.3390/cryst8050217.
- [117] Y. Katoh, L.L. Snead, Silicon carbide and its composites for nuclear applications – Historical overview, *J. Nucl. Mater.* 526 (2019) 151849, <https://doi.org/10.1016/j.jnucmat.2019.151849>.
- [118] S. Castelletto, A. Boretto, Silicon carbide color centers for quantum applications, *J. Phys. Photonics* 2 (2) (2020) 022001, <https://doi.org/10.1088/2515-7647/ab77a2>.
- [119] L.M. Soltys, I.F. Mironyuk, I.M. Mykityn, I.D. Hnylytsia, L.V. Turovska, Synthesis and Properties of Silicon Carbide (Review), *Phys. Chem. Solid. State* 24 (1) (2023) 5–16, <https://doi.org/10.15330/pcss.24.1.5-16>.
- [120] M. Lu, et al., Transferable 3C-SiC nanowire network film for high performance flexible UV photodetectors with a simple, low cost and large scale production, *Sens. Actuators A Phys.* 363 (2023) 114741, <https://doi.org/10.1016/j.sna.2023.114741>.
- [121] A. Khecho, E.B. Joyee, Direct Writing of SiC-polymer nanocomposites for humidity sensing with enhanced performance, *Ceram. Int.* 50 (23) (2024) 50427–50435, <https://doi.org/10.1016/j.ceramint.2024.09.388>.
- [122] H.-P. Phan, et al., Long-Lived, Transferred Crystalline Silicon Carbide Nanomembranes for Implantable Flexible Electronics, *ACS Nano* 13 (10) (2019) 11572–11581, <https://doi.org/10.1021/acsnano.9b05168>.
- [123] M.A. Huynh, et al., Wafer-Level Fabrication of Flexible Silicon Carbide Bioelectronics for Electrical Stimulation, *ACS Appl. Electron. Mater.* 7 (18) (2025) 8364–8376, <https://doi.org/10.1021/acsaem.5c00951>.
- [124] M. Moetasam Zorab, N. Mohammadjani, M. Ashengroph, M. Alavi, Biosynthesis of Quantum Dots and Their Therapeutic Applications in the Diagnosis and Treatment of Cancer and SARS-CoV-2 (in eng), *Adv. Pharm. Bull.* 13 (3) (Jul 2023) 411–422, <https://doi.org/10.34172/apb.2023.065>.
- [125] M.A. Mimona, et al., Quantum dot nanomaterials: Empowering advances in optoelectronic devices, *Chem. Eng. J. Adv.* 21 (2025) 100704, <https://doi.org/10.1016/j.cej.2025.100704>.
- [126] M. Alizadeh-Ghods, M. Pourhassan-Moghaddam, A. Zavari-Nematabad, B. Walker, N. Annabi, A. Akbarzadeh, State-of-the-Art and Trends in Synthesis, Properties, and Application of Quantum Dots-Based Nanomaterials, *Part. Part. Syst. Charact.* 36 (2) (2019) 1800302, <https://doi.org/10.1002/ppsc.201800302>.
- [127] A.M. Wagner, J.M. Knipe, G. Orive, N.A. Peppas, Quantum dots in biomedical applications, *Acta Biomater.* 94 (2019) 44–63, <https://doi.org/10.1016/j.actbio.2019.05.022>.
- [128] K. Agarwal, H. Rai, S. Mondal, Quantum dots: an overview of synthesis, properties, and applications, *Mater. Res. Express* 10 (6) (2023) 062001, <https://doi.org/10.1088/2053-1591/acda17>.
- [129] C. Zhu et al., High-Luminescence Electrospun Polymeric Microfibers In Situ Embedded with CdSe Quantum Dots with Excellent Environmental Stability for Heat and Humidity Wearable Sensors, *Nanomaterials*, vol. 12, no. 13, p. 2288doi: 10.3390/nano12132288.
- [130] A. Kishore, A.M. Varughese, B. Roth, C. Zeilinger, Functionalized Quantum Dot-Based Portable Sensor for Dual Detection of Stress Biomarkers in Blood Serum and Saliva, *J. Biophotonics* 19 (4) (2026) e70268, <https://doi.org/10.1002/jbio.70268>.
- [131] K.J. McHugh, et al., Biocompatible near-infrared quantum dots delivered to the skin by microneedle patches record vaccination, *Sci. Transl. Med.* 11 (523) (2019) eaay7162, <https://doi.org/10.1126/scitranslmed.aay7162>.
- [132] A. VahidMohammadi, J. Rosen, Y. Gogotsi, The world of two-dimensional carbides and nitrides (MXenes), *Science* 372 (6547) (2021) eabf1581, <https://doi.org/10.1126/science.abf1581>.
- [133] Y. Lei, et al., A MXene-Based Wearable Biosensor System for High-Performance In Vitro Perspiration Analysis, *Small* 15 (19) (2019) 1901190, <https://doi.org/10.1002/sml.201901190>.
- [134] J. Hu, A. Stein, P. Bühlmann, Rational design of all-solid-state ion-selective electrodes and reference electrodes, *TrAC. Trends Anal. Chem.* 76 (2016) 102–114, <https://doi.org/10.1016/j.trac.2015.11.004>.
- [135] M. Parrilla, M. Cuartero, G.A. Crespo, Wearable potentiometric ion sensors, *TrAC. Trends Anal. Chem.* 110 (2019) 303–320, <https://doi.org/10.1016/j.trac.2018.11.024>.
- [136] C. Jiang, G. Wang, R. Hein, N. Liu, X. Luo, J.J. Davis, Antifouling Strategies for Selective In Vitro and In Vivo Sensing, *Chem. Rev.* 120 (8) (2020) 3852–3889, <https://doi.org/10.1021/acs.chemrev.9b00739>.
- [137] A.J. Bhandolkar et al., Battery-free, skin-interfaced microfluidic/electronic systems for simultaneous electrochemical, colorimetric, and volumetric analysis of sweat, *Science Advances*, vol. 5, no. 1, p. eaav3294, doi: 10.1126/sciadv.aav3294.
- [138] Y. Khan et al., Classification, Synthetic, and Characterization Approaches to Nanoparticles, and Their Applications in Various Fields of Nanotechnology: A Review, *Catalysts*, vol. 12, no. 11, p. 1386doi: 10.3390/catal12111386.
- [139] N. Ali, et al., Chapter 4 - Fabrication strategies for functionalized nanomaterials, in: M.B. Tahir, M. Sagir, A.M. Asiri (Eds.), *Nanomaterials: Synthesis, Characterization, Hazards and Safety*, Elsevier, 2021, pp. 55–95.
- [140] S. Kumar, P. Bhushan, S. Bhattacharya, Fabrication of Nanostructures with Bottom-up Approach and Their Utility in Diagnostics, Therapeutics, and Others, in: S. Bhattacharya, A.K. Agarwal, N. Chanda, A. Pandey, A.K. Sen (Eds.), *Environmental, Chemical and Medical Sensors*, Springer Singapore, Singapore, 2018, pp. 167–198.
- [141] V. Harish et al., Nanoparticle and Nanostructure Synthesis and Controlled Growth Methods, *Nanomaterials*, vol. 12, no. 18, p. 3226doi: 10.3390/nano12183226.
- [142] S. Kumari, et al., A comprehensive review on various techniques used for synthesizing nanoparticles, *J. Mater. Res. Technol.* 27 (2023) 1739–1763, <https://doi.org/10.1016/j.jmrt.2023.09.291>.
- [143] Y. Zhou, M. Hou, X. Yang, X. Zhang, H. Xiong, F. Liang, Dimensional engineering: Fabrication, performance, and perspectives of multidimensional nanomaterials for lithium-ion batteries, *Rev. Mater. Res.* 1 (5) (2025) 100104, <https://doi.org/10.1016/j.revmat.2025.100104>.
- [144] A. Levish, S. Joshi, M. Winterer, Chemical vapor synthesis of nanocrystalline iron oxides, *Appl. Energy Combust. Sci.* 15 (2023) 100177, <https://doi.org/10.1016/j.jaecs.2023.100177>.
- [145] G. Chen, et al., Multi-step chemical vapor synthesis reactor based on a microplasma for structure-controlled synthesis of single-walled carbon nanotubes, *Chem. Eng. J.* 444 (2022) 136634, <https://doi.org/10.1016/j.cej.2022.136634>.
- [146] M.I. Sohail, et al., Chapter 7 - Sufficiency and toxicity limits of metallic oxide nanoparticles in the biosphere, in: M.B. Tahir, M. Sagir, A.M. Asiri (Eds.), *Nanomaterials: Synthesis, Characterization, Hazards and Safety*, Elsevier, 2021, pp. 145–221.
- [147] Y.S. Jo, et al., Chemical Vapor Synthesis of Nonagglomerated Nickel Nanoparticles by In-Flight Coating (in eng), *ACS Omega* 6 (42) (Oct 26 2021) 27842–27850, <https://doi.org/10.1021/acsomega.1c03468>.
- [148] Y. Su, Y. Zhang, Carbon nanomaterials synthesized by arc discharge hot plasma, *Carbon* 83 (2015) 90–99, <https://doi.org/10.1016/j.carbon.2014.11.023>.
- [149] S.A. Shah, S. Cui, Preparation of silicon nanomaterials by arc discharge, *Mater. Sci. Semicond. Process.* 40 (2015) 491–500, <https://doi.org/10.1016/j.mssp.2015.06.037>.
- [150] S.-P. Chai, A.R. Mohamed, U. Hashim, Synthesis and characterization of graphene and carbon nanotubes: A review on the past and recent developments, *J. Ind. Eng. Chem.* 20 (4) (2014) 1171–1185, <https://doi.org/10.1016/j.jiec.2013.08.028>.
- [151] V.P. Madhurima, K. Kumari, P.K. Jain, Synthesis and study of carbon nanomaterials through arc discharge technique for efficient adsorption of organic dyes, *Diam. Relat. Mater.* 141 (2024) 110538, <https://doi.org/10.1016/j.diamond.2023.110538>.
- [152] A.M. El-khatib, I.I. Bondouk, K.M. Omar, A. Hamdy, M. El-khatib, Impact of changing electrodes dimensions and different ACs on the characteristics of nano composites ZnO/MWCNTs prepared by the arc discharge method, *Surf. Interfaces* 29 (2022) 101736, <https://doi.org/10.1016/j.surf.2022.101736>.
- [153] Z.U.R. Farooqi, A. Qadeer, M.M. Hussain, N. Zeeshan, P. Ilic, Chapter 5 - Characterization and physicochemical properties of nanomaterials, in: M.B. Tahir, M. Sagir, A.M. Asiri (Eds.), *Nanomaterials: Synthesis, Characterization, Hazards and Safety*, Elsevier, 2021, pp. 97–121.
- [154] G. Jin, S.-H. Kim, and H.-J. Han, Synthesis and Future Electronic Applications of Topological Nanomaterials, *International Journal of Molecular Sciences*, vol. 25, no. 1, p. 400doi: 10.3390/ijms25010400.

- [155] M. Weber, et al., Assessing the Environmental Impact of Atomic Layer Deposition (ALD) Processes and Pathways to Lower It (in eng), *ACS Mater. Au* 3 (4) (Jul 12 2023) 274–298, <https://doi.org/10.1021/acsmaterialsau.3c00002>.
- [156] H. Van Bui, V.P. Cao, D. Liu, J.R. van Ommen, S.-H. Kwon, Surface engineering and functionalization of powder-based materials by fluidized-bed atomic layer deposition for emerging applications, *RSC Adv.* 16 (17) (2026) 15845–15876, <https://doi.org/10.1039/d5ra07278f>.
- [157] C. Shen, Z. Yin, F. Collins, N. Pinna, Atomic Layer Deposition of Metal Oxides and Chalcogenides for High Performance Transistors, *Adv. Sci.* 9 (23) (2022) 2104599, <https://doi.org/10.1002/advs.202104599>.
- [158] J.S. Adu, G.K. Asare, H.H. Park, Atomic layer deposition of metal halide perovskites: chemistry, growth mechanisms, and emerging prospects, *Chem. Commun.* 62 (27) (2026) 7087–7100, <https://doi.org/10.1039/d5cc06809f>.
- [159] R. Zazpe, G. Cha, J. Prikyr, I. Hwang, J.M. Macak, P. Schmuki, Uniform ALD deposition of Pt nanoparticles within 1D anodic TiO₂ nanotubes for photocatalytic H₂ generation, /01/01/ 2018, *Electrochem. Commun.* 86 (2018) 6–11, <https://doi.org/10.1016/j.elecom.2017.10.017>.
- [160] M.M. ur Rahman, Chapter 2 - Sources of nanomaterials, in: M.B. Tahir, M. Sagir, A.M. Asiri (Eds.), *Nanomaterials: Synthesis, Characterization, Hazards and Safety*, Elsevier, 2021, pp. 15–29.
- [161] P. Szczeglewska, A. Feliczak-Guzik, and I. Nowak, Nanotechnology—General Aspects: A Chemical Reduction Approach to the Synthesis of Nanoparticles, *Molecules*, vol. 28, no. 13, p. 4932doi: 10.3390/molecules28134932.
- [162] M.S. Aguilar, R. Esparza, G. Rosas, Synthesis of Cu nanoparticles by chemical reduction method, *Trans. Nonferrous Met. Soc. China* 29 (7) (2019) 1510–1515, [https://doi.org/10.1016/S1003-6326\(19\)65058-2](https://doi.org/10.1016/S1003-6326(19)65058-2).
- [163] K. Hachem, et al., Methods of Chemical Synthesis in the Synthesis of Nanomaterial and Nanoparticles by the Chemical Deposition Method: A Review, *BioNanoScience* 12 (3) (2022) 1032–1057, <https://doi.org/10.1007/s12668-022-00996-w>.
- [164] C. Daruich De Souza, B. Ribeiro Nogueira, M.E.C.M. Rostelato, Review of the methodologies used in the synthesis gold nanoparticles by chemical reduction, /08/25/ 2019, *J. Alloy. Compd.* 798 (2019) 714–740, <https://doi.org/10.1016/j.jallcom.2019.05.153>.
- [165] C. Lyu, et al., Microbial nanofactories: A mini-review on sustainable biosynthesis of nanomaterials, *Bioresour. Technol. Rep.* 32 (2025) 102322, <https://doi.org/10.1016/j.biteb.2025.102322>.
- [166] L. Zou, F. Zhu, Z.-e Long, Y. Huang, Bacterial extracellular electron transfer: a powerful route to the green biosynthesis of inorganic nanomaterials for multifunctional applications, *J. Nanobiotechnol.* 19 (1) (2021) 120, <https://doi.org/10.1186/s12951-021-00868-7>.
- [167] J. Joy, A. Krishnamoorthy, A. Tanna, V. Kamathe, R. Nagar, and S. Srinivasan, Recent Developments on the Synthesis of Nanocomposite Materials via Ball Milling Approach for Energy Storage Applications, *Applied Sciences*, vol. 12, no. 18, p. 9312doi: 10.3390/app12189312.
- [168] D.V. Dudina and B.B. Bokhonov, Materials Development Using High-Energy Ball Milling: A Review Dedicated to the Memory of M.A. Korchagin, *Journal of Composites Science*, vol. 6, no. 7, p. 188doi: 10.3390/jcs6070188.
- [169] Y. Li, et al., Past, present and future of high-nickel materials, *Nano Energy* 119 (2024) 109070, <https://doi.org/10.1016/j.nanoen.2023.109070>.
- [170] W. Liu, H. Zhi, X. Yu, Recent progress in phosphorus based anode materials for lithium/sodium ion batteries, *Energy Storage Mater.* 16 (2019) 290–322, <https://doi.org/10.1016/j.ensm.2018.05.020>.
- [171] M. Martínez-Carmona and M. Vallet-Regí, Advances in Laser Ablation Synthesized Silicon-Based Nanomaterials for the Prevention of Bacterial Infection, *Nanomaterials*, vol. 10, no. 8, p. 1443doi: 10.3390/nano10081443.
- [172] M.C. Sportelli et al., The Pros and Cons of the Use of Laser Ablation Synthesis for the Production of Silver Nano-Antimicrobials, *Antibiotics*, vol. 7, no. 3, p. 67doi: 10.3390/antibiotics7030067.
- [173] N. Tarasenska, Laser ablation in liquids for shape-tailored synthesis of nanomaterials: status and challenges (/), *Beilstein J. Nanotechnol.* 16 (2025) 1963–1997, <https://doi.org/10.3762/bjnano.16.137>.
- [174] A.M. Elsieid, P.C. Dieffenbach, P.K. Diwakar, A. Hassanein, Nanosecond laser-metal ablation at different ambient conditions, *Spectrochim. Acta Part B At. Spectrosc.* 143 (2018) 26–31, <https://doi.org/10.1016/j.sab.2018.02.012>.
- [175] M. Li, Y. Chen, W. Luo, and X. Cheng, Interfacial Interactions during Demolding in Nanoimprint Lithography, *Micromachines*, vol. 12, no. 4, p. 349doi: 10.3390/mi12040349.
- [176] S. Fialkova et al., Nanoimprint Lithography for Next-Generation Carbon Nanotube-Based Devices, *Nanomaterials*, vol. 14, no. 12, p. 1011doi: 10.3390/nano14121011.
- [177] Y. Cao, D. Ma, H. Li, G. Cui, J. Zhang, and Z. Yang, Review of Industrialization Development of Nanoimprint Lithography Technology, *Chips*, vol. 4, no. 1, p. 10doi: 10.3390/chips4010010.
- [178] N. Unno and T. Mäkelä, Thermal Nanoimprint Lithography—A Review of the Process, Mold Fabrication, and Material, *Nanomaterials*, vol. 13, no. 14, p. 2031doi: 10.3390/nano13142031.
- [179] P. Lee, et al., Highly Stretchable and Highly Conductive Metal Electrode by Very Long Metal Nanowire Percolation Network, *Adv. Mater.* 24 (25) (2012) 3326–3332, <https://doi.org/10.1002/adma.201200359>.
- [180] M.D. Dickey, Stretchable and Soft Electronics using Liquid Metals, *Adv. Mater.* 29 (27) (2017) 1606425, <https://doi.org/10.1002/adma.201606425>.
- [181] S.P. Lacour, S. Wagner, Z. Huang, Z. Suo, Stretchable gold conductors on elastomeric substrates, *Appl. Phys. Lett.* 82 (15) (2003) 2404–2406, <https://doi.org/10.1063/1.1565683>.
- [182] S.-K. Kang, et al., Bioresorbable silicon electronic sensors for the brain, *Nature* 530 (7588) (2016) 71–76, <https://doi.org/10.1038/nature16492>.
- [183] S.F. Cogan, Neural Stimulation and Recording Electrodes, *Annu. Rev. Biomed. Eng.* 10 (2008) 275–309, <https://doi.org/10.1146/annurev.bioeng.10.061807.160518>.
- [184] C. Boehler, F. Oberueber, S. Schlabach, T. Stieglitz, M. Asplund, Long-Term Stable Adhesion for Conducting Polymers in Biomedical Applications: IrOx and Nanostructured Platinum Solve the Chronic Challenge, *ACS Appl. Mater. Interfaces* 9 (1) (2016) 189–197, <https://doi.org/10.1021/acsami.6b13468>.
- [185] M. Pogorielov, K. Smyrnova, S. Kyrylenko, O. Gogotsi, V. Zahorodna, and A. Pogrebnyak, MXenes—A New Class of Two-Dimensional Materials: Structure, Properties and Potential Applications, *Nanomaterials*, vol. 11, no. 12, p. 3412doi: 10.3390/nano11123412.
- [186] J. Li, Q. Wu, J. Wu, *Synthesis of Nanoparticles via Solvothermal and Hydrothermal Methods*, in: M. Aliofkhaezai (Ed.), *Handbook of Nanoparticles*, Springer International Publishing, Cham, 2015, pp. 1–28.
- [187] M. Baričić, et al., Advancements in polyol synthesis: expanding chemical horizons and Néel temperature tuning of CoO nanoparticles, *Sci. Rep.* 14 (1) (2024) 12529, <https://doi.org/10.1038/s41598-024-54892-2>.
- [188] J.A. Gutierrez, J.J. Silber, R.D. Falcone, N.M. Correa, Modified reverse micelle method as facile way to obtain several gold nanoparticle morphologies, *J. Mol. Liq.* 331 (2021) 115709, <https://doi.org/10.1016/j.molliq.2021.115709>.
- [189] W.-R. Zhuang, et al., Applications of π - π stacking interactions in the design of drug-delivery systems, *J. Control. Release* 294 (2019) 311–326, <https://doi.org/10.1016/j.jconrel.2018.12.014>.
- [190] D. Lombardo, P. Calandra, L. Pasqua, and S. Magazù, Self-Assembly of Organic Nanomaterials and Biomaterials: The Bottom-Up Approach for Functional Nanostructures Formation and Advanced Applications, *Materials*, vol. 13, no. 5, p. 1048doi: 10.3390/ma13051048.
- [191] J. Park, J.C. Hwang, G.G. Kim, J.-U. Park, Flexible electronics based on one-dimensional and two-dimensional hybrid nanomaterials, *InfoMat* 2 (1) (2020) 33–56, <https://doi.org/10.1002/inf2.12047>.
- [192] D. Ağaoğulları, S.J. Madsen, B. Ögüt, A.L. Koh, R. Sinclair, Synthesis and characterization of graphite-encapsulated iron nanoparticles from ball milling-assisted low-pressure chemical vapor deposition, *Carbon* 124 (2017) 170–179, <https://doi.org/10.1016/j.carbon.2017.08.043>.
- [193] H. Matsumoto, T. Okabe, J. Taniguchi, Microchannel fabrication via ultraviolet-nanoimprint lithography and electron-beam lithography using an ultraviolet-curable positive-tone electron-beam resist, *Microelectron. Eng.* 226 (2020) 111278, <https://doi.org/10.1016/j.mee.2020.111278>.
- [194] S.M.M. Shanab, A.M. Partila, H.E.A. Ali, M.A. Abdullah, Impact of gamma-irradiated silver nanoparticles biosynthesized from *Pseudomonas aeruginosa* on growth, lipid, and carbohydrates of *Chlorella vulgaris* and *Dictyochloropsis splendida*, *J. Radiat. Res. Appl. Sci.* 14 (1) (2021) 70–81, <https://doi.org/10.1080/16878507.2020.1856599>.
- [195] F. de Andrés, V. Moreno, A. Ríos, M. Zougagh, Sustainable nanomaterial synthesis in supercritical fluids for advanced analytical applications, *Microchem. J.* 221 (2026) 116743, <https://doi.org/10.1016/j.microc.2025.116743>.
- [196] S. Tarhan, A. Ekinci, O. Baytar, A. Akdag, Ö. Şahin, Green-synthesized ZrFeO nanoparticles as efficient cathode materials in PEM fuel cells, *Int. J. Hydrog. Energy* 142 (2025) 852–863, <https://doi.org/10.1016/j.ijhydene.2025.01.046>.
- [197] V.I. Kolesnikov, O.V. Kudryakov, I.Y. Zabyaka, E.S. Novikov, D.S. Manturov, Structural Aspects of Wear Resistance of Coatings Deposited by Physical Vapor Deposition, *Phys. Mesomech.* 23 (6) (2020) 570–583, <https://doi.org/10.1134/S1029959920060132>.
- [198] N. Hou, J. Ling, H. Liu, H. Zhang, Collaborative fabrication of high-hardness and self-lubricating Ni/Ni-Co coatings reinforced by SiC nanoparticles and 2D materials using electrochemical deposition process, *Mater. Des.* 260 (2025) 115106, <https://doi.org/10.1016/j.matdes.2025.115106>.
- [199] X. Liang, S. Yu, B. Meng, Y. Ju, S. Wang, and Y. Wang, Machine-Learning-Guided Design of Nanostructured Metal Oxide Photoanodes for Photoelectrochemical Water Splitting: From Material Discovery to Performance Optimization, *Nanomaterials*, vol. 15, no. 12, p. 948doi: 10.3390/nano15120948.