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Review

Titanium Alloys at the Interface of Electronics and Biomedicine: A Review of Functional Properties and Applications

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Abstract

Recent studies show that titanium (Ti)-based alloys combine established mechanical strength, corrosion resistance, and biocompatibility with emerging electrical and electrochemical properties relevant to bioelectronics. The main goal of the present manuscript is to give a wide-ranging overview on the use of Ti-alloys in electronics and biomedicine, focusing on a comprehensive analysis and synthesis of the existing literature to identify gaps and future directions. Concurrently, the identification of possible correlations between the effects of the manufacturing process, alloying elements, and other degrees of freedom influencing the material characteristics are put in evidence, aiming to establish a global view on efficient interdisciplinary efforts to realize high-added-value smart devices useful in the field of biomedicine, such as, for example, implantable apparatuses. This review mostly summarizes advances in surface modification approaches—including anodization, conductive coatings, and nanostructuring that improve conductivity while maintaining biological compatibility. Trends in applications demonstrate how these alloys support smart implants, biosensors, and neural interfaces by enabling reliable signal transmission and long-term integration with tissue. Key challenges remain in balancing electrical performance with biological response and in scaling laboratory modifications for clinical use. Perspectives for future work include optimizing alloy composition, refining surface treatments, and developing multifunctional designs that integrate mechanical, biological, and electronic requirements. Together, these directions highlight the potential of titanium alloys to serve as foundational materials for next-generation bioelectronic medical technologies.

Keywords: titanium alloys; bioelectronic materials; biocompatibility; electrical conductivity; biomedical applications; smart implants; biosensors

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1. Introduction

Titanium (Ti) and its alloys have become indispensable in biomedical engineering, particularly in the design and realization of load-bearing implants, dental prostheses, and cardiovascular devices. Their widespread use is grounded in a combination of favorable properties: high mechanical strength, low density, high corrosion resistance in physiological environments, and a well-documented biocompatibility profile [1]. Among these, Ti-6Al-4V remains the most commonly employed alloy [2], although newer systems such as Ti-Nb, Ti-Ta, and Ti-Zr have gained attention due to their improved biological performance and reduced cytotoxicity [3–5]. Representative examples of these applications are illustrated in Figure 1, which highlights the use of titanium alloys in hip implants, dental screws, and vascular stents [1].

Historically, Ti alloys have been regarded as passive structural materials, optimized for mechanical integrity and chemical stability. Their role in biomedical applications has largely focused on ensuring long-term durability and minimizing adverse tissue reactions. However, the emergence of bioelectronic technologies—including implantable sensors, neural interfaces, and electrically active scaffolds—has prompted a reevaluation of Ti alloys from a functional perspective [6,7]. In these contexts, materials are expected not only to support biological integration but also to participate in electronic communication with surrounding tissues.

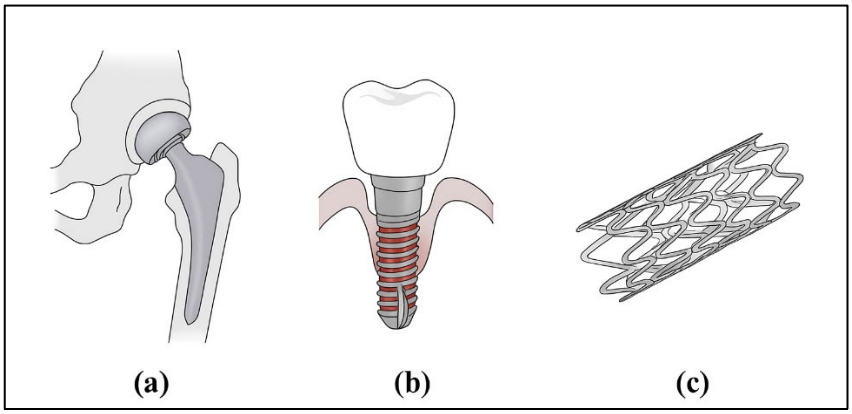

Figure 1. Representative biomedical applications of titanium alloys. (**a**) Hip implant. (**b**) Dental screw. (**c**) Stent.

Electrical conductivity, electrochemical behavior, and surface charge dynamics are increasingly relevant parameters in the design of next-generation biomedical devices. Ti alloys, while not inherently conductive in the same way as traditional electronic materials, can be engineered through surface modifications, alloying strategies, and hybridization with conductive coatings to exhibit tailored electrical responses [8,9]. These adaptations open new possibilities for integrating Ti-based components into systems that rely on electrical stimulation, signal transduction, or real-time monitoring.

Recent reviews have highlighted alternative bioelectronic materials, such as hydrogel-based piezoelectric systems, which offer soft, flexible architectures capable of dynamic mechanical-to-electrical conversion in implantable devices. While such materials excel in mimicking tissue mechanics and enabling transient electronics, they often lack the long-term stability, load-bearing capacity, and corrosion resistance required for permanent implants. In contrast, titanium alloys provide a unique balance: they combine structural durability with tunable electronic functionality, positioning them as complementary to softer bioelectronic platforms. This distinction underscores why Ti remains in the broader context of bioelectronics, serving as a robust backbone for devices that must endure mechanical stress while simultaneously engaging in electrical communication with biological systems [4,10].

The interdisciplinary nature of this evolution—bridging materials science, bioengineering, and electronics—calls for a comprehensive review of the current state of knowledge. This paper aims to synthesize existing research on the functional properties of Ti alloys at the interface of electronics and biomedicine. We begin by outlining the metallurgical and biological foundations of commonly used Ti-based systems, followed by an analysis of their electrical and electrochemical characteristics. Surface engineering approaches that enhance both biological and electronic performance are discussed, along with representative applications in smart implants and biosensing platforms. Finally, we identify key challenges and propose directions for future investigation, with the goal of supporting the development of multifunctional materials suited for emerging bioelectronic technologies.

2. Overview of Ti Alloys

Titanium alloys form a versatile class of metallic materials widely used in biomedical engineering due to their promising combination of mechanical, chemical, and biological properties. Their classification is based on phase composition, resulting in three major categories: α (alpha), β (beta), and α+β (dual-phase) alloys. Each category exhibits distinct microstructural features that influence mechanical behavior, corrosion resistance, and biological performance [11,12].

2.1. Metallurgical Classification and Phase Behavior

- Alpha alloys (e.g., commercially pure (CP) Ti grades 1–4) are stabilized by elements such as aluminum, oxygen, nitrogen, and carbon, with zirconium sometimes acting as a weak stabilizer. They are non-heat-treatable, possess good weldability, and significant creep resistance. Their ultimate tensile strength typically ranges from 240 to 550 MPa, with an elastic modulus around 105 GPa [13].
- Beta alloys (e.g., Ti-15Mo, Ti-13Nb-13Zr, Ti-12Mo-6Zr-2Fe) are metastable and heat-treatable. They offer high strength (up to 900 MPa), improved corrosion resistance, and lower elastic modulus values between 55 and 80 GPa, which is closer to that of cortical bone (~20 GPa), helping reduce stress shielding [14,15].
- Alpha+Beta alloys, such as Ti-6Al-4V, combine the advantages of both phases. This alloy remains the most widely used in clinical practice due to its balanced mechanical properties: tensile strength of 800–950 MPa, yield strength of 750 MPa, and elastic modulus around 110 GPa. Its fatigue strength is typically 500–600 MPa, making it suitable for dynamic loading conditions [15].
- Near-alpha alloys (e.g., Ti-6242S, Ti-834, Ti-XT) are primarily α-phase with a small amount of β stabilizers, giving them enhanced high-temperature performance. They are strengthened by aluminum and stabilized with elements such as tin, zirconium, and silicon, while limited β stabilizers like molybdenum or niobium improve toughness. These alloys are heat-treatable and exhibit excellent creep resistance, fatigue strength, and thermal stability, making them particularly valuable in aeronautical applications such as compressor disks and turbine components. Their tensile strength typically ranges from 800 to 1100 MPa, with elastic modulus values around 110 GPa, supporting use under demanding service conditions [16].

Beyond their mechanical properties, the microstructures of titanium alloys further explain their performance. α-titanium alloys consist solely of the α phase, which has a hexagonal close-packed (HCP) structure that contributes to adequate strength and good corrosion resistance. β-titanium alloys crystallize in a body-centered cubic (BCC) structure containing the β phase, which is responsible for their higher strength compared to α-titanium alloys. The most common alloys are α+β titanium alloys, which can be heat-treated and combine the characteristics of both phases. Near-alpha alloys, with their predominantly α-phase matrix and limited β stabilizers, display microstructures optimized for high-temperature stability, explaining their widespread use in aerospace components subjected to extreme thermal and mechanical loads.

2.2. Alloying Elements and Biological Implications

The choice of alloying elements significantly affects both mechanical and biological behavior. While aluminum and vanadium improve strength and phase stability, concerns over their long-term cytotoxicity have led to the development of alternative systems. For example:

- Ti-Nb-Zr-Ta alloys are free of potentially toxic elements and exhibit notable biocompatibility and corrosion resistance [17].
- Ti-13Nb-13Zr shows minimal ion release and supports osteoblast adhesion and proliferation [18].
- Ti-15Mo and Ti-35Nb alloys have been reported to show favorable cell responses and reduced inflammatory reactions. At the same time, molybdenum has been associated with cytotoxic effects under certain conditions, so its biological impact requires careful evaluation [19,20].

The chemical composition and biological roles of alloying elements in Ti-based alloys are schematically illustrated in Figure 2. The figure highlights how different alloying additions contribute to the multifunctional performance of titanium systems in biomedical contexts.

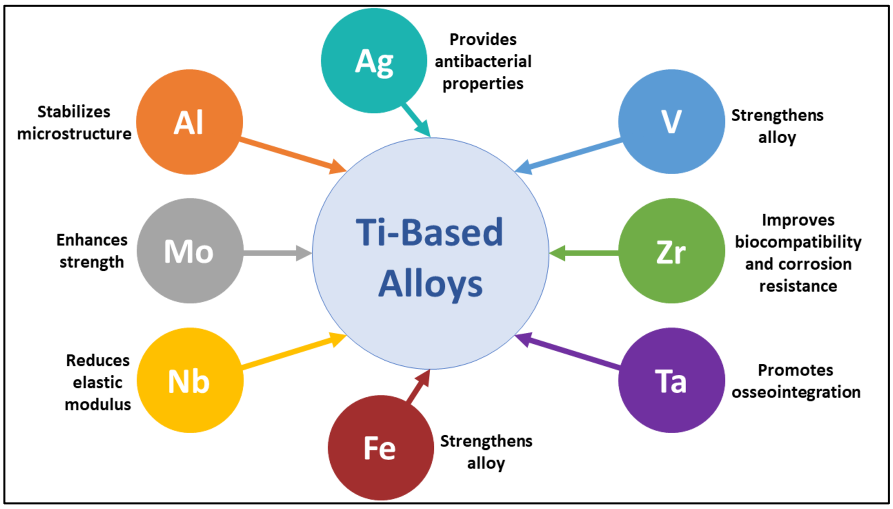

Figure 2. Schematic representation of alloying elements in Ti-based alloys and their biological roles.

These newer systems also exhibit lower elastic moduli (as low as 55 GPa) and improved corrosion resistance in simulated body fluids, making them suitable for long-term implantation.

2.3. Mechanical Properties Relevant to Biomedical Use

Ti alloys are valued for their high strength-to-weight ratio. For biomedical applications, the following mechanical properties are particularly relevant, as reported in Table 1.

Table 1. Mechanical properties of selected Ti alloys used in biomedical applications.

Alloy Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fatigue Strength (MPa)	References
CP Ti (Grade 2)	350–500	100–110	~300	[13]
Ti-6Al-4V	800–950	110	500–600	[15]
Ti-13Nb-13Zr	750–850	70–80	~450	[18]
Ti-15Mo	800–900	60–70	~500	[19,20]
Ti-29Nb-13Ta-4.6Zr	850–950	55–65	~500	[17]

Lower elastic modulus values are desirable to reduce stress shielding and promote bone remodeling. Beta alloys, in particular, offer a modulus closer to bone, which is a key advantage in orthopedic applications.

2.4. Corrosion Resistance and Passive Layer Formation

Ti alloys exhibit high corrosion resistance due to the spontaneous formation of a stable oxide layer (TiO_2) on their surface. This passive film is typically 2–10 nm thick and protects against ion release and degradation in physiological environments [21].

- In simulated body fluids (SBF), Ti alloys show corrosion rates below 0.01 mm/year, indicating long-term stability [22].
- Beta alloys such as Ti-13Nb-13Zr and Ti-15Mo form more uniform and protective oxide layers, enhancing their performance in chloride-rich environments like blood plasma [18–20].

Surface treatments such as anodization, acid etching, and plasma spraying can further improve corrosion resistance and prepare the surface for biological or electronic functionalization. These modifications are particularly relevant for bioelectronic applications, where surface conductivity and stability are essential.

3. Biocompatibility and Surface Behavior

As Ti alloys transition from purely structural roles to multifunctional components in biomedical devices, their surface properties become increasingly critical. Biocompatibility is no longer evaluated exclusively in terms of inertness or corrosion resistance, but also in relation to how the surface interacts with biological tissues and electronic systems. This chapter explores the biological response to Ti surfaces, the influence of alloying elements, and the role of surface treatments—with particular attention to how these features affect both cellular behavior and electrochemical performance in bioelectronic contexts.

3.1. Biological Response to Ti Surfaces

Ti surfaces rapidly form a passive oxide layer (TiO_2) upon exposure to air or physiological fluids, typically measuring 2–10 nm in thickness. This layer facilitates protein adsorption, which governs subsequent cell adhesion and signaling. Studies using osteoblast-like cells (e.g., MG-63, SaOS-2) report adhesion rates above 90% within the first 24 h on polished Ti surfaces [23–25].

Protein adsorption kinetics are influenced by surface energy and wettability. Hydrophilic surfaces with contact angles below 65° promote better cell spreading and proliferation. For example, surfaces with a contact angle of 45–55° show up to 30% higher alkaline phosphatase (ALP) activity compared to hydrophobic ones [23,26].

Zeta potential measurements in phosphate-buffered saline (PBS) reveal values between −20 and −30 mV, which favor electrostatic interaction with positively charged domains of fibronectin and vitronectin, enhancing integrin-mediated adhesion [27].

3.2. Influence of Alloying Elements on Cytocompatibility

The biological response of Ti alloys is directly linked to the surface mechanisms described in Section 3.1. Alloying elements modify the passive TiO_2 layer, which in turn affects protein adsorption, cell adhesion, and signaling.

- Oxide layer stability: Elements like Nb, Zr, or Ta can enhance corrosion resistance, while others may release ions that interfere with protein binding [17,28].
- Surface wettability: Changes in hydrophilicity alter cell spreading and ALP activity, reinforcing the importance of contact angle control [29].
- Surface charge: Alloy composition can shift zeta potential, influencing electrostatic interactions with fibronectin and vitronectin, and thus integrin-mediated adhesion [30].

In summary, each alloying element plays a specific role by tuning the oxide layer, wettability, and charge—ultimately modulating the cytocompatibility established in Section 3.1. Table 2 summarizes the composition and cytocompatibility of representative Ti alloy systems.

Table 2. Composition and cytocompatibility of selected Ti alloys.

Alloy System	Composition (wt%)	Cell Viability (%)	Notes	References
Ti-6Al-4V	6% Al, 4% V	~85–90	Vanadium may cause an inflammatory response	[3]
Ti-13Nb-13Zr	13% Nb, 13% Zr	>95	Strong osteoblast proliferation	[31]
Ti-15Mo	15% Mo	>90	Stable in SBF, low ion release	[32]
Ti-35Nb	35% Nb	>95	Low modulus, high biocompatibility	[33]
Ti-29Nb-13Ta-4.6Zr	Nb, Ta, Zr	>96	Used in spinal and cardiovascular implants	[34]

In vitro cytotoxicity assays (MTT, LDH) confirm that niobium, tantalum, and zirconium are bioinert and support long-term cell viability. Alloys with high Nb content also exhibit reduced inflammatory markers (e.g., IL-6, TNF-α) in macrophage cultures [35].

3.3. Surface Topography and Roughness

Surface roughness influences protein adsorption, cell morphology, and differentiation. Microroughness (Ra = 1–2 μm) enhances osteoblast anchorage, while nanostructures (<100 nm) promote stem cell differentiation and reduce bacterial adhesion.

Laser-treated surfaces with Ra ≈ 1.5 μm show up to 40% higher ALP activity and 25% more calcium deposition compared to smooth controls [36]. AFM studies reveal that filopodia preferentially anchor to topographic peaks, suggesting mechanical guidance cues. Table 3 presents comparative data on roughness, ALP activity, and cell coverage for various surface types.

Table 3. Effect of surface roughness on biological response.

Surface Type	Ra (μm)	ALP Activity (%)	Cell Coverage (%)	References
Polished Ti	<0.2	Baseline	~70	[37]
Acid-etched Ti	1.0–2.0	+25–30%	~85	[38]
Laser-textured Ti	1.5	+40%	>90	[36]
Nanotube arrays	~0.1	+35%	>95	[39]

3.4. Surface Treatments and Coatings

Surface modification techniques enhance both biological and electronic functionality. Anodization, acid etching, and plasma spraying alter surface chemistry and topography, while coatings introduce bioactive or conductive layers. Table 4 outlines the effects of various treatments and coatings on roughness, biological response, and electronic performance.

Table 4. Surface treatments and their dual impact on biocompatibility and electronic behavior.

Method	Ra (µm)	Coating Type	Biological Effect	Electronic Effect	References
Anodization	0.5–2.0	TiO_2 nanotubes	↑ Cell adhesion, ↑ ALP	↑ Capacitance, ↓ Impedance	[40]
Acid etching	1.0–3.0	None	↑ Osseointegration	↑ Surface conductivity	[38]
Plasma spraying	2.0–5.0	Hydroxyapatite (HA)	↑ Bone bonding	↓ Electrical resistance	[41]
Dip-coating	~0.5	PEDOT:PSS	↑ Cell viability	↑ Signal transduction	[42]

↑ = increased; ↓ = decreased

A comparative overview of surface modification techniques is presented in Figure 3, where the introduction of Hydroxyapatite (HA) and conductive polymer coating (PEDOT:PSS layer), in different thicknesses, enhances several performances. Each method—anodization, plasma spraying, and dip-coating—alters surface chemistry and structure in ways that influence both biological and electronic performance.

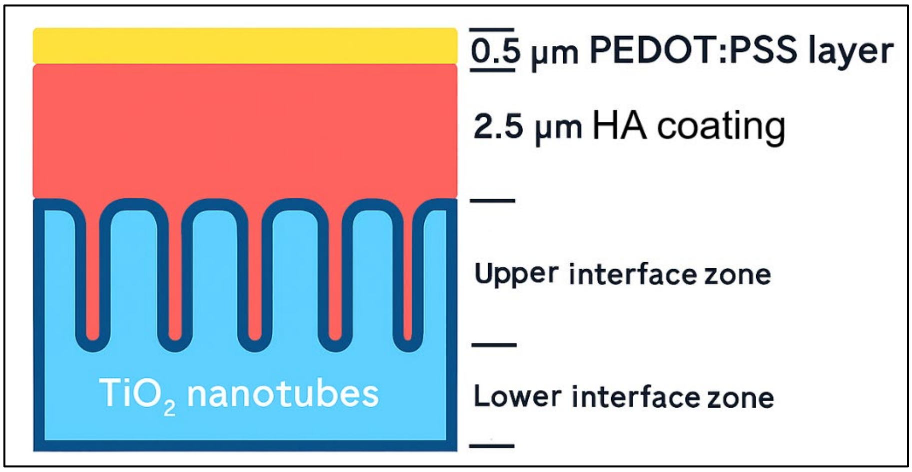

Figure 3. Coated Titanium Surfaces.

TiO_2 nanotube arrays (diameter 70–100 nm) support both osteogenic differentiation and electrical stimulation [43]. Conductive polymer coatings preserve high levels of cell survival (exceeding 90%) while enabling real-time signal recording in biosensor platforms [44].

3.5. Electrochemical Behavior in Physiological Conditions

Ti alloys exhibit notable electrochemical stability in SBF and PBS, critical for long-term implant performance and bioelectronic integration.

- Open Circuit Potential (OCP): −0.2 to −0.4 V vs. saturated calomel electrode (SCE).
- Corrosion Current Density (I_{corr}): <1 $\mu A/cm^2$.
- Polarization Resistance (R_p): >100 $k\Omega \cdot cm^2$.
- Capacitance (C_{dl}): 10–100 $\mu F/cm^2$ depending on surface treatment [45].

Electrochemical impedance spectroscopy (EIS) shows that anodized surfaces have higher capacitance and lower charge transfer resistance, improving signal fidelity in implantable electrodes [46].

3.6. Dual Role of Surface Properties in Bioelectronic Interfaces

The integration of Ti alloys into bioelectronic systems requires surfaces that simultaneously support biological compatibility and electronic performance. Achieving this dual functionality presents a complex design challenge, as improvements in one domain may compromise the other. For instance, increasing surface roughness enhances cell adhesion and osseointegration, yet may reduce electrical conductivity due to elevated electron scattering and surface resistance. Conversely, highly polished surfaces facilitate better charge mobility but can hinder protein adsorption and cellular anchorage.

To address this trade-off, hybrid strategies have emerged that combine bioactive substrates with conductive coatings. Ti surfaces modified with graphene oxide, carbon nanotubes, or conductive polymers such as PEDOT:PSS consistently sustain robust cellular compatibility (viability rates above 90%), while simultaneously facilitating electrical stimulation and signal transduction. Impedance values for such coated surfaces typically fall below 10 kΩ at 1 kHz, making them suitable for biosensing and neural interface applications [46,47].

To visualize the balance between biological compatibility and electrical conductivity, Figure 4 maps the trade-offs involved in surface design. Hybrid coatings emerge as promising solutions for achieving dual functionality.

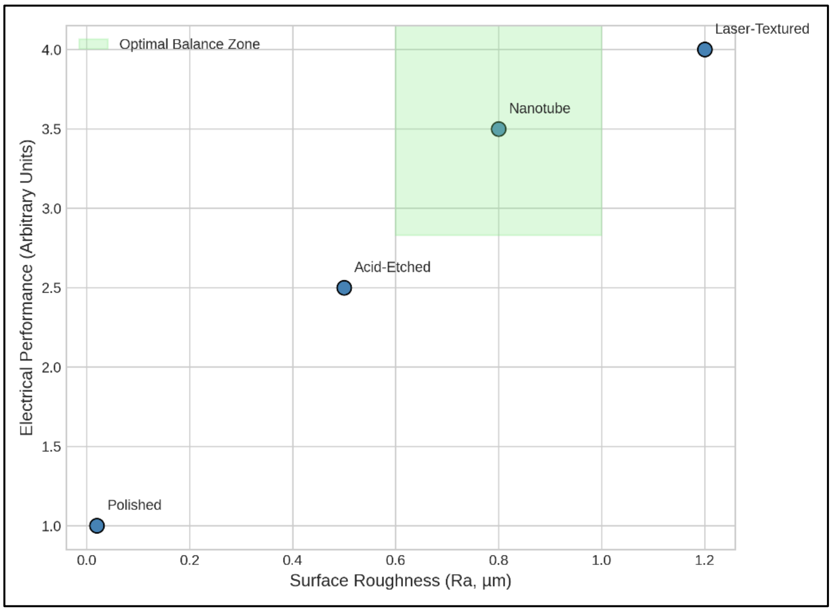

Figure 4. Biocompatibility vs. Conductivity trade-off [46,48].

In addition to topographical and coating-based modifications, surface charge, wettability, and oxide layer composition play critical roles in modulating biological and electronic interactions. Zeta potential values ranging from −20 to −30 mV support protein adsorption and cell adhesion, while also contributing to electrochemical stability [49]. Capacitance values between 10 and 100 µF/cm^2, depending on surface treatment, enhance signal fidelity in implantable devices [45].

The chemical composition and microstructure of the alloy further influence performance across both domains. Beta-type alloys with lower elastic modulus (e.g., Ti-35Nb-5In, ~63 GPa) reduce stress shielding and promote favorable charge distribution across the surface [50]. Surface treatments such as anodization or laser texturing can be precisely tuned to create hierarchical topographies that support both osteogenic differentiation and charge storage [51,52].

Beyond conventional surface treatments, advanced forming methods can also tailor surface properties for bioelectronic use. A notable advancement in processing Ti alloys is Direct Pulse Current Electromagnetic Forming (DPCEMF), which combines electromagnetic forming with pulse current heating. Beyond improving bulk mechanical properties, this technique directly influences surface microstructure and phase distribution, thereby affecting both biological and electronic interactions. The refined surfaces produced by DPCEMF can enhance charge transfer while maintaining favorable cell responses, making the method relevant to bioelectronic integration. Although complex geometries can be achieved through several approaches, DPCEMF is highlighted here because it simultaneously addresses low conductivity and high deformation resistance in Ti, offering a pathway to surfaces that balance mechanical strength with electronic functionality [53]. Figure 5 outlines the main steps of the process: the electromagnetic forming setup applies a pulsed magnetic field, leading to rapid deformation of the workpiece and resulting in microstructure refinement.

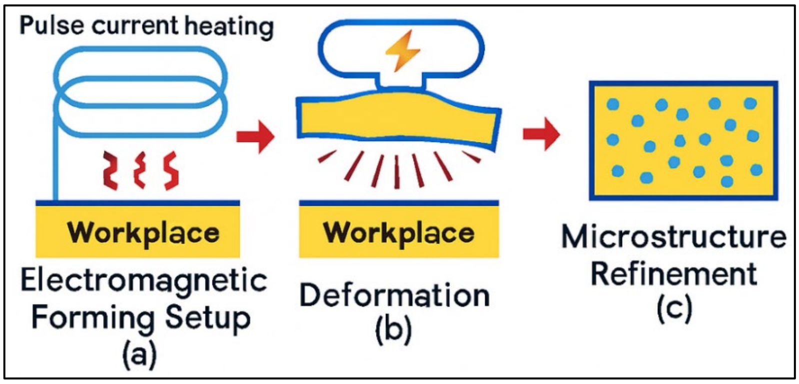

Figure 5. DPCEMF processing stages.

4. Electrical and Electrochemical Properties

With the growing demand for materials that bridge biological function and electronic responsiveness, Ti alloys have emerged as promising candidates for bioelectronic applications. No longer viewed solely as passive structural components, these alloys exhibit a spectrum of electrical and electrochemical behaviors that can be tailored through alloy design, thermomechanical processing, and surface modification [49,54]. This chapter examines the foundational electrical properties of Ti-based systems and highlights their functional relevance in biomedical devices that rely on electronic interaction with living tissues.

The multifunctionality of Ti alloys in bioelectronic platforms is schematically illustrated in Figure 6, highlighting their role in bridging biological tissue and electronic responsiveness through tailored surface and structural properties.

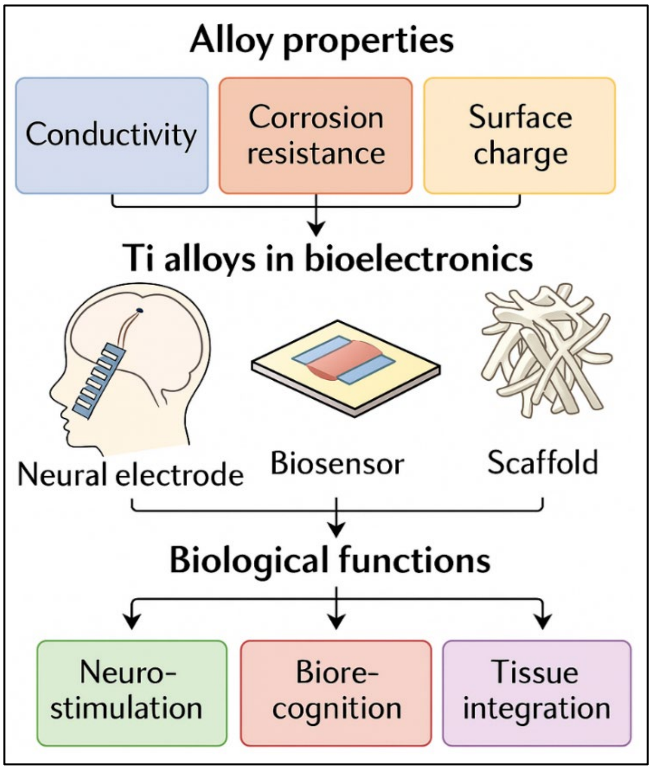

Figure 6. Ti alloy interface with soft tissue in bioelectronic platforms.

4.1. Intrinsic Electrical Properties of Ti Alloys

Ti and its alloys are not inherently conductive in the same way as traditional electronic materials such as copper or gold. At the same time, their electrical resistivity and conductivity vary significantly depending on alloy composition, phase structure, and processing history [55]. These intrinsic properties are particularly relevant in applications involving electrical stimulation, signal transduction, or impedance-based sensing [56].

Beta-type Ti alloys tend to exhibit higher electrical conductivity than alpha or alpha+beta systems due to their BCC structure, which facilitates more uniform electron transport [57]. Alloying elements such as molybdenum, niobium, iron, and tantalum influence electron mobility and phase stability, contributing to improved conductivity in multicomponent systems [58,59].

Recent studies have characterized compositions like Ti-25Nb-5Zr-3Fe and Ti-29Nb-13Ta-4.6Zr, which show promising electrical behavior for bioelectronic applications. These alloys combine moderate conductivity with high biocompatibility and corrosion resistance, making them suitable for multifunctional implantable devices [14,60,61].

The comparative electrical conductivity of representative Ti alloys is summarized in Table 5.

Table 5. Electrical conductivity of selected Ti alloys used in biomedical applications.

Alloy System	Electrical Conductivity (S/m)	Notes	References
Ti-6Al-4V	$0.6–1.0 \times 10^6$	$\alpha+\beta$ structure, widely used	[3]
Ti-13Nb-13Zr	$\sim 1.2 \times 10^6$	β-phase stabilized, good biocompatibility	[31]
Ti-15Mo	$\sim 1.5 \times 10^6$	High β-phase content	[32]
Ti-35Nb	$\sim 1.6 \times 10^6$	Low modulus, enhanced conductivity	[33]
Ti-25Nb-5Zr-3Fe	$\sim 1.7–2.0 \times 10^6$	Fe improves electron mobility	[14]
Ti-29Nb-13Ta-4.6Zr	$\sim 1.6–1.9 \times 10^6$	Ta improves corrosion resistance	[60,61]

Understanding the intrinsic electrical behavior of these alloys—including emerging multicomponent systems—provides a foundation for evaluating their stability, responsiveness, and adaptability under physiological conditions, where electrochemical interactions become increasingly relevant [62].

4.2. Electrochemical Stability in Physiological Media

In biomedical environments, Ti alloys are exposed to electrolytic fluids such as blood plasma, interstitial fluid, and SBF. Their electrochemical stability determines long-term performance, especially in implantable devices where corrosion resistance and interface integrity are critical [63,64].

Titanium develops a protective TiO_2 passive film that enhances corrosion resistance. Its characteristics vary with alloy composition and surface treatment [65]. Stability is typically evaluated using electrochemical parameters such as OCP, I_{corr}, and R_p [66].

Table 6 presents representative electrochemical values for Ti alloys in PBS and SBF environments.

Table 6. Electrochemical parameters of Ti alloys in physiological media.

Alloy System	OCP (V vs. SCE)	I_{corr} (μA/cm^2)	R_p (kΩ·cm^2)	Notes	References
Ti-6Al-4V	−0.35	<1.0	~100	Stable but V release possible	[3,67]
Ti-13Nb-13Zr	−0.30	<0.5	>150	High passivation	[68]
Ti-15Mo	−0.25	<0.3	>200	High corrosion resistance	[69]
Ti-25Nb-5Zr-3Fe	−0.28	<0.4	~180	Fe improves passive film	[70]
Ti-29Nb-13Ta-4.6Zr	−0.32	<0.3	>220	Ta enhances oxide stability	[61,71]

Electrochemical impedance spectroscopy (EIS) confirms that β-type and multicomponent Ti alloys exhibit higher R_p and lower charge transfer rates, supporting their use in long-term bioelectronic systems [64,72].

Evaluating electrochemical stability under physiological conditions enables more accurate prediction of material behavior in vivo and informs the design of surfaces that maintain both biological and electronic integrity.

Beyond conventional electrochemical behavior, Ti alloys exhibit unique interactions with electromagnetic fields. For example, electromagnetic stirring during coating production improves phase distribution and reduces segregation [73]. Additionally, Ti's ability to reversibly absorb and release hydrogen under electromagnetic influence has been explored for solid-state hydrogen storage, highlighting its potential in energy-related biomedical systems [74].

4.3. Surface Charge and Capacitance Behavior

Beyond bulk conductivity and corrosion resistance, the surface electrostatic properties of Ti alloys play a key role in bioelectronic performance. Parameters such as zeta potential and double-layer capacitance influence protein adsorption, cell adhesion, and signal transduction [75,76].

Zeta potential values for Ti surfaces in PBS typically range from −20 to −30 mV, favoring interaction with positively charged biomolecules. Surface treatments can shift this potential and modulate biological response [75,76].

Capacitance values depend on surface area, oxide composition, and the type of electrolyte. Anodized surfaces and nanotube arrays exhibit increased C_{dl}, often reaching 10–100 μF/cm^2, which enhances charge storage and signal fidelity in sensing applications [76,77].

Table 7 summarizes typical surface electrostatic parameters for Ti alloys.

Table 7. Surface charge and capacitance behavior of Ti alloys.

Surface Type	Zeta Potential (mV)	C_{dl} (μF/cm^2)	Notes	References
Polished Ti	−20 to −25	~10	Baseline surface	[78]
Acid-etched Ti	−25 to −30	~20	Increased roughness and charge	[79]
Anodized TiO$_2$ nanotubes	−30 to −35	50–100	High surface area, enhanced storage	[76]
TiNbZrTa alloy surface	−28 to −32	~80	Stable oxide, good electrochemical response	[80]

These surface-level properties directly influence the interface between tissue and device, enabling controlled stimulation, sensing, and signal propagation in bioelectronic platforms.

4.4. Effect of Surface Treatments on Electrical Performance

Surface treatments improve biocompatibility and modulate electrical behavior. Techniques such as anodization, acid etching, and coating deposition alter surface morphology, oxide composition, and charge transport characteristics [73,81].

Anodized surfaces typically show increased capacitance and reduced impedance, while coatings with conductive polymers or carbon-based materials enhance signal transduction [82–84]. Table 8 presents comparative data on electrical performance before and after surface modification.

The sequence and impact of surface treatments on Ti alloys are summarized in Figure 7, which outlines the progression from mechanical polishing to advanced coating deposition and their corresponding effects on electrical properties.

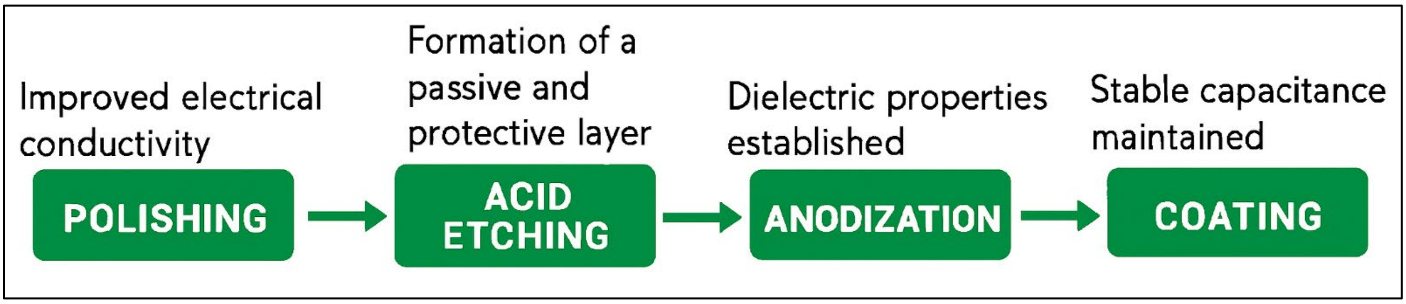

Figure 7. Surface treatment steps and their electrical effects.

Table 8. Influence of surface treatments on electrical properties of Ti alloys.

Treatment Method	Impedance at 1 kHz (kΩ)	Capacitance (μF/cm^2)	Notes	References
Polished Ti	>50	~10	Low surface area	[85]
Acid-etched Ti	~30	~20	Moderate improvement	[79]
Anodized TiO$_2$ nanotubes	<15	50–100	High charge storage	[76]
PEDOT:PSS coating	<10	>100	Conductive polymer, signal fidelity	[82]
Graphene oxide layer	~12	~90	Biocompatible and conductive	[83,84]

The ability to tailor surface electrical properties through treatment and coating strategies enables the development of Ti-based platforms suitable for advanced bioelectronic integration.

4.5. Electrical Behavior in Bioelectronic Applications

In bioelectronic systems, Ti alloys are used in components such as implantable electrodes, biosensors, and active scaffolds. Their electrical behavior must meet specific criteria for impedance, signal fidelity, and long-term stability [86].

Acceptable impedance values for neural and cardiac interfaces typically fall below 10 kΩ at 1 kHz, while capacitance above 50 μF/cm^2 supports efficient charge delivery [87]. Ti surfaces modified with conductive coatings maintain these parameters while preserving biocompatibility [88].

Applications include:

- Neural electrodes: Ti-based microelectrodes with PEDOT coatings [89].
- Biosensors: Ti substrates functionalized with enzyme or antibody layers [90].
- Smart scaffolds: Electrically active Ti meshes for tissue stimulation [91].

These systems benefit from the alloy's mechanical robustness, corrosion resistance, and tunable electrical interface.

Understanding the electrical behavior of Ti alloys in applied contexts reinforces the importance of surface engineering and electrochemical optimization, especially when transitioning toward multifunctional biomedical platforms.

Design criteria for Ti-based bioelectronic systems are briefly illustrated in Figure 8, which maps key electrical thresholds and surface engineering strategies across neural, sensing, and scaffold applications.

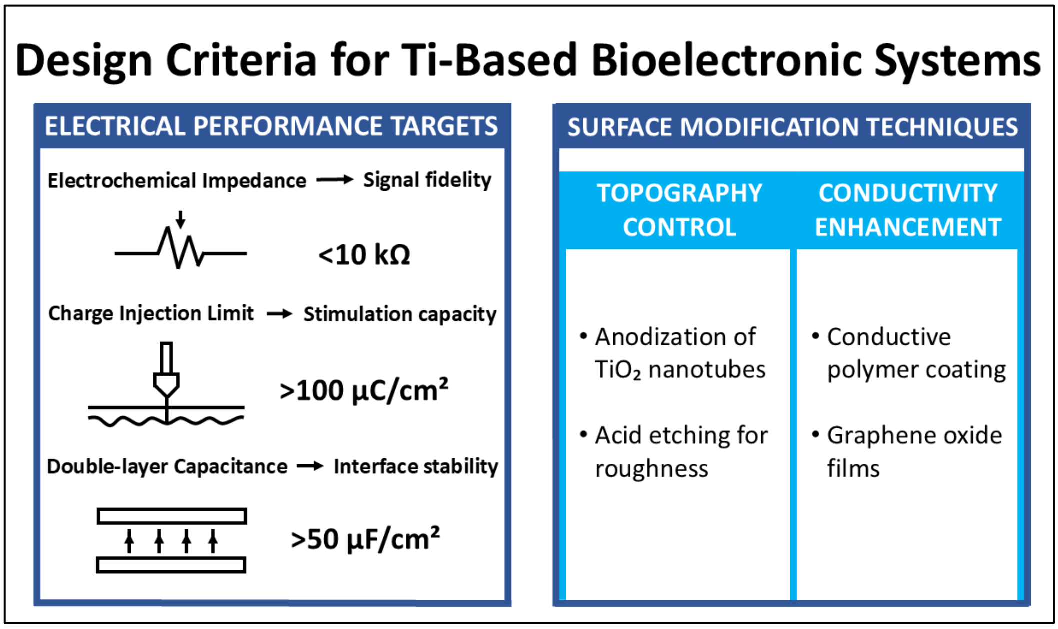

Figure 8. Electrical design targets for Ti-based biomedical systems.

5. Surface Modification for Dual Functionality

As Ti alloys evolve from passive implants to active bioelectronic interfaces, surface modification becomes a key strategy for achieving dual functionality—biological integration and electronic performance. The surface acts as the primary mediator between the material and its environment, influencing protein adsorption, cell behavior, corrosion resistance, and charge transport. This chapter explores how various surface treatments and coatings can be tailored to optimize both biological and electrical characteristics, enabling multifunctional applications in advanced biomedical systems [92,93].

5.1. Physical Surface Treatments

Physical modification techniques modify the topography and roughness of Ti surfaces without changing their chemical composition. Methods such as sandblasting, laser texturing, and mechanical polishing are commonly used to enhance cell adhesion and to modulate electrical impedance [94–96].

Laser-treated surfaces with microgrooves (Ra ≈ 1.5 μm) show improved osteoblast alignment and up to 40% higher ALP activity compared to polished controls. At the same time, these textures reduce impedance by increasing effective surface area [97].

Beyond conventional physical treatments, several mechanical surface modification processes, including shot-peening, laser shock peening, and surface rolling, have also been explored for Ti alloys. These techniques introduce beneficial compressive residual stresses in the subsurface region, which significantly enhance fatigue resistance while simultaneously altering surface roughness and waviness. Such mechanically induced topographies can influence protein adsorption, early cell attachment, and electrochemical behavior by modifying the local strain state and defect distribution. Although their impact on high-temperature oxidation is less relevant for biomedical applications, these treatments become particularly valuable when combined with subsequent processes such as anodization, where improved oxide adhesion and stability have been reported. Incorporating mechanical treatments into the surface-engineering toolbox, therefore, broadens the range of tunable parameters for optimizing both biological and electrical performance [98,99].

Table 9 summarizes the effects of physical treatments on biological and electrical parameters.

Table 9. Impact of physical surface treatments on Ti alloy performance.

Treatment Method	Ra (μm)	ALP Activity (%)	Impedance at 1 kHz (kΩ)	Notes	References
Polished	<0.2	Baseline	>50	Low cell adhesion	[94]
Sandblasted	1.0–2.0	+25–30%	~30	Improved roughness	[97]
Laser-textured	~1.5	+40%	<20	Directional cell growth	[95]

Physical treatments lay the groundwork for further chemical or functional modifications, especially when targeting specific biological or electronic responses.

5.2. Chemical Surface Treatments

Chemical treatments modify the surface composition and reactivity, often enhancing oxide layer stability and bioactivity. Techniques include acid etching, anodization, and alkali treatment [100]. Generally, chemical treatments provide a versatile platform for tuning surface reactivity, enabling synergistic improvements in both biological and electronic domains.

Anodization produces TiO_2 nanotube arrays with diameters between 70 and 100 nm, which promote osteogenic differentiation and increase capacitance [101]. Acid-etched surfaces improve protein adsorption and reduce I_{corr} [102]. These effects are illustrated in Figures 9 and 10, which show comparative electrochemical performance metrics for different chemical treatments, and Table 10 presents comparative data on the chemical treatments.

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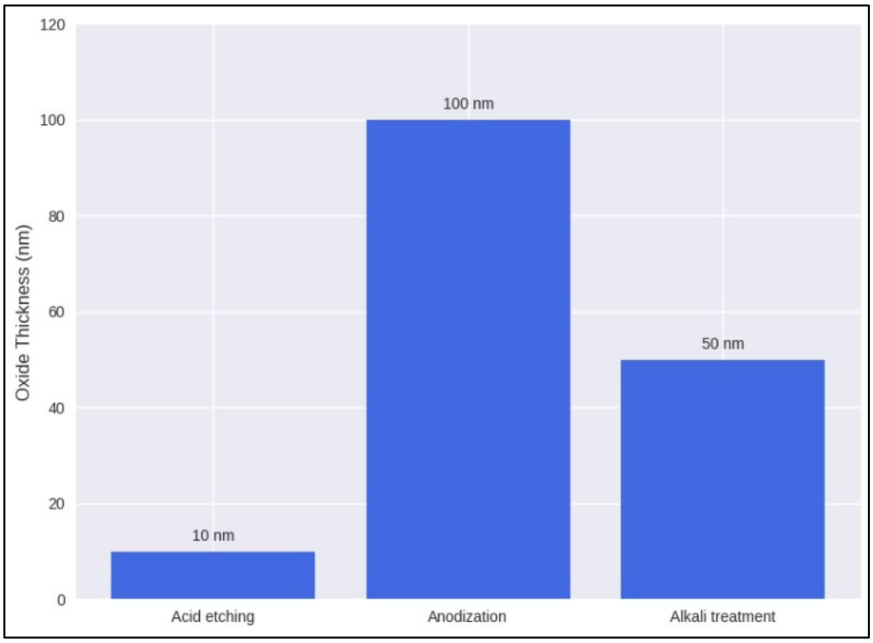

Figure 9. Oxide thickness by surface treatment.

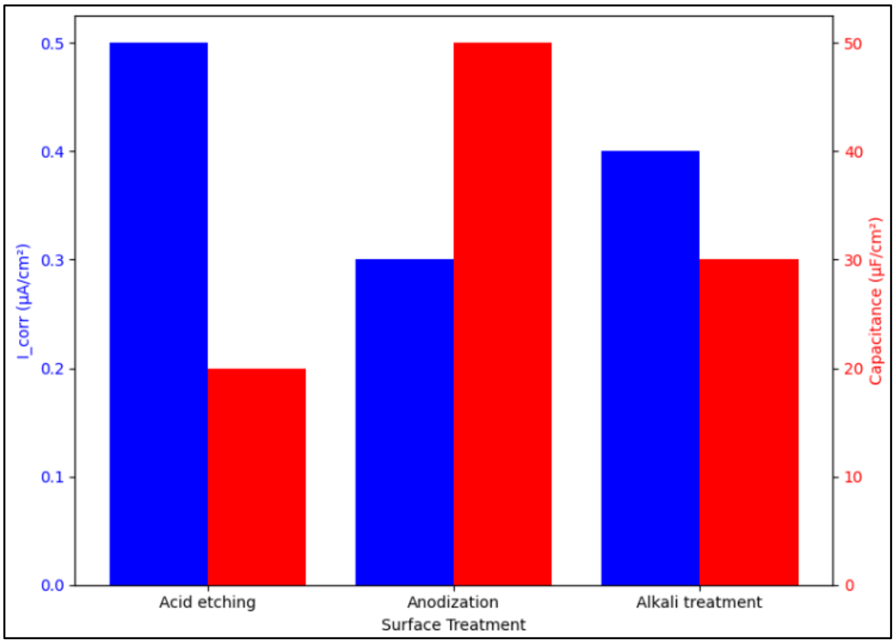

Figure 10. Comparison of I_{corr} and capacitance.

Table 10. Effects of chemical surface treatments on Ti alloy bioelectrochemical behavior.

Treatment Method	Oxide Thickness (nm)	I_{corr} (µA/cm²)	C_{dl} (µF/cm²)	Notes	References
Acid etching	~10	<0.5	~20	Enhanced protein binding	[102]
Anodization	100–150	<0.3	50–100	Nanotube formation	[103,104]
Alkali treatment	~50	<0.4	~30	Bioactive sodium titanate layer	[105]

5.3. Functional Coatings for Bioelectronic Integration

Functional coatings introduce new surface properties by applying bioactive or conductive layers. These coatings can be organic (e.g., polymers), inorganic (e.g., HA), or hybrid composites [106,107].

Conductive polymers such as PEDOT:PSS ensure high cytocompatibility (over 90% viable cells) and reduce impedance below 10 kΩ at 1 kHz [108,109]. Graphene oxide coatings enhance signal fidelity while supporting stem cell proliferation [110]. HA improves bone bonding but has limited conductivity [111].

Table 11 compares key coating types and their dual functionality.

Table 11. Functional coatings and their impact on biological and electrical performance.

Coating Type	Cell Viability (%)	Impedance at 1 kHz (kΩ)	Notes	References
HA	>95	>50	Notable osseointegration	[112]
PEDOT:PSS	>90	<10	Conductive, biocompatible	[108]
Graphene oxide	>92	~12	Signal enhancement, cell support	[84]

Functional coatings enable precise control over surface behavior, bridging the gap between biological compatibility and electronic responsiveness.

5.4. Hybrid and Multilayer Strategies

Hybrid approaches combine multiple treatments or coatings to achieve layered functionality. For example, anodized surfaces coated with PEDOT:PSS offer both high capacitance and high cell adhesion [108]. Multilayer systems may include bioactive primers, conductive layers, and protective topcoats [113].

These strategies allow for spatial control of properties—such as having conductive zones for stimulation and bioactive zones for integration—within a single device.

Hybrid surfaces have demonstrated impedance values below 8 kΩ, with cell coverage exceeding 95%, making them ideal for multifunctional implants [92].

Integrating multiple surface strategies into a unified architecture opens new possibilities for responsive, adaptive biomedical platforms that interact dynamically with tissue and electronics.

6. Applications in Bioelectronics

The convergence of materials science, electronics, and biomedicine has enabled the development of bioelectronic systems that interact directly with living tissues. Ti alloys, with their unique combination of biocompatibility, mechanical strength, and tunable electrical properties, are increasingly used in devices that sense, stimulate, or modulate biological activity. This chapter explores key application areas where Ti-based platforms enhance the functionality, reliability, and longevity of bioelectronic devices, with emphasis on neural stimulation, bio-implants, and clinical translation.

6.1. Implantable Electrodes and Neural Interfaces

Ti alloys are widely used in implantable electrodes for neural stimulation and recording. Their corrosion resistance and stable oxide layer make them suitable for long-term implantation, while surface modifications enhance charge transfer and reduce impedance [114,115].

Electrodes coated with PEDOT:PSS or TiO_2 nanotubes exhibit impedance values below 10 kΩ at 1 kHz and maintain signal fidelity over extended periods [108]. In deep brain stimulation (DBS) and spinal cord interfaces, Ti substrates provide mechanical stability and compatibility with surrounding neural tissue [116].

Figure 11 illustrates a Ti-based DBS electrode, highlighting the layered structure and tissue interface.

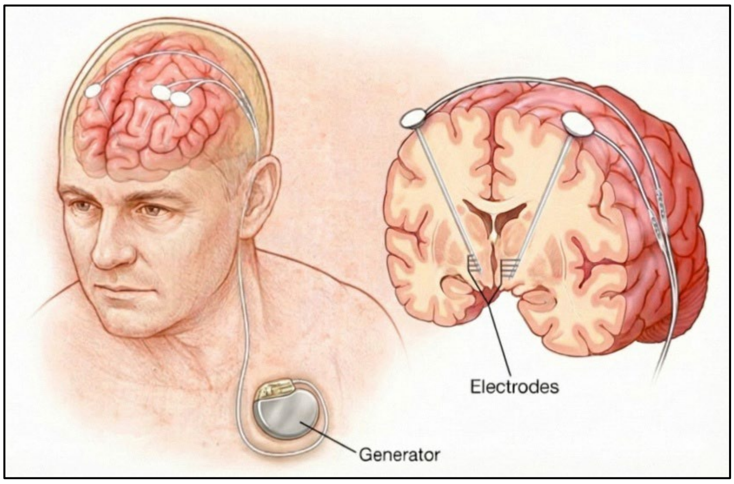

Figure 11. Ti-based deep brain stimulation electrode.

Figure 12 shows a spinal cord implant concept using Ti alloy electrodes for long-term stimulation and recording.

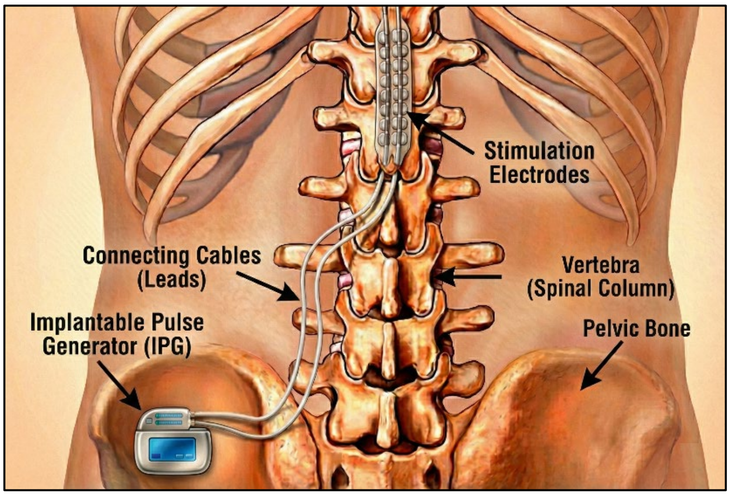

Figure 12. Spinal cord implant with Ti alloy electrodes.

Beyond their electrical performance, Ti-based neural interfaces are increasingly applied in clinical therapies. In DBS, Ti electrodes deliver controlled pulses to modulate abnormal brain activity in conditions such as Parkinson’s disease and epilepsy, while maintaining long-term stability in the brain environment. Spinal cord stimulation systems employ Ti alloy electrodes to reduce chronic pain and restore motor function, benefiting from the alloy’s mechanical resilience under dynamic loading. Compared to noble metals like Pt or Ir, Ti alloys offer a balance of biocompatibility, cost-effectiveness, and tunable surface properties, making them attractive for next-generation neural prostheses.

Table 12 summarizes performance metrics for Ti-based neural electrodes.

Table 12. Electrical performance of Ti-based neural electrodes.

Electrode Type	Impedance at 1 kHz (kΩ)	Charge Storage Capacity (μC/cm²)	Notes	References
Polished Ti	>50	~10	Low signal quality	[117]
TiO_2 nanotubes	<15	~50	Enhanced surface area	[118]
PEDOT:PSS coating	<10	>100	High fidelity, flexible	[119]
TiNbZrTa alloy surface	~12	~80	Stable and biocompatible	[120]

The performance of neural interfaces depends not only on electrical properties but also on long-term biostability, which is addressed through surface engineering and alloy selection [121].

6.2. Biosensors and Diagnostic Platforms

Ti alloys serve as substrates for biosensors that detect biochemical signals such as glucose, lactate, or neurotransmitters. Their surface can be functionalized with enzymes, antibodies, or aptamers to enable selective detection [122,123]. Figure 13 illustrates the layered design of the Ti-based biosensor, where the titanium substrate supports a conductive polymer and enzyme layer. The analyte interacts at the surface, producing a signal that is transduced through the underlying layers.

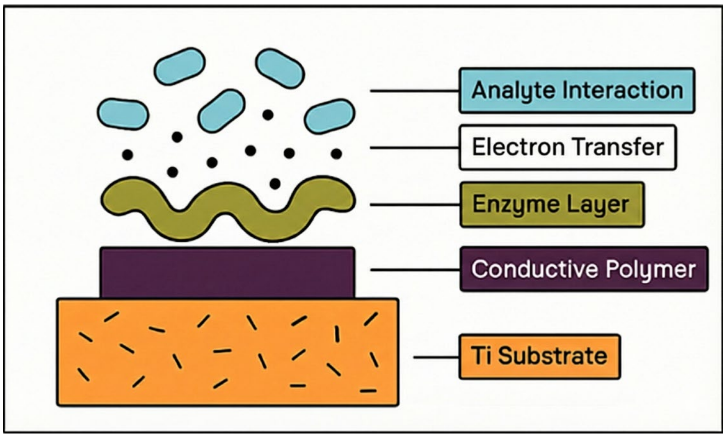

Figure 13. Ti-based biosensor structure.

Electrochemical biosensors based on Ti show sensitivity in the range of 10–100 μA/mM, with response times under 5 s [124]. Nanostructured surfaces improve signal-to-noise ratio and enable miniaturization for wearable or implantable formats [125]. Figure 14 illustrates the conceptual design of a Ti-based biosensor implant. The figure highlights how the titanium substrate and functional layers interact with biological analytes in vivo, enabling continuous monitoring and signal generation within a biomedical environment.

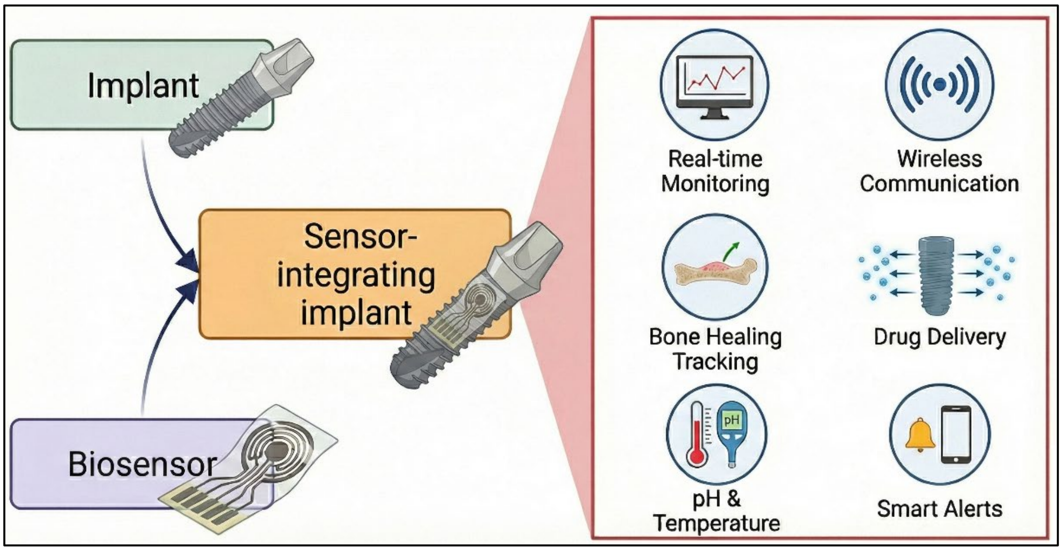

Figure 14. Ti-based biosensor implant concept.

Ti-based biosensors are increasingly applied in clinical and point-of-care diagnostics. Glucose sensors support diabetes management by enabling continuous monitoring of blood sugar levels, while lactate sensors are used to track metabolic activity during critical care and sports medicine. Dopamine sensors provide insights into neurological disorders, offering real-time monitoring of neurotransmitter fluctuations. The ability to integrate these sensors into implantable or minimally invasive devices makes Ti alloys particularly valuable for long-term patient monitoring, where biocompatibility and stability are essential.

Table 13 presents typical performance parameters for Ti-based biosensors.

Table 13. Performance metrics of Ti-based biosensors.

Sensor Type	Sensitivity (μA/mM)	Response Time (s)	Detection Limit (μM)	Notes	References
Glucose sensor (TiO_2)	~50	<5	~10	Enzyme-functionalized surface	[126]
Lactate sensor (PEDOT)	~70	<3	~5	Conductive polymer interface	[127]
Dopamine sensor (TiNbZrFe)	~90	<2	~1	High selectivity, low noise	[128]

The adaptability of Ti surfaces for biochemical functionalization supports the development of integrated diagnostic systems with real-time feedback capabilities [129].

6.3. Electrically Active Scaffolds for Tissue Engineering

In regenerative medicine, Ti-based scaffolds offer more than structural support—they can actively participate in tissue healing through electrical stimulation [130]. Figure 15 presents a 3D model of a porous Ti scaffold with embedded conductive coatings, designed to deliver localized electrical cues. This figure illustrates how the porous titanium structure, combined with conductive layers, enables controlled stimulation to guide cell growth and regeneration. By delivering controlled currents, these scaffolds influence cell proliferation, alignment, and differentiation, especially in muscle and nerve regeneration [131].

Scaffolds with embedded conductive coatings deliver stimulation currents in the range of 10–100 μA, promoting regeneration without inducing cytotoxicity [132]. The biological effect of electrical stimulation is visualized in Figure 16, which compares cell proliferation on stimulated versus non-stimulated scaffolds. Here, panel (a) shows limited growth without stimulation, while panel (b) demonstrates enhanced proliferation under electrical cues, highlighting the regenerative benefit. Porosity levels between 40 and 70% support nutrient diffusion and vascularization [133].

To achieve this, a controlled in vitro setup is used to apply electrical pulses to the scaffold. Figure 17 shows a typical experimental configuration used for electrical stimulation of Ti-based scaffolds in tissue culture environments. This figure depicts the laboratory setup where electrical pulses are applied, illustrating how stimulation is delivered during cell culture experiments.

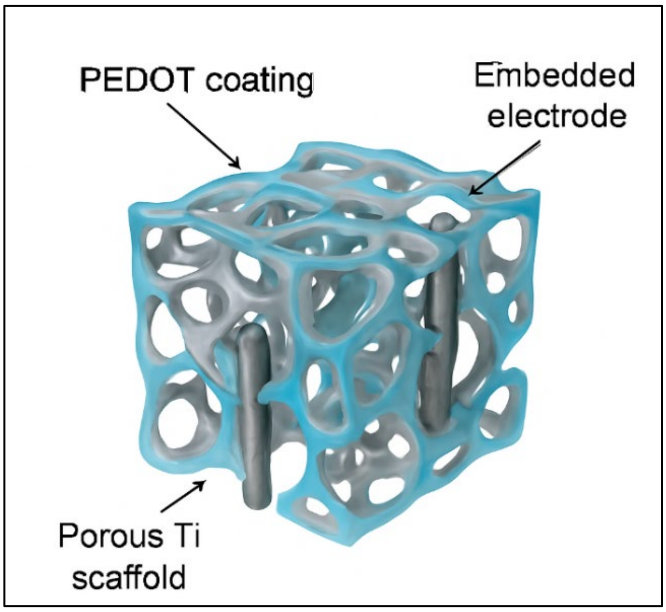

Figure 15. Porous Ti scaffold model.

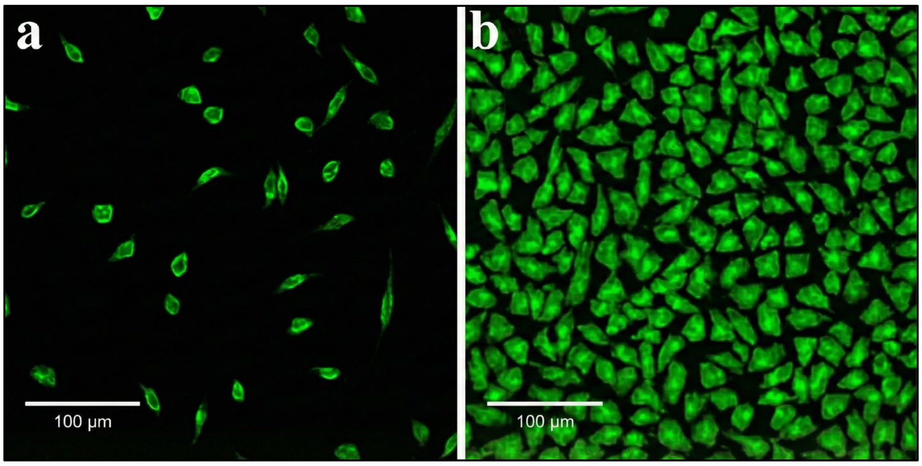

Figure 16. Cell growth with electrical stimulation. (**a**) Non-stimulated. (**b**) Stimulated.

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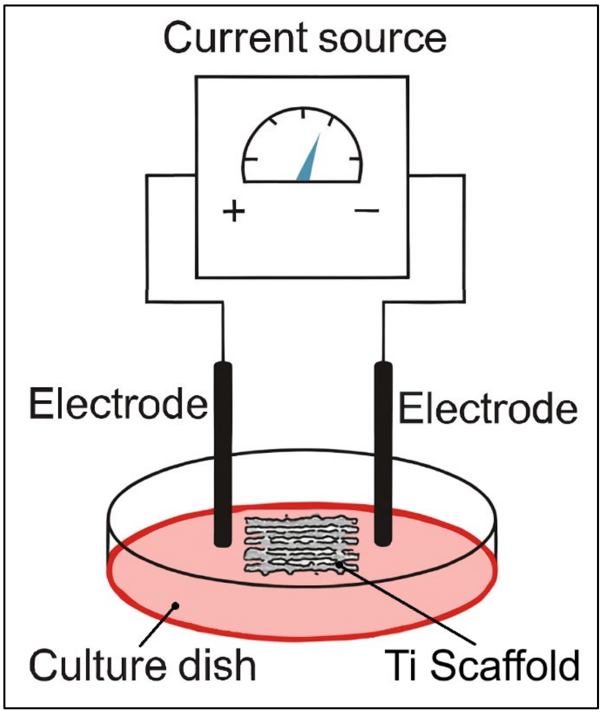

Figure 17. Setup for scaffold stimulation.

Clinically, Ti scaffolds are being investigated for bone healing, peripheral nerve repair, and muscle regeneration, where their combination of mechanical strength and bioelectrical activity supports faster recovery and improved tissue integration.

Table 14 outlines key parameters for electrically active Ti scaffolds.

Table 14. Properties of Ti-based scaffolds for tissue engineering.

Scaffold Type	Porosity (%)	Stimulation Current (μA)	Cell Viability (%)	Notes	References
Ti mesh (uncoated)	~40	Passive	~80	Structural support only	[134]
Ti + PEDOT coating	~50	10–50	>90	Enhanced proliferation	[130]
TiNbZrTa porous foam	~70	50–100	>95	High conductivity and biocompatibility	[135]

The ability to combine mechanical integrity with electrical stimulation makes Ti scaffolds a promising platform for smart regenerative implants and bioresponsive materials [136].

6.4. Cardiovascular and Muscular Interfaces

Beyond neural and regenerative systems, Ti alloys play a vital role in bioelectronic devices designed for cardiac and muscular tissues. Their fatigue resistance, corrosion stability, and adaptability to dynamic environments make them ideal for components such as pacemaker leads, defibrillator electrodes, and muscle stimulators [137].

Electrodes must deliver pulses with amplitudes of 1–5 V and durations of 0.1–1 ms, while maintaining low impedance and high charge injection capacity [138]. Ti-based systems successfully meet these requirements while also minimizing inflammatory response [139].

Applications in cardiac pacing and muscle rehabilitation demonstrate the versatility of Ti alloys in highly dynamic, load-bearing environments where electrical performance is critical [140].

Figure 18 illustrates a Ti-based muscle stimulation electrode, emphasizing adaptability in dynamic, load-bearing environments.

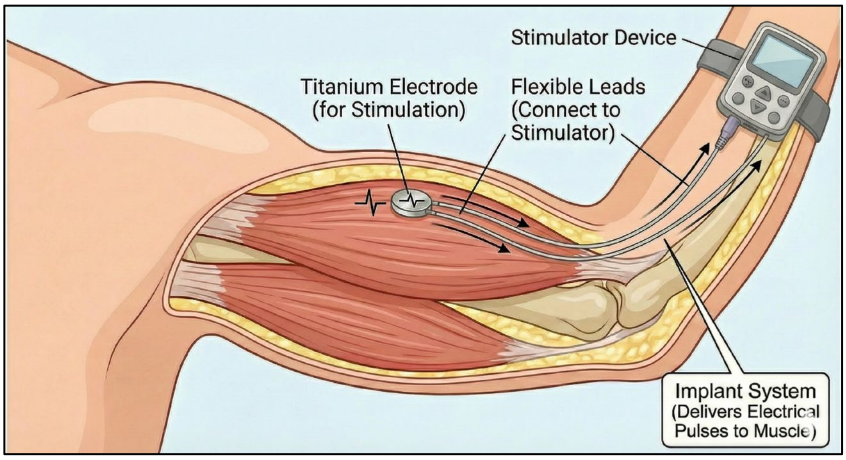

Figure 18. Muscle stimulation electrode using Ti alloys.

Figure 19 depicts a cochlear implant electrode array based on Ti alloys, showing integration with polymeric coatings for reliable auditory stimulation.

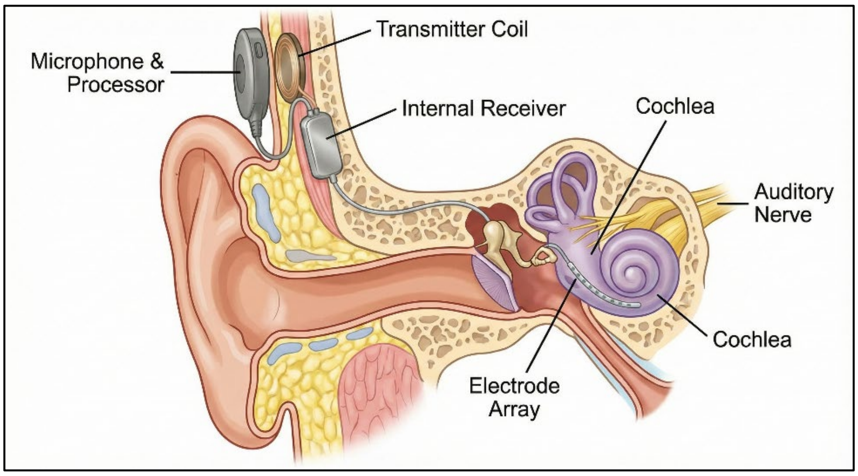

Figure 19. Cochlear implant electrode array with Ti substrate.

Clinically, Ti alloys are widely used in pacemaker leads and defibrillator electrodes, where their corrosion resistance ensures long-term reliability inside the cardiovascular system. In muscle rehabilitation, Ti-based stimulators deliver controlled electrical pulses to restore function after injury or surgery. Cochlear implants benefit from Ti substrates that provide stable electrode–tissue interfaces, enabling precise auditory stimulation and long-term implant durability. These applications highlight the role of Ti alloys in improving patient outcomes across cardiac, muscular, and sensory systems.

Ti alloys continue to expand their role in bioelectronic applications, offering a platform that supports both biological integration and electronic functionality. Their adaptability across diverse systems—from neural interfaces to regenerative scaffolds—reinforces the importance of advanced surface engineering and electrochemical optimization in next-generation biomedical devices [141].

In environments where magnetic interference must be minimized, Ti alloys serve as effective electromagnetic shields. Although pure Ti is weakly paramagnetic and does not retain magnetism, its alloys can attenuate electromagnetic fields, particularly in the 5G frequency range. This makes them suitable for housing highly sensitive bioelectronic components, especially in implantable or wearable systems operating in electromagnetically active settings [142].

7. Challenges and Limitations

Despite the promising performance of Ti alloys in bioelectronic systems, several challenges remain that limit their widespread adoption and long-term reliability. These limitations arise from material properties, fabrication constraints, biological interactions, and system-level integration. Understanding these barriers is essential for guiding future improvements and ensuring safe, effective deployment in clinical and research settings [1,62].

7.1. Electrical Constraints of Ti Alloys

Ti alloys exhibit moderate electrical conductivity compared to traditional electronic materials. While sufficient for low-current biomedical applications, their intrinsic resistivity can limit performance in high-frequency or high-resolution systems [62].

Efforts to improve conductivity through alloying or surface coatings must balance electrical gains with biocompatibility and corrosion resistance. Excessive doping or aggressive treatments may compromise biological safety or mechanical integrity [143].

Additionally, the variability in conductivity across different alloy batches and processing routes introduces inconsistency in device performance, requiring tighter control during manufacturing [144].

Recognizing the electrical limitations of Ti alloys helps define the boundaries of their application and encourages the development of hybrid systems that compensate for these constraints [1].

7.2. Surface Stability and Long-Term Performance

Although Ti forms a stable oxide layer, its electrochemical behavior can degrade over time in vivo due to protein adsorption, ion exchange, and mechanical wear. These changes may increase impedance, reduce signal fidelity, or trigger inflammatory responses [145].

Surface treatments such as anodization or coating deposition improve initial performance but may delaminate, dissolve, or lose functionality under physiological conditions. Multilayer coatings are especially vulnerable to mechanical stress and fluid infiltration [146].

Long-term studies have shown that impedance values can vary by 20–40% over several months, depending on surface architecture and implantation site. Such variability complicates calibration and reliability in chronic applications [147].

Addressing surface degradation requires a deeper understanding of dynamic biological environments and the development of self-healing or adaptive surface technologies [49].

7.3. Mechanical and Structural Trade-Offs

Optimizing Ti alloys for bioelectronic functionality often involves trade-offs with mechanical properties. For example, increasing porosity or applying soft coatings may reduce fatigue strength or compromise structural stability [148].

Beta-type alloys with lower elastic modulus are preferred for reducing stress shielding, but they may exhibit lower wear resistance or increased notch sensitivity. In load-bearing implants, these factors can lead to premature failure or reduced lifespan [149].

Fabrication techniques such as additive manufacturing offer design flexibility but introduce residual stresses and microstructural heterogeneity that affect both mechanical and electrical behavior [150].

Balancing mechanical robustness with electronic responsiveness remains a central challenge in multifunctional implant design [113].

7.4. Biological Compatibility Under Dynamic Conditions

While Ti alloys are generally biocompatible, their performance can vary under dynamic physiological conditions such as inflammation, infection, or mechanical loading. Processes such as ion release, surface roughening, and biofilm formation may alter tissue response and compromise device function [151].

In neural and cardiovascular applications, even subtle changes in surface chemistry or topography can influence cell adhesion, signal transmission, and immune activation. Multicomponent alloys must be carefully evaluated for cytotoxicity, especially when introducing elements such as Fe or Ta, which may affect biological response depending on concentration and release kinetics [141].

Interindividual biological variability—including age, metabolic rate, and immune profile—further complicates standardization and prediction of in vivo behavior. These factors underscore the need for personalized evaluation and adaptive design strategies [152].

Understanding the biological limitations of Ti alloys under real-world conditions is essential for developing safer and more adaptable bioelectronic platforms capable of maintaining long-term functionality in diverse patient populations.

Although Ti alloys are largely non-magnetic and considered safe for magnetic resonance imaging (MRI) environments, their presence can occasionally cause minor image distortions or signal artifacts. These effects depend on implant geometry, anatomical location, and imaging parameters, and must be evaluated clinically on a case-by-case basis to ensure diagnostic accuracy and patient safety [153].

8. Future Perspectives

Ti alloys have demonstrated remarkable versatility in bioelectronic systems, but their full potential is still unfolding. As research advances, future directions will focus on transforming these materials from passive interfaces into intelligent, responsive platforms that adapt to biological complexity.

One promising avenue is the development of smart surfaces—interfaces capable of sensing and reacting to environmental stimuli such as pH, temperature, or biochemical signals. These surfaces may incorporate:

- Stimuli-responsive polymers that adjust conductivity or release therapeutic agents.
- Self-healing coatings that restore electrochemical stability after damage.
- Bioactive layers that adapt to cellular signals and promote regeneration.

Such innovations could enable implants that not only integrate with tissue but also actively participate in therapeutic processes.

Another key direction involves the integration of Ti alloys with flexible and hybrid electronics. While Ti is inherently rigid, combining it with stretchable substrates, conductive polymers, or thin-film components can yield devices that conform to soft tissues. This opens possibilities for:

- Wearable biosensors with Ti foils and printed electronics.
- Flexible neural interfaces embedded in elastomeric matrices.
- Multilayered scaffolds combining structural support with electronic functionality.

In this context, hydrogel incorporation emerges as a complementary strategy. Hydrogels provide softness, biocompatibility, and water-rich environments that mimic native tissues. When combined with Ti alloys, they can reduce mechanical mismatch, enhance durability under physiological conditions, and enable flexible implant designs.

Hybrid Ti–hydrogel systems may therefore support long-term use in neural stimulation, bio-implants, and regenerative scaffolds.

Advances in custom manufacturing will also play a critical role. Additive techniques and laser-based processing allow for patient-specific implants with tailored geometries, porosity, and surface features. Future developments may include:

- Multi-material printing that fuses Ti with bioresorbable or conductive phases.
- On-demand fabrication for rapid prototyping and clinical translation.
- Graded structures that optimize mechanical and electrical performance simultaneously.

Looking ahead, long-term monitoring and adaptive feedback systems will become increasingly important. Ti-based platforms may serve as anchors for embedded sensors, wireless telemetry, and closed-loop control systems that adjust stimulation or sensing parameters in real time. Key features may include:

- Integrated impedance monitoring to track tissue response.
- Wireless communication modules for data transmission and power delivery.
- Closed-loop control that adapts stimulation based on physiological feedback.

These capabilities will enhance safety, personalization, and therapeutic efficacy in chronic applications.

The future of Ti alloys in bioelectronics lies in their ability to support multifunctional, adaptive systems that respond intelligently to the body’s needs. Continued progress will depend on interdisciplinary collaboration and a deeper understanding of how materials, biology, and electronics converge at the interface of innovation.

9. Conclusions

Ti alloys have evolved from conventional structural materials into multifunctional platforms capable of enabling advanced bioelectronic applications. Through careful alloy design, surface engineering, and electrochemical optimization, these materials now offer a unique balance of biocompatibility, mechanical integrity, and electrical responsiveness.

This review paper has explored the intrinsic electrical and electrochemical properties of Ti-based systems, highlighting how variations in composition and surface treatments influence conductivity, impedance, and long-term stability. By integrating physical, chemical, and functional modifications, Ti surfaces can be tailored to meet the dual demands of biological integration and electronic performance.

The key goal of the present paper was to provide an extensive overview of the use of Ti-alloys in electronics and biomedicine, focusing on a comprehensive analysis and synthesis of existing literature data to identify gaps and future research directions. To the best of our knowledge, in scientific literature, there are no review papers reporting the state of the art of the topic indicated in the title. Multidisciplinary research on the development of medical devices requires us to consider a comprehensive review of the existing materials, technology, fabrication/development, and/or characterization aspects, etc., rather than focusing on the novelty, which, in turn, is represented by the efficient integration of these aspects during the development of the specific smart devices; hence, for now, novelty aspects have been placed in the second plane in the experimental investigation of this research area.

Applications ranging from neural interfaces and biosensors to regenerative scaffolds and cardiovascular devices demonstrate the versatility of Ti alloys in complex and dynamic physiological environments. While challenges remain, including conductivity limitations, surface degradation, and mechanical trade-offs, ongoing research continues to push the boundaries of what these materials can achieve.

Looking ahead, the future of Ti in bioelectronics lies in its ability to support adaptive, intelligent systems that respond to the complexity of living tissues. Interdisciplinary collaboration will be essential to unlock new functionalities, improve long-term reliability, and translate laboratory innovations into clinically viable solutions.

This study provides a foundation for further exploration and development, positioning Ti alloys not just as passive components but as active participants in the evolution of biomedical technology.

Emerging applications such as electromagnetic forming, shielding, and hydrogen-based energy systems further expand the functional landscape of Ti alloys, suggesting new roles in responsive, energy-integrated biomedical platforms.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Ti	Titanium
CP	Commercially pure
HCP	Hexagonal close-packed
BCC	Body-centered cubic
SBF	Simulated body fluids
ALP	Alkaline phosphatase
PBS	Phosphate-buffered saline
MTT	Dimethylthiazol
LDH	Lactate dehydrogenase
AFM	Atomic force microscopy
HA	Hydroxyapatite
PEDOT	Conductive polymer
PEDOT:PSS	Conductive polymer mixed with polystyrene sulfonate
OCP	Open circuit potential
I_{corr}	Corrosion current density
R_p	Polarization resistance
C_{dl}	Capacitance
EIS	Electrochemical impedance spectroscopy
DPCEMF	Direct pulse current electromagnetic forming
DBS	Deep brain stimulation
MRI	Magnetic resonance imaging

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