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Ultrathin, Lightweight Materials Enabled Wireless Data and Power Transmission in Chip-Less Flexible Electronics

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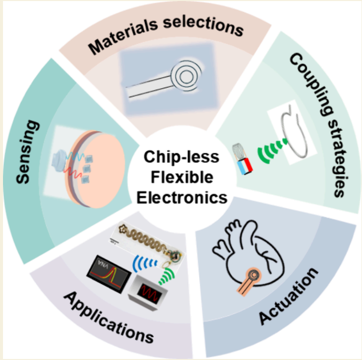
ABSTRACT: The surge of flexible, biointegrated electronics has inspired continued research efforts in designing and developing chip-less and wireless devices as soft and mechanically compliant interfaces to the living systems. In recent years, innovations in materials, devices, and systems have been reported to address challenges surrounding this topic to empower their reliable operation for monitoring physiological signals. This perspective provides a brief overview of recent works reporting various chip-less electronics for sensing and actuation in diverse application scenarios. We summarize wireless signal/data/power transmission strategies, key considerations in materials design and selection, as well as successful demonstrations of sensors and actuators in wearable and implantable forms. The final section provides an outlook to the future direction down the road for performance improvement and optimization. These versatile, inexpensive, and low-power device concepts can serve as alternative strategies to existing digital wireless electronics, which will find broad applications as bidirectional biointerfaces in basic biomedical research and clinical practices.



KEYWORDS: *Chip-less Electronics, Biosensing, Actuation, Thin-film Materials, Wireless Communication*

INTRODUCTION

In recent years, significant progress at the intersection of conventional technical fields has driven the surge of flexible electronics in various health-related domains such as biomedical research, precision medicine, and point-of-care.[1−4] Applications utilizing flexible electronics in these fields benefit from miniaturized form factors, enhanced biocompatibility, and improved conformability to living systems for reducing artifacts and minimizing resources.[5−7] A key technical requirement for bioelectronics is the wireless data and power transmission[8−10] capability for continuous and distanced monitoring. However, a major issue with conventional digital wireless schemes, such as near-field communication protocols and Bluetooth standards, is the use of rigid and bulky electronic components which include but are not limited to microprocessors, analog-to-digital converters, and power supply/management systems. The nonideal form factors of these subsystems usually lead to constraints of natural motions, reduced sensitivity, as well as overheating issues.[2,11]

To address this issue, chip-less technologies based on thin film materials have emerged as a promising alternative solution due to the remarkable improvement in production cost, power efficiency, fabrication ease, versatility, and biocompatibility. These technologies leverage the unique properties of thin film materials serving as sensing components, functional units, electrical interconnects, and substrates, to create electronic systems that do not require conventional integrated circuit chips. This perspective provides a brief overview of recently reported, representative chip-less bioelectronic systems designated to biomedical research and healthcare-related applications.[12,13] It covers material strategies involving the wireless transmission of data and power through the coupling of radiofrequency (RF),[14−16] acoustic,[17,18] and magnetic signals,[19,20] along with integrated electronics customized for various application scenarios spanning sensing, stimulation, drug delivery, illumination, and others. A concluding section summarizes current challenges and provides brief outlooks to the future roadmap, with the goal of inspiring continued efforts in this thriving field.

OVERVIEW OF RECENT CHIP-LESS BIOELECTRONICS

The development of chip-less bioelectronics requires the synergy of materials selection, structural engineering, wireless transmission strategies, and the careful coupling of key components to create lightweight and reliable functional

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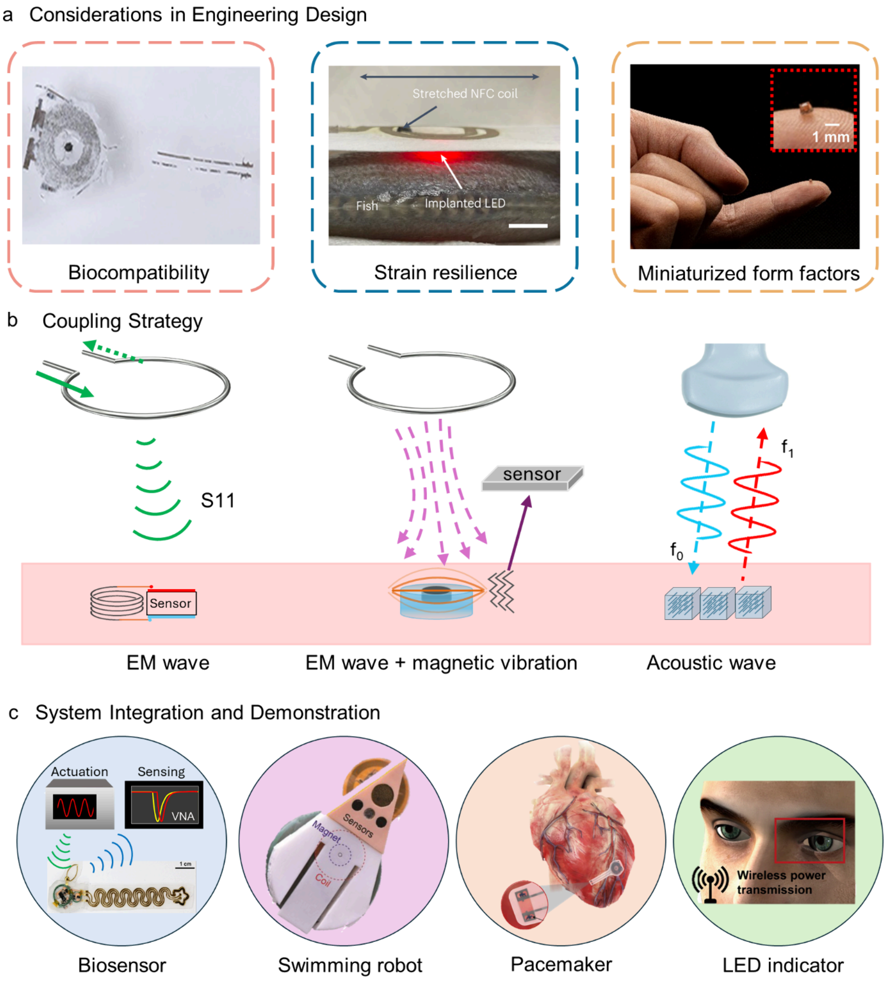

Figure 1. An overview of existing chip-less devices based on lightweight and/or thin film materials. (a) Key considerations in engineering design including biocompatibility (reprinted from ref 21 with permission from Springer Nature, Copyright 2021), strain resilience (reprinted from ref 23 with permission from Springer Nature, Copyright 2024) and miniaturization (reprinted with permission under a Creative Commons CC-BY 4.0 from ref 14 Copyright 2022 Advancement of Science (AAAS)). (b) Exemplary data and power transmission strategies involving the use of EM wave, magnetic vibration, acoustic wave, and their combinations. (c) Demonstrations of integrated chip-less electronics spanning biosensor (reprinted from ref 15 with permission from American Chemical Society, Copyright 2022), swimming robot (reprinted with permission under a Creative Commons CC-BY 4.0 from ref 24 Copyright 2024 American Association for the Advancement of Science (AAAS)), pacemaker (reprinted from ref 21 with permission from the Springer Nature, Copyright 2021), and LED indicator (reprinted from ref 25 with permission from American Association for the Advancement of Science (AAAS), Copyright 2018).

systems. Figure 1a summarizes some key considerations in engineering design reported in recent works, which include but are not limited to (1) Biocompatibility[21,22] of materials used to ensure a safe and seamless integration of the bioelectronics into the biological systems. Specifically, in the context of implantable devices, the use of bioresorbable materials for the entire chip-less device can reduce the risk of infection and eliminate the need for extraction surgery. (2) Strain resilience of materials to accommodate mechanical deformation, which may otherwise induce performance changes and potential interference with target signals.[17,23] (3) Miniaturized form factors[14,19] and structures reduce the burden on target hosts and constraint on natural motion while maintaining the coupling efficiency with the external power source.

Figure 1b shows schematic illustrations of predominant data and power transmission strategies commonly employed for chip-less devices in the research community: (1) Coupling an external transmitter and a biointegrated receiver through passive resonance: Emitting an RF wave from a coupling coil generates an electromagnetic (EM) field (Figure 1b, left). This induces an AC current flow in the receiver coil, allowing wireless power transmission within the working range. Furthermore, integrating responsive elements in the chip-less devices can lead to changes in the inductance, capacitance, and/or resistance of the resonance circuit in the presence of biosignals. This will result in a modulation of the characteristics around the resonance peak (i.e., amplitude or frequency change) of the receiver coil. Scanning the frequency band using the receiver coil determines the reflection coefficient S_{11}, which quantifies the modulation in these resonance characteristics correlated to target biosignals.[15] However, there are still several drawbacks to passive resonance. Although several studies have successfully incorporated fully biocompatible and even biodegradable components,[21,26] challenges remain in the miniaturization of such implants. The inclusion of circuit elements hinders the miniaturization of implant size and leads to biocompatibility and bioresorbability issues. Also, to ensure a high coupling coefficient, the distance between primary and receiver coils[27] should be close enough, which limits the communication range of the wireless system. Moreover, the

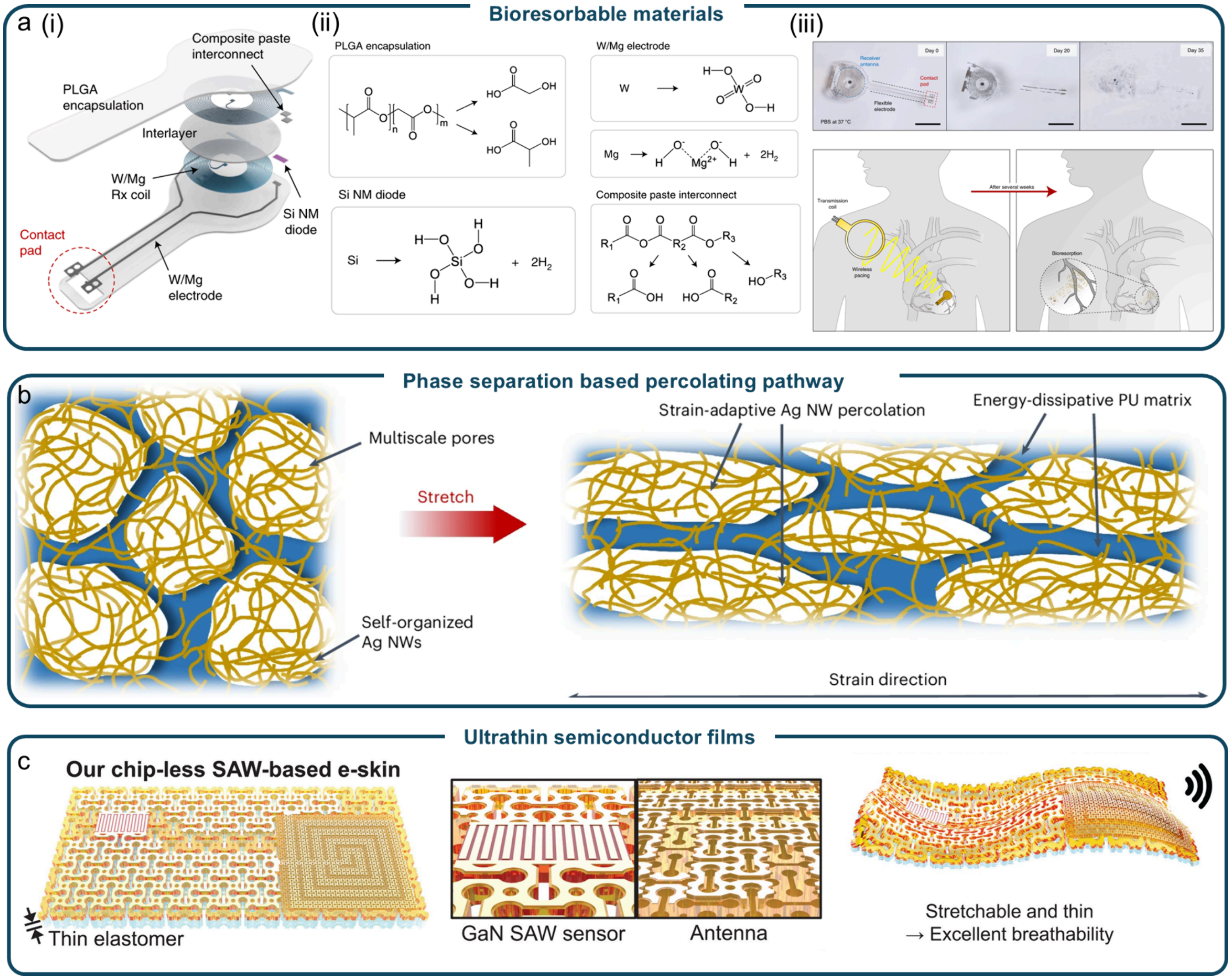

Figure 2. Materials strategies for designing chip-less devices to enhance the compatibility as flexible bio electronics. (a) Bioresorbable materials for implantable cardiac pacemakers without leads or batteries. Reprinted from ref 21 with permission from Springer Nature, Copyright 2021. (b) Phase-separated nanocomposite materials with ultralow percolation threshold. Reprinted from ref 23 with permission from Springer Nature, Copyright 2024. (c) Ultrathin semiconductor films used as SAW sensors in electronic skin facilitating chip-less and wireless data transmission. Reprinted from ref 17 with permission from the American Association for the Advancement of Science (AAAS), Copyright 2022.

performance of the resulting bioimplants is easily influenced by signal interferences from physiological surroundings and the geometry change.[17,18] All these factors impede the EM coupling-based electronics from further applications. To address these issues, recent works further introduces the combination of other strategies, including: (2) Surface acoustic wave (SAW) sensors[17,28] which contain an input interdigitated transducer (IDT)[29] to convert an EM signal into an acoustic wave and an output IDT working in the opposite way. The space between the two IDTs allows the SAW propagating with a much slower speed compared to RF waves, causing a measurable delay relative to the physical phenomena changes such as strain, pressure, mass and so on. (3) Magnetic resonator[19,20] which can be excited by EM waves without the need for any circuit elements or batteries (Figure 1b, middle). The excitation then initiates either a mechanical vibration or an EM signal, which could be modulated in both amplitude and frequency upon the binding of target analytes to the surface of the implants. An external transducer then captures the signals, conveying various biosignals to determine biophysical and biochemical conditions. (4) Metastructured hydrogel sensor[18] which is designed for ultrasonic monitoring of intracranial signals (Figure 1b, right). By applying the Bloch boundary conditions for the reflection of ultrasound waves, this wireless implantable sensor can monitor parameters in the human body, including pressure, flow rate, temperature and pH, and at the same time achieve millimeter-scale, bioresorbability, and long-distance sensing. More details are included in later sections.

Based on the considerations outlined above, recent years have witnessed successful system integrations of various device formats specialized for diverse target applications (Figure 1c). Examples include miniaturized sensors with designated biorecognition elements for biomarkers, wireless powered light emitting diode (LED) indicators for real-time display of sensing results, fully bioresorbable bioimplants such as pacemakers, and swimming robots for water quality monitor.[15,21,24,25] Details and exemplary demonstrations appear in the following sections of this perspective.

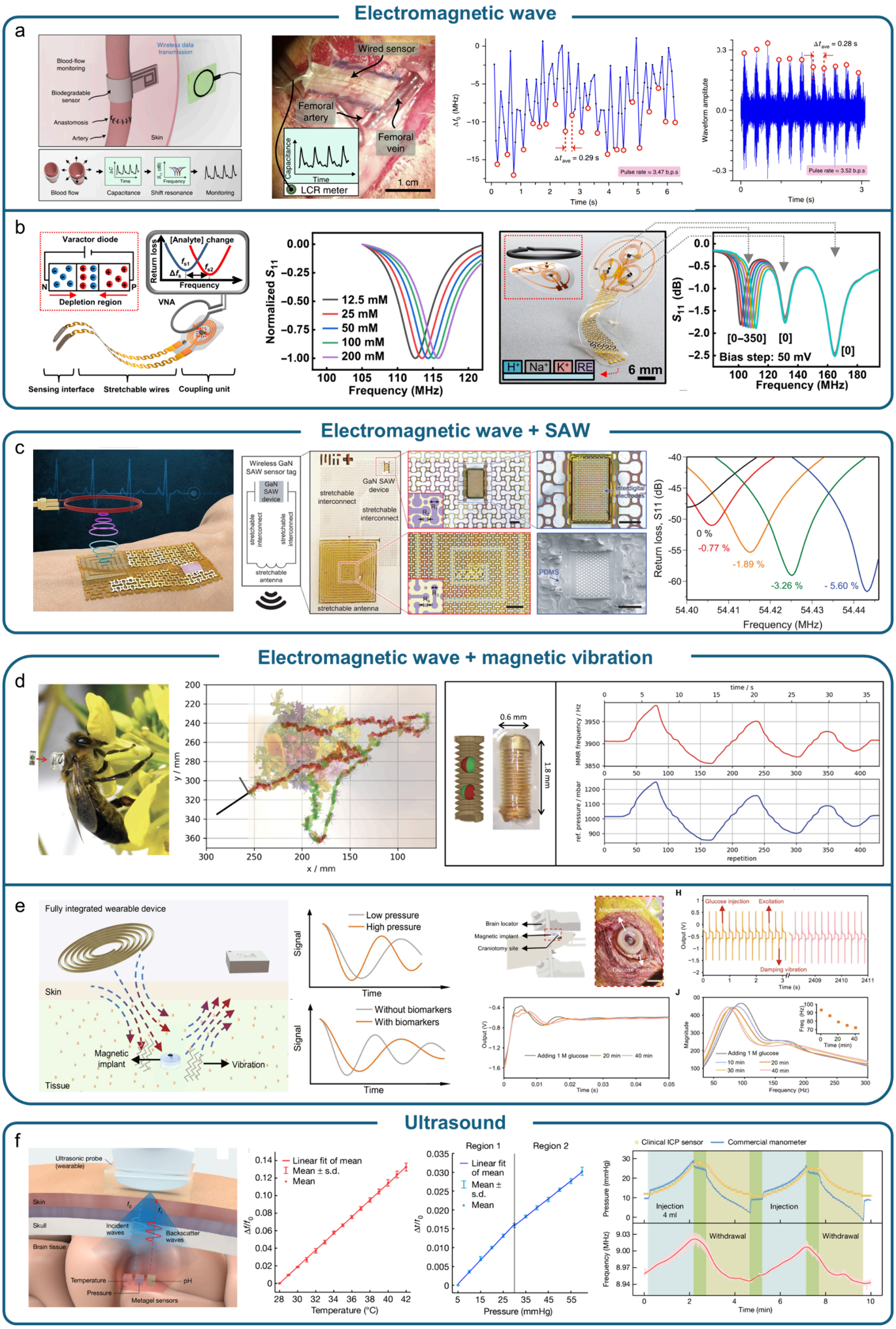

Figure 3. Recent advances in coupling strategies used for chip-less, passive wireless sensors for detection of various biosignals. (a) A biodegradable, flexible arterial pulse sensor leveraging an LCR resonance circuit for wireless blood flow monitoring. Validated through experiments on rat femoral arteries for dynamic blood flow recording. Reproduced with permission from ref 26 Copyright 2019, Springer Nature. (b) A wireless sensor system using LCR resonance with varactor diodes for detecting ions, serotonin, and glucose in body fluids. Multiplexed sensing is achieved by designing different sensors to operate with distinct resonance frequencies. Reprinted with permission under a Creative Commons CC-BY 4.0 from ref 14 Copyright 2022 AAAS. (c) A chip-less wireless electronic skin equipped with SAW sensors for monitoring strain, UV intensity, and ion concentration. The ultrathin single-crystal GaN converts electrical signals into surface acoustic waves, with quantifiable frequency shifts in response to strain. Reproduced with permission from ref 17 Copyright 2022 AAAS. (d) A wireless passive sensor based on magneto-mechanical resonators

Figure 3. continued

for monitoring position, posture, and pressure. Electromagnetic waves generated by the relative motion between magnets are reconstructed into position and angle information, enabling precise monitoring of movement and pressure changes. Reproduced with permission from ref 20 Copyright 2023 AAAS. (e) A wireless passive sensor system based on magnetoelastic resonators for detecting liquid viscosity, pressure, and biomarker concentration. This system enables wireless measurement of cerebrospinal fluid viscosity, intracranial pressure, and glucose concentration in rats. Reproduced with permission from ref 19 Copyright 2024 AAAS. (f) A wireless passive sensor based on ultrasonic metamaterial hydrogel for measuring intracranial pressure, temperature, and pH. Structural changes due to variations in these parameters cause shifts in the reflected ultrasonic frequency. Reproduced with permission from ref 18 Copyright 2024, Springer Nature.

MATERIALS STRATEGIES TO ENHANCE THE COMPATIBILITY FOR THE USE AS FLEXIBLE ELECTRONICS AND/OR BIOELECTRONICS

The elimination of rigid chips in such wireless electronics offers unique advantages for applications relying solely on thin-film materials. The following section briefly reviews recent works addressing key considerations in resorbability, stability, and performance reliability, emphasizing the importance of rational design and careful selection of building materials. First, the use of bioresorbable materials circumvents the need for extraction surgery, thereby reducing surgical risks for patients. As one example, for temporary cardiac pacemakers utilized in surgical recovery, adopting a chip-less design with wireless power transmission eliminates the need for percutaneous leads, thereby mitigating the associated infection risks. Figure 2a (i)[21] presents a design of a fully implantable and bioresorbable cardiac pacemaker without leads or batteries. This device incorporates bioresorbable poly(lactide-*co*-glycolide) (PLGA) as the encapsulation and interlayer material. Tungsten-coated magnesium (W/Mg) serves as the receiver coil and flexible extension electrode. The composite paste interconnect comprises W microparticles in Candelilla wax. Silicon nanomembrane (Si NM) functions as the RF PIN diode. The device undergoes bioresorption through hydrolysis and metabolic processes within the body. As depicted in Figure 2a (ii), PLGA resorbs into glycolic and lactic acid monomers, while W, Mg, and Si NM degrade into WOx, $Mg(OH)_2$, and $Si(OH)_4$, respectively. The cleavage of ester anhydride and hydrolysis facilitates the dissolution of Candelilla wax. Figure 2a (iii) shows that immersion in PBS at 37 °C results in the dissolution of the constituent materials within 5 weeks, with residues completely disappearing after 7 weeks. This bioresorbable device offers a promising solution to risks associated with removal. In addition to this example, there have been other similar recent works focusing on wireless bioresorbable pacemakers.[30,31] One study employs PLGA as an encapsulating layer, Mg as the metal interconnects, and a multifunctional interfacing hydrogel (MIH) as the contact to biotissues.[31] This MIH is a composite of silver nanoparticles, gallic acid, poly(acrylic acid) , 3-sulfonic acid propyl methyl acrylic acid potassium, and demonstrates both comparable mechanical strength and excellent adhesive properties.

Considering the absence of on-chip signal processing units, empowering the reliable operation of chip-less devices necessitates strain-resilient conductive elastic composites. Conductive fillers dispersed within elastomers, referred to as soft elastic conductive composite materials, serve as viable solutions toward this goal. Reducing the minimum required amounts of conductive fillers, known as the percolation threshold (V_c), enhances cost-effectiveness, stretchability, and flexibility of the composite. Specially, metal nanowires are particularly favored as fillers due to the high aspect ratio which helps reduce V_c. Figure 2b[23] presents a novel nanocomposite exhibiting an ultralow V_c and strain insensitivity. This material, termed phase-separated porous silver nanowire (Ag NW) nanocomposite (PSPN), offers significant advancements in the field. The fabrication of PSPN involves the initial mixing of polyurethane (PU) in tetrahydrofuran (THF) with a conductive filler solution composed of Ag NWs in ethanol. The subsequent evaporation of THF and ethanol induces phase separation between PU-rich and PU-poor phases, with Ag NWs preferentially residing within the PU-poor phase. This demixing process results in the formation of continuous porous structures within the PU matrix. Since the porous microstructure is energy-dissipative and there is a significant mechanical mismatch between the pores and the PU matrix, the AgNWs can retain their interconnected conductive networks within the pores even when the PU matrix undergoes significant deformation under strain. The microscale porous architecture is responsible for the observed ultralow percolation threshold. This PSPN material shows promise for application in chip-less bioelectronics for sensing and power transmission purposes. The device utilizing this material achieves wireless power transmission and sweat biomarker sensing with less than 10% performance variation, even under 50% strain. Other alternatives in this field involve the use of nanomaterials such as carbon nanotubes or nanosheets,[32,33] which also offer promising solutions for enhancing the performance of soft elastic conductive composites in chip-less bioelectronics.

For wearable electronics, another desirable key feature is the conformability to the skin and breathability. It is necessary to develop mechanically compliant thin-film semiconductors for on-chip signal transduction to replace conventional chips. A previous chip-less wireless strain sensor uses a resonant absorbing structure with a dipole array and stretchable silver-coated nylon fibers as the piezoresistive (PZ) material. Stretching the PZ sheet alters the sheet resistance, varying the reflection coefficient at the resonance frequency, from which the strain is extracted.[34] Figure 2c[17] introduces an epitaxial freestanding single-crystalline piezoelectric membrane of gallium nitride (GaN) for transducing signals based on SAW. A GaN ultrathin single-crystalline piezoe-lectric membrane, approximately 200 nm in thickness, can be grown on GaN substrates coated with 2D materials such as graphene or boron nitride. This membrane is subsequently released through a 2D material-based layer transfer (2DLT) process. The material exhibits high sensitivity to mechanical, optical, and biochemical signals, which it transduces into changes in resonance frequency. Integration of this material on a thin polydimethylsiloxane (PDMS) film, approximately 20 μm thick, enables breathability and the transfer of skin byproducts through perforations. This design eliminates the need for traditional chips and circuit components. Utilizing only the GaN film and interdigital electrodes, the device functions as a strain sensor. Additionally, coating the SAW device with ion-selective membranes (ISM) allows for the detection of variations in ionic concentration.

CHIP-LESS BIOELECTRONICS FOR SENSING

The EM coupling based on coils enables wireless data and energy transmission, which has been widely applied in sensing and actuation systems. Among these, the inductor-capacitor-resistor (LCR) resonance circuit represents a well-established model for wireless passive sensors. By connecting a network analyzer to the transmitting coil, the system emits sweeping EM waves, scans the frequency band, and monitors the energy inflow and outflow in real-time, represented by the S_{11} parameter.

When the input RF signal frequency matches the resonance frequency of the LCR circuit, the capacitive and inductive reactance cancel each other out, resulting in the impedance of the circuit reaching its minimum, leaving only the resistive component. At this point, the LCR circuit absorbs a significant amount of EM waves from the trans- mitting coil, causing the value of the S_{11} parameter to reach its lowest. The peak of the S_{11} parameter absorption indicates the resonance frequency of the LCR circuit, given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

where f_0 is the resonance frequency, L is the inductance, and C is the capacitance.

Relating the capacitance or inductance to the target signals enables wireless passive sensing. In practice, capacitive sensors are usually preferred in LCR circuits compared with inductive components due to their simple structure and high sensitivity. Figure 3a presents a biodegradable, flexible arterial pulse sensor for monitoring blood flow wirelessly, where the capacitive pressure sensor responds to the pressure signals from the blood vessel.[26] Wrapping the sensor around the femoral artery of a rat allows real-time monitoring. The measured pulse rate of 3.47 Hz closely matches the 3.52 Hz measured by external Doppler ultrasound. Occluding the femoral artery for 1 min and then releasing it shows a significant increase in the resonance frequency, demonstrating the effectiveness of the device in recording the dynamic blood flow process.

Due to the mechanism of capacitive sensing, the measured signals are primarily confined to physical signals such as temperature, stress, and strain. Expanding the capability to encompass biochemical sensing can be further achieved by integrating biorecognition elements at the interface. Figure 3b demonstrates a battery-free wireless sensor system for detecting biomarkers in body fluids.[14] This system utilizes the LCR resonance effect by replacing the traditional capacitive sensor with a varactor diode that converts surface potential change into capacitance modulation. The LCR resonance system is modularized into an alternating current (AC) part (coupling unit) that can be encapsulated separately and a functionalized direct current (DC) part (sensing interface) that contacts the target biological fluid. By using ISM, aptamers, and enzymes, the system enables wireless detection of ions such as K^+, Ca^{2+}, Na^+, and H^+, as well as serotonin and glucose. Designing the frequency distribution of the LC circuit allows for multiplexed sensing. Combining the modalities can potentially create various types of engineering tools for monitoring multiple biosignals through seamless and stable integration with target biosystems in wearable and implantable formats.

Due to the inherent mechanism of passive resonance, LCR sensors usually exhibit limited sensitivity, and their resonance frequency can be influenced by multiple factors, such as geometry of coils, lateral/vertical displacement, physiological electrical signals, and environmental noises. This leads to a certain level of unreliability even with pre- and postcalibrations. Alternatively, converting the RF waves to SAWs can enhance both the sensitivity and the anti-interference performance. Figure 3c presents a chip-less wireless electronic skin based on SAW sensors, achieving high sensitivity, low power consumption, and long-term monitoring of strain, ultraviolet (UV) intensity, and ion concentration.[17] A 200 nm ultrathin single-crystal GaN piezoelectric film, epitaxially grown and transferred onto a flexible patch, serves as the sensing element. When an external wireless reader emits EM waves, the stretchable receiver coil transfers the signal to the single-crystal GaN, acting as a piezoelectric resonator that converts the electrical signal into a SAW. Mechanical strain, mass changes (ion adsorption/desorption), and UV exposure cause frequency shifts in the piezoelectric resonator, which are converted back into electrical signals and transmitted to the external reader. Compared to LCR sensors (approximately 1%), it exhibits ultrahigh strain sensitivity (0.048%) and enables wireless monitoring of pulse signals. The matched bandgap of GaN also offers high selectivity of UV light, eliminating the need for filters and simplifying the sensor design. By integrating an ISM, ion adsorption induces mass and resonance frequency changes, achieving high accuracy in Na^+ detection.

Sensors based on passive RF resonance rely on coupling of coils for the quantification of return loss, which limits the working distance. In contrast, magnetically resonant sensors based on excitation separate energy supply from the sensing process. In this scheme, external coils provide initial energy for vibration, and sensing information is obtained by measuring changes in the frequency and amplitude of the electromagnetic field during oscillation. This method expands the sensing range, as the measurement of the electromagnetic field is less constrained by distance. Figure 3d demonstrates a sensor based on magneto-mechanical resonators for high-precision position, posture, and pressure sensing.[20] The sensor consists of two spherical NdFeB magnets: one fixed in a cylindrical housing and the other suspended by a thin wire. The magnetic pulses generated by the external coil array cause the suspended magnet to oscillate, producing electromagnetic waves that are then captured by the coil array. The frequency depends on the restoring torque of the fixed magnet, which is determined by the distance between the magnets. Using measurements from the external coil array, the position and orientation of the sensor (six degrees of freedom) can be reconstructed. Compared with conventional contact-based sensors, this system offers advantages such as smaller size, lighter weight, longer sensing range, and battery-less operation. While optical systems can also monitor position and posture, they rely on a clear line of sight and have lower accuracy in distance measurement without depth sensing technology. This allows real-time monitoring of bee movements (pitch, yaw, roll) and high-precision internal localization in gelatin phantoms.

When fixed in compressible housings, pressure changes alter the distance between magnets, leading to frequency shifts.

Since the external coil array functions both as a transmitting and receiving coil and requires analyzing the signal of each coil for sensor localization, complex external circuitry is needed, leading to a larger readout device. Further separating the activation and sensing components is expected to reduce complexity, minimize the external readout device size and enable bioelectronics applications. Figure 3e presents a wireless passive sensor for detecting liquid viscosity, pressure, and biomarker concentration.[19] An external coil excites a magnet on an elastic membrane, causing it to displace and vibrate. These vibrations are detected by a tunneling magnetoresistance (TMR) sensor. The decay of the vibration signal of the magnet depends on the viscosity of the liquid: higher viscosity leads to faster decay. The vibration frequency of the magnet in a sealed chamber (1 atm) depends on external pressure: higher pressure results in higher frequency. After surface-specific chemical modification, glucose can specifically bind to the sensor; higher glucose concentrations lead to lower vibration frequencies. This setup enables wireless measurement of the viscosity of cerebrospinal fluid (CSF), intracranial pressure, and CSF glucose concentration in rats.

Table 1. Chip-Less Bioelectronics for Sensing Discussed in This Perspective

Sensing principle	Sensing target	Sensing range	LoD	Sensitivity	Resonance frequency	Sensing distance	Ref
EM	Pressure	0−300 kPa		0.84 fF kPa^{-1}	−30−10 MHz (frequency shift)	Contact	26
EM	K^+	12.5−200 mM	10^{-6} μM	2.66 MHz decade^{-1}	100−180 MHz	Contact	14
	Ca^{2+}	0.625−20 mM		1.10 MHz decade^{-1}			
	Na^+	18.75−250 mM		1.42 MHz decade^{-1}			
	H^+	0.044−37.16 uM		2.36 MHz decade^{-1}			
	Serotonin	10^{-8}−100 uM		0.1 MHz decade^{-1}			
	Glucose	100−700 uM	27 μM	0.00154 MHz uM^{-1}			
EM + SAW	Strain Na^+	−5.6−16.6% 0−85 mM	0.048% 0.86 mM	2 MHz %$^{-1}$ 0.073 dB mM^{-1}	54.40−54.45 MHz	14 mm	17
EM + magnetic vibration	Position				3850−4000	25 cm	20
	Pressure	0−400 mbar		0.34 Hz mbar^{-1}	Hz		
EM + magnetic vibration	Viscosity	3.466−4.787 cP		5.05 fitted damping factor cP^{-1}	70−180 Hz	5 mm	19
	Pressure	3−5 kPa		4.44 Hz kPa^{-1}			
	Glucose	2−30 mM		−0.1036 Hz mM^{-1}			
Ultrasound	Pressure	0−70 mmHg	0.1 mmHg	5.7 kHz mmHg^{-1}	8.4−9.6 MHz	10 cm	18
	Temperature	2−43 °C	0.1 °C	80 kHz °C^{1-}			
	pH	pH 2−8	0.5 pH	256.4 kHz pH^{-1}			

Table 2. Chip-Less Bioelectronics for Modulation and Actuation Discussed in This Perspective

Device format	Resonance frequency	Actuation mechanism	Location	Target application	Ref
Swimming robot	5.3 MHz	RF energy wirelessly powering the electromagnetic swimmer periodically beating its tail for locomotion	Water pipe, pool, and others	Monitoring water quality in environment	24
Wearable "flower-shaped" sensor	13.3 MHz	RF energy controlling proton release from Pd electrode, enabling the regeneration of sensors with pH-sensitive aptamers	Skin surfaces (such as the forehead, arm, back, and so on)	Continuous detection of addictive drugs such as cocaine	15
Cardiac pacemaker	13.5 MHz	Electrical pulses inducing ventricular contraction	Myocardial tissue	Cardiac surgery recovery	21
Smart contact lens	50 MHz	RF energy wirelessly powering the LED	Eyeball	Indication of high glucose concentration in tears	25
Implantable illuminator	50 MHz	RF energy wirelessly powering the LED	Between the skin and muscle on the ventral side of the animal	N/A	23
Smart contact lens	850 kHz	RF energy wirelessly facilitating iontophoresis from hydrogels	Eyeball	Acute angle-closure glaucoma treatment	35

For the operation of chip-less devices, ultrasound serves as another promising transmission medium in addition to EM waves as the predominant species discussed here due to its higher penetration depth and resistance to interference. Figure 3f presents a sensor based on ultrasonic metamaterial hydrogel for passive measurements of intracranial pressure, temperature, and pH.[18] The ultrasonic system comprises an ultrasonic transducer, a transmitter/receiver unit, and a data acquisition card. The ultrasonic transducer converts electrical signals into ultrasound waves (transmission mode) and transforms ultrasound waves back into electrical signals (reception mode). The probe first emits ultrasound waves, which are reflected by the sensor. At this point, the transducer swiftly switches to reception mode to capture the reflected waves. The data acquisition card records the signals measured by the ultrasonic transducer in real time, and the data is then analyzed and processed using MATLAB. The sensor consists of a hydrogel matrix with periodically arranged internal air channels, reflecting incident ultrasonic waves. Environmental changes cause deformation of the microstructure, leading to frequency shifts in the reflected waves. Poly(vinyl alcohol)/carboxymethyl cellulose gel, thermosensitive poly(vinyl alcohol)/polyacrylamide gel, and protonated poly(vinyl alcohol)/chitosan gel achieve resolutions of 0.1 mmHg for pressure, 0.1 °C for temperature, and 0.5 pH units. In vivo experiments on rats and pigs demonstrate detection accuracy comparable to commercial sensors, successfully measuring intracranial pressure fluctuations caused by respiration (approximately 1 mmHg). A comprehensive summary of the sensing principles, targets, and performance metrics of all sensors discussed in this section is provided in Table 1.

CHIP-LESS BIOELECTRONICS FOR MODULATION AND ACTUATION

In addition to sensing applications, coupling the chip-less devices with an external power source can enable the actuation to target systems. The operation typically requires a higher power supply than that needed for sensing, to trigger the onset of the modulation process. Recently reported examples include swimming robots, regenerate sensors, pacemakers, implantable illuminators, LED indicators, and drug delivery contact lenses, as detailed in this section (Table 2).

Creating lightweight, battery-free, and wireless transmission systems is critical for mobile electronic systems designed to detect water quality in domestic and industrial pipes, where wiring presents significant challenges in long pipelines. Figure 4a[24] illustrates a design for a swimming robot aimed at water quality detection. This robot employs an Arduino Leonardo

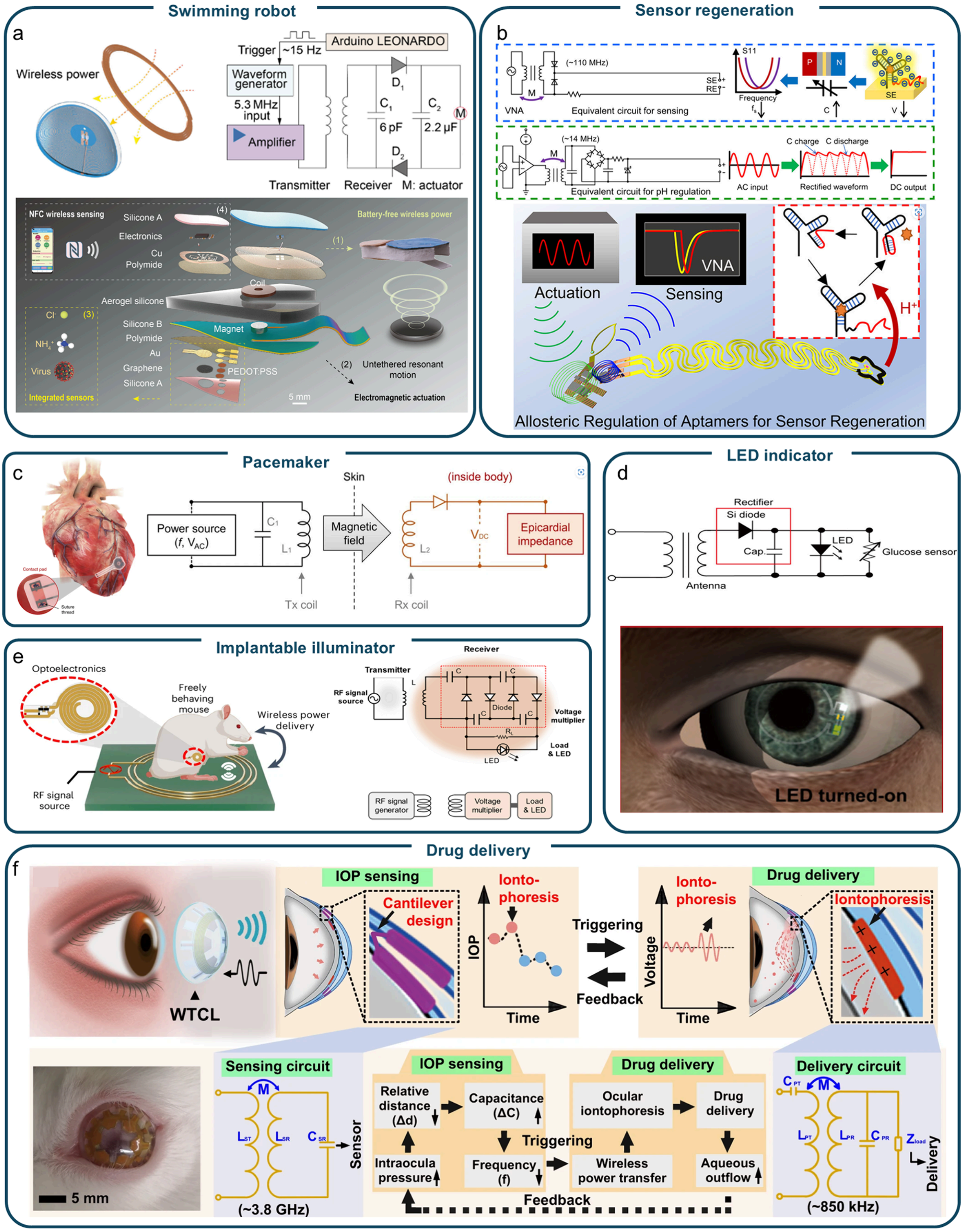

Figure 4. Different chip-less, flexible actuators with wireless data and power transmission capability for modulating the environment, and the corresponding circuits. (a) A wirelessly powered swimming robot for detecting the water quality. Reprinted from ref 24 with permission from American Association for the Advancement of Science (AAAS), Copyright 2024. (b) A regeneratable cocaine sensing scheme enabled by allosteric regulation of pH sensitive aptamers. Reprinted from ref 15 with permission from American Chemical Society, Copyright 2022. (c) An implantable cardiac pacemaker. Reprinted from ref 21 with permission from the Springer Nature (AAAS), Copyright 2021. (d) An LED indicator on smart contact lens indicating changes in glucose concentration in tears. Reprinted from ref 25 with permission from American Association for the Advancement of Science (AAAS), Copyright 2018. (e) An implantable illuminator with wireless power controlled on and off. Reprinted from ref 23 with permission from Springer Nature, Copyright 2024. (f) A wireless theragnostic contact lens for antiglaucoma drugs administration. Reprinted with permission under a Creative Commons CC-BY 4.0 from ref 35 Copyright 2022 Springer Nature.

board to generate a low-frequency signal ranging from 10 to 20 Hz, serving as a trigger to switch a waveform generator on and off, which then delivers a 5.3 MHz input. The amplified signal is transmitted through a coil emitting RF EM waves. A receiver coil on the robot with a matching 5.3 MHz resonance frequency captures the RF energy. After rectification and stabilization, the periodic voltage is applied to an actuation coil, generating periodic Lorentz forces on the magnets attached to the soft tail of the robot for propulsion. The robot incorporates an NFC module for the collection and transmission of data regarding SARS-CoV-2, temperature, NH_4^+, and Cl^- in the water to a smartphone app. To minimize interference between the sensing and actuation units, the operation frequencies are carefully separated.

Specifically, the wireless data transmission module operates at 13.56 MHz, while the actuation system functions at 5.3 MHz.

When paired with properly designed biochemical interfaces, powering chip-less devices using RF energy can support wireless sensing followed by sensor regeneration for continuous monitoring of biomarkers. A recent study shows an example of using pH-sensitive allosteric aptamers for regeneratable cocaine sensing (Figure 4b[15]). The binding of cocaine to aptamers results in a conformational rearrangement of the negatively charged backbones of the DNA strand. The change in surface potential can be wirelessly transmitted through a passive LC resonance circuit with a pair of varactor diodes (as described in Figure 4b). A palladium (Pd) electrode located surrounding the sensing electrode allows for controlled modulation of the pH value in the localized area when powered by an EM wave: Under a negative voltage, the formation of PdH_x stores protons; under a positive voltage, protons are released, resulting in localized pH regulation. The pH-sensitive aptamer can release cocaine in an acidic environment. Increasing the pH allows the aptamer to interact with cocaine again. A vertically aligned transmission coil wirelessly transfers RF power at 13.3 MHz to the inductive coupling unit on the pH regulation circuit. After rectification by a full-wave bridge rectifier, smoothing by a capacitor, and voltage stabilization by a Zener diode regulator, the final DC voltage of approximately 1.1 V is applied to the Pd-coated metal trace around the sensing site, achieving local pH modulation. Separating the resonance frequency of the coupling unit for sensing and actuation minimizes the interference.

Wireless and chip-less technologies also offer significant benefits for bioimplants, such as pacemakers in cardiac science. Conventional pacing leads require epicardial implantation, while the external power supply and control system must remain outside the body. This leads to potential risks of infection and dislodgement due to the transcutaneous connecting wire. Figure 4c[21] illustrates a wireless and implantable pacemaker design built on bioresorbable materials. A function generator produces alternating currents, delivering monophasic RF energy at 13.5 MHz to the transmission coil, with voltage amplified to 7 V. The power is then captured by the receiving coil on the implanted and converted to direct current using an RF diode. The electrode pads deliver the output voltage to the myocardial interface, initiating cardiac excitation when the voltage exceeds the threshold. Adjustments to the output voltage are achieved by varying the coil-to-coil distance, resonance frequency, and other parameters to meet therapeutic requirements, guided by the patient's ECG signals. This design eliminates the risks associated with transcutaneous wires and provides a safer and more reliable solution for cardiac pacing.

Smart contact lenses serve as promising candidates for wirelessly and continuously detecting important biomarkers in tears. However, one significant challenge is the presence of rigid chips that obstruct vision and may irritate the eyes and eyelids. Additionally, the bulky equipment required for signal measurement is typically inconvenient. Chip-less passive resonators can effectively address this issue by minimizing the discomfort level. Figure 4d[25] depicts a design that enables the wireless activation of an LED pixel and a glucose sensor. The coil receives RF signals from transmitter coil, which are rectified by a diode and a capacitor, converting the AC signal into DC to power the LED and sensor. Variations in glucose concentration alter the resistance of the sensor, subsequently influencing the bias applied to the LED, resulting in its activation or deactivation. This design facilitates the wireless, real-time display of glucose concentration changes.

For bioimplants, wireless power transmission and chip-less construction are advantageous for enabling the subject's free movement. Figure 4e[23] shows a wireless illuminator utilizing a stretchable PSPN as the conductor. This material facilitates the fabrication of the implanted receiver coil and circuit, allowing adaptation to curved body contours while maintaining a high stability in electrical performance. The device is implanted between the skin and muscle on the ventral side of a mouse, where it captures the RF signal from an external transmitter. Through rectification and the multiplication of a voltage multiplier composed of capacitors and diodes, the system generates DC voltage to illuminate a red LED, suggesting the capability of using the wireless transmission strategy to control bioimplants.

For glaucoma patients, an increase in intraocular pressure (IOP) poses significant risks, potentially leading to vision deterioration. A chip-less contact lens with wireless

data and power transmission offers a solution by delivering antiglaucoma drugs promptly and in situ, without obstructing vision. Figure 4f[35] illustrates a wireless theragnostic contact lens (WTCL) utilizing a cantilever design that responds ultrasensitively to IOP changes. The LCR circuit in the lens detects these changes, causing a shift in the resonance frequency around 3.8 GHz. Upon detecting this shift, an exterior coil wirelessly transmits an RF power at 850 kHz to the receiver coil on the lens. This activation powers an iontophoresis electrode, generating an electric field of approximately 3–6 V. The electric field drives the charged drugs loaded in hydrogel across the corneal barriers, delivering them to the aqueous chamber. The significant difference between the operational frequencies for sensing and powering prevents cross-coupling for efficient operation.

OUTLOOK

The simple structure and low infrastructure demand make them practical choices for researchers in diverse fields to readily integrate wireless electronics into their studies. While the potential of this technology can transition to basic and clinical practices in the future, several critical challenges need to be further addressed.

First, it is necessary to ensure and further improve the stability of chip-less electronics for reliable operation under mechanical stress and strain, as their flexible nature makes them particularly susceptible to deformation. The dynamic living system exhibits biological processes and functions that may cause changes in the geometry of devices. The fluctuation of environmental factors introduces additional complications and interference.

Taking RF energy powered devices as an example, changes in the inductance, capacitance, and resistance of responsive electronic components can impact the wireless transmission process, and it is difficult to isolate individual contributing factors in practice. This makes it challenging to accurately analyze/interpret recorded data and/or effectively transfer power to the target. To this end, one practical solution is to modularize the design, where the receiver coil is fixed or encapsulated to ensure stable electrical performance, while the flexible/stretchable interface extends to the target biotissues as the contact. However, the parasitic oscillation originated from the deformable interface part still represents a potential source of noise which should not be neglected.[36]

Moreover, current chip-less systems, with those powered by RF energy as the predominant species, are often constrained by distance and alignment requirements between the external transmitter and/or recording device and the receiver. This limits the mobility of the target being monitored and reduces the practicality of these devices in dynamic environments. For operation within deep tissues, the penetration depth of passive resonance is usually constrained to a few centimeters or less, as the energy of the electromagnetic field decreases rapidly with an increasing distance from the reader. The modularized design mentioned in the preceding section can partially address this issue by enabling the positioning of the receiver coil close to the surface. Nevertheless, the target usually needs to be fixed in practical applications to ensure stable and reliable coupling. The recently reported miniaturized electronic readers that can be attached to skin surface or clothes provide a promising route addressing this issue.[37] However, the field is still in its infancy with further exploration, development, evaluation, and optimization needed. In such operation schemes, while monitoring static signals might be relatively easier, capturing dynamic signal patterns within a short period presents greater challenges because of the need of high frequency sweep speed over a broad range. Human motion and environmental noise can introduce additional complications for continuous recording during the recording. Robust validation is necessary to further assess the efficacy of this scheme and compare its performance and competitiveness with standard digital wireless systems.

Finally, due to the relatively low accuracy of passive resonance, achieving the desired performance (e.g., sensitivity, power transfer efficiency) within the working range of the resonator demands codesign of the circuit model and functional materials, where the overall design should be guided by quantitative objectives and measures. Systematic studies are usually necessary to fully uncover the structure-performance interrelationships of custom designed devices suited for specific applications, where the dimension, coupling coefficient, quality factor, resonance frequency, bandwidth, and sensitivity of the biointerface all play important roles and should be considered as a complete unit. Tackling these challenges will be crucial in advancing chip-less bioelectronics toward more reliable and user-friendly healthcare solutions. Combining and optimizing the materials, circuit models, operation modalities, and recording systems discussed both within and beyond this perspective will lead to the creation of various engineering tools capable of monitoring multiple static/dynamic biophysical/biochemical signals for continued basic and applied research.

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Notes

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