

Review Article

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Efficient electromechanical conversion regulation to enhance the sensitivity of flexible strain sensors

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Abstract

Flexible strain sensors have emerged as fundamental components in intelligent sensing systems, attributed to their lightweight, wearability, stretchability and responsiveness to strain. Traditional flexible strain sensors are plagued by inadequate interface bonding strength and dispersed distribution of stress fields. These factors result in the diminished electromechanical conversion efficiency, thereby significantly hindering the sensitivity of micro strain monitoring in intricate configurations. In response to this challenge, this review proposes theoretical framework for the collaborative regulation of interface and structures, with the objective of facilitating efficient electromechanical conversion. The interface strengthening mechanism and regulation methods of localized and gradient stress fields have been systematically elucidated, thereby uncovering the mechanism by which stress transfer induces electrical signal mutation in polymer composite materials. Simultaneously, it is essential to elucidate the trajectory of technological advancement from single modal responses to multimodal perception, ultimately to the integration of functional systems at the comprehensive level. Finally, this study will explore the critical scientific challenges related to micro strain sensing limitation and programmable sensitivity regulation. The objective of this investigation is to promote the advancement of sophisticated intelligent sensing systems that are marked by deep integration of interactions among humans, machines and objects.

Keywords: Flexible electronics, flexible strain sensors, conductive polymer composites, electromechanical conversion efficiency, high sensitivity



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INTRODUCTION

Flexible electronic technology reshapes the physical configuration of electronic components, endowing intelligent equipment with brand-new capabilities of flexibility, deformability and conformality. Flexible strain sensors, serving as the fundamental sensing components in intelligent systems, exhibit significant promise in advanced domains involving human health monitoring, electronic skin, human-computer interaction interface and soft robotics^[1-4]. This potential is attributed to their lightweight, wearability, stretchability and responsive characteristics to strain. The primary function of flexible strain sensors is to effectively transform the applied mechanical strain into readable electrical signals. This electromechanical conversion process essentially encompasses the intricate interactions between mechanical and electrical systems. Its core chain [Figure 1] could be succinctly outlined as follows: when external force is applied to the sensor, stress field distribution is generated within the material, significantly altering the microstructure and interface characteristics of the stress-sensitive region. This behavior triggers specific signal conversion mechanisms (such as tunneling effect, crack effect and decoupling effect) to achieve the strain perception. In inherent material systems, interfacial inadequate stress transfer between the conductive layer and the elastic substrate, coupled with the dispersed distribution of stress fields within composite materials, poses significant challenges to the efficient conversion of mechanical stimulation into variations in electrical signals^[5]. This phenomenon significantly compromises the device sensitivity. Consequently, the attainment of elevated electromechanical conversion efficiency has emerged as a critical scientific challenge that necessitates urgent resolution within strain sensing domain. This advancement is essential for substantially enhancing sensitivity to address the monitoring requirements associated with soft and intricate small strain deformations. The core glossary for the critical technical terminology utilized in this context is presented in Table 1^[6-10].

The key to overcoming the low sensitivity limitations of flexible strain sensors under the constraint framework of maintaining the intrinsic material properties is to construct the collaborative control system of interface and structures. The objective of this system is to optimize the stress field distribution, regulate the stress transfer efficiency, affect the electronic transport behavior, and ultimately significantly improve the device sensitivity through the precise regulation of interfacial bonding strength and the meticulous design of multi-level structures. At the interface level, the enhancement of strain energy transfer and mitigation of interface failure between heterogeneous materials could be accomplished through various techniques, such as physical adsorption, mechanical interlocking and chemical grafting^[11-15]. These methods contribute to improving stress transmission efficiency at the interface. At the structural level, the stress field is reconfigured through the design of macro and micro topologies, facilitating the transformation of invalid energy dissipation through multi-dispersed paths into localized high-energy state extremum fields^[16-21]. This transformation subsequently triggers the fracture response of the conductive network.

Regrettably, the majority of contemporary reviews primarily concentrate on the optimization of material systems and iterative processes, while failing to provide the comprehensive integration and analysis of the regulatory methods and sensing mechanisms pertinent to efficient electromechanical conversion^[22-26] [Figure 2]. This oversight hinders the establishment of an intact theoretical framework. Consequently, it is imperative to develop the theoretical approaches for efficient conversion of strain-electrical signals. The sensing mechanisms associated with the effective transformation of mechanical energy into electrical signals at the multiscale level are elucidated. Such advancements contribute to establishing a universal paradigm for developing flexible strain sensors with high sensitivity.

In light of the fragmented research on strain-resistance conversion control methods and sensing mechanisms, taking fiber and film strain sensors as the research objects, this work provides a

Table 1. Core glossary for the critical technical terminology utilized in this context

Ref.	Designation	Physical meaning	Mathematical representation
/	Electromechanical conversion efficiency	Ratio of input mechanical energy (W) to effective output electrical energy (E)	$\eta = \frac{E}{W}$
[6]	Stress field distribution	Internal stress state (such as strain level, direction) of materials exhibits variability with respect to spatial position, which is induced by external loads or boundary constraints	/
[7]	Sensitivity	Ratio between the output variation quantity of sensors and the input change that causes this change	/
[8]	GF	Basic sensitivity measurement, used to quantify sensitivity	$GF = \frac{100 * (R - R_0)}{R_0 * \varepsilon}$
[9]	Programmable sensitivity	Implementation of active control strategies enables the dynamic modulation of response relationship between output signals and input strain, facilitating the sensitivity customization on demand and allowing for real-time adjustments	/
[10]	Strain energy dissipation	The segment of external mechanical work applied to sensors is transformed into thermal energy or other forms of irreversible energy as a result of irreversible microscopic phenomena (such as viscous flow, internal friction and plastic deformation) within materials or structures	/

Notes: R_0 is the initial resistance, R is the real time resistance, and ε is the applied strain. The logical relationship among several associated concepts is delineated as follows: strain energy dissipation → electromechanical conversion efficiency → sensitivity. The difference and relationship between sensitivity and programmable sensitivity: sensitivity is an inherent physical characteristic of sensors and the foundation of programmable sensitivity. Programmable sensitivity is a configurable function of the system that allows devices to adjust sensing capabilities according to actual application requirements. GF: Gauge factor.

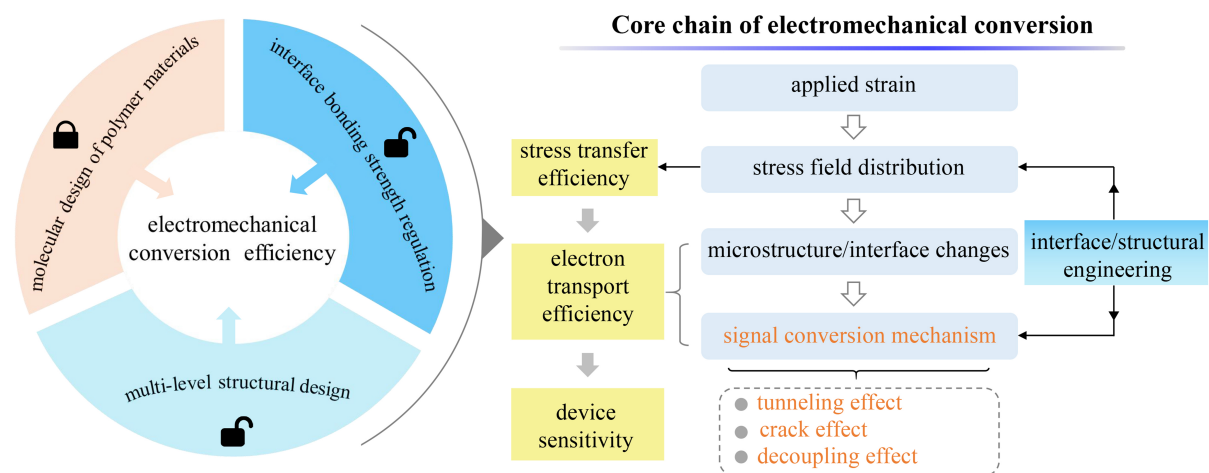


Figure 1. Schematic diagram of sensitivity improvement by the synergistic effect of interface/structural engineering to control electromechanical conversion efficiency.

comprehensive overview of the latest breakthroughs in flexible sensing technology with high sensitivity. It initiates its discussion with material interface engineering and macro and microstructures design [Figure 3]^[27-34], clarifying the interface strengthening mechanism and control methods of localized and gradient stress fields.

Specifically, enhancing the interfacial bonding strength could effectively stabilize and constrain the localized high-stress regions that arise from structural design, preventing premature failure and facilitating efficient strain transfer from the elastic layer to the conductive layer. The specific structural design has the capacity to tailor and control both the location and intensity of stress concentration at the interface. It puts forward specific requirements for interface bonding strength, guides the direction for interface optimization strategies and determines the primary mode of signal conversion. Consequently, the two are not

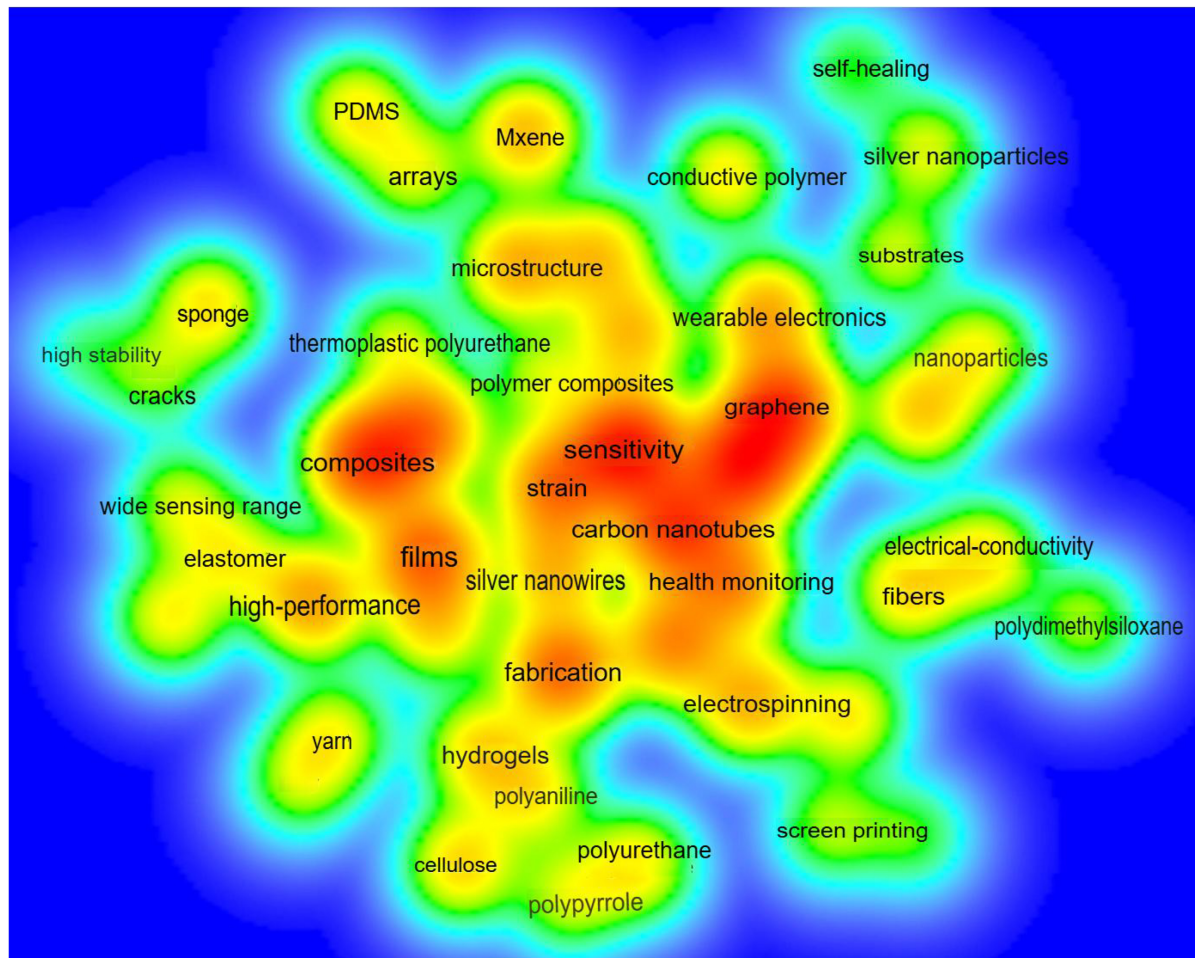


Figure 2. Density visualization of research clusters pertaining to flexible strain sensors (data from Web of Science).

independent modules. Rather, they collaboratively influence the stress transfer efficiency and electron transport efficiency by synergistically optimizing the stress field distribution, which ultimately leads to a substantial improvement in the device sensitivity. The sensitivity enhancement mechanism of abrupt changes in electrical signal induced by stress transfer in polymer composite materials is revealed in detail. In the context of technological evolution, there exist progressive evolutionary pathways that encompass the development of singular sensing capabilities, integration of multimodal perception and fusion of multifunctional systems, with particular cases being examined. Finally, this study discusses the fundamental scientific challenges associated with micro strain sensing limitations and the programmable sensitivity regulation, which provides a theoretical and technical foundation for developing flexible strain sensors with high performance.

MULTI-SCALE ELECTROMECHANICAL CONVERSION REGULATION

In the domain of flexible strain sensors, the primary control mechanism governing the sensitivity emphasizes the synergistic enhancement of interface interactions and structural design^[35]. To significantly enhance the clarity, comprehensiveness and systematicity of this review for facilitating readers to better grasp the overall logical framework, this review employs a framework based on multi-scale electromechanical conversion regulation to systematically organize its content. This framework sequentially

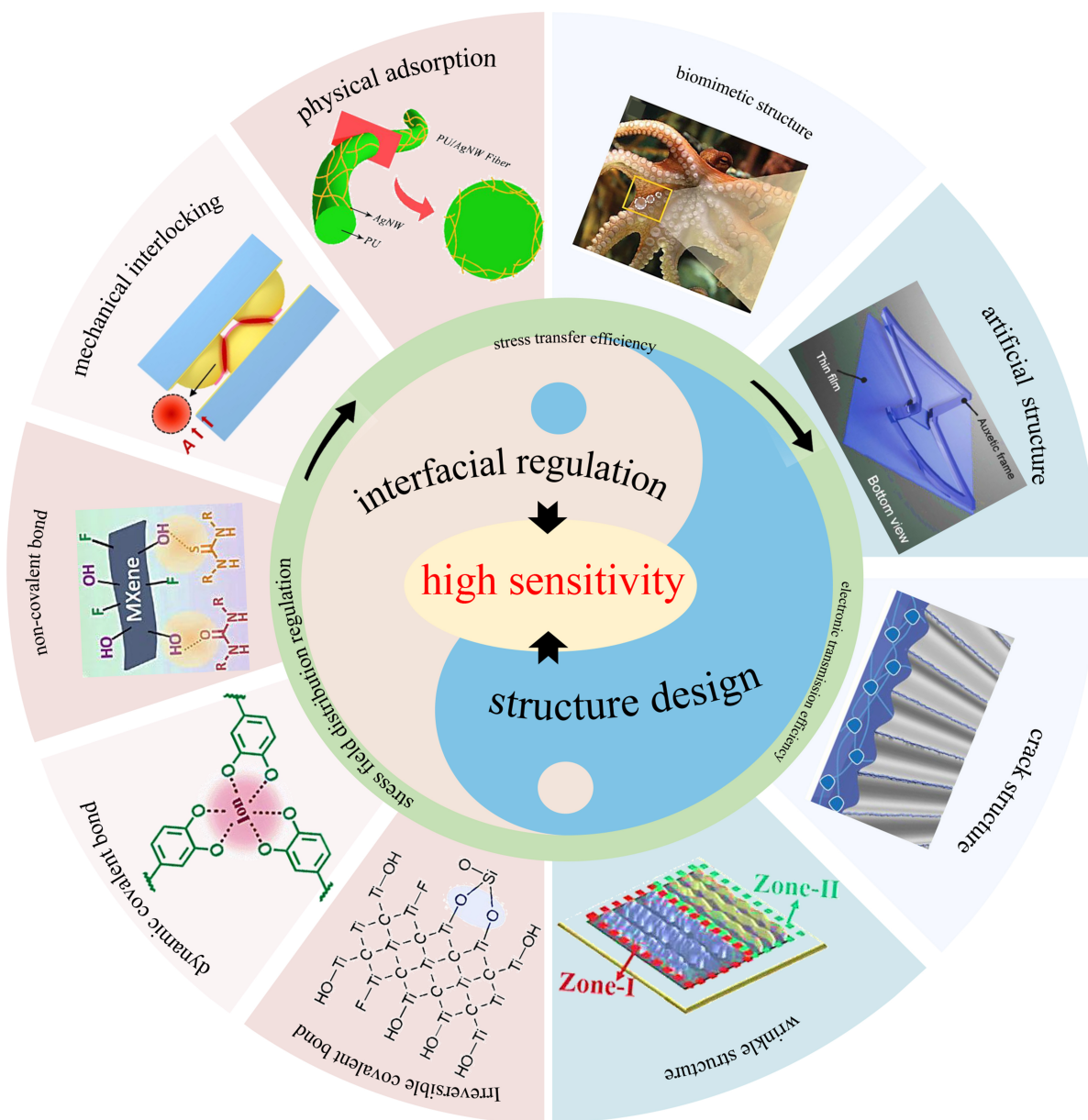


Figure 3. Framework diagram of research ideas for improving the sensing sensitivity^[27-34].

covers the mesoscopic interface regulation (such as physical adsorption, mechanical interlocking, non-covalent/covalent bond), mesoscopic microstructure design (such as biomimetic structure, crack structure, wrinkle structure) and macroscopic structure design. A comprehensive discussion of efficient electromechanical conversion on the regulation methods, structure-activity relationship and sensitization mechanism has been conducted.

From the perspective of interface regulation, enhancing the binding strength of physical and chemical cross-linking networks markedly improves the shear resistance at the interface^[36-38], thereby mitigating the stress peeling phenomenon that occurs between conductive layer and elastic substrate. The establishment of inherent relationships among interface cross-linking types, interface bonding strength and elastic modulus,

along with the formulation of adaptation guidelines of interface bonding strength, provides systematic approaches for developing highly sensitive and robust interface adhesion systems. At the structural design level, gradient stress field distribution systems are established through biomimetic structure^[39-41], artificial structure^[42-44], crack and wrinkle structures^[45-49], which aim to amplify strain effect and provide theoretical insights for improving the sensitivity.

Mesososcopic interface regulation

The interface regulation strategies primarily depend on the physical and chemical cross-linking. Physical cross-linking establishes an adaptive interface via intermolecular physical adsorption, mechanical interlocking at the micro and nanoscale and non-covalent interactions^[50]. In contrast, chemical cross-linking mitigates strain energy through the reversible reconfiguration of dynamic covalent bonds, alongside the stable anchoring provided by irreversible covalent bonds^[51]. Stress transmission efficiency is optimized through the regulation of interfacial bonding strength, thereby enhancing the conversion efficiency of strain-resistance to improve the sensitivity.

Physical adsorption

Physical adsorption as an important methodology of interface physical cross-linking facilitates non-bonded adhesion through adhesion and capillary action, which provides the crucial technical pathway for developing the stable conductive layers on the surfaces of elastomers. In terms of adhesion regulation, Wu *et al.* effectively employed the robust adhesive properties of polydopamine to facilitate the direct adsorption of conductive carbon nanotube onto the surfaces of supramolecular elastomer composites^[52]. This innovative approach enabled the fabrication of flexible strain sensors without the necessity for supplementary adhesives [Figure 4A]. In contrast to the adhesion strategy, Zhu *et al.* effectively utilized the siphon principle of glass capillaries, along with an embedded structural design, to adsorb silver nanowires onto the surface of polyurethane fibers^[27] [Figure 4B]. This approach is characterized by its straightforward methodology and ease of implementation, providing significant insights for the fabrication of fibers with specialized structures. Additionally, Liu *et al.* prepared thickness gradient thin film based on the self-pinning effect of carbon nanotubes by driving liquid level to shrink through evaporation, achieving a sensitivity factor of up to 161^[53] [Figure 4C].

Mechanical interlocking

As compared to physical adsorption at the interface, mechanical interlocking circumvents reliance on molecular forces by utilizing geometric anchoring, thereby significantly improving the strength of interfacial bonding. Drawing inspiration from the microstructural characteristics of the skin's surface, Pang *et al.* developed various surface microstructures including domes, pyramids and microcolumns to successfully attain the tailored modulation of sensitivity^[54] [Figure 5A]. In alignment with the design principles of dome microstructures, Wang *et al.* introduced the novel design framework centered on multi-layer interlocking sandwich structure^[28] [Figure 5B]. The fundamental objective was to establish face-to-face, staggered and complementary interlocking configurations through the interaction between the upper and lower surfaces of the conductive layer of the micro dome. This innovative design facilitated the construction of strain sensors characterized by high sensitivity and an extensive response range. Nonetheless, while this particular microstructure is capable of attaining high sensitivity due to the ease of deformation at the tip, an increase in load results in stress accumulation from the tip's deformation. This accumulation inhibits the deformation in other regions of the microstructure, ultimately resulting in a reduction of sensitivity under conditions of elevated load. To address this limitation, Li *et al.* drew inspiration from the filamentous papillae structure found on the tongues of cats and successfully developed an array that simulated this structure^[55] [Figure 5C]. This innovative design effectively mitigates stress accumulation by employing dynamic interlocking at the tips of the papillae, thereby resolving the issue of low sensitivity.

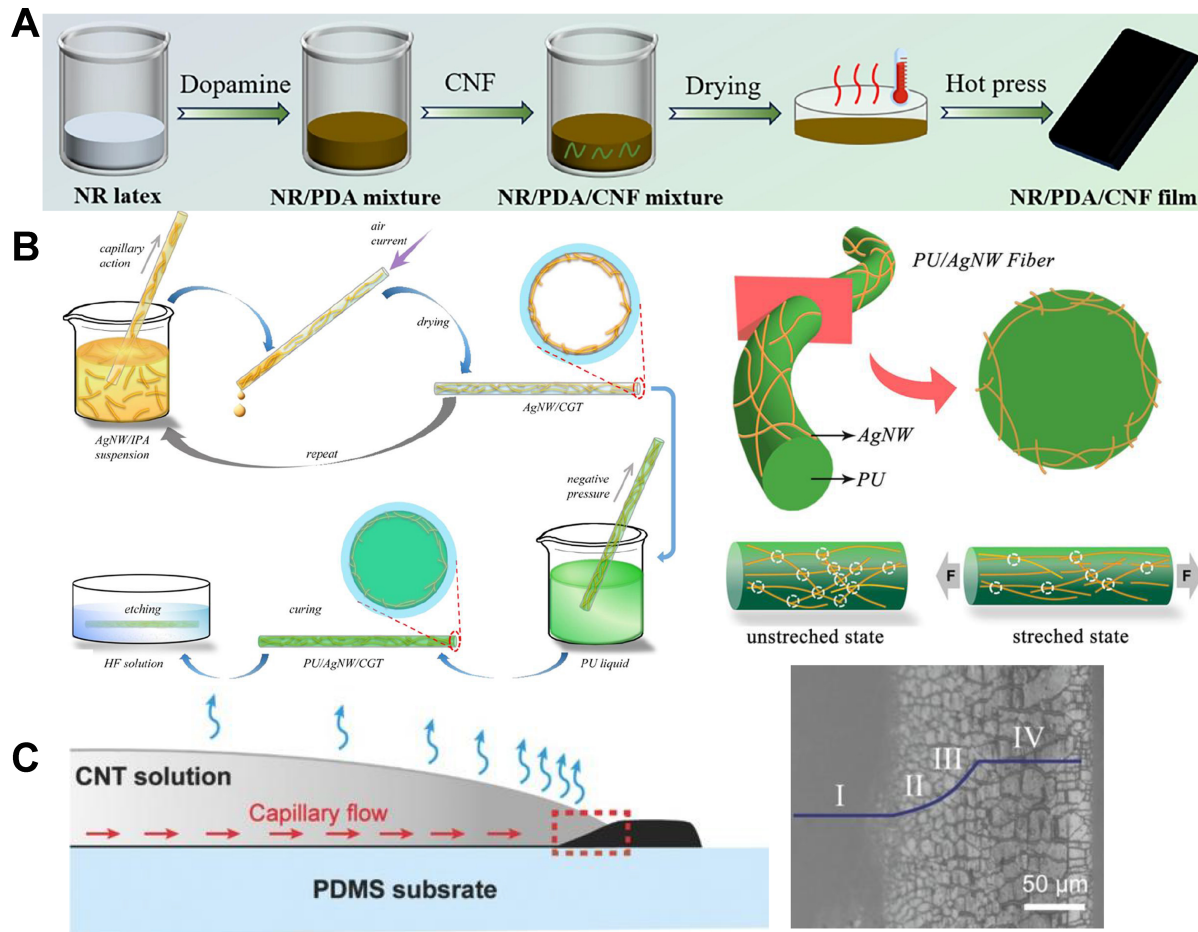


Figure 4. (A) Robust adhesive properties of polydopamine to adsorb carbon nanotubes^[52]; (B) Siphon principle of glass capillary tube^[27]; (C) Self pinning effect of carbon nanotubes^[53].

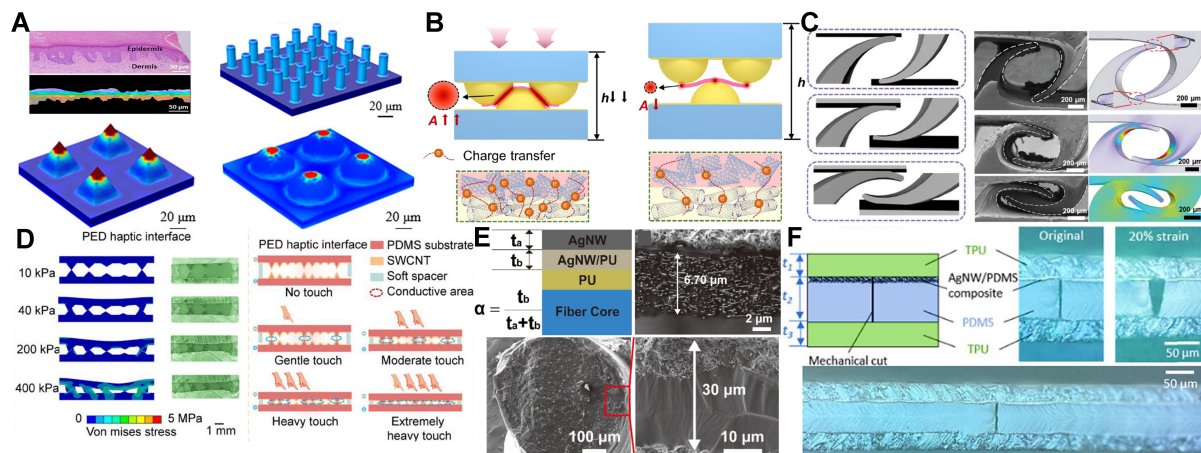


Figure 5. (A) Surface microstructures of domes, pyramids, or micro columns^[54]; (B) Multi-layer interlocking sandwich structure^[28]; (C) Filamentous mastoid structure array^[55]; (D) Gradient pyramid meta-surface structure^[56]; (E) Dynamic mechanical interlock interface^[57]; (F) Interfacial mechanical interlocking microstructure^[58].

Concurrently, other researchers have concentrated on the precise modulation of contact behavior. Lin *et al.* developed a gradient pyramid meta-surface structure to optimize the contact area between the upper and lower sensitive layers [Figure 5D], thereby significantly enhancing perception accuracy^[56]. In the pursuit of improving interface performance, Cao *et al.* developed dynamic mechanical interlocking interface by varying the embedding depth of silver nanowire networks^[57] [Figure 5E]. This approach not only concurrently increased the bonding strength and stress transfer efficiency of the interface, but also facilitated the establishment of pertinent interface interaction models. To address the interface issues, Wu *et al.* developed the mechanical interlocking microstructures utilizing hot pressing and plasma surface treatment techniques^[58]. The stress transfer pathway was optimized, which significantly mitigated interface slip and localized stress concentration during repeated deformation [Figure 5F]. This work establishes a critical foundation for ensuring the reliability of strain monitoring within complex environments.

Non-covalent bond

Given the intrinsic constraints associated with low interface bonding strength of physical adsorption and inadequate dynamic reversibility of mechanical interlocking, non-covalent bonding at the interface has emerged as a pivotal approach for attaining robust, adaptive and repairable interface adhesion. The primary benefit of this strategy resides in the dynamic disruption and reformation of various weak interactions (such as hydrogen bonding and π - π stacking)^[59], which concurrently augment both the interface bonding strength and the efficiency of energy dissipation.

Drawing inspiration from the hierarchical microstructure of the human Achilles tendon, Xu *et al.* employed the various interactions between MXene nanosheets and polyurea polymer to develop self-healing flexible composite materials at room temperature^[60] [Figure 6A]. In the domain of high-performance sensing, Lin *et al.* engineered wire sensors with a high strain factor [Gauge factor (GF) = 25.98] through the establishment of hydrogen bond cross-linked network comprising carboxylated styrene-butadiene rubber and silk glue [Figure 6B], which was non-covalently modified with carbon nanotubes^[61]. In terms of material assembly, Yang *et al.* employed nano-restricted water to facilitate basal alignment and π - π sheet bridging for the directional assembly of MXene-bridged graphene nanosheets [Figure 6C]. This approach establishes a framework for the macroscopic organization of isotropic 2D nanosheets^[62]. Moreover, the incorporation of 1-aminopyrene-disuccinate (AD) conjugated molecules has led to a permanent fixation of the orientation of graphene sheets, which was achieved through stretching process [Figure 6D]. This modification has resulted in an enhancement of the sheet strength, reaching a value of 1.55 GPa^[63]. Finally, the synergistic integration of MXene nanosheets and AD molecules resulted in a significant reduction of the pore size within the graphene layers, while simultaneously optimizing the arrangement density. The π - π bridging interaction at the interface facilitated the attainment of enhanced strength [Figure 6E], toughness and functional integration^[64].

Covalent bond

To improve the interfacial bonding strength between elastomers and conductive layers, the development of robust cross-linked networks through interfacial chemical cross-linking has emerged as a predominant approach for augmenting interfacial adhesion. Based on the principle of reversibility in bonding methods, cross-linking could be classified into two distinct categories: permanent networks, which are established through irreversible covalent bonds, and reversible networks, which are formed through dynamic covalent cross-linking that allows for fracture and recombination.

With regard to the regulation of irreversible covalent bonds, researchers have successfully addressed the issue of inadequate interfacial bonding strength through the meticulous design of bond types and reaction

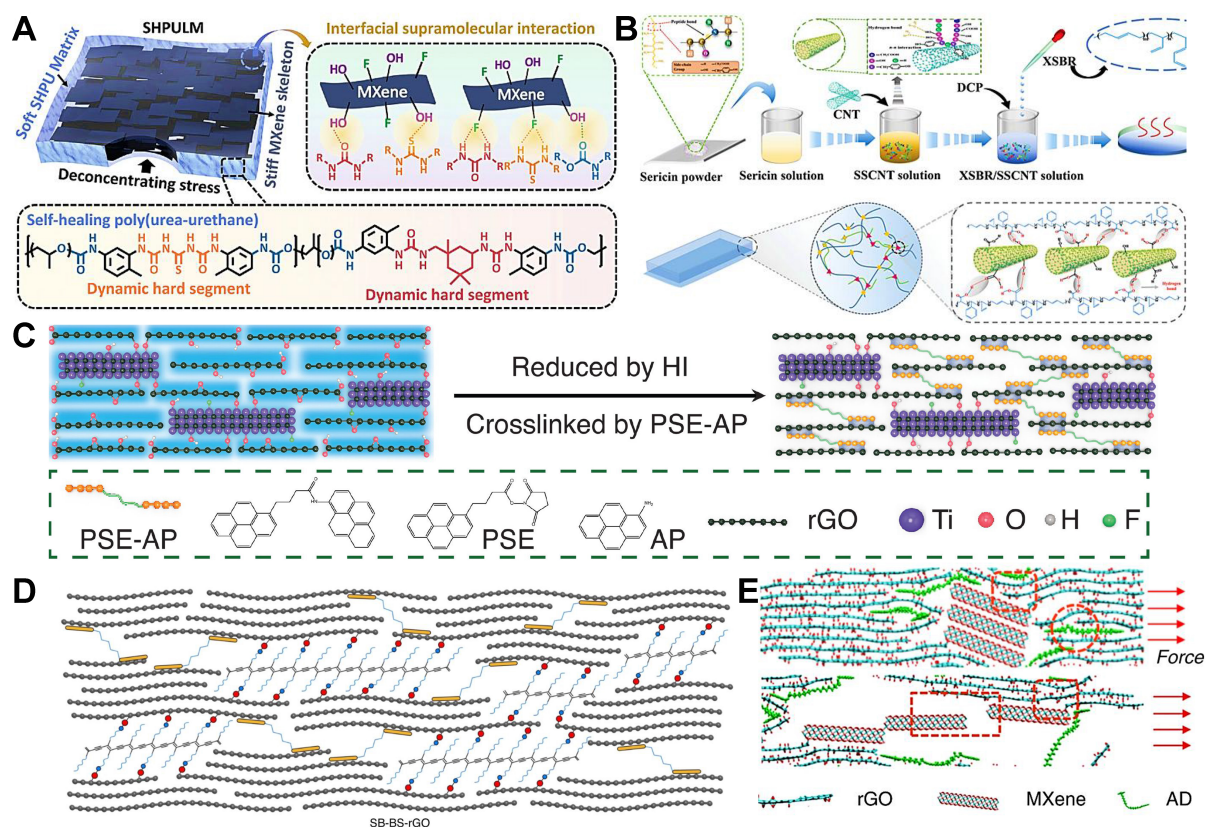


Figure 6. (A) Interfacial hydrogen bonding between MXene nanosheets and polyurea^[60]; (B) Hydrogen bond cross-linking network of non-covalently modified carbon nanotubes^[61]; (C) Nano-restricted water to facilitate basal alignment and π - π sheet bridging^[62]; (D) π - π interaction of AD conjugated molecule^[63]; (E) π - π bridging between MXene nanosheets and AD molecules^[64]. AD: 1-Aminopyrene-disuccinate.

pathways. Within this foundational framework, Pan *et al.* employed (3-mercaptopropyl) trimethoxysilane as a bifunctional coupling agent, which facilitated the formation of robust Au-S bond with gold via its thiol functional group^[9]. Concurrently, the siloxane moiety underwent condensation with polydimethylsiloxane (PDMS) prepolymer, resulting in the establishment of Si-O-Si network. The synergistic interaction of dual chemical bonds contributed to the attainment of significant interfacial adhesion [Figure 7A]. Further expanding the bonding strategy, Pan *et al.* introduced an innovative method for strengthening interface click chemistry [Figure 7B]. This method involves the precise alignment of chemical reactivity of conductive layer with the reactive groups of the substrate, thereby facilitating the formation of highly stable bonding interface^[30]. This significant advancement has led to the establishment of a mathematical correlation model that relates adhesion strength to durability, thereby paving the way for the development of high-performance flexible sensors. In the context of photo-controlled *in-situ* bonding, Shi *et al.* performed free radical copolymerization of polyurethane acrylate prepolymer with silane coupler under ultraviolet irradiation [Figure 7C]. This process facilitated the directional incorporation of methoxy silane groups into the polymer chain, ultimately resulting in the formation of robust interfacial bonding through the establishment of irreversible Ti-O-Si covalent bonds^[65].

In the domain of dynamic covalent bond engineering, scholars have successfully enhanced the interfacial stress transfer efficiency through the meticulous type design of reversible chemical bonds and their responsiveness to stimuli. In the realm of biomimetic material, Yang *et al.* developed the biologically

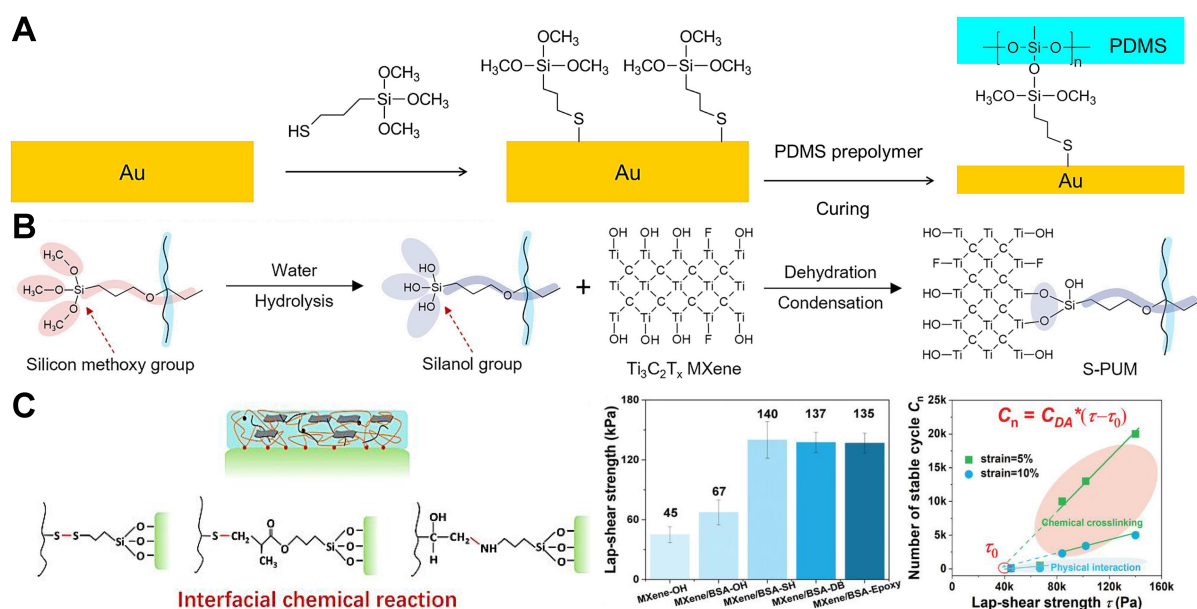


Figure 7. (A) Synergistic interaction of dual chemical bonds at the interface^[9]; (B) Strengthening interface click chemistry^[30]; (C) Free radical copolymerization under ultraviolet irradiation^[65].

inspired dynamic covalent polymers with the framework of catechol hydrogen bonds [Figure 8A]. This innovative approach incorporates the enhancement of metal coordination and dynamic recombination properties of disulfide bonds^[29]. As a result, the study presents a sustainable alternative to conventional covalent elastomers, thereby advancing the evolution of tactile sensing technology. Further expanding to the functional design of ion conductors, Wang *et al.* have engineered self-healing polyurethane-based solid-state ion-conductive elastomers [Figure 8B]. This innovation incorporates diels-alder bonds and acylurea dynamic covalent networks, thereby offering a novel generation of sensing substrates for multifunctional strain sensors^[66]. In the realm of flexible substrate functionalization, Dong *et al.* introduced the sensing system of dynamic rigid hybrid silk yarns [Figure 8C]. This system establishes the dynamic imine bond networks via condensation reaction between amino groups in silk yarns and aldehyde groups of aldehyde cellulose nanocrystals^[67]. Concurrently, pyrrole undergoes oxidation and polymerization at the hydroxyl sites of the nanocrystals, thereby constructing the rigid conductive pathways that markedly improve interfacial stress conduction.

Multi-level structural design

As compared to the regulation of interface bonding strength, multi-level structural design results in a significant enhancement in sensing sensitivity, achieving an increase by an order of magnitude. This improvement is accomplished through the precise regulation of strain field distribution and the amplification of localized electrical response signals^[68-71]. Through the designs of biomimetic structure, artificial structure and crack structure, strain distribution induced by external loads is optimized. This process facilitates the establishment of gradient stress field distribution system, which effectively transforms minor mechanical deformations into substantial variations in monitored electrical signals. This approach provides a robust physical foundation for the development of flexible strain sensors with ultra-high sensitivity.

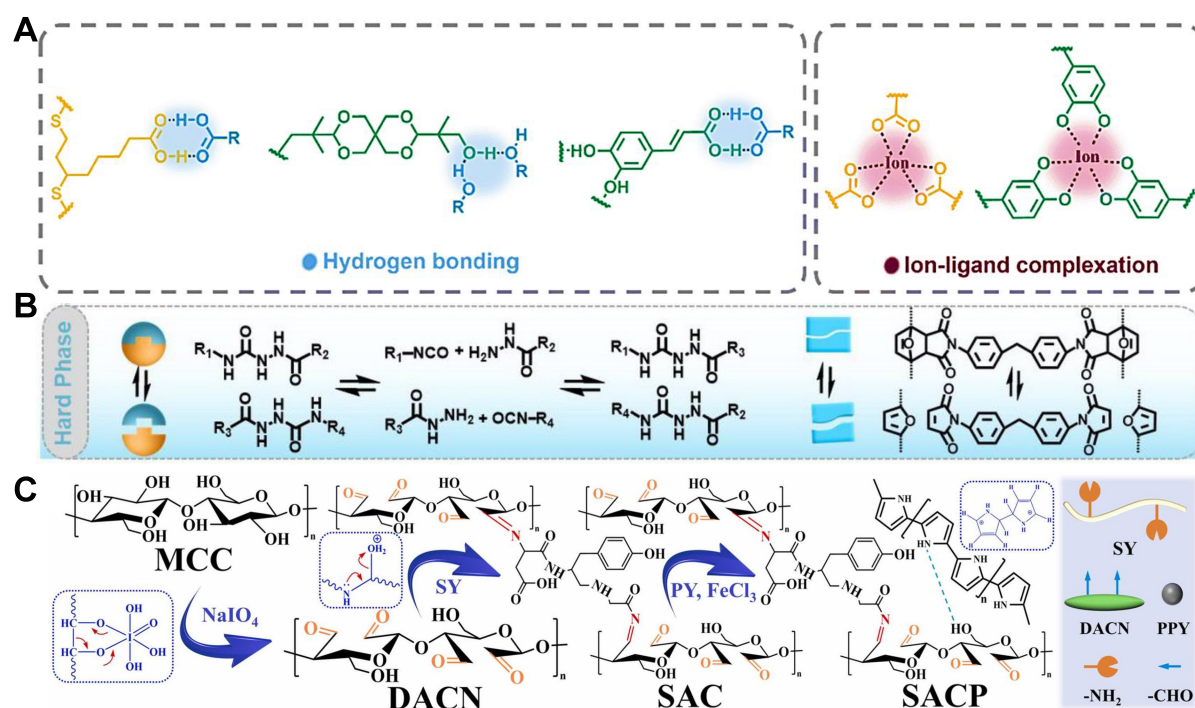


Figure 8. (A) Metal coordination and dynamic recombination of disulfide bonds^[29]; (B) Diels-Alder bonds and acylurea dynamic covalent networks^[66]; (C) Dynamic imine bond networks^[67].

Mesoscopic microstructure design

Biomimetic structure

Biomimetic structural design leverages insights gained from the process of natural evolution by analyzing the functional forms of organisms. This approach involves the translation of their physical and chemical principles into programmable artificial microstructures. This strategy of natural inspiration and engineering reconstruction not only solves traditional problems such as rigid flexible coupling and interface adaptation, but also demonstrates irreplaceable advantages in multimodal perception integration.

Drawing inspiration from the remarkable contact properties from octopus tentacles equipped with multi-level suction cups, Chen *et al.* developed the programmable flexible sensing array with multi-level dome structures [Figure 9A]. Empirical studies indicate that meticulous regulation of hierarchical organization of this multi-tiered dome structure is essential for attaining the tailored strain response range^[31]. The distinctive multi-level design enhances the amplification of minor deformation signals, consequently leading to a marked increase in the device's sensitivity. Inspired by the biological geometric arrangement of slit-sensing organs found in scorpion legs, Liu *et al.* introduced the closed-loop design paradigm primarily governed by geometric effect [Figure 9B]. This paradigm involves the construction of stress-guiding structure through predetermined curvature field of the hole's edge, the programming of crack initiation orientation and the establishment of strain-resistance response relationship, all of which are defined by the geometric constraint of 3D crack path^[72]. Consequently, the random crack network is transformed into a biomimetic sensing pathway that is controllable in multiple directions. Drawing inspiration from the biological geometries observed in spider web, Wang *et al.* introduced a strategy for controlling geometric effect that utilizes V-shaped grooves [Figure 9C]. This approach involves the dynamic optimization of geometric topology of these grooves through the customization of cross-sectional parameters, with the aim of enhancing local strain energy density and facilitating an adaptive increase in perceptual sensitivity^[73].

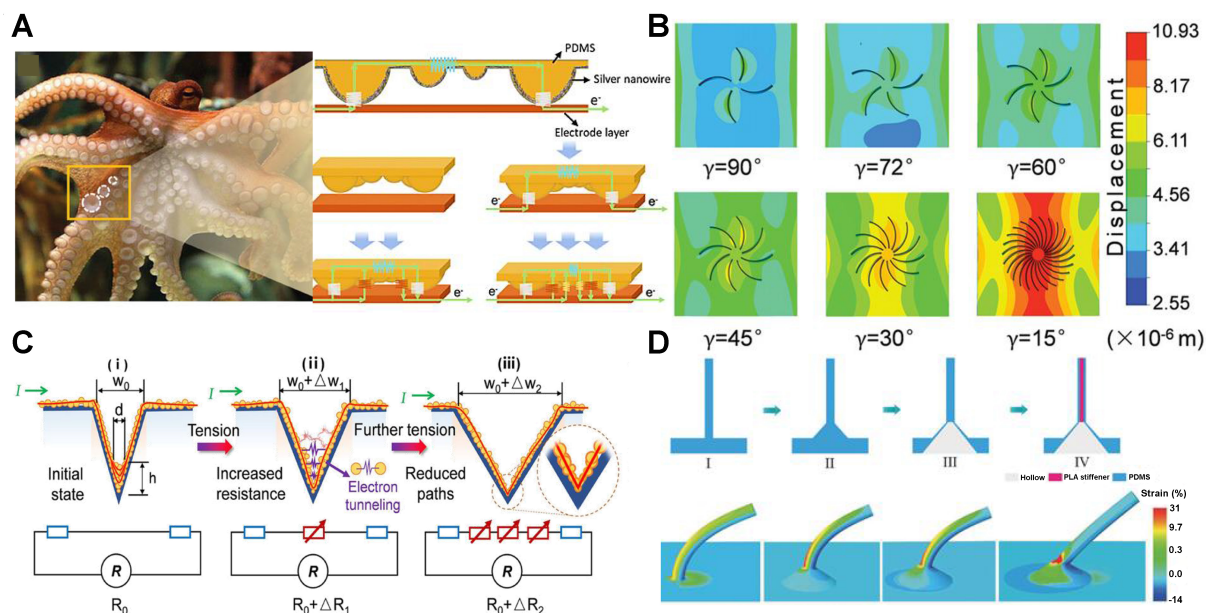


Figure 9. (A) Multi-level dome structures^[31]; (B) Curvature field of predetermined hole boundary^[72]; (C) Customized V-shaped grooves^[73]; (D) 3D heterogeneous structure of spatial gradient modulus^[74].

Inspired by the normal growth of epidermal vegetation, Liu *et al.* developed a strategy that leverages 3D geometric effect [Figure 9D]. A heterogeneous structure with spatial gradient modulus utilizing 3D printing technology was constructed^[74]. This innovative approach effectively directs crack propagation to specific regions, thereby facilitating cross-dimensional decoupling and enabling high-precision sensing of out-of-plane mechanical responses.

Crack structure

Crack structural design converts material imperfections into functional benefits. By meticulously regulating the crack propagation behavior, this approach alters the electronic transmission pathways, thereby significantly enhancing the electrical signal variations induced by mechanical stimulation. This ultimately results in a substantial improvement in the sensitivity.

In accordance with this principle, Qu *et al.* developed plasma induced multiple structures with folds and cracks that leverage the crack effect to effectively control the propagation of cracks [Figure 10A]. This design optimizes the electronic transmission pathway, resulting in a substantial enhancement of electrical signal response when subjected to mechanical stimulation^[75]. In the realm of microchannel design, Lee *et al.* developed parallel linear patterns to facilitate the formation of nanochannel fractures [Figure 10B]. This approach was integrated with thermally responsive shape memory polymers, enabling the reversible reconfiguration of crack networks between their temporary and original configurations^[32]. This innovation presents a novel paradigm for sensitivity and reversible response. To enhance the control of crack propagation pathways, Guo *et al.* developed a pre-cut curved crack configuration [Figure 10C]. During the deformation of the elastic substrate, the cross-sectional area of the crack experiences a pronounced alteration, which leads to an exponential variation in the ion current traversing the crack^[46]. In the context of crack characteristic management, Park *et al.* introduced a methodology that involved the application of external tension following the formation of the initial crack [Figure 10D]. This approach facilitates meticulous regulation of both crack depth and gap displacement, which in turn optimizes the local electric

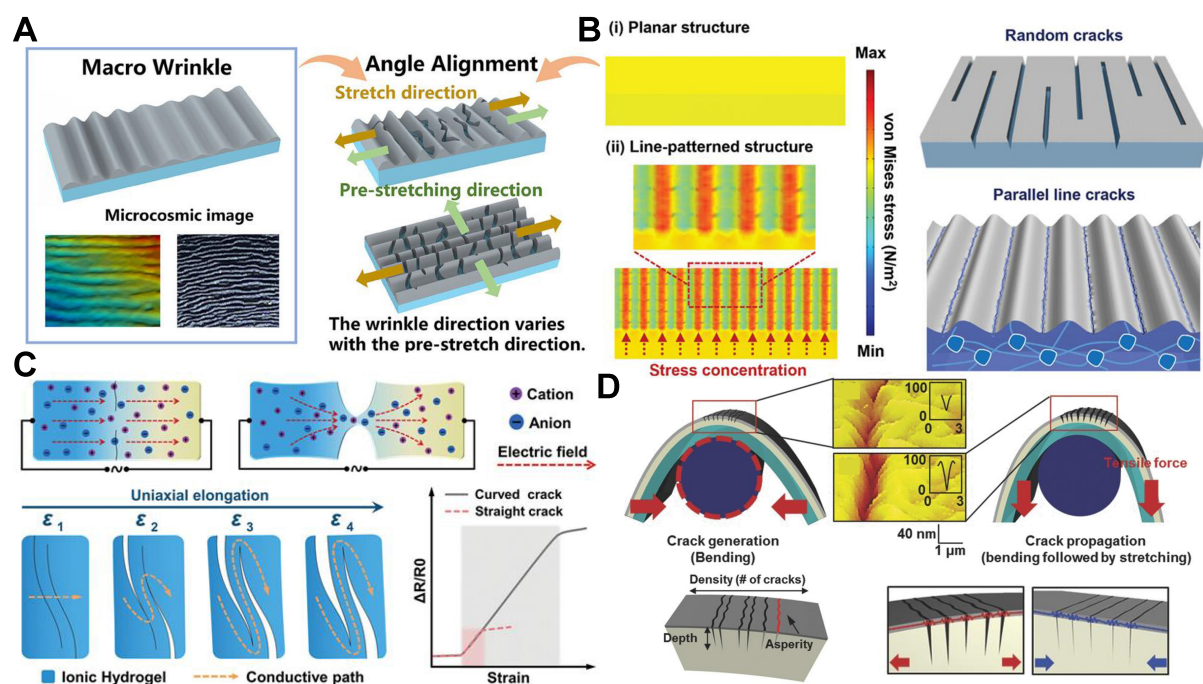


Figure 10. (A) Plasma induced multiple structures with folds and cracks^[75]; (B) Parallel linear pattern^[32]; (C) Pre-cut bending crack structure^[46]; (D) Control and optimization of crack depth and gap displacement^[76].

field distribution in proximity to the crack tip^[76]. Consequently, this strategy significantly amplifies the alterations in electrical effect induced by minor strains, ultimately leading to precise optimization and a substantial enhancement of device sensitivity.

Wrinkle structure

Wrinkle structure, characterized by its distinctive controllable instability properties and capability for dynamic strain field reconstruction, is emerging as a fundamental design paradigm for addressing challenges related to high sensitivity and multimodal sensing. The phenomenon of polymer surface wrinkling could be realized through the material's intrinsic instability. This instability arises from the mismatch in material modulus, which generates internal compressive stress. This stress subsequently leads to surface buckling deformations, causing the wrinkle formation. This process effectively serves the purpose of stress dissipation.

To construct gradient entangled double network gel and regulate its patterned fold structure, Wang *et al.* manipulated both gel thickness and the concentration of the cross-linking agent to elucidate the fundamental principles governing the formation of wrinkle patterns [Figure 11A]. Their findings enabled the successful and controlled fabrication of a variety of patterned shapes and sizes^[77]. In addressing the enduring trade-off between sensitivity and range in flexible strain sensing, Chu *et al.* introduced dual pre-strain programming strategies to develop gradient wrinkled topology structure within graphene oxide and PDMS systems [Figure 11B]. This innovative approach provides a novel solution for attaining high sensitivity throughout the entire measurement range^[33]. In contrast to the previously discussed physical induction mechanism, Wu *et al.* devised a chemical-induced wrinkling approach by hydrothermal activation [Figure 11C]. This method enables precise regulation of nanoscale wrinkling spacing while simultaneously facilitating the formation of a hierarchical interconnected structure with the coexistence of surface wrinkle and bulk gradient pores^[49]. This innovative strategy presents new opportunities for

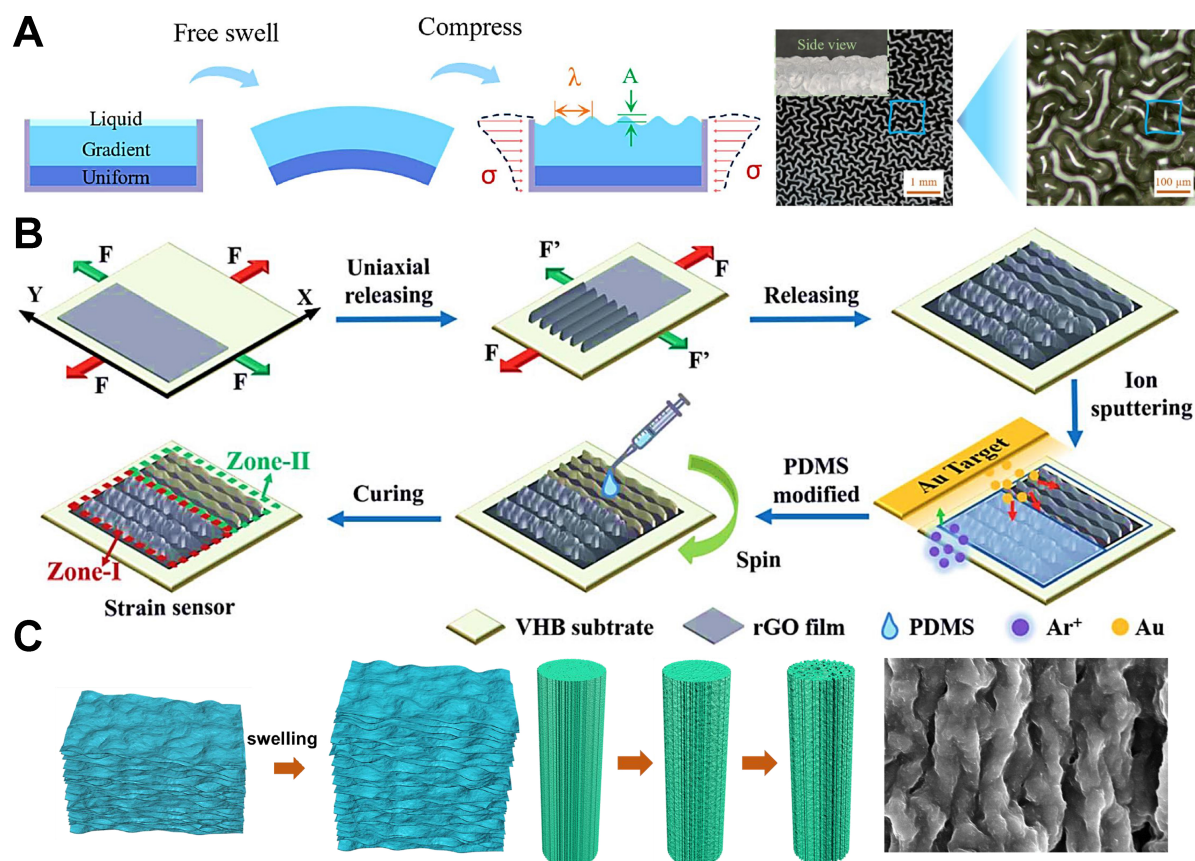


Figure 11. (A) Patterned fold structure^[77]; (B) Gradient wrinkled topology structure^[33]; (C) Chemical-induced wrinkle structure^[49].

advancing high-quality perception capabilities.

Macroscopic structure design

The artificial structural design transcends the limitations of traditional material mechanics by leveraging the negative Poisson's ratio effect to facilitate in-plane two-dimensional structural expansion. This mechanism enhances the local electrical response, resulting in a substantial increase in the sensitivity. In the domain of structural engineering, Yu *et al.* conducted an investigation into artificial units, resulting in a notable enhancement in sensitivity [Figure 12A]. This improvement was accomplished by doubling the local strain energy density through the implementation of multi-scale parametric design and the control of patterned topology^[78]. In light of the distinctive benefits associated with 2D expansion structures, Jiang *et al.* introduced an innovative strategy for enhancing strain sensitivity that leverages the negative Poisson's ratio effect [Figure 12B]. The researchers employed template methods to fabricate an embedded tensile artificial pattern structure, which facilitated the generation of highly localized strain fields^[34]. This approach effectively harnessed the characteristics of 2D expansion, resulting in a marked enhancement in sensitivity. To expand the adjustable range of structural Poisson's ratio, Wu *et al.* introduced a method for designing controllable artificial patterned structures [Figure 12C]. This approach integrates finite element analysis simulations with sensor testing for collaborative validation^[79]. A quantitative relationship between the structural Poisson's ratio and sensitivity was established, thereby providing a novel framework for optimizing the distribution of strain fields. To further regulate the microstructure Poisson's ratio, Li *et al.* introduced an innovative approach for the assembly of carbon nanotubes on porous substrates

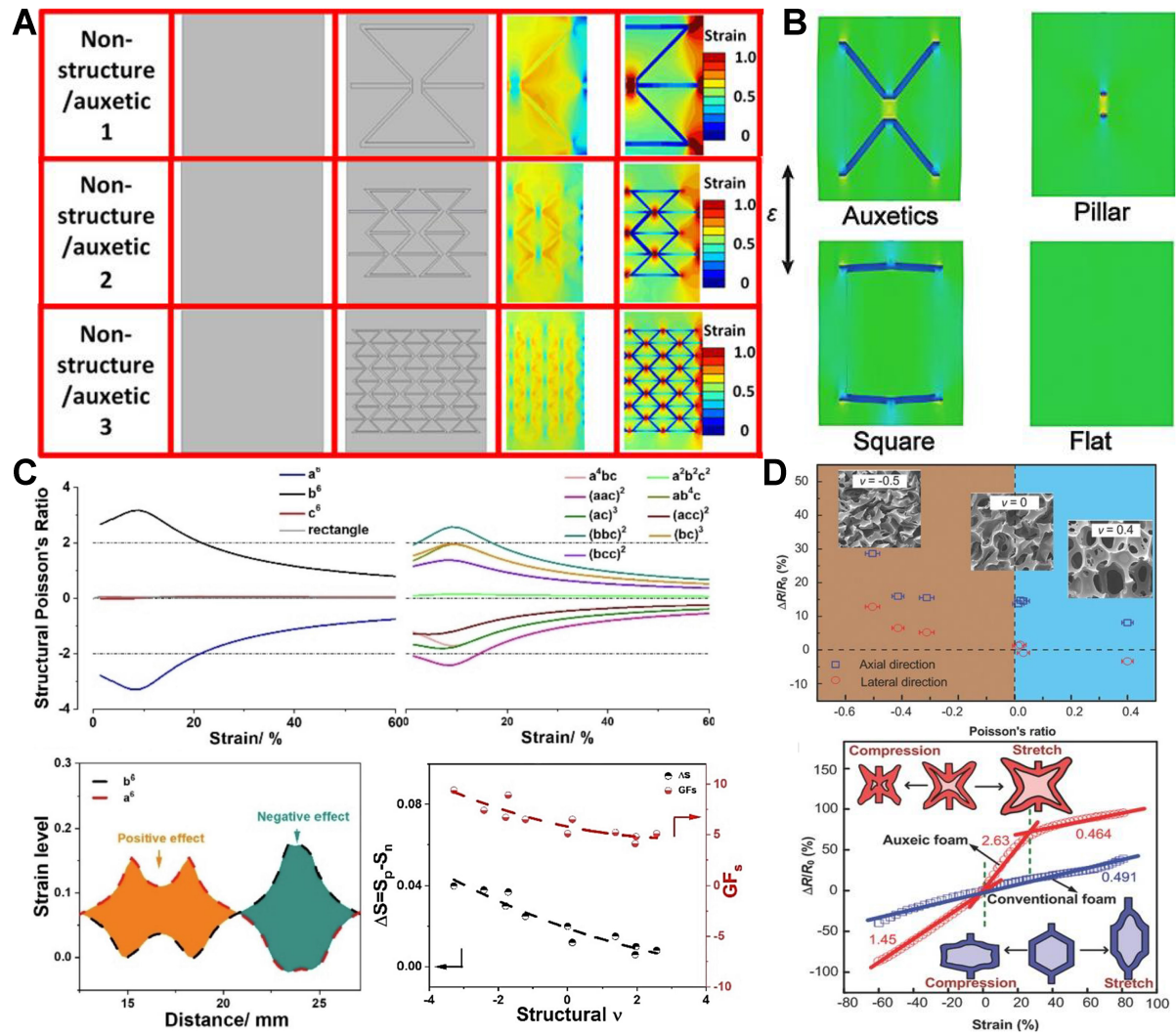


Figure 12. (A) Parametric design and patterned control of artificial units^[78]; (B) Embedded artificial pattern structure^[34]; (C) Intrinsic relationship between structural Poisson's ratio and sensitivity^[79]; (D) Porous structure with Poisson's ratio adjustable^[44].

[Figure 12D]. A functional relationship between structural Poisson's ratio and the sensing performance is established, while also clarifying the mechanism by which sensitivity is enhanced in porous structures through the modulation of the Poisson's ratio^[44].

In order to reinforce the claim of the interface-structure collaboration framework, the synergistic mechanism between interface regulation and structural design has been elucidated through schematic diagram [Figure 13]. Figure 13 distinctly demonstrates how interfacial regulation and structural designs synergistically influence stress transfer and electromechanical response. With regard to interface regulation, the enhancement of interfacial bonding strength could markedly increase interfacial shear strength, stabilize the high stress region derived from structural design and optimize the stress transfer efficiency, which could ultimately prevent electronic transmission failure induced by crack propagation. At the structural design level, the implementation of multi-layer structural design facilitates the reconstruction of localized stress fields to enable the precise regulation of interface stress states, thereby achieving the optimization of interface bonding strength. The synergistic effect of interface regulation and structural design can

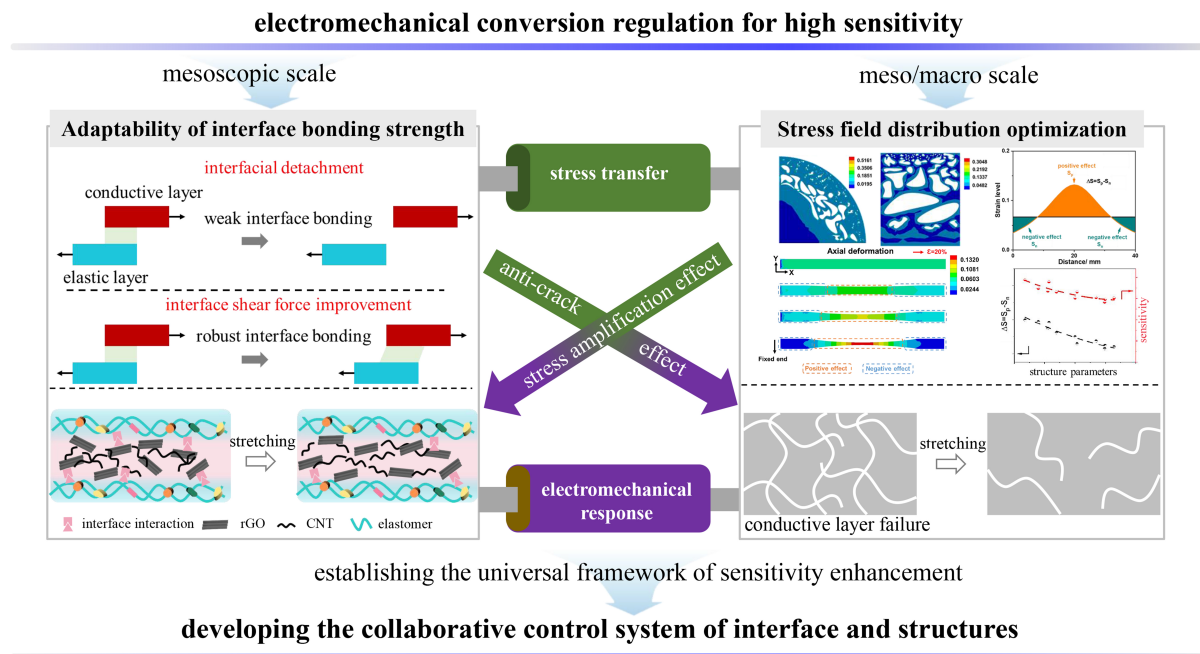


Figure 13. Schematic diagram of correlation mechanism between interface regulation and structural design to enhance sensitivity.

significantly affect the signal conversion process, thereby laying the theoretical foundation for developing a unified framework of sensitivity improving.

SENSING MECHANISM

The fundamental operational principle of resistive flexible strain sensors is based on the electrical signal response that arises from the alterations in the conductive network when subjected to strain stimuli. Given the diversity of material systems, as well as variations in macro and microstructures and processing methods, the mechanisms for enhancing sensing sensitivity in polymer composite materials could be systematically categorized into three distinct physical paradigms: tunnel effect, crack effect and separation mechanism.

Tunneling effect

In the investigation of quantum tunneling phenomenon, meticulous regulation of nanoscale interlayer spacing within conductive materials is essential for the successful observation of electron tunnel behavior. According to classical physics, electrons are unable to traverse energy barriers that exceed their kinetic energy. At the quantum scale, when the distance between neighboring conductive layers is reduced to the nanometer range, electrons are capable of traversing the potential barrier via the phenomenon of quantum tunneling, thereby generating an electric current. When external strain leads to a modification in the interlayer spacing, the likelihood of electron tunneling is affected correspondingly, which in turn causes an exponential variation in the resistance of the material. Within the photon thermal electron cross-dimensional sensing chain, Zheng *et al.* successfully demonstrated the thermally induced exponential temperature response characteristics of tunneling resistance [Figure 14A]. This was accomplished through the strategic design of rigid conductive networks utilizing percolation state carbon-based rubber composite materials^[80]. To reconcile the trade-off between sensitivity and response time, Wei *et al.* developed strain response mechanism primarily governed by quantum tunneling [Figure 14B]. This was achieved through the exploitation of inherent narrow bandgap properties of tellurium nanonets, along with the incorporation

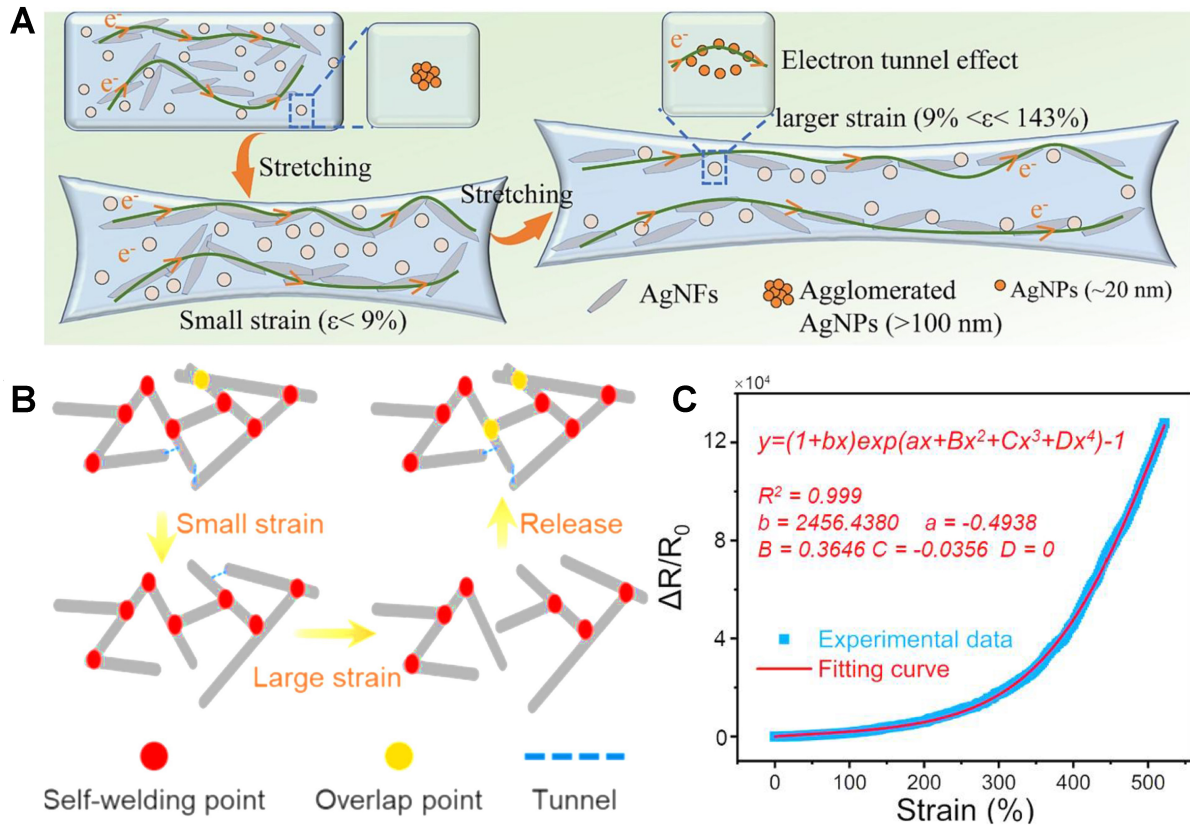


Figure 14. (A) Thermally induced exponential temperature response of tunneling resistance^[80]; (B) Strain response mechanism dominated by quantum tunneling^[81]; (C) Fitting the resistance strain curve based on the theoretical model of tunneling effect^[82].

of sub-nanometer scale node gaps^[81]. To assess the influence of tunneling effect, Qu *et al.* employed a theoretical model to fit the resistance strain curve [Figure 14C], demonstrating that the tunneling effect served as the primary physical mechanism to govern the variations in fiber resistance^[82]. In the tunnel model, the overall resistance of the strain sensor is determined based on^[83]:

$$R = \frac{M}{N} \left[\frac{8\pi\hbar s}{3c^2 e^2} \exp(rs) \right], \quad r = \frac{4\pi}{h} \sqrt{2\phi m_e} \quad (1)$$

where M represents the quantity of carbon nanotubes within a singular conductive pathway, N denotes the total number of conductive pathways, and c^2 refers to the effective cross-sectional area. Additionally, e signifies the charge of an electron, $\hbar$ represents the Planck constant, s indicates the minimum separation between neighboring conductive fillers, m_e is the mass of an electron, and ϕ denotes the height of the tunneling barrier. It is posited that the tunneling distance between neighboring conductive fillers exhibits a linear variation, while the quantity of conductive pathways demonstrates an exponential variation, as given in

$$S = S_0 (1 + A\varepsilon), \quad N = \frac{N_0}{\exp(A\varepsilon + B\varepsilon^2 + C\varepsilon^3 + D\varepsilon^4)} \quad (2)$$

where the variables S_0 and S denote the distance between conductive fillers prior to and following the application of tensile stress, while N_0 and N signify the corresponding number of conductive pathways.

Given that the escalation of strain results in the progressive deterioration of the conductive pathway, the tensile process $\Delta R/R_0$ is determined using^[82]

$$\frac{\Delta R}{R_0} = \left(\frac{SN_0}{Ns_0}\right) \exp[r(s-s_0)] - 1 = (1+b\varepsilon) \exp[A\varepsilon + B\varepsilon^2 + C\varepsilon^3 + D\varepsilon^4] - 1 \quad (3)$$

The strain-resistance curve is fitted based on the theoretical tunnel models, with the intention of demonstrating the influence of tensile strain on the distance between neighboring conductive fillers and the quantity of conductive pathways. The tunnel effect aims to clarify the impact of structural design on the sensitivity.

Crack effect

As the applied strain intensifies, the primary mechanism of strain sensing transitions from the initial tunneling effect to the crack effect. This shift is attributed to the expansion of the microcrack network within the pre-strain induced conductive layer, which is induced by its dynamic opening and closing behavior, as well as the concurrent fracture and reconstruction processes of the conductive pathway. Collectively, these factors contribute to a substantial step change in resistance.

To address the fundamental trade-off between strain resolution and the maximum sensing threshold, Lee *et al.* have engineered a high-performance strain sensor that utilized the meta crack opening mechanism [Figure 15A]. This mechanism is fundamentally based on the meticulous regulation of crack opening behavior, achieved through artificial structure design, which substantially elevates the minimum detectable strain to approximately 10^{-4} . Furthermore, the incorporation of an integrated parallel mechanical circuit design significantly improves the maximum detectable strain limit^[84]. In terms of regulating crack opening/closing behavior, Yao *et al.* introduced a closed-loop local crack strain mechanism to leverage the adjustable opening of predetermined cracks in response to strain [Figure 15B], thereby facilitating the swift modulation of resistance^[85]. Additionally, Jiang *et al.* concentrated on the engineering of structural Poisson's ratio [Figure 15C], leveraging the distinctive negative Poisson's ratio phenomenon associated with artificial structures. This approach enables the precise modulation of crack opening and closing dynamics within the conductive layer, ultimately enhancing the resistance response of the device and improving its overall sensitivity^[34]. In the investigation of crack fracture and reconstruction mechanisms, Yang *et al.* identified directional crack behavior in textile strain sensors. Under longitudinal tension, the conductive layer experiences interfacial delamination along the fiber axis. Conversely, in transverse tension, the relative movement between yarns leads to the separation of contact points [Figure 15D], which markedly enhances strain sensitivity^[86]. To complement this, Wang *et al.* investigated the dynamic response mechanism of the conductive network within carbonized silk fabrics [Figure 15E], which facilitated the propagation of strain-induced directional microcracks and resulted in abrupt changes in resistance^[87]. The total resistance of a flexible strain sensor based on crack effect is calculated according to^[17,88]

$$R = \frac{a_2 R_1 R_c + b_2 R_1 R_2 + c_2 R_2 R_c}{a_1 R_1 + b_1 R_c + c_1 R_2} \quad (4)$$

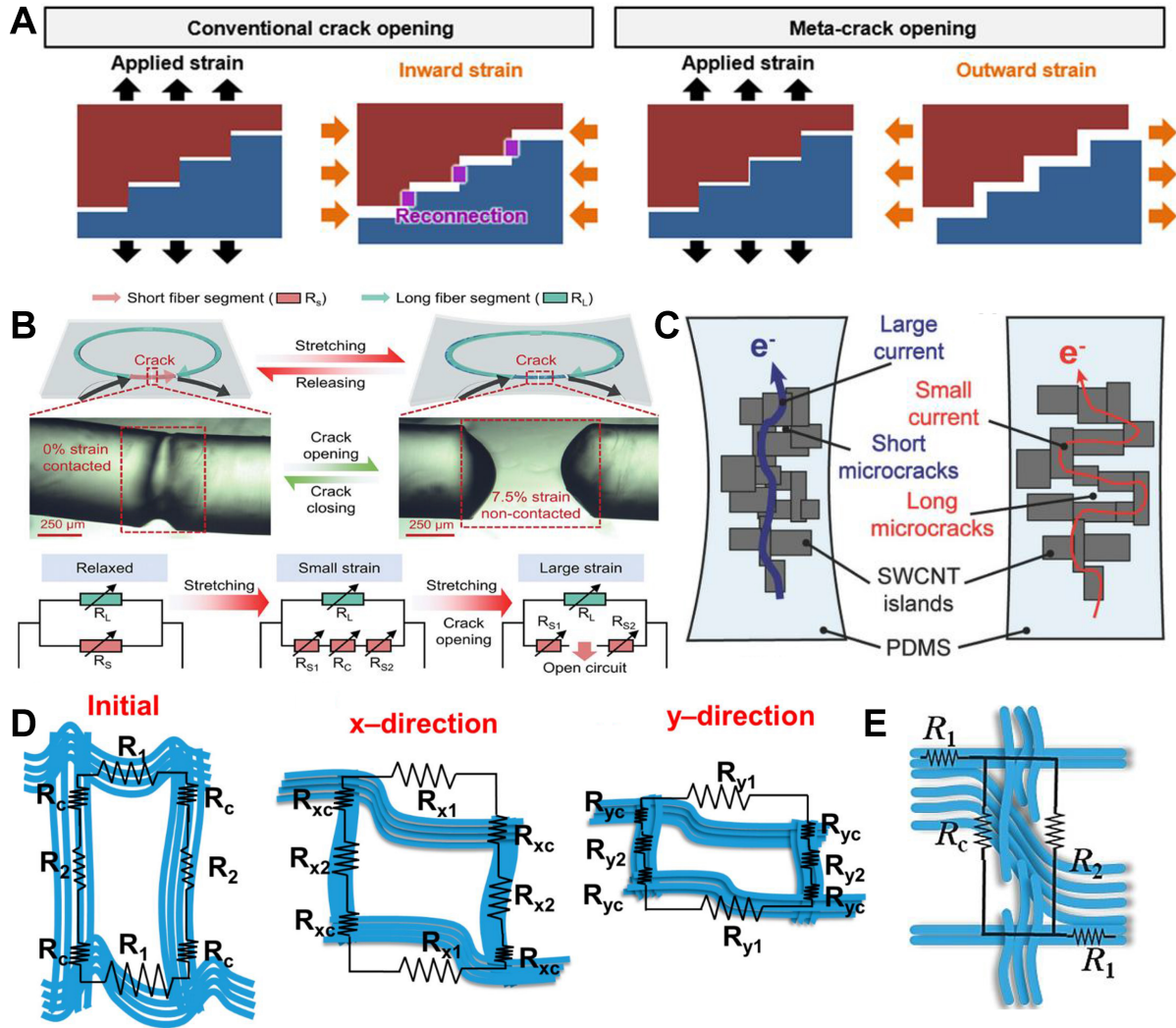


Figure 15. (A) Meta crack opening mechanism^[84]; (B) Closed-loop local crack strain mechanism^[85]; (C) Conductive path evolution under artificial structure^[34]; (D) Longitudinal and transverse crack behavior in textile strain sensors^[86]; (E) Dynamic response mechanism of conductive network within carbonized silk fabrics^[87].

where R_1 , R_2 and R_c represent the resistances associated with islands, bridges and gaps, respectively, whereas a , b , and c denote specific constants.

Decoupling mechanism

As stress levels continue to increase, considerable slippage is observed at the interface of conductive fillers, which leads to a marked reduction in the effective contact area between neighboring conductive materials. When the applied stress surpasses a specific critical threshold, the previously established conductive network is entirely disrupted, resulting in a sudden and nonlinear escalation in resistance.

Based on longitudinal strain and the slip separation mechanism associated with transverse strain, Lee *et al.* leveraged the disparity between the increase in fiber spacing [Figure 16A]. By exploiting the directional dependence of the electrical response induced by the structural anisotropy of highly oriented fiber films, they were able to effectively differentiate between strain components in both parallel and perpendicular

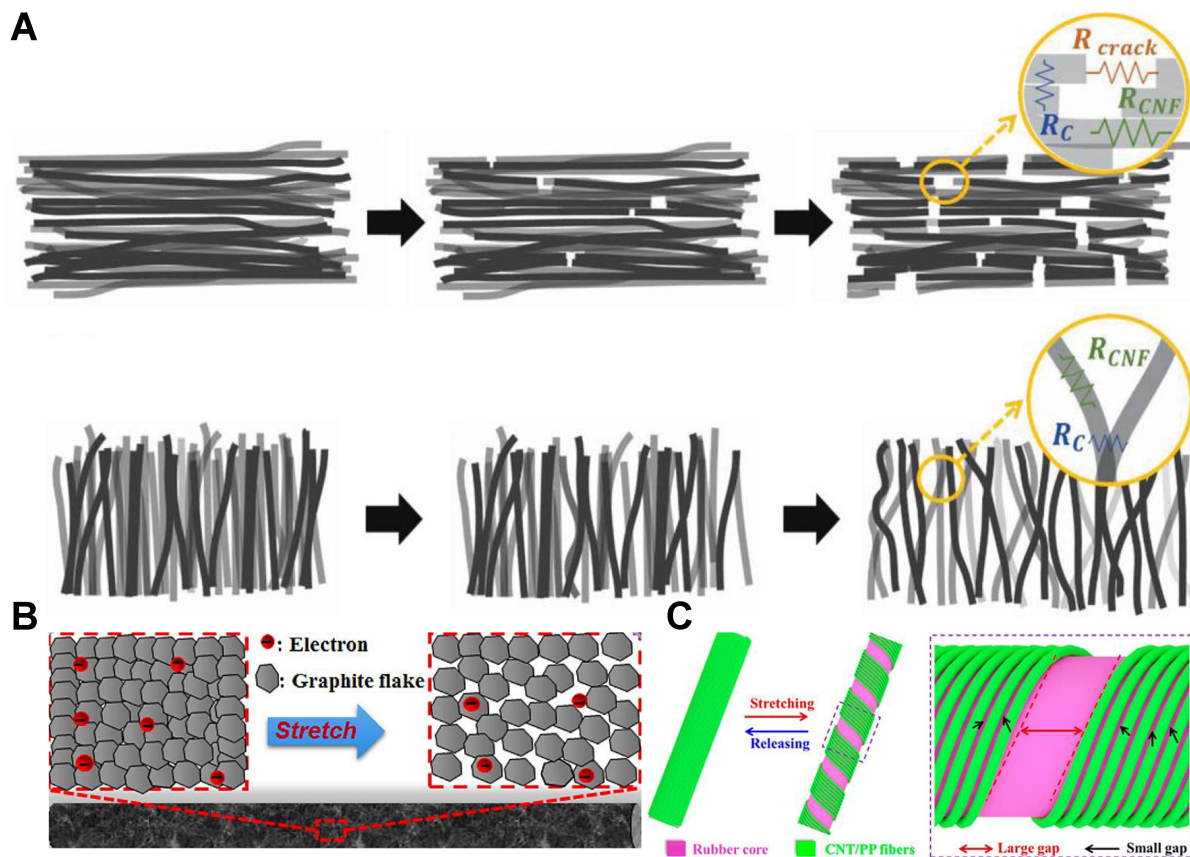


Figure 16. (A) Difference in transverse and longitudinal sensing of highly oriented fiber film^[89]; (B) Tensile slip of graphite conductive network^[90]; (C) Spiral double-layer gap structure^[91].

orientations, thus constructing a selective sensing system^[89]. Zhang *et al.* identified that the substantial disparities in elastic modulus contributed to relative slip and localized separation at the interface of graphite/silk fibroin sheath core fiber strain sensors [Figure 16B]. This phenomenon leads to the formation of cracks, fractures and potential detachment from the core layer of the initially continuous graphite conductive network when subjected to tensile stress, thereby culminating in a significant increase in the overall resistance of the fibers^[90]. Furthermore, Lu *et al.* developed an innovative spiral double-layer gap configuration [Figure 16C]. As the tensile strain escalates, the separation between the spiral structures progressively widens to result in a notable increase in the physical distance between the conductive layers and a marked elevation in contact resistance^[91].

To elucidate the intrinsic relationship between the mentioned interface/structure strategies and sensing mechanism (such as tunneling effect, crack and decoupling effect) in this review and the corresponding efficacy, a related summary table has been drawn [Table 2]. Table 2 delineates the intrinsic relationship of electromechanical conversion regulation strategies, sensitivities and corresponding sensing mechanisms, with the objective of enhancing the conceptual connection between materials design and signal transduction.

APPLICATION

Conventional application

Due to advantageous properties of being light, thin and flexible along with superior strain sensing

Table 2. Summary of the mentioned design strategies and signal conversion mechanisms

Ref.	Design strategies	Sensitivity	Conversion mechanism
[52]	Physical adsorption	77.59	Crack effect
[27]	Physical adsorption	3,051	Decoupling effect
[53]	Self-pinning method	161	Crack effect
[54]	Mechanical interlock	600 kPa ⁻¹	Decoupling effect
[28]	Mechanical interlock	82.17 kPa ⁻¹	Tunneling effect
[55]	Mechanical interlock	504.5 kPa ⁻¹	Decoupling effect
[57]	Mechanical interlock	9,557	Crack effect
[61]	Non-covalent bond	25.98	Decoupling effect
[9]	Irreversible covalent bond	38	Crack effect
[30]	Irreversible covalent bond	-1.85	Tunneling effect Decoupling effect
[65]	Interfacial click chemistry	149.6	Crack effect
[29]	Dynamic chemical bond	1.58 kPa ⁻¹	Tunneling effect Decoupling effect
[66]	Dynamic chemical bond	5.89	Decoupling effect
[67]	Dynamic chemical bond	27	Decoupling effect
[31]	Biomimetic structure	14.9 kPa ⁻¹	Decoupling effect
[72]	Biomimetic structure	18,000	Decoupling effect
[73]	Biomimetic structure	940.5	Crack effect
[78]	Artificial structure	1,744	Crack effect
[34]	Artificial structure	835	Crack effect
[79]	Artificial structure	21.8	Decoupling effect
[75]	Crack structure	454	Crack effect
[32]	Crack structure	2.7 × 10 ⁹	Crack effect
[76]	Crack structure	2,000	Crack effect
[77]	Wrinkle structure	10.96	Decoupling effect
[33]	Wrinkle structure	167,665.6	Crack effect
[49]	Wrinkle structure	24.4	Crack effect Decoupling effect

capabilities, flexible strain sensors serve as essential components in wearable smart devices. These sensors are propelling advancements and innovation across various domains, including wearable electronics, electronic skin technology, human-computer interaction and soft robotics. Utilizing the foundational concepts of traditional Chinese medicine, Wang *et al.* have developed a wearable adaptive pulse monitoring system capable of reliably and continuously monitoring both pulse and non-invasive blood pressure [Figure 17A]^[92]. Based on MXene strain sensors, Yang *et al.* developed a high-precision dynamic monitoring system for whole-body motion [Figure 17B]. The fundamental aspect of their approach involves the implementation of an adaptive strain electrical signal conversion algorithm, which facilitates the precise reconstruction of limb motion trajectories^[93]. Furthermore, they have made significant advancements in dynamic tracking by integrating machine learning models, particularly in the context of optimizing athletic posture. To address the challenges associated with dynamic surface fitting and the adaptation to complex deformation, Tang *et al.* developed an integrated technology that combined hot press interlocking with an electronic vest [Figure 17C]. This innovation effectively overcomes the constraints posed by flexible and rigid interconnects in stretchable circuits, thereby facilitating the practical implementation of ultra-stretchable electronics^[94].

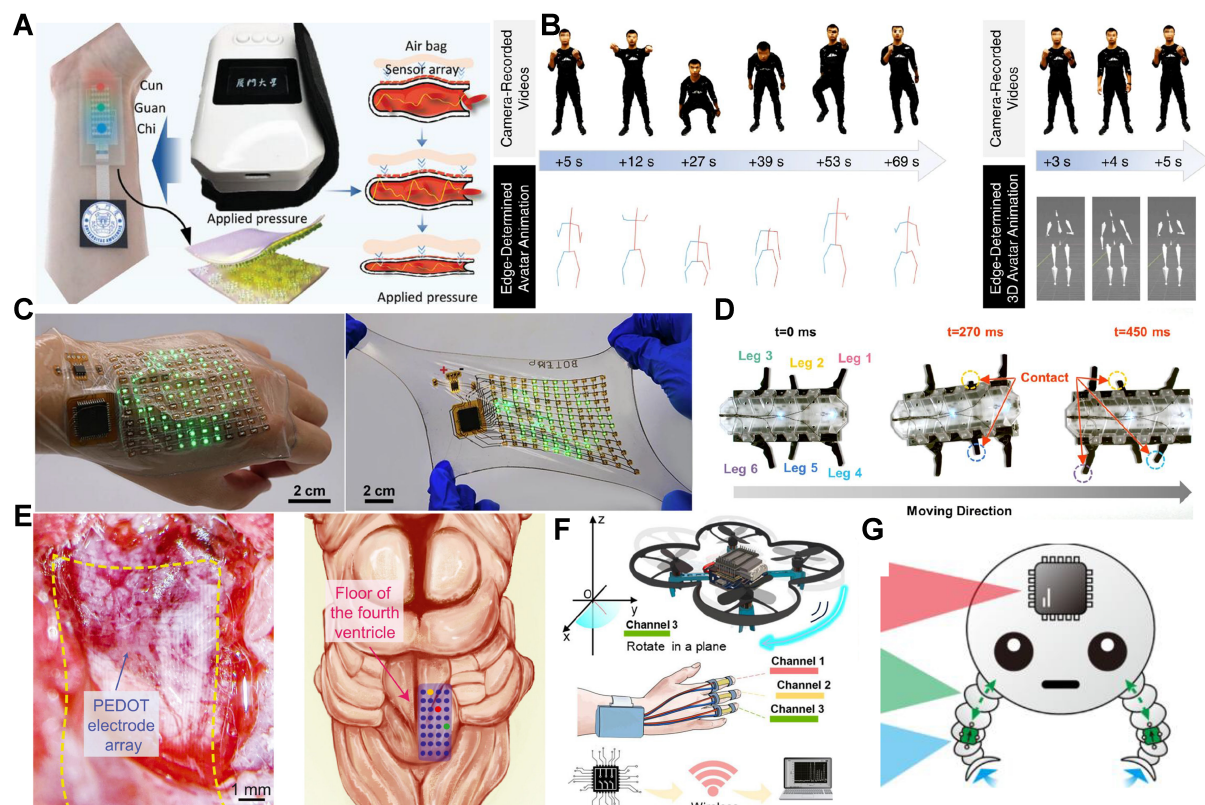


Figure 17. (A) Adaptive pulse monitoring system^[92]; (B) High precision whole-body motion dynamic monitoring^[93]; (C) Stretchable circuit soft hard interconnection device^[94]; (D) Small-legged robots^[95]; (E) Local neural regulation of mouse brainstem^[96]; (F) Three degrees of freedom control for unmanned aerial vehicles^[97]; (G) New fluid-driven soft robots^[98].

To facilitate effective mechanical interaction between robots and surroundings, Kim *et al.* have designed biomimetic tactile sensors that emulate crack patterns [Figure 17D]. Through meticulous control of the sensor's crack characteristics and the incorporation of deep learning algorithms, this innovation enables small-legged robots to sustain enhanced maneuverability and adaptability across diverse and intricate terrains^[95]. Utilizing topological supramolecular networks, Jiang *et al.* developed an innovative implantable bioelectronic approach [Figure 17E]. Following implantation into the brainstem of murine subjects, this method enables localized neural regulation at the resolution of individual neurons, thereby facilitating the precise modulation of device-specific activity^[96]. In pursuit of achieving natural human-computer interaction, Zhao *et al.* designed gesture control systems for unmanned aerial vehicles that utilized environmentally sustainable, multifunctional hydrogel sensors [Figure 17F]. These sensors translate the user's hand movements into electrical signals, which are subsequently transformed into accurate control commands with three degrees of freedom for the drone^[97]. Leveraging the hierarchical intelligence exhibited by octopuses, Yue *et al.* engineered an innovative fluid-driven soft robot. This robot is designed to locally integrate perceptual and control functions within its structure [Figure 17G], thereby imparting the system with capabilities for low-level autonomous behavior reminiscent of that of octopuses^[98].

Ultra-sensitive application

Traditional flexible strain sensor typically necessitates several percent of large strain to achieve high sensitivity ($GF > 200$), making it difficult to accurately detect the minor deformations (typically below 10^{-2} strain) from soft materials and complex morphological structures. The constraint of this detection threshold seriously impedes the accurate responsiveness of strain sensors to subtle mechanical stimuli. Consequently,

it is essential to develop flexible strain sensors with exceptional sensitivity. The core value of ultra-sensitivity lies in breaking through the sensing bottleneck of conventional strain sensors, thereby enabling the accurate measurement of extremely subtle strains that are previously difficult to detect. Specifically, with regard to the acquisition of ultrafine physiological signals, ultra-sensitivity could precisely identify the subtle physiological activities (such as minute skin deformation and blood vessel pulsation)^[99], thereby providing a novel methodology for emotional prediction and non-invasive health monitoring. In the context of early pathological feature detection, it is capable of accurately identifying subtle tremors in the limbs of individuals with early-stage neurodegenerative disorders (such as Parkinson's disease)^[100]. This capability aims to strive for a critical time window for the provision of ultra-early warnings and interventions for the condition. In the realm of weak biomechanical signal analysis, high-resolution perception capabilities enable the differentiation between the sounds produced by the opening and closing of heart valves^[101], as well as the subtle movements of laryngeal muscles during silent speech. This technological advancement provides significant support for the evaluation of cardiovascular function and the development of innovative assistive communication methods. Consequently, ultra-sensitive strain sensors extend beyond merely enhancing sensitivity levels. Their revolutionary significance lies in unlocking new dimensions for accurate sensing within the intricate dynamics of microscale environments, soft materials and biological entities. This advancement provides unprecedentedly powerful tools for cutting-edge medical diagnosis and fundamental research in life sciences.

To improve the correlation between effective electromechanical conversion strategies and practical application cases, a case summary table has been drawn [Table 3]. Table 3 clearly presents the logical chain from design strategy to sensing mechanism and ultimately to target application, thereby enhancing the persuasiveness of the primary argument and highlighting the depth and applicability of the technology.

CONCLUSION AND OUTLOOK

Notwithstanding considerable advancements in the sensitivity of flexible strain sensors derived from polymer composite materials, interface failure problems between heterogeneous materials continue to pose a significant challenge that hinders their sustained and stable development over the long term. Recently, ionic gels have emerged as a key material system with remarkable flexibility, high ionic conductivity and the absence of interface issues, attributable to their inherent adjustability (such as polymer topological network, selection of ionic liquids or salts, and the incorporation of functional additives) and the intrinsic ionic conduction mechanisms. These properties indicate substantial potential for developing high-performance flexible strain sensors. The primary benefit of this material is its inherent homogeneity or near-homogeneity, which fundamentally mitigates issues related to debonding, sliding and unstable contact resistance at the filler-matrix interface. These issues typically arise in conventional polymer composite materials due to modulus mismatch, inadequate adhesion, or cyclic deformation. Consequently, this characteristic provides a novel solution to the challenges associated with interface failure, thereby facilitating the development of high-sensitivity sensing system. It is important to note that ion gel-based strain sensors currently encounter significant challenges in practical applications, which include the potential for ion leakage during prolonged use, hysteresis in mechanical response, and diminished signal stability due to environmental influences. Consequently, forthcoming research should prioritize the advancement of a novel generation of high-performance ion gel systems. It is essential to investigate the effective packaging strategies for mitigating ion leakage, as well as to thoroughly elucidate the structure-activity relationship pertaining to the microstructure, ion transport and sensing performance of these systems. Such efforts are crucial for enhancing their practical applications.

Table 3. Summary of the logical chain from design strategy to sensing mechanism and subsequently to target application

Ref.	Design strategy	Sensing mechanism	Sensitivity	Target application
[92]	Microstructure design	Decoupling effect	3.99 kPa ⁻¹	Wearable adaptive pulse monitoring
[93]	Microstructure design	Crack effect	1,000	High-precision dynamic monitoring
[94]	Mechanical interlocking	Decoupling effect	/	Ultra-stretchable electronics
[95]	Microstructure design	Crack effect	3600	Small-legged robots
[96]	Molecular and microstructure design	Decoupling effect	/	Localized neural regulation
[97]	Dynamic covalent bond	Ion conduction	0.21	Gesture control for unmanned aerial vehicles
[102]	Non-covalent bond	Decoupling effect	13,462.1%/RH	Humidity field detection
[103]	Microstructure design	Decoupling effect	-160.90 fF°C ⁻¹	Temperature-strain dual-mode sensing

RH: Relative humidity.

The advancement toward the next generation of intelligent flexible strain sensors is fundamentally dependent on the implementation of multimodal sensing techniques and the integration of multifunctional capabilities. Multimodal perception equips a singular device with the capability to concurrently assess various physical stimuli, emulate the mechanisms of tactile perception, and establish a basis for the integration of multidimensional information in intricate environmental interactions. Multifunctional integration is designed to address complex scenarios by optimizing system performance, with particular emphasis on the integration of self-powered energy storage systems, sensing capabilities, and the enhancement of tolerance to extreme environmental conditions.

Multimodal sensing

The advancement of an intelligent sensing system that integrates both single and multimodal perception, along with adaptive response capabilities, is fundamental to enhancing the efficient and widespread development of wearable technology. Nonetheless, the development of fundamental components capable of facilitating multi-mode signal sensing while exhibiting high responsiveness continues to represent a significant technical challenge in addressing the aforementioned functional requirements.

In the domain of humidity-stress coupling sensing, Zhang *et al.* have devised a scalable methodology for array preparation utilizing ionic liquid/polymer composite materials [Figure 18A]. This approach enables precise regulation of the sensitive layer's thickness, thereby ensuring uniformity in the response of array units^[102]. Consequently, it facilitates the successful development of high-performance sensing arrays that are well-suited for rapid and uniform detection of humidity fields. In the context of temperature-strain coupling, Li *et al.* developed a flexible dual-mode sensor utilizing mechanical neutral layer architectures [Figure 18B]. This design enabled crosstalk-free synchronous sensing by implementing a decoupling strategy for the strain and temperature physical fields^[103]. For wireless passive biomechanical monitoring, Zhang *et al.* have constructed a strain sensing platform utilizing flexible magnetoelastic materials [Figure 18C]. This research explores the capability to attain high-sensitivity detection of microscale biomechanical signals, while simultaneously reducing interference with biological processes^[104]. In the context of optical encryption applications, Li *et al.* employed wet spinning technology to incorporate perovskite photoluminescent fibers into fiber matrix [Figure 18D]. By applying strain to modulate the spacing of quantum dots, they effectively created an encrypted smart textile that featured dynamically adjustable luminescent color gamut characteristics, thereby attaining a high level of information security through encryption^[105]. In response to the ongoing requirement for the continuous monitoring of intra-abdominal pH levels, Li *et al.* have developed a bioabsorbable wireless passive sensing system [Figure 18E]. This innovative system is designed to provide early detection of gastrointestinal fistulas by facilitating real-time, *in situ* observation of fluctuations in intra-abdominal pH dynamics^[106].

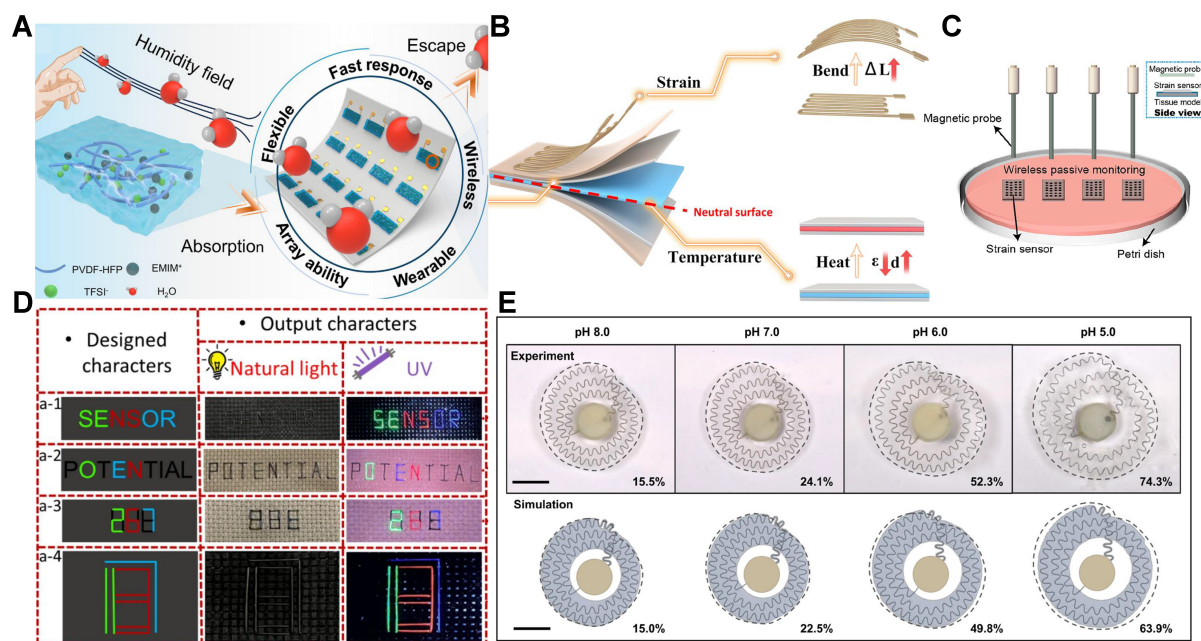


Figure 18. (A) Humidity-stress coupling sensing system^[102]; (B) Temperature-strain coupling domain^[103]; (C) Wireless passive biomechanical monitoring based on flexible magnetoelastic materials^[104]; (D) Optical encryption applications^[105]; (E) Continuous monitoring of intra-abdominal pH levels^[106].

Multifunctional integration

The design of system-level fusion for flexible multifunctional electronic devices is emerging as a fundamental evolutionary framework for innovative wearable technologies and advanced diagnostic and therapeutic systems. This design concept incorporates self-driven energy harvesting, micro-scale energy storage and multifunctional sensing capabilities within a single architecture.

To enhance the safe operation of commercial batteries, Fan *et al.* have devised an embedded intelligent sensing system that could be non-destructively integrated into commercial battery cells [Figure 19A]. This system facilitates the real-time monitoring of various physical field signals, leading to the development of a data-driven model utilizing deep confidence networks^[107]. This model is designed to provide early warnings for critical failure modes, including lithium dendrite formation, internal short circuits and electrolyte depletion. In light of the increasing requirement for extreme environmental sensing capabilities, Liu *et al.* have engineered a cellulose-based frictional electric material that exhibits stability at elevated temperatures [Figure 19B]. This innovative material facilitates multimodal tactile sensing at approximately 200 °C through the utilization of frictional nanogenerators^[108]. The developed sensor transcends the thermal stability constraints of current technologies, enabling it to respond with heightened sensitivity to variations in both pressure and temperature under extreme conditions. Its detection capabilities significantly surpass the perceptual thresholds of human sensory systems. In the domain of multi-interface collaborative engineering, Shi *et al.* have successfully developed multi-level programmable microstructure thin films utilizing advanced alternating layer deposition techniques [Figure 19C]. These films exhibit remarkable integrated functionalities, such as efficient broadband photothermal conversion, superhydrophobic self-cleaning properties, high effectiveness in electromagnetic interference shielding, rapid joule heating response, and enhanced capabilities for ice melting and snow removal^[109]. This innovation presents a multifunctional platform that holds significant promise for multimodal energy conversion and health monitoring applications in the forthcoming generation of intelligent wearable systems.

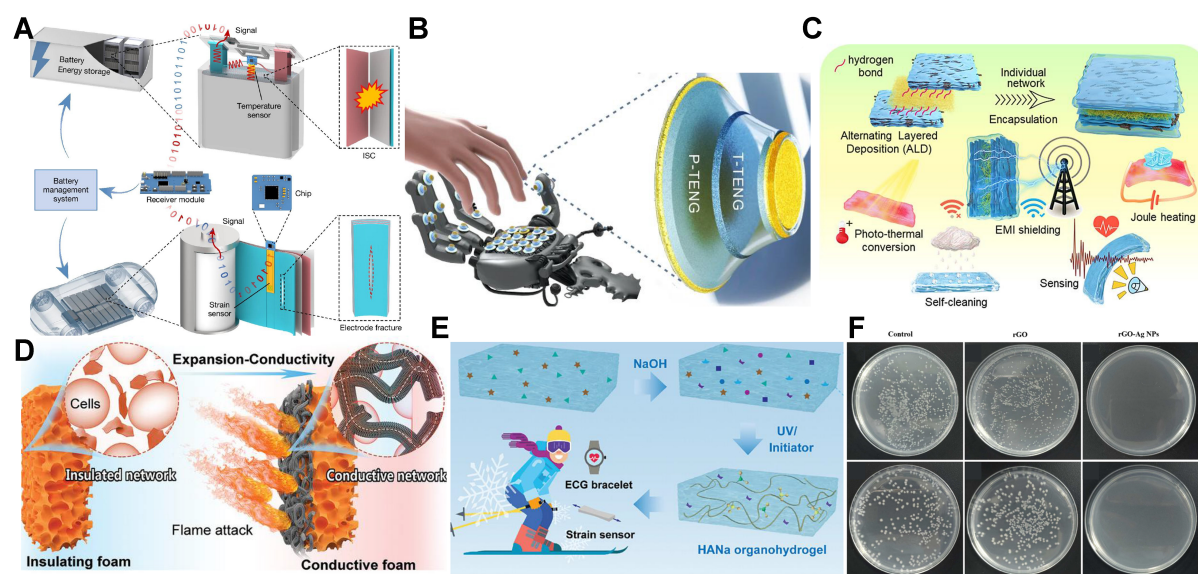


Figure 19. (A) Intelligent sensing system for non-destructive implantation of commercial battery cells^[107]; (B) Multimodal tactile sensing of high temperature resistant based on friction nanogenerator^[108]; (C) Multifunctional thin films with multi-level programmable microstructure^[109]; (D) Lignin-based fire-resistant polyurethane foams^[110]; (E) Frost-resistant hydrogel strain sensors^[111]; (F) Piezoresistive sensors with intrinsic waterproofing and active antibacterial properties^[112].

To develop a new generation of thermal insulation materials, Sun *et al.* conducted a study on lignin-based polyurethane foam insulation materials to investigate their thermal remolding, expansion behavior, and the microscopic mechanisms underlying the conductivity [Figure 19D]. Additionally, a highly sensitive fire alarm system characterized by an extended response time to enhance safety was developed^[110]. In the advancement of freeze-resistant hydrogel strain sensors, drawing inspiration from cold-resistant organisms and superabsorbent materials, Huang *et al.* employed a strategy of modifying charged polar groups within the polymer chain [Figure 19E]. This approach significantly improved the water binding capacity of the polymer^[111]. In the realm of antibacterial research, Cao *et al.* have engineered a wearable piezoresistive sensor that integrates inherent waterproof capabilities with active antibacterial properties [Figure 19F]. This innovation provides dual protection, ensuring both effective waterproofing and active antibacterial functionality^[112]. Consequently, it establishes a dependable sensing platform that mitigates environmental interference, particularly in specialized contexts such as medical monitoring.

This review provides a comprehensive overview of controlling the interfacial bonding strength to optimize stress transfer efficiency and designing multi-level structures to reconstruct stress fields, ultimately improving device sensitivity. In light of this, a comprehensive analysis was conducted to identify the critical scientific challenges that must be urgently addressed in order to enhance the interface bonding mechanism and stress amplification effect. Furthermore, the mechanisms underlying sensitivity enhancement in polymer composite materials were elucidated. This study provides an in-depth analysis of the evolution of flexible strain sensors, discussing their transition from singular modal response to multimodal collaborative perception framework, and ultimately to traditional application paradigm by system-level functional integration. The analysis is systematically organized, focusing on critical sensing functions, the expansion of perceptual dimensions and the integration of multifunctional systems. Notwithstanding the considerable accomplishments attained thus far, there remain several challenges that necessitate additional contemplation.

(i) In the polymer composite strain sensing system, a notable discrepancy in modulus exists between conductive fillers and flexible elastomer matrix. This disparity hinders the efficient dissipation of strain energy via the slip and extension mechanisms associated with the conductive fillers. In the failure condition of energy transfer pathway, flexible elastic materials emerge as the primary medium for significant energy dissipation. It is important to recognize that the macroscopic mechanical behavior of polymer materials is influenced by their molecular architecture. This architecture governs the polymer chain dynamics, which in turn regulates the development of aggregated structural states. Such changes ultimately result in the reconfiguration of charge transport networks, thereby impacting the device sensitivity. The primary scientific challenge that presently hinders advancements in sensitivity enhancement is the absence of quantitative structure-activity relationship models that correlate the dynamic evolution of polymer aggregation structures with sensitivity. This issue necessitates further investigation.

(ii) Constrained by the intrinsic mechanical behavior of positive Poisson's ratio, crack fracture and reconnection in tensile mode could cause the device sensitivity to drop below 10 at strains below 10^{-3} , resulting in the loss of micro strain monitoring capability. The fundamental approach to overcoming this bottleneck is through the meticulous regulation of crack opening behavior. Currently, we are confronted with a twofold challenge. On the one hand, there exists an immediate necessity for advancements in the innovative structure design to mitigate the fracture and reconnection of cracks. On the other hand, the full structure-activity relationship regarding Poisson's ratio, stress field distribution, crack evolution paths and sensitivity response function has not yet been established.

(iii) The inherent randomness, disorder and unpredictability associated with crack formation contribute to the ineffectiveness of tailored sensitivity control. A fundamental approach to overcoming this limitation involves the precise programming of crack propagation dynamics. However, this process is governed by the modulus compatibility of the material system, the distribution of local stress fields and interface bonding strength. There exists a deficiency in the comprehension of how to quantitatively manage the intrinsic correlation mechanism between the crack propagation path and sensitivity response function, particularly through the dynamic coupling effect of the aforementioned three factors. Consequently, further investigation is warranted.

The strategic optimization of interfacial stress transfer efficiency and the precise modulation of stress field distribution emerge as pivotal methodologies for significantly augmenting the electromechanical conversion efficiency in flexible strain sensors. This enhanced electromechanical coupling directly translates to superior device sensitivity. Consequently, these advancements furnish both a robust theoretical framework elucidating interfacial design principles and actionable technological paradigms for engineering high-performance flexible strain sensors. Ultimately, this synergistic approach drives the evolution of next-generation stretchable electronics by enabling more sophisticated, reliable and efficient functional devices.

DECLARATIONS

Authors' contributions

Wrote the original draft: Wu, C.

Supervised the manuscript: Zhu, H.; Wang, X.; Yuan, W.; Tian, Y.; Jiang, X.; Han, Y.; Gao, X.

Revised the manuscript: Lai, W.

Availability of data and materials

Not applicable.

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Conflict of interest

All authors declare that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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