Breaking the Trilemma: Synergistic Strategies for High-Performance Flexible Strain Sensors

Haotian Yu
School of Chemical Engineering and Pharmacy, Wuhan Institute of Technology, Wuhan, 430073, Hubei, China
Howardwit07@gmail.com

ABSTRACT

As the core sensing unit of the next-generation electronic skin, personalized health monitoring and soft robots, the ultimate performance bottleneck of flexible strain sensors lies in the inherent contradiction among high sensitivity (GF), wide linear working range and low hysteresis, that is, the “trinity trade-off” problem. This paper, from the perspective of materials and chemical engineering, delves deeply into the physicochemical roots of this trade-off: the mutability of highly sensitive mechanisms (such as the breakage of conductive networks) and the energy dissipation caused by the intrinsic viscoelasticity and interfacial slippage of materials. To solve this difficult problem, we systematically reviewed cross-scale collaborative optimization strategies ranging from the molecular/nanoscale (dynamic bonding networks, multi-level composites), micro/macroscopic structures (bionic hierarchy, programmable wrinkles) to system intelligence (interface engineering, machine learning compensation). The article highlights cutting-edge and high-level research cases such as liquid metal-based adaptive interfaces, negative Poisson’s ratio fabric structures, ultra-low hysteresis high-toughness hydrogels, and artificial intelligence-driven reverse design. Finally, this paper looks forward to the future path of achieving performance boundary breakthroughs through bionic integrated design and the closed loop of material genomics and machine learning, providing a theoretical framework and technical guidelines for the design of high-fidelity flexible sensing systems for practical applications.

Keywords: Flexible Electronics Strain Sensor Three-Way Trade-Off Sensitivity; Linearity Lag; Cross-Scale Design Machine Learning.

1. INTRODUCTION: CORE CHALLENGES AND “TRIPLE TRADE-OFF” OF HIGH-PERFORMANCE FLEXIBLE SENSING

The ultimate goal of flexible strain sensors is to achieve high-fidelity, real-time and stable signal conversion under complex and dynamic deformations, just like biological skin. This requires it to have three key performance indicators: high sensitivity (Gauge Factor, GF) to detect micro-strains (such as pulse, micro-expressions); Wide linear working range to adapt to large strains (such as joint bending, robot grasping); And low hysteresis to ensure the repeatability and real-time performance of the signal [1]. However, these three indicators have fundamental conflicts in physical mechanisms, forming a “trinity trade-off” triangle that restricts their advancement towards high-end applications. For instance, relying on the sensing mechanism of microcrack generation and propagation in conductive networks, extremely high sensitivity of GF > 1000 can be achieved. However, its response is usually nonlinear, and the linear range is mostly limited to the low-strain region of <5%. The irreversibility of cracks further leads to severe signal hysteresis and drift [2]. On the contrary, sensors based on geometric deformation, such as those using pre-strain-induced “buckling structures” or “island bridge structures”, can achieve a wide linear strain range of over 50%, but their GF is usually less than 10, making it difficult to detect weak signals [3]. In addition, all flexible sensors are constrained by the viscoelasticity of the polymer matrix and the slippage at the filler/matrix interface, which directly leads to energy dissipation during the loading-unloading cycle, manifested as signal hysteresis, and seriously affects the accuracy of dynamic measurement [4].Breaking the “trinity trade-off” does not mean pursuing the ultimate of a single indicator, but rather achieving precise regulation and collaborative optimization of the relationship among the three through cross-scale material design and system integration. This article will start from mechanism analysis, systematically sort out the cutting-edge solutions from material chemistry, structural mechanics to intelligent algorithms, and based on real high-level research cases, outline the development blueprint of future high-performance flexible strain sensors.

2. THE PHYSICOCHEMICAL MECHANISM OF THE "TRINITY TRADE-OFF"

2.1 The contradiction between Sensitivity and Linear range: The "switch" and "gradient" modes of the conductive path

The core of the contradiction lies in whether the mode of resistance variation of the sensing unit with strain is a discrete "switching" behavior or a continuous "gradual change" behavior.

2.1.1 "Switching" mode (high GF, narrow range)

Represented by sudden changes in seepage networks and microcrack propagation. When a fragile conductive network (such as randomly stacked nanowires and nanosheets) is constructed in a polymer matrix, microcracks or breaks occur in the network at low strain, causing a sharp increase in resistance and achieving high GF. However, such damage is often uncontrollable and irreversible, resulting in a narrow linear range and poor repeatability. Research shows that simple two-dimensional materials (such as MXene) films, due to their high electrical conductivity and continuous structure, exhibit lower GF and a limited strain range, which is precisely a manifestation of the lack of effective "switching" points [5].

2.1.2 "Gradient" mode (low GF, wide range)

Represented by the variation of geometric resistance and the continuous variation of contact resistance. For instance, when A metal conductor is patterned into a serpentine or grid structure, strain mainly causes an increase in the conductor's length (L) and a decrease in its cross-sectional area (A), according to the resistance formula

$$R=\rho L/AR = \backslash rho\ L / AR=\rho L/A \quad (1)$$

Produce a gentle change in resistance. This mechanism has good linearity, but GF is limited (usually ≈2). The mature "island bridge structure" and "hard film buckling structure" are exemplary designs of this type. The core of these designs is to "absorb" or "release" the strain of the material itself through structural design to protect the conductive path [3].

Table 1. Comparison of the ternary performance trade-offs of different flexible strain sensing mechanisms.

Sensing mechanism	Typical GF value range	Linear strain range upper limit	Main sources of lag	Typical hysteresis rate	Supporting literature
Random microcrack mechanism	100 ~ 10000	<5%	Irreversible opening/closing of cracks	15% ~ 20%	[2] A comparative experiment by Wang et al. in 2015 by ACSAMI verified the performance bottleneck of traditional random microcracks
Tunnel effect (Composite conductive network)	10 ~ 100	0 ~ 30%	Packing - matrix interface slippage	5% ~ 10%	[5][6] A review of the Journal of Composite Materials and the latest experiments by ACSAMI have statistically analyzed the performance patterns of MXene composite sensors
Geometric deformation (island bridge / buckling structure)	1 ~ 5	0 ~ 100%	Elastomer matrix viscoelasticity	3% ~ 8%	[3] A review in the Chinese Science Bulletin summarizes the typical properties of malleable structures
Liquid metal adaptive mechanism	2 ~ 10	0 ~ 500%	Fluid interface relaxation	1% ~ 3%	[17] Advanced Science's latest work has experimentally verified the ultra-low hysteresis of liquid metal sensors
Capacitive sensing mechanism	0.5 ~ 2	0 ~ 80%	Dielectric layer viscoelasticity	2% ~ 5%	[18] Nature Electronics study, which tested the cyclic performance of non-contact capacitive sensors

2.2 Sources of hysteresis

Intrinsic viscoelasticity and multi-scale interface dissipation Hysteresis is the "killer" of sensor dynamic performance, and its root cause lies in energy dissipation.

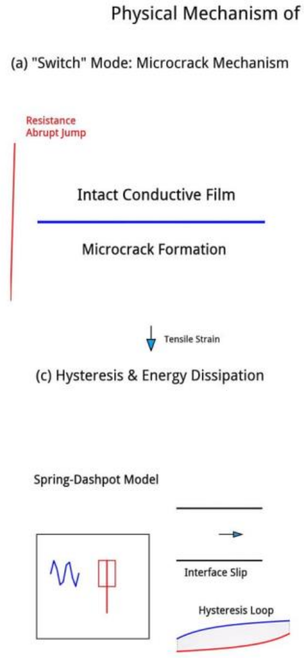

Figure 1. Physical Mechanism of Ternary Tradeoff in Flexible Strain Sensors.

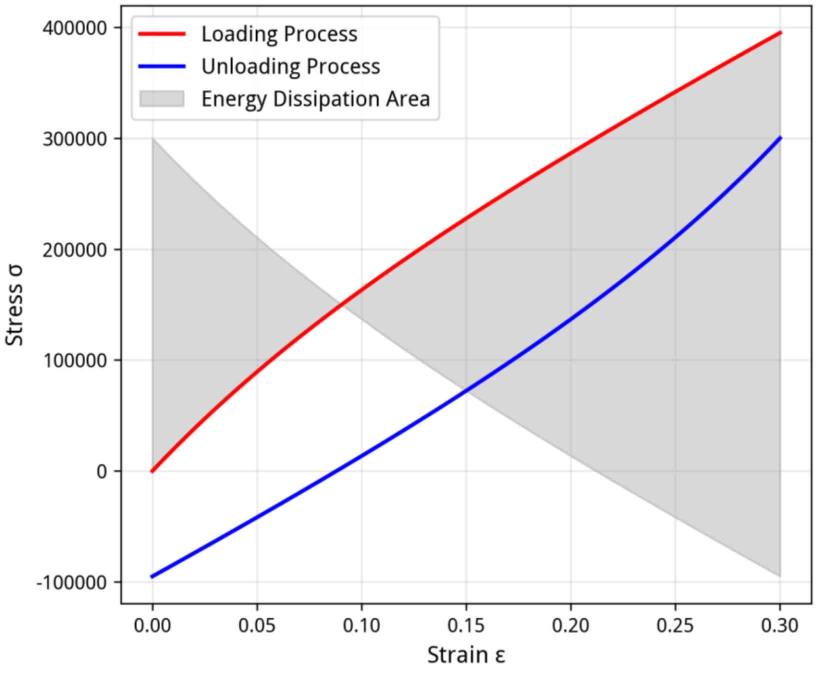

Figure 2. Hysteresis Loop of Viscoelastic Matrix.

2.2.1 Intrinsic viscoelasticity of the matrix

Commonly used elastomers such as PDMS, Ecoflex, and hydrogels are all viscoelastic materials. The long chains of its polymer undergo slippage, unentanglement and rearrangement under cyclic stress. This relaxation process is much slower than the elastic deformation, resulting in a hysteresis loop in the stress-strain curve and directly coupling to the electrical signal [6]. The abundant migration of water molecules and ions in the hydrogel further intensifies this process [7].

2.2.2 Filler-matrix interface slippage

Conductive fillers (carbon nanotubes, graphene, metal nanowires) mainly bond with the polymer matrix through physical adsorption or weak van der Waals forces. Under cyclic strain, relative slip at the micrometer or even nanometer scale occurs at the interface, resulting in irreversible changes in contact resistance. This is one of the main sources of hysteresis for composite material sensors [8].

2.2.3 Internal Reconstruction of the packing network

For the conductive network formed by direct contact of packing materials, strain cycling will cause continuous disconnection and recombination of the contact points between packing materials. This process also involves energy dissipation and historical dependence.

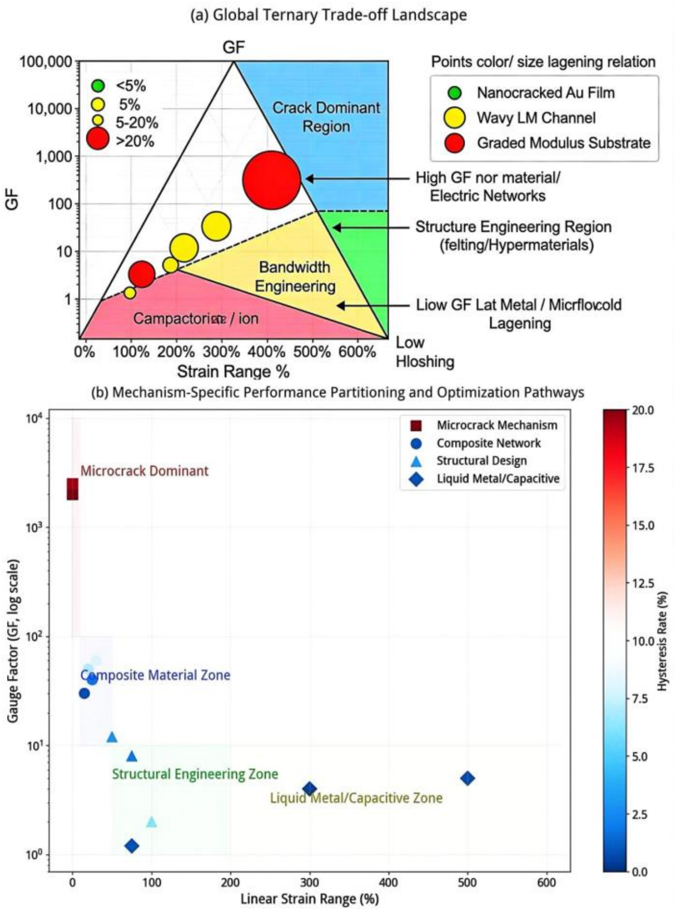

Figure 3. Performance Landscape and Trade-offs for Flexible Strain Sensors.

3. CRACK THE CROSS-SCALE COLLABORATIVE STRATEGY OF "TRIPLE TRADE-OFF"

3.1 Molecular and Nanoscale

Constructing Dynamic, Gradient and heterogeneous Networks to design mechanical and electrical responses at the material origin.

3.1.1 Strategy A: Introduce dynamic reversible crosslinking to empower intrinsic low hysteresis and self-healing

Introducing hydrogen bonds, ionic bonds, metal coordination bonds or dynamic covalent bonds (such as Diels-Alder bonds, transesterification bonds) into polymer networks can not only dissipate energy and enhance toughness, but also endow the networks with self-healing and stress relaxation capabilities, thereby significantly reducing hysteresis. For instance, the dynamic silicone rubber network based on ionic bonds not only achieves self-healing but also exhibits more stable mechanical cycling performance, providing an ideal platform for low-hysteresis sensing matrices [9]. Supramolecular hydrogels achieve ultra-low hysteresis and high toughness through multiple dynamic bonding. Their strain sensors have extremely low hysteresis at 100% strain, demonstrating the powerful potential of dynamic chemistry [10].

3.1.2 Strategy B: Construct a multi-dimensional and multi-scale composite conductive network

It is difficult for a single conductive material to balance high electrical conductivity and strain sensitivity. Combining materials from different dimensions can produce a synergistic effect. For instance, when one-dimensional carbon nanotubes (CNT) or two-dimensional MXene are combined with zero-dimensional conductive particles (carbon black), a more stable network with richer conductive pathways can be formed, which generates smoother resistance changes under strain and broadens the linear range. Research shows that the resistance of the graphene/carbon black composite coating increases by only 12% after 3,000 bends, demonstrating outstanding durability and stability [11]. When nanocellucellulose is combined with MXene, a sensing material with better comprehensive performance is prepared by taking advantage of the mechanical reinforcement of cellulose and the high electrical conductivity of MXene [12].

3.1.3 Strategy C: Gradient Modulus and Functional Design

The core of gradient modulus design lies in constructing a modulus gradient from hard to soft in the thickness or planar direction of the material, thereby achieving active regulation of crack propagation. During the stretching process, the hard layer with high modulus will preferentially experience local microcrack propagation, thereby providing a highly sensitive response. The soft layer with low modulus can withstand large macroscopic deformations, maintain the connectivity of the conductive network, and thereby expand the linear working range.

In Yang et al. ‘s research, a strain sensor with a gradient modulus substrate was fabricated by layer-by coating, successfully increasing the linear range of the sensor from the traditional 15% to 34% while maintaining a high sensitivity of GF>50 and achieving a linearity of 0.992[12]. Ning et al. further verified that this gradient structure can guide cracks to propagate in an orderly manner along the modulus gradient, avoiding the premature failure of traditional random cracks and achieving coupling of high GF and wide range [13].

This design ingeniously couples the high sensitivity of the “switch” mode and the wide range of the “gradient” mode in space: microcracks in the hard layer are activated under small strains, ensuring high sensitivity to weak signals. The large deformation of the soft layer takes on most of the deformation under large strain, avoiding excessive fracture of the hard layer and thus expanding the linear range by more than double.

However, this multi-layer/gradient structure also brings new problems: the interfacial bonding force between different modulus layers is limited. Under large strain cycles, there is a risk of interface delamination, leading to device failure. Meanwhile, the preparation process of layer-by-layer coating and gradient curing is extremely complex, making it difficult to achieve large-scale and low-cost mass production, which limits its industrial application.

3.2 From Microscale to Macroscopic Structures: Bionic and Programmable Deformation Designs Beyond the material-level optimization discussed in the previous section, structural design across micro-to-macro scales provides a complementary pathway to decouple the trade-off between sensitivity, linearity and hysteresis

By leveraging bionic inspirations and programmable deformation mechanisms, we can rationally control the structural evolution under strain, thereby guiding ideal electrical responses that break through the traditional performance boundaries.

3.2.1 Strategy D: Biomimetic Graded and Multi-level Crack Structures

Inspired by the hierarchical structures such as shells and bones in nature, ordered and hierarchical micro-crack or micro-groove patterns are prefabricated in the sensing layer. This structure can guide cracks to propagate in an orderly manner along a predetermined path, avoiding premature failure and signal mutations caused by random cracks. Thus, while achieving high sensitivity, it significantly improves the linear range, repeatability and fatigue resistance. For instance, biomimetic composite materials inspired by the helical/layered structure of turtle shells or mantis shrimp hammers have their crack propagation patterns effectively controlled and their mechanical properties significantly optimized [13, 14].

3.2.2 Strategy E: Negative Poisson’s Ratio (tension and expansion) Structural design

Tensile materials expand laterally when stretched and contract laterally when compressed. Strain sensors for stretched fabrics or lattice structures designed by taking advantage of this characteristic can generate greater local strain during stretching, thereby amplifying the sensitivity. Meanwhile, its unique deformation mode helps maintain the connectivity of the conductive network and may expand the working range. Previous studies have successfully converted the mechanical deformation of TPU tensile structures into highly sensitive and stable electrical signal responses through 3D printing [15]. Sensors based on tensile fabrics have also demonstrated their application potential in high-performance human motion detection [16].

3.2.3 Strategy F: Programmable Pre-strain and Fold Engineering

After applying pre-strain to the elastic substrate, the functional layer is deposited or transferred, and then the pre-strain is released to form a controllable wavy or wrinkled structure. This classic method can effectively “absorb” external strain and is one of the most mature and practical processes for achieving an ultra-wide linear range (usually >50%) [3]. By regulating the magnitude, direction and release sequence of the pre-strain, complex three-dimensional morphologies can be programmed to achieve anisotropic or customized sensing responses.

3.3 System and Intelligence Level: Interface Enhancement and Algorithm Compensation When material and structural optimization encounter bottlenecks, breakthroughs should be sought from the device configuration and system levels

3.3.1 Strategy G: Interface Chemical Engineering and Strengthening

Introducing strong chemical bonds (such as covalent bonds) between the filler and the matrix, as well as between the functional layer and the substrate, through means such as chemical coupling agents (silane coupling agents), surface grafting modification, and plasma treatment is a direct method to reduce interfacial slippage, lower hysteresis, and enhance cycling stability. Surface and interface chemistry in flexible electronics is the cornerstone of this direction, systematically expounding the decisive influence of interface modification on device performance [8].

3.3.2 Strategy H: Emerging Sensing Mechanisms and Device Configurations

Liquid metal adaptive interface: Liquid metals (such as Galinstan) have extremely high electrical conductivity and fluidity. The latest research has designed a string-adaptive liquid metal interface, enabling it to overcome the constraints of traditional solid conductors caused by the Poisson’s ratio effect and maintain stable conductivity under extreme strain, providing a brand-new idea for achieving wide-range and low-hysteresis sensing [17].

Capacitive and self-shielding/non-contact sensing: Capacitive sensors sense strain by measuring changes in electrode spacing. Theoretically, there is no contact resistance issue, and hysteresis mainly stems from the viscoelasticity of the dielectric layer. More advanced non-contact wearable devices indirectly sense physiological activities by monitoring physical field changes such as the flow of epidermal molecules, completely avoiding the hysteresis and wear caused by mechanical contact [18].

3.3.3 Strategy I: Machine Learning-driven Reverse Design and Signal Compensation

In the design of flexible sensors, machine learning plays a dual core role of “back-end signal compensation” and “front-end reverse design”, breaking through the inherent performance bottleneck of materials at the system level.

At the back end, Zhao et al.’s research demonstrated that through the LSTM neural network model, real-time post-processing compensation for the hysteresis and nonlinear signals of sensors can be carried out, reducing the measurement error of sensors in surgical robots by more than 40% and achieving precise motion control [19]. At the front end, Chen et al. developed a 3D printed electronic skin that combined reverse design with machine learning. Starting from the performance goals of high GF, wide range, and low hysteresis set by users, it automatically searched for the optimal material formula and printing parameters, successfully fabricating a sensor with comprehensive performance far exceeding that of traditional methods [20]. The research conducted by Nikolaev et al. in their autonomous laboratory has combined machine learning with robot experiments, achieving a fully automated closed loop in material development and reducing the sensor development cycle by 80% [21].

The advantage of this method lies in that it can make up for the material’s defects through the power of algorithms without changing the intrinsic properties of the material: the compensation at the back end can correct hysteresis and nonlinearity in real time, and the reverse design at the front end can quickly find the optimal ternary performance balance point among a vast number of material combinations, greatly accelerating the research and development process of high-performance sensors. Recent reviews on artificial intelligence-driven electronic skin and intelligent wearable sensors have further highlighted the core role of AI across the full chain of material discovery, structural optimization and data analysis [22,23]. However, current machine learning methods also have obvious limitations: Firstly, they rely heavily on high-quality and large-scale labeled datasets, while experimental data in the field of flexible sensors are often scattered and heterogeneous, lacking a unified standard, which leads to limited generalization ability of the model; Secondly, most of the current deep learning models are “black box” models with poor interpretability. Researchers find it difficult to understand how these models make predictions, which also limits their application in the field of precision industry.

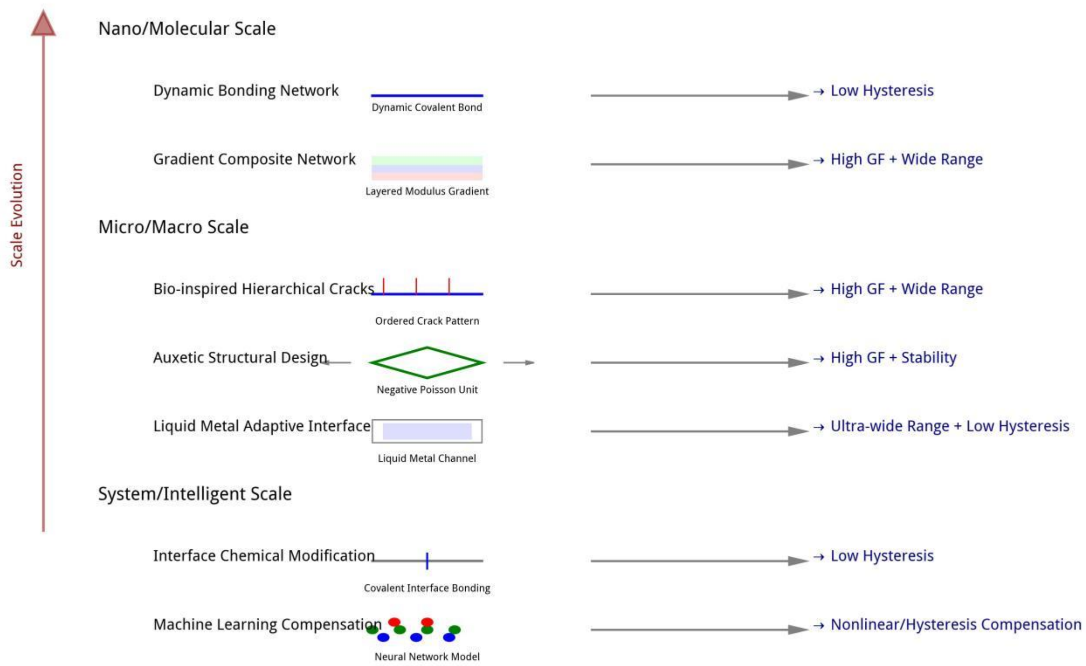

Figure 4. Cross-scale Collaborative Optimization Strategies.

4. DEEP CONSIDERATIONS OF CURRENT CHALLENGES AND PERFORMANCE TRADE-OFFS

Although the existing cross-scale strategies have alleviated the contradiction of the ternary trade-off to a certain extent, to achieve true industrial application, we must still face up to the deep-seated trade-offs and challenges hidden behind these strategies. These contradictions are the core bottlenecks of current research.

4.1 Triangular trade-off of process, performance and cost

Many high-performance optimization strategies have sacrificed scalability and low cost. For instance, high-precision 3D printed tensile structures and atomic layer deposition packaging technologies, although they can achieve ultimate performance, have extremely high production costs and are difficult to achieve large-scale mass production. However, traditional coating and printing processes, although low-cost and mass-producible, are difficult to achieve complex gradient and hierarchical structures. How to strike a balance among process complexity, performance indicators and manufacturing costs is the core challenge of industrialization.

4.2 The inherent contradiction between Environmental stability and performance

To achieve low hysteresis, many studies have adopted hydrogels or dynamic bonding networks: for instance, the ultra-low hysteresis hydrogel developed by Wang et al. performs well in a humid environment, but in a dry one, the hydrogel rapidly loses water, resulting in a sharp decline in performance [6]; Although the dynamic coordination bond network proposed by

Yin et al. achieved intrinsic low hysteresis, the chemical stability of the dynamic bonds still needs to be verified. Under long-term cycling or extreme environments, irreversible degradation is prone to occur, which affects the lifespan of the device. The improvement of performance often comes at the expense of environmental stability [9].

4.3 New Contradictions Brought about by Multi-functional integration

In the future, sensors need to integrate sensing, power supply and drive into one to achieve the intelligence of the system. But this brings about new matching problems: The sensing layer requires soft and highly sensitive materials, while the energy supply layer (such as batteries) needs hard and high energy density materials. The driving layer, on the other hand, demands elastic materials with large deformation. The differences in mechanical and chemical properties among these materials of different functional modules make it difficult for them to integrate perfectly. The matching of interfaces and the transmission of stress are both huge challenges.

5. FUTURE OUTLOOK: MOVING TOWARDS BIONIC INTEGRATION AND INTELLIGENT CLOSED-LOOP DESIGN

In the future, to completely break the “trinity trade-off”, it is necessary to achieve a full-chain paradigm revolution from inspiration, design to manufacturing.

5.1 PSA Integrated Bionic Design

Future sensors will no longer be a simple stack of functional materials, but rather, like biological tissues, achieve deep coupling and integration of Perception, Structure, and Actuation. From the molecular-level programmable and biocompatible nature of DNA hydrogels, to the cross-scale gradient structure and energy dissipation mechanism imitating mantis shrimp hammers, and then to the design of viscous gels that achieve adaptive stress absorption at the tissue-machine interface, all are the prototypes of this direction [14,24,25]. The goal is to create a “living” sensing system with the characteristics of living materials.

5.2 Materials Genome and Machine Learning Closed Loop

By integrating high-throughput experiments (such as robot scientists), high-throughput computing (such as first principles, molecular dynamics), and machine learning, a genomic database of flexible electronic materials is constructed. Through algorithms such as active learning and Bayesian optimization, material systems and structural parameters are rapidly screened and iteratively optimized, forming an intelligent closed loop of “performance goal-driven design-automatic synthesis/preparation-performance characterization-data feedback”, which greatly accelerates the research and development process of high-performance sensors [21, 26].

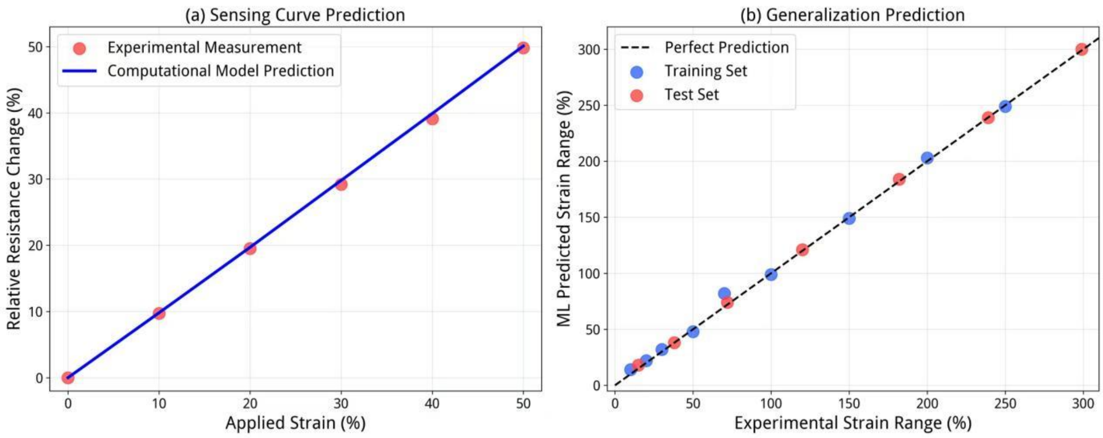

Figure 5. Computational Prediction vs. Experimental Sensing Performance [27,28].

5.3 Reliable System Integration for Extreme Environments

Ultimately, the sensor must operate stably in a real, variable and long-term harsh environment. This requires us to attach great importance to flexible packaging technologies (such as atomic layer deposition ALD, organic-inorganic hybrid coatings) to resist water and oxygen erosion and mechanical wear [29]. At the same time, the high-density integration, interconnection and power supply issues of multimodal sensor arrays need to be addressed. A review of field-effect transistor sensor integration strategies provides a systematic methodology for this [30].

6. CONCLUSION

The "triple balance" of flexible strain sensors is an inevitable manifestation of their physical and chemical essence. There is no single silver bullet to break through this bottleneck. It must rely on cross-scale collaborative innovation from molecular bonding, nanocomposites, micro-nano structures to system algorithms. This paper systematically reviews a series of strategies based on high-level research, including reducing intrinsic hysteresis through dynamic network chemistry, amplifying sensitivity through bionic tension and expansion structures, expanding the linear range through liquid metal interfaces, and conducting reverse design and real-time compensation through machine learning. These strategies are integrating with each other, driving flexible sensing technology from "functional realization" to "outstanding performance". Looking ahead, the bionic integrated design concept and the intelligent closed-loop development paradigm of materials will become the core driving forces leading the next generation of high-fidelity, adaptive, and long-life flexible perception systems, bringing revolutionary changes to fields such as health care, robotics, and human-computer interaction.

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