Recent advances in piezotronics and piezo-phototronics

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The field of piezotronics and piezo-phototronics has made remarkable advancements since the previous *MRS Bulletin* on piezotronics was published in 2018, building upon the foundational work initiated by Z.L. Wang in 2007. Researchers have made significant strides in leveraging piezoelectric semiconductors to manipulate charges and electric fields in various devices, such as ultrasensitive piezotronic sensors and self-powering systems (Figure 1). Recent studies in the field have focused on 1D semiconductors such as ZnO and GaN, and 2D semiconductors such as MoS_2 and WSe_2, which exhibit noncentrosymmetric crystal structures essential for piezotronic functionality. Progress in fundamental understanding and device fabrication has broadened the scope of applications, including more sophisticated logic computations, chemical sensing, enhanced optoelectronics, and advanced tactile imaging. Moreover, the expansion into piezo-phototronics has unveiled new possibilities by exploring the synergistic effects of the mechanical, piezoelectric, and optical interactions in piezoelectric semiconductors. This has enabled the creation of high-performance solar cells, photodetectors, light-emitting diodes, and other optoelectronic devices with enhanced strain-engineered performances, pushing the boundaries of what these technologies can achieve. The recently discovered flexoelectronic effect further expands the strain gating of charge carriers even in centrosymmetric semiconductors such as silicon, allowing for the implementation of high-performance electrochemical applications leveraging state-of-the-art semiconductor technologies. We have seen rapid growth in the research of piezotronics and piezo-phototronics worldwide (Figure 2). The articles in this issue highlight recent progress in piezotronics and piezo-phototronics, and this introductory article places them into perspective.

Piezotronic effect and piezotronics

In 2006, the piezoelectric nanogenerator was first demonstrated utilizing ZnO nanowires.[1] It was hypothesized that the electrical generation observed from mechanical straining was due to the piezoelectric potential caused by the piezoelectric polarization charges.[2] It was also suggested that the piezoelectric-modulated potential barrier at the interface between the metal and ZnO serves as a "gate" voltage to explain the transistor behavior observed in a metal-ZnO-metal structure,[3] as well as the strain-gated diode effect at a metal-ZnO interface.[4] In 2007, the term "piezotronics" was introduced as a new field of study, building upon these first endeavors (**Figures** 1, 2).[5,6]

Piezotronic effect

The piezotronic effect originates from the noncentrosymmetric crystal structure of piezoelectric semiconductors, which produces static polarization charges on the surface/interface when mechanical strain is applied. In metal–semiconductor interfaces with moderate impurity/vacancy doping, the static polarization charges generated by the piezoelectric effect are not fully screened, enabling modulation of the Schottky barrier height and, thus, electronic transport through applied tensile or compressive strain (**Figure** 3). This modulation dictates the electronic transport properties: reducing the barrier height facilitates electron transport, whereas increasing it limits the current flow, akin to a diode function.[7,8] This phenomenon, known as the piezotronic effect, leverages piezoelectric polarization charges as a "gating" signal to control carrier transport across interfaces or junctions. Numerous reports have experimentally validated the piezotronic effect through applications such as piezotronic logic computation and field-effect transistor gating.[9,10] Theoretical efforts have also been made to explain the piezotronic functionality. This piezotronic concept has driven the development of a new

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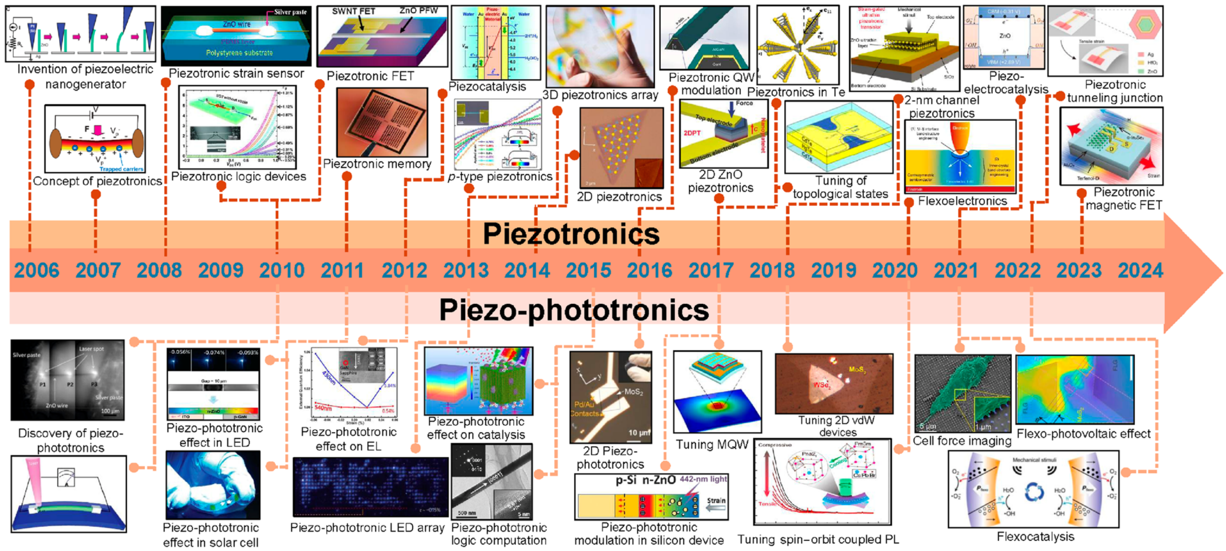

Figure 1. Historical timeline and milestones in the fields of piezotronics and piezo-phototronics. Top, from left to right: Reprinted with permission from References 2 (© 2006 AAAS), 6 (© 2007 Wiley), 7 (© 2008 ACS), 9 (© 2010 Wiley), 10 (© 2010 American Chemical Society), 14 (© 2011 American Chemical Society), 54 (© 2012 Wiley), 12 (© 2013 American Chemical Society), 11 (© 2013 AAAS), 13 (© 2014 Springer Nature), 16 (© 2016 Wiley), 18 (© 2017 Wiley), 20 (© 2017 IOP Science), 23 (© 2017 American Chemical Society), 19 (© 2018 American Chemical Society), 57 (© 2021 Wiley), 64 (© 2020 Springer Nature), 50 (© 2022 Springer Nature), 47 (© 2023 Wiley). SWNT FET, single-walled carbon nanotube field-effect transistor. Bottom, from left to right: Reprinted with permission from References 31 (© 2010 American Chemical Society), 32 (© 2010 American Chemical Society), 38 (© 2010 American Chemical Society), 39 (© 2011 American Chemical Society), 36 (© 2012 American Chemical Society), 37 (© 2013 Springer Nature), 52 (© 2015 American Chemical Society), 17 (© 2015 Wiley), 41 (© 2016 Wiley), 71 (© 2017 Wiley), 70 (© 2017 American Chemical Society), 27 (© 2018 Wiley), 49 (© 2020 American Chemical Society), 45 (© 2021 AAAS), 67 (© 2021 AAAS), 69 (© 2022 Wiley). LED, light-emitting diode; EL, electroluminescence; MQW, multiple quantum well; vdW, van der Waals; PL, photoluminescence.

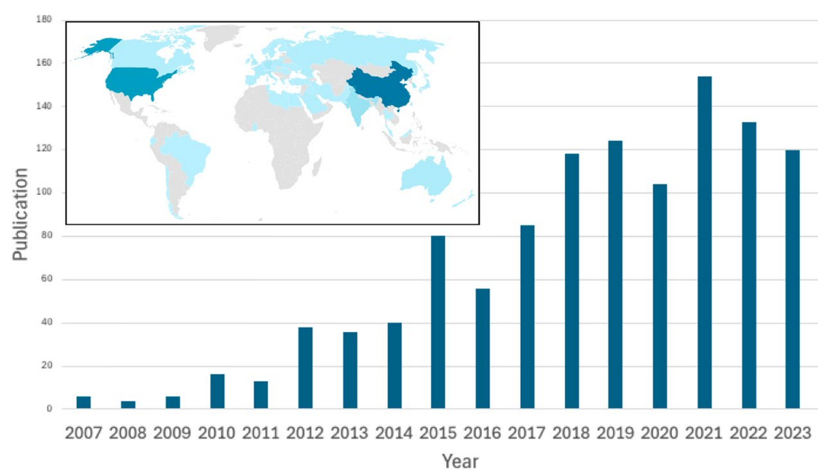

Figure 2. From Science Citation Index (SCI) database, papers that have been published in the fields of piezotronics and piezo-phototronics since 2007.

category of electronics known as piezotronics, in which devices exploit the interplay between piezoelectric effects and semiconductor properties to achieve innovative functionalities and enhanced performance.

Piezotronics device structure and applications

Piezotronic transistors exhibit unique strain-dependent transport behaviors. Integrating piezoelectric and semiconductor properties has led to innovative devices with unprecedented functionalities. Since 2007, and notably, from 2018 to 2024, advancements have focused on device structures featuring Schottky or ohmic contacts with *p–n* junctions, utilizing strain-induced polarization at materials surface/interface such as ZnO nanowires[11,12] or 2D MoS_2[13] to control electronic signals. Early research has developed strain-gated transistors[9] for logic computations and piezotronically gated resistive memory devices.[14] Piezotronic principles enable the development of 3D nanoelectronics, including vertical nanowire transistors.[11] Schottky-contact piezotronic devices have been demonstrated in nanoscale semiconductors, such as GaN,[15,16] CdS,[17] ZnO,[18,19] and tellurium.[20] These devices, including sensors for biochemical, gas, and humidity detection, leverage strain-induced polarization charges for enhanced sensitivity. Yang and co-authors discuss the recent advance in piezotronic and piezo-phototronic sensors in this issue.[21]

Since 2018, theoretical explorations in piezotronics and piezo-phototronics have witnessed significant advancements in understanding the device physics underlying these phenomena. Researchers have delved into the design and exploration of piezotronic and piezo-phototronic processes in strongly confined systems, where discrete bound states need to be considered.[22,23] These investigations have shed light on the interplay between piezoelectric polarization and quantum confinement, paving the way for developing quantum-engineered piezotronic devices.[24] Integrating data-driven machine learning (ML) techniques could revolutionize the discovery and prediction of materials for piezotronic applications. ML and deep learning (DL) strategies could accelerate the identification of promising piezoelectric materials and optimized device designs. Researchers have developed ML models to predict properties, such as bandgaps and piezoelectric coefficients, based on structural descriptors and processing conditions.[25] These approaches have streamlined the screening process, reducing the time and resources required for experimental exploration. Additionally, ML models could offer design guidance for piezotronic devices and optimize parameters, such as doping concentrations and structural dimensions, for enhanced performance. Furthermore, researchers have examined the nonlinear behavior of piezoelectric materials, doping effects, and influence of substrates on piezotronic and piezo-phototronic phenomena. These studies have provided valuable insights into the complex interplay between various materials properties, structural parameters, and external stimuli, enabling more accurate modeling and optimization of the device performance. The article by Zhang et al. in this issue reviews recent progress in the theoretical study of the fundamental effects in multifunctional piezotronic and piezo-phototronic devices with diverse applications.[26]

Various materials have been explored in individual piezotronic device architectures, such as III-nitrides, oxides, and 2D semiconductors.[13,15,27] Zhai and co-authors provide a summary and perspective of the recent progress in exploring piezotronics and piezo-phototronics in atomically thin materials.[28] Research efforts have also concentrated on emerging approaches for nanomanufacturing large-scale piezotronic array devices. By utilizing advanced fabrication techniques, researchers have successfully created scalable piezotronic arrays for applications such as tactile sensors.[11] Integrating nanomanufacturing methods with innovative design concepts has enhanced device performance and functionality. Researchers have characterized the performance of piezotronic arrays under different conditions and have utilized advanced measurement techniques and data analysis algorithms to improve the functionality and responsiveness of these devices. The development of novel piezotronic devices, including artificial synapses,[29] represents a significant advancement in the field, demonstrating the potential for integrating piezoelectric effects into intelligent electronics for applications in neuromorphic and brain-inspired computing systems. Sun and co-authors discuss in this issue the advance in integrated intelligent piezotronic devices.[30]

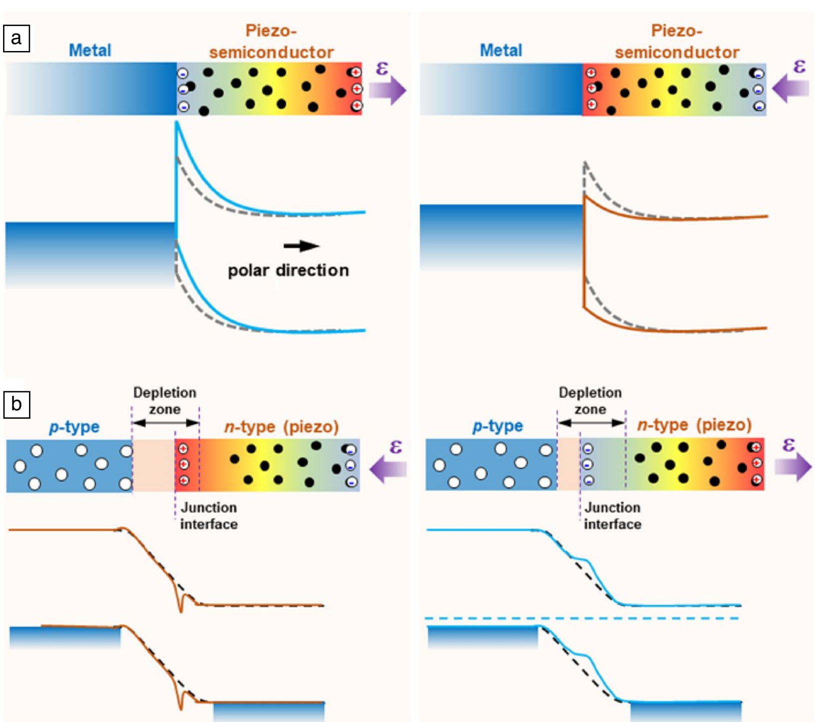

Figure 3. Piezotronic and piezo-phototronic effects. (a) The schematic energy diagrams illustrate the piezotronic effect in a Schottky contact when tensile and compressive strains are applied. (b) The schematic energy diagrams illustrating the piezotronic effect in a *p–n* junction when tensile and compressive strains are applied.

Piezo-phototronic effect and piezo-phototronics

The piezo-phototronic effect, discovered in 2010,[31,32] modulates the generation, separation, combination or transport process of photo-induced carriers by strain-induced piezoelectric polarization in Schottky-contact or *p–n* junction devices comprising piezoelectric semiconductors. Piezoelectric polarization induced at the contact or junction interface could modulate the Schottky barrier height in a metal-ZnO-metal structure, while photon excitation lowered the barrier by increasing the local carrier density. This effect enhances the optoelectronic processes by controlling the carrier behavior at Schottky contacts or *p–n* junctions. The piezo-phototronic effect arises from the interaction between piezoelectricity, photoexcitation, and semiconductor transport in piezoelectric semiconductors,[33–36] which enables the development of active and adaptive optical devices. Since the first demonstration using ZnO nanowires, extensive research has focused on strain-gated flexible nano-LEDs, photodetectors, and solar cells, exploring the fundamental piezo-phototronic processes.

Piezo-phototronic effect

The modulation of the contact or junction by piezoelectric polarization affects the generation, separation, transport, and recombination of various photo-induced carriers at *p–n* junctions. The piezo-phototronic effect leverages piezoelectric polarization charges to control electronic and optical processes, effectively using mechanical strain as a "gating" signal. This has been experimentally validated in various optoelectronic devices such as light-emitting diodes (LEDs), solar cells, and photodetectors.[37–39] This has led to significant advancements in adaptive optoelectronic devices, where mechanical strain can dynamically modulate the device performance. The coupling of piezoelectric charges with semiconductor properties and optical excitation enables the modulation of photogenerated carriers, leading to improved device performance and sensitivity. Theoretical models have been developed to explain this three-way coupling mechanism,[40] which has driven the development of innovative piezo-phototronic devices.

Piezo-phototronic devices and applications

Recent advancements in piezo-phototronics and integrated optoelectronic devices have significantly progressed in the field since 2018, focusing on fundamental principles and technological innovations to design high-efficiency adaptive optoelectronics. Various materials, such as 1D and 2D semiconductors,[41] have been explored to utilize the piezo-phototronic effect to improve the performance of novel device architectures, including brain-inspired devices and quantum optoelectronics. Researchers have demonstrated the effectiveness of the piezo-phototronic effect in enhancing the performance of optoelectronic devices by controlling carrier generation, transport, separation, and recombination at metal–semiconductor or *p–n* junctions. For example, the piezo-phototronic effect has been instrumental in the development of high-performance flexible photodetectors, self-powered photodetectors, and photovoltaic cells. The Hu et al. article in this issue reviews the recent progress in piezo-phototronics and integrated optoelectronic devices.[42] Recent theoretical developments in piezo-phototronics since 2018 have focused on advancing device physics, data-driven ML-enabled discovery, and exploring various topics, such as quantum effects.[43,44] Researchers have delved into the fundamental principles underlying piezo-phototronic devices, elucidating the mechanisms governing carrier generation, transport, and recombination at metal–semiconductor interfaces and *p–n* junctions. Data-driven ML-enabled approaches could be employed to discover and predict novel piezo-phototronic materials, providing valuable design guidance for optimizing device performance. The exploration of quantum effects, nonlinearity, and substrate influences has further expanded the understanding of piezo-phototronics, offering insights into enhancing device functionalities and efficiency. Researchers have explored the piezo-phototronic effects on Schottky contacted and *p–n* junction sensors, demonstrating improved performance through the modulation of carrier generation, transport, and recombination at interfaces. Additionally, emerging prototypical demonstrations have shown the versatility and potential of piezo-phototronic sensors in various fields. Experimental studies have focused on optimizing device efficiency and sensitivity by controlling the carrier behavior and interface properties. The integration of piezoelectric and photonic effects has led to the development of high-performance flexible photodetectors, self-powered photodetectors, and photovoltaic cells. These advancements highlight the promising applications of piezo-phototronic sensors in enhancing optoelectronic systems for various practical applications, such as photodetection, energy harvesting, and sensing applications. Recent efforts have also explored the manipulation of optoelectronic processes in 2D materials through the piezo-phototronic effect, leading to the development of flexible and multifunctional nano-optoelectromechanical systems. Studies have demonstrated that 2D semiconductors, such as transition-metal dichalcogenides (TMDCs),[41] exhibit unique electrical, optical, and mechanical properties, making them promising candidates for piezo-phototronic applications.

Dynamic real-time imaging of living cell traction force at sub-μm resolution

Dynamic mapping of the cell-generated force of cardiomyocytes will help provide an intrinsic understanding of the heart. However, real-time, dynamic, and high-resolution mapping of the force distribution across a single living cell remains a challenge. Zheng et al. have established a force mapping method based on a "light nanoantenna" array using piezo-phototronic effect.[45] A spatial resolution of 800 nm and a temporal resolution of 333 ms have been demonstrated for force mapping for the first time. The dynamic mapping of the cell force of live cardiomyocytes was directly derived by locating the antennas' positions and quantifying the light intensities of the piezo-phototronic light nanoantenna array. This study presents a rapid and ultrahigh-resolution methodology for the fundamental study of cardiomyocyte behavior at the cell or subcellular level. It can provide valuable information about disease detection, drug screening, and tissue engineering for heart-related studies. This study is also an important application of the nanowire array-based piezo-phototronic effect for bioscience.

Impacts of piezotronic and piezo-phototronic effects on other processes

Significant progress has been made since 2018 in coupling piezotronics and piezo-phototronics with various physical processes, including magnetic transport,[46,47] spin transport,[48] and quantum effects,[22,46,49] leading to the development of multifunctional devices and enhanced technologies. Quantum tunneling effects integrated with piezotronics have led to the development of quantum piezotronic devices that utilize piezoelectric potential to modulate tunneling currents in quantum wells and heterostructures for enhanced quantum sensors and transistors.[50]

In addition to these advancements, piezotronics and piezo-phototronics have been coupled with other physical processes such as electrochemical catalysis and photochemical reactions. The piezotronic and piezo-phototronic principles can engineer electrochemical processes at semiconductor/electrolyte interfaces for efficient photoanodes, improved catalysts, and enhanced redox reactions.[51–54] Piezotronic modulation has been utilized to enhance the efficiency of electrochemical reactions in energy conversion and storage devices by influencing charge-carrier distribution and reaction kinetics through mechanical strain. Wang et al. discusses in this issue the fundamental principle of piezocatalysis and the application of the piezotronic effect in designing more efficient catalysis.[55] Recent advancements in piezocatalysis,[54] piezo-phototronic catalysis,[56] and piezo-electrocatalysis[57] have deepened our understanding and applications of these processes in chemical and catalytic reactions. Piezocatalysis uses mechanically induced polarization charges to promote charge transfer during catalytic processes, whereas piezo-phototronic catalysis leverages mechanical stimuli for the separation and transport of photo-induced charge carriers. Piezo-electrocatalysis converts mechanical energy into chemical or electrical energy, thereby aiding advanced oxidation processes. Material considerations and design guidance for future device implementation have focused on enhancing catalytic activity through surface charge energy alteration, photogenerated charge-carrier separation, and catalytic activity enhancement. The impact of piezocatalysis, piezo-phototronic catalysis, and piezo-electrocatalysis on chemical processes lies in their ability to convert mechanical energy into chemical or electrical energy, facilitating redox reactions, CO_2 reduction, and H_2 generation. These processes offer new avenues for sustainable energy production, environmental remediation, and catalytic transformations, highlighting the potential of piezo-driven catalytic systems for advancing green chemistry and energy technologies. The coupling of piezotronics and piezo-phototronics with various physical processes has expanded the functional capabilities of these devices, offering new application possibilities and improved performance across a range of technological domains. Wang et al. discusses these aspects in this issue.[58]

Tribotronics

Piezotronics is about the polarization charges generated by strain distorted crystal symmetry of piezoelectric semiconductors. As inspired by this idea, an electric field can also be generated by contacting a semiconductor surface with another dielectric medium, which is the contact-electrification effect. Using the potential generated by triboelectric charges, a new field termed as tribotronics was proposed in 2014.[59] Tribotronics, an emerging field that combines triboelectricity and semiconductor properties,[60] has witnessed significant progress since 2015. This field explores the control and tuning of semiconductor transport by using triboelectricity. Studies have focused on the fundamental coupling between triboelectricity, charge transport, optical excitation, and other physical processes. The integration of triboelectricity with these physical and chemical phenomena has opened new avenues for multifunctional device applications and enhanced technology. For instance, tribotronic devices utilize the triboelectric potential generated by friction as a gate voltage to modulate the carrier transport in semiconductors, leading to the creation of tribotronic transistors.[61] Building on the triboelectric field effect, researchers have demonstrated various tribotronic functional devices, such as tactile switches, memories, hydrogen sensors, and phototransistors. Progress has also been made in the understanding of the theoretical foundations of tribotronics.[62] Additionally, studies have explored the effects of different semiconductor materials, interface structures, and mechanical input parameters on the characteristics of semiconductor interfaces for triboelectric power generation. Zhang et al. discuss in this issue the recent progress achieved in tribotronics.[63] Piezotronics and tribotronics, while distinct in their fundamental mechanisms, share a conceptual relationship, as they both involve the coupling of mechanical stimuli with electronic properties. They can complement each other in multifunctional systems. For example, tribotronic interfaces can provide input signals for piezotronic components, enabling integrated systems for energy harvesting, sensing, and human–machine interfacing.

Flexoelectronics

Flexoelectronics, an emerging field that explores the coupling between flexoelectricity and charge carriers, has gained significant attention in recent years.[64] Unlike piezotronics, where coupling is limited by material symmetry constraints, flexoelectronics leverages strain gradient-induced polarization that can occur in a broader range of materials, including centrosymmetric semiconductors such as silicon (Si) and germanium (Ge).This feature offers unprecedented versatility, enabling the design of innovative microelectromechanical systems (MEMS) and next-generation electronic devices built on state-of-the-art semiconductor technologies.[65,66] Flexoelectronics holds particular promise for advancing the capabilities of semiconductor technologies by enabling

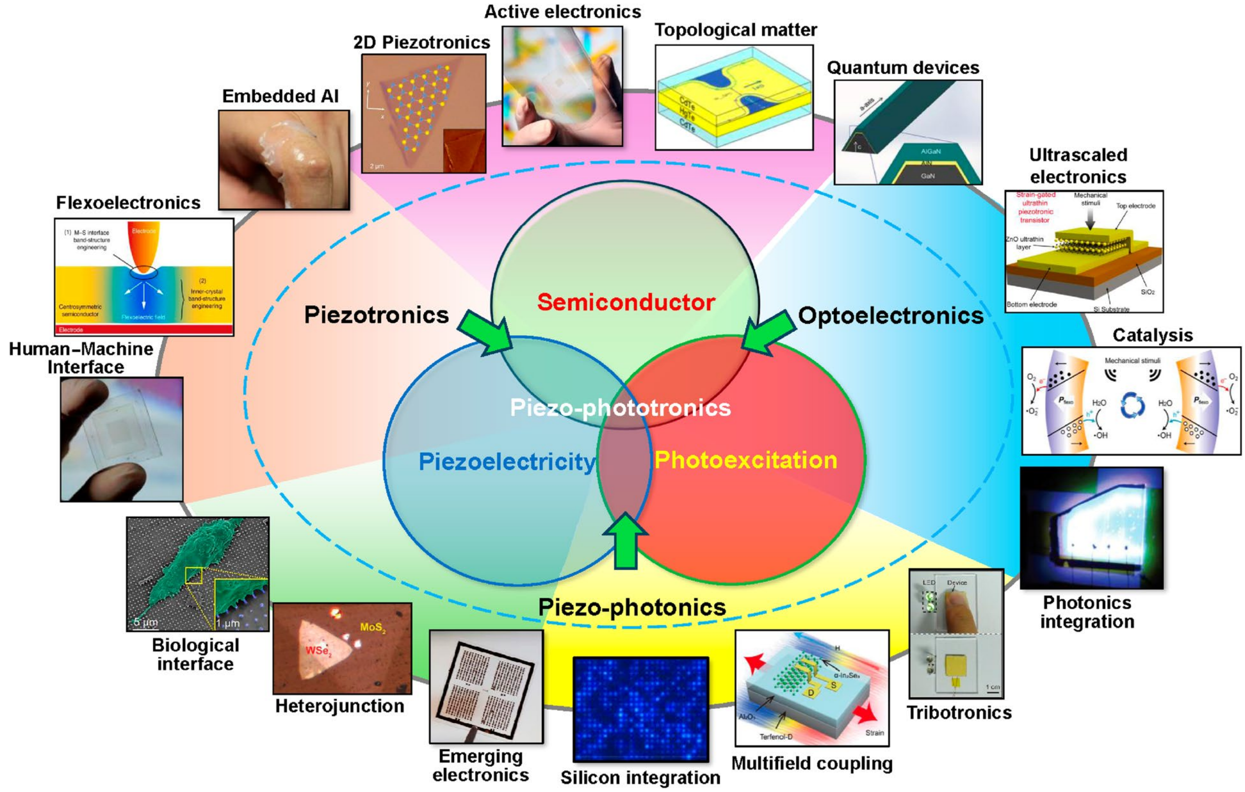

Figure 4. The plethora of opportunities for fundamental research and technological implementation in piezotronics and piezo-phototronics. The three-way active coupling among piezoelectricity, photoexcitation and semiconducting property in piezoelectric semiconductor materials is the fundamental process for piezotronics, piezo-photonics, and piezo-phototronics. This diagram shows the potential applications that have been demonstrated using piezotronic and piezo-phototronic effects in various fields. Reprinted with permission from References 11 (© 2013 AAAS), 13 (© 2014 Springer Nature), 14 (© 2011 American Chemical Society), 16 (© 2016 Wiley), 19 (© 2018 American Chemical Society), 23 (© 2018 American Chemical Society), 37 (© 2013 Springer Nature), 69 (© 2022 Wiley), 60 (© 2016 Elsevier), 47 (© 2023 Wiley), 27 (© 2018 Wiley), 45 (© 2021 AAAS). LED, light-emitting diode.

novel functionalities and enhancing device performance. By incorporating flexoelectric modulation, researchers can achieve precise control over the charge-carrier dynamics in materials that were previously inaccessible to piezotronic principles. This is particularly impactful for silicon- and germanium-based devices, as it opens doors to integrating flexoelectric effects into well-established complementary metal oxide semiconductor (CMOS) platforms, ensuring compatibility with the existing manufacturing infrastructure. The coupling of flexoelectric effects with photo-induced charge-carrier dynamics has led to the field of flexo-phototronics, where strain gradients can modulate the generation, transport, and recombination of photogenerated carriers. This mechanism has profound implications in the development of highly sensitive photodetectors, flexible photovoltaics,[67] and light-emitting devices.[68,69] Beyond traditional electronic applications, flexoelectronics also extends to catalysis, where strain gradients drive significant enhancements in chemical reactivity and selectivity. This has been demonstrated in fields such as flexocatalysis and flexo-photocatalysis, in which flexoelectricity facilitates energy-efficient chemical transformations. For example, flexoelectric fields can lower the activation energy of chemical reactions, enabling novel mechanochemical processes.[68,69] As semiconductor devices continue to miniaturize, the strain gradients inherent at the nanoscale become increasingly pronounced, naturally aligning with the principles of flexoelectronics. This makes flexoelectronics a crucial enabler of next-generation nanoscale devices. Furthermore, integrating flexoelectronic effects into flexible and wearable electronics can unlock new possibilities in health care monitoring, soft robotics, and human–machine interfaces. In conclusion, flexoelectronics represents a transformative paradigm in leveraging strain gradient-induced polarization to innovate across a spectrum of fields, from advanced semiconductor devices to catalysis. Its compatibility with existing technologies and unique material versatility make it a cornerstone for future technological advancements.

Perspectives

The piezotronics and piezo-phototronics fields have witnessed significant progress in recent years, offering exciting research opportunities and facing unique challenges. By coupling piezoelectric and semiconductor properties, researchers have explored novel functionalities and applications in emerging nanoelectronics, optoelectronics, energy harvesting, and sensor technologies (**Figure** 4). Research opportunities in piezotronics and piezo-phototronics lie in the exploration of advanced materials and device architectures to optimize the transduction efficiency and sensitivity. The advancement of these fields requires an understanding of fundamental physics and quantum phenomena, as well as technological implementations of piezotronic and piezo-phototronic devices.[23,48,70] Sophisticated characterization methods, such as direct probing of the interfacial dynamics and determination of the distribution of piezoelectric polarization charges, are required to provide a reliable interpretation of the fundamental materials and structural characteristics related to piezotronic and piezo-phototronic effects. Optimization and exploration of materials and the design, fabrication, and characterization of arrays of piezotronic devices are essential to promote the application of fields from a single device to a practically workable system. However, challenges remain in understanding the complex piezotronic and piezo-phototronic interactions, as well as in optimizing the device performance and reliability. Additionally, the development of scalable and sustainable materials for related devices presents a key challenge for realizing practical applications in various fields.

These novel effects of piezotronics and piezo-phototronics can be harnessed within CMOS-based devices by incorporating piezoelectric materials as active layers or interfaces, enabling mechanical stress to dynamically reconfigure the electronic and optoelectronic properties.[71] For instance, in CMOS transistors, piezoelectric-induced polarization can enhance the carrier mobility or threshold voltage control, thereby improving the energy efficiency and computational performance. Similarly, piezo-phototronics can enable mechanically tunable light sources or detectors compatible with CMOS platforms, paving the way for adaptive and multifunctional electronic systems for smart sensing, human–machine interaction, and next-generation computing architectures. This fusion of piezoelectric effects with mature CMOS technology presents a pathway for sophisticated and energy-efficient devices, fueling innovation across consumer electronics, health care, and industrial automation.

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Author contributions

Z.L.W. and W.Z.W. contributed to conceptualization, writing-review and editing the manuscript.

Conflict of interest

The authors declare no competing financial interests.

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Publisher's note

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