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Development status of optical-electrical-magnetic high-flux coupling materials

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Abstract In recent years, the development of multifunctional materials with multiphysics coupling effect has attracted great research interest. The coupling effect between magnetoelectric, electro-optical and magneto-optical has always been a hot spot in physics of condensed matter and the study of materials, and has numerous uses for magnetoelectric sensors and display devices. However, with the development of science and technology, the requirements for the performance of photoelectromagnetic materials are becoming higher and higher, people are no longer only satisfied with the effects of photoelectric, magnetoelectric and magneto-optical coupling, the development trend of device miniaturization, multi-function and high performance has encouraged more and more researchers to participate in the research of photoelectromagnetic coupling. Therefore, in recent years, excellent research results of photoelectromagnetic materials have emerged one after another, and the application research of Xiangxing is also in full swing. In this paper, various materials related to the photo-electrical-magnetic coupling effect in recent years are summarized, the challenge is analyzed, and the future development direction is prospected.

Keywords: Optical-electrical-magnetic coupling, Functional Ceramics, Magnetoelectric, Coupling effect, Multiferroelectric Materials, Heterojunctions.

1. Introduction

For decades, researchers have been working on single-source energy capture devices that can generate electricity using solar, thermal, or kinetic energy for compact intelligent devices and wireless sensor networks. When a single energy source is inadequate to provide the needed quantity of power, multi-source energy harvesting is required. To harvest numerous energy sources at the same time, current technology frequently combines different separate harvesters. This does, however, increase the multi-source harvester’s total dimensions, but in the world of microelectronics, shrinking is of paramount significance.

Traditional sensors are independent for the corresponding detection of external stimuli, so when the system is integrated, the equipment is large and there are defects that cannot be miniaturized. For this multifunctional detection, on the one hand, it is to inherit the design, on the other hand, there is also the development of resistant to multifunctional materials.

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Although advances in biodevice power technology have resulted in significant improvements in storage potential and significant reductions in overall size, regular replacement surgery is unavoidable within a few years due to the limited lifespan of implanted power batteries, resulting in supplementary health dangers and financial burdens for patients. Several methods such as piezoelectricity, magnetostriction, electromagnetic induction, and triboelectricity have been used. Among these, the piezoelectric effect is the most appealing technique for the conversion of mechanical energy to electrical energy because to its high efficiency, light weight, and small size.

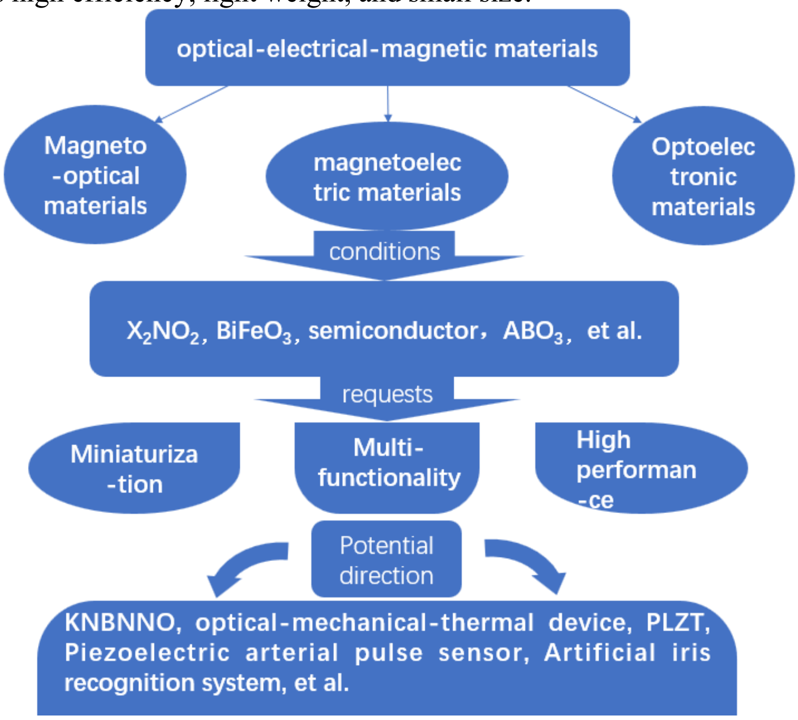

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Figure 1 General context of the article.

The development of multifunctional materials has always been one of the focuses of the material community and the physics community. For external stimuli, such as light, magnetism, force, electricity, etc., most of them can only detect at least two of the physical responses. In this review, we first briefly review the development of multifunctional materials: from monofunctional materials to multifunctional materials; Secondly, the development status of multifunctional materials, especially multifunctional materials with high-throughput physical field responses such as light, magnetism, force, and electricity, is analyzed, and the research status of multifunctional materials in device miniaturization and multi-function is summarized. After that, the author will describe a few of the obstacles experienced in the development of optical-electrical-magnetic multifunctional materials, and according to these challenges, the emerging concept devices based on multifunctional materials, such as new energy conversion materials, flexible photo-thermal automatic energy devices, piezoelectric arterial pulse sensors and artificial iris recognition systems, are prospected.

Through this review, the problems and bottlenecks of current multifunctional photoelectromagnetic materials will be effectively solved, and popular development directions such as miniaturization, multi-function and high performance can be developed into practical applications on the basis of existing theories. The development prospects of multifunctional photoelectromagnetic materials will become clear, and the research direction of researchers will also have clear goals.

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2. Classifications of magneto-optical-electronic multifunctio-nal materials

At present, the main multifunctional materials are two functional compounds, including optoelectronic materials, magneto-optical materials and magnetoelectric materials. In this part, we mainly describe the concepts and basic principles of the above three materials.

2.1. Magneto-optical materials

Magneto-optical materials refer to materials with optical information functionality and magneto-optical phenomena that operate in the ultraviolet to infrared spectrum [1]. Such materials' magneto-optical characteristics and the interplay and transformation of magnetic, electricity, and light are used to make optical devices with various functions. For example, modulators, isolators, circulators, magneto-optical switches, deflectors, phase shifters, optical information processors, laser gyro bias magnetic mirrors, magnetometers, magneto-optical sensors, etc [2].Under the action of magnetic field, the electromagnetic characteristics of the substance (such as magnetic permeability, magnetization strength, magnetic domain structure, etc.) will change, so that the transmission characteristics of light waves within it (such as polarization state, light intensity, phase, transmission direction, etc.) will also change the phenomenon is called the magneto-optical effect [3].

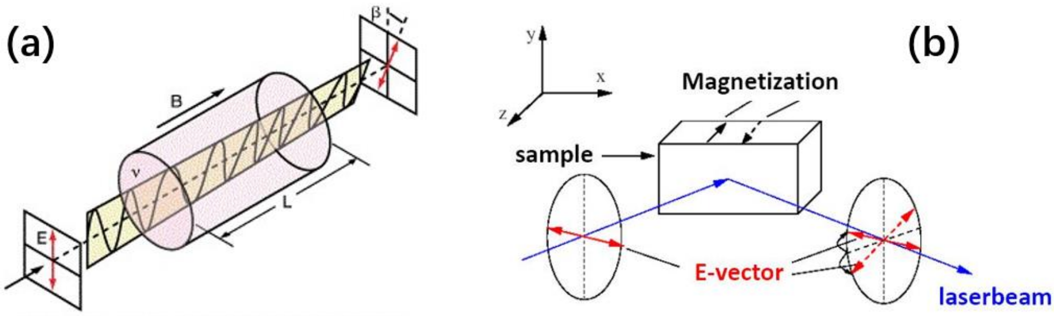

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Figure 2 (a) Schematic diagram of Faraday effect, one of magneto-optic effects; **(b)**Schematic diagram of magneto-optic Kerr effect, one of magneto-optic effects [3]. Copyright 2016, American Chemical Society.

2.2. magnetoelectric materials

The effect of spontaneous polarization of materials under the action of applied magnetic field or induced magnetization strength under the action of applied electric field is called magnetoelectric effect, and materials with magnetoelectric effect are called **magnetoelectric materials** [4]. From the definition of magnetoelectric effect, it can be seen that magnetoelectric materials can directly convert magnetic fields into electric fields, and can also directly convert electric fields into magnetic fields. This conversion between different energy fields is done in one step and does not require additional equipment, so the conversion efficiency is high and easy to operate [5]. The use of magnetoelectric materials and magnetoelectric effects can flexibly and easily apply electric or magnetic fields to achieve the control of their magnetization or polarization state, and adjust the electric field (magnetic field) to control the magnetic field (electric field) [6]. Based on this, magnetoelectric materials and magnetoelectric effects are attracting more and more attention from scientists around the world [7].

2.3. Optoelectronic materials

Optoelectronic materials refer to materials used in the manufacture of various optoelectronic devices (mainly including various active and passive photovoltaic sensors, equipment for processing and storing optical data and optical communications, etc.), mainly including infrared materials, laser materials, optical fiber materials, nonlinear optical materials, etc [8]. The working principle of photoelectric conversion material is to make the same material or two different semiconductor materials into PN junction cell structure, when the light irradiates the surface of the PN junction cell construction material to produce a new hole-electron pair. The hole flows from the n area to the p region under the impact of

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the p-n junction electric field, and the electrons flow from the p region to the n region, and the current is created once the circuit is turned on. This is the operation of optoelectronic materials [9].

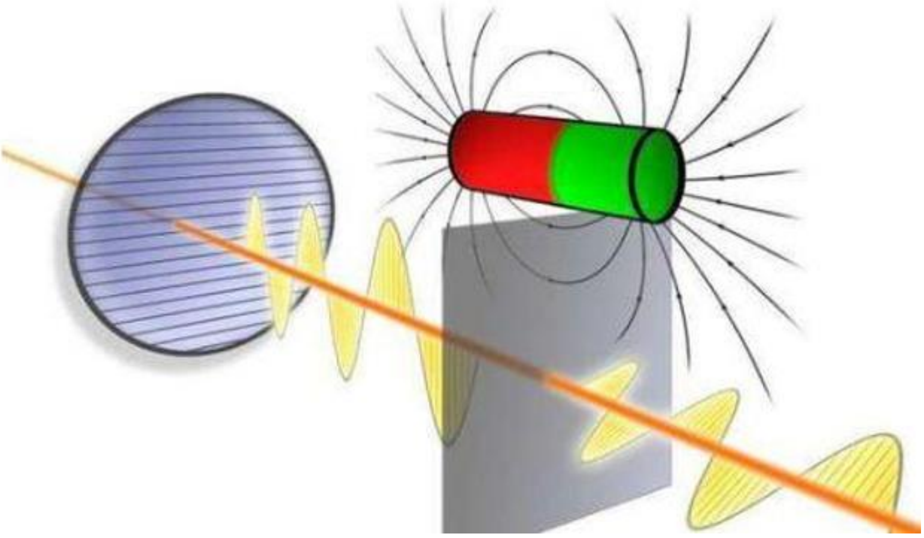

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Figure 3 Schematic diagram of magnetoelectric effect [5]. Copyright 2021, American Chemical Society.

Most of the traditional multifunctional materials consider the intrinsic physical properties caused by the average structure, and it is difficult to further multi-function [10]. But, with the continuous development of high and new technology, all kinds of electronic devices are gradually becoming miniaturized, functional and intelligent. This makes it necessary to continuously develop and explore new properties of materials on the basis of studying the original properties of materials, that is, to develop the multifunctional properties of materials. Therefore, multifunctional materials have become one of the hot spots for materials researchers [11].

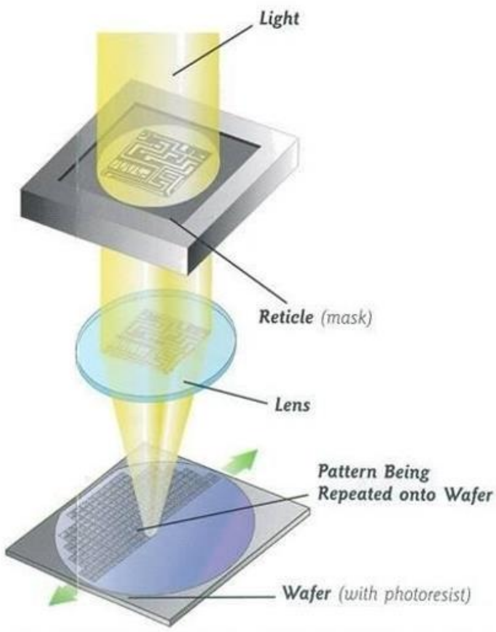

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Figure 4 Schematic diagram of Optoelectronic effect [9]. Copyright 2009, American Chemical Society.

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3. Recent progresses in optical-electrical-magnetic multifunctional materials and devices

Functional ceramics refer to advanced ceramics that use one or more properties provided by their electrical, thermal, magnetic, acoustic, optical and other single or coupling effects to achieve a certain use function in high-tech ceramics, such as electromechanical coupling, magnetoelectric coupling, electro-optical coupling and magneto-optical coupling, etc [12].

In recent years, substantial research results have been achieved in some ferroelectric materials or materials with multiferricity as the core research: ferroelectricity in two-dimensional material X_2NO_2 (X=In, Tl) can coexist with ferromagnetism generated by p-orbital [13]; Based on the multi-ferroity of BFO, some breakthroughs have been made in the research of ferroelectric photovoltaics [14-16]; Some laws of diluted ferromagnetic semiconductors at high Curie temperatures have been summarized [17]; Based on the relevant prospects proposed in previous articles, some scientists have added other elements to the structure of the ferroelectric $BaTiO_3$, so that the new $BaTiO_3$ system can achieve a balance of ferroelectricity and ferromagnetism [18-22].

3.1. Coexistence of ferroelectricity and p-orbital ferromagnetism in two-dimensional material X2NO2 (X=In, Tl).

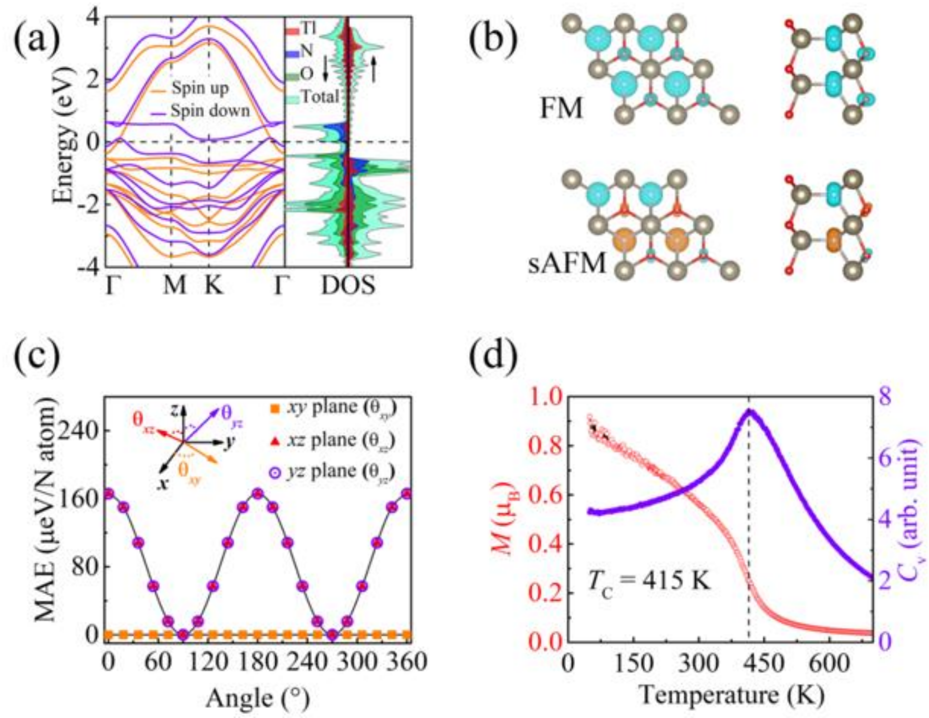

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Figure 5. Magnetic and electronic characteristics. (a) The band structure of spin polarization (left) and PDOS with element-resolution (right) for FEWZ′ X_2NO_2 monolayer at the Fermi level, which is set to zero, at the PBE level. The very symmetric points in reciprocal space are Γ(0, 0, 0), M(1/2, 0, 0), and K(1/3, 1/3, 0). (b) Top and side views of spin charge density of FM and sAFM FEWZ′ X_2NO_2 monolayers. One electron for every three is the value that defines the isovalue. The hues cyan and orange, respectively, stand in for spin-up and spin-down electrons. (c) An energy that is magnetically anisotropic and has magnetic moments placed on the xy, xz, and yz planes. The energy are adjusted to zero for the spin along the easy magnetization planes (xy/xz). The x, y, and z axes are shown in the inset along with the angles that the spin vector makes with each. (d) The magnetic moment M (in red) and specific heat (in violet) of the FEWZ′ Tl_2NO_2 monolayer as a function of temperature [13]. Copyright 2022, American Chemical Society.

In recent years, two-dimensional (2D) multiferroics have piqued the interest of researchers in fundamental science and technology [13]. Nevertheless, according to the empirical d0 rule, the vast majority of already existing 2D magnetic ferroelectrics are based on d-electron magnetics, which both makes them uncommon and limits the temperatures at which they can be used to perform their magnetization phase transitions [23]. In this study, ferroelectricity and ferromagnetism caused by p-electrons coexist lacking metallicity and the d0 rule in the class of stable 2D MXene-analogous oxynitrides, X_2NO_2 (X=In, Tl).

Surprisingly, strong ferromagnetic metallic states may be produced as a result of the p electrons' itinerant nature [24]. Additionally, by interface engineering, a putative magnetoelectric effect is shown in a Tl2NO2/WTe2 heterostructure. Our discoveries add to the understanding of ferroelectric metals and give an alternate path toward 2D multiferroics. Figure 5 depicts X_2NO_2's electrical and magnetic characteristics [25].

3.2. BiFeO3-based multiferroic photovoltaic materials

Multi-ferromaterials, with their peculiar properties of two or more ferrologic orders such as ferroelectric, ferromagnetic or ferroelastic sequence, point out a way for the miniaturization of microelectronic devices, the high integration of circuit chips and the high density of information storage [14-15]. At the same time, it has also become the focus of research in the fields of information science, materials science, condensed matter physics and so on. Semiconductor photocatalysis is an advanced oxidation technology with extensive potential applications in the disciplines of chemical and environmental engineering [16]. Therefore, the study of multi-ferrous materials and semiconductor photocatalytic materials will become an inevitable choice in the current era of energy and environmental science and technology (ET) [26].

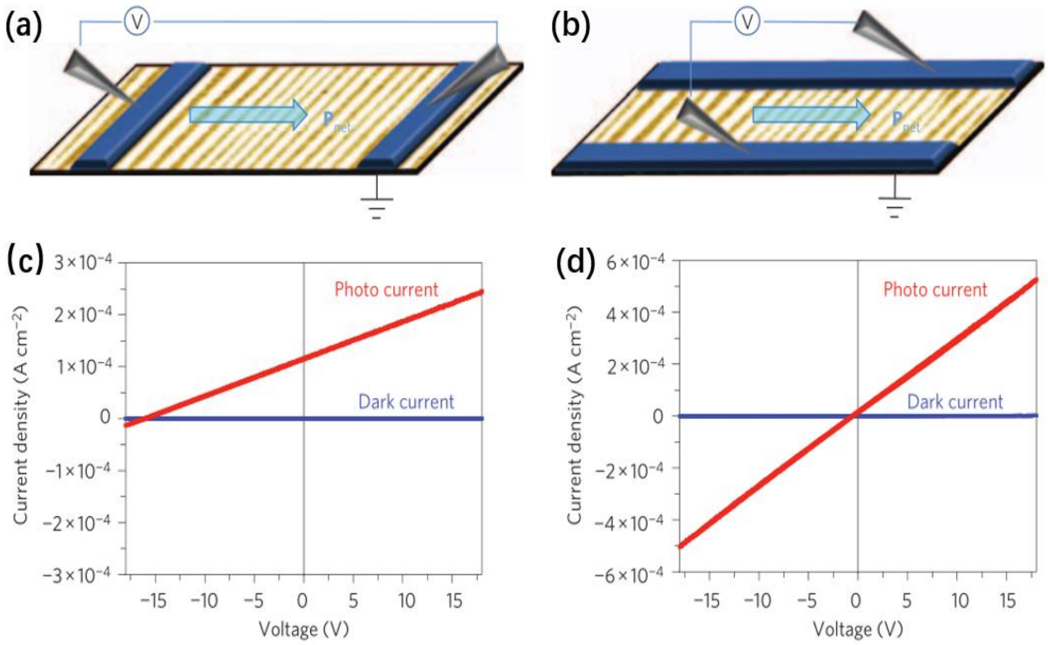

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Figure 6 I-V readings in the light and dark. Schematics of the parallel ($DW_{\parallel}$) **(b)** and perpendicular ($DW_{\perp}$) **(a)** device geometries. **(c)**, **(d)** Comparable I-V readings for the $DW_{\perp}$ **(c)** and $DW_{\parallel}$ **(d)** devices. [16] Copyright 2010, American Chemical Society.

$BiFeO_3$ has both magnetic order and ferroelectric order, but its cycloidal magnetic structure prevents magnetization of the bulk and linear magnetoelectric coupling. While it is devoid of magnetic order across vast distances, a solid solution of aferroelectricandaspin-glass perovskite blends reversible polarization with vitreous magnetism [27]. Room-temperature polar ferromagnets have recently been created using perovskite crystal engineering of a multilayer material, although the electrical polarization is not switchable [28].

Based on the research on BFO, ferroelectric photovoltaic materials can be further explored. Light absorption in a semiconductor creates electron-hole pairs that are divided by an electric field across a depletion area of micrometer thickness in traditional solid-state photovoltaics [29]. The highest voltage produced by these devices is equivalent to the bandgap of semiconductor electronics. We present here the finding of a completely new process of separating solar charges that works over 1-2 nm of space and produces voltages that are significantly higher than the bandgap [30]. The complex oxide BiFeO3 exhibits the separation at hitherto unobserved nanoscale electrostatic potential steps that emerge spontaneously at ferroelectric domain boundaries. By manipulating domain structure with an electric field, it is possible to switch the polarity of the photovoltaic effect or turn it off entirely. It's possible that optoelectronic devices may make use of this higher level of control and the high voltages produce. [31].

3.3. Diluted ferromagnetic semiconductor

Dilute ferromagnetic oxides with Curie temperatures much above 300 K and very high ordered moments per transition-metal cation call into question our knowledge of magnetism in solids. These are high-k dielectrics with thermally activated or degenerate n-type semiconductivity. At a few percent magnetic cation concentrations, conventional superexchange or interactions involving two exchanges cannot establish long-range magnetic orde. [17]. According to J. M. D. COEY et al., this and other diluted ferromagnetic possess shallow donor electrons, resulting in bound magnetic polarons that converge to create a spin-split impurity band, which is the mechanism for ferromagnetic exchange in these materials [32]. In the mean-field approximation, the Curie temperature changes as (x) 1/2, where x and represent the concentrations of magnetic cations and donors, correspondingly [33]. In order for there to be high Curie temperatures, there must first be an empty minority-spin or majority-spin d state located at the Fermi level within the impurity band. The magnetic phase diagram illustrates the ferromagnetic properties of both metallic and semiconducting materials, as well as cluster paramagnetism, spin glass, and canted anti-ferromagnetism [34].

The syndrome that is associated with ferromagnetic behavior at high temperatures in diluted magnetic oxides was investigated by using a model of indirect exchange mediated by shallow donors. This model was approached by employing a two-sublattice mean-field approximation, and the results of the investigation were published [35]. In order to achieve high Curie temperatures at the Fermi level, hybridization and charge transfer from a band of donor-derived impurity to an unoccupied 3d site are required.

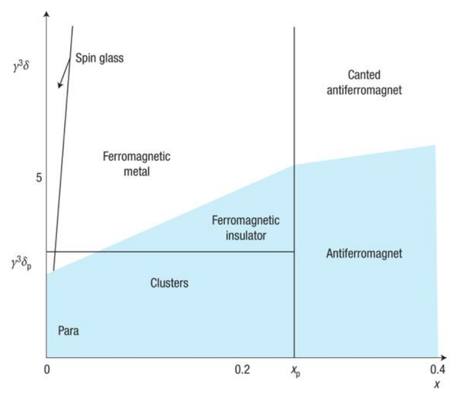

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Figure 7. Dilute ferromagnetic semiconductor magnetic phase diagram. The electrons are concentrated in the shaded region. Percolation thresholds for both cations and donors in the polaron system are represented by X-p and -p, respectively. the ratio of the radius of the Bohr orbit to the radius of the hydrogenic donor orbital [17]. Copyright 2005, American Chemical Society.

For predictions relating to the direction and strength of the spin splitting of the conduction band (red shift of the bandgap) below TC, the variation of TC with donor concentration and magnetic impurity concentration x, the location of the impurity in the 3d series, and the potential for ferromagnetism in d0 oxides, experimental testing and model improvement are both possible options [36]. The model also indicates how compensation might be used to modify interactions. It should contribute to the first ferromagnetic semiconductors capable of useful operation at ambient temperature [37].

Table 1 Ferromagnetism at high temperatures in diluted ferromagnetic oxides and nitrides [17]. Copyright 2005, American Chemical Society.

Material	Eg (eV)	Doping x	Moment (μ_B)	Tc (K)	Reference
GaN	3.5	Mn-9% Cr	0.9 -	940 >400	34 35
AlN	4.3	Cr-7%	1.2	>600	36
TiO_2	3.2	V-5% Co-1-2% Co-7% Fe-2%	4.2 0.3 1.4 2.4	>400 >300 650-700 >300	28 4 37 38
SnO_2	3.5	Fe-5% Co-5%	1.8 7.5	610 650	39 6
ZnO	3.3	V-15% Mn-2.2% Fe-5%, Cu-1% Co-10% Ni-0.9%	0.5 0.16 0.75 2 0.06	>350 >300 550 280-300 >300	27 40 41 5 42
Cu_2O	2	Co-5%, Al-0.5%	0.2	>300	43
$In_{1.8}Sn_{0.2}O_3$	3.8	Mn-5%	0.8	>300	44

3.4. Diluted ferromagnetism in perovskite ABO3 ferroelectrics

Xu et al. reported that the $BaTiO_3$-$CaTiO_3$ system doped with Pr has electrostrictive, mechanical luminescence and electroluminescence effects, which can respond to electrical, mechanical and optical signals at the same time, and is expected to be used in complex sensing and drive system applications [38]. Wang et al. systematically studied the applied magnetic field and temperature effects of $NaYF_4$:(Yb^{3+}/Er^{3+}) nanocrystals The tunable nature of synergistic energy transfer and nonlinear upconversion emission has obvious inhibitory effect on photoluminescence due to the change of radiation transition probability caused by magnetic field, which makes it a potential application prospect in the design and preparation of multifunctional rare earth nanocrystals with efficient energy transfer and excellent magneto-optical response. J.E. Spanier et al. published the photovoltaic effect of $BaTiO_3$

ferroelectric crystals in NaturePhotonics in 2016 [39]. By efficiently collecting the generated thermal carriers, they obtained photoelectric flux densities as high as 19 mA/cm^2, and energy conversion efficiencies of 4.8%, surpassing the Shawkle-Quessell energy conversion efficiency limit of 3.2 eV with a band gap of 3.2 eV on a microscopic scale, too It shows the attractive application prospect of ferroelectric materials in the field of optical voltaic. In 2010, Kundys et al. found that BFO (bismuth ferrite) has a photocontraction effect at room temperature, and the polarization direction of incident light and the applied magnetic field strength strongly affect the variables of photocontraction, that is, the piezoelectric characteristics of ferroelectric materials and their photovoltaic characteristics play an important role in photocontraction [18].

Although the above studies have made the research of ferroelectric materials and photovoltaic materials go further, the coexistence of ferromagnetism and ferroelectricity in multiferromagnetic materials has not been effectively studied and explored [40]. In this context, some researchers have further developed the coexistence of ferromagnetism and ferroelectricity in BaTiO3 materials by adding dopants to BaTiO3 materials. Here are two examples.

L. B. Luo et al. present extensive structural and magnetic investigations of room-temperature ferroelectricity and ferromagnetism in an epitaxial thin film of $BaTi_{0.98}Co_{0.02O3}$ (CBTO). The films are solitary phase with an inhomogeneous dispersion of Co_2+ dopants [41]. Ferromagnetic hysteresis and a ferroelectric loop were detected at room temperature. Surprisingly, the exchange bias and training effects are visible in regard to the topic cooling hysteresis loops. The complicated magnetic behavior of CBTO was understood in terms of bound magnetic polaron production with dopant distribution inhomogeneity. Exchange bias has also been demonstrated to be a useful tool for studying the mechanism of dopant-induced ferromagnetism in this study [18].

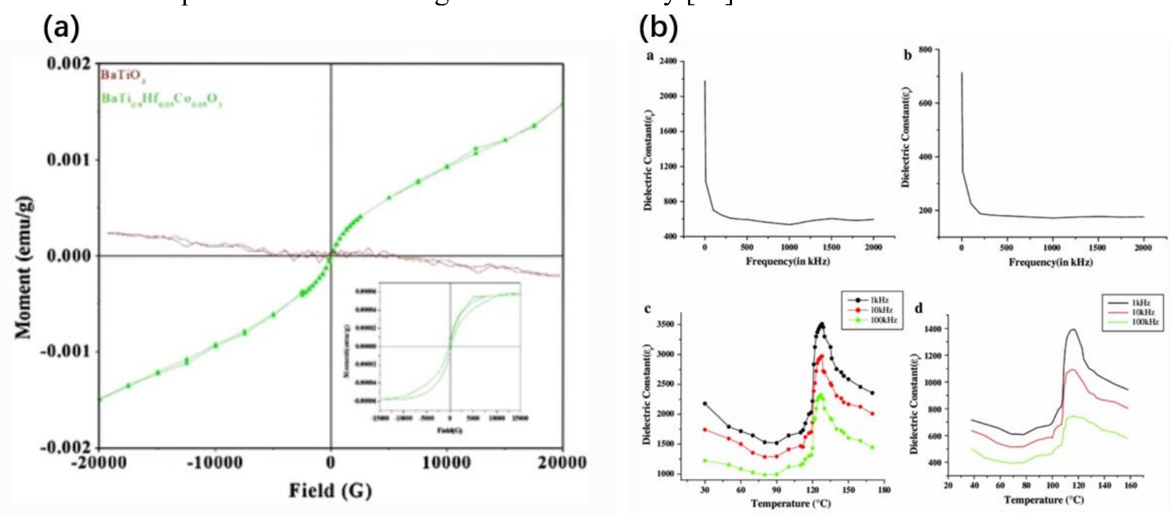

Figure 8 (a) Magnetic hysteresis loops of $BaTiO_3$ and $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ ceramic samples at room temperature. The hysteresis loops of $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ ceramic after eliminating paramagnetic components are shown in the figure inset. **(b)** Room-temperature frequency dependency relative dielectric in a $BaTiO_3$, b $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ ceramic samples, c $BaTiO_3$ dielectric constant against temperature curve at different frequencies, and d $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ dielectric constant vs temperature curve at different frequencies [18]. Copyright 2020, American Chemical Society.

Similarly, there is a report by S. K. Das et al. Magnetism, particularly ferromagnetism, can be generated in a oxide ferroelectric nonmagnetic like barium titanate ($BaTiO_3$) by selecting appropriate dopants [42]. The influence of Co and Hf substitution on the structural, magnetic, and ferroelectric characteristics of $BaTiO_3$ was examined using a polycrystalline specimen with great density of $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ [43]. The magnetic order observed in the previous sample is inherent. The ferromagnetic behavior of the $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ ceramic might be attributed to efficient exchange interactions between oxygen vacancies and Co ions. Ferroelectric (lossy type) behavior has also been seen in $BaTi_{0.9}Hf_{0.05}Co_{0.05}O_3$ ceramic [20].

While the relevant theories and properties of perovskite have been continuously explored, the frontier applications of perovskite are also developing [44]. Here are two examples.

To speed the identification and design of novel ferroelectric ABO3-type perovskites, a multiproperties machine learning technique was developed [45]. Initially, a classification model was built using data from published papers to discriminate ferroelectric and nonferroelectric perovskites. LOOCV and the test set had classification accuracies of 87.29% and 86.21%, respectively. The regression models were then built using two machine learning methodologies, SISSO and Machine-Learning Workflow, to predict the band gap (Eg), specific surface area (SSA), dielectric loss (tan δ) of ABO3-type perovskites, and Curie temperature (Tc) [46] . The LOOCV correlation coefficients in the best models for SSA, Eg, and Tc are 0.935, 0.891, and 0.971, respectively, but the correlation coefficient between the SISSO model's anticipated and observed values for predicting tan may reach 0.913. Based on the models, it was determined that 20 ABO3 ferroelectric perovskites with three different application possibilities did not possess the necessary properties. This discovery might make sense if one considers the relationships that exist between the appropriate descriptors and the attributes discovered by SHAP [47]. Moreover, the developed models were made into online servers to assist researchers in hastening the logical design and identification of ABO3 ferroelectric perovskites with essential numerous properties [21].

Ferroelectric field effect transistors (FeFETs) based on ferroelectric materials lead zirconate titanate (PZT) and amorphous-indium-gallium-zinc oxide (a-IGZO) were developed and described. The PZT material was sol-gel produced and then employed as a ferroelectric gate [48]. The a-IGZO thin films, which serve as channel semiconductors, were deposited using radio-frequency magnetron sputtering at 50°C. The features of a conventional field effect transistor with a SiO2 gate insulator built on heavily doped silicon were compared to those of a PZT-based FeFET. The FeFETs shown promising performance in terms of I on / I off ratio (i.e.106) and IDS retention behavior [22]. The above studies have successfully induced certain ferromagnetism on the basis of ensuring ferroelectricity by different theories and methods, and have made outstanding contributions to the development of ferromagnetism and ferroelectric balance and coexistence in multiferroelectric materials [49].

4. Challenges

To date, the research on ceramics with multifunctional properties has made great progress, but there are few materials with similar coupling of multiple physical effects in a single material. One of the most common and popular is the study of the multiferroicity of materials. Magnetoelectric ferrotic materials must have both ferroelectric and ferromagnetic, and the physical, structural and electrical properties must meet the requirements of ferroelectric ferromagnetic materials at the same time [50].

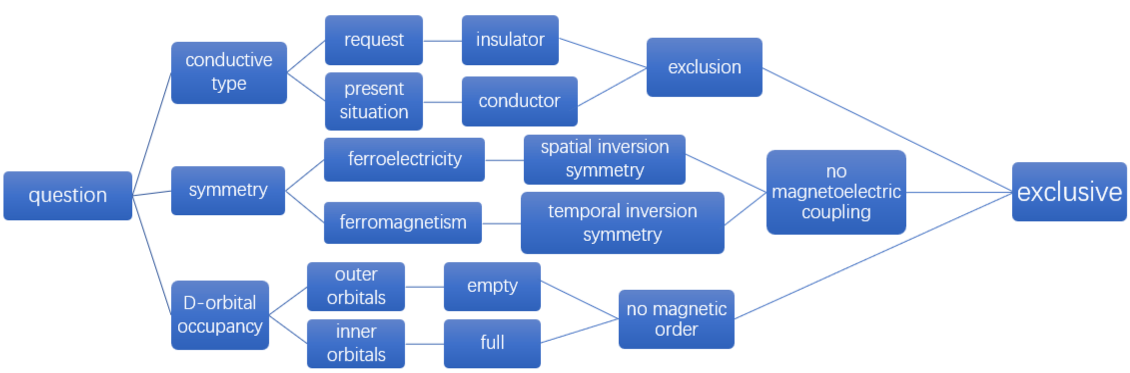

Figure 9. The key words of the challenge [50-59] Copyright 2002-2023, American Chemical Society.

However, first of all, from the perspective of conductive properties, ferroelectric materials are generally required to be insulators, because when an applied electric field, in order to polarize the ferroelectrics or change the direction of polarization, the surface of the ferroelectrics must appear polarized charge, but if it is a conductor, the current formed at this time is the current [51]. In contrast to ferroelectric materials, most ferromagnets tend to be metals. Although ferromagnets do not require conductivity, the generation of magnetism mainly comes from the higher electron state density of transition metal elements at the Fermi surface, which directly leads to the metallicity of ferromagnets [52]. Of course, there are not insulating ferromagnets in nature, such as ferrite materials, non-common materials with spin or materials with spin loss. They can produce iron polarization by spin-orbit coupling, but their magnetic properties are generally weak, and it is difficult to meet practical application requirements [53].

On the other hand, from the perspective of symmetry, ferroelectricity must destroy spatial inversion symmetry, while ferromagnetism must destroy temporal inversion symmetry [54]. Therefore, magnetoelectric polyferism requires the inversion symmetry of time and space to be broken [55]. Due to this condition, there are very few single-phase materials that can spontaneously generate magnetoelectric coupling, and even if they exist, the excited magnetoelectric coupling is quite weak according to the polyferrogeneous Ginzburg-Landau theory [56].

Finally, since in most ABO3 perovskite ferroelectric materials, the B position occupies metal ions, and their d orbitals are empty, which will facilitate their hybridization with the 2p orbital of anion O to form covalent bonds, thereby reducing the energy of the lattice [57]. However, for elements that can produce ferromagnetism, if the inner orbitals are all full, and the outer orbitals have no electrons, it is impossible to produce any magnetic order, so the general perovskite ABO3 ferroelectric material is not magnetic [58].

It can be seen that whether from the perspective of conductive type, symmetry or D-orbital occupancy, ferroelectricity and ferromagnetism are mutually exclusive, which is the main reason why ferrometallic materials are very rare in nature [59].

5. Future prospect Potential direction

5.1. New energy conversion materials

As a component for multiple sources of data gathering and sensing, use a single adaptable material[60]. The substance may simultaneously absorb kinetic energy from the piezoelectric effect, changes in temperature from the thermoelectric effect, and visible light (sunlight) from the photovoltaic effect. The cantilever energy harvester's only functioning component is made of this one material [61]. The adaptability of single-material devices can thus enable multi-source energy harvesting, sensing, and acquisition-sensing. This notion, which has been implemented in a real device for the first time, has the potential to significantly enhance how existing hybrid, multi-source energy harvesting and sensing systems function. coupling effect's equivalent circuit [62]. KNBNNO, for example, is a ferroelectric material with a high energy bandgap (1.6 eV) and strong piezoelectric and thermoelectric sensitivity to external electric fields, stresses.

KNBNNO has a far greater energy conversion efficiency than the Olsen cycle alone. An original multi-source energy-conversion material has been used to build and explain a single-material, sensing device and multipurpose energy harvesting, KNBNNO. This is the first device of its kind in the field of energy harvesting research that collects energy simultaneously from thermal, solar, and kinetic energy sources utilizing a single energy conversion material or component [63]. The device may be able to perform a variety of functions, such as multi-stimuli sensing, multi-source energy harvesting, and harvesting-sensing integration using just one material or component [64]. In applicable smart electronic devices and wireless sensor networks, such a single-material characteristic may render the usually recognized tradeoff of employing multifunctionality to design downsizing unnecessary. This also helps to keep those gadgets and sensors running efficiently [65]. When compared to standard hybrid arrangements, at least 67% space savings may be predicted [66].

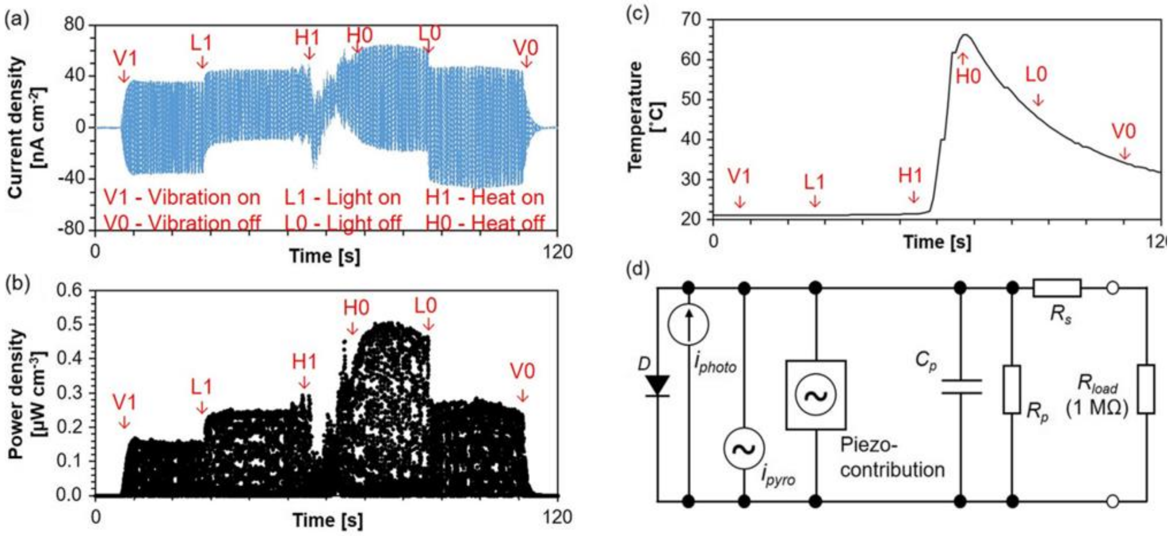

Figure 10 (a) discharge current density and **(b)** Using vibration, light, and heat as input energy sources, the KNBNNO cantilever outputs a high power density. **(c)** Temperature profile of the measurements depicted in **(a)** and **(b)**. **(d)** The piezoelectric-photovoltaic-pyroelectric temperature fluctuations, and light inputs [63]. Copyright 2022, American Chemical Society.

5.2. Self-powered photodetector

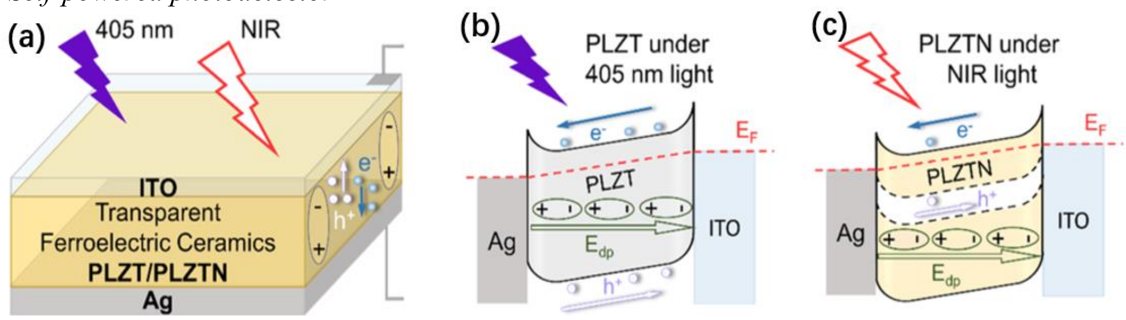

Figure 11. JV (current density versus voltage) graphs and light/dark photo response show the FE photovoltaic effect of PLZTN ceramics. (a) A schematic representation of the device's construction and operation. Separating photoinduced charge carriers would be facilitated by the intrinsic electric field generated by FE polarization. (b) E F stands for the E dp and Fermi level for the depolarization electric field within the FE material in this schematic representation of the band structure of a PLZT device illuminated by 405 nm light. (c) An illustration of the band structure of a PLZTN device lit by NIR light. The gap state introduced by Ni_2+ is represented by the band gap break. At this energy level, there are fewer carriers accessible [67]. Copyright 2020, American Chemical Society.

It is critical to employ the photoelectric effect of FE oxide for light sensing in order to achieve quick light response and high stability [68]. Examples of prospective applications for photodetectors based on NIR light-stimulated photovoltaic effects include biological pattern identification (850, 1310, and 1550 nm), optical fiber networking (850, 1310 nm), and navigation (1500 nm) [67]. Transparent FE ceramics, which are commonly employed in electro-optical devices, are seen as a viable substitute for transparent self-powered photodetectors in forthcoming transparent optoelectronic systems, such as smart structures, transparent display devices, and smart electronics. Bandgap engineering was used on transparent FE ceramics in this study to make Ni^{2+}-modified lanthanum lead zirconate titanate (PLZT) respond to visible and near-infrared light, allowing it to be constructed as a self-powered near-infrared photodetector [69]. Transparent ferroelectrics have intriguing uses in transparent optoelectronic systems and have particular advantages for self-powered photodetection. Instead of relying on the pyroelectric effect, photodetectors that generate their own electricity and operate on the principle of the photovoltaic effect are more stable and have a quicker response time [70]. Nevertheless, prior ferroelectric ceramics were usually opaque and lacked a photovoltaic response when triggered by infrared light. Consequently, hotodetectors based on infrared light-stimulated photovoltaic effect and/or transparent ferroelectric ceramics would be highly useful. Hot-pressing sintering was used to create extremely optical transparent pure lead lanthanum zirconate titanate (PLZT) and band gap-engineered Ni-doped PLZT ceramics with outstanding piezoelectric/ferroelectric characteristics. The photovoltaic performance of pure PLZT and band gap-engineered PLZT was stable and outstanding [71]. The short-circuit current density is significantly higher than that seen in earlier PLZT research by at least two orders of magnitude [72]. For the first time, transparent PLZT and Ni-doped PLZT ferroelectric ceramics are used as self-powered photodetectors for 405 nm and near-infrared light, respectively. Under 405 nm light, PLZT devices exhibit high detectivity (7.15 107Jones) and quick response (9.5 ms for rise and 11.5 ms for decay), while Ni-doped PLZT devices exhibit high detectivity (6.86 107Jones) and short response time (8.5 ms), indicating great potential for future transparent photodetectors [73].

5.3. Piezoelectric arterial pulse sensor

Studies have shown that there is a connection between piezoelectric artery pulse waves on the nanoscale and blood pressure waves, and that this connection extends all the way up to the macroscopic thickness of the piezoelectric functional layer. As a result of the posture-specific nature of the obtained raw arterial pulse waves, it is possible to decrease motion artifacts by employing arterial pulse piezoelectric responses; hence, this technology is suitable for use in wearable continuous blood pressure monitoring [74]. Furthermore, our findings suggest that this can only be accomplished using a single-piezoelectric-sensor wireless monitoring system, which is more portable than systems that need several sensors to measure pulse wave velocity. This method has the potential to lead to the creation of wearable, continuous blood pressure monitoring devices for both primary hypertension prevention and daily hypertension therapy [75].

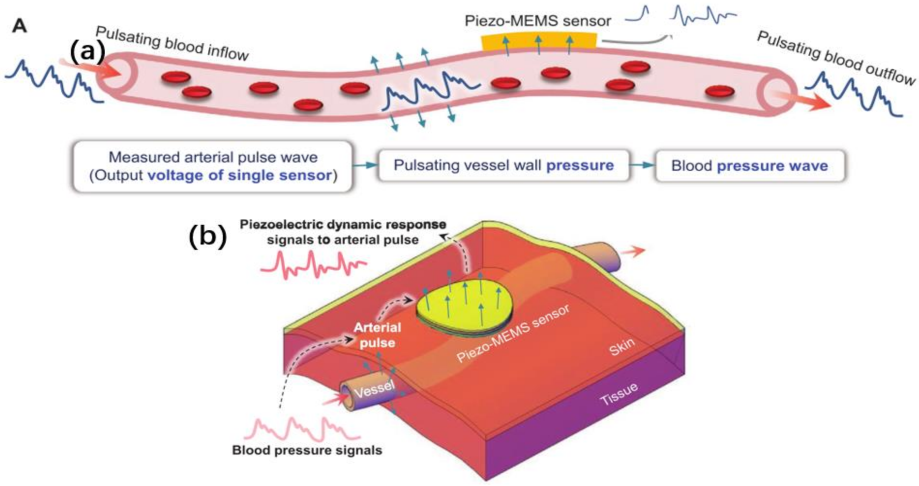

Figure 12 (a) Illustration of the pressure transmission mechanism; **(b)** An example of the piezoelectric dynamic response to an arterial pulse traveling from the arterial arteries to the skin [75]. Copyright 2022, American Chemical Society.

5.4. Artificial iris recognition system

The self-powered artificial retinal perception system creates a scalable cross-array structure for high-density and low-power neural networks in the retinal system that is inspired by biological systems. This structure is accomplished with the assistance of two terminal solar cells that function as artificial neurons and perovskite-based memristors that function as artificial synapses [76]. A presynaptic electrical signal is created in the solar cell by light stimulation of varying wavelengths and intensities, which is then sent to a perovskite-based memristor for additional information preprocessing. The use of artificial retinal systems in neuromorphic computing, in particular, has been found to improve contrast and minimize noise [77]. The ocular perception system may conduct feature extraction by implementing some convolutional neural network (CNN) operations at the hardware level, enhancing recognition speed, rate, and energy consumption [78].

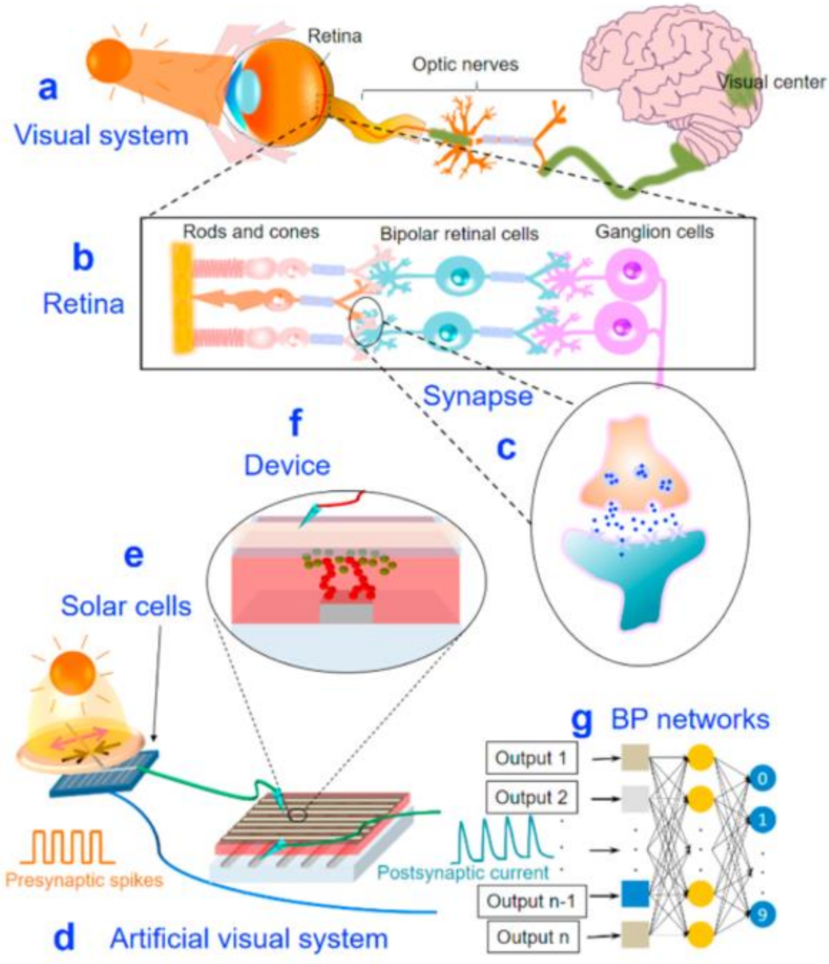

Figure 13. Design of Self-powered Artificial Retina System The biological and artificial visual system. **a**: The biological visual system consisting of the retina (receiving and preprocessing), optic nerves (transmitting), and the visual center (processing and memory system); **b**: a schematic image of the retina; **c**: the schematic illustration of biological synapses between rods (or cones) and bipolar retinal cells; **d**: the artificial visual system consisting of solar cells (working as the retina), perovskite memristors (working as synapses), and ANNs (working as the visual center); the output of post-synaptic current can secondarily input into ANNs; **e**: solar cells; **f**: devices with conductive filaments; **g**: ANNs [79]. Copyright 2020, American Chemical Society.

The double-ended construction of photovoltaic cells and memristors assures that combining the design of silicon solar cells and halide perovskite memristors may enable the extension of biomimetic retinal systems to the cross-array structure of high-density neural networks. Owing to the robust photovoltaic conversion capacities of polycrystalline silicon solar cells, artificial retinal perception systems can be self-powered and exhibit broadband responses to near-infrared and visible light. The enhanced ITO/$CsPbBr_2I$/poly(3-hexylthiophene) (P3HT)/Ag structure achieves a low operating voltage of around 0.4V and the attenuation process of perovskite-based memristors, enabling dual-mode STP-LTP functionality and an effective light-start weight updating process[80]. The solar cell generates an electrical output signal by light stimulation of varying wavelengths and intensities, which is then sent to a perovskite-based memristor for information pre-processing [81].

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