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Review

Advances in piezotronic transistors and piezotronics

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ABSTRACT

Innovative technologies beyond or can augment the conventional metal-oxide-semiconductor (CMOS)-based technology to achieve adaptive and seamless interactions between electronics/machine and human/ambient are urgently needed for smart systems. Piezotronic transistors are a new type of devices designed using completely different principles from CMOS-based technology, which utilize inner-crystal piezoelectric potential as the gate controlling signal to control the electrical transport process, which have been widely demonstrated for the third-generation semiconductors (such as ZnO, GaN). Such devices are innovative in a way that the traditional external channel-width gating is replaced by an inner interface gating or inner channel-width gating. These nanodevices and integrated nanosystems show great potential to achieve complementary functionalities to the state-of-the-art CMOS technology. Coupling the piezoelectricity and the electrical transport process in piezoelectric semiconductors results in the emerging field of piezotronics, which show promises for advanced nano-electromechanical devices and micro/nano-electromechanical systems. This manuscript reviews the advances in piezotronic transistors, provides an overview of the development and gives in-depth understandings in the new area of piezotronics. A perspective is given about their further development and potential applications in energy harvesting, active electronics and intelligent sensing.

Contents

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1. Introduction

The adaptive and seamless interactions between electronics (functional devices, machine, *etc.*) and human/ambience are essential for emerging technologies such as self-powered wearable electronics, human-machine interfacing, biomedical engineering, robotics, Internet of Things and artificial intelligence [1,2]. Although mechanical signals such as biological movements and vibration in ambient are abundant and ubiquitous in environment, however, it is not easy to interface them directly with the CMOS-based technology that relies on external gate control of charge carriers in semiconductor [3–6]. The most conventional method is to use sensors that are sensitive to changes in stress/strain. The mechanical signals can be detected and recorded by conventional CMOS-based technology, but they cannot be utilized to further control the electronics [7–10], which can be considered as passive electronics. Such pressure sensing not only needs complex integration of heterogeneous components, but also lacks direct and active interaction between electronic components and external mechanical stimuli. These limitations severely hinder the advancement and widespread use of electronic technologies to convert mechanical signal. Therefore, innovative designs and technologies are needed to adaptively and seamlessly combine the electronics with mechanical actuations.

Recently, utilizing piezoelectric semiconductors with wurtzite structures (ZnO [11–13], GaN *etc.*), a new kind of transistor, the piezotronic transistor has a two-terminal metal-semiconductor-metal configuration was introduced by Wang and co-workers at 2008 and whose electronic transport is gated/controlled by the inner-crystal potential generated by stress/strain-induced piezoelectric polarization charges in the semiconductor at the metal-semiconductor contacts [14–19]. Such devices innovatively use interface piezoelectric potential gating instead of the external voltage channel-width gating in CMOS technology. Using digital signals directly generated by mechanical actuations to control electronics, piezotronic transistors can function as active nanodevices for great applications in self-powered tactile sensing, memory nanodevice, human-electronics interfacing *etc* [20–22]. The two-way coupling among piezoelectricity and semiconductor-based electronics in piezoelectric semiconductors under mechanical actuations results in the emerging field of piezotronics, which was first proposed by Wang and co-workers in 2007 [16,17]. The stress/strain induced piezoelectric polarization charges at semiconductor region can effectively modulate the metal-semiconductor Schottky barrier by making a huge influences on the concentration and distribution of free carriers at the contact, so as to control the electronic transport. This is well known as the piezotronic effect [23,24], of which the fundamental physics and practical potential applications has been elaborated and demonstrated in the past few years [25–28]. Here, we will review the advances in piezotronic transistors and piezotronics, in which milestone progress in the development of piezotronic transistors are systematically presented, in-depth understanding about piezotronics and the perspective of the field about their further developed and future applications are provided.

2. Fundamentals of piezotronic transistor and piezotronics

2.1. Piezopotential in piezoelectric semiconductors-the core of piezotronic transistor and piezotronics

Wurtzite-structured materials, such as ZnO, GaN *etc.*, simultaneously have piezoelectricity and semiconducting property, that is, the piezoelectric semiconductors. The non-centrosymmetric structure in these crystals, for instance, the ZnO with a hexagonal structure (Fig. 1a, top), will generate piezoelectric property along c-axis direction. When subjected to axial stress/strain, piezoelectric polarization charges are generated at both surfaces within thickness of one to two atomic layers of the crystal along certain orientations. Simply, metal cations Zn^{2+} and anions O^{2-} are tetrahedral co-ordinated, in which the centers of positives ions and negative ions are overlapped with each other at strain free case. Upon a stress/stain along an apex of the tetrahedron, the centers of Zn^{2+} cations and O^{2-} anions are relatively displaced, which results in an electrical dipole moment (hence a piezoelectric polarization) (Fig. 1a, bottom). Since all units in ZnO have such a dipole moment under stress/strain, an electrical potential distribution called the piezopotential (piezoelectric potential) is macroscopically generated along the stress/strain direction (Fig. 1b). This is the piezoelectricity of ZnO along c-axis, which is usually the growth direction of ZnO nanowire/nanosheets [34,35]. Piezopotential generated by the stress/strain induced piezoelectric polarization charges in piezoelectric semiconductors form the basis of piezotronic transistor and piezotronics, which allows modulation of the electrical transport processes across the interface of metal-semiconductor Schottky contact under mechanical stimuli.

2.2. Effect of piezopotential on metal-semiconductor (M-S) contact

M-S contact is the fundamental construction in piezoelectric semiconductor based piezotronic devices. When metal and semiconductor come into contact, free charges near the junction will redistribute significantly and hence the Fermi levels of the M-S system reaches thermal equilibrium, forming either non-rectifying Ohmic contact or rectifying Schottky contact depending on their contact configurations [36]. For Schottky contact, a Schottky barrier would be induced with height ($q\phi_{\mathrm{Bn}}$) and width (W_{Bn}), which dominates the charge carriers transport across the M-S interface when reversely biased [37]. Upon applying the normal stress/strain, the piezoelectric polarization charges presented at M-S contact can effectively modulate the interface Schottky barrier by making a huge influence on the concentration and distribution of free carriers at the contact and hence control the charge carriers transport [23–28]. Here, we take n-type piezoelectric semiconductor as an example. For simplicity, the surface states, screen effect and other anomalies in the crystal are ignored and the M-S junction is at zero bias. In general, the negative piezoelectric polarization charges, and hence the negative piezopotential repels electrons from M-S interface, which results a further depleted region and increased Schottky barrier (Fig. 2a), whereas the positive piezoelectric polarization charges and hence the positive piezopotential attracts electrons

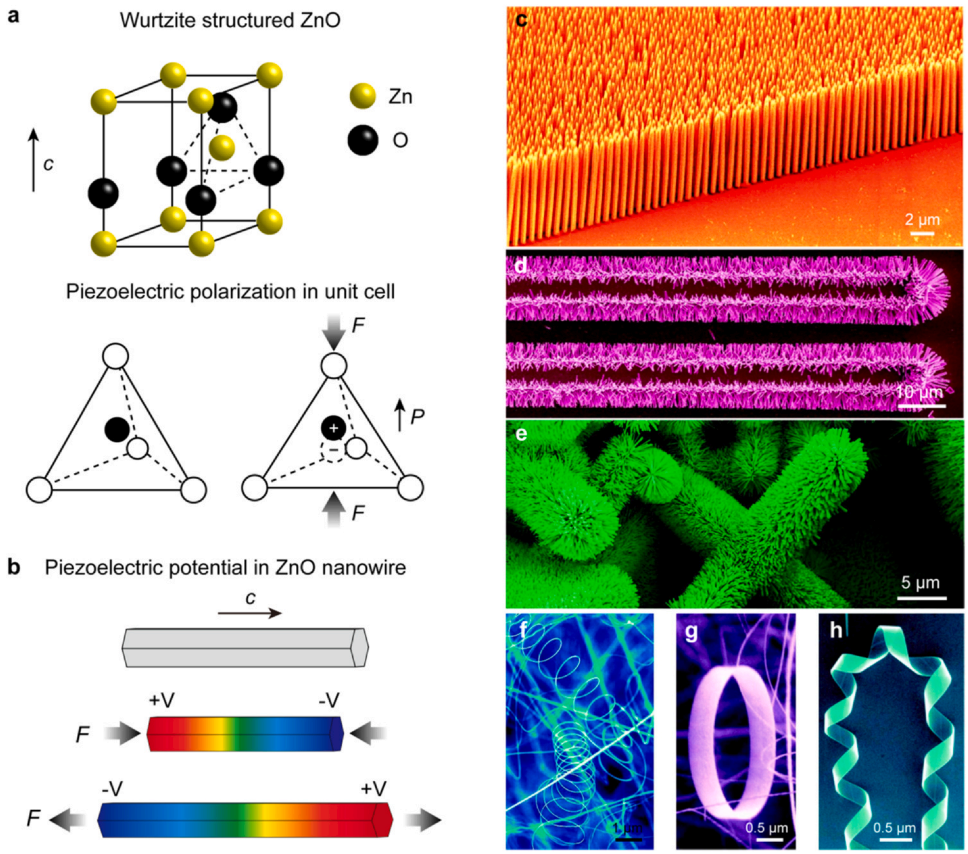

Fig. 1. Piezoelectricity in wurtzite semiconductors. a, Atomic model of the wurtzite-structured ZnO and the origin of piezoelectricity. b, Piezopotential distributed along ZnO nanowire under axial forces. Scanning electron microscope images of ZnO nanostructures: c,d, ZnO nanowire array. e, Radially grown ZnO nanowires around fine wires. f, ZnO nanospring. g, ZnO nanoring. h, Nanohelix formed by a single-crystal ZnO nanobelt. Copyright 2007 Materials Research Society.
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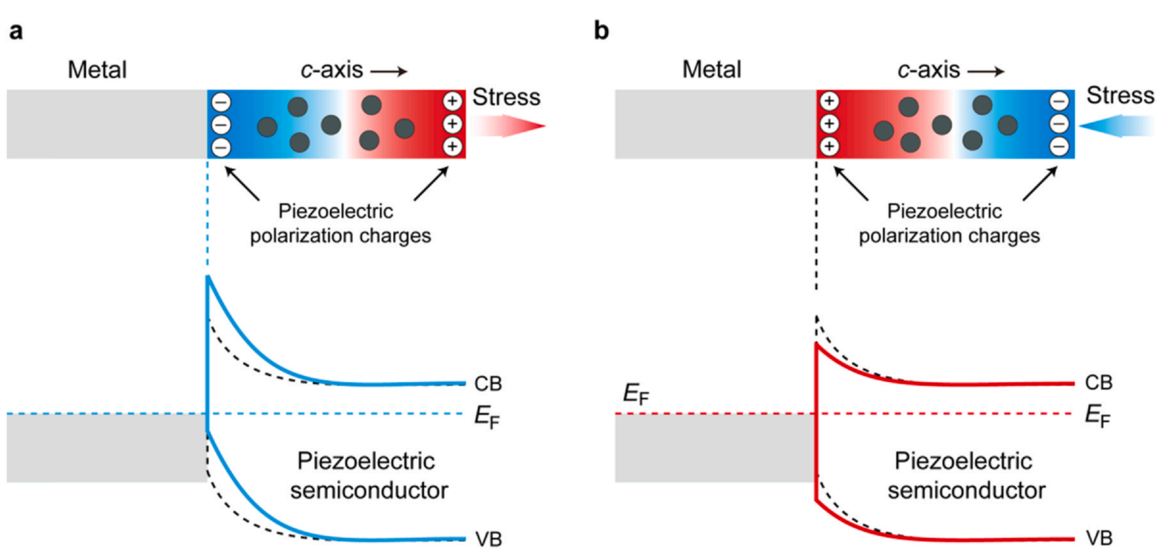

Fig. 2. Piezopotential on metal-semiconductor (n-type) contacts. a, Stress-induced negative piezoelectric polarization charges (and hence the negative piezopotential) at M-S interface increase the Schottky barrier height. b, Stress-induced positive piezoelectric polarization charges (and hence the positive piezopotential) at the M-S interface decrease the Schottky barrier height.

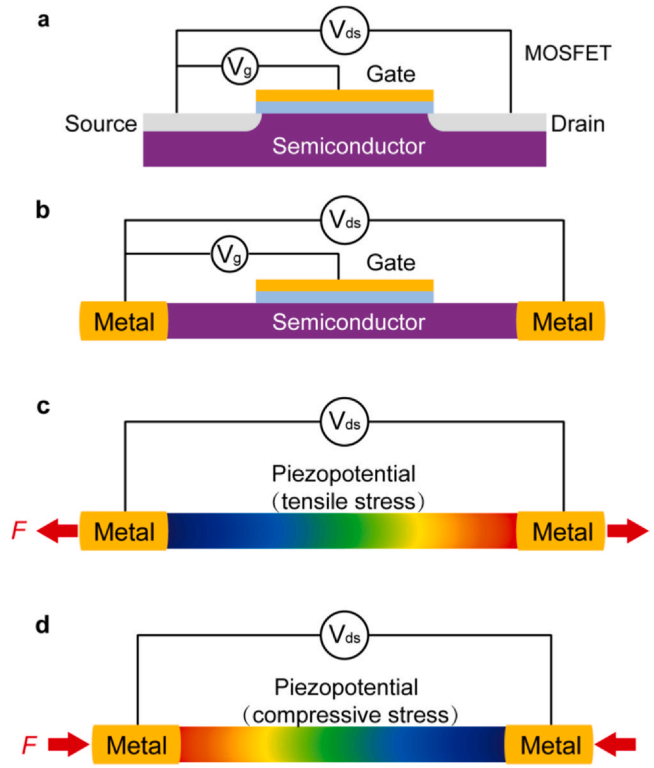

Fig. 3. Schematics of (a) an n-channel MOSFET and (b) a field-effect transistor (FET). Schematics of piezotronic transistors with (c) tensile stress and (d) compressive stress. Reprinted with permission from [23]. Copyright 2011 WILEY-VCHVerlag GmbH & Co. KGaA, Weinheim.

towards the M-S interface, which results a less depleted contact and hence decreased Schottky barrier (Fig. 2b). The magnitude and polarity of the piezopotential within a piezoelectric semiconductor depend on the crystallographic orientation of the crystal and the magnitude and polarity of the applied stress/strain. The above is the basis of piezotronic effect, which has been widely demonstrated in wurtzite-structured semiconductors (ZnO, GaN *etc.*).

According to the theory [23,24,36,37], the ideal SBH without external stress/strain can be given by:

$$q\phi_{Bn} = W_m - \chi, \tag{1}$$

where W_m is the work function of metal, and χ is the affinity energy of semiconductor. The piezotronic effect under finite uniform strain can be considered as a perturbation. For n-type ZnO nanowire, the stress/strain induced piezoelectric polarization is given by:

$$P_z = e_{33}s_{33} = q\rho_{piezo}W_{piezo} \tag{2}$$

where ρ_{piezo} is the density of piezoelectric polarization charges and W_{piezo} denotes the corresponding distribution width of piezoelectric polarization charges. Then we can derive the modified barrier height given by:

$$q\phi'_{Bn} = q\phi_{Bn} - \frac{q^2\rho_{piezo}W_{piezo}^2}{2\varepsilon_s}. \tag{3}$$

where ε_s is the dielectric constant of semiconductor. Therefore, we can modulate the SBH via external applied stress/strain. According to the diffusion theory, the electrical transport across the Schottky junction is given by:

$$J_n = J_D\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right]. \tag{4}$$

Here, J_D is the saturation current density, expressed as:

$$J_D = \frac{q^2D_nN_c}{k_BT}\sqrt{\frac{2qN_D(\psi_{bi} - V)}{\varepsilon_s}}\exp\left(-\frac{q\phi_{Bn}}{k_BT}\right), \tag{5}$$

Where D_n is the electron diffusion coefficient, N_C is the effective density of states in the conduction band, k_B is the Boltzmann constant, T is the temperature, is the donor concentration, and ψ_{bi} is the built-in potential. By replacing $q\phi_{Bn}$ with $q\phi'_{Bn}$ under external stress/strain, we can obtain the current density, given by:

$$J_n = J_D\exp\left(\frac{qe_{33}s_{33}W_{piezo}}{2\varepsilon_s k_BT}\right)\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right]. \tag{6}$$

Therefore, the above arguments present a qualitative explanation of the piezotronic effect. The stress/strain-induced piezoelectric polarization charges can effectively modulate the Schottky barrier and exponentially tune/gate the current density across the contact, depending on the magnitude and polarity of the applied local stress/strain (compressive or tensile) [23,24].

2.3. Basic principles of piezotronic transistor and piezotronics

Piezotronic transistors are a new type of device with a typical two-terminal configuration of metal-semiconductor-metal (M-S-M) structure (Fig. 3c, d) [23]. Piezotronic transistors are designed using different principles from CMOS devices (Fig. 3a, b), which use inner-crystal piezopotential generated by stress/strain-induced piezoelectric polarization charges at the contact in semiconductor region as the gate voltage to control the charge carriers transport across the M-S junction. Such two-terminal transistors are innovative in a way that the electrical channel-width gating is replaced by interface polarization gating.

When a strain is induced in a piezotronic transistor, there are two main effects that may affect the electrical transport characteristics of the device. One of them is the piezoresistive effect [38,39], resulting from the stress/strain-induced changes in bandgap, charge carrier density and density of states in the conduction band of a semiconductor. However, the piezoresistive effect is a volume effect without polarity, and hence is not the dominant effect of a piezotronic transistor. Piezoresistive effect is widely exist in semiconductors, such as Si and GaAs based first- and second-generation semiconductors, which is not limited to the ZnO and GaN based third-generation semiconductors. The other effect is the piezotronic effect, which has an asymmetric modulate effect on the M-S contacts at the source and drain due to the polarity of the inner-crystal piezoelectric polarization. The piezoelectric polarization charges presented at the ends of a piezoelectric semiconductor, can directly affect the barrier of M-S contacts. The polarity of the piezopotential in a semiconductor can be switched by changing the sign of applied stress/strain (Fig. 3c, d). Therefore, the piezotronic transistor can be gated from a control at one side to another contact simply by reversing the sign of stress/strain applied to the device. The coupling of piezoelectricity and electronic transport characteristics in piezoelectric semiconductors results in the emerging field of piezotronics (Fig. 4). Using inner-crystal piezopotential generated by the piezoelectric polarization charges as a 'gate' controlling signal to modulate the interfacing barrier and achieve tunable electronic processes is the piezotronics [16,21–28], which can be considered as active electronics. By directly generating digital signals to control electronics using mechanical actuations without the need for external gate electrode, piezotronic effect shows promise for intelligent electronic nanodevices and nanosystems.

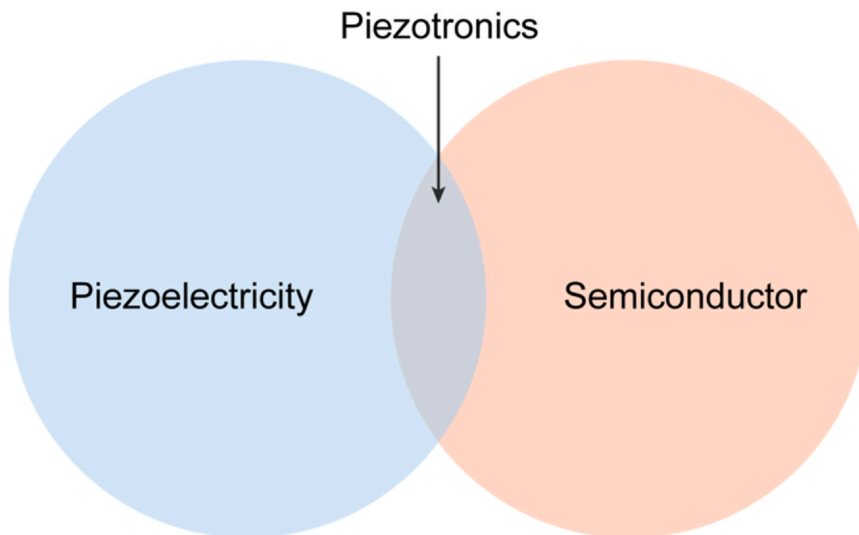

Fig. 4. Coupling the piezoelectricity and the semiconducting property resulting in the emerging field of piezotronics.

2.4. Materials system for piezotronic transistors and piezotronics

The third-generation semiconductors, represented by wide bandgap ZnO and GaN (Fig. 1c), are ideal materials for piezotronic transistors and piezotronics due to their wide bandgap, semiconducting property and strong piezoelectricity along c-axis, which provides ideal platforms for exploring the fundamental coupling between the piezoelectricity and other interesting physical processes, for instances, (high-frequency) electronic transport, photoexcitation and two-dimensional (2D) electron gas in related piezotronic devices [22,28,40]. Additionally, the third-generation semiconductors have attracted great attention for some emerging technologies, such as consumer electronics and information products, 5G communication systems, electric vehicles, optoelectronics and even defense and security applications, due to their superior material properties such as high-voltage resistance, high-temperature resistance, high-switching frequency and high-radiation resistance [28,41]. The fundamental research and development of piezotronic effect and piezotronics (including piezotronic transistors) of the third-generation semiconductors will be promoted and advanced by the commercial feasibility and maturity of related technological processes in manufacturing and integrating these materials, and can also in turn promote related emerging technologies based on these materials [28,41]. Furthermore, 2D materials (especially the monolayer or odd-layer transition-metal dichalcogenides, TMDCs) exhibit strong piezoelectricity due to their non-centrosymmetric structures. High crystallinity, superior semiconducting and excellent mechanical property of 2D TMDCs shows promise as high performance piezotronic materials for atomically thin piezotronic transistors and piezotronics [42].

3. Piezotronic transistors of the third-generation semiconductors and their applications

3.1. Taxel-addressable matrix of vertical-nanowire piezotronic transistors for active and adaptive tactile imaging

In above sections, we have reviewed the fundamentals of piezotronic transistors, piezotronic effect and piezotronics. Here, we focus on the new trend in the researches of piezotronic transistors and their applications.

Wang's team conducted two independent studies in 2006. One is the piezoelectric field effect transistor (PE-FET) and another is the piezoelectric-diode (PE-diode), which are the prototype of piezotronic transistor [14,15]. The first piezotronic transistor was proposed by Zhou, Wang and co-workers in 2008 [18], of which a ZnO nanowire was laterally bonded on a polystyrene substrate. Bending of the substrate can stretch or compress the nanowire, resulting in the piezoelectric polarization charges at two back-to-back Schottky contacts, and hence to modulate the electrical transport characteristics of the nanodevice. This kind of horizontal piezotronic transistor has been widely used in flexible electronics and optoelectronics. Another latterly developed vertical piezotronic transistors or piezotronic transistor array are more conductive for stress detection, particularly for tactile imaging with high resolution. This idea of applying high-density vertical piezotronic transistors for tactile imaging was first proposed by Han, Wang and co-workers in 2012, and first achieved by Wu, Wen and Wang in 2013, which opens a new chapter of piezotronic transistor and piezotronics in the field of tactile sensing (from nanoscience to nanotechnology) [43,44].

The basic structure of a 3D strain-gated vertical piezotronic transistor consists of a vertically grown piezoelectric nanowire (ZnO, CdS, *etc.*) in contact with bottom and top electrodes. Owing to the non-centrosymmetric wurtzite structure, a piezopotential can be induced along the ZnO nanowire when it is subjected to external mechanical deformation, which can be used as the driving stimuli or gate signal to tune the electrical transport properties across the interface between the nanowires and the electrodes (Fig. 5a). The two-terminal configuration and interface gating mechanism of piezotronic transistor offer a new approach for 3D structuring. The 3D taxel-addressable matrix of vertical-nanowire piezotronic transistor arrays are made of a large-scale integrated circuit basing on 92×92 3D strain-gated vertical piezotronic transistors arrays for tactile imaging [43]. Each vertically aligned ZnO nanowire cluster based piezotronic transistor array is an active basic unit as well as a tactile pixel (Fig. 5b, c). By using this active nanodevice, self-powered tactile imaging has been achieved with a high spatial resolution of ~100 μm, a response time of ~0.15 s and a high-pressure sensitivity of ~2.1 μS/kPa. The pressure sensing range can be varied from kPa to 30 kPa, which matches well with people's pressure perception range (10–40 kPa) [44,45]. Such device not only can realize shape-adaptive tactile imaging but also can achieve multidimensional active sensing by measuring the current change of output signals of each taxel (Fig. 5d). Furthermore, the devices can be integrated on a large scale on the flexible substrate for smart skin (Fig. 5e). The simplification of the matrix integration paves the way for the development of functional large-scale intelligent sensors. It's worth noting here, the authors also carefully clarify the

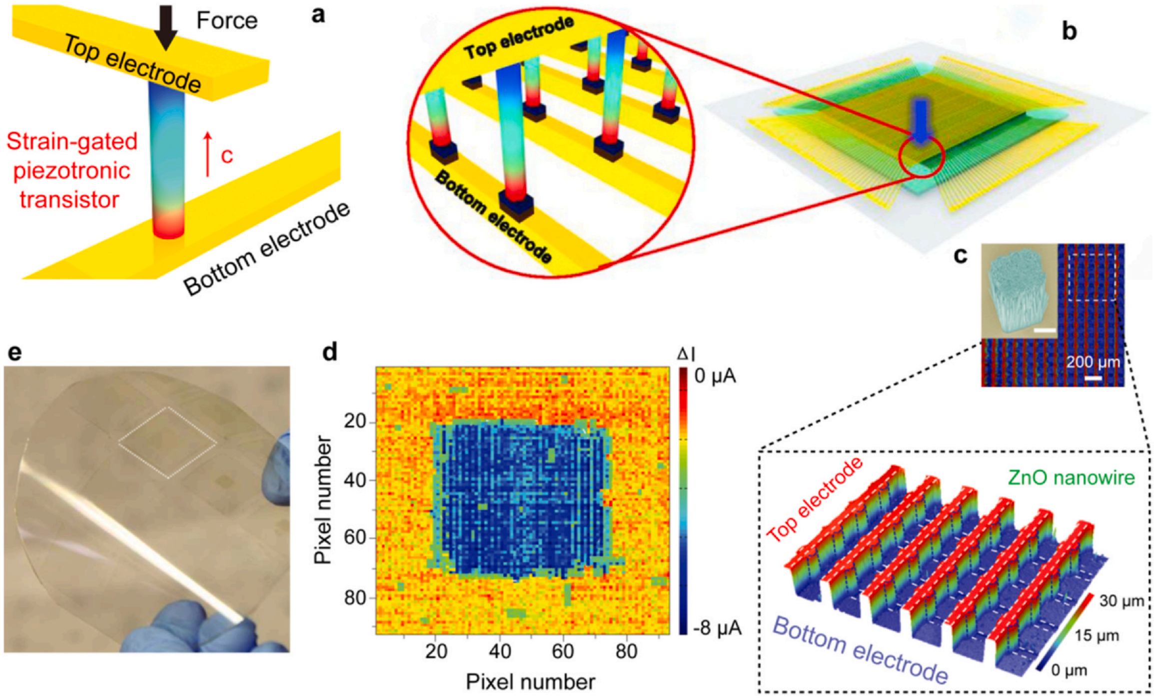

Fig. 5. Taxel-addressable matrix of vertical-nanowire piezotronic Transistors. a, Strain-gated piezotronic transistor based on a vertically aligned ZnO nanowire. b, Illustration of the taxel-addressable matrix of vertical-nanowire piezotronic transistor arrays. c, Topological profile image of the piezotronic transistors arrays and a scanning electron microscopy (SEM) image of an individual taxel. d, Tactile imaging by the fully integrated 92 × 92 piezotronic transistors arrays. e, Photograph of taxel-addressable matrix of vertical-nanowire piezotronic transistors integrated on the flexible substrate.
d, Reprinted with permission from [43]. Copyright 2013 the American Association for the Advancement of Science. e, Reprinted with permission from [27]. Copyright 2016 Nature Publishing Group.

dominant role of the functional devices, which is piezotronic effect other than piezoresistive effect.

The 3D matrix can be used as self-powered and active tactile sensors by directly converting mechanical actions into digital control signals with no need for external gate voltage. The 3D piezotronic transistors arrays show promise for human-machine interfacing and micro /nanoelectromechanical systems.

3.2. Nanoplatelet based piezotronic transistor array for high resolution tactile imaging

Buckling effect is a common phenomenon in micro/nanowires, resulting in a weaken piezotronic effect. As shown in Fig. 6a, the nanowire will bend under compressive stress with an offset (Δl) to the center of nanowire. By finite-element analysis, the lateral bend deflection (D_{max}) can be found to be more than ten times larger than the vertical deformation when the aspect ratio is as high as 50 [46,47]. Due to the buckling effect in nanowire, the piezoelectric polarization charges generated at the ends of nanowire will be uneven, which has a negative influence on the piezotronic effect and in turn decrease the sensitivity of a piezotronic transistor. To eliminate the buckling effect and enhance the sensitivity of a piezotronic transistor, 2D ZnO nanoplatelet based piezotronic transistor (2DPT) with high pressure sensitivity was successfully developed (Fig. 6b) [46]. The ZnO nanoplatelet possesses an aspect ratio of about 0.42 with a smaller upper surface and larger bottom surface, and hence the buckling effect can be effectively avoided when the device under external applied stress/strain [46,47]. As increase the compressive stresses from 0.02 to 3.64 MPa, the *I-V* characteristics gradually changes from asymmetric Schottky characteristics to symmetrical Ohmic characteristics, which indicates a gradually decreased Schottky barrier height with increased compressive pressures. The M-S Schottky contact and hence the electronic transport of the 2DPT can be gated effectively by the stress-induced inner-crystal piezopotential (Fig. 6c–f). High pressure sensitivity of ZnO 2DPT has been obtained of 60.97–78.23 meV/MPa, which is nearly three orders of magnitude larger than that of single ZnO nanowire based piezotronic transistor. The gauge factor of 2DPT can even reach ~1.5×10^7, which is the highest one among previous studies [46]. Moreover, the 2DPT can be used as a tactile sensor with a wide pressure detection range (a few kPa to ~MPa) and may have great application in smart skin. The special 2D geometry and the strong piezoelectricity of ZnO nanoplatelet are the keys to the ultrahigh pressure sensitivity of 2DPT.

Additionally, 2D piezotronic transistor array was developed using the self-assembly method and micro-fabrication techniques (Fig. 7a, b). The pixel area density of the self-assembly 2DPT array is about 2.9×10^7 cm^{-2}, which corresponds to a resolution of 12,700 dpi. It is about 50 times higher than the resolution of the 3D matrix of vertical-nanowire piezotronic transistors array (8464 cm^{-2}) and much higher than that of mechanoreceptors implanted in the skin of human fingertip (~240 cm^{-2}). The ZnO 2DPT array responds well to the static and dynamic stimuli and distinct changes can be obtained for all pixels before and after external applied forces (Fig. 7c). Based on the 2DPT array, an “encode-decode” process that converts the digital series (314159265358) representing the input pressure signal into the corresponding digital sequence of the output electrical signal was exhibited (Fig. 7d). The spatial distribution of all applied mechanical stimuli can be distinguished and electronically mapped with high resolution. The study demonstrates the great advantage of ZnO 2DPT array as a fundamental component of piezotronics and its potential for future e-skin application.

3.3. Nanoplatelet based double channel piezotronic transistor

Among previous reports, piezotronic transistors are usually three-dimensional, with a piezoelectric semiconductor nanowire sandwiched between the top and bottom electrodes, in which only one M-S contact plays an effective regulatory role (the reverse-biased Schottky contact), while the other has an opposite modulate effect [43,46,48–52]. Thus, the sensitivity of those devices can be further enhanced through innovative design on the structure. Moreover, the structural reliability of the single channel based piezotronic transistor is relative poor, because when the channel failure (for instance, the Schottky contact changes into an Ohmic contact), the device cannot work. To achieve large-scale vertical piezotronic transistor array with more reliability and enhanced sensitivity, the double-channel piezotronic transistor (DCPT) based ZnO nanoplatelet with high pressure-sensitivity and high structural reliability was designed and developed [53].

The DCPT has double Schottky contacts formed between the two bottom metal electrodes and the bottom surface of ZnO nanoplatelet, and hence a planar compatible structure is realized by replacing the 3D sandwiched structure with a two-layer planar structure (Fig. 8a). Owing to design of double channels, the DCPT can still work normally even if there is a problem with one channel, resulting in a high structural stability. The band diagrams of DCPT with and without strains are detailed the working mechanism (Fig. 8b). When applied compressive stress/strain, positive piezoelectric polarization charges presented at the interfaces of both M-S Schottky contacts owing to the symmetric structure of DCPT, which can symmetrically reduce the Schottky barriers and thus symmetrically increase the electronic transport of the device (Fig. 8c).

The DCPT can also response well to external dynamic stimuli with high pressure sensitivity (Fig. 8d–f). In order to eliminate the influence of contact barrier, the dynamic response of DCPT under increased pressures from 0.75 to 1.00 MPa with a step of 63.5 kPa was recorded. The pressure sensitivity ($S = \Delta_{SBH}/\Delta_{Pressure}$) is obtained from the linear fitting curve, which is up to 84.2–104.4 meV/MPa and even higher than that the highest value of 2DPT reported in the above section [53]. The main factor that enhances the pressure-sensitivity is the double channel regulation mechanism, which results in a more effectively modulate on the Schottky barrier of both M-S contacts.

Moreover, a kind of integrated DCPTs has been easily developed by the existing planar micro-fabrication technology, which benefits from its planar compatible structure (Fig. 9). The device manufacturing involves two steps. First, perform a large-scale self-assembly of ZnO nanoplatelets on a silicon wafer which can be at least 4 in.. Second, use semi-dry PDMS to transfer ZnO nanoplatelet array to a substrate with interdigitated electrodes. The structural reliability and high pressure-sensitivity of the integrated DCPTs show promise for applications in touch sensing technology and human-machine interfacing.

3.4. Piezotronic transistor based on twin nanoplatelet for ultrahigh pressure sensitivity

To further enhance the pressure sensitivity of a piezotronic transistor, novel approaches or designs are needed to enable the more effectively modulation of stress/strain on M-S Schottky barrier. Based on this original idea, a new kind of ZnO twin nanoplatelet based piezotronic transistor (TNPT) was developed [54]. The TNPT has a sandwich structure composed of a ZnO twin nanoplatelet, a top and a bottom electrode (Fig. 10a). The new type of ZnO twin nanoplatelets were synthesized by hydrothermal method with a hexagonal geometry and a mirror symmetric structure (Fig. 10b). As one of the most important factors of piezotronic transistor, the piezoelectricity

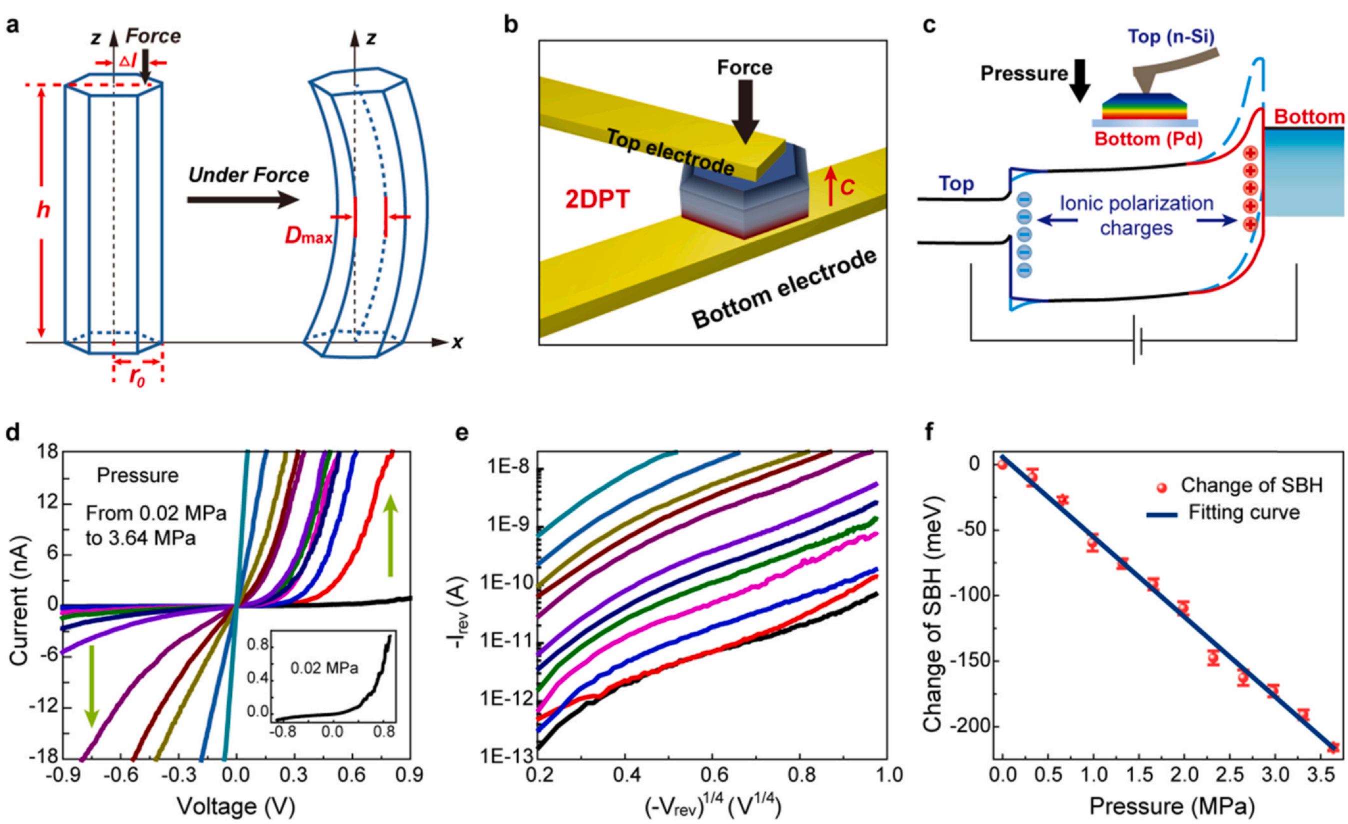

Fig. 6. 2D ZnO piezotronic transistor (2DPT). a, Buckling effect in vertical ZnO nanowire. The r_0, h and D_{max} represent radius, height and the maximal lateral deflection of the nanowire. b, Schematic illustration of 2DPT. c, Band diagram used to explain the working mechanism of 2DPT. d, Electronic transport of 2DPT as a function of pressures. e, Current (I) presented in semilog form versus $(-V_{rev})^{1/4}$. f, Changes of Schottky barrier height (SBH) as a function of applied pressure.
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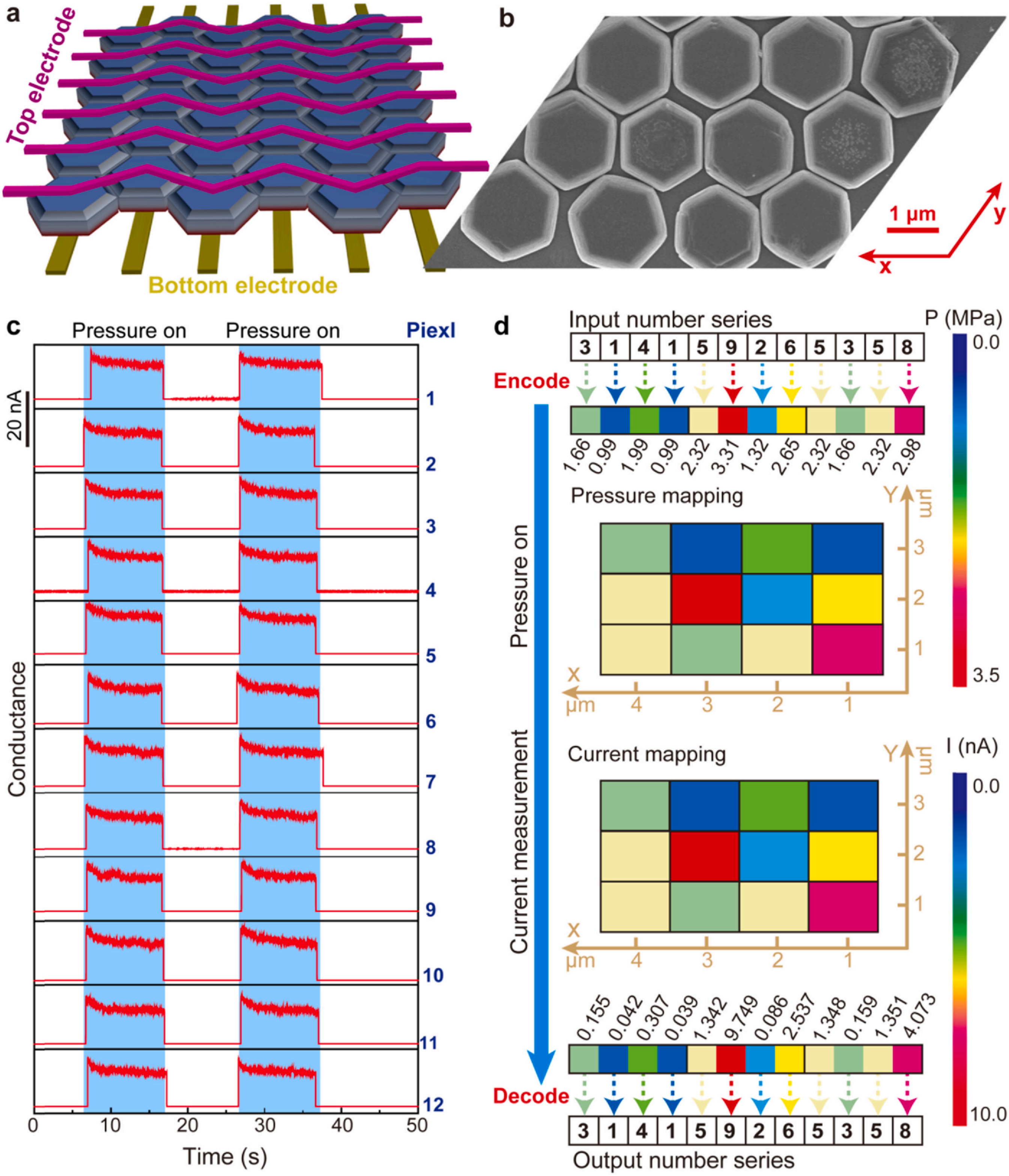

Fig. 7. Tactile imaging by the 2DPT array. a, Schematic illustration of 2DPT array. b, SEM image of ZnO array. c, Conductance measurement of each 2DPT. d, Using 2DPT array to achieve an "Encode-Decode" process that converts the digital series (the input pressure signal) into the corresponding digital sequence (output electrical signal). Reprinted with permission from [46]. Copyright 2017 WILEY-VCHVerlag GmbH & Co. KGaA, Weinheim.

(effective piezoelectric coefficient d_{33}) of the ZnO nanoplatelet and the ZnO twin nanoplatelet was characterized by piezo-response force microscopy (PFM) (Fig. 10b). The d_{33} of ZnO nanoplatelet that can be considered as half part of the twin nanoplatelet, is about 18–22.5 pm/V, indicating that it has strong piezoelectricity, whereas the value of ZnO twin nanoplatelet is small enough to be negligible, which further demonstrates its mirror symmetric structure. With the unique mirror symmetric geometry and the relative strong piezoelectricity, ZnO twin nanoplatelet is an excellent candidate piezoelectric semiconductor for ultrasensitive piezotronic transistor.

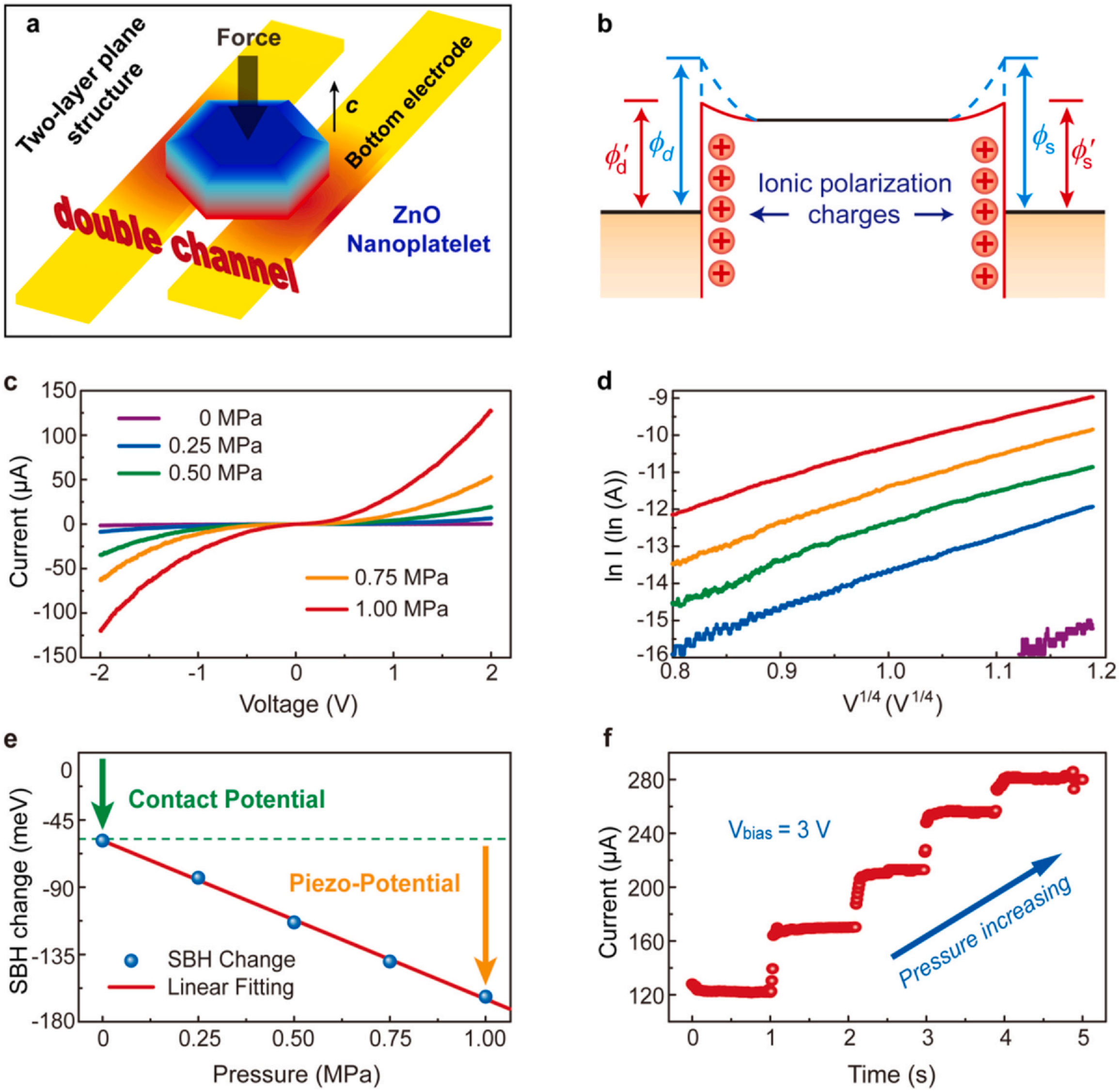

Fig. 8. ZnO based Double channel piezotronic transistor (DCPT). a, Schematic illustration of DCPT. b, Band diagram of DCPT without (blue dashed line) and with (red solid line) strain/stress illustrates the working mechanism. c, Pressure-dependent *I-V* characteristics. d, ln(I) vs $V^{1/4}$. e, Changes of Schottky barrier height (SBH). f, Current response to dynamic stimuli with increasing pressures from 0.75 to 1.00 MPa with a step of 63.5 kPa.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

When apply a normal compressive strain or stress, an axial strain can be induced in ZnO twin nanoplatelet. Owing to the non-centrosymmetric crystal structure and the mirror symmetric geometry of ZnO twin nanoplatelet, piezopotentials are generated distributed along the ZnO twin nanoplatelet with positive piezoelectric polarization charges presenting at the top and bottom surfaces, which can simultaneously reduce the Schottky barriers of source and drain and dramatically enhance the electrical transport performance of TNPT. Thus, the charge carrier transport across the Schottky junction can be gated effectively by the strain/stress induced positive piezoelectric polarization charges (Fig. 10c). An ultrasensitive piezotronic transistor is therefore introduced with the dual Schottky junctions' synergistic modulation. The electrical transport property of TNPT under various static compressive stresses was characterized. (Fig. 10d) The current significantly increases as the pressure increased, and the I-V curve gradually changes from the Schottky characteristics to the Ohmic characteristics, which indicates that the pressure-induced positive piezoelectric polarization charges effectively decreases the dual Schottky barriers.

Besides, the current responses under dynamic stress/strain have also been characterized, which demonstrates a high sensitivity of pressure change at low pressure region (from ~kPa to hundreds of kPa). It shows promise of TNPT for tactile sensing applications such as smart skin and human-machine interface (Fig. 10e). A ultrahigh pressure sensitivity of 1448.08–1677.53 meV/MPa has been achieved, which is the highest value among all previous studies and is ~50 times larger than that of the 3D matrix of vertical-nanowire piezotronic transistor array and more than 20 times than that of 2DPT (Fig. 10f) [43,46,54]. The key to achieving the ultrasensitive piezotronic transistor is the mechanism of dual Schottky barriers' synergistic modulation by using ZnO twin nanoplatelet with strong piezoelectricity and mirror structure, which is the core of TNPT.

3.5. Atomic thin piezotronic transistor for smart skin

The continuous miniaturization of Si-based microelectronics is the fundamental driving force of the information technology revolution. However, the fabrication of sub-5 nm Si transistor is

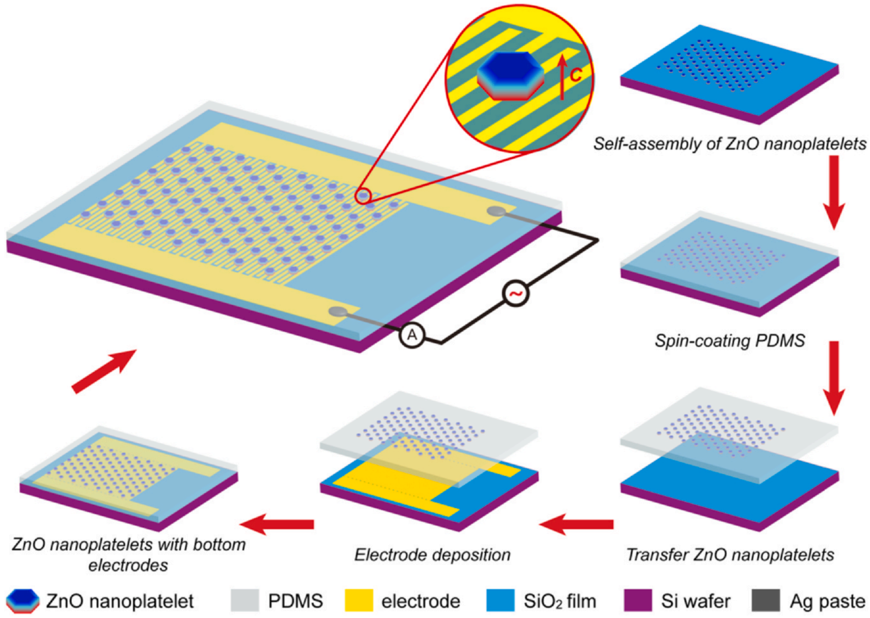

Fig. 9. Schematic showing the integrated ZnO nanoplatelet pressure sensor and its fabrication process.
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extremely challenging because the electrostatic gate control on the channel may lose effectiveness [55–59]. Therefore, exploration of new channel materials beyond Si and new operation mechanism are of utmost interest.

Atomic thin ZnO piezotronic transistor with a ~2-nm physical channel length was developed by utilizing the self-generated piezopotential in ZnO nanosheet to gate the transistor (Fig. 12a), which breaks the 5-nm limit for transistors reported in literatures [60]. The single crystal p-ZnO nanosheets were synthesized by water-air method [61]. The morphology of ZnO nanosheet is a single triangular with thickness of ~2 nm and edges of ~10–40 μm (Fig. 11a–c). The out-of-plane piezoelectricity of ZnO nanosheet was investigated by PFM (Fig. 11d–i), from which the effective piezoelectric coefficient (d_{eff}) of ZnO nanosheet was obtained as high as ~23.7 pm/V (Fig. 11j). It has been reported that, under weak nano-indentation, the tip-surface junction and a high dielectric constant of sample lead to a significant potential drop between the tip and surface, and hence the piezoelectric coefficient (d_{33}) is approximated twice larger than the measured d_{eff} [62]. These results demonstrate the strong out-of-plane piezoelectricity of ZnO nanosheet and its potential for atomic thin piezotronic device.

The electrical transport characteristics of atomic thin ZnO piezotronic transistor were characterized. For the atomic thin device, the current gradually increases under forward bias, whereas decreases under revised bias under compressive stresses (Fig. 12b). The stress/strain gated asymmetric behavior indicates that the dominant role is the piezotronic effect. The working principle of atomic thin ZnO piezotronic transistor is illustrated in Fig. 12c. When subjected to axial stress, strong piezoelectric polarization field can be induced within ZnO nanosheet due to its atomic thin and strong out-of-plane piezoelectricity, which has a huge influence on the concentration and distribution of free carriers of all region of ZnO nanosheet as well as on the distribution of electronic charges at metal-ZnO interfaces. Thus, the stress-induced inner piezoelectric polarization field can directly modulate the Au-ZnO Schottky barriers, so as to effectively control the electrical transport characteristics.

The atomic thin ZnO piezotronic transistor can respond well to the periodically switched stress with a fast response time of ~3 ms (Fig. 12d), which demonstrates that the modulate effect of the mechanical actions on carrier transport is reversible. The device can work as an on/off switch transistor, in which the current flowed through it can be controlled by external stimuli. In other words, applying a compressive strain can enhance the carrier transport, while removing it can decrease the current to its original state. This kind of stress-controlled on/off switch can be functioned as an atomic thin piezotronic logic circuit. The reliability and stability of the atomic thin transistor are also demonstrated by applying repeated on/off cycles, in which the response exhibited no obvious degradation. Such device shows strong piezotronic effect and offers the ultimate scaling of thickness with atomic-level control by external stimuli. The atomic thin nature of ZnO and the two-terminal configuration of the piezotronic transistor realize the study of physics of inner-crystal piezopotential control at ultra-short channel, which is still a challenge at scale of a few nanometers in traditional COMS technology. This work exhibits the effectiveness of the piezotronic effect at nanometer scale, with great potential for applications in human-machine interfacing and nano-electromechanical system, which also paves the way for atomic thin electronics and computing.

3.6. 2D piezotronics: interface gating and channel-width gating

The physical mechanism of the c-axis piezotronic transistor is interface gating by using inner-crystal piezoelectric polarization charges to modulate the M-S Schottky barrier via affecting the distribution of free carriers and realize active electronics. This is an interface effect. Nevertheless, new physical mechanism may generate or the original modulated effect can be enhanced when atomic thin materials meet the out-of-plane piezoelectricity and the electronic property. Different from the 1D nanowire and 2D films with in-plane piezoelectricity, axial stress/strain induced piezoelectric polarization charges will exist at all surfaces of the atomic thin materials with out-of-plane piezoelectricity, resulting in an enormous influence on the free carriers' concentration and distribution in all volume/area owing to their atomic thickness and strong out-of-plane piezoelectricity, which means channel-width gating and hence the volume effect can be

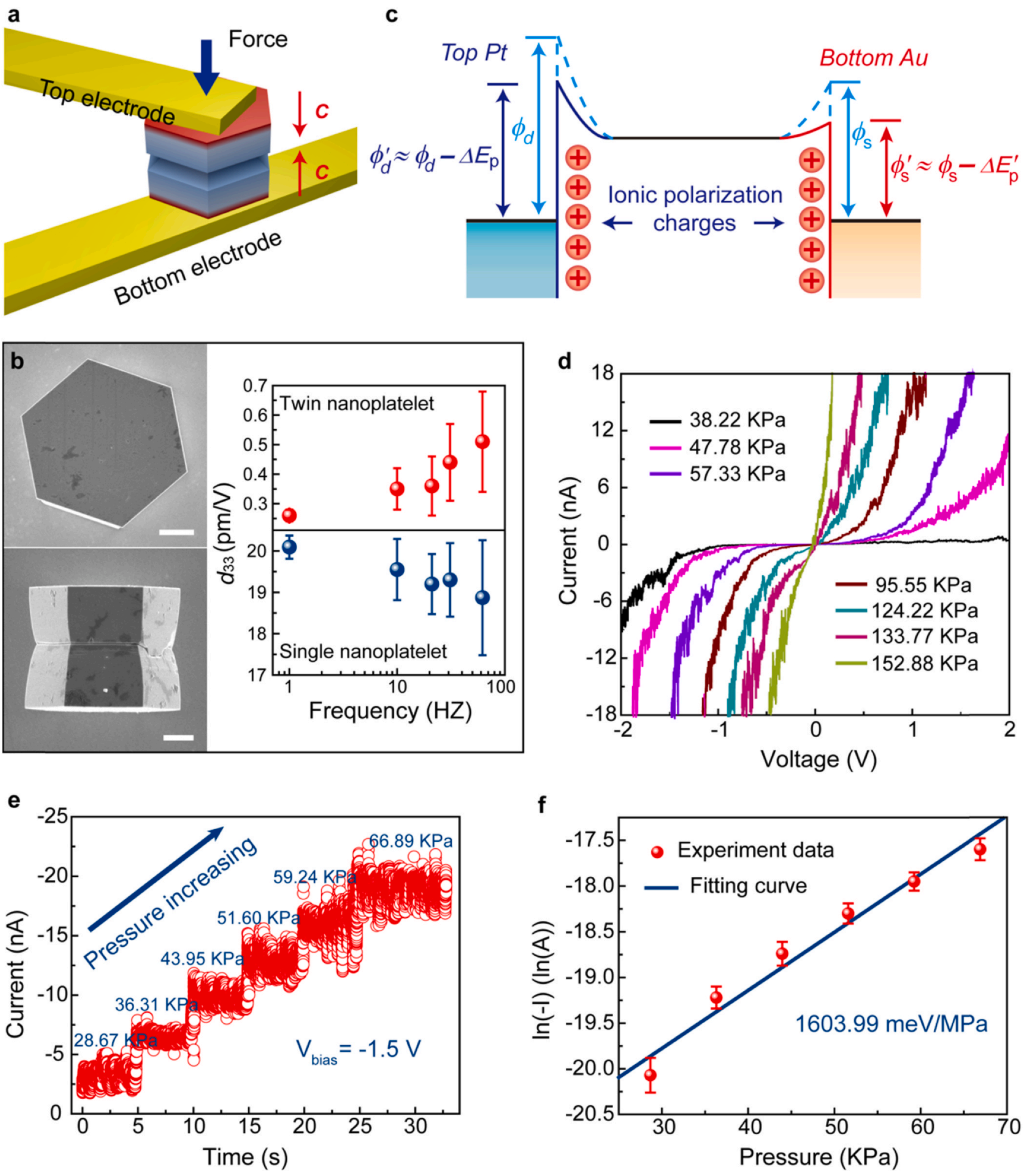

Fig. 10. ZnO twin nanoplatelet based piezotronic transistor (TNPT). a, Schematic illustration of TNPT. The red arrows represent the c-axis of ZnO twin nanoplatelet. b, SEM images of ZnO twin nanoplatelet and piezoelectric coefficient (d_{33}) of ZnO single and twin nanoplatelet acquired with different frequency. The scale bars indicate 1 μm. c, Band diagrams illustrate the working mechanism of TNPT. d, Electronic transport of TNPT under static pressures. e, The current response of TNPT under dynamic pressures. f, ln(I)-P curve of TNPT showing a high pressure sensitivity.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
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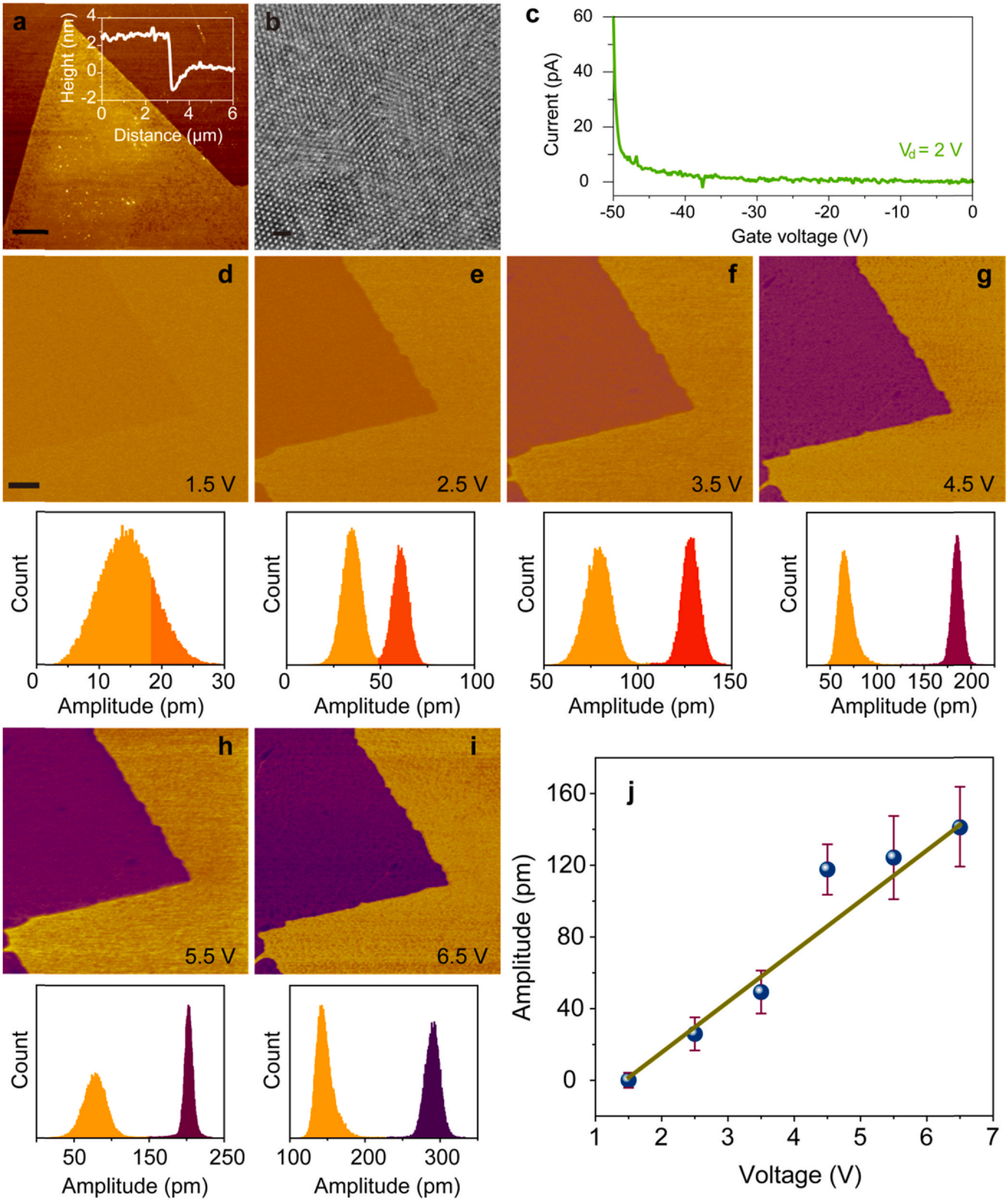

Fig. 11. Characterization of ZnO nanosheet. a, Atomic force microscopy topography of a ZnO nanosheet. The scale bar represents 3 μm. b, High resolution transmission electron microscope (HRTEM) image of the ZnO nanosheet. The scale bar represents 1 nm. c, Electronic property of ZnO nanosheet. d–i, Amplitude images observed by contact piezo-response force microscopy technology. The scale bar represents 500 nm. j, Effective piezoelectric coefficient (d_{eff}) obtained from d-i. Error bars indicate standard deviations. Reprinted with permission from [60]. Copyright 2018 American Chemical Society.

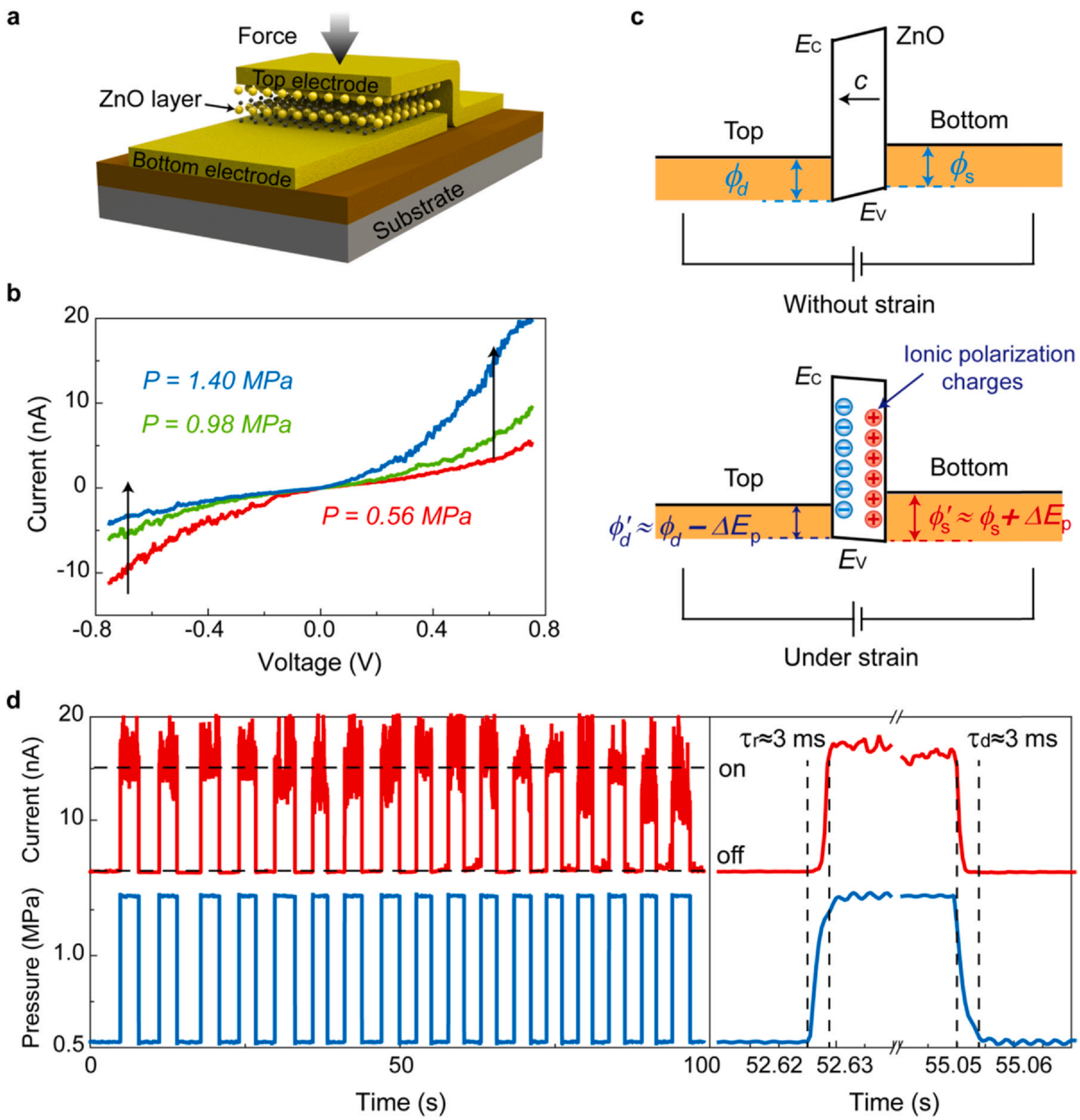

Fig. 12. Performance and working mechanism of atomic thin ZnO piezotronic transistor. a, Schematic illustration atomic thin ZnO piezotronic transistor. b, The electronic transport of atomic thin piezotronic transistor under static stresses. c, Band diagrams explaining the working mechanism of the device. d, Current response of atomic thin piezotronic transistor under dynamic stresses.
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introduced in atomic thin material based piezotronic transistor and the gating effect should be significant [63].

The piezotronic transistors based on atomic thin p-ZnO nanosheet with c-axis perpendicular to the plane were packaged with polymethyl methacrylate (PMMA) (Fig. 13a). For the atomic thin piezotronic transistor, the electrical transport processes are effectively gated by the external mechanical signal, arising from the joint modulation of the piezoelectric polarization charges at M-S contacts and ZnO channel. The piezoelectric polarization charges at M-S contacts can effectively modulate the Schottky barrier height, which is the interface gating effect. The piezoelectric polarization charges created at surfaces of ZnO nanosheet can effectively control the width of conductive channel, resulting in the volumetric channel-width gating effect. Using inner-crystal out-of-plane piezopotential in atomic thin materials as the gate signal to modulate the interface barrier height and control the width of conductive channel, and hence achieving the tunable electronics is 2D piezotronics [63].

The interface gating effect and channel-width gating effect in 2D piezotronic transistor are detailed separately as following: when compressive forces applied on electrodes, the piezoelectric polarization charges will be induced at M-S contacts, strongly affecting the concentration and distribution of free carriers near the M-S contact. Take p-ZnO as an example, the negative piezoelectric polarization charges are induced, attracting the holes near the interfaces, which will lower the Schottky barrier heights of the M-S contacts and hence enhance the electronic transport (Fig. 13b); When ZnO nanosheet channel subjected axial compressive stress/strain, negative piezoelectric polarization charges are induced at top

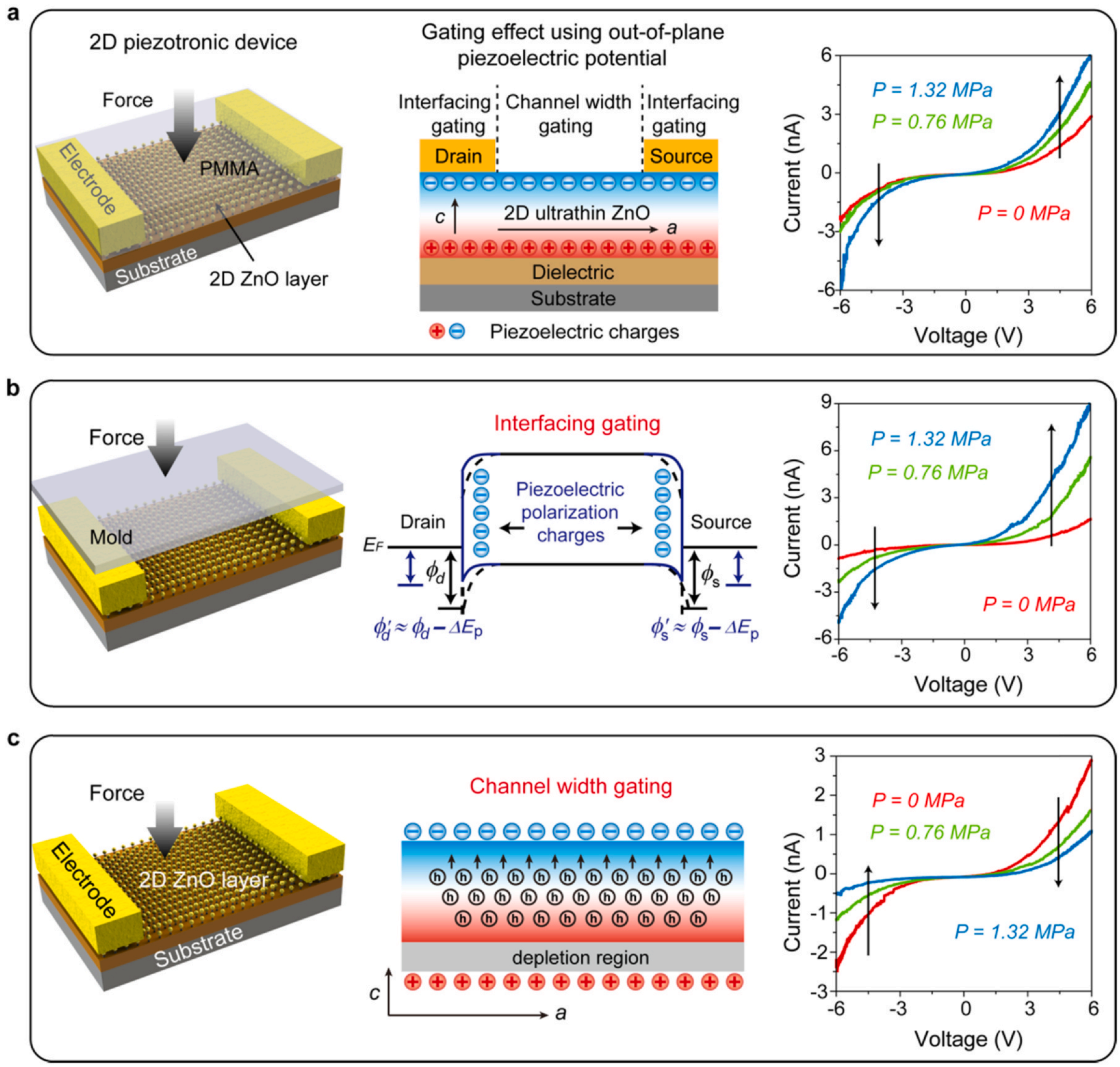

Fig. 13. 2D piezotronics: interface gating and channel-width gating. a, 2D piezotronics: (left) Schematic illustration of ZnO nanosheet based piezotronic transistor under stress; (middle) The mechanism of 2D piezotronics; (right) Electronic transport of the device. b, Interfacing gating effect: (left) Schematic illustration of the device under force on the M-S contacts; (middle) Band diagrams explain the interface gating effect; (right) Electronic transport of the device under applied forces on the M-S contacts. c, Channel-width gating effect: (left) Schematic illustration of the device under applied force on the channel; (middle) Physical mechanism of channel-width gating effect; (right) Electronic transport of the device under applied force on the channel.
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surface attracting the holes along c-axis direction, whereas the positive piezoelectric polarization charges are induced at bottom surface repelling the holes along c-axis direction, resulting a depletion region at the bottom of ZnO nanosheet. This depletion region will significantly reduce the ZnO channel width and hence weaken the electronic transport of the device (Fig. 13c).

In fact, the atomic thin ZnO nanosheet based piezotronic transistor is a kind of ultrathin a-axis piezotronic devices. The structure and mechanism of which is the same as that of previously reported a-axis piezotronic devices [64–67]. Different from the c-axis piezotronics, the a-axis piezoelectric semiconductor based piezotronics contains two gating effects: the interface gating effect, which uses piezoelectric polarization charges at M-S interface to modulate the Schottky barrier; and the volume gating effect, which uses piezoelectric polarization charges presented at upper and bottom surfaces of the conductive channel to control the channel width. The extensive studies in a-axis piezoelectric semiconductor further improve the theoretical framework and expand the applications of piezotronics (Fig. 14). However, the axial dimension of a-axis piezoelectric semiconductors used in previously reports such as GaN nanobelt is on the order of microns. Thus, the magnitude of channel-width gating effect may be affected to a certain degree. Different from that of 1D GaN nanobelt, the channel-width gating effect in the ZnO nanosheet can be significantly enhanced due to its atomic thickness (~2 nanometers) and strong out-of-plane piezoelectricity. This study provides in-depth understandings about the piezotronics, which is the 2D piezotronics of interface gating and channel-width gating in atomic thin materials with strong out-of-plane piezoelectricity, paving the way for the applications of atomic thin materials with out-of-plane piezoelectricity and semiconducting property in novel nanodevices and nanosystems.

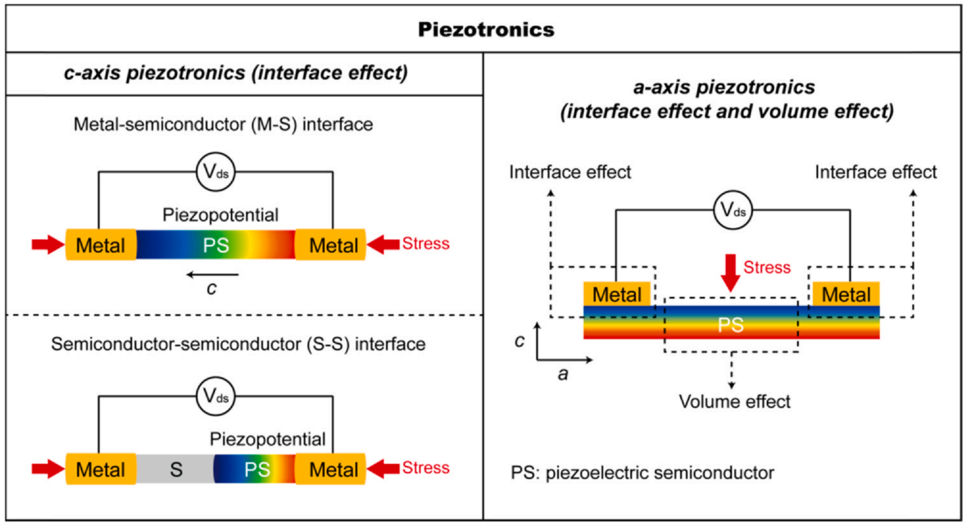

Fig. 14. Categories of piezotronics.

4. Comparison between traditional field effect transistor and piezotronic transistor

The piezotronic transistor is a fundamental device in piezotronics, which is completely different from, but still relates to the conventional metal-oxide-semiconductor-field-effect transistor (MOSFET). By comparing the piezotronic transistor with MOSFET, the differences between piezotronic transistor and MOSFET can be summarized as follows (Fig. 15). First, the conventional MOSFET or FET is a kind of three-terminal device controlled by the external voltage gating on the channel; whereas the piezotronic transistor is a new type of two-terminal device, which uses stress/strain induced inner-crystal piezopotential to asymmetrically modulate local Schottky barrier at both M-S terminals, or to gate on the channel width. The ON/OFF ratio of a piezotronic transistor can be rather high since the current transport across the M-S interface is the exponential of the reverse biased local barrier height. Second, the MOSFET/FET is mainly based on the first and second generation semiconductors such as Si, Ge, and GaAs; whereas the piezotronic transistor can be realized in almost any piezoelectric semiconductors, especially in the third-generation semiconductors such as ZnO and GaN. Recently it has also been extended to 2D TMDCs such as MoS_2 and WS_2. Third, the operation speed of MOSFET or FET can be as fast as GHz, which is mainly used in electronics, logic circuits, computation, photonics *etc*; whereas the driving force of piezotronic transistor is mechanical stimuli of biological moment and environment, and hence the running speed of the device is relatively slow

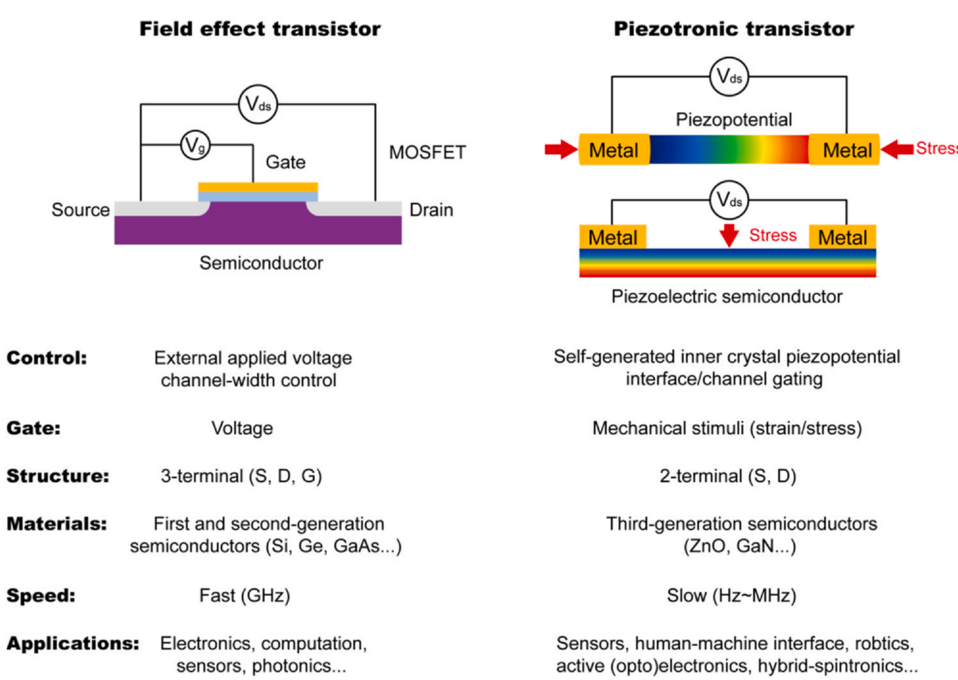

Fig. 15. Comparison between traditional field-effect-transistor and piezotronic transistor. Reprinted with permission from [68]. Copyright 2013 American Chemical Society.

(Hz~MHz), which has important applications in active electronics, sensors, human-machine interface, robotics *etc*. On the other hand, combining the physical mechanism of piezotronics with other intriguing processes can stimulate some new researches such as piezo-phototronics [69–71], flexotronics [72], hybrid-spintronics *etc* [73,74]. Based on the above analysis, piezotronic transistor is a new type of transistor designed using interface piezoelectric polarization engineering, which is likely to have complementary applications to conversional CMOS technology.

5. Expansion of piezotronic effect (piezotronics) to flexotronic effect (flexotronics)

5.1. Flexotronic effect and flexotronics in centrosymmetric semiconductors

Piezotronics has attracted much attention as promising approaches for energy harvesting, active electronics and intelligent sensing. However, it is only effective in semiconductors with special non-centrosymmetric crystal structures, such as wurtzite structured ZnO and GaN, which greatly limits their applications in centrosymmetric-structured semiconductors, such as Si and GaAs based the first- and second-generation semiconductors. Thus, we wondered whether there was a way that could expand the piezotronic effect into centrosymmetric semiconductors. As we know, flexoelectricity is an electromechanical property that enables mechanical manipulation of polarization by coupling between the local electrical polarization and the strain-gradient in dielectrics. The strain-gradient can break any materials' inversion symmetry owing to distorted crystal structure by strain, resulting in a polarization with a preferred direction and enabling a piezoelectric-like response but containing no piezoelectric elements [75–81]. Previous studies on flexoelectricity are mainly focus on the nanoscale dielectric insulators to produce large strain-gradient and relatively strong flexoelectric polarization for applications in actuators [82], transducers [83] and ferroelectric polarization control [84]. However, it has not yet been explored in centrosymmetric semiconductors.

Coupling the flexoelectricity and electronic transport property in centrosymmetric semiconductors, a novel electronic regulation mechanism of *flexotronics* was observed, which uses inner-crystal flexoelectric polarization potential produced by asymmetry-strain-induced asymmetric lattice change in semiconductors to modulate local Schottky barrier height of the M-S and achieve tunable electronics [72]. It has no restriction to the crystal structures, doping type and dimensions, and can be realized in any types of semiconductors, largely expanding flexoelectricity into the most popular Si, Ge and GaAs based first and second-generation semiconductors used in today's industry (Fig. 16b and c). The schematic diagram illustrates the concept and mechanism of *flexotronics* (Fig. 16a). Owing to the flexoelectric effect, the flexoelectric polarization field can be induced in a semiconductor upon an inhomogeneous strain/stress. Due to the large local inhomogeneous strain, the polarization field not only exists on the surface of the crystal, but also distributes inside the crystal within a certain length/volume, which has an enormous influence on the concentration and distribution of free carriers at the interface region and inner crystal (Fig. 16a(i)), correspondingly resulting in the interfacing band-structure engineering and the inner-crystal band-structure engineering (Fig. 16a(ii)). In general, the negative flexoelectric polarization charges generated at semiconductor region can repel electrons to the M-S interface, while attracting holes near the interface, resulting in upward bending of the energy band. Hence, the strain-gradient-induced flexoelectric polarization field can effectively modulate the height and width of M-S Schottky barrier, thereby controlling the transport of charge carriers, which is analogous to the piezotronic effect [16,17,21–28]. The magnitude and polarity of the flexoelectric polarization field within a semiconductor depend on the magnitude and polarity of the local inhomogeneous stress/strain. Here we call it flexotronic effect, which is widely exists in almost any semiconductors. Using inner-crystal flexoelectric polarization (hence the flexoelectric potential) as the gate to modulate the M-S Schottky barrier and achieve tunable electronics is the flexotronics. The operation principle is fundamentally new, which uses mechanical actuation directly generated digital signals to control all semiconductor-based electronics.

Giant flexotronic effect has been demonstrated in bulk centrosymmetric semiconductors of Si, TiO_2 and Nb-$SrTiO_3$, which exhibits a high strain sensitivity with a gauge factor > 2650 [72]. Specifically, it can be used to mechanically switch the electronics in the nanoscale volume of semiconductors with a fast response of ~4 ms and high resolution of ~0.78 nm by using dynamic flexoelectric polarization field (Fig. 17). This research expands the piezotronics into the Si, Ge and GaAs based first and second-generation semiconductors, and gives a brand new strain-modulated electronics in centrosymmetric semiconductor, which fundamentally paves the way for polarization-controlled semiconductor-based electronics.

5.2. Relationship between piezotronic effect and flexotronic effect

The flexotronic effect is closely related to, but is different from the piezotronic effect [72]. The differences and relationship between the two effects can be summarized as follows. First, both of the effects are normally interface gating effect, which both uses the polarization charges (and hence the polarization potential) to asymmetrically modulates interface barriers of M-S at source and drain (Fig. 18). Second, the piezotronic effect generally only exists in piezoelectric semiconductors, such as wurtzite structured ZnO and GaN based third-generation semiconductors, regardless of whether there is a strain-gradient. Nevertheless, the flexotronic effect is universal in any type semiconductors (including the first and second-generation semiconductors) regardless their crystal structures, the driving force of which is inhomogeneous stress or strain. Third, the magnitude of piezoelectric polarization in piezoelectric materials is normally stronger than the flexoelectric polarization in centrosymmetric materials so that the magnitude of tuning by piezotronic effect could be much more effective than that of flexotronic effect. Fourth, the strain/stress-induced piezoelectric polarization charges only exist at polar surfaces of the piezoelectric materials within one to two atomic layer thickness, whereas the inhomogeneous stress/strain induced flexoelectric polarization distributes in the semiconductor within a certain length or volume (several nanometers to tens of nanometers), and hence its modulating effect is not limited at the interface but over length. Thus, the flexotronic effect seems to be an "integration" of many piezotronic segments, which is similar to the integration and differentiation in calculus. Compared with the interface gating of piezotronics (including c-axis piezotronic device and a-axis piezotronic device), the flexotronic effect in the tip/surface model can be considered as a length/volume effect, whereas it is still an interface effect relative to the scale of bulk centrosymmetric semiconductor. So in essence, the flexotronic effect is not absolute volume effect, which is completely different from the volume effect of channel-width gating in a-axis piezotronic device. Finally, it should be emphasized that those materials with a piezotronic effect also can display a flexotronic effect.

6. Summary and outlook

Piezotronic transistor is new type of two-terminal device, the basic principle of which is to use inner-crystal piezoelectric polarization charges (hence the piezoelectric potential) in semiconductor

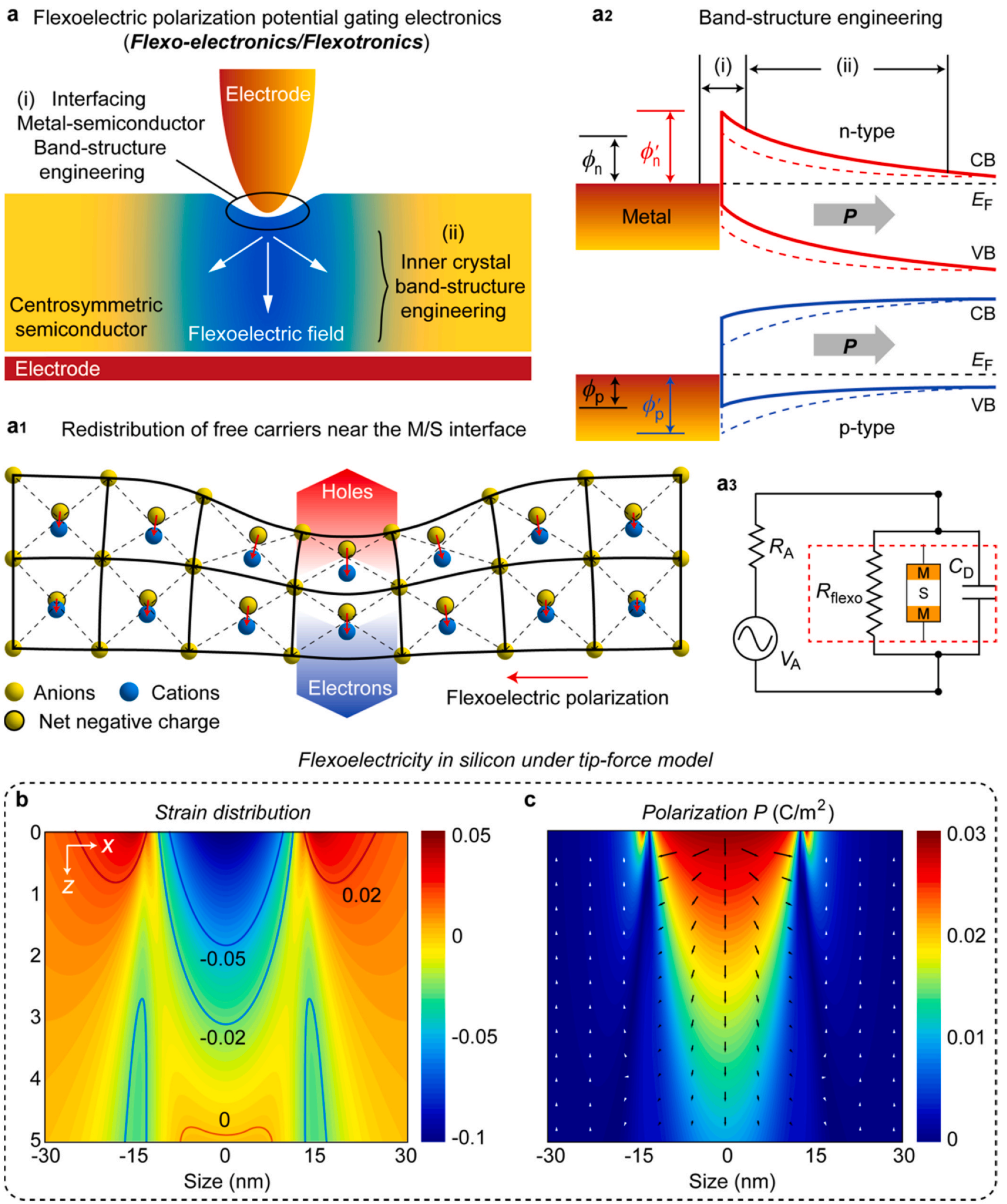

Fig. 16. Flexotronics in centrosymmetric semiconductors. a, Schematics showing the concept and mechanism of flexotronics: M-S interface band-structure engineering and inner crystal band-structure engineering by flexoelectric polarization. Flexoelectricity in silicon under a tip-force model: theoretical simulated strain distribution (b) and the corresponding flexoelectric polarization distribution (c). Arrows in (c) represent the magnitude and polarity of the polarization.
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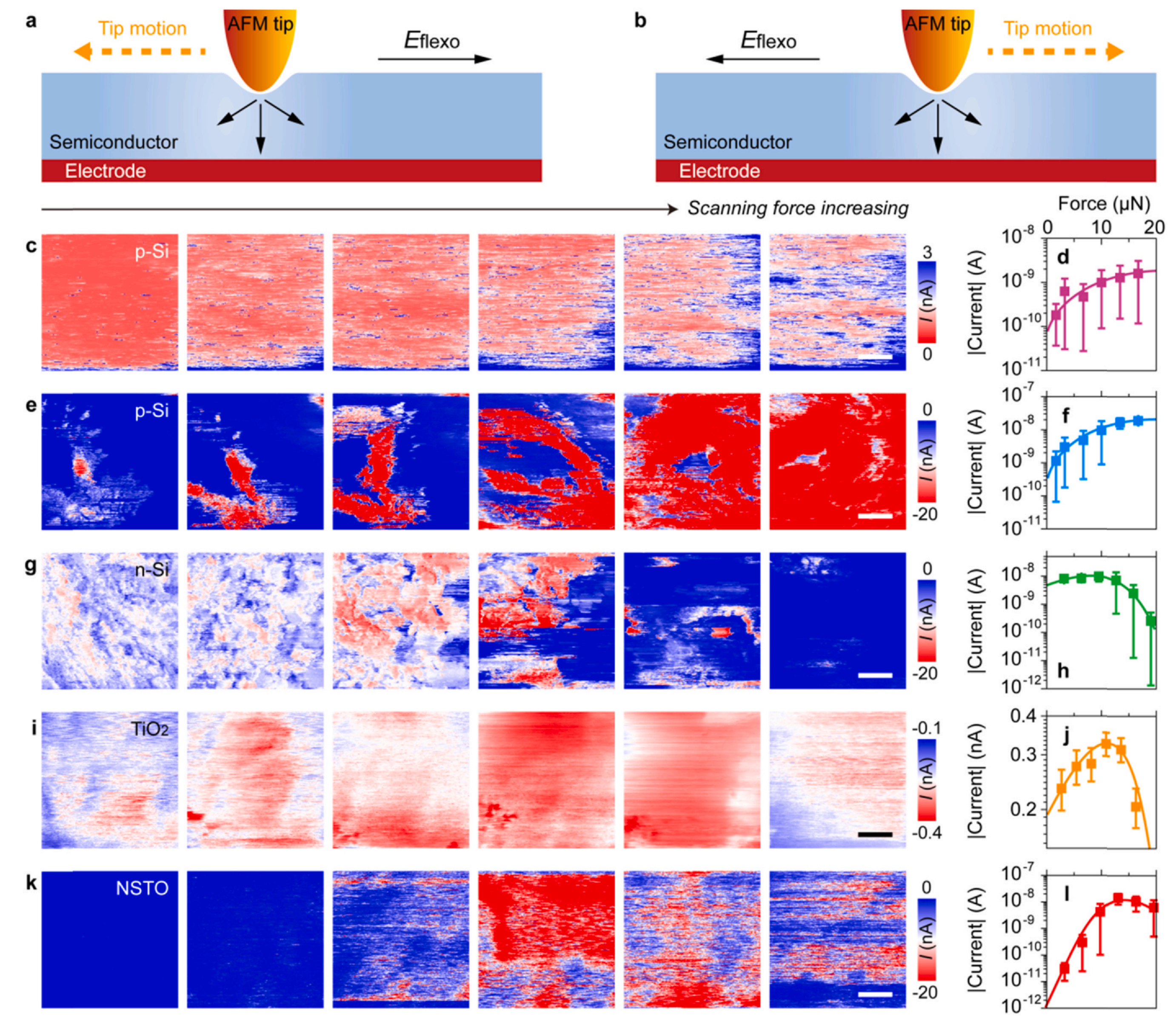

Fig. 17. Dynamic flexotronics in nanometer scale. a, b, Schematics illustrating the mechanical 2D scanning processes. c, e, g, i, k, Current mappings in centrosymmetric semiconductors of Si, TiO_2 and Nb-$SrTiO_3$ (NSTO) under increased loading forces. The scale bars represent 50 nm. d, f, h, j, i, The corresponding absolute average current variations versus loading forces calculated from statistical distributions of the current mappings (c, e, g, i, k). Error bars indicate the standard deviations.
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region as a gate voltage to control the electronic transport, which has been widely demonstrated for wurtzite-structured semiconductors, especially the third-generation semiconductors. Such devices are innovatively using inner interface gating or inner channel-width gating instead of the traditional external channel-width gating. The role played by a piezotronic transistor in human-machine interface technology is similar to the mechanical sensation in physiology, which is the mechanism of response to mechanical stimulation. Converting mechanical stimuli into neuronal signals is the physiological basis for the senses of tactile, hearing or balance. The fundamentals of piezotronic transistors and their applications in adaptive tactile sensing, ultrasensitive sensing, atomic thin electronics *etc.* have been systematically reviewed in this paper. In addition to this, significant progress has been made using piezotronic transistors in other applications such as memory devices [85], logic circuits [86], neural signal simulations [87], topological application [88] *etc.*

Piezotronics is an emerging field by coupling of piezoelectricity and charge carriers transport in piezoelectric semiconductors. Piezotronic effect and piezotronics widely exist in the third-generation semiconductors (ZnO, GaN, *etc.*) and two-dimensional transition metal dichalcogenides (MoS_2, WS_2, *etc.*), which is an inherent effect in these materials. In this review, new understandings of piezotronics have been proposed: first, piezotronic effect is still effective in ultra-short channel length (~2 nm) based atomic thin nanodevice; second, 2D piezotronics in both inner interface gating and inner channel-width gating in 2D materials with out-of-plane piezoelectricity has been proposed; third, piezotronic effect (piezotronics) has been expanded to flexotronic effect (flexotronics), largely expanding the piezotronics into the centrosymmetric

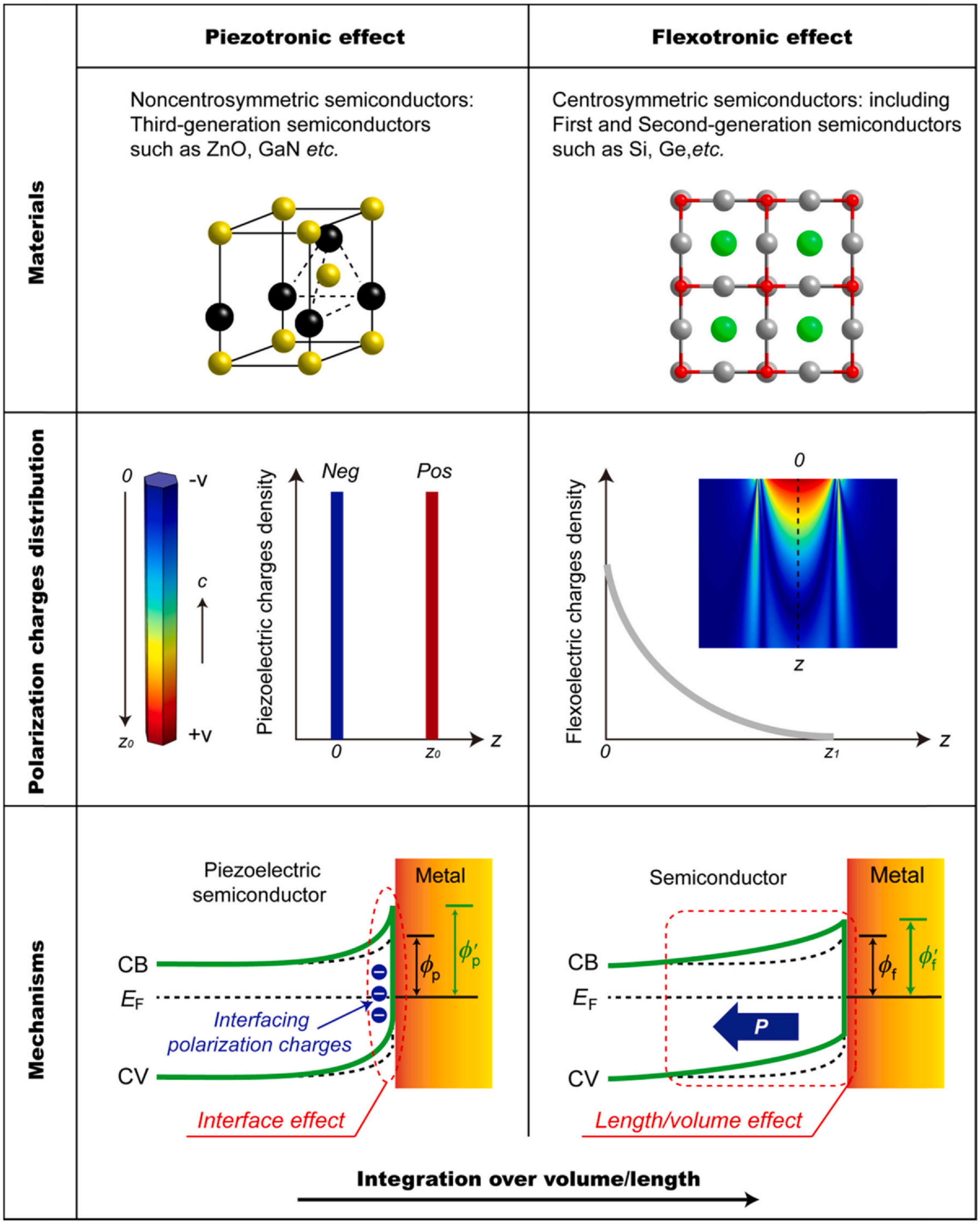

Fig. 18. Relationship between piezotronic effect and flexotronic effect. Expand the piezotronic effect to the flexotronic effect, which introduces the piezotronic effect into centrosymmetric semiconductors including Si, GaAs based first and second-generation semiconductors. Copyright 2020 Nature Publishing Group.
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semiconductors, especially the Si, Ge and GaAs based first and second-generation semiconductors.

During last 13 years, piezotronics have made great applications in energy harvesting (enhanced solar technology [89–95], catalysis [96–101]), electronics (self-powered nanodevice [43] active electronics [60,63,109]) and intelligent sensing (adaptive tactile sensing [46], LED [102–108], human-machine interface), and are likely to have important applications in MEMS, nanorobotics, artificial intelligence (Fig. 19). Coupling between the piezotronics and other intriguing processes can also stimulate some new researches such as hybrid-spintronics and flexotronics. Nevertheless, to further develop the field of piezotronics, in-depth understanding of physics, quantum mechanical calculations, and advanced technological implementations are needed.

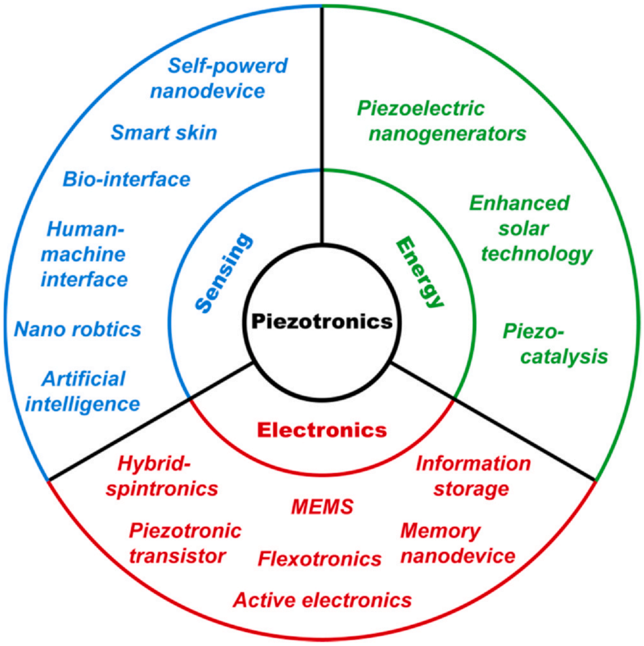

Fig. 19. Applications of piezotronic transistors and piezotronics.

CRediT authorship contribution statement

Longfei Wang: Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Zhong Lin Wang:** Conceptualization, Supervision, Writing-review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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