

Entangled bulk-interface piezotronic effect in polar heterojunction

Gongwei Hu¹✉, Yihan Zhang¹, Lihao Jiang¹, Yanshan Xiao¹✉, Junjun Hu^{2,3}, Lijie Li⁴✉, and Fobao Huang^{2,3}✉

¹Hubei Engineering Research Center of Weak Magnetic-field Detection, College of Mathematics and Physics, China Three Gorges University, Yichang 443002, China

²State Key Laboratory of Flexible Electronics (LoFE) & School of Integrated Circuits (School of Microelectronics), Northwestern Polytechnical University, Xi'an 710072, China

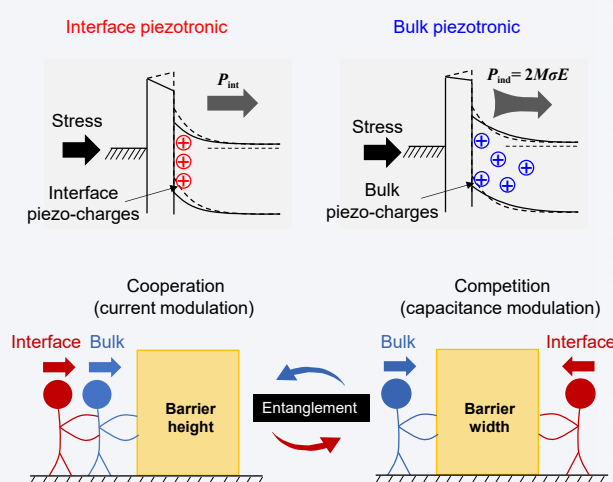
³Shenzhen Research Institute of Northwestern Polytechnical University, Shenzhen 518057, China

⁴Faculty of Science and Engineering, Swansea University, Swansea, SA1 8EN, UK

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ABSTRACT: Piezotronics is new-branch interface engineering for efficient electromechanical coupling of semiconductor heterojunctions, with broad applications in tactile sensing, human-machine communications and tunable electronics. The piezotronic modulation is usually dominated by intrinsic inversion-asymmetry piezoelectric polarization, while the piezoelectric polarization induced by ubiquitous and field-induced structural asymmetry remains largely overlooked. Motivated by the symmetry-governed spin-orbit physics, we here reveal an entangled interface-bulk piezotronic effect in polar metal-insulator-piezoelectric semiconductor tunneling heterojunctions. The interface and electric-field-induced bulk piezotronic effects coexist and jointly modulate quantum tunneling transport and capacitance property. Depending on the polar direction of heterojunction, two piezotronic effects regulate the tunneling current either cooperatively or competitively through barrier-height modulation. External pressure and bias voltage can optimize the cooperation and competition. In addition, device capacitance shows the opposite cooperation-competition relationship because it is governed by barrier-width modulation. Therefore, cooperative current modulation is accompanied by competitive capacitance modulation, and vice versa, indicating their entangled relationship. This work establishes capacitance as an effective probe of hidden bulk piezotronic effects and provides a framework for designing interface-engineered tunneling sensors and mechanically tunable semiconductor devices.

KEYWORDS: bulk and interface piezotronics, induced piezoelectricity, entangled cooperation-competition mechanism, current and capacitance modulation



1 Introduction

Electronic sensors that enable highly mechanical-to-electrical transduction have become increasingly demand in many new-emerging applications in wearable electronics, human-machine interfaces, robotic technologies, microelectromechanical systems,

and biomedical monitoring [1–6]. In semiconductor devices, one powerful strategy to achieve such transduction is to translate mechanical stimuli into changes in interfacial electron transport. Piezotronics offers a particularly sensitive mechanism for this purpose by coupling piezoelectric polarization with semiconductor carrier transport [7–11]. In a typical piezotronic device, strain-induced piezoelectric charges and the associated piezopotential serve as an internal gate that reshapes band bending, interface barrier and carrier injection. Because thermally activated carrier injection follows a Boltzmann dependence on the barrier height, a small mechanical stimulus can be amplified into a large change in current [12–14]. Such amplification mechanism renders piezotronic sensors a sensitivity advantage over many piezoresistive [15], capacitive [16] and piezoelectric sensing [17, 18], and makes it

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✉Address correspondence to Gongwei Hu, gwhu@ctgu.edu.cn; Yanshan Xiao, yanshanxiao@foxmail.com; Lijie Li, L.Li@swansea.ac.uk; Fobao Huang, fbhuang@nwpu.edu.cn

promise for the applications in tactile imaging [19], human-machine interfaces, optoelectronics and micro/nano-electromechanical systems.

So far, most piezotronic sensors are demonstrated in materials with the crystal inversion asymmetry (Fig. 1(a)(i)) such as ZnO, GaN, and MoS₂. Such materials have intrinsic piezoelectricity with interface-dominated polarization governed in piezotronics devices [8–11, 13, 14, 20–23]. Concretely, under an external strain, the discontinuity of piezoelectric polarization at a semiconductor junction generates interface polarization charges that dominates the modulation in the local barrier and hence the carrier injection (Fig. 1(a)(ii)). Such interface-dominated piezotronics has been implemented in a wide range of semiconductor structures,

including p-n junctions [24], Schottky junctions [14, 22, 23], tunneling junctions [8, 10, 11, 13, 21], and field-effect transistors [25]. These junctions are not defined by interface polarization alone. Built-in electric fields and band bending, as commonly found in depletion regions of p-n and Schottky junctions, also create structural inversion asymmetry at interfaces. Recently, such structural asymmetry has reported to drive the piezoelectricity even though the pristine materials are centrosymmetric [26, 27]. The stimuli such as electric field and crystal orientation can tune the structural asymmetry and thus the piezoelectric coefficients [12, 28]. Different from intrinsic piezoelectricity fixed by the pristine crystallographic symmetry, such induced piezoelectricity by structural asymmetry emerges from electric-field-coupled

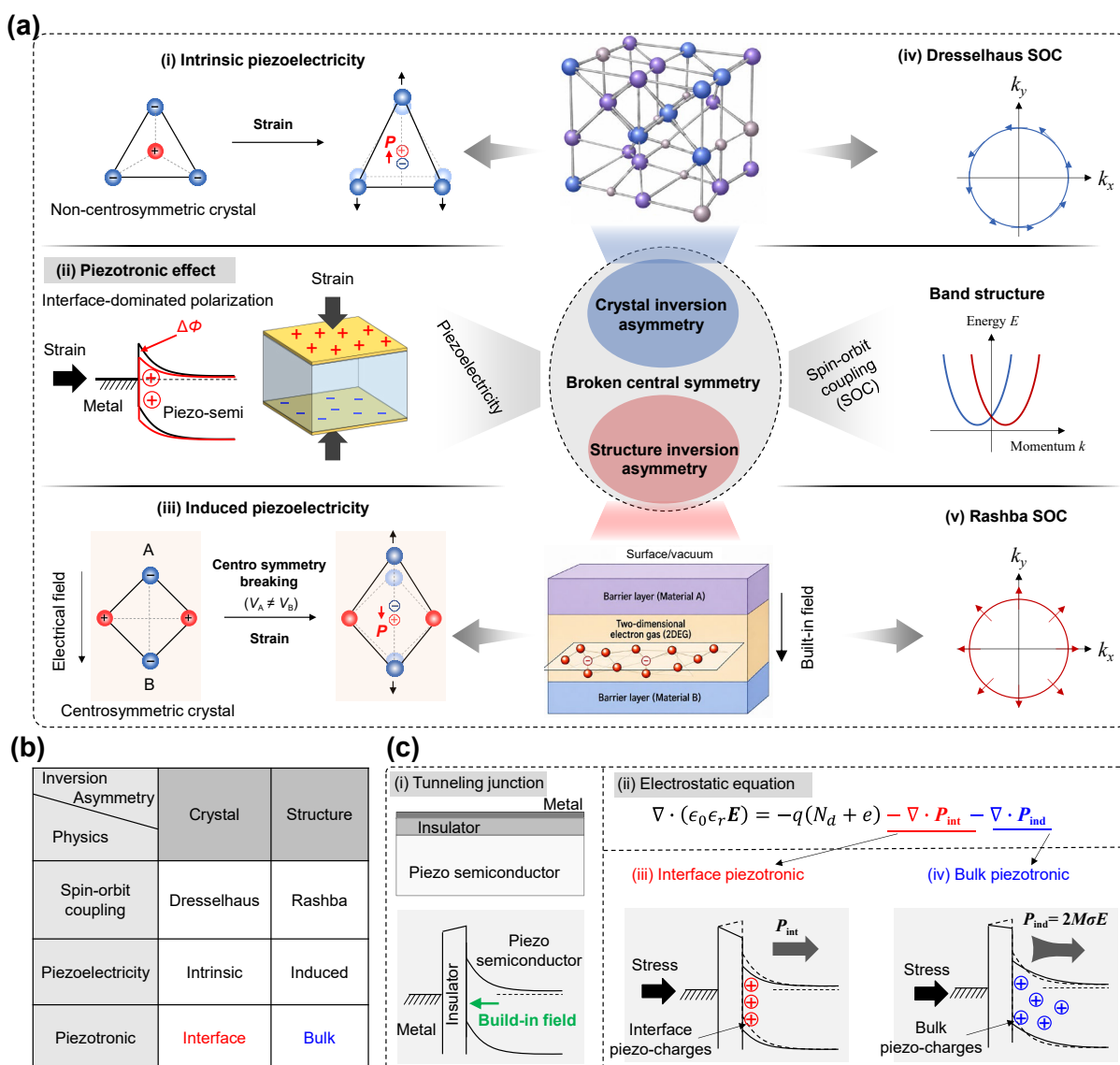


Figure 1 Symmetrical engineering and the mechanism of bulk and interface piezotronic effects. (a) The piezoelectricity and SOC induced by crystal and structure inversion asymmetry. The broken central symmetry involves crystal and structure inversion asymmetry, which drives intrinsic (a)(i) and electrical-field-induced piezoelectricity (a)(iii). In a centrosymmetric material, an electrical field breaks potential symmetry of atom A and B (i.e., $V_A \neq V_B$), leading to an induced piezoelectricity. Both piezoelectricity can trigger piezotronic effect to adjust Schottky barrier height (a)(ii). In parallel, two inversion asymmetries cause the spin band structure with the Dresselhaus (a)(iv) and Rashba SOC (a)(v). (b) A table to summarize the inversion-asymmetrical engineering of SOC, piezoelectricity and piezotronic effect. (c) Bulk and interface piezotronic effect in a polar tunneling junction. The MIPS tunneling device (c)(i) has a band diagram with a built-in electric field. The electrostatic Poisson equation involves two contribution of piezoelectric polarization (c)(ii), which causes interface (interface piezo-charges, (c)(iii)) and bulk (bulk piezo-charges due to uneven built-in electric field, (c)(iv)) piezotronic effect.

electrostriction (Fig. 1(a)(iii)), and is therefore an engineerable property of the junction. Induced piezoelectric effect, that is not restricted by the inherent material symmetry, makes it possible to achieve all-material piezotronic applications [7]. However, the impact of such ubiquitous electric-induced piezoelectric effect has long been ignored in a piezotronic devices. The question of whether transport modulation differs from conventional interface-dominated piezotronics and how to identify it in a piezoelectric heterojunction remains further uncovered. Actually, a close analogy found in spin-orbit physics implies the significance, where bulk inversion asymmetry produces Dresselhaus coupling (Fig. 1(a)(iv)) [29], whereas structural inversion asymmetry yields tunable Rashba coupling (Fig. 1(a)(v)) [30]. The latter has been proven to be more attractive for interfacial spin phenomena as well as applications in spin field-effect transistors [31, 32].

Inspired by the symmetry analogy of spin-orbit physics (see Fig. 1(b)), we study the coupled interface-bulk piezotronic effect in polar metal-insulator-piezoelectric semiconductor tunneling heterojunctions. We incorporate both intrinsic interface piezo-charges and electric-field-induced bulk piezo-charges into the electrostatic transport framework. This model shows that the two piezotronic effects coexist and jointly modulate quantum tunneling. Their relationship is controlled by the polarity of heterojunctions. When the two types of piezo-charges lower the tunneling barrier together, the current modulation is cooperative. When they modulate the barrier height in opposite directions, the current modulation becomes competitive. We further show that capacitance follows the opposite rule. This is because current is mainly governed by barrier-height modulation, whereas capacitance is dominated by barrier-width modulation. As a result, cooperative current modulation is accompanied by competitive capacitance modulation, and vice versa, showing an entangled piezotronic mechanism. These findings identify capacitance as an effective probe of hidden field-induced bulk piezotronics and provide design principles for interface-engineered tunneling sensors and mechanically tunable semiconductor electronics.

2 Methods and theory

In this section, we establish the theoretical framework for carrier transport and piezotronic modulation in a polar tunneling junctions with a metal-insulator-piezoelectric semiconductor architecture. In such devices, the tunneling current is governed not only by quantum transmission across the ultrathin insulating barrier, but also by the electrostatic potential, carrier distribution and piezoelectric polarization in the semiconductor. Therefore, a self-consistent model is required to couple semiconductor carrier transport with strain-induced piezoelectric polarization and quantum tunneling through the insulating layer.

In the semiconductor region, carrier transport is described by the drift-diffusion equations, in which the electron and hole current densities consist of electric-field-driven drift currents and concentration-gradient-driven diffusion currents [33], expressed as

$$J_n = q\mu_n nE + qD_n \nabla n, J_p = q\mu_p pE - qD_p \nabla p \quad (1)$$

where J_n and J_p denote the electron and hole current densities, respectively. q is the elementary charge. n and p are the carrier concentrations, and E is the electric field. μ_n and μ_p are the carrier mobilities, and D_n and D_p are the diffusion coefficients satisfying the Einstein relation $D_{n,p} = \mu_{n,p} k_B T / q$. The two terms in Eq. (1) represent

drift and diffusion transport, respectively. The carrier concentrations further satisfy the continuity equations

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot J_n + G_n - R_n, \frac{\partial p}{\partial t} = \frac{1}{q} \nabla \cdot J_p + G_p - R_p \quad (2)$$

where G and R denote the carrier generation and recombination rates, respectively. The carrier transport equations are coupled to the electrostatic field through the Poisson equation, where free carriers, ionized dopants and piezoelectric polarization collectively determine the potential distribution

$$\nabla(\epsilon_0 \epsilon_r E + P_{\text{piezo}}) = q(p - n + N_D^+ - N_A^-) \quad (3)$$

where ϵ_0 is the vacuum permittivity, ϵ_r is the relative permittivity of the semiconductor, and N_D^+ and N_A^- are the ionized donor and acceptor concentrations, respectively. P_{piezo} denotes the piezoelectric polarization induced by mechanical strain. From the electrostatic equation, piezoelectric polarization provides the key coupling to reshape the electric field, interfacial barrier and carrier transport.

Piezoelectricity can originate from crystal or structural inversion asymmetry [34]. In conventional piezoelectric semiconductors, such as wurtzite ZnO and GaN, the lack of inversion symmetry gives rise to an intrinsic piezoelectric response. Under an axial stress, the intrinsic piezoelectric polarization can be written as

$$P_{\text{int}} = d_{\text{int}} \cdot \sigma \quad (4)$$

Here d_{int} is the piezoelectric constant, σ is external stress. Intrinsic piezoelectricity is restricted to crystal with the inversion asymmetry. However, a material with the center symmetry can host an effective piezoelectric response when inversion symmetry is broken in structure, such as, by an electric field. This induced piezoelectricity originates from electrostriction [26–28, 34], a universal electromechanical coupling in which strain scales quadratically with electric field

$$\epsilon = \Delta x / x = ME^2 \quad (5)$$

where ϵ is the electric-field-induced strain, E is the electric field, and M is the electrostrictive coefficient. To illustrate how a linear piezoelectric response emerges from this quadratic electrostrictive effect, we consider a centrosymmetric material subjected to an electric field composed of an external perturbation E_{ext} and a built-in field E_{bi} , namely $E = E_{\text{ext}} + E_{\text{bi}}$. The resulting strain is then

$$\epsilon = \Delta x / x = ME_{\text{ext}}^2 + ME_{\text{bi}}^2 + (2ME_{\text{bi}})E_{\text{ext}} \quad (6)$$

The first two terms in Eq. (6) are electrostrictive contributions associated with the external and built-in fields, respectively. By contrast, the cross term $2ME_{\text{bi}}E_{\text{ext}}$ is linear in the external field E_{ext} , which meets the definition of converse piezoelectric effect [34]. The piezoelectric coefficient is then $d_{\text{ind}} = 2ME_{\text{bi}}$ [26, 28], and induced by using a built-in field E_{bi} to break local inversion symmetry. Band bending and built-in electric fields are ubiquitous at semiconductor interfaces, including Schottky contacts, tunneling junctions, and p-n junctions. Therefore, the induced piezoelectricity is universal even when the semiconductor is not intrinsically piezoelectric. However, this universal contribution has been widely overlooked in piezotronic devices.

In non-centrosymmetric piezoelectric semiconductor interface, the total stress-induced polarization contains two contributions. The first is the intrinsic piezoelectric polarization, while the second

is the field-induced piezoelectric polarization. Therefore, under an external stress σ , the total piezoelectric polarization can be expressed as

$$P_{\text{piezo}} = P_{\text{int}} + P_{\text{ind}} = (d_{\text{int}} + d_{\text{ind}}) \sigma \quad (7)$$

where $P_{\text{ind}} = 2\sigma ME$ represents the electric-field-induced piezoelectric polarization. Substituting the total polarization into the Poisson equation gives

$$\nabla(\epsilon_0 \epsilon_r E + 2\sigma ME + d_{\text{int}} \sigma) = q(p - n + N_D^+ - N_A^-) \quad (8)$$

Equation (8) indicates both piezoelectric polarizations contributing to the electrostatic potential through their associated polarization. Under a uniform stress, the intrinsic polarization mainly introduces piezo-charges at material interface, whereas the field-induced counterpart yields bulk piezo-charges within junction region (or depletion region). The latter contribution can be incorporated into a modification of the effective dielectric constant ($\epsilon_r \rightarrow \epsilon_r + 2\sigma M/\epsilon_0$), due to the same electric-field dependence of electric displacement $\epsilon_0 \epsilon_r E$ and induced piezoelectric polarization $2\sigma ME$ (see Note S1 in the Electronic Supplementary Material (ESM)).

Solving Eqs. (1)–(8) requires a self-consistent numerical scheme because they are strongly coupled. Here, we solve them in the COMSOL multiphysics. Once the electric field and potential are attained, the tunneling current is evaluated using the Tsu–Esaki formalism [35]

$$J_T = \frac{qm^* k_B T}{2\pi^2 \hbar^3} \int_{E_{\text{min}}}^{E_{\text{max}}} T_t(E_T) \ln \left[\frac{1 + \exp((E_F - E_T)/k_B T)}{1 + \exp((E_F - E_T - qV)/k_B T)} \right] dE_T \quad (9)$$

where m^* is the carrier effective mass, $\hbar$ is the reduced Planck constant, E_F is the Fermi level in the semiconductor, and E_T denotes the transverse carrier energy. k_B is the Boltzmann constant, T is the temperature, E_C and E_V are the conduction-band minimum and valence-band maximum, respectively, and V is the applied drain-source bias. The term $T_t(E_T)$ represents the energy-dependent tunneling probability through the insulating barrier, which is attained by the Wentzel–Kramers–Brillouin approximation [13, 20]

$$T_t(E_T) = \exp \left(\frac{-2}{\hbar} \int \sqrt{2m^*(E_T - E_C)} dx \right) \quad (10)$$

3 Results and discussion

3.1 Interface and bulk piezotronic effect

In a metal-insulator-piezoelectric semiconductor (MIPS) tunneling junction, both bulk and interface piezotronic effects can coexist. As shown in Fig. 1(c)(i), the band diagram in MIPS structure has a built-in electric field that breaks the local inversion symmetry and could induce an additional piezoelectricity. Therefore, the stress-generated polarization includes contribution from intrinsic and induced piezoelectricity.

To describe their coupled influence, we incorporate both P_{int} and P_{ind} into the electrostatic Poisson equation of the MIPS junction, as illustrated in Fig. 1(c)(ii). This model allows us to distinguish the barrier modulation caused by different piezoelectricity or piezo-charges. From the electrostatic equation, these two polarizations affect band bending and tunneling transport in different forms.

According to the Poisson equation, polarization charges are determined by the divergence of the polarization vector. Hence, the spatial nonuniformity of the polarization field governs the distribution of polarization charges. Owing to the distinct spatial distributions of the interface and bulk piezotronic polarizations, polarization charges emerge at different locations within the device (see Note S2 and Fig. S2 in the ESM).

Under a uniform external stress, the intrinsic polarization appears to produce interface piezo-charges near the insulator-semiconductor surface (Fig. 1(c)(iii)), corresponding to the interface piezotronic effect for transport modulation. By contrast, the field-induced polarization is governed by the local built-in electric field. Because the electric field is spatially varied, the stress-generated piezo-charges do not populate at interface but within depletion region (Fig. 1(c)(iv)). Therefore, such piezoelectricity produces bulk piezo-charges, whose modulation in transport corresponds to the bulk piezotronic effect. Both piezotronic effects can reshape the barrier and tune the tunneling process, while they do so through different charge distributions and also transport modulation.

In contrast to interface piezo-charges localized at the semiconductor surface, the field-induced bulk piezo-charges are distributed throughout the depletion region because they originate from the spatially varying built-in electric field. Therefore, their direct modulation of the interfacial barrier height is weaker than that of interface piezo-charges. However, bulk piezo-charges, sensitive to bias voltage (see Note S3 in the ESM), can more effectively regulate the depletion-region width, making the bulk piezotronic effect more pronounced in capacitance modulation.

3.2 Cooperative interface-bulk piezotronic effect

In order to yield an induced piezoelectricity (bulk piezotronic) comparable to the intrinsic one (interface piezotronic), the material should have a prominent electrostrictive effect. Actually, most reported (intrinsic) piezoelectric materials have a very weak electrostriction, except for wurtzite GaN [36]. Although its high electrostriction coefficient has controversy [37], we stick to use it only as an example for illustration. The crystal of wurtzite GaN has a polar c -axis relative to the direction of polarization (see Fig. 2(a)). The material parameters used in the simulation of the MIPS tunnel junctions are listed in Table S1 in the ESM. Depending on the polar direction, the MIPS tunneling junction can be classified into two types, that is, the c -axis parallel and antiparallel to built-in electric field. These two configurations could cause different piezotronic modulation, as demonstrated above.

When the polar axis is parallel to built-in field, external stress induces interface and bulk piezo-charges with the same positive sign (Fig. 2(b), left). They could cause the barrier at insulator-semiconductor interface that is simultaneously reduced. Hence, two piezotronic effects would exhibit cooperative relationship in the enhancement of entire piezotronic performance (Fig. 2(b), right).

To reveal such cooperative relationship, we calculate the current–voltage (I – V) characteristics of polar tunneling junction under different piezotronic configurations (see Fig. 2(c)). By setting piezo-charges in the simulation, we can compare the impact of only interface and bulk piezotronic effects, as well as their combination. The result shows that in all three cases, the current increases rapidly at low bias but follows a slower increase at higher bias. Those two different piezotronic responses correspond to the insulator-semiconductor surface with the electrons that are depleted and accumulated. Due to weak (strong) shielding of piezo-charges by

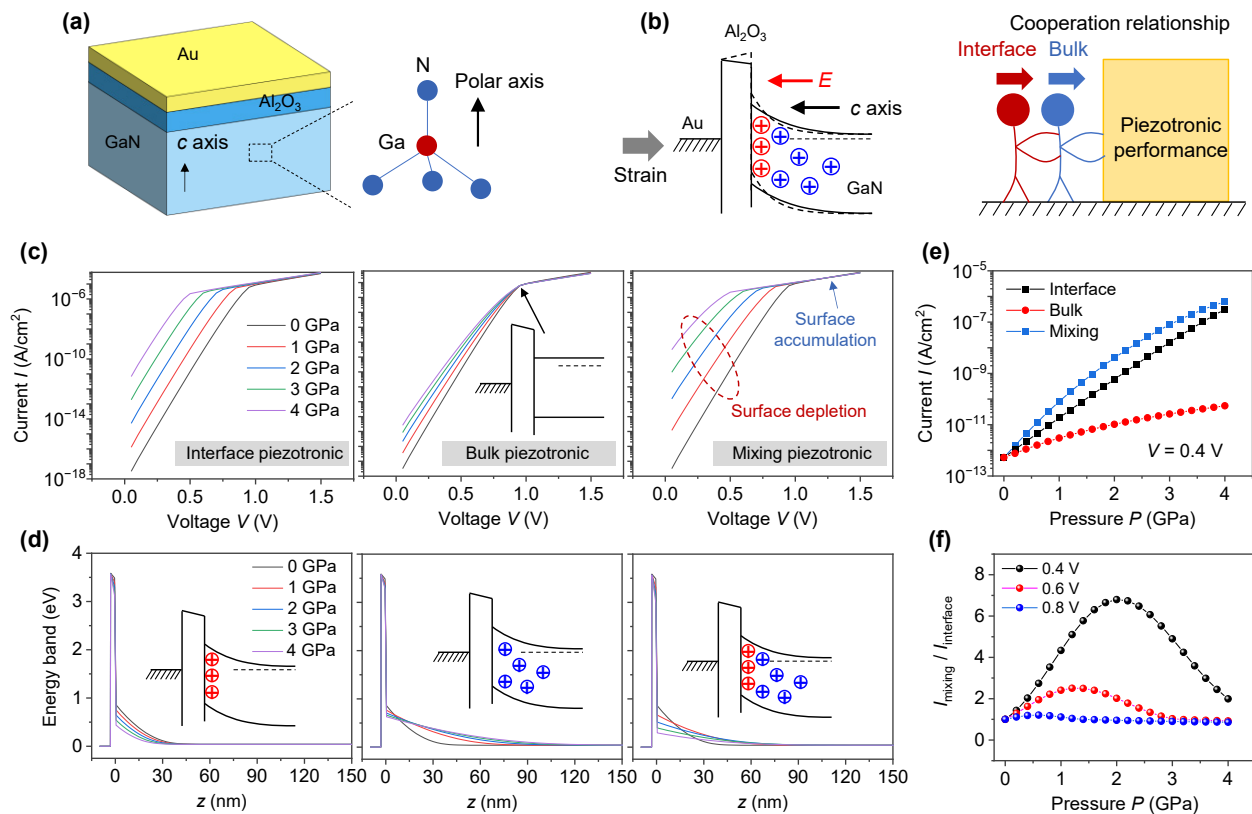


Figure 2 Cooperative mechanism of bulk and interface piezotronic effects in MIPS junction. (a) Schematic illustration of Au/Al₂O₃/n-GaN MIPS junction for GaN crystal with the polar c -axis parallel to built-in field. (b) Positive piezo-charges on the surface and in the bulk jointly modulate the energy band structure (left), exhibiting a cooperative relationship (right) to tune the piezotronic performance via interface and bulk piezotronic effects. (c) I - V characteristics modulated by individual interface piezotronic (left), bulk piezotronic (middle), and mixing piezotronic (right). It shows surface accumulation and depletion states. Insets: the critical point of zero surface electric field, where the semiconductor surface switches from depletion to accumulation. (d) Band diagrams modulated by interface piezotronic (left), bulk piezotronic (middle), and mixing piezotronic (right). Insets: the distribution of pressure-induced piezo-charges. (e) Pressure-dependent current characteristics at a fixed bias $V = 0.4$ V. (f) The ratio of $I_{\text{mixing}}/I_{\text{interface}}$ at bias of 0.4, 0.6, and 0.8 V.

free electrons, the current in depletion (accumulation) state shows sensitive (insensitive) pressure response [21]. In addition, the current in interface piezotronic effect (Fig. 2(c), left) responds more sensitively to pressure than the bulk piezotronic case (Fig. 2(c), middle). Especially at the bias voltage approaching the critical point (transition from depletion to accumulation with a flat band, see the inset in middle of Fig. 2(c)), the bulk piezotronic response gradually diminishes because the interfacial built-in field or bulk piezoelectricity tends to disappear.

In spite of a synchronously reduced barrier height, the barrier width (depletion region) is narrowed by interface piezo-charges but widened by bulk charges (Fig. 2(d), left and middle). This result indicates a distinct piezotronic modulation. As well known, interface positive piezo-charges attract electrons and narrow depletion region, as observed in most piezotronic devices [8–12, 14, 23, 25]. By contrast, bulk piezo-charges has a complex impact because it couples interface electrical field each other. Dielectric effect can be used to simplify the interpretation by converting the impact of bulk piezo-charges into the dielectric constant $\epsilon_r \rightarrow \epsilon_r + 2\sigma M/\epsilon_0$ (see discussion in Theory section). According to classical theory of semiconductor device [33], the depletion width increases with growing the dielectric constant.

It should be noted that the bulk piezo-charges are bound polarization charges rather than free carriers. Therefore, they do not change the doping-determined majority carrier concentration in the neutral semiconductor region. Instead, they redistribute local

carriers in the depletion region by modifying the electrostatic potential and band bending (see Fig. S4 in the ESM). For the positive bulk piezo-charges considered here, electrons are attracted toward the depletion region, resulting in downward band bending and a reduced interfacial barrier height. Meanwhile, the modified depletion width further affects tunneling transport across the barrier.

Figure 2(c) also shows distinct shifts of the critical point under the two piezotronic mechanisms. With increasing pressure, the critical point shifts for the interface piezotronic effect but remains nearly unchanged for the bulk piezotronic effect. This behavior can be understood from the field-induced nature of the bulk piezotronic effect. At the critical point, the interface electric field vanishes because the built-in field is compensated by the applied bias. As a result, the induced polarization ($P_{\text{ind}} = 2ME\sigma = 0$) becomes zero, and the bulk piezotronic modulation does not occur. In contrast, the intrinsic interface piezoelectric polarization is not directly determined by the interface electric field, allowing the critical point to shift under pressure. Since both piezotronic effects enhance the current in the depletion regime at low bias, their combined action further improves the overall piezotronic performance (Fig. 2(c), right). The corresponding band diagram also shows a more pronounced lowering of the tunneling barrier (Fig. 2(d), right).

To directly compare the piezotronic modulation, we plot the pressure-dependent current at a fixed bias of $V_{\text{ds}} = 0.4$ V (Fig. 2(e)).

The interface piezotronic current shows a stronger pressure-induced increase than the bulk piezotronic current, while the mixing current reaches the highest value. This result confirms the enhanced piezotronic response arising from cooperative modulation. However, unlike the monotonic increase of the interface piezotronic current, both the bulk and mixing currents gradually approach saturation with increasing pressure. To further quantify the cooperative enhancement, we extract the ratio of the mixing current to the interface piezotronic current at different biases (Fig. 2(f)). In all cases, the ratio first increases and then decreases with pressure, showing a clear peak. This non-monotonic behavior indicates that simply increasing pressure does not always improve device performance; instead, an optimal pressure exists for maximizing the cooperative effect. The ratio also depends strongly on bias. A higher bias leads to a smaller ratio, a lower peak and a lower optimal pressure. In this regime, the mixing current becomes nearly identical to the interface piezotronic current. For example, at $V_{ds} = 0.8$ V, the current ratio approaches unity, indicating that the contribution from the bulk piezotronic effect becomes negligible.

3.3 Competitive interface-bulk piezotronic effect

Although the cooperative mechanism strengthens piezotronic modulation, the coupled response of the tunneling junction is not limited to this case. We then reverse the polar c -axis of GaN, as illustrated in Fig. 3(a). In this configuration, the polar c -axis is antiparallel to the built-in electric field. Under pressure, the interface and bulk piezotronic effects generate piezo-charges with opposite signs (Fig. 3(b), left). These opposite charges induce contrary band modulations, leading to a competitive relationship in piezotronic performance (Fig. 3(b), right). The polarity of the two

piezotronic charges is controlled by different factors. Interface piezo-charges are determined by the polar c -axis of GaN and the stress direction. In contrast, field-induced bulk piezo-charges follow $P = 2M\sigma E$, and are therefore governed by the local electric field and stress direction.

To demonstrate this competitive mechanism, we compare the I - V characteristics of the three piezotronic configurations in Fig. 3(c). Owing to the reversed direction of the intrinsic piezoelectric polarization, the interface piezotronic current in the depletion regime decreases with increasing pressure (Fig. 3(c), left). This trend is opposite to that of the bulk piezotronic current (Fig. 3(c), middle). The opposite modulation can be understood from the corresponding band diagrams. Negative interface piezo-charges increase the interfacial barrier height (Fig. 3(d), left), whereas positive bulk piezo-charges slightly reduce the barrier height (Fig. 3(d), middle). Because the barrier-height increase induced by the interface piezotronic effect is stronger than the barrier lowering induced by the bulk piezotronic effect, the interface contribution dominates the coupled response. Consequently, when both types of piezo-charges coexist, the mixing current follows the interface-dominated trend and decreases with pressure due to the increased tunneling barrier height (Figs. 3(c) and 3(d), right).

We further simulate the pressure-dependent current response under the three piezotronic configurations at a fixed bias of $V_{ds} = 0.4$ V (Fig. 3(e)). With increasing pressure, the bulk piezotronic current increases, whereas the interface piezotronic current decreases. This opposite pressure dependence indicates a competitive modulation between the bulk and interface piezotronic effects. As a result, the mixing current decreases relatively slowly, because the interface piezotronic modulation is partially

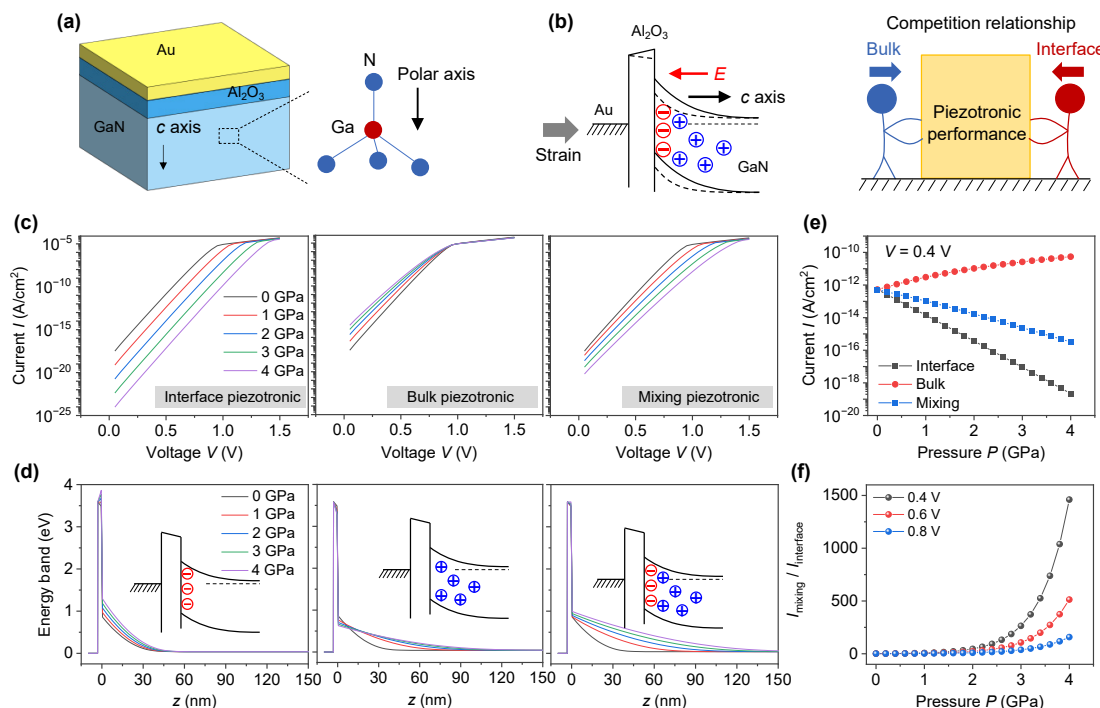


Figure 3 Competitive mechanism of bulk and interface piezotronic effects in MIPS junction. (a) Schematic illustration of Au/Al₂O₃/n-GaN MIPS junction for GaN crystal with the polar c -axis is antiparallel to built-in field. (b) Negative piezo-charges on the surface and positive piezo-charges in the bulk jointly modulate the energy band structure (left), exhibiting a competitive relationship (right) to tune the piezotronic performance via interface and bulk piezotronic effects. (c) I - V characteristics modulated by individual interface piezotronic (left), bulk piezotronic (middle), and mixing piezotronic (right). It shows surface accumulation and depletion states. (d) Band diagrams modulated by interface piezotronic (left), bulk piezotronic (middle), and mixing piezotronic (right). Insets: the distribution of pressure-induced piezo-charges. (e) Pressure-dependent current characteristics at a fixed bias $V = 0.4$ V. (f) The ratio of $I_{\text{mixing}}/I_{\text{interface}}$ at bias of 0.4, 0.6, and 0.8 V.

counteracted by the opposite bulk contribution. To quantify the competition, we extract the pressure-dependent ratio of the mixing current to the interface piezotronic current at different biases (Fig. 3(f)). The ratio increases monotonically with pressure and becomes larger at lower bias. These results suggest that the competition of two piezotronic effects is intensified by either generating more oppositely signed bulk and interface piezo-charges under high pressure or strengthening the interface depletion state under low bias.

3.4 Competitive capacitance modulation under cooperative current modulation

The current modulation discussed above confirms the coexistence of interface and bulk piezotronic effects in the MIPS junction. Since the intrinsic-polarization-driven interface piezotronic effect produces a stronger barrier-height modulation, the mixing current largely follows the trend of the interface piezotronic current. As a result, current measurements alone can hardly distinguish the contribution from the field-induced bulk piezotronic effect.

Actually, the band diagrams in Figs. 2(d) and 3(d) suggest a different probe. The barrier height is dominated by the interface piezotronic effect, whereas the barrier width is more sensitive to the bulk piezotronic effect. Since the semiconductor capacitance directly reflects depletion-width modulation, it can be used to detect the otherwise hidden bulk piezotronic effect. We therefore turn to capacitance modulation that shows an opposite cooperative-competitive relationship to current modulation.

When the polar c -axis of the piezoelectric semiconductor is parallel to the built-in electric field, external pressure induces positive interface and bulk piezo-charges that jointly modulate the band structure (Fig. 4(a)). Both contributions lower the interfacial barrier height, thereby producing cooperative modulation of the tunneling current. However, they affect the barrier width in opposite ways. The interface piezotronic effect generates positive piezo-charges at the semiconductor interface, which attract electrons and narrow the depletion region. In contrast, the bulk piezotronic effect produces field-induced piezo-charges inside the depletion region, which effectively widen the barrier width. Therefore, although the two effects cooperate in barrier-height modulation, they compete in barrier-width modulation. This gives rise to an entangled modulation mechanism: cooperative current regulation through the barrier height, but competitive capacitance regulation through the barrier width (Fig. 4(b)).

To further clarify the effect of pressure-induced piezo-charges on the MIPS junction, we plot the surface potential (or interfacial barrier height) as a function of bias voltage (Fig. 4(c)). Here, both interface and bulk piezo-charges are considered. Consistent with the analysis above, the interface and bulk piezotronic effects cooperatively lower the barrier height under pressure. This pressure dependence is pronounced in the depletion regime at low bias, where the piezo-charges are weakly screened. In contrast, the barrier height becomes less sensitive to pressure in the accumulation regime at high bias, where free electrons strongly screen the piezotronic modulation. Meanwhile, the surface electric field is also modified by pressure (Fig. 4(d)). With increasing pressure, the surface electric field gradually decreases. As the bias voltage increases, the surface electric field first approaches zero and then increases rapidly with the opposite polarity. Around the critical bias of $V_{ds} \approx 1.0$ V, the built-in field is nearly compensated by the applied bias, marking the transition from surface depletion

to surface accumulation.

We then calculate the semiconductor capacitance that is $C_D = -dQ_s/d\Phi$ with total surface charges in semiconductor [33]. By setting piezo-charges in simulation, we can obtain the interface, bulk and mixing capacitances. Figure 4(e) shows all capacitances that increase with bias voltage and have a sharp variation near the critical bias of $V_{ds} \approx 1.0$ V. However, their pressure responses are different. With increasing pressure, the interface piezotronic capacitance increases because the positive interface piezo-charges narrow the depletion region. In contrast, the bulk piezotronic capacitance decreases because the field-induced bulk piezo-charges widen the depletion region. Therefore, when both effects coexist, the mixing capacitance exhibits a competitive pressure response (Fig. 4(e)(iii)). Specifically, the capacitance increases with pressure at low bias but decreases with pressure at high bias. This non-monotonic pressure-dependent behavior is distinct from the individual interface and bulk piezotronic cases. Compared with monotonic current modulation (Figs. 2(c) and 3(c)), such bias-dependent capacitance response provides an effective electrical signature for identifying the hidden bulk piezotronic contribution.

3.5 Cooperative capacitance modulation under competitive current modulation

The above results show that competitive capacitance modulation can emerge even when the current modulation is cooperative. We next examine the opposite polarity configuration, where the current modulation becomes competitive. When the polar c -axis of the piezoelectric semiconductor is antiparallel to the built-in electric field, external pressure reverses the sign of the interface piezo-charges, while the field-induced bulk piezo-charges remain positive (Fig. 5(a)). In this case, the two effects modulate the barrier height in opposite directions. The negative interface piezo-charges raise the interfacial barrier, whereas the positive bulk piezo-charges tend to lower it. This opposite barrier-height modulation leads to a competitive current response. However, both effects widen the depletion region. Thus, their effects on the barrier width are cooperative rather than competitive. This gives rise to the opposite entangled relationship: competitive current modulation through barrier height, but cooperative capacitance modulation through barrier width (Fig. 5(b)).

We further plot the surface potential and surface electric field as functions of bias voltage (Figs. 5(c) and 5(d)). They are obtained by simultaneously considering interface and bulk piezo-charges. The surface potential increases with pressure in the depletion regime, consistent with the interface-dominated increase in barrier height. However, because the bulk piezotronic effect partially compensates this barrier-height modulation, the pressure dependence of the mixing barrier height is weaker than that of the interface piezotronic effect alone. The surface electric field shows a similar bias-dependent transition to that in Fig. 4(d), where the built-in field is gradually compensated by the applied bias near the critical point. The calculated capacitance further confirms the cooperative barrier-width modulation (Fig. 5(e)). Unlike the non-monotonic mixing capacitance in the current-cooperative case (Fig. 4(e)(iii)), all three capacitance curves decrease with increasing pressure because both interface and bulk piezo-charges widen the depletion region. When the two effects coexist, the mixing capacitance exhibits a stronger pressure response (Fig. 5(e)(iii)), indicating cooperative capacitance modulation.

Experimentally, the hidden bulk piezotronic contribution can be

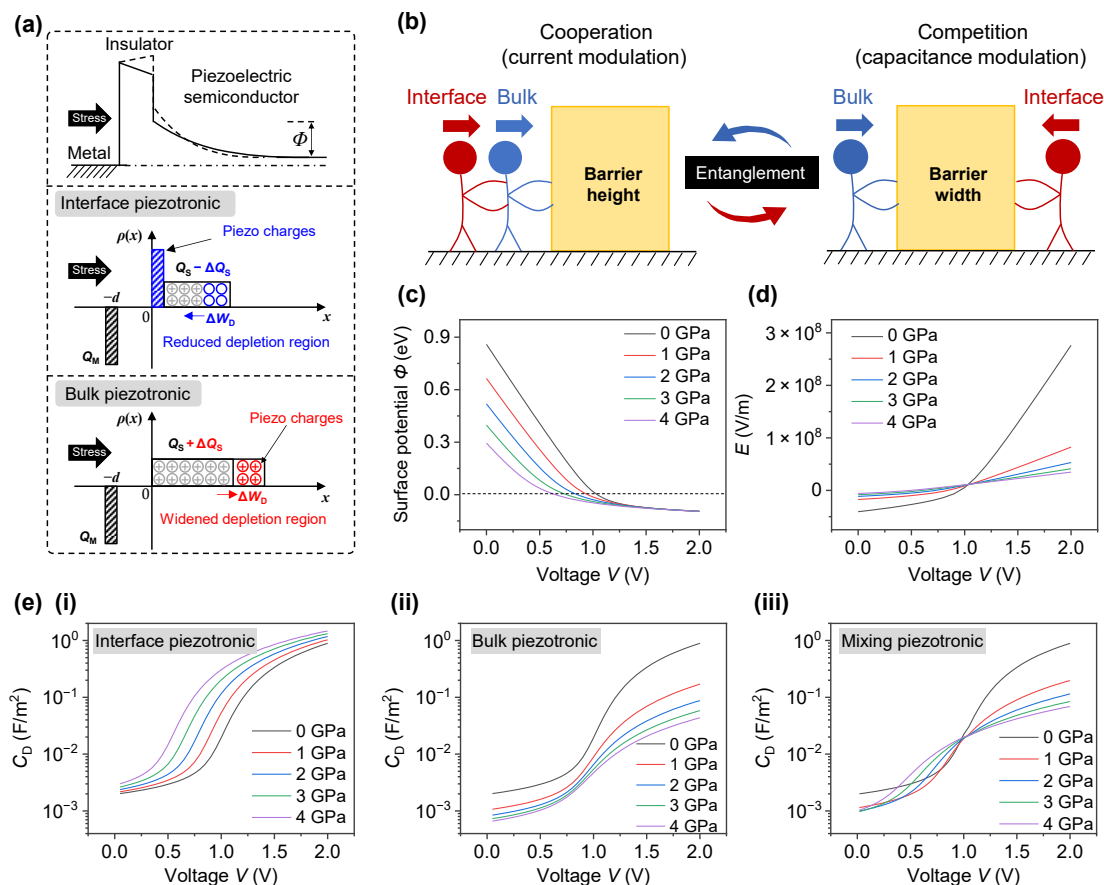


Figure 4 Competitive modulation of two piezotronic effects on semiconductor capacitance in MIPS junction. (a) Band diagram of the MIPS junction when the polarity c -axis of the bulk piezotronic effect is parallel to built-in field (top), along with charge distributions under interface piezotronic (middle) and bulk piezotronic (bottom). Here, Φ is the semiconductor interface barrier, d is the insulator width, Q_M and Q_S are the charges per unit area on the metal and semiconductor, respectively, and ΔW_D is the change in depletion layer width under applied pressure conditions. (b) Entanglement between cooperative modulation of barrier height and competitive modulation of barrier width by interface and bulk piezotronic effects, reflecting cooperative regulation of current and competitive regulation of capacitance. Surface barrier (c) and surface electric field (d) as functions of bias voltage under coupled two piezotronic effects. (e) Semiconductor capacitance C_D as a function of bias voltage under different pressures for interface piezotronic (i), bulk piezotronic (ii), and mixing piezotronic (iii).

verified by pressure-dependent capacitance–voltage (C – V) measurements. By recording C – V curves under different pressures and opposite GaN polarities, the bulk contribution can be identified from the bias- and polarity-dependent capacitance response. For the polarity configuration with cooperative current modulation, the mixed capacitance is expected to show a competitive pressure response. In contrast, for the configuration with competitive current modulation, the mixed capacitance should exhibit cooperative pressure modulation. Such pressure-dependent C – V characteristics provide a direct electrical signature for distinguishing the field-induced bulk piezotronic effect from the conventional interface piezotronic effect.

Note that the bulk piezotronic effect is not limited to GaN, but may generally exist in semiconductor heterojunctions. For non-centrosymmetric piezoelectric semiconductors such as ZnO and AlN, the intrinsic interface and field-induced bulk piezotronic effects coexist. However, their low electrostrictive coefficient makes it difficult to observe bulk piezotronics [38]. For centrosymmetric semiconductors such as Si and Ge, the intrinsic interface piezotronic effect is absent, while field-induced bulk piezotronics may still occur. However, their small electrostrictive coefficients usually require large mechanical stress [39], under which the piezoresistive effect may dominate and obscure the bulk piezotronic

contribution. Centrosymmetric materials with large electrostriction, such as SrTiO₃ [40], are more promising for realizing strong induced piezoelectricity [12, 26, 27], and bulk piezotronic modulation. Thus, GaN is used here as a representative system to illustrate a general mechanism.

4 Conclusion

In summary, we have revealed an entangled interface-bulk piezotronic effect in polar metal-insulator-piezoelectric semiconductor tunneling heterojunctions. By incorporating both intrinsic interface piezo-charges and electric-field-induced bulk piezo-charges into the electrostatic transport model, we show that the two piezotronic effects coexist and jointly modulate tunneling transport. Depending on the polarity of heterojunctions, the current modulation is either cooperative or competitive due to the barrier-height modulation. In contrast, capacitance exhibits an opposite cooperation–competition relationship because it is dominated by barrier-width modulation. This entangled current–capacitance behavior provides an effective route to identify hidden field-induced bulk piezotronic contributions that are difficult to resolve from current measurements alone. These findings extend piezotronic device physics from conventional interface-dominated

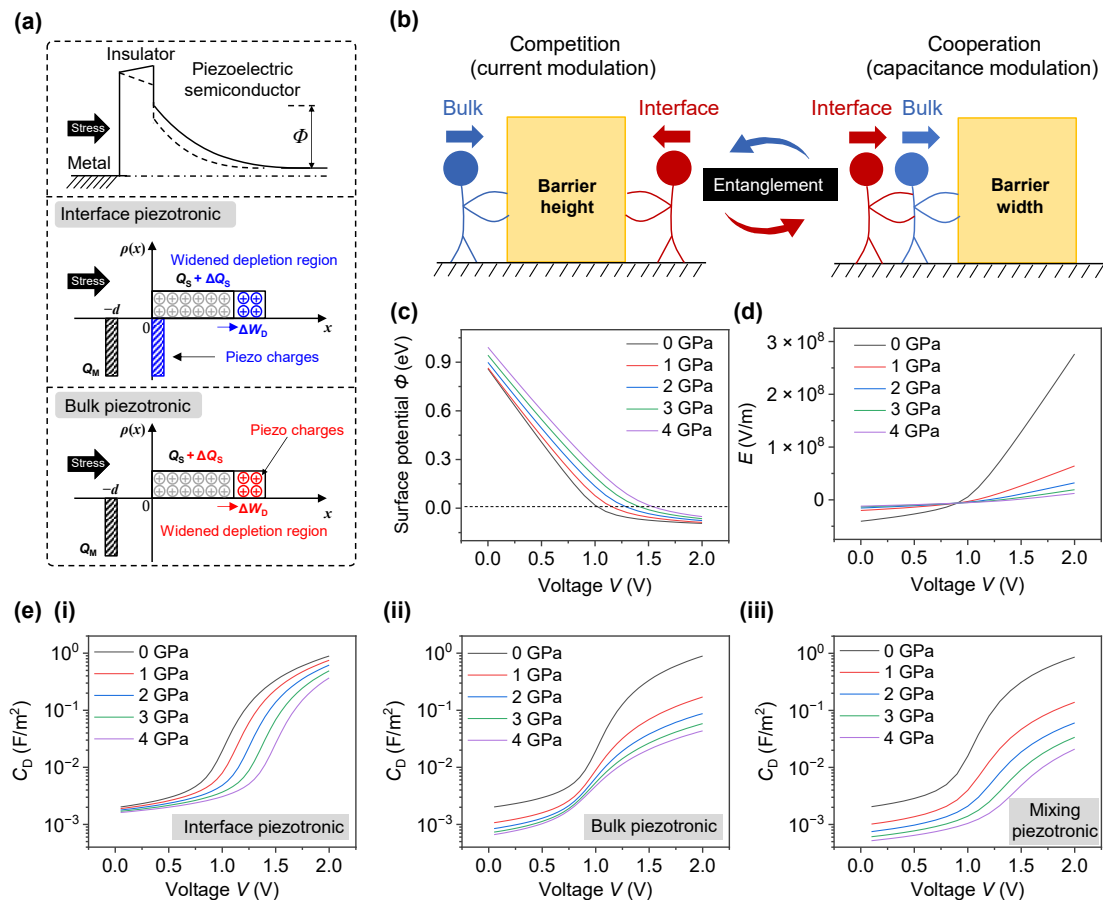


Figure 5 Cooperative modulation of two piezotronic effects on semiconductor capacitance in MIPS junction. (a) Band diagram of the MIPS junction when the polarity c -axis of the bulk piezotronic effect is antiparallel to the built-in electric field (top), along with charge distributions under interface piezotronic (middle) and bulk piezotronic (bottom). Here, Φ is the semiconductor interface barrier, d is the insulator width, Q_M and Q_S are the charges per unit area on the metal and semiconductor, respectively, and ΔW_D is the change in depletion layer width under applied pressure conditions. (b) Entanglement between competitive modulation of barrier height and cooperative modulation of barrier width by interface and bulk piezotronic effects, reflecting competitive regulation of current and cooperative regulation of capacitance. Surface barrier (c) and surface electric field (d) as functions of bias voltage under coupled two piezotronic effects. (e) Semiconductor capacitance C_D as a function of bias voltage under different pressures for interface piezotronic (i), bulk piezotronic (ii), and mixing piezotronic (iii).

transport to coupled interface–bulk electromechanical modulation, offering guidance for the design of high-sensitivity tunneling sensors and mechanically tunable semiconductor devices.

Electronic Supplementary Material: Supplementary material (induced piezoelectric polarization, interfacial and bulk piezo-charges, characteristics of bulk piezo-charges, simulation material parameters, and bulk piezotronic effect) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909098>.

Data availability

All the simulation data in this paper can be reproduced using the described methodology. The relevant data are available upon reasonable request.

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Declaration of competing interest

All authors have no conflicts to disclose.

Author contribution statement

G. W. H., Y. S. X., L. J. L., and F. B. H. designed the project, conducted the data analysis. Y. H. Z., L. H. J., and J. J. H. conducted the theoretical study and draft writing.

Use of AI statement

None.

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