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C-V characteristics of piezotronic metal-insulator-semiconductor transistor

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Abstract

Third generation semiconductors for piezotronics and piezo-phototronics, such as ZnO and GaN, have both piezoelectric and semiconducting properties. Piezotronic devices normally exhibit high strain sensitivity because strain-induced piezoelectric charges control or tune the carrier transport at junctions, contacts and interfaces. The distribution width of piezoelectric charges in a junction is one of important parameters. Capacitance-voltage (C-V)

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characteristics can be used to estimate the distribution width of strain-induced piezoelectric charges. Piezotronic metal-insulator-semiconductor (MIS) has been modelled by analytical solutions and numerical simulations in this paper, which can serve as guidance for C-V measurements and experimental designs of piezotronic devices.

Keywords: Piezotronic effect; Capacitance-voltage (C-V) characteristics; Metal-insulator-semiconductor; Distribution width of strain-induced piezoelectric charges

1. Introduction

Wurtzite structure semiconductors, such as ZnO and GaN exhibiting coupled piezoelectric and semiconducting properties, have been developed in many novel high performance devices [1-5]. Polarization of ions in these crystals can be used to tune or control the charge transport behavior in the nanowire based devices [6]. Piezotronics is a new emerging field for third generation semiconductor applications [1, 4]. Novel nanodevices including nanogenerators [7, 8], multifunctional strain-gated logic nanodevices [9], flexible transistors [10, 11], high-performance piezotronic diodes [12], biomedical sensors [13] and piezophototronic LEDs [13, 14] have been demonstrated with excellent performances.

Based on the fundamental theoretical framework of piezotronics [14-16], analytical solutions and numerical simulations are presented for better understanding and quantitatively calculating the carrier transport behavior in the device. Recently, models of piezotronic p-n junction, metal-semiconductor contact [15] and heterojunctions [17, 18] have been studied based on the principle of piezotronic effect. Piezotronic effect on novel quantum states such as topological insulator [19], Rashba spin-orbit interaction [20] has also been studied based on quantum theory and experiments. Furthermore, piezotronic effect has been used to enhance the performance of nanodevices such as solar cells [21], the enhancement of luminescence [22-25]. Piezotronic logic units based on strain-gated transistors have been demonstrated in [26, 27].

From fundamental theory of piezotronics [28], the distribution width of strain-induced piezoelectric charges is an important parameter. It is an open question to obtain the width from experiments by semiconductor physics measurement. Here, capacitance-voltage (C-V) characteristics of the metal-insulator-semiconductor (MIS) contact has been studied for providing a method to estimate the distribution width of strain-induced piezoelectric charges. We provide analytical solutions and conduct the numerical simulation using the COMSOL software package. For a typical MIS contact, a thin insulator sits between a metal contact and semiconductor, as shown in Figure 1a. Metal serves as the gate, which controls the carrier transport by an applied gate voltage. The piezotronic MIS structure is made by a piezoelectric semiconductor material. Figure 1b and c shows a piezotronic nanowire device under tensile and compressive strain, respectively. Detailed analysis of the C-V characteristics of the device is presented in the following sections.

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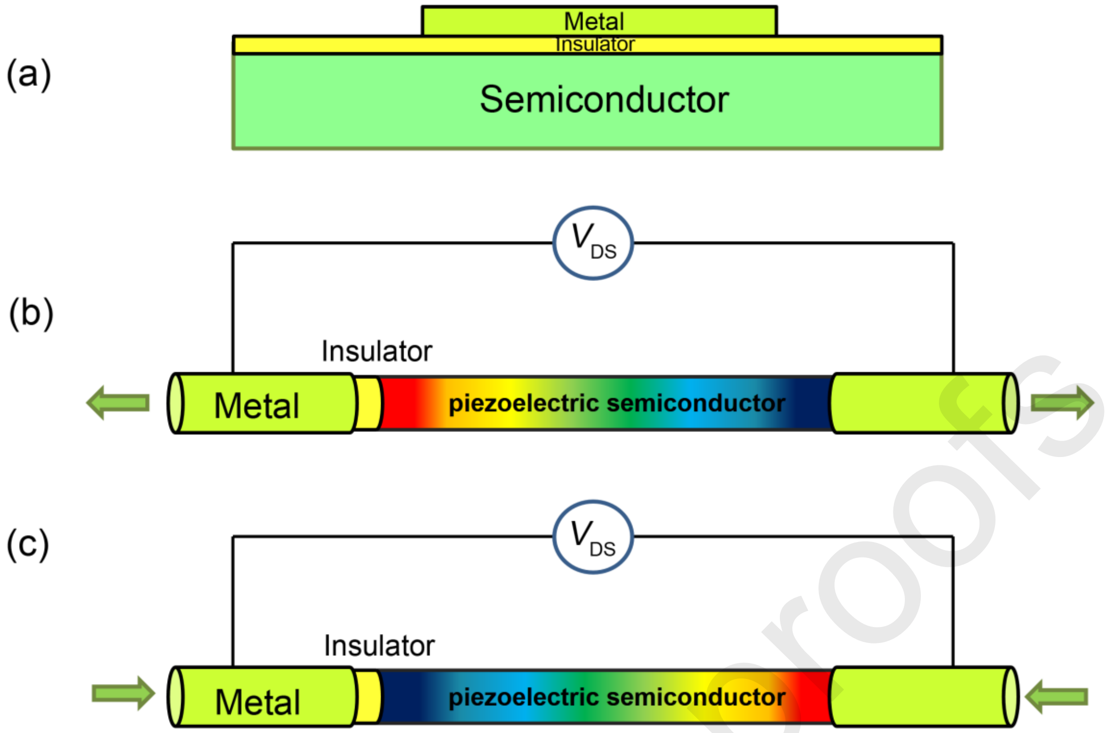

Figure 1 (a) Schematic of a typical metal-insulator-semiconductor (MIS) transistor. Piezotronic MIS transistor under tensile (b) and (c) compressive strain.

2. Analytical solution for 1D piezotronic MIS structure

Piezotronic theory includes electrostatic equations, current density equation and continuity equation based on semiconductor physics [29-32]. Piezoelectric equation is used to describe the induced charges under applied strain [33]. MIS structure is one of the most useful modern devices to investigate semiconductor surfaces. C-V characteristics are important for device operations [34]. A variety of theories and articles have been put forward on the MIS characteristics since the model was first presented [35-37]. An ideal and simplified model is used to study the characteristics of piezotronic MIS. For convenience, a few assumptions are made below: the working function differences between the metal and the semiconductor are neglected; surface states and other anomalies are not considered in this model; the resistance of the insulator is infinite, i.e., no current going through the insulator.

The semiconductor part of MIS is designated by a ZnO nanowire synthesized along the *c*-axis. The positive piezocharges are created at the interface of insulator and semiconductor while compressive strain is applied along the *c*-axis. As in our previous work, it is assumed that for nanodevices the piezocharges are distributed at the insulator and semiconductor interface within a width of W_{piezo}.

The ZnO is n type and the distribution of impurity is in box profile with the donor concentration N_{D}. Acceptors are fully ionized in the depletion zone; we use the Poisson's equation to calculate the electronic potential distribution in the device. The 1D model of the Poisson's equation would be degenerated to

$$-\frac{\mathrm{d}^2\psi_{\mathrm{i}}}{\mathrm{d}x^2}=\frac{\mathrm{d}E}{\mathrm{d}x}=-\frac{\rho(x)}{\varepsilon_{\mathrm{s}}}=\frac{1}{\varepsilon_{\mathrm{s}}}[qN_{\mathrm{D}}(x)+q\rho_{\mathrm{piezo}}] \ , \tag{1}$$

where ψ_{i} is electric potential, $\rho(x)$ is the charge density distribution, ε_{s} is the dielectric constant of the semiconductor, E is the electric field, N_{D} is the donor concentration, ρ_{piezo} is the piezocharges density, W_{Dn} is the depletion layer width, and d_{i} is the thickness of the insulator as shown in Figure 2a. When the charge distribution is given, the electric field can be integrated using the Poisson's equation (Figure 2b).

$$E(x)=\begin{cases}\dfrac{qN_{\mathrm{D}}(x-W_{\mathrm{Dn}})}{\varepsilon_s}+\dfrac{q\rho_{\mathrm{piezo}}(x-W_{\mathrm{piezo}})}{\varepsilon_s} & (0\le x\le W_{\mathrm{piezo}})\\ \dfrac{qN_{\mathrm{D}}(x-W_{\mathrm{Dn}})}{\varepsilon_{\mathrm{s}}} & (W_{\mathrm{piezo}}\le x\le W_{\mathrm{Dn}})\end{cases} \ . \tag{2}$$

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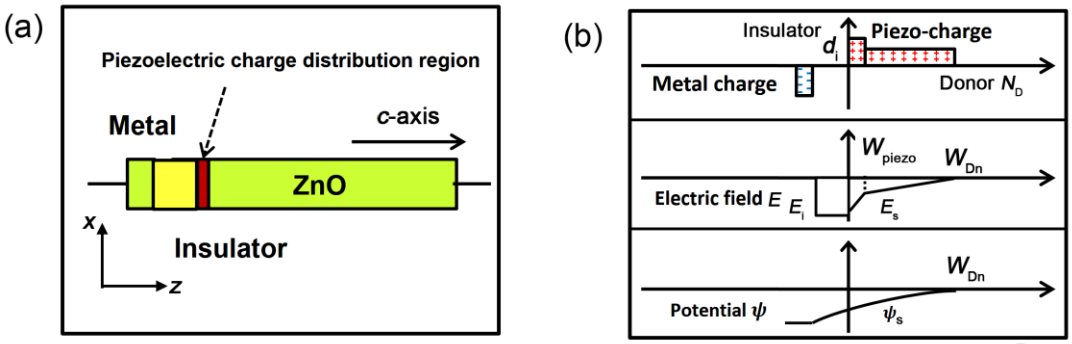

Figure 2 (a) Schematic of a piezotronic ZnO nanowire MIS. (b) Piezoelectric charges and donor charges distribution, electric field distribution, and potential distribution.

At the interface x=0, we can obtain the electric field in the semiconductor and insulator, respectively. According to the Poisson's equation, relationship of the two electric fields is as follows

$$E_{s}(0)\varepsilon_{s} = E_{i}(0)\varepsilon_{i} = -Q_{s} \quad , \tag{3}$$

where ε_s and ε_i are the dielectric constants of the semiconductor and the insulator respectively, Q_s is the total charge in the semiconductor.

$$Q_{s} = q(N_{D}W_{Dn} + \rho_{piezo}W_{piezo}) \quad . \tag{4}$$

The potential distribution is shown in Figure 2b. ψ_s is the surface potential of the semiconductor,

$$\psi(x) = \begin{cases} -\dfrac{qN_{D}(x-W_{Dn})^{2}}{2\varepsilon_{s}} - \dfrac{q\rho_{piezo}(x-W_{piezo})^{2}}{2\varepsilon_{s}} & (0 \le x \le W_{piezo}) \\ -\dfrac{qN_{D}(x-W_{Dn})^{2}}{2\varepsilon_{s}} & (W_{piezo} \le x \le W_{Dn}) \end{cases} \quad . \tag{5}$$

The surface potential can be calculated as

$$\psi_{s} = \psi(0) = -\frac{q}{2\varepsilon_{s}}(N_{D}W_{Dn}^{2} + \rho_{piezo}W_{piezo}^{2}) \quad . \tag{6}$$

To calculate the total capacitance, the relation between Q_s and ψ_s should be calculated first. The external voltage is applied on both the insulator and semiconductor. As there is no charge in the insulator, the electric field is constant in the insulator.

$$V_{\mathrm{a}} = V_{\mathrm{i}} + \psi_{\mathrm{s}} = E_{\mathrm{i}} d_{\mathrm{i}} + \psi_{\mathrm{s}} \quad . \tag{7}$$

From Eqs. (6) and (7), we can get a quadratic equation of the depletion layer width W_{Dn}.

$$\frac{qN_{\mathrm{D}}}{2\varepsilon_{\mathrm{s}}} W_{\mathrm{Dn}}{}^{2} + \frac{qN_{\mathrm{D}} d_{\mathrm{i}}}{\varepsilon_{\mathrm{i}}} W_{\mathrm{Dn}} + V_{\mathrm{a}} + \frac{q\rho_{\mathrm{piezo}} W_{\mathrm{piezo}} d_{\mathrm{i}}}{\varepsilon_{\mathrm{i}}} + \frac{q\rho_{\mathrm{piezo}} W_{\mathrm{piezo}}{}^{2}}{2\varepsilon_{\mathrm{s}}} = 0 \quad . \tag{8}$$

Solving Eq. (8) we can get the depletion layer width

$$W_{\mathrm{Dn}} = -\frac{\varepsilon_{\mathrm{s}} d_{\mathrm{i}}}{\varepsilon_{\mathrm{i}}} + \varepsilon_{\mathrm{s}} \sqrt{\left(\frac{d_{\mathrm{i}}}{\varepsilon_{\mathrm{i}}}\right)^{2} - \frac{2}{\varepsilon_{\mathrm{s}}} \left(\frac{V}{qN_{\mathrm{D}}} + \frac{\rho_{\mathrm{piezo}} W_{\mathrm{piezo}} d_{\mathrm{i}}}{\varepsilon_{\mathrm{i}} N_{\mathrm{D}}} + \frac{\rho_{\mathrm{piezo}} W_{\mathrm{piezo}}{}^{2}}{2\varepsilon_{\mathrm{s}} N_{\mathrm{D}}}\right)} \quad . \tag{9}$$

The capacitance of MIS is equivalent to the total capacitance of the two capacitances of the insulator and semiconductor connected in series. The insulator is a planar plate capacitor, which is a constant. In the depletion region, the capacitance is closely related to the depletion layer width. Classical theory gives the expression of the capacitance

$$C = \frac{1}{\frac{1}{C_{\mathrm{s}}} + \frac{1}{C_{\mathrm{i}}}} \quad , \tag{10}$$

where C_{s} is the semiconductor capacitance, C_{i} is the insulator capacitance and C is the total capacitance of the MIS.

The capacitances of insulator and semiconductor can be obtained by [38]

$$C_{\mathrm{i}} = \frac{\varepsilon_{\mathrm{i}}}{d_{\mathrm{i}}} \qquad C_{\mathrm{s}} = \frac{\varepsilon_{\mathrm{s}}}{W_{\mathrm{Dn}}} \quad . \tag{11}$$

Additionally, when the strain is applied at the piezoelectric semiconductor, the piezoelectric charge is [15]

$$P_{\mathrm{z}} = e_{33} s_{33} = q\rho_{\mathrm{piezo}} W_{\mathrm{piezo}} \quad , \tag{12}$$

where the e_{33} and s_{33} are the piezoelectric constant of material and the applied strain, respectively. The P_z is the strain induced piezoelectric polarization.

By substituting Eqs. (9), (11) and (12) to Eq. (10), the Eq. (10) is rewritten by

$$\frac{1}{C^2}=(\frac{d_\mathrm{i}}{\varepsilon_\mathrm{i}})^2-\frac{2}{\varepsilon_\mathrm{s}}(\frac{V}{qN_\mathrm{D}}+\frac{e_{33}s_{33}d_\mathrm{i}}{q\varepsilon_\mathrm{i}N_\mathrm{D}}+\frac{e_{33}s_{33}W_\mathrm{piezo}}{2q\varepsilon_\mathrm{s}N_\mathrm{D}}) \quad . \tag{13}$$

Moreover, the difference of $\frac{1}{C^2}$ with and without strain ($\Delta\frac{1}{C^2}$) can be given by

$$\Delta\frac{1}{C^2}=-\frac{e_{33}s_{33}}{q\varepsilon_\mathrm{s}N_\mathrm{D}}(\frac{2d_\mathrm{i}}{\varepsilon_\mathrm{i}}+\frac{W_\mathrm{piezo}}{\varepsilon_\mathrm{s}}) \quad . \tag{14}$$

Solving Eqs. (13) and (14), we can obtain the piezoelectric charges distribution width

$$W_\mathrm{piezo}=-\left(\frac{q\varepsilon_\mathrm{s}^2N_\mathrm{D}}{e_{33}}\frac{\mathrm{d}1/C^2}{\mathrm{d}s_{33}}+\frac{2\varepsilon_\mathrm{s}d_\mathrm{i}}{\varepsilon_\mathrm{i}}\right) \quad . \tag{15}$$

Therefore, we can use the capacitance to estimate the piezoelectric charges distribution width. Previous works [38] have described that estimating semiconductor natural parameter by measuring C-V characteristic is a general method. In Ref. [39], it was also shown an experimental setup to measure electronic properties of piezotronic devices in different strains. By combining the traditional experimental method and piezotronic theory, we propose a MIS model to estimate piezoelectric charges distribution width. In this device structure, we only need to measure the total capacitance of MIS structure by the traditional experimental method in different strains. Finally, we can calculate and estimate the piezoelectric charges distribution width by the curves ($\Delta\frac{1}{C^2}-s_{33}$). Piezotronic and piezo-phototronic devices have promising potential applications in next-generation flexible electronics, self-powered and wearable systems [40]. In these devices, strain-induced piezoelectric charges at a contact, junction, or interface can effectively modulate and control the carrier recombination, generation, and transport properties [15, 41]. Therefore, the estimation method of piezoelectric charges distribution width can be further applied for piezotronic and piezo-phototronic devices due to the analogical modulation mechanism.

For a simple case, C_s and C_i are constants, for example, $C_i = \varepsilon_i / d_i$ and $C_s = \varepsilon_s / W_{Dn}$, the total capacitance changes with the semiconductor capacitance. To qualitatively analyze the device, the negative piezocharges are generated at the interface for a tensile strain. C_s increases while W_{Dn} decreases. Obviously, the MIS capacitance C will become smaller. For the compressive strain, C becomes larger. Capacitance is influenced not only by the sign of the strain but also by the magnitude of the strain. This is the operation mechanism of the piezotronic MIS structure.

3. Numerical simulation of piezotronic MIS

The analytical solutions of piezotronic MIS give a qualitative understanding of the C-V characteristics. Here we numerically solve the equations and present a model for a better understanding of the working mechanism of the piezotronic MIS structure. The model consists of a *c*-axis n type ZnO nanowire attached to an insulator. According to fundamental theory of piezotronics, the electrical contact between the nanowire and the metal is set to be ideal Ohmic contact, so the boundary condition of electric potential and carrier concentration is Dirichlet condition. To be practical, the doping profile is described as Gaussian distribution. The general recombination process using traps in the forbidden band gap of the semiconductor is called Shockley-Read-Hall recombination.

In the simulation, the ZnO nanowire is n type, the length and radius are 80nm and 10nm. The background doping concentration is $N_{Dn} = 1 \times 10^{15} \mathrm{cm}^{-3}$, the maximum acceptor doping concentration is $N_{Dn,max} = 1 \times 10^{17} cm^{-3}$. The piezoelectric constant is $e_{33} = 1.22 C / m^2$. The intrinsic carrier density is $n_i = 1 \times 10^6 \mathrm{cm}^{-3}$, the electrons and

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holes mobility is μ_n=μ_p=180 cm^2/(V s), the carrier lifetime is τ_n=τ_p=0.1 μs. The relative dielectric constants of semiconductor are $k_{\perp}^{r}=7.77$ and $k_{\parallel}^{r}=8.91$. The relative dielectric constants of insulator is $k_{i}^{r}=4$. The thickness of insulator d_i=2 nm. The control constant *ch*=4.66 nm, temperature *T*=300 K. The nanowire is along the *c*-axis, and the piezocharges distribution is supposed to be box profile at each end of the nanowire. The width of piezocharges is $W_{piezo=}$0.25 nm in the model. The voltage is applied to the metal, and semiconductor is grounded.

Figure 3a illustrates current-voltage characteristics of piezotronic devices. The positive strain (tensile strain) inducing negative piezoelectric charges can raise the barrier height of interface and the current subsequently decreases. By contrast, the positive piezoelectric charges at interface lowers the barrier height of interface, therefore current increases. As shown in Figure 3b, the relative current density is a function of strain at a fixed voltage. For the strain range from –0.1% to 1%, the current varies slowly in the region of positive strains (tensile strains), however increases rapidly in the region of negative strains (compressive strains). Figure 3c shows the capacitance C as a function of applied voltage. When the strain varies from –0.08% to 0.08%, the results suit perfectly with the analytical solution we presented. In the model, for the tensile strain, the negative piezoelectric charges are generated at the semiconductor surface, capacitance becomes smaller. For the compressive strain, the positive piezoelectric charges are generated at the semiconductor surface, capacitance becomes larger. Moreover, Figure 3d demonstrates the theoretical Gauge Factor varies slowly at positive strain values and changes abruptly at larger negative strains in the region from −4% to 1%. This shows that the sensitivity of the piezotronic devices can reach over 10^3 in an

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accessibly experimental strain range.

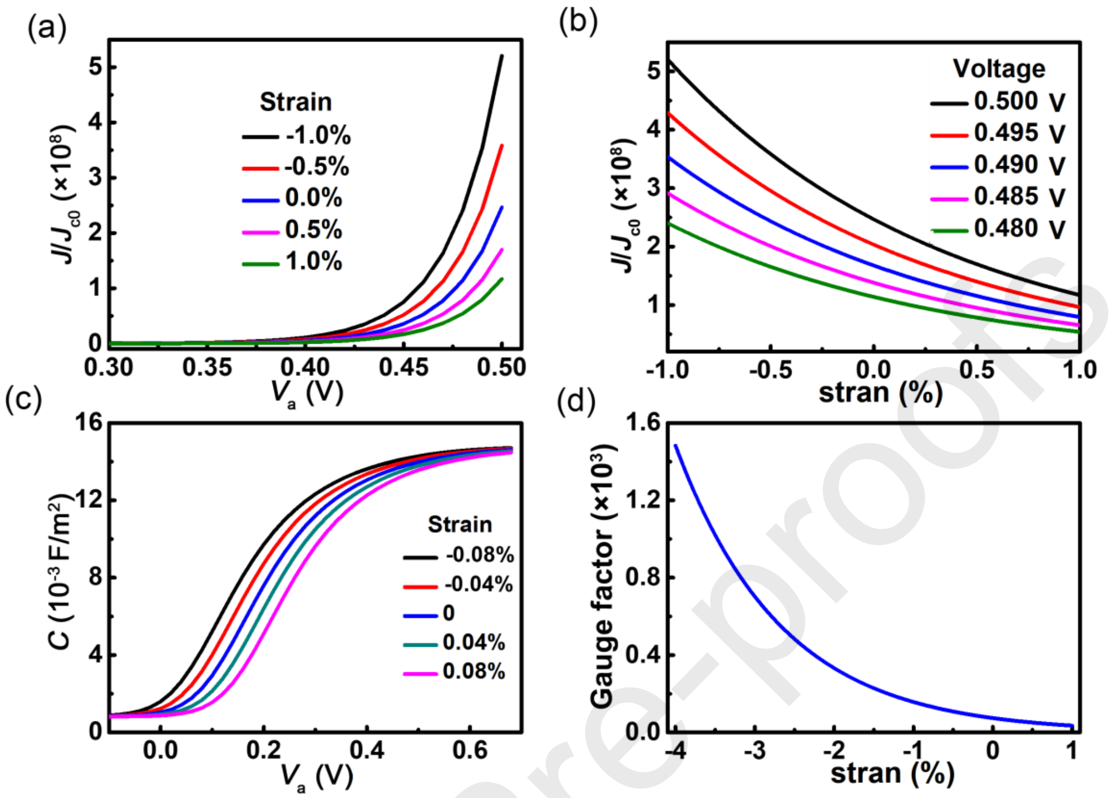

Figure 3. The electric characteristics of an ideal piezotronic device with piezoelectric charges. (a) The current-voltage curves at different strains from –1% to 1%. (b) Relative current density as a function of strain at different fixed voltages from 0.48 to 0.5 V. (c) Calculated capacitance C as a function of applied voltage at different strains from –0.08% to 0.08%. (d) Gauge Factor as a function of strain from –4% to 1%.

Figures 4a, b shows the charge density Q and capacitance C as a function of applied strain. Figure 5a shows the charge density Q as a function of surface potential ψ_s at different strains. For negative ψ_s the charge density grows very fast as the surface potential increases, which is corresponding to the accumulation region. Based on these curves we calculate the *C*-*V* curves, Figure 5b shows the charge density Q as a function of applied voltage. The strain varies from –0.08% to 0.08% the result suits perfectly with the analytical solution we presented. In the model, for the tensile strain, the negative piezoelectric charges are generated at the semiconductor surface, capacitance becomes smaller. Figure 5c and d shows electrons and holes concentration in the ZnO nanowire at a fixed voltage. In the case of negative strain (or compressive strain), positive charges are accumulated at the surface which will attract electrons and repel holes. Once a positive strain (or tensile) is applied, the result will be opposite. At thermal equilibrium the carrier concentration is an exponential function of surface potential, so the charge density changes more intensively with the voltage as the electron concentration is higher.

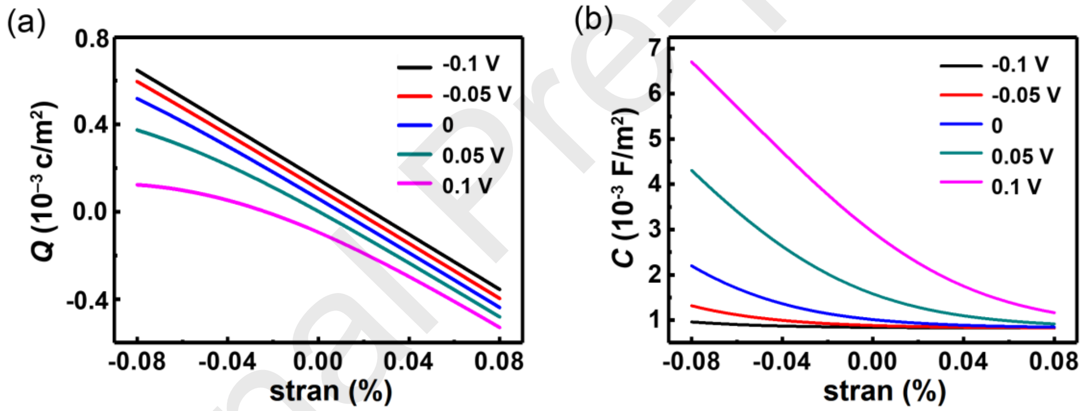

Figure 4 Charge (a) and capacitance (b) with different voltages across the MIS as the applied strain varies from –0.08% to 0.08%.

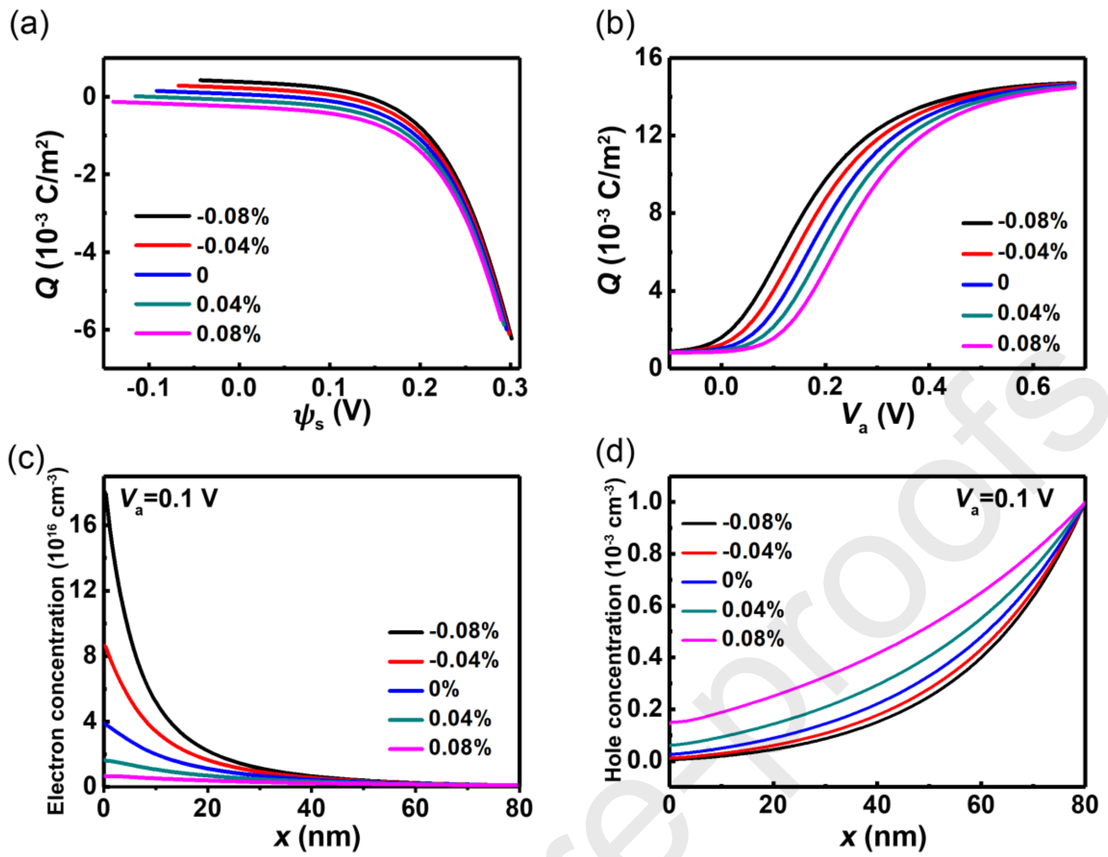

Figure 5 The electric characteriatic of piezotronic MIS structure under different strains. (a) Calculated surface potential ψ_{s} and charge Q. (b) Calculated charge Q and voltage V_{a}. Distribution of electrons (c) and distribution of holes (d) at a fixed voltage of 0.1 V across the MIS for the applied strain varying from –0.08% to 0.08%.

In addition, we give the results of *C*-*V* curves and carrier concentration distribution at different doping concentrations. The background doping concentration N_{Dn} is set to 1×10^{15} cm^{-3}. The maximum donor concentration varies from 5×10^{16} to 1×10^{18} cm^{-3}, as shown in Figure 6. As it can be seen from Eq. (12), W_{Dn} get thinner as N_{D} varies from 5×10^{16} to 1×10^{18} cm^{-3}, thus the capacitance becomes larger. The curves shown in Figure 6b illustrate that acceptor concentration has a major influence on the C-V characteristics. The electrons and holes concentration distributions are also given in Figure 6c and d.

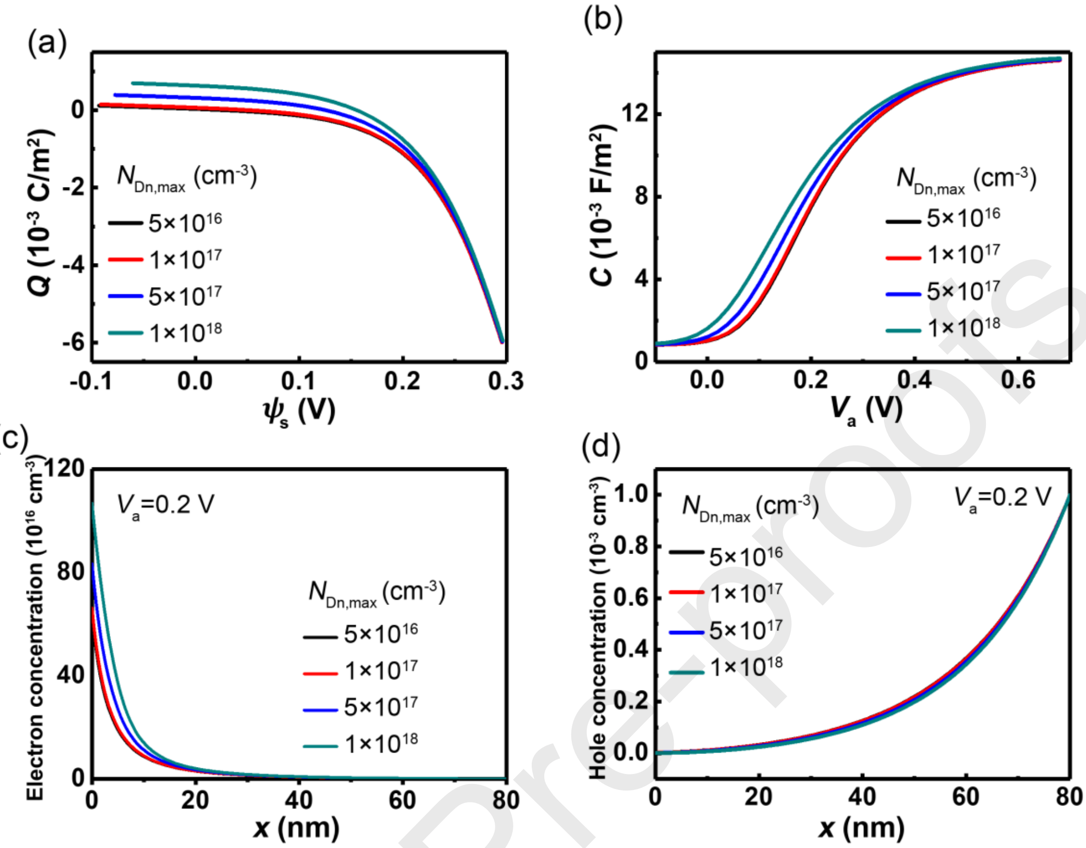

Figure 6 The electric characteriatic of piezotronic MIS structure at different doping concentrations. (a) Calculated piezotronic MIS $Q-\psi_s$ curves and (b) *C-V* curves at different maximum donor doping concentrations (c) holes and (d) electrons distribution at an applied forward voltage of 0.2 V at different maximum donor doping concentrations.

Figure 7a demonstrates $\Delta\frac{1}{C^2}$ as a function of applied strain at different piezoelectric charge distribution widths. The $|\Delta\frac{1}{C^2}|$ increases with the raising strain. This shows that the strains have obvious influence on the total capacitance. In addition, the $|\Delta\frac{1}{C^2}|$ has more obvious varieties in a greater W_{piezo} at the same strain from the enlargement part. Figure 7b and c shows $\Delta\frac{1}{C^2}$ as a function of W_{piezo} at tensile and compressive strains, respectively.

The result is consistent with Figure 7a. Figure 7d illustrates $\frac{\mathrm{d}1/C^2}{\mathrm{d}s_{33}}$ as a function of strain and it is a constant. Moreover, the $\frac{\mathrm{d}1/C^2}{\mathrm{d}s_{33}}$ has different values in different W_{piezo}. Therefore, we can calculate piezoelectric charges distribution width by measuring total capacitance of devices. Previous works [15] show performance and the physical control mechanism of piezotronic devices. Meanwhile, the authors firstly proposed W_{piezo} and investigated the importance of W_{piezo} on performance of piezotronic devices. However, how to estimate W_{piezo} is still a challenging task. In this study, we propose a method by analyzing C-V characteristic of MIS structure and combining the traditional measurement method and piezotronic theory to estimate W_{piezo}. Meanwhile, the method is general and mature in estimating semiconductor intrinsic parameters [38]. Thus, analyzing C-V characteristic of MIS structure to estimate the value of W_{piezo} is a feasible approach in the experiment.

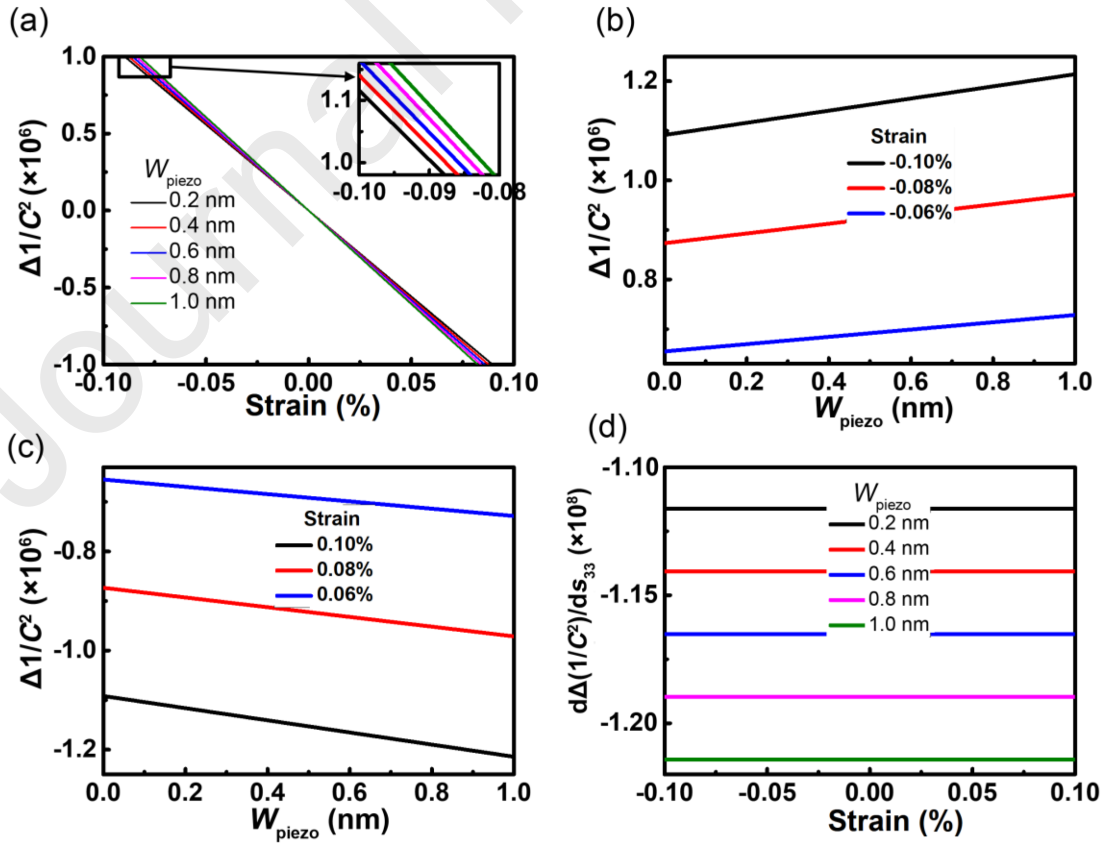

Figure 7 Relation of capacitance and piezoelectric charges distribution width. (a) Calculated $\Delta\frac{1}{C^2}$ as a function of strain at different piezoelectric charges distribution. (b, c) $\Delta\frac{1}{C^2}$ as a relation of piezoelectric charges distribution width at tensile and compressive strain, respectively. (d) $\mathrm{d}\frac{1}{C^2}/\mathrm{d}s_{33}$ as a function of strain at different piezoelectric charges distribution width.

Optoelectronic devices consisting of metal-insulator-ZnO nanowire have been investigated in several previous papers [42, 43]. In addition, ZnO thin film-based MIS structure have also been fully investigated for electronic devices [44-46]. Besides, the thin insulator layer usually exists between metal and semiconductor in one end and the other end is only comprised of metal and semiconductor. Importantly, recent research [47] has demonstrated ZnO thin film grown along *c*-axial in the experiment. Therefore, the devices can also be built by metal-insulator-ZnO thin film along *c*-axial. Like above researches, we adopt a typical MIS structure consisting of metal-insulator-piezoelectric semiconductor as analytic model in our study. Hence, we can use it to calculate the piezoelectric charges distribution width.

Moreover, in order to efficiently examine semiconductor intrinsic properties of the MIS structure, we adopt a novel approach based on neural network models. For simplicity, we train and test our neural network model based on the *Q*-*V* curves in Figure 5b. We treat these curves as linear functions and find the correlation between the linear part and the strain value. The intercept of each linear part is calculated and then used as input value to our neural network while strain value is used as the target value to train it. The process to obtain our neural network model is demonstrated in Figure 8a. Our neural network is a simple doubly

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layered feed-forward neural network using identity activation linear function with one input unit, one hidden layer consisting of three hidden units, and one output unit to accommodate the continuous property of the strain value [48]. We train our neural network using back-propagation with mean squared error as loss function [49]. A validation dataset, consisting of 100 data points, is generated through the calculated linear relation between intercept and strain value. We use this validation dataset as inputs to the trained neural network to produce corresponding predictions and test the accuracy and validity of our model. As shown in Figure 8b, our model starts to exhibit 100% prediction accuracy at around iteration 50 with learning rate of 0.01 on our validation dataset. With this result, we are confident to say that neural network has promising potential application for examining intrinsic characteristics of semiconductors with sufficient efficiency and accuracy.

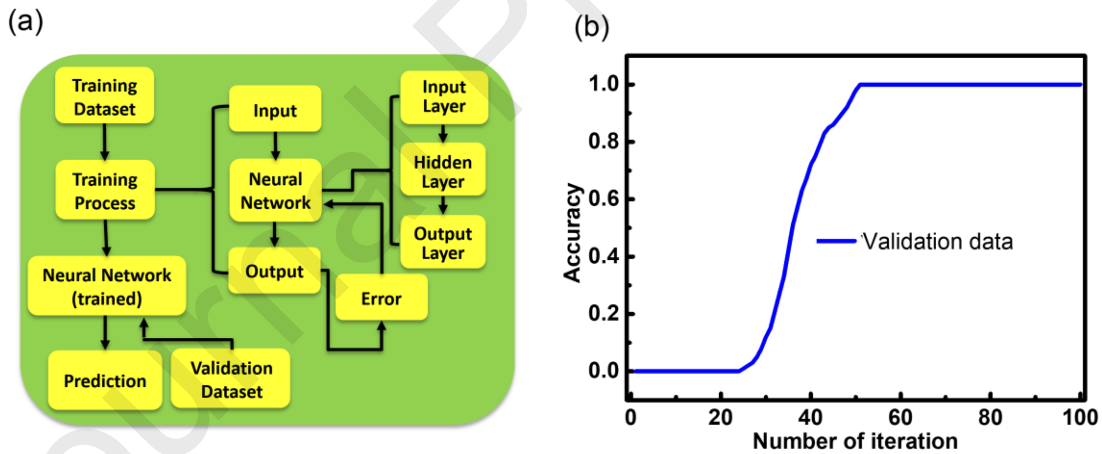

Figure 8 (a) Procedure of our experiment consists of training process and inference process after obtaining trained neural network. (b) Accuracy on validation set as a function of number of training process iteration. The presented result is achieved using 100 iterations and 0.01 learning rate.

Among conventional methods of analyzing the simulation results, the most commonly used ones are still based on curve fitting to approximate the result [50]. These methods, such as the least-squares method, usually utilize implicit functions (including both independent and dependent variables) to express their target variables [50]. Because of the existence of both independent and dependent variables, complexity of analyzing the simulation result increases and errors can also be introduced [50]. Additionally, nonlinear fitting algorithms, such as quasi-Newton method, have also been proposed to extract intrinsic properties of the simulation result. However, these methods do not guarantee an accurate result at convergence if the initial value is not carefully chosen [51]. On the other hand, neural networks do not need to learn with pre-defined target variable expressions and is capable of learning any functions [48]. Although learning in neural networks relies on the optimization of a non-convex function in this task, the local minimums are actually very close to the global minimum when the neural networks is fully connected (each unit in each layer connects to all units in the next layer) [49]. As a result, even an arbitrary initial value can lead to an accurate result in very few training iterations (only about 40 to 50 iterations). Moreover, since there are often extensive experimental data, neural networks can utilize these data and do not require using experts' knowledge by directly classifying based on simulation result [52].

4. Conclusion

We present a numerical model of a piezotronic MIS for analyzing the effect of the piezocharges on its C-V characteristics. Analytical solutions are given in this work to introduce the mechanism of the piezotronic MIS. Numerical simulation is also presented to demonstrate a better understanding of the model. We find that the total capacitance becomes smaller when negative piezocharges generated at the interface and becomes larger when positive piezocharges are generated. This work can be utilized as guidance for future device

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design and implementation.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Jiayang Zheng, Yongli Zhou, and Yaming Zhang contributed equally to this work. Yan Zhang conceived the idea and guided this work. Jiayang Zheng, Yongli Zhou, Yaming Zhang, and Yan Zhang fabricated theoretic frame and analysed the data. Jiayang Zheng, Yongli Zhou, Yaming Zhang, Lijie Li, and Yan Zhang wrote this paper. All the authors discussed the results and commented on the manuscript.

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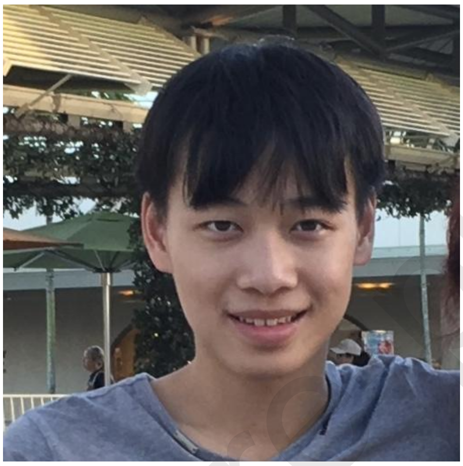

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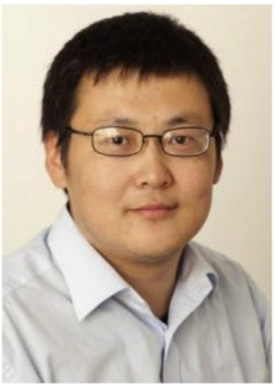

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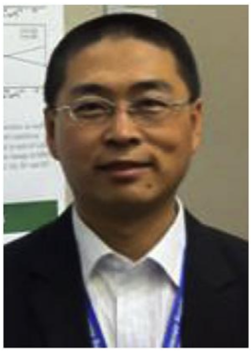

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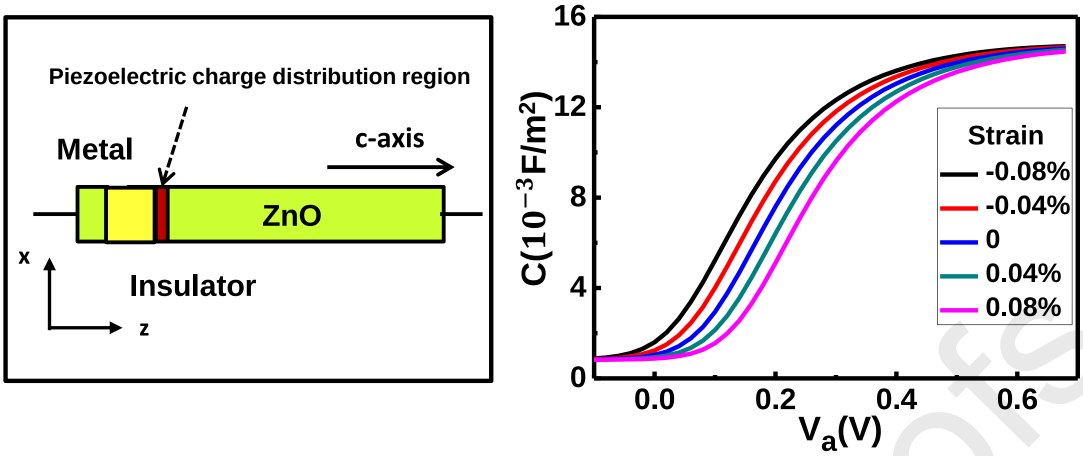

The distribution width of piezoelectric charges induced by strain in a junction is one of important parameters for piezotronic devices. Capacitance-voltage characteristics based on piezotronic MIS structure can be used to estimate the distribution width of piezoelectric charges, which can be applied to piezotronic and piezo-phototronic devices.