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Piezotronic P-I-N Diode for Microwave and Piezophototronic Devices

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Abstract

Piezotronic and piezophototronic, the two emerging fields that combine piezoelectric and semiconductor properties of materials have drawn much attention recently. Piezopotential caused by the piezo-charges can change energy band and carrier transport of piezoelectric semiconductor materials. The p-i-n diodes have been widely used in high frequency microwave circuit. In this paper, we present the theoretical calculations of piezotronic p-i-n diode, including the built-in-potential, current-voltage characteristic, and junction capacitance for microwave and radio frequency application. Furthermore, the photovoltaic and luminescence properties of p-i-n piezophototronic photodetector and light emitting diode have been provided under applied strain.

Keywords: piezotronic; piezophototronic; P-I-N diode ; microwave; photodetector;LED

1. Introduction

Due to the coupling of piezoelectric and semiconductor properties of wurtzite materials, such as ZnO and GaN, the piezo-potential induced by piezo-charges with external applied strain can not only tune or control carrier transport but also photon emission process in piezoelectric semiconductor [1]. These are named as piezotronic and piezo-phototronic effects, which have a seriers applications in emerging electric nanodevices [2], sensors [2,3], solar cell, LED and micro-robots [4,5,6]. Fundamental theory of piezotronics has been established based on physics of semiconductor device and piezoelectric theory [7]. The model of piezo-phototronic light-emitting diode and solar cell [5,6] have been investigated by theoretical calculations of carrier transport, luminous emission and photovoltaic [4]. Based on classical ballistic Boltzmann transport equation, the characteristics of the piezotronic ballistic transistor has been modeled by two-dimensional piezoelectric semiconductor materials [8]. Quantum models also have been developed for understanding piezotronic, which provide an important factor for piezotronic: the width of the piezoelectric charge distribution [9]. These theoretical studies have present properties of piezotronic and piezophototronic devices under applied strain, which can provide good understanding for characteristic of piezotronic device under direct-current or low frequency application. For high frequency application, the junction capacitance can be tuned by applied strain in piezotronic devices, which affect the frequency properties. As a result, piezocharge can tune the high frequency properties of piezotronic and piezo-phototronic devices, which can be used for microwave or radio frequency (RF) devices.

A typical structure for microwave and phototronic devices is p-i-n, which has an intrinsic layer between p and n-type region [10]. P-i-n diodes have been widely used for high frequency application: such as microwave and RF circuits [10,11,12]. In this paper, we theoretically investigated the charge transport behaviors in piezotronic and piezophototronic p-i-n diode. The potential distribution and current-voltage characteristic of piezotronic p-i-n diode have been solved under applied strain. The junction capacitance controlled by strain-induced piezoelectric charges has been investigated, which is an important factor for frequency properties of piezotronic p-i-n diode, especially at microwave or radio frequency. We also demonstrated the properties of piezo-phototronic photodetector and LED based on p-i-n diode. These results not only provide understanding for piezocharge tuning high frequency signal of piezotronic and piezophototronic but also give a guidance for piezotronic microwave or RF p-i-n diode design.

2. Model of piezotronic p-i-n diode

Piezoelectric semiconductor materials have semiconductor and piezoelectric properties. The basic equations for describing the behavior of carriers transportation are electrostatic equations, current density equations, continuity equations, and piezoelectric equations, which describes the behavior of piezo-charges in semiconductor with applied strain [7].

A p-i-n diode is a p-n junction with an intrinsic layer (i-region) sandwiched between the p-layer and the n-layer, which is a fundamental building block in various modern electronic devices. A typical structure of ZnO nanowire p-i-n junction is showed in Fig.1(a). In this structure, p-type and i-type are non-piezoelectric materials while n-type piezoelectric. Positive piezo-charges are at the left side of n-type ZnO when compressive strain applied along the c axis (the direction of ZnO grown) and the negative piezo-charges created by tensile strain, as shown in Fig. 1(b) and (c). The piezocharges, electric field and potential distribution are modified by strain, resulting in the change of energy band structure, as showed in Fig.2. Hence the piezo-charges induced by external strain can tune and control the transport of carriers.

2.1 Basic Equations

The Poisson equation describes electrostatic behavior of piezocharges in p-i-n devices:

$$\nabla^2 \psi_i = -\frac{\rho(\vec{r})}{\varepsilon_s} \tag{1}$$

where ψ_i is the electric potential distribution and $\rho(\vec{r})$ is the charge density distribution, ε_s is the permittivity of the material.

The behavior of piezocharges in p-i-n junction is described by conventional theory of piezoelectricity. The constitutive equation can be written as [7,13]:

$$\begin{cases} \boldsymbol{\sigma} = \mathbf{c_E S} - \mathbf{e^T E} \\ \mathbf{D} = \mathbf{eS} + \mathbf{kE} \end{cases} \tag{2}$$

where $\boldsymbol{\sigma}$ is stress, $\mathbf{c_E}$ is the elasticity tensor, $\mathbf{E}$ is the electric field, $\mathbf{D}$ is the electric displacement, e is the piezoelectric coefficient matrix, and k is the dielectric matrix. For a small strain, the polarization vector $\mathbf{P}$ can be given as,

$$(\mathbf{P})_i = (\mathbf{e})_{ijk}(\mathbf{S})_{jk} \qquad (3$$

where the third order tensor $(\mathbf{e})_{ijk}$ is the piezoelectric tensor.

2.2 Built-in-potential of piezotronic p-i-n diode

A p-i-n diode consists of an intrinsic region sandwiched between heavily doped p+ and n+ regions. The depletion layer is almost completely defined by the intrinsic region. In practice, the intrinsic region can be highly resistive, e.g. lightly doped p or n region. The current-voltage (I-V) characteristics of p-i-n diodes can provide a better understanding of piezoelectric p-i-n junction. The electric field, the potential distribution and the energy band are shown in Fig. 2c and 2d. An abrupt junction model is shown in Fig. 2a , in which the impurity concentration in a p-i-n junction changes abruptly from acceptor N_A to donor N_D. The i-region is the charge depletion region of the junction cause the higher doping in n and p-type compare to the middle. The electric field and potential distribution inside the p-i-n junction by Poisson equation:

$$-\frac{d^2\Psi_i}{dx^2} = \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon_s} = \frac{1}{\varepsilon_s}\left[qN_D(x) - qn(x) - qN_A(x) + qp(x) + q\rho_{piezo}(x)\right] \qquad (4)$$

where N_D is the donor concentration, N_A is the acceptor concentration, and ρ_{piezo} is density of polarization charges (in units of electron charge). W_{Dp} and W_{Dn} are defined to be the depletion layer widths in the p-side and the n-side, respectively. W is the length of i-region. The electric field is obtained by integrating Equ. (4), as shown in Fig. 2(b):

$$E(x) = -\frac{qN_A(x+W_{Dp})}{\varepsilon_s} \;, \quad \text{for } -W_{Dp} \le x \le -W \qquad (5\text{-a})$$

$$E(x) = -\frac{q}{\varepsilon_s}\left[N_a(x+W) + N_A(W - W_{Dp})\right] \;, \quad \text{for } -W \le x \le 0 \qquad (5\text{-b})$$

$$E(x) = -\frac{q}{\varepsilon_s}[N_D(W_{Dn} - x) + \rho_{piezo}(W_{piezo} - x)] \text{,for } 0 \le x \le W_{piezo} \qquad (5\text{-c})$$

$$E(x) = -\frac{qN_D}{\varepsilon_s}(W_{Dn} - x) \quad \text{,for} W_{piezo} \le x \le W_{Dn} \qquad (5\text{-d})$$

The maximum field E_m that exists at $\mathbf{x} = 0$ is given by:

$$\left|E_{\max}\right| = \frac{q}{\varepsilon_s}(N_D W_{Dn} + \rho_{\mathbf{piezo}} W_{piezo}) \tag{6}$$

The potential distribution $\psi_i(x)$ is given by:

$$\Psi_i(x) = \frac{qN_A}{2\varepsilon_s}(x + W_{Dp})^2 \text{ , } \quad \text{for} \quad -W_{Dp} \le x \le -W \tag{7-a}$$

$$\Psi_i(x) = \Psi_i(-W) + \frac{qN_a}{2\varepsilon_s}(x+W)^2 - \frac{qN_A}{\varepsilon_s}(W - W_{Dp})(x - W), \qquad \text{for} -W \le x \le 0 \tag{7-b}$$

$$\Psi_i(x) = \Psi_i(0) + \frac{qN_D}{\varepsilon_s}(W_{Dn}x - \frac{1}{2}x^2) + \frac{q\rho_{piezo}}{\varepsilon_s}(W_{piezo}x - \frac{1}{2}x^2), \qquad \text{for} \quad 0 \le x \le W_{piezo} \tag{7-c}$$

$$\Psi_i(x) = \Psi_i(W_{piezo}) + \frac{qN_D}{\varepsilon_S}(W_{Dn}x - W_{Dn}W_{piezo} - \frac{1}{2}x^2 + \frac{1}{2}W_{piezo}{}^2), \qquad \text{for} \quad W_{piezo} \le x \le W_{Dn} \tag{7-d}$$

Thus, the built-in potential ψ_{bi} is obtained as:

$$\Psi_{bi} = \frac{q}{2\varepsilon_s}(N_A W_{Dp}^2 + N_a W^2 + \rho_{piezo} W_{piezo}^2 + N_D W_{Dn}^2) \tag{8}$$

where N_a is the acceptor concentration of i-region. According to Equ. (8). The built-in potential of the p-i-n junction changes with piezocharges.

2.3 Current-Voltage characteristics of piezoelectric p-i-n diode

The forward current and the reverse current is formed by regeneration and recombination of electrons and holes in barrier region. The current depended the recombination centre in i-region of p-i-n diode [10,14]. For simplicity, the energy level of recombination centers is assumed at same level as the intrinsic Fermi level, and $r_n = r_p = r$ (where r_n and r_p are electron and hole recombination coefficient respectively).

Thus the recombination rate U is

$$U = \frac{rN_t(np - n_i^2)}{n + p + 2n_i} \tag{9}$$

where r is recombination coefficient, N_t is the concentration of recombination centre, n_i is the intrinsic carrier density, n and p are concentration for electrons and holes respectively.

In junction region, the concentration of electrons and holes can be decribed by:

$$np = n_i^2 \exp(\frac{qV}{k_0T}) \tag{10}$$

where V is the external voltage, and k_0 is Boltzmann constant.

While $n = p$, the electrons and holes concentration are given by:

$$n = p = n_i \exp[qV/(2k_0T)] \tag{11}$$

Substituting Eqs. (10), and (11) into Eq. (9) , the maxium recombination rate is given by:

$$U_{\max} = rN_t \frac{n_i[\exp(\frac{qV}{k_0T}) - 1]}{2[\exp(\frac{qV}{2k_0T}) - 1]} \tag{12}$$

When $qV >> k_0T$,

$$U_{\max} = \frac{1}{2}\frac{n_i}{\tau}\exp(\frac{qV}{2k_0T}) \tag{13}$$

where $\tau = 1/rN_t$, which is the lifetime of carriers.

Thus the forward current can be obtianed as :

$$J_r = \int_0^W qU_{\max}dx \approx \frac{qn_iW}{2\tau}\exp(\frac{qV}{2k_0T}) \tag{14}$$

The reverse current is given by:

$$J_s = qU_{\max}W = qn_iW/2\tau \tag{15}$$

Thus, the current-voltage characteristics can be obtained by Eqs. (14) and (15):

$$J = J_S[\exp(\frac{qV}{2k_0T}) - 1] \tag{16}$$

The i-region is light p-doped, the resistance is very higher than p and n region. The recombination lifetime is given as following [10,14]:

$$\tau = \frac{P_1}{N_t r_n} \frac{1}{P_0} \tag{17}$$

where P_0 and P_1 are hole concentration in equilibrium condition and non-equilibrium condition:

$$P_0 = N_v \exp[-(\frac{E_F - E_V}{k_0 T})] \tag{18a}$$

$$P_1 = N_v \exp[-(\frac{E_t - E_V}{k_0 T})] \tag{18b}$$

where N_v is the effective density of states in the valance band, E_V is the valance band, and E_t is the band of recombination centre.

Substituting Eq. (18) into Eq. (9) yields following equation

$$\tau = \frac{1}{N_t r_n} \exp(\frac{E_F - E_t}{k_0 T}) \tag{19}$$

Thus, the reverse current is obtianed as:

$$J_s = \frac{1}{2} q n_i W N_t r_n \exp[-\frac{(E_F - E_t)}{k_0 T}] \tag{20}$$

$$J = \frac{1}{2} q n_i W N_t r_n \exp[-\frac{(E_F - E_t)}{k_0 T}][\exp(\frac{qV}{2k_0 T}) - 1] \tag{21}$$

Eq. (21) described the current-voltage characteristic of p-i-n junction.

J_{s0} and E_{F0} are the saturation current density and the Fermi level with the absence of piezocharges,

$$J_{s0} = \frac{1}{2} q n_i W N_t r_n \exp[-\frac{(E_{F0} - E_t)}{k_0 T}] \tag{22}$$

According to Eqs. (7a), (7b), (7c),(7d) and (8), the Fermi level E_F with the presence of piezopotenital is given by:

$$E_F = E_{F0} - \frac{q^2 \rho_{piezo} W_{piezo}^2}{2\varepsilon_s} \tag{23}$$

Substituting Eq. (22) and (23) into Eq. (21), we obtain current-voltage characteristics of the piezoelectric p-i-n junction.

$$J = J_{s0}\exp\left(\frac{q^2\rho_{piezo}W_{piezo}^2}{2\varepsilon_s k_0 T}\right)\left[\exp\left(\frac{qV}{2k_0T}\right)-1\right] \tag{24}$$

According to the Equation(24), the current J is an exponential function of piezo-charges ρ_{piezo}, which sign depends on the strain. Hence, not only the magnitude but also the sign of the strain can effectively tune or control the current-voltage of p-i-n device. This is the work mechanism of the p-i-n junction based on piezoelectronic effect.

3. Microwave and piezophototronic devices based on p-i-n diode

3.1 Piezotronic p-i-n diode for microwave devices

The high-frequency characteristic of p-i-n diode play important role in microwave application. The typical equivalent circuit model (ECM) is described in Refs. [15 ,16]. The basewidth of i-region is divided into two main regions-depleted and undepleted. Each of them is represented by R and C elements (subscripts j and i corresponding to the depleted and undepleted regions). For simplicity, the resistances of p^+ and n^+ layer are neglected, and the fraction of depleted region length in n^+ layer can be neglected. The nonlinear characteristics of p-i-n diode are calculated using algebraical equations given below.

The capacitances of the two base regions are [10]:

$$C_j = \frac{\varepsilon\varepsilon_0 S}{W_j} \tag{25a}$$

$$C_i = \frac{\varepsilon\varepsilon_0 S}{W - W_j} \tag{25b}$$

where S is the diode cross section area, W is the basewidth of the diode, W_j is the width of depletion region in i-layer.

$$W_j = \sqrt{\frac{2\varepsilon\varepsilon_0\varphi_b}{qN}} \tag{26}$$

where φ_b is the barrier (built-in) potential, N is the base doping concentration.

The resistance of depleted and undepleted region are given by $R_i = \frac{R_{i0}R_{i1}}{R_{i0}+R_{i1}}$, where R_{i0} and R_{i1} are small-signal and large-signal resistance of undepleted region respectively.

$R_j = \dfrac{R_{j0} R_{j1}}{R_{j0} + R_{j1}}$, where R_{j0} and R_{j1} small-signal and large-signal resistance of depleted region respectively.

Thus the width of depletion region in i-layer W$_j$ can be obtained as:

$$W_j = \sqrt{\frac{2\varepsilon\varepsilon_0 \varphi_b}{qN}} = \sqrt{\frac{2\varepsilon\varepsilon_0}{qN}\left(\frac{q}{2\varepsilon_s}(N_A W_{Dp}^2 + N_a W^2 + \rho_{piezo} W_{piezo}^2 + N_D W_{Dn}^2)\right)} \\ = \sqrt{\frac{N_A W_{Dp}^2 + N_a W^2 + \rho_{piezo} W_{piezo}^2 + N_D W_{Dn}^2}{N}} \tag{27}$$

This equation means the depleted width is a function of the piezocharges, the sign of which depends on the strain (tensile versus compressive). Therefore, the depleted width of the i-layer can be tuned or controlled not only by the magnitude of the strain but the sign of the strain.

Furthermore, the capacitance of junction can be obtained as:

$$C_j = \frac{\varepsilon\varepsilon_0 S}{W_j} = \frac{\varepsilon\varepsilon_0 S}{\sqrt{\dfrac{N_A W_{Dp}^2 + N_a W^2 + \rho_{piezo} W_{piezo}^2 + N_D W_{Dn}^2}{N}}} \tag{28}$$

The capacitance also can be tuned or controlled by the piezocharges created by external strain, thus the microwave characteristic of the circuit can be controlled by the external strain exactly. This is the mechanism of piezotronic p-i-n diode for microwave application. It must be noted that Wpiezo can also turn the the frequency characteristic of p-i-n diode by changing the capacitance of the diode. W$_j$ and Cj are calculated with typical material constants: piezoelectric constant $\mathbf{e}_{33}$=1.22 Cm^{-2} relative dielectric constant ε_s=8.91, the width of piezo-charges W_{piezo}=0.25 nm, and the temperature T =300 K. The acceptor concentration N_A and donor concentration N_D are 10^{19} cm^{-3}, base concentration N_a is 10^{13} cm^{-3}, the width of i-layer W is 150 nm, and the recombination coefficient r_n is 6.3×10^{-8} cm^{-3}.

Fig.3(a) shows Cj of per unit area with applied strain varied from -0.004% to 0.008%. The W$_j$ as a function of external applied strain varied from -.004% to 0.004%, and as shown in insert.

The frequency equation of the p-i-n junction is $f = \frac{1}{2\pi RC}$. While R is constant, we can obtain frequency property with applied strain, as showed in Fig. 4. The frequency with presence of piezo-charge is

$$f_{piezo} = \frac{1}{2\pi R} \frac{\sqrt{(N_A W_{Dp}^2 + N_a W^2 + \rho_{piezo} W_{piezo}^2 + N_D W_{Dn}^2)/N}}{\varepsilon\varepsilon_0 S} \tag{29}$$

Fig.3(b) describes relative frequency f_{piezo} / f varied with external strain, where f is the frequency without applied strain. It is obviously that sensitivity of frequency change with various strain. The change of frequency increases monotonically with strain.

3.2 Piezophototronic photodetector based on the p-i-n diode

Optical excitation can created electron-hole pairs in p-i-n diode. While $h\nu > E_g$ (where $h\nu$ is the photon energy, and E_g is the band gap of semiconductor), electron-hole pairs induced by optical excitation will have an additional contribution to the total current across the junction [17]:

$$I_{op} = qAg_{op}(L_n + L_p + W) \tag{30}$$

where A is the area of the junction, and g_{op} is the light generation rate, W is the depletion width(the i-region width), L_n and L_p are electron diffusion length and hole diffusion length respectively.

Then the total current of piezoelectric p-i-n junction is given by:

$$J = J_{s0} \exp\left(\frac{q^2 \rho_{piezo} W_{piezo}^2}{2\varepsilon_s k_0 T}\right)\left[\exp\left(\frac{qV}{2k_0 T}\right) - 1\right] - qAg_{op}(L_n + L_p + W) \tag{31}$$

The open circuit voltage V_{oc} is given as:

$$V_{oc} = \frac{2k_0 T}{q} \ln\left[\frac{qAg_{op}(L_n + L_p + W)}{J_{s0} \exp\left(\frac{q^2 \rho_{piezo} W_{piezo}^2}{2\varepsilon_s k_0 T}\right)} + 1\right] \tag{32}$$

Fig. 4(a) shows the current in illumination condition as a function of the externally applied voltage V with various strain. The strain can turn or controll the the transported current. The open circuit voltage (V_{oc}) change with applied strain, as shown in Fig.4(b).

3.3 Piezophototronic p-i-n LED

The piezophototronic LED can be designed based on p-i-n diode. The luminescence can be turned or controlled by applied strain. The optical power density P_{optic} is a non-linear function of the current density J in led. This feature can be used to design high sensitivity strain sensor. For example, the optical power density P_{optic} can be assumed as a typical nonlinear function: power law function, as shown in our previous works [5]. According to Equ. (24), the optical power density P_{optic} can be obtained as:

$$P_{\mathbf{optic}} = \beta J^{b} = \beta\{J_{s0}\exp(\frac{q^{2}\rho_{piezo}W_{piezo}^{2}}{2\varepsilon_{s}k_{0}T})[\exp(\frac{qV}{2k_{0}T})-1]\}^{b} \tag{33}$$

where β is a constant describing on device materials and structures, $b = 1$ and $b \neq 1$ correspond to linear and nonlinear function, respectively. The typical parameter in experimental value of piezophototric LED is 1.6 [18].

Fig.5(a) shows J/J_{s0} changes with applied voltage V , while strain varies from -1% to 1%. Relative light intensity as a function of applied voltage at various applied strain (–1% to 1%) is showed in Fig.5(b), and the inset shows relative external quantum efficiency as a function of applied strain. The external strain can effectively tune the current of the device.

The calculation results of intensity and applied voltage with various strains from -0.08% to 0.08% is showed in Fig.5(c). The relative light intensity as a function of applied strain (–0.04% to 0.04%) at a fixed forward bias voltage of 0.9 V is shown in Fig.5(d). The inset shows the external quantum efficiency as a function of applied strain with linear approximation, parabolic approximation, and fitting parameter from previous experiments data.

4. Conclusion

In summary, we have presented the theoretical frame work of piezotronic p-i-n junction, and obtained a quantitative analysis of both piezotronic microwave diode, piezophototronic detector and piezophototronic LED. Piezo-charges induced the external strain play an important role in tunning/controlling the transportation of carriers in p-i-n structure devices.The current-volatge and frequency characteristics can be changed by piezo-potential.

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Table of Symbols

Symbol	Description	Unit
$\boldsymbol{\sigma}$	Stress	
$\mathbf{c}_{\mathbf{E}}$	Elasticity tensor	
D	Electric displacement	C/m
k	Dielectric tensor	
$\boldsymbol{S}_{jk}$	Strain	Pa
P	Polarization vector	
$(\mathbf{e})_{ijk}$	Piezoelectric tensor	C/m^2
E	Electric field	N/C
ψ_i	Electric potential distribution	V
ρ	Charge density distribution	/cm^3
N_A	Acceptor concentration of p-type	/cm^3
N_a	Acceptor concentration of i-region	/cm^3
ρ_{piezo}	Density of polarization charges	/cm^3
W_{Dp}	Depletion width in p-side	m
W_{Dn}	Depletion width in n-side	m
W	Width of i-region	m
W_{piezo}	Distribution width of piezo-charges	m
r_n	Electron recombination coefficient	cm^3/s
r_p	Hole recombination coefficient	cm^3/s
r	Recombination coefficient	cm^3/s
U	Recombination rate	/cm^{3}s
N_t	Concentration of recombination centre	/cm^3

n_i	Intrinsic carrier density	$/\mathrm{cm}^3$
n	Electron concentration	$/\mathrm{cm}^3$
p	Hole concentration	$/\mathrm{cm}^3$
k_0	Boltzmann constant	J/K
T	Temperature	K
V	Voltage	V
τ	Lifetime of carriers	s
J_r	Forward current density	$\mathrm{A/cm}^3$
J_s	Reverse current density	$\mathrm{A/cm}^3$
J	Total current density	$\mathrm{A/cm}^3$
P_0	Hole concentration in equilibrium	$/\mathrm{cm}^3$
P_1	Hole concentration in non-equilibrium	$/\mathrm{cm}^3$
N_v	Effective density of states in the valance band	$/\mathrm{cm}^3$
E_V	Valance band	eV
E_t	Band of recombination centre	eV
E_F	Fermi level	eV
E_{F0}	Fermi level with the absence of piezocharges	eV
J_{s0}	Saturation current density with the absence of piezocharges	$\mathrm{A/cm}^3$
ε_s	Permittivity of semiconductor	F/m
ε_0	Permittivity of vacuum	F/m
q	Electron	C
C_j	Capacitance of depletion region	F
C_i	Capacitance of non-depletion region	F

W_j	Width of depletion region in i-layer	m
φ_b	Barrier (built-in) potential	eV
N	Base doping concentration	/cm^3
R_i	Resistance of depleted region	Ω
R_j	Resistance of undepleted region	Ω
R_{i0}	Small-signal resistance of undepleted region	Ω
R_{i1}	Large-signal resistance of depleted region	Ω
R_{j0}	Small-signal resistance of depleted region	Ω
R_{j1}	Large-signal resistance of depleted region	Ω
S	Diode cross section area	m^2
f	Frequency	Hz
f_{piezo}	Frequency with presence of piezo-charge	Hz
I_{op}	Optical current density	A/cm^3
A	Area of the junction	m^2
L_n	Electron diffusion length	m
L_p	Hole diffusion length	m
$\boldsymbol{V_{oc}}$	Open circuit voltage	V
P_{optic}	Optical power density	J/cm^3

Figure Caption:

Figure 1. Schematic of (a) a typical p-i-n nanowire diode, a piezotronic diode with (b) compressive and (c) tensile strain, where the color code represents the distribution of piezopotential at the n-type nanowire. The red side has a higher piezopotential, while the blue side is a low piezopotential side.

Figure 2. Piezoelectric p-i-n junction with the presence of piezocharges in voltage V=0 (thermal equilibrium). (a) the distribution of piezocharges, acceptor charges, and donor charges. (b) Electric field, (c) potential distribution and d) Energy band diagram with the presence of piezoelectric charges, dashed lines represents the energy band without the piezoelectric charges and solid lines indicates the cases when piezopotential is applied on the n-type side.

Figure 3. (a) The depleted width in i-region and various applied strain (-0.005%-0.005%). (b) The capacitance of the i-region as a function of applied strain (-0.005%-0.005%). Insert is modified frequency sensitivity varies with external strain.

Figure 4 (a) Calculated current-voltage characteristics of a piezophotodetector based on p-i-n diode under various strain changes from -1% to 1%. (b) The open voltage of the piezo-photodetector as a function of applied strain (-1%-1%).

Figure 5. (a) Calculated current-voltage characteristics of piezo-LED with a p-i-n structure when the applied strain changes from -1% to 1%. (b) Relative light intensity as a function of applied voltage at various applied strain (-1%-1%). The insert is relative external quantum efficiency as a function of applied strain. (c) Calculated relative intensity–voltage curves of the p-i-n LED at various applied strain (–0.08% to 0.08%). (d) Relative light intensity as a function of applied strain (–0.04% to 0.04%) at a fixed forward bias voltage of 0.9 V. The insert is relative external quantum efficiency as a function of applied strain at a fixed forward bias voltage of 0.9 V with linear approximation, parabolic approximation, and fitting parameter from our previous experiments data.

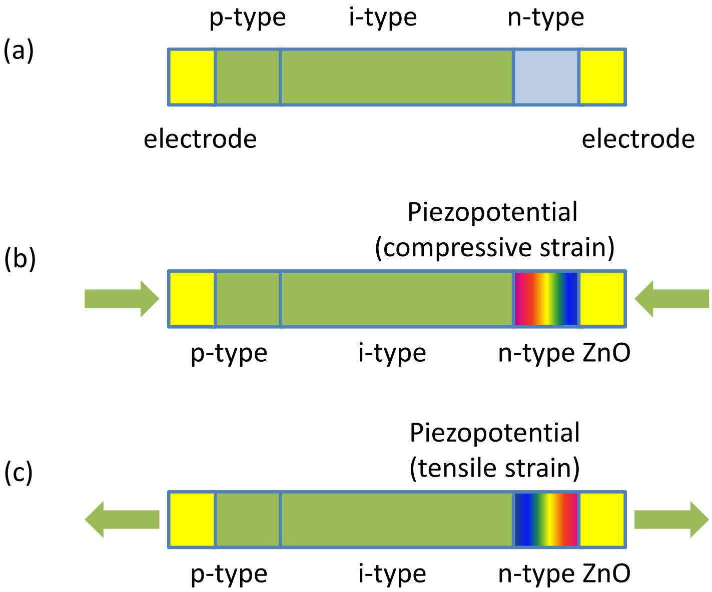
(a)
p-type
i-type
n-type
electrode
electrode
(b)
Piezopotential
(compressive strain)
p-type
i-type
n-type ZnO
(c)
Piezopotential
(tensile strain)
p-type
i-type
n-type ZnO

Fig.1

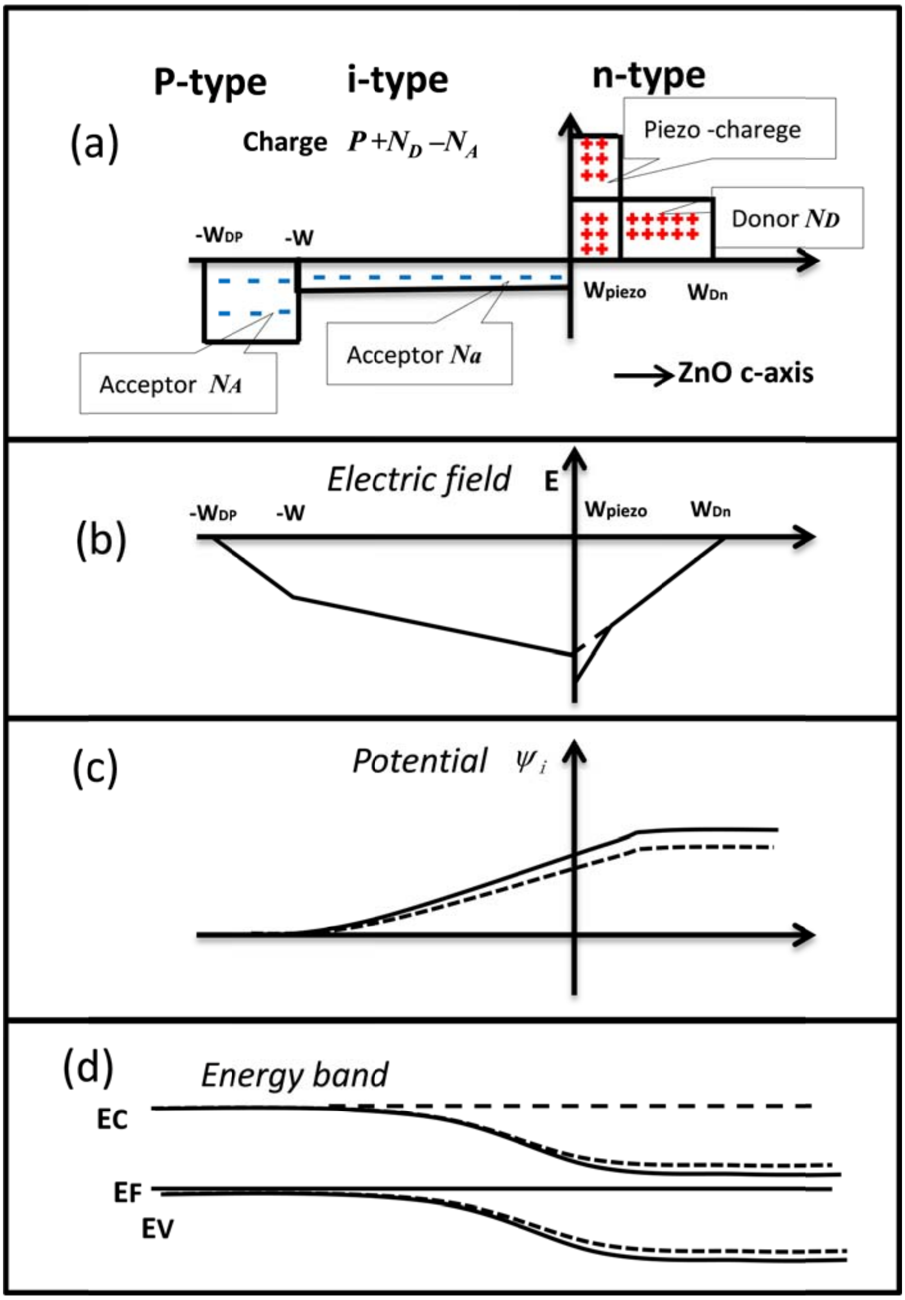
P-type
i-type
n-type
(a)
Charge $P+N_D-N_A$
Piezo -charege
Donor N_D
-W_DP
-W
W_piezo
W_Dn
Acceptor N_A
Acceptor N_a
ZnO c-axis
(b)
Electric field
E
-W_DP
-W
W_piezo
W_Dn
(c)
Potential ψ_i
(d)
Energy band
EC
EF
EV

Fig.2

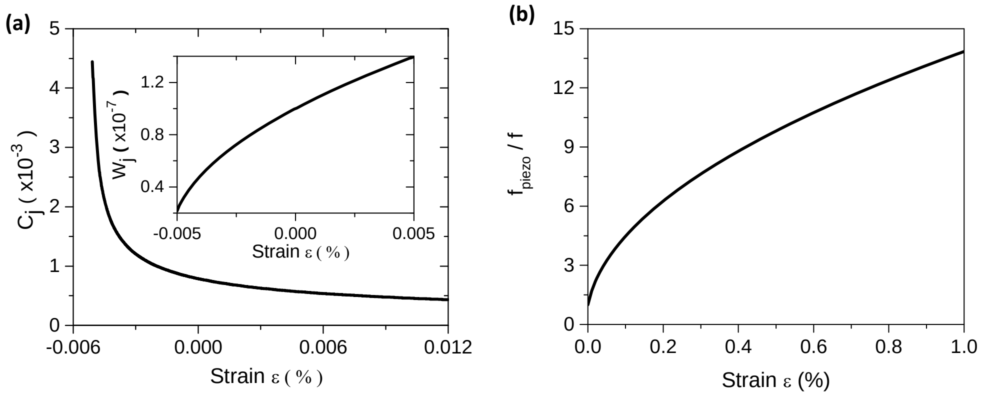
(a)
C_j (x10^{-3})
0
1
2
3
4
5
-0.006
0.000
0.006
0.012
Strain ε (%)
W_j (x10^{-7})
0.4
0.8
1.2
-0.005
0.000
0.005
Strain ε (%)
(b)
f_{piezo} / f
0
3
6
9
12
15
0.0
0.2
0.4
0.6
0.8
1.0
Strain ε (%)

Fig.3

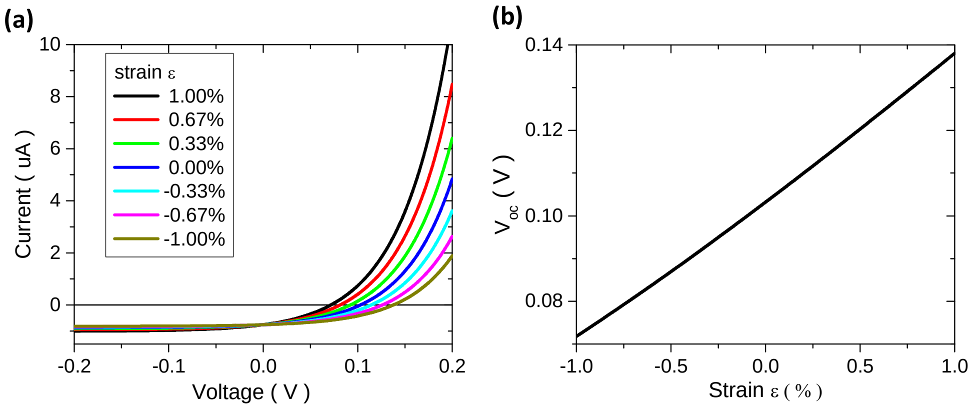
(a)
Current (uA)
0
2
4
6
8
10
-0.2
-0.1
0.0
0.1
0.2
Voltage (V)
strain ε
1.00%
0.67%
0.33%
0.00%
-0.33%
-0.67%
-1.00%
(b)
V_{oc} (V)
0.08
0.10
0.12
0.14
-1.0
-0.5
0.0
0.5
1.0
Strain ε (%)

Fig.4

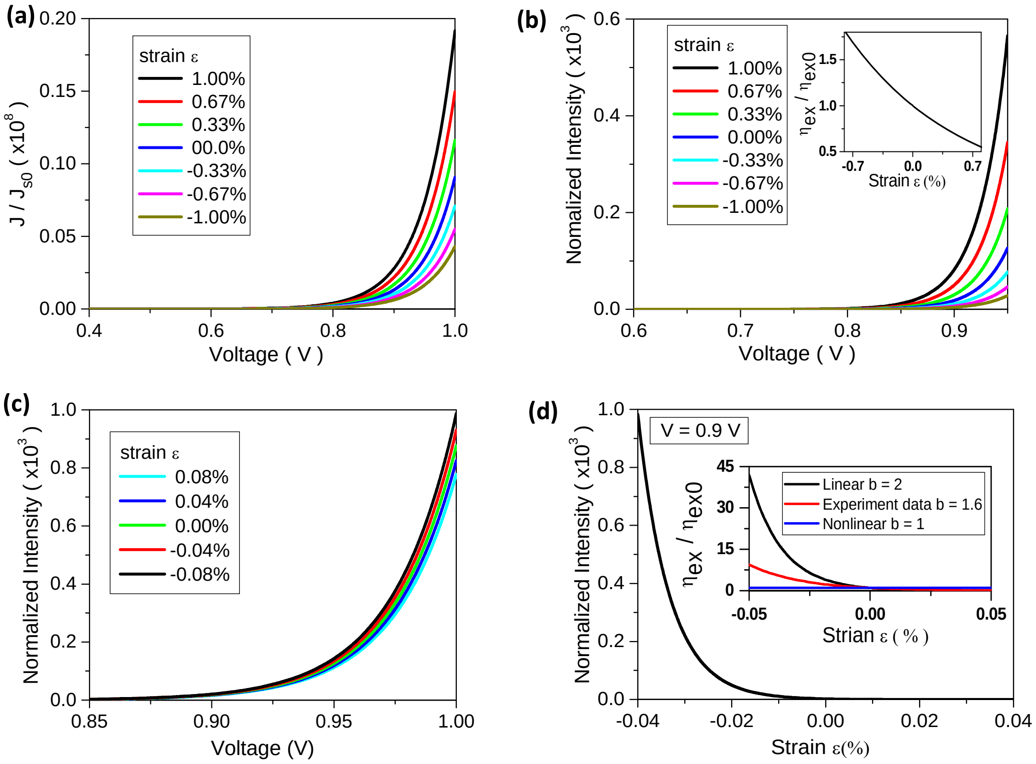
(a)
J / J_s0 (x10^8)
0.20
0.15
0.10
0.05
0.00
0.4
0.6
0.8
1.0
Voltage (V)
strain ε
1.00%
0.67%
0.33%
00.0%
-0.33%
-0.67%
-1.00%
(b)
Normalized Intensity (x10^3)
0.6
0.4
0.2
0.0
0.6
0.7
0.8
0.9
Voltage (V)
strain ε
1.00%
0.67%
0.33%
0.00%
-0.33%
-0.67%
-1.00%
η_ex / η_ex0
1.5
1.0
0.5
-0.7
0.0
0.7
Strain ε (%)
(c)
Normalized Intensity (x10^3)
1.0
0.8
0.6
0.4
0.2
0.0
0.85
0.90
0.95
1.00
Voltage (V)
strain ε
0.08%
0.04%
0.00%
-0.04%
-0.08%
(d)
Normalized Intensity (x10^3)
1.0
0.8
0.6
0.4
0.2
0.0
-0.04
-0.02
0.00
0.02
0.04
Strain ε(%)
V = 0.9 V
η_ex / η_ex0
45
30
15
0
-0.05
0.00
0.05
Strian ε (%)
Linear b = 2
Experiment data b = 1.6
Nonlinear b = 1

Fig.5