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Dynamic model for piezotronic and piezo-phototronic devices under low and high frequency external compressive stresses

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Abstract
In this work, we aim to establish a theoretical method for modelling dynamic characteristics of piezotronics and piezo-phototronic devices. By taking the simplest piezotronic device—PN junction as an example, we combine the small signal model and the unified approach to investigate its diffusion capacitance and conductance when it is under both low and high frequency external compressive stresses. This approach is different from the traditional considerations that treat the piezopotential as a static value. Furthermore, we expand the theory into piezo-phototronic devices e.g. a light emitting diode (LED). The dynamic recombination rate and light emitting intensity are quantitatively calculated under different frequencies of external compressive stresses.

Key Words: Piezotronics, Piezo-phototronics, Dynamics, Diffusion capacitance, Recombination rate

1. Introduction
Two emerging physical effects namely piezotronics and piezo-phototronics have been rapidly developed in recent years¹. From the invention of single ZnO (zinc oxide) nanowire generator ² to the demonstration of piezoelectricity in single-layer MoS₂³, from the observation of the coupling between piezoelectricity and photoexcitation in ZnO nanowires ⁴ to the successful applications of using piezopotential in active optoelectronics, such as luminescence devices for adaptive sensing ⁵, LEDs array for pressure imaging ⁶, photodetectors ⁷ ⁸ ⁹, solar cells ¹⁰ ¹¹, and energy conversion ¹², these two phenomena have been evolving toward more attractive research fields, bringing great potential in the development of wearable electronics, robotics, the IOT (internet of things), biomedical engineering and human–machine interfacing ¹³, ¹⁴ ¹⁵ ¹⁶. The piezotronic effect of nanodevices has been thoroughly experimented using various
methodologies\textsuperscript{17}. These achievements could not have been reached without understanding the fundamental physics behind the experimental observations. So far the theory of piezotronics and piezo-phototronics is based on the semi-analytical abrupt junction model \textsuperscript{18}. The first principle simulations of piezotronic transistors have been conducted, which was based on the width changing of the piezoelectrically charged area \textsuperscript{19}. In our previous work \textsuperscript{20}, a quantum scattering model was employed for investigating the ballistic carriers transportation in piezotronics. Meanwhile, numerical simulations using the DFT (density function theory) and FEM (finite element method) have also been conducted to investigate the device interfaces and carriers modulation on piezotronics \textsuperscript{21 22}. These theoretical developments have satisfactorily helped understand the existing experimental works \textsuperscript{23 24}.

So far only the static characteristics of the devices have been simulated, in which the piezopotential was treated as a static value corresponding to a static compressive or tensile stress. In terms of dynamic investigation, models for piezotronics and piezo-phototronics have not been reported. The dynamic analysis for piezotronic and piezo-phototronic devices under a dynamic external force at a high frequency is usually essential in research and development of piezotronic and piezo-phototronic devices. For example in references \textsuperscript{6 23}, authors fabricated an array of LEDs to detect a dynamic pressure by emitting optical light based on the piezo-phototronic effect, where the impact of the frequency of the exerted pressure is important. Moreover, the quantitative dynamic effects due to the piezopotential on the carriers generation, recombination and transportation are not clear \textsuperscript{25}, although these terms are qualitatively used in explaining the experimental works \textsuperscript{10, 26}.

In this work, we develop a novel dynamic model for piezotronics and piezo-phototronics to investigate quantitatively how the dynamic stress affects the carriers generation and recombination processes, and to explore the dynamic light-emitting mechanism in piezo-phototronic LEDs. We use the most basic piezotronic device – a PN junction in the analysis, trying to construct a general model for peizotronic devices subject to dynamic external forces. External forces at both low and high frequencies are considered using a small-signal model together with the unified approach \textsuperscript{27}. Furthermore, we calculate the dynamic recombination rate and light emitting rate in piezotronic and piezo-phototronic LEDs, providing a thorough understanding of the dynamic process of carriers under the piezopotential. The work complements existing theories for piezotronics and piezo-phototronics \textsuperscript{18 14}.

2. Basic theory
Schematically shown in Figure 1, the structure studied here is a typical PN junction with the $n$-area made by ZnO. Due to the piezoelectricity of ZnO, piezoelectric charges will be accumulated at the two ends of the $n$-area of the PN junction when a compressed or tensile force is applied. The width of the distributed piezoelectric charges is denoted by $W_{pz}$, taking $x=0$ at the interface of $P$ and $N$ region. The PN junction is assumed to be metallurgical. The depletion widths on the $N$ and $P$ regions are represented by $W_p$ and $W_n$, respectively. $V_{dc}$ is the forward applied bias. First, we consider the case when $V_{dc}$ is off and only a static compressive force is applied to one end of the $N$ region. The electrical filed across the depletion region of the PN junction can be easily derived, which are given by following equations (1-3).
3. When time-variant compressive stress applied.

Now we assume there is a compressive stress varying as a sinusoidal function applied to the right end of ZnO, i.e. \( F = F_0 + F_1 \sin(\omega t) \), where \( F_0 \) are \( F_1 \) represent amplitudes of the stress. \( \omega \) is the frequency of the varying stress. \( W_p, \rho_{pz}, N_A, N_D \) are all considered to be constants during one period of the applied stress. When the applied stress is varying, the value of generated charges (\( A_d \rho_{pz} \omega, A_d \) denotes the cross-sectional area, a constant for nanowire devices) varies. Hence \( W_{pz} \) varies in the same way as the external applied stress. Only \( W_{pz} \) is varying with the same frequency as \( F \), the static built-in potential is then replaced by

\[
\varphi_{bi}(t) = \frac{e}{2 \varepsilon_s} \left( N_A W_p^2 + \rho_{pz} W_{pz}^2 + N_D W_n^2 + \omega^2 \left( W_{pz0} - W_{pz1} \right) \frac{2 N_A W_p \rho_{pz} W_{pz}}{N_D} \right)
\]

where \( W_{pz0} \) is the width of piezoelectric charge region when only \( F_0 \) is added, and \( W_{pz1} \) is the width of piezoelectric charge region corresponding to \( F_1 \). The equation (7) can be rewritten to

\[
\varphi_{bi}(t) = c_1 + c_2 - c_3 \sin\omega t + c_4 \sin^2\omega t
\]

by taking:

\[
c_1 = \frac{e}{2 \varepsilon_s} N_A W_p^2 + \frac{e}{2 \varepsilon_s} \frac{N_A W_p^2}{N_D}, \quad c_2 = \frac{e}{2 \varepsilon_s} \rho_{pz} W_{pz}^2 + \frac{e}{2 \varepsilon_s} \frac{\rho_{pz} W_{pz}^2}{N_D} W_{pz0} - \frac{e}{2 \varepsilon_s} \frac{2 N_A W_p \rho_{pz} W_{pz}}{N_D} W_{pz0}
\]

\[
(9)
\]
To have a clear picture of the dynamic built-in potential, we have calculated the \( \phi_{bi} \) in Figure 2. The parameters are taken as: \( N_A = 1 \times 10^{16} \) cm\(^{-3} \), \( N_D = 1 \times 10^{15} \) cm\(^{-3} \), \( \varepsilon_s = 8.91 \), \( W_{pz0} = 2 \times 10^{-7} \) cm and \( W_{pz1} = 2 \times 10^{-8} \) cm. In determining \( \rho_{pz} \) we have used the relation: \( \varepsilon_33s_3 = \rho_{pz} W_{pz0} \), in which \( \varepsilon_33 = 1.22 \) C m\(^{-2} \) and \( s_33 = 0.05\% \). The frequency of dynamical compressive force is taken as 1 KHz. From Figure 2, it is seen that the built-in potential varies with time with an approximate sinusoidal pattern. Moreover, we have shown the energy band changing under different compressive stains in Figure 3. The stains are changing from 0.002% to 0.1%; it is seen that the piezoelectric potential and the built-in potential \( \phi_{bi} \) both increase accordingly. It should be noted that due to the change of piezoelectric potential, the width of depletion region also changes mainly from the change of n-region.

Based on the above results, we will consider the cases when the PN junction is forward biased and applied a varied compressive stress at the same time in the followed section. Admittance is the most important index in dynamic analysis of the PN junction. Therefore, we will study the small signal admittance brought by the varying piezoelectrical charges generated by the time-varying compressive stress \( F \).

### 3.1 Low Frequency—small single model

Under the condition of thermal-equilibrium the relationship between minority carrier concentration in the n- part of the junction and majority carrier concentration on the p-side is given by:

\[
p_{n0} = p_{p0} \exp\left(-\frac{e\phi_{bi0}}{kT}\right)
\]  

(11)

where, \( \phi_{bi0} \) is original built-in potential without applying any force and voltage, \( p_{n0} \) is hole concentration in n-side of the junction, \( p_{p0} \) is the hole concentration in p-side, \( k \) is Boltzmann constant and \( T \) is thermal temperature. When the \( V_{dc} \) is applied to the junction, the thermal-equilibrium is broken and the hole concentration in n-side becomes:

\[
p_n = p_{p0} \exp\left(-\frac{e(\phi_{bi0}-V_{dc})}{kT}\right)
\]  

(12)

Now consider the case when there is also a time varied compressive strains existing, we can write the \( p_n \) as:

\[
p_n = p_{p0} \exp\left(-\frac{e(c_1+c_2-c_3\sin\omega t+c_4\sin^2\omega t-V_{dc})}{kT}\right)
\]  

(13)

where we have taken equation (8) into consideration. The equation (13) can be further simplified as:

\[
p_n(x = 0) = p_{p0} \exp\left(\frac{e(V_{dc}' + v_1(t) - v_2(t))}{kT}\right) = p_n(0, t)
\]  

(14)

where \( V_{dc} = V_{dc}' + c_1c_2 \), \( v_1(t) = c_3\sin\omega t \) and \( v_2(t) = c_4\sin^2\omega t \). If we assume \( V_{dc}' = V_{dc} - \phi_{bi0} \), the equation (14) can be rewritten as:

\[
p_n(0, t) = p_{dc}'' \exp\left(\frac{e(v_1(t) - v_2(t))}{kT}\right) \approx p_{dc}'' \left(1 + \frac{v_1(t) - v_2(t)}{V_c}\right)
\]  

(15)
where \( p_{dc} = p_{0n}\exp(eV_{dc}/kT) \), \( kT/e = V_t \), equation (11) and Taylor expansion of the exponential term have been applied, and \( |v_1(t) - v_2(t)| < V_t \) have been assumed. Equation (15) will be taken as the boundary condition. Due to \( c_t < c_j \) in PN junction, the \( v_2(t) \) will be ignored in the following analysis.

The electric field in the neutral \( n \) region is assumed to be zero. Thus, the behavior of the excess minority carriers (holes) that flow from \( p \) region can be described by:

\[
P_x \frac{\partial^2(p_n)}{\partial x^2} + \frac{\partial p_n}{\tau_{po}} = \frac{\partial p_n}{\partial t}
\]

(16)

Since the AC voltage that comes from the time-varying component of the built-in potential can be seen to superimpose on the DC level, we can write the \( \delta p_n = \delta p_{0n}(x) + p_1 e^{j\omega t} \), where \( p_1 \) is magnitude of the AC component of the excess concentration. Substituting \( \delta p_n \) into equation (16), according to a standard small signal analysis for the PN junction, the DC component of the holes diffusion current density can be given by:

\[
f_{p0} = \frac{eD_{p}p_{dc}'}{L_{p}} \left[ \exp \left( \frac{eV_{dc}'}{kT} \right) - 1 \right]
\]

(17)

where \( L_{p}^2 = D_{p}\tau_{po} \) and \( C_{p}^2 = (1 + j\omega\tau_{po})/L_{p}^2 \), \( \tau_{po} \) is the holes lifetime. This only represents the situation at \( x=0 \). The current density phasor for the sinusoidal component of the diffusion current density is given by:

\[
f_p = eD_{p}C_{p} \left[ p_{dc}' \left( \frac{V_{t}}{V_{dc}'} \right) \right] e^{-C_{p}x}
\]

(18)

The equation (18) can be further written as:

\[
f_p = f_{p0}\sqrt{1 + j\omega\tau_{po}} \left( \frac{V_{t}}{V_{dc}'} \right)
\]

(19)

where \( J_{\omega} = eD_{p}p_{dc} \). Likewise, we can derive the current density phasor for minority carrier (electrons) in \( p \) region, which is given by:

\[
f_n = J_{n0}\sqrt{1 + j\omega\tau_{po}} \left( \frac{V_{t}}{V_{dc}'} \right)
\]

(20)

Combining equations (19) and (20), the PN junction admittance can be derived, that is

\[
Y = \frac{J_{p0} + J_{n0}}{I_p} = \left( \frac{1}{\omega} \right) \left[ f_{p0}\sqrt{1 + j\omega\tau_{po}} + f_{n0}\sqrt{1 + j\omega\tau_{n0}} \right]
\]

(21)

If the AC signal induced by dynamic compressive stress is not large, i.e. \( \omega \tau_{po} < 1 \) and \( \omega \tau_{n0} < 1 \) (\( \omega \) is ignored as \( \tau \approx 10^{-7} \) s). The equation (21) can be written as: \( Y = g_{dc} + j\omega C_{dc} \), where \( g_{dc} \) and \( C_{dc} \) are diffusion conductance and diffusion capacitance, respectively. Specifically, \( g_{dc} = (1/2V)(I_{p0} + I_{n0}) \) and \( C_{dc} = (1/2V)(I_{p0}\tau_{po} + I_{n0}\tau_{n0}) \).

The equivalent circuit diagram of the studied PN junction is shown in Figure 4, where dynamic compressive forces are applied. Generally, the \( C_{dc} \) is replaced by a series of piezoelectric diffusion capacitors, i.e. \( C_{pd0}, C_{pd1}, C_{pd2} \ldots \). It is true that all the periodic dynamic external forces applied can be expressed via Fourier expansion with each sinusoidal term leading to one-to-one corresponding diffusion capacitors. \( C_{j} \) is junction capacitance, \( r_d \) is resistor of the PN junction, and \( r_s \) represents the resistor of the external circuit. \( I_{p0} \) is the external current. Based on the above analysis, the admittance \( Y \) under a dynamic force with the frequency varying in [1 Hz, 1 KHz] is numerically calculated, where \( g_{dc} \) and \( C_{dc} \) are approximately to be 16.8 Ω and 2.97 nF, respectively, shown in Figure 5. Figure 5 shows the admittance \( Y \) (from the equation (21))
when the device is under the stress at low frequency. It illustrates how the admittance is formed by conductance $g_d$ and diffusion capacitance $C_d$ induced by the external stress. As $Y$ is a complex number, we only show few points in the figure. The unit of $g_d$ is $1/\Omega$. Under the small signal model, the dynamic compressive force introduces DC components $c_1$ and $c_2$ which modulate the external voltage $V_{dc}$, therefore changing the currents $I_{dc}$ and $I_{ph}$, which are closely related to $Y$.

To see how the external compressive stress affects the current output, we have calculated the case when $V_{dc}=1V$ and $\omega=10Hz$ with other parameters unchanged. The result is shown in Figure 6. It is seen that an AC output with the same frequency as the external compressive stress when there is only $V_{dc}$ applied, which means that the external stress can modulate the current output of the device and acts as an alternating voltage source. The DC output component is indicated in Figure 6. It should be noted that this DC component is different with the one provided only by $V_{dc}$. In other words, the external stress not only adds the AC component but also modulates the DC component.

### 3.2 High Frequency

For high frequency external forces, we employ the unified approach $^{27}$ for analyzing the dynamic characteristics. When the compressive force is applied at a high frequency, the excess carrier concentration in the $n$ region is then expected to be a more general form:

$$
\delta p_n(x, t) = \sum_{k=1}^{\infty} \delta p_{nk}(x) e^{ik\omega t}
$$

(22)

Inserting above expression into equation (16) considering the orthogonality of harmonics, the general solutions for $\delta p_{nk}(z)$ and $\delta n_{pk}(z)$ (excess carrier concentrations of holes in $n$ region and electrons in $p$ region when the external voltage is applied) can be derived:

$$
\delta p_{nk}(x) = C_{pk}^+ \exp \left( A_{pk} \frac{x-W_n}{l_p} \right) + C_{pk}^- \exp \left( A_{pk} \frac{x-W_n}{l_p} \right)
$$

(23)

where $C_{pk}^+$ and $C_{pk}^-$ are constants for each harmonics and $A_{pk}=a_{pk}+ib_{pk}$ with:

$$
a_{pk} = \frac{1}{\sqrt{2}} \sqrt{1 + \sqrt{1 + (k\omega l_p)^2} }, \quad b_{pk} = \frac{k\omega l_p}{2a_{pk}}
$$

(24)

When the thickness of the neutral part of the PN junction is much larger than the width of the depletion, i.e. $d_n>>W_n$, the $C_{pk}^-$ in equation (23) should be 0 so that $\text{Re}A_{pk}=a_{pk}$ can be satisfied. The constant $C_{pk}^+$ in equation (23) can be found by applying conventional injection boundary conditions $\delta p_{nk}(W_n, t)=p_{sof}(t)$, in which $f(t)=exp(qv(t)/kT)-1$ with $v(t)=p_{dc}''+v_1(t)-v_2(t)$. Then $C_{pk}^+$ is given by:

$$
C_{pk}^+ = p_{n0} F_k, \quad F_k = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(t) e^{-ikt} dt
$$

(25)

Substituting $f(t)$ into $F_k$, it arrives:

$$
F_0 = I_0 (\beta V_-) \exp (\beta V_0) - 1; \quad F_k = F_{-k} = I_k (\beta V_-) \exp (\beta V_0)
$$

(26)

where in equation (26) the modified Bessel functions have been introduced, which is defined by:

$$
I_k (\beta V_-) = \frac{1}{\pi} \int_{0}^{\pi} e^{\beta V_- \cos \omega t} \cos k\omega t \, d\omega
$$

(27)

In equations (26) and (27), $\beta=e/kT$, $V_-$ represents the amplitude of the time-varying signal that
is created by time varied compressive stress. Taking equations (23-27) together into consideration, the $\delta p_n(x,t)$ is finally given by:

$$\delta p_n(x,t) = p_{n0} \sum_{k=-\infty}^{\infty} F_k \exp(-A x / L_p) e^{ik\omega t}$$

(28)

Likewise, the excess carrier of electron in $p$ region also can be derived, which is given by:

$$\delta n_p(x,t) = n_{p0} \sum_{k=-\infty}^{\infty} F_k \exp(A x / L_n) e^{ik\omega t}$$

(29)

The current flowing through the junction is then given by:

$$J(t) = -qD_p \frac{\partial \delta p_n}{\partial x} \bigg|_{x=W_n} A + qD_n \frac{\partial \delta n_p}{\partial x} \bigg|_{x=-W_p} A$$

(30)

Based on the reference 27, the dynamic characteristics of the PN junction, i.e. dynamic conductance $g_d$ and diffusion capacitance $C_d$ for the P+N type junction are

$$g_d(\omega, V_\omega) = \frac{1}{\sqrt{2}} \frac{I_s(\beta V_\omega - V_\omega)}{\beta V_\omega / 2} g_{d0}(V_0)$$

(31)

$$C_d(\omega, V_\omega) = \frac{1}{\sqrt{2}} \frac{I_s(\beta V_\omega - V_\omega)}{\beta V_\omega / 2} C_{d0}(V_0)$$

(32)

where $g_{d0}(V_0)=2/\tau_p C_{d0}(V_0)=J_s \exp(\beta V_0)/(kT/e)$. In this work, the $V_0=V_{dc}$ and $V_\omega \approx c_3$, with $c_4$ assumed to be a much smaller value in our case. By setting $k=0$, we have DC current $J_0$ from equation (30). It is noted that the dynamic compressive force affects the $J_0$ as well as dynamic part of overall external current.

Numerically, we have investigated the DC current $J_0$ under compressive forces with different amplitudes, indicated by different initial piezoelectric charge width $W_{pz1}$ shown in Figure 8, to reveal that the static current changes with the applied dynamic compressive force. As seen in Figure 8, $V_{dc}$ is taken in the range of [0, 1.3V], however, due to the dynamic built-in potential introducing other DC voltage terms, i.e. $c_1$ and $c_2$, the actual voltage applied $V_{dc''}$ is changing with different compressive forces. Specifically, the $J$-$V$ curve shifts due to various piezoelectrically induced depletion width.

Subsequently, we have calculated the dynamic characteristics, i.e. diffusion capacitance $C_d$ and diffusion conductance $G_d$ shown in Figure 9. As the $C_d$ and $G_d$ are closely related to the frequency $(\omega_0)$ of dynamic compressive force, we then vary the $\omega_0$ in a higher range $[1x10^7, 1x10^{10}]$ to reveal the frequency dependence of $C_d$ and $G_d$. As different dynamic compressive forces cause different initial stains $\epsilon_0$, it is obvious that $G_d$ increases with $\omega_0$ and sensitive to the initial dynamic compressive strain. The $C_d$ on the other hand decreases sharply at the lower range of $\omega_0$ and saturates as $\omega_0$ becomes higher. It is sensitive to the initial dynamic compressive strain. In contrast to the static case, we have derived the relation between the diffusion capacitance and the dynamic external stress. By analysing the diffusion capacitance, the dynamic characteristics of piezoelectric device can be obtained. The equations of the diffusion capacitance for the stresses with low and high frequencies are described respectively. For high frequency stresses, both dynamic conductance $g_d$ and diffusion capacitance $C_d$ vary with the
4. Dynamic analysis of recombination process in piezotronics and piezo-phototronics

The piezopotential affects the recombination process happening in the depletion region, and the recombination process subsequently affects the carriers transportation and electron-photon interactions in piezotronics and piezo-phototronics. Therefore, understanding the mechanism of the recombination subject to the piezotronic effect is essential. In the PN junction studied in previous sections with one of its n-part made by the ZnO, the recombination process happening in the depletion region is mainly attributed to the defect assisted bulk and surface recombination-generation process, which is given by:

\[ \mathcal{R} = \frac{c_n c_p n_i (np - n_i^2)}{c_n (n + n_i') + c_p (p + p_i')} \]  

By taking \( n = n_i \exp((E_{fn} - E_{fi})/kT) \) and \( p = n_i \exp((E_{fi} - E_{fp})/kT) \), the recombination rate \( \mathcal{R} \) in depletion region when the device is applied by a compressive force can be calculated. The calculation results are shown in Figure 10. It is seen that the \( \mathcal{R} \) has a peak at the interface of PN junction, and the peak increases as the compressive strain increases. The position of the maximum \( \mathcal{R} \) shifts slightly to the right when the compressive strain is increased. Dynamically, we have also calculated the maximum \( \mathcal{R} \) subject to dynamic compressive force with different frequencies \( f = 1 \text{ Hz} \) and \( f = 10 \text{ Hz} \) in Figure 11. When there is a dynamic compressive force with certain frequency is applied, the recombination rate \( \mathcal{R} \) is dynamically varying with the same pattern as the applied force. The calculation provides a quantitative analyzing method on the impact on the recombination and transportation process due to the piezotronic effect.

In a typical PN junction, the total forward-bias current is the sum of recombination and the diffusion current. Therefore, different external compressive stresses will lead to the different recombination rates, and in turn modulating the total current as well as the light emitting intensity in piezotronic LEDs. For illustrating on how the dynamic compressive force modulates the light emitting intensity in piezotronic LEDs, we have conducted the following analysis.

As shown in Figure 7, we treat the dotted box as the active region in which light emitting and recombination are happening and related. In this region, the rate equation of carriers (holes) can be modeled as:

\[ \frac{dp}{dt} = \eta I - [A(p - p_i) + B(p^2 - p_i^2) + C(p^2 - p_i^2)] \]  

where \( A \) is coefficient of defect assisted recombination, \( B \) and \( C \) are the coefficients of radiative recombination-generation and Auger recombination, respectively. \( p_i \) is intrinsic electron concentration. \( \eta \) is the fraction of the total current that is due to the recombination in the active region. \( V_a \) is the volume of the active region. \( I \) is the total current flowing through the external circuit in forward bias direction. Taking the parameters as: \( A = 1 \times 10^7, B = 1 \times 10^{-9}, C = 5 \times 10^{-29}, N_p = 1 \times 10^{17}/\text{cm}^3, N_d = 1 \times 10^{15}/\text{cm}^3, \) initial piezoelectric strain \( \varepsilon_0 = 0.02/100, \) and by fixing \( I = 0.1 \text{ A}, \) we have calculated the number of photons emitted per second in \( V_a \). The result is shown in Figure 12, where six different frequencies of dynamic compressive forces are studied. The light emitting in piezotronics devices is closely related to the dynamic force applied.
Conclusion

To conclude, dynamic built-in potential is induced in the piezotronic PN junction when a dynamic compressive stress is applied. The dynamic built-in potential contributes both DC and AC parts together with the applied external voltage, which can modulate current-voltage characteristics, threshold, diffusion capacitance and conductance. The work has thoroughly investigated these dynamic characteristics under external compressive stresses at both low and high frequencies based on the small signal model and unified approach, respectively. The results are self-consistent and provide a general procedure for treating dynamic phenomenon of piezotronics. The piezotronic PN junction is the fundamental element of the piezo-phototronic LEDs. The work has quantitatively calculated the dynamic recombination rate and light emitting intensity. Unlike the previous work, this work presents detailed results assisting in understanding how the piezo-potential affects the dynamic process of carriers in the piezo-phototronic LEDs.

References

17. Y. Zhang, X. Yan, Y. Yang, Y. Huang, Q. Liao and J. Qi, Advanced Materials 24 (34), 4647-4655 (2012).
27. A. A. Barybin and E. J. P. Santos, Semicond Sci Tech 22 (11), 1225-1231 (2007).

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Additional information
Competing financial interests: The authors declare no competing financial interests.

Figure Captions:
Figure 1. Schematic diagram of the piezotronics effect: a typical PN junction with N part made by ZnO.
Figure 2. Calculation of dynamic built-in potential when there is a dynamic compressed force applied with frequency $\omega_p=1$ KHz.
Figure 3. Energy bands of the studied PN junction under different strains. From red to green, strains are 0.002, 0.005, 0.008 and 0.01.
Figure 4. General equivalent circuit diagram of the studied PN Junction under small signal assumption.
Figure 5. Admittance calculation when the device is under an external compressed
force with frequency varying in [1 Hz, 1 KHz].

Figure 6. Current density calculation when the external compressive stress is at $\omega=10\text{Hz}$.

Figure 7. Minority carriers (holes) concentration changes after diffusing into $n$ region with dynamic compressed force applied. Red box indicates the active region for light emitting in piezophototronics.

Figure 8. Static current–voltage calculation of the PN junction when dynamic compressive force is applied. Three compressive forces with different amplitudes are discussed.

Figure 9. Diffusion conductance (a) and diffusion capacitance (b) subject to different dynamic compressive strains are calculated.

Figure 10. Recombination rated $R$ changes with different strains.

Figure 11. Dynamic recombination rate when there is dynamic compressive force with frequencies 1 Hz and 10 Hz respectively.

Figure 12. Photons emitted per second in active region when dynamic compressive force with different frequencies ($f_1=100\text{Hz}, f_2=300\text{Hz}, f_3=500\text{Hz}, f_4=700\text{Hz}, f_5=900\text{Hz}, f_6=1200\text{Hz}$) applied.