Piezo-phototronics enables tuning and controlling of the electro-optical process

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The inner-crystal piezopotential, generated by the piezoelectric effect as a gate voltage to tune and control opto-electronic processes at the p-n junction, is useful for energy and sensor applications.

Wurtzite materials—such as zinc oxide (ZnO), gallium nitride (GaN), indium nitride (InN), and zinc sulfide (ZnS)—possess a non-central symmetric crystal structure, and they inherently exhibit the piezoelectric effect (charge accumulation under strain). The electric field created inside these materials can significantly change their charge-transport properties, as seen in simple field-effect transistors (FET). These are two-ends-bonded semiconductor wires in which the two electric contacts at the ends are the source and drain. The gate voltage can be applied either at the top of the wire through a gate electrode, or at its bottom on the substrate. When a ZnO nanowire (NW) is strained axially along its length, two effects are typically observed: piezoresistance and piezotronics.

The piezoresistance effect is a consequence of the change in bandgap and density of states in the semiconductor. This effect has no polarity, such that it has an equivalent (identical) effect on the source and drain of the FET. On the other hand, a piezopotential is created along the length of the FET. For an axial-strained NW, the piezoelectric potential continuously drops from one side of the NW to the other, meaning that the electron energy continuously increases from one side to the other. Meanwhile, the Fermi level is flat over the entire NW when equilibrium is attained, since there is no external electrical field. Consequently, the effective barrier height and/or width of the electron energy barrier between ZnO and metal electrode is raised at one side and lowered at the other. It, therefore, has a non-symmetric effect on the source and drain. This is the piezotronic effect.

An improved understanding of the piezotronic effect can be attained by comparing it with the most fundamental structure in semiconductor devices: the Schottky contact and p-n junctions.

Figure 1. Energy-band diagrams illustrating the effects of laser excitation and piezo-electricity on a Schottky-contacted metal-semiconductor interface. (A) Initial band diagram. (B) Band diagram after excitation by a laser of photonic energy that is higher than the bandgap, which is equivalent to a reduction in the Schottky barrier (SB) height. (C) Band diagram after applying a strain in the semiconductor. The piezopotential created in the semiconductor is of low polarity, with the end in contact with the metal. $\phi_{SB}$: Energy at SB. $\phi$: Energy at threshold value. $\phi'$: Increased local SB energy. $E_{piez}$: Piezo-electric energy. $E_F$: Fermi energy.

Continued on next page
Figure 2. Energy-band diagram illustrating the effect of piezo-electricity on a p-n junction, with (black curve) and without (red curve) the piezo-electric effect at the n-type side. The effect of reversing polarity is presented. $E_C$: Conduction band energy. $E_V$: Valence band energy.

When a metal and an n-type semiconductor form a contact, a Schottky barrier (SB, of energy $e\phi_{SB}$) is created at the interface if the work function of the metal is appreciably larger than the electron affinity of the semiconductor (see Figure 1A). Current can only pass through this barrier if the applied external voltage is larger than a threshold value ($e\phi_{SB}$), and its polarity is with the metal-side positive (for n-type semiconductors). If a photonic excitation is introduced, the newly-generated electron-hole pairs not only greatly increase the local conductance, but they also reduce the effective height of the SB as a consequence of charge redistribution (see Figure 1B).

Once a strain is created in the semiconductor that also features piezoelectric properties, a negative piezopotential at the semiconductor side effectively increases the local SB height to $e\phi'$ (increased local SB energy: see Figure 1C), while a positive piezopotential reduces the barrier height. The polarity of the piezopotential is dictated by the direction of the $c$-axis for ZnO. The role played by the piezopotential is to effectively change the local contact characteristics through an internal field, and thus the charge-carrier transport process is tuned (gated) at the metal-semiconductor contact. By considering the change in piezopotential polarity by switching the strain from tensile to compressive, the local contact characteristics can be tuned and controlled by the magnitude and sign of the strain. This is central to piezotronics.

When p- and n-type semiconductors form a junction, the holes in the p-type side and the electrons in the n-type side tend to redistribute to balance the local potential. With the creation of a piezopotential in one side of the semiconductor material under strain, the local band structure near the p-n junction is changed (modified). The creation of piezoelectric charges at the junction region can create a bump or dip near the interface depending on the polarity of the charges. As shown in Figure 2, when the semiconductor side effectively increases the local SB height to $e\phi'$ (increased local SB energy: see Figure 1C), while a positive piezopotential reduces the barrier height. The polarity of the piezopotential is dictated by the direction of the $c$-axis for ZnO. The role played by the piezopotential is to effectively change the local contact characteristics through an internal field, and thus the charge-carrier transport process is tuned (gated) at the metal-semiconductor contact. By considering the change in piezopotential polarity by switching the strain from tensile to compressive, the local contact characteristics can be tuned and controlled by the magnitude and sign of the strain. This is central to piezotronics.

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n-type side is piezo-electric and a strain is applied, the local band structure is greatly changed. This significantly affects charge-carrier flow through and/or temporary trapping at the interface region, a central concept of piezotronics. The piezo-phototronic effect is a coupling between the semiconductor, photonic excitation, and piezoelectricity, which involves tuning and controlling electro-optical processes by a strain-induced piezopotential.

If both the p- and n-type semiconductors exhibit the piezo-electric effect and their polarities are in parallel, the piezopotential across the p-n junction tends to drive the holes in the p-type side, and the electrons in the n-type side towards the junction region. Their recombination possibly results in photonic emission, i.e., piezo-photonics.6

In summary, a piezopotential is created in a piezoelectric material by applying a stress, and is generated by ion polarization in the crystal. Piezo-phototronics is a consequence of three-way-coupling among piezo-electricity, photonic excitation, and semiconductor transport (see Figure 3). This effect enables tuning and controlling of the electro-optical process by a strain-induced piezo-electric potential, with great potential for enhancing the performance of light-emitting diodes, photocells and solar cells,7 as well as photonic detectors.8,9 In the future, effective integration of piezo-phototronic devices with silicon-based complimentary metal-oxide-semiconductor technology will facilitate unique applications in human-computer interfacing, sensing and actuating in nanorobotics, smart and personalized electronic signatures, as well as smart micro- and nanoelectromechanical systems.10

References

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Zhong Lin Wang is the Hightower Chair in Materials Science and Engineering, Regents’ Professor, as well as Engineering Distinguished Professor. He originated and pioneered the fields of piezotronics and piezo-phototronics by introducing the piezo-electric potential-gated charge-transport process, towards fabricating new electronic and opto-electronic devices.