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Piezoelectric Effect, Piezotronics and Piezophototronics: A Review

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***Abstract**: Piezoelectricity, a phenomenon known for centuries, is an effect that is about the production of electrical potential in a substance as the pressure on it changes. Due to the polarization of ions in a crystal that has non-central symmetry, a piezoelectric potential (piezopotential) is created in the crystal by applying a stress. For materials such as ZnO, GaN, and InN in the wurtzite structure family, the effect of piezopotential on the transport behavior of charge carriers is significant due to their multiple functionalities of piezoelectricity, semiconductor and photon excitation. In this article a brief review about piezoelectric effect, piezotronics and piezophototronics are discussed.*

1. Introduction

Piezoelectricity, a phenomenon known for centuries, is an effect that is about the production of electrical potential in a substance as the pressure on it changes. The most well known material that has piezoelectric effect is the provskite structured Pb(Zr, Ti)O3 (PZT), which has found huge applications in electromechanical sensors, actuators and energy generators. But PZT is an electric insulator and it is less useful for building electronic devices. Piezoelectricity has its own field and is being largely studied in the ceramic community. Wurtzite structures, such as ZnO, GaN, InN and ZnS, also have piezoelectric properties but they are not extensively used as much as PZT in piezoelectric sensors and actuators due to their small piezoelectric coefficient. Therefore, the study of wurtzite structures is mainly in the electronic and photonic communities due their semiconductor and photon excitation properties.

In this review, we will explore the piezoelectric effect, piezopotential generated in the wurtzite structures and how to use it to serve as a ‘‘gate’’ voltage for fabricating new electronics. One of the most common electronic devices is a single channel field effect transistor (FET) based on a semiconductor nanowire (NW), in which a source and drain are located at the two ends of the device, and a gate voltage is applied to the channel and the substrate . By applying a source to drain driving voltage, *VDS*, the charge carrier trans- port process in the semiconductor device is tuned/gated by the gate voltage *VG*, which is an externally applied potential. Alternatively, the gate voltage can be replaced by the piezopotential generated inside the crystal (inner potential), so that the charge carrier transport process in FET can be tuned/gated by applying a stress to the device. This type of device is called piezotronic device as triggered or driven by a mechanical deformation action. Alternatively, for a device with Schottky contacts at either or both of the source or drain, by introducing a laser excitation at the source/drain, a coupling has been demonstrated among piezoelectricity, photoexcitation and semiconductor characteristics, leading to the piezo-phototronic effect. This paper is to review the piezoelectric effect and its application in piezotronics and piezo-phototronics..

2. Piezoelectric effect

A piezoelectric substance is one that produces an electric charge when a mechanical stress is applied (the substance is squeezed or stretched). Conversely, a mechanical deformation (the substance shrinks or expands) is produced when an electric field is applied. This effect is formed in crystals that have no center of symmetry. To explain this, we have to look at the individual molecules that make up the crystal. Each molecule has a polarization, one end is more negatively charged and the other end is positively charged, and is called a dipole. This is a result of the atoms that make up the molecule and the way the molecules are shaped. The polar axis is an imaginary line that runs through the center of both charges on the molecule. In a monocrystal the polar axes of all of the dipoles lie in one direction. The crystal is said to be symmetrical because if you were to cut the crystal at any point, the resultant polar axes of the two pieces would lie in the same direction as the original. In a polycrystal, there are different regions within the material that have a different polar axis. It is asymmetrical because there is no point at which the crystal could be cut that would leave the two remaining pieces with the same resultant polar axis.

In order to produce the piezoelectric effect, the polycrystal is heated under the application of a strong electric field. The heat allows the molecules to move more freely and the electric field forces all of the dipoles in the crystal to line up and face in nearly the same direction. The piezoelectric effect can now be observed in the crystal. Example of piezoelectric effect are - If the material is compressed, then a voltage of the same polarity as the poling voltage will appear between the electrodes (a). If stretched, a voltage of opposite polarity will appear (b). Conversely, if a voltage is applied the material will deform. A voltage with the opposite polarity as the poling voltage will cause the material to expand, (c), and a voltage with the same polarity will cause the material to compress (d). If an AC signal is applied then the material will vibrate at the same frequency as the signal (e).

3. Piezotronics and piezophototronics effect

A most simple FET is a two end bonded semiconductor wire, in which the two electric contacts at the ends are the source and drain, and 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 NW is strained axially along its length, two typical effects are observed. One is the piezoresistance effect, which is introduced because of the change in bandgap and possibly density of states in the conduction band. This effect has no polarity so that it has equivalent/ identical effect on the source and drain of the FET. On the other hand, piezopotential is created along its length. For an axial strained NW, the piezoelectric potential continuously drops from one side of the NW to the other, which means that the electron energy continuously increases from one side to the other. Meanwhile, the Fermi level will be flat all over the NW when equilibrium is achieved, since there is no external electrical field. As a result, the effective barrier height and/or width of the electron energy barrier between ZnO and metal electrode will be raised at one side and lowered at the other side, thus, it has a non-symmetric effect on the source and drain. This is the piezotronic effect. A better understanding about the piezotronic effect is to compare it with the most fundamental structure in semiconductor devices: Schottky contact and p—n junction. When a metal and a n-type semiconductor forms a contact, a Schottky barrier (SB) (e φSB) is created at the interface if the work function of the metal is appreciably larger than the electron affinity of the semiconductor (Fig. 1A). Current can only pass through this barrier if the applied external voltage is larger than a threshold value (φ_i) and its polarity is with the metal side positive (for n-type semiconductor). If a photon excitation is introduced, the newly generated electron—hole pairs not only largely increase the local conductance, but also reduce the effective height of the SB as a result of charge redistribution (Fig.1B).

Once a strain is created in the semiconductor that also has piezoelectric property, a negative piezopotential at the semiconductor side effectively increases the local SB height to $e\varphi_1$ (Fig. 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, thus, the charge carrier transport process is tuned/gated at the metal—semiconductor (M—S) 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 of the strain and the sign of strain. This is the core of piezotronics. When a p-type and a 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, the interdiffusion and recombination of the electrons and holes in the junction region forms a charge depletion zone (Fig. 2A). Once an external potential is applied across the junction with the n-type side positive, the width of the charge depletion zone is enlarged, thus, few charge carriers flow across it. But once the p-type side is applied with a positive bias and when the strength of the bias is high enough to overcome the barrier formed by the depletion zone, charge carrier can flow across the junction.

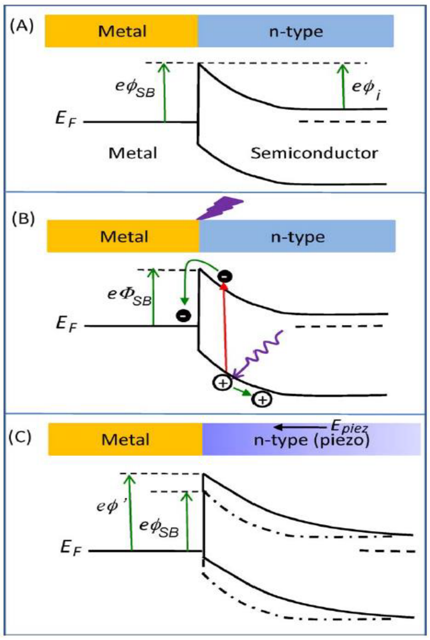

Fig.1. Energy band diagram for illustrating the effects of laser excitation and piezoelectricity on a Schottky contacted metal—semiconductor interface. (A) Band diagram at a Schottky contacted metal—semiconductor interface. (B) Band diagram at a Schottky contact after exciting by a laser that has a photon energy higher than the bandgap, which is equivalent to a reduction in the Schottky barrier height. (C) Band diagram at the Schottky contact after applying a strain in the semiconductor. The piezopotential created in the semiconductor has a polarity with the end in contacting with the metal being low.

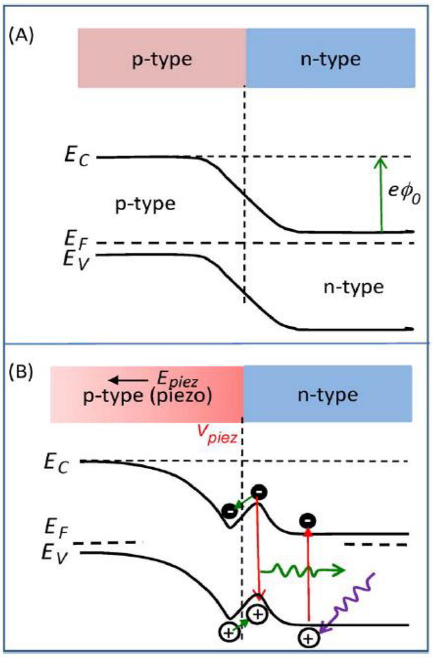

Fig.2. Energy band diagram for illustrating the effect of piezoelectricity on a pn junction. (A) Band diagram at a conventional pn junction made by two semiconductors have almost the same bandgaps. (B) Band diagram of the pn junction with the presence of a piezopotential at the p-type side with a polarity of higher potential at the junction side.

This is the working principle of the pn diode. With the creation of a piezopotential in one side of the semiconductor material under strain, the local band structure near the pn junction is changed/modified. For easy understanding, we include the screening effect of the charge carriers to the piezopotential in the discussion, which means that the positive piezopotential side in n-type material is largely screened by the electrons, while the negative piezopotential side is almost unaffected. By the same token, the negative piezopotential side in p-type material is largely screened by the holes, but leaves the positive piezopotential side almost unaffected. As shown in Fig. 2B for a case that the p-type side is piezoelectric and a strain is applied, the local band structure is largely changed, which significantly affects the characteristic of charge carriers flow through the interface. This is the core of the piezotronic effect. In addition, the holes in the p-type side can drift to the n-type side to combine with the electrons in the conduction band, possibly resulting in an emission of photon. This is a process of piezopotential induced photon emission, e.g., *piezophotonics* . The following conditions may need to be met in order to observe the piezophotonic process. The magnitude of the piezopotential has to be significantly large in comparison to φ_i, so that the local piezoelectric field is strong enough to drive the diffusion of the holes across the pn junction. The straining rate for creating the piezopotential has to be rather large, so that the charge carriers are driven across the interface within a time period shorter than the time required for charge recombination. The width of the depletion layer has to be small so that there are enough charge carriers available in the acting region of the piezopotential. Finally, a direct bandgap material is beneficial for the observation of the phenomenon. The fundamental working principles of the p—n junction and the Schottky contact are that there is an effective barrier that separates the charge carriers at the two sides to across. The height and width of the barrier are the characteristic of the device. In piezotronics, the role played by the piezopotential is to effectively change the width of p—n junction or height of SB by piezoelectricity.

For a material that simultaneously has semiconductor, photon excitation and piezoelectric properties, besides the well known coupling of semiconductor with photon excitation process to form the field of optoelectronics, additional effects could be proposed by coupling semiconductor with piezoelectric to form a field of piezotronics, and piezoelectric with photon excitation to form a field of piezophotonics. Furthermore, a coupling among semiconductor, photon excitation and piezoelectric is a field of *piezo-phototronics* , which can be the basis for fabricating piezo-photonic—electronic nanodevices. The piezo-phototronic effect is about the tuning and controlling of electro-optical processes by strain induced piezopotential (Fig. 3). The applications of piezo-phototronics will be elaborated later.

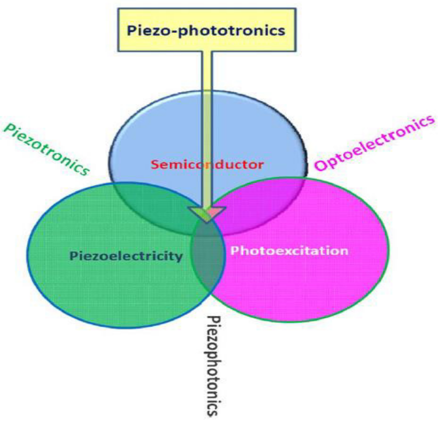

Fig.3. Schematic diagram showing the three-way coupling among piezoelectricity, photoexcitation and semiconductor, which is the basis of piezotronics (piezoelectricity— semiconductor coupling), piezophotonics (piezoelectric— photon excitation coupling), optoelectronics, and piezo-phototronics (piezoelectricity—semiconductor— photoexcitation). The core of these coupling relies on the piezopotential created by the piezoelectric materials.

4. Conclusion

Piezopotential is created in a piezoelectric material by applying a stress, and it is generated by the polarization of ions in the crystal. The introduction of this inner potential in semiconductor materials can significantly change/modify the band structure at a pn junction or metal—semiconductor Schottky barrier, resulting in significant change in the charge transport property. This is the core science of piezoelectricity on electronic and photonic devices. Piezotronics is about the electronics fabricated by using piezopotential as a ‘‘gate’’ voltage for controlling the charge transport process. Its applications have been demonstrated as diode, strain/force/sensors, triggers, and logic gates. Piezo-phototronics is a result of three-way coupling among piezoelectricity, photonic excitation and semiconductor transport. This effect allows tuning and controlling of electro-optical process by strain induced piezoelectric potential, with potential applications in light emitting diode, photocell and solar cell, and photon detector. Although the response time of the piezotronics is slower than the conventional CMOS technology and it is mostly likely to work at lower frequencies, the functionality it offers are complimentary to CMOS technology. An effective integration of piezotronic and piezo-phototronic devices with silicon based CMOS technology, unique applications can be found in areas such as human—computer interfacing, sensing and actuating in nanorobotics, smart and personalized electronic signatures, smart MEMS/NEMS.

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6. References

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