EDITORIAL

Preface to the Special Section on Piezotronics

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For wurtzite structures that have non-central symmetry, such as ZnO, GaN and InN, a piezoelectric potential (piezopotential) is created in the crystal by applying a strain. Owing to the semiconducting and piezoelectric properties of the wurtzite family, the strain-created inner-crystal piezopotential can serve as a "gate voltage" that can effectively tune/control the charge transport across an interface/junction, which has been named the *piezotronic effect*; electronics that are fabricated based on such a mechanism are coined as *piezotronics*,[1–3] with applications in force/pressure triggered/controlled electronic devices, sensors, logic units and memories. Piezotronics is likely to serve as "mechanosensation" for directly interfacing biomechanical action with silicon-based technology and active flexible electronics, which responses/feeds-back/generates electronic control signals in a corresponding substrate-induced mechanical deformation. By using the piezotronic effect, it is shown that the optoelectronic devices fabricated using wurtzite materials can have a much enhanced performance as solar cell, photon detector, or light emitting diode.[2,3]

Two typical effects can be observed when a wurtzite structure is strained. One is the piezoresistance effect, which occurs due to a change in bandgap width and possibly in density of states in the conduction band. This effect has no polarity and as a result it has an identical effect on modifying the source and drain electrodes of a field effect transistor (FET) made by using the material. On the other hand, a piezopotential is created across the materials. The polarization-induced piezoelectric potential continuously drops from one side to the other of the material, indicating that the electron energy continuously increases from one end to the other. The effective barrier height and/or width of the electron energy barrier between ZnO and the metal electrode will hence be increased at one side and decreased at the other side owing to the presence of polarization ionic charges of opposite signs at the two ends. This is the *piezotronic effect*,[4] which has a non-symmetric effect on the source and drain contacts.

A better understanding of the piezotronic effect can be obtained by comparing it with fundamental concepts in conventional semiconductor physics: the Schottky contact and *p-n* junction. When, for example, a metal and a *n*-type semiconductor forms a contact, a Schottky barrier (SB) is created at the interface if the work function of the metal is appreciably larger than the electron affinity of the semiconductor (**Figure 1**a). Current can only pass through this barrier if the applied external voltage is larger than the threshold value and the metal side is positively biased (for an *n*-type semiconductor). The presence of ionic charges introduced by piezoelectric polarization can effectively tune the carrier transport at the interface. If a photon excitation is introduced, the newly generated electron-hole pairs not only increase the local conductance, but also reduce the effective height of the Schottky barrier due to charge redistribution.

Once a strain is induced in the semiconductor which also has piezoelectric property, a negative piezopotential at the semiconductor side effectively increases the local SB height to $e\phi'$ (Figure 1a), whereas a positive piezopotential reduces the barrier height. The polarity of the piezopotential is dictated by the polarization direction of the material. 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 at the metal-semiconductor contact. The local contact characteristics can be tuned and controlled by the magnitude and the polarity of strain, which is the core of piezotronics.

The presence polarization charges at a *p-n* junction can effectively distort the local band structure and consequently affect the carrier transport, separation or recombination (Figure 1b). Applying either a compressive or tensile strain depending on the polarization of the piezoelectric material, the efficiency for charge carrier separation or recombination can be effectively enhanced. By introducing photon excitation, a coupling among semiconductor, photon excitation and piezoelectricity creates a new field of research called piezo-phototronics.[2] The *piezo-phototronic effect* is the tuning and controlling of charge carrier generation, separation or recombination at a *p-n* junction by the strain-induced piezopotential.[5] The effect has been effectively used to improve the performance of LEDs, solar cells, and photon detectors.[6–9]

The piezotronic and piezo-phototronic effects are likely to have following major impacts:

1 Conventional CMOS (complementary metal oxide semiconductor) based logic units are electronically triggered and driven by externally applied "static" electrical voltages, which control the source-drain current by controlling the width of the conducting channel. Piezotronics makes it possible to use

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DOI: 10.1002/adma.201202888

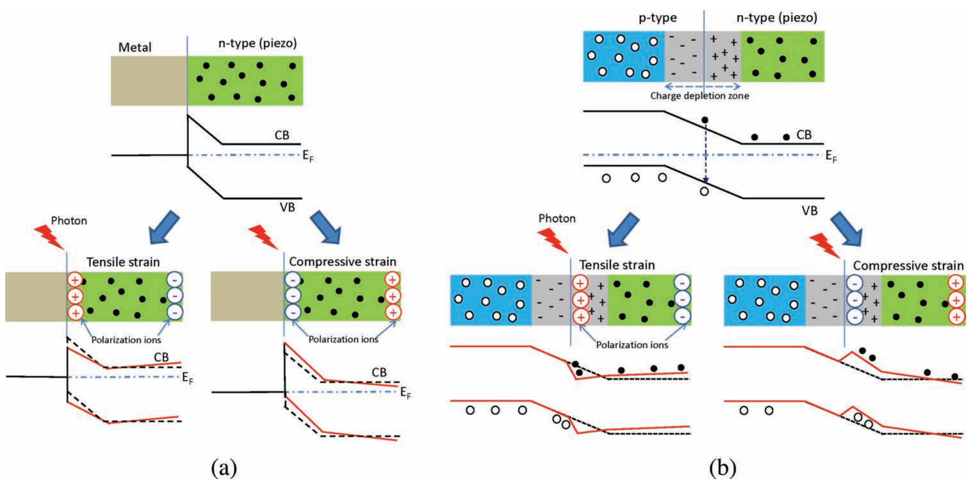

Figure 1. Energy band diagram for illustrating the piezotronic effect at (a) metal-semiconductor contact and (b) *p-n* junction. The presence of piezoelectric induced polarization charges at the interface/junction can greatly influence/control the charge carrier transport. New electronics can be fabricated by using the piezotronic effect. Photon excitation can also be introduced in the process, resulting in three-way coupling among semiconductor, piezoelectricity and photon excitation. This is the piezo-phototronic effect. Note: VB-valence band; CB-conduction band; E_f,— Fermi level.

deformation to control electronics, which is likely to be important for human-CMOS interfacing interfacing.[10,11]

2 MEMS is about the coupling of mechanical and electrical properties. Since mechanical action is the control force in piezotronics, piezotronics and MEMS would have a natural integration. Such an integration not only introduces new materials and nanostructures for smart MEMS, but also leads to a direct interfacing between MEMS and biological systems.

3 The piezotronic transistor is a two-terminal transistor without the presence of a gate electrode.[12] The replacement of an external voltage gating by an inner crystal potential gating makes it possible to fabricate arrays of devices using vertical nanowires that can be individually addressed/controlled. This is advantageous for fabricating a high-density device matrix for electro-mechanical transduction, such as sensors and touch pad technology.

4 The introduction of piezotronics allows the fabrication of active flexible electronics. The current research standard in flexible electronics is to use a flexible substrate but with a design that minimizes or eliminates the effect of substrate deformation to the performance of electronic devices. Such a design is attributed as passive flexible electronics. In contrast, we can use the mechanical deformation induced electronic signal in piezotronics to effectively control the CMOS electronics, resulting in a new emerging field: active flexible electronics, which remain to be studied in the near future.

5 The tuning/controlling of charge carrier transport at pn junction by introducing a static mechanical deformation can be effectively for energy sciences and technology, such as solar cell, LED and photon detector.

6 The piezotronic effect can be used to enhance electrochemical processes. This has been demonstrated for water splitting by tuning the energy barrier for charge transfer[14] and self-charging power cells.[15] It has also been used to stimulate the diffusion of Li ions in rechargeable batteries.

This special section reports on the progress in the fields of piezotronics and piezo-phototronics. The new science introduced by piezotronic and piezo-phototronic effects can change the fundamental design and working mechanism of electronic and photonic devices, which is likely to inspire a lot of fundamental research and practical applications. The piezotronic and piezo-phototronic effects are room-temperature effects and they are mostly known to occur in wurtzite-structured materials systems, such as ZnO, GaN, InN, CdSe and CdS, but both effects have also been observed in other materials systems such as $ZnSnO_3$.[13] With the expansion of new materials for piezotronics, we anticipate to see a rapid and broad development of the field in the next few years.

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