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Research Highlights in the Beijing Institute of Nanoenergy and Nanosystems

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The Beijing Institute of Nanoenergy and Nanosystems (BINN), Chinese Academy of Sciences, was founded in 2012 by Wang. The mission of BINN is to carry out fundamental research related to nanoenergy and nanosensors as well as train future scientists. The two major areas of BINN's research are nanogenerators for self-powered systems and blue energy and piezotronics and piezo-phototronics for third-generation semiconductors. After 7 years of development starting from scratch, BINN now has about 400 members including graduate students. This special issue published in Advanced Functional Materials showcases a group of selected papers submitted by colleagues at the BINN to represent some of the on-going research in the institute.

Figure 1. A "science tree" theme that summaries the on-going research conducted at BINN.

Based on piezoelectric and triboelectric effects, nanogenerators represent a new approach that converts tiny mechanical energy into electric power, which now has attracted worldwide attention, particularly in the era of Internet-of-things, sensor networks, artificial intelligence, and robotics. Piezoelectric nanogenerators (PENGs) were first invented in 2006 using the piezoelectric effect obtained from nanowire materials. The triboelectric nanogenerator (TENG) was first invented in Wang's group in 2012 by using a conjunction of contact-electrification and electrostatic induction effects. TENGs have quickly gained worldwide attention and now comprise a new field of research that involves fundamental physics, chemistry, materials, electric engineering, and mechanical engineering.

Nanogenerators have shown very broad applications in different fields. Firstly, they serve as the micro-power source for wireless distributed mobile/wearable electronics, Internet-of-things, sensor networks, and implantable medical electronics, which require a tremendous amount of mobile power sources, and in many cases, the batteries could not completely satisfy the practical requirements in terms of size, capacity, flexibility, or non-replaceable in vivo. Secondly, nanogenerators can serve as a self-powered sensor (or active sensor) for detecting mechanical triggering, pressure fluctuation, and environmental stimulation without requiring external power being supplied to the sensor tip, which thus possesses great potential for human-machine interfacing, security systems, physiological characterization, and infrastructure monitoring. They also have applications in smart skin, robotics, MEMS, and biomedical science among other fields. Lastly, nanogenerators can be a possible approach for harvesting large-scale energy from ocean waves. By constructing units that are the size of a baseball, inside which the TENGs are installed, millions or even billions of such units can be interconnected into a "fishing net," which can float on the water surface for harvesting the kinetic energy. This technology has the merits

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of low cost, light weight, high efficiency, high output power density, and easy scaling, leading towards the dream of "blue energy", the energy from the ocean.

Piezotronics is a term coined by Wang in 2007, which involves using the piezoelectric effect to control electronics via mechanical stimuli. For wurtzite structures that have non-central symmetry, such as ZnO, GaN, and InN, piezoelectric polarization charges are created at the interface/surface by applying a strain. The strain created inner-crystal piezopotential can serve as a "gate voltage" that can effectively tune/control the charge transport across an interface/junction. This mechanism is termed the piezotronic effect and the electronics fabricated based on such a mechanism is coined as piezotronics, with applications in force controlled electronic devices, sensors, logic units, memories, and catalysts. Analogically, new electronic components can be fabricated as well by using the electric potential created by contact-electrification as a gating voltage, which is called tribotronics.

The presence of polarization charges at a p-n junction can effectively distort the local band structure and consequently affect carrier transport, separation, or recombination. 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. The combination of photon excitation, coupling among semiconductors, photon excitation, and piezoelectricity represents a new field of research called piezo-phototronics. The piezo-phototronic effect is the tuning and controlling of charge carrier generation, separation or recombination at a heterojunction by the strain induced piezoelectric polarization charge. This effect could lead to tremendous performance gain in LEDs, laser diodes, photodetectors, photovoltatic devices, and catalysis by applying static or quasi-static mechanical strains.

The fields of research conducted at BINN can be summarized using a "science tree" (**Figure 1**) to project its main "trunk", major fields, and applications. The main trunk is based on functional materials and fundamental physics effects, which leads to new and innovative fields. The major fields of research are self-powered systems, triboelectric nanogenerators, hybridized nanogenerators, blue energy, tribotronics, piezotronics, and piezo-phototronics, which are in the middle of the tree. The small branches are the potential applications, as well as future perspectives. We anticipate this tree will grow fast and expand quickly with abundant fruits in the near future.