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High power Co_3O_4/ZnO p–n type piezoelectric transducer

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ABSTRACT

Enhancing the output power of piezoelectric transducer is essential in order to supply sufficient and sustainable power to wireless sensor nodes or electronic devices. In this work, a Co_3O_4/ZnO p–n type power piezoelectric transducer which can be operated at low frequencies has been developed by utilizing n-type semiconducting zinc oxide (ZnO) and p-type semiconducting tricobalt tetroxide (Co_3O_4). We utilize ZnO to be the piezoelectric transducer and build a multi-layer (Au/Co_3O_4/ZnO/Ti) thin film structure. The ZnO thin film with preferred orientation along the (002) plane was deposited under optimized deposition conditions on the flexible titanium (Ti) foil with thickness of 80 μm. The Co_3O_4/ZnO interface forms a p–n junction and increases the difference in Fermi levels between the two electrodes, resulting in the great enhancement of output power. The measured output power of the p–n type piezoelectric transducer with optimal resistance of 100 kΩ is 10.4 μW at low operating frequency of 37 Hz, which is 10.9 times of output power of ZnO piezoelectric transducers.

1. Introduction

Small wireless electronic devices have attracted increasing research attention in the past few years. With the development of cutting-edge wireless communication systems and low-power electronic devices, the power consumption of sensors embedded in the systems of such devices has been significantly decreased. Therefore, the conventionally insufficient environmental energy sources such as solar energy [1,2], thermal energy [3,4] or kinetic energy [5] can be converted into electricity to supply power with advanced transducers. Currently, converting mechanical energy such as vibration into electrical energy is one of the most commonly used energy harvesting technologies for powering the low-powered electronic devices including wireless and self-powered microsystems [6].

The piezoelectric transducer is a kind of transduction mechanism that employs active materials such as zirconate titanate (PZT) [7,8], polyvinylidene fluoride (PVDF) [9,10], gallium nitride (GaN) [11], and zinc oxide (ZnO) [12,13] to generate an electrical potential when the transducer is mechanically stressed. The usable voltage outputs can be obtained directly from the piezoelectric material itself, and such a transduction mechanism can be applied in devices fabricated in the microscale as a power source for miniature systems. Furthermore, the power density of piezoelectric energy harvesting is larger than that of electrostatic and electromagnetic transducers [14]. Among the active materials, PZT is a potential piezoelectric material for generating electricity with high output voltage due to it having the highest piezoelectric coefficient [15]. However, its output current is relatively low and is therefore unsuitable as an effective power source for powering low-powered electronic devices. The use of PZT is also toxic and causes serious environmental issues. On the other hand, ZnO is a lower-cost and environmentally-friendly piezoelectric semiconductor material which exhibits good long-term stability in clean energy applications [12,13]. The relatively simple fabrication process from depositing ZnO with highly (002) preferred orientation shows a good piezoelectric effect, whereas PZT requires single orientation of the piezoelectric grains by the poling process [15]. Despite the higher output current the ZnO can deliver, the output voltage of ZnO piezoelectric transducer is still low due to piezoelectric potential screening effect, resulting in lower total output power [16].

Wang and his research group proposed an approach by using the p-type poly(3-hexylthiophene) (P3HT) polymer layer on a ZnO thin film to enhance the power generation, and the carrier transportation was also improved by adding phenyl-C_{61}-butyric acid methyl ester (PCBM) in P3HT to improve carrier transportation [16]. The p-type semiconducting material they used was a polymer. It requires a critical fabrication environment to avoid the oxidation on the P3HT and P3HT:PCBM blend layer in the coating process, thus making the process more complicated. The oxidation on the P3HT and P3HT:PCBM blend layer will affect the performance of the whole device. Therefore, in this study, we developed a Co_3O_4/ZnO p–n type piezoelectric transducer with a simple fabrication process by utilizing n-type semiconducting ZnO and p-type semiconducting tricobalt tetroxide (Co_3O_4). The Co_3O_4/ZnO interface forms a p–n junction and increases the difference in Fermi levels between the two electrodes, resulting in the great

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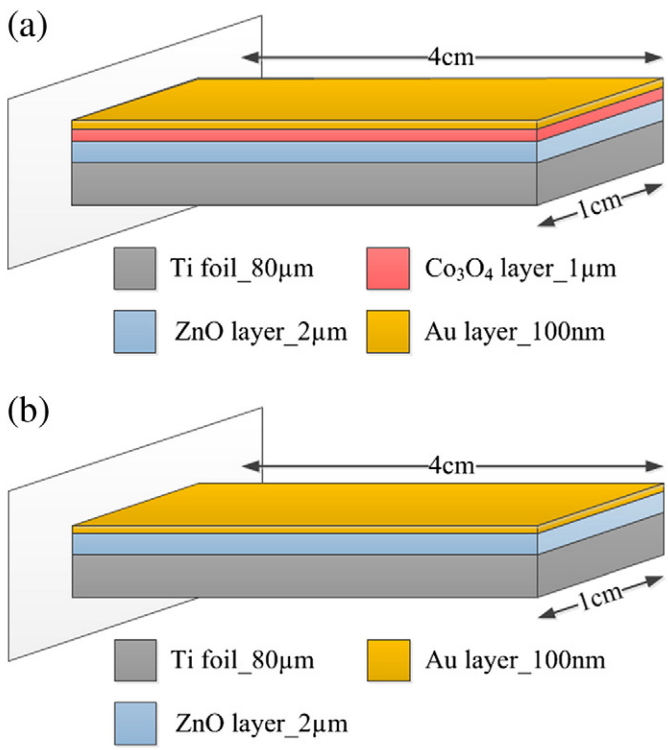

Fig. 1. A schematic diagram of (a) Co_3O_4/ZnO p–n type piezoelectric transducer and (b) ZnO piezoelectric transducer.

enhancement of output power in comparison with the ZnO piezoelectric transducer. The well-deposited Co_3O_4 layer on the ZnO thin film can be relatively easily obtained by the radio frequency (RF) sputtering process. A flexible titanium (Ti) foil was used as the substrate and bottom electrode because it has high conductivity, thermal stability and mechanical strength.

2. Methods

2.1. Fabrication process

The Co_3O_4/ZnO p–n type piezoelectric transducer is a cantilever beam, which is composed of 4 layers, as shown in Fig. 1a. The substrate (bottom-electrode layer) is a flexible Ti foil of 80 μm. The titanium foil was cleaned by consequential dipping in ethanol, acetone, isopropyl alcohol, and deionized water. The RF sputter (ULVAC, F.S.E. Corp.) was used for depositing ZnO and Co_3O_4 thin films under optimized sputtering parameters. The sputtering process parameters are detailed in Table 1. A 2 μm thickness ZnO piezoelectric layer was directly deposited on the titanium foil and a 1 μm thickness Co_3O_4 layer was then deposited on the ZnO layer by RF sputtering respectively. Finally a gold (Au) layer (top-electrode layer) was deposited on the Co_3O_4 layer by turbo sputter coater (K575X, Quorum Technologies Ltd.). For fabrication of the pure ZnO piezoelectric transducer, the process is similar with the p–n type piezoelectric transducer but without a Co_3O_4 layer, as shown in Fig. 1b.

Table 1
Deposition parameters of ZnO and Co_3O_4 thin films.

Parameters	ZnO	Co_3O_4
Substrate–target distance (mm)	60	60
Temperature (°C)	190	300
RF power (W)	170	170
Sputtering pressure (Pa)	1.3×10^{-2}	1.3×10^{-2}
Base pressure (Pa)	1.3×10^{-4}	1.3×10^{-4}
O_2 flow (sccm)	2	0
Ar flow (sccm)	30	20

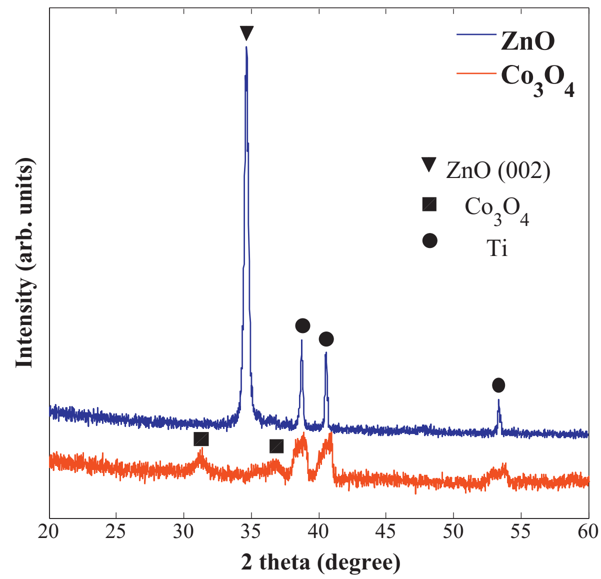

Fig. 2. XRD patterns of ZnO and Co_3O_4 layer.

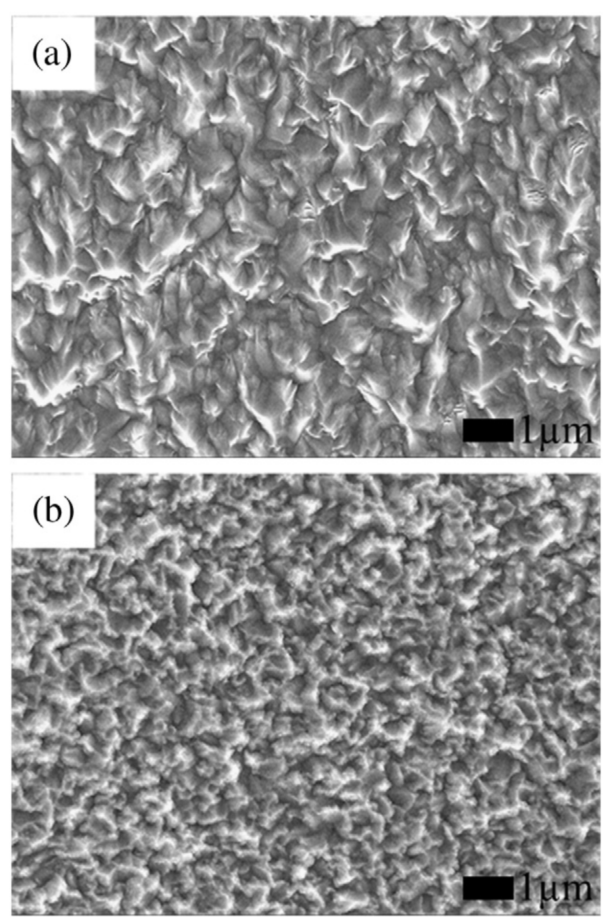

Fig. 3. SEM images of (a) ZnO and (b) Co_3O_4 layer surface.