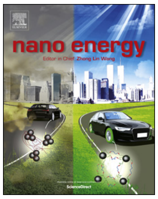
Nano Energy 50 (2018) 744–749

Contents lists available at ScienceDirect

Nano Energy

journal homepage: www.elsevier.com/locate/nanoen



Full paper

Ultra-high sensitivity strain sensor based on piezotronic bipolar transistor

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ARTICLE INFO

Keywords:
Piezotronics
Bipolar transistor
Ultrahigh sensitivity strain sensor

ABSTRACT

Due to the coupling of piezoelectric and semiconductor properties, the wurtzite structure semiconductors have been used for fabricating high performance piezotronic devices. The carrier transport behavior can be effectively controlled by the polarized charges induced by applied strain. High-sensitive piezotronic strain sensors have potential application in next generation self-powered, flexible electronics and wearable systems. In this study, a piezotronic bipolar transistor has been studied through theoretical calculation and numerical simulation. The output current, gauge factor and carrier concentration have been simulated under the influence of different strains. The piezotronic bipolar transistor based strain sensor has ultrahigh sensitivity and the gauge factor can reach over 10^4. This investigation not only provides a theoretical insight into the piezotronic effect on bipolar transistor, but also presents a new approach to design ultra-high sensitivity strain sensor.

1. Introduction

Piezoelectric semiconductors, such as ZnO, GaN, InN, CdS and monolayer MoS_2, have recently attracted widespread attention for innovative piezotronic and piezophototronic devices [1,2], such as nanogenerators [3–5], piezoelectric field-effect transistors [6], high sensitivity piezotronic strain sensor [7], taxel-addressable matrices [8], photon-strain sensor arrays [9], single-atomic-layer MoS_2 piezotronic transistor [10], and strain control piezotronic logic devices [11]. Piezotronic nanodevices show potential application because of its high performance by using strain-induced piezoelectric charges to modulate the transport characteristics. [12] High-resolution dynamic pressure sensor array based on a composite of sandwiching InGaN/GaN multiple quantum wells (MQW) between p-AlGaN/p-GaN layers and n-GaN layers display a high photoluminescence intensity by small strain range (0–0.15%) [13]. A flexible GaN membrane-based ultraviolet photoswitch exhibits on-to-off ratio of up to 4.67×10^5[14]. A two-terminal piezotronic transistor using ZnO twin nanoplatelet by the mirror symmetrical structure has a high sensitivity property of $1448.08 - 1677.53\,\mathrm{meV/MPa}$ [15]. Electric skins have been demonstrated based on the low-power or self-powered properties [16]. Moreover, piezotronic strain sensor can be used for designing piezotronic analog-to-digital converter devices for strain imaging and analog computing [17]. Piezotronic integrated chips have been developed next generation self-powered, flexible electronics and wearable systems [12].

High sensitivity, fast response, and low power consumption are key characteristics of sensors for internet of things and self-powered applications. Using strains to effectively control carrier transport in nanodevices is one of important ways to design high sensitivity strain sensors. Because the strain-induced piezoelectric field can precisely control carrier transport, the first reported piezotronic strain sensor demonstrated an ultra-high gauge factor (GF) ~1250 [7]. In comparison with the carbon-based high sensitivity devices, the strain sensor can also be developed based on carbon nanotubes (CNTs) with GF ~1000 [18]. A strain sensor based on the composite of reduced graphene oxide microtubes – elastomer with polymer coating process has the GF of 630 with the strain range of 21.3% [19]. By using high conductivity performance of the carbon/graphene composites nanofiber yarn (CNY), GF value of the strain sensor can achieve 416 [20]. An electromechanical sensor has been reported to detect small stresses with GF above 500, by assembling graphene and lightly crosslinked polysilicone. [21] For silicon-based devices, flexible strain sensors fabricated fabric consisting of long Si nanowires demonstrate gauge factor of up to 350, which can be employed to detect human motions or broader applications in other wearable devices [22]. Polymer materials

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https://doi.org/10.1016/j.nanoen.2018.06.035
Received 6 May 2018; Received in revised form 6 June 2018; Accepted 9 June 2018

show highly stretchable, for example, a sensor with two interlocked arrays of high-aspect-ratio Pt-coated polymeric nanofibers on the surface of thin polydimethylsiloxane layers exhibits strain detection sensitivity of about 11.45 GF [23].

Although the on-off process is another way to design high sensitivity strain sensors, the design is more suitable for strain trigger or switch applications. For example, mechanical crack-based sensor shows a gauge factor of above 2000, based on disconnection–reconnection with nanoscale crack junctions. [24] However, the strain only varies from 0% to 2%. Recent theoretical results found ultra-high on-off ratio up to 10^{10} for an excellent strain-controlled switch by using piezoelectric potential to control the quantum states of HgTe quantum well topological insulator [25], indicating piezotronic devices will show higher gauge factor and larger strain range in on-off mode devices.

In this study, we theoretically demonstrate piezotronic bipolar transistor for designing ultra-high sensitivity sensor. The mechanism of piezotronic strain sensor is that piezopotential by strain-induced piezoelectric charges can change the built-in electric potential in junction or local Schottky barrier height in metal-semiconductor contact, and control the carrier transport. Bipolar transistor is a three-terminal device including base, emitter, and collector, as shown in Fig. 1(a). In this work, we investigate current-voltage characteristics of piezotronic bipolar transistors in the common-emitter model under the influence of externally applied strains. The base and emitter have different piezoelectric property. While a strain is supplied to the transistor, piezoelectric charges will be induced at the interface of base-emitter junction, as shown in Fig. 1(b) and (c). Therefore, carriers transport in the bipolar transistor can be effectively controlled by the strain. A piezoelectric bipolar transistor model has been established using a p-n-p or n-p-n structure. Finite element method (FEM) simulation presents the variation of the carrier transport at the emitter-base junction under applied strain. The basic principle provides not only a deeper understanding for the mechanism of ultrahigh sensitivity piezotronic strain sensors, but also an innovative and practical approach for designing ultrahigh sensitivity strain sensors.

2. Ultra-high sensitivity strain sensor based on piezotronic bipolar transistor

The p-n junctions play key role in electronic devices. In a bipolar transistor, there are two p-n junctions in series connection, which leads to two doping types in the devices: n-p-n type and p-n-p type. The piezoelectric material is located at the intermediate layer. Taking n-p-n type piezotronic bipolar transistor as an example, p-type and n-type are chosen as semiconductor material with different piezoelectric property. Base and emitter are made by different piezoelectric coefficient materials. Typical design also includes p-n junction of nonpiezoeletric and piezoelectric material, and opposite growth direction of same piezoelectric semiconductor. The strain-induced piezoelectric charges are distributed within the width of W_{piezo} at the interface of left p-n junction, as shown in Fig. 2(a). The band structure and carrier transport characteristics of the transistor will be changed by applied strain. Depending on which lead is common to the input and output circuits, bipolar transistor can be connected in three circuit configurations: the common-base, common-emitter, and common-collector configurations. For n-p-n transistor connected in common-emitter configurations as example, base-emitter voltage V_{BE} is forward biased and collector-emitter voltage V_{CE} is reverse biased. Thus, the V_{BE} is external bias voltage in our BJT model, so the external strain modulate the build-in potential of emitter-base junction, and does not change the voltage V_{BE}. For simplicity, the DC parameters are assumed as constants in this manuscript. The DC parameters, for example, current gain beta factor generally varies with collector current. Thus, the DC parameters of BJT can be modulated by strain-induced piezoelectric field.

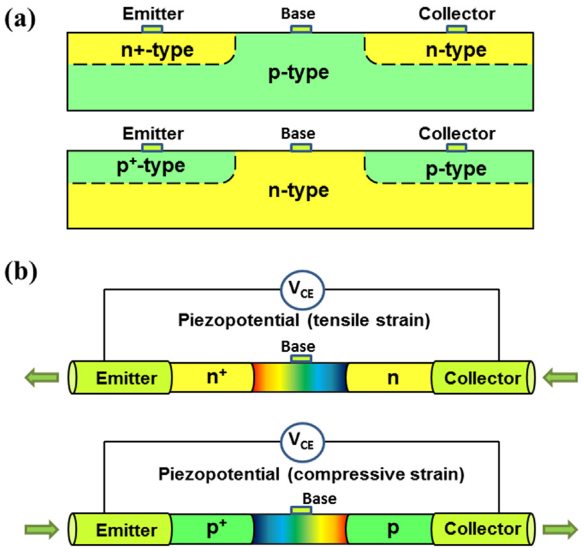

Fig. 1. Schematic of the n-p-n type and p-n-p type piezotronic bipolar transistor. (a) A typical three-terminal diagram without strain and (b) with strain. The intermediate layer is piezoelectric semiconductor material and the induced piezopotential has opposite signs for tensile and compressive strain.

When bipolar transistor is biased in normal mode [26], the electronic current at the emitter terminal I_{nE} and the collector terminal I_{nC} are given by:

$$\begin{cases} I_{nC} = \frac{A_E q D_n n_{p0}}{L_n} \cos ech\left(\frac{W}{L_n}\right) \exp\left(\frac{qV_{BE}}{kT}\right) \\ I_{nE} = \frac{A_E q D_n n_{p0}}{L_n} \coth\left(\frac{W}{L_n}\right) \exp\left(\frac{qV_{BE}}{kT}\right) \end{cases}, \tag{1}$$

where A_E is the cross-sectional area of the emitter-base junction, q is the absolute value of the unit electronic charge, W is the width of base region, n_{p0} is the thermal equilibrium electron concentration in the p-type semiconductor, $L_n = \sqrt{D_n \tau_n}$ are diffusion lengths of holes, D_n is the diffusion coefficients for electrons.

For the common-emitter mode, the terminal current should meet the following relation in the absence of strain:

$$I_{B0} = I_{E0} - I_{C0}, \tag{2}$$

where I_{B0}, I_{E0} and I_{C0} are the initial base current, emitter current and collector current, respectively.

While a strain is applied to the bipolar transistor, the base current will be changed by a α factor that is associated with the piezoelectric charges [27]:

$$I_B = \alpha I_{B0} = \exp\left(\frac{q^2 \rho_{piezo} W_{piezo}^2}{2\varepsilon_s kT}\right) I_{B0}, \tag{3}$$

where ρ_{piezo} is the density of piezoelectric charges.

The collector current can be obtained from the base current times a β factor:

$$I_C = \beta I_B = \beta \exp\left(\frac{q^2 \rho_{piezo} W_{piezo}^2}{2\varepsilon_s kT}\right) I_{B0}, \tag{4}$$

Under the strain along the c-axis of wurtzite structure GaN, the density of piezoelectric charges direction can be given by:

$$P = q\rho_{piezo} W_{piezo} = e_{33} s_{33}, \tag{5}$$

where e_{33}, is the piezoelectric coefficient and s_{33} is the applied strain.

The current sensitivity of piezoelectric bipolar transistor can be defined as:

$$R = \frac{\Delta I_C}{s_{33}} = \frac{q e_{33} W_{piezo}}{2\varepsilon_s kT} I_C, \tag{6}$$

where R is the sensitivity of output current by applying a strain.