Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp477-478

J-5-02

Efficient Coupling of Lateral Force in GaN Nanorod Piezoelectric Nanogenerators by Vertically Integrated Pyramided Si Substrate

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Abstract

Piezoelectric energy harvesting is a promising technique for scavenging ambient mechanical motion for driving compact, low-power, multi-functional electronic devices. To adapt to various ambient surroundings, the geometric configurations and sizes varied in wide ranges with high operational reliabilities and piezoelectric performance have been regarded as a key for piezoelectric harvester design. Herein, by applying a normal force, we report an innovative structure for harvesting electric energy from bending the obliquely aligned GaN piezoelectric nanorods (NRs) that are integrated in the vertically integrated nanogenerator (VING). The single-crystalline GaN NRs used here were successfully synthesized with obliquely alignments on the pyramided Si substrate by plasma-assisted molecular beam epitaxy (PA-MBE). Using conductive atomic force microscope (c-AFM), a remarkable change in the Schottky barrier height (SBH) between the tip and GaN NR is observed upon bending an oblique-aligned GaN NR. This demonstrates that a remarkably enhanced piezoelectric performance of GaN NRs can be achieved by coupling a lateral force. We anticipate that this work will provide an efficient approach for coupling the lateral loading to enhance the electric potential in piezoelectric NRs-embedded VING, and thus open a new path for efficiently generating electric energy.

1. Introduction

Piezoelectricity is the key phenomenon in micro-/nano-electronic devices, which generates electrical energy from mechanical energy, or convert electrical energy into mechanical energy to meet a growing need for autonomous sensors and power sources. However, the piezoelectric effect tends to degrade when piezoelectric materials are synthesized as thin films because the electro-mechanical movement and induced external mechanical strain becomes more highly constrained on the rigid substrate. Therefore, the development of isolated nano-sized piezoelectric materials with the one-dimensional shape, i.e., nanorods (NRs) or nanowires (NWs), represents the most effective route for obtaining a higher maximum flexion and for enhancing the piezoelectric and piezotronic/piezophototronic performance [1-4]. Among the different piezoelectric NRs, due to the non-centrosymmetry that characterizes the wurtzite structures, ZnO and GaN NRs are the most studied, and their piezoelectric properties more than double at the nanoscale [5]. In previous works, a periodically compressed strain applied to the vertically aligned NRs via vertical mechanical loading to create a piezoelectric potential along the NRs has been demonstrated in the vertical integrated nanogenerator (VING), which results in an alternating electrical output [6-10]. This type of nanogenerator configuration consists of vertical NRs with top and bottom electrodes, has the advantage of using mainly the longitudinal (compressed) operation mode of the piezoelectric NRs. However, due to the constraint of the device configuration, the output performance of VING cannot be further enhanced easily by coupling another transverse (bended) operation mode, where previous experiment and simulation results revealing higher piezoelectric potential existing in the bended NRs [11-14].

2. General Instructions

How to efficiently harvesting piezoelectric energy is a critical issue for scavenging ambient mechanical motion for driving compact, low-power, multi-functional electronic devices. Herein, by applying a normal force, we report an innovative structure for harvesting piezoelectric energy from bending the obliquely aligned GaN piezoelectric nanorods (NRs) that are integrated in the vertically integrated nanogenerator (VING) by using plasma-assisted molecular beam epitaxy (PA-MBE) technique (as shown in Fig. 1). Using conductive atomic force microscope (AFM), a remarkable change in the Schottky barrier height (SBH) between the tip and GaN NR is observed upon bending an oblique-aligned GaN NR. This device demonstrates a remarkably enhanced piezoelectric performance of GaN NRs can be achieved by coupling a lateral force (as shown in Fig. 1). Importantly, this energy-harvesting device, which is integrated into the Si-based technology, shows better compatibility with the complementary metal oxide semiconductor (CMOS) technology, and allows easier hybridization with Si based-energy generating devices for enhanced performance [15-21].

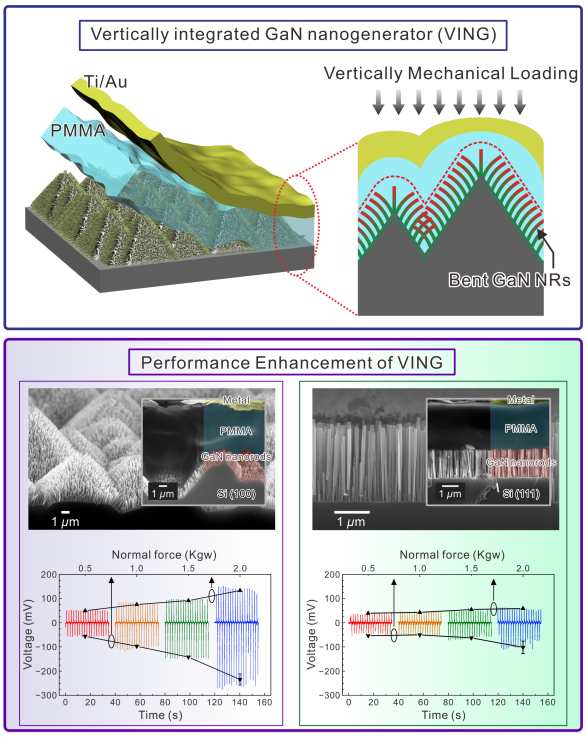

Fig. 1 Schematics of the obliquely aligned GaN piezoelectric nanorods (NRs) integrated in the vertically integrated nanogenerator (VING), and its electric output enhancement.

3. Conclusions

In summary, to our knowledge, this work is the first demonstration of the obliquely aligned GaN NRs for use as a power generator with a larger electrical output. Under the vertical mechanical loading, the efficient coupling of the lateral bending mode in the oblique NR-embedded VING on the Si substrate can enhance the performance of piezoelectric energy output, which is governed by the larger SBH change in NRs. Moreover, integrating the Si-based technology and understanding the energy band diagram of the GaN NRs/textured Si substrate are demanded by the emerging self-powered and hybrid Si solar devices. Additional levels of optimization of our obliquely aligned NRs embedded VING can be achieved by well control of the textured size [32-34] and conformal deposition of insulating and electrode layers on the pyramided substrate. The enhanced piezoelectricity that is offered by such obliquely aligned NRs can also provide a practical functionality for piezoelectric energy harvesters and sensors.

Acknowledgements

This work was supported by the Ministry of Science and Technology in Taiwan.

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