Free carrier screening effects on piezotronic properties and piezoelectric nanogenerators of GaN nanowire arrays

Wei-Shun Liao(1,*) , Nai-Jen Ku(1) , Chao-Hung Wang (1), Chuan-Pu Liu(1,2,3,4)

1. Department of Materials Science and Engineering, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan

2. Institute of Microelectronics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan

3. Advanced Optoelectronics Technology Center, No.1, University Road, Tainan City 701, Taiwan

4. Center for Micro/Nano Science and Technology,No.1, University Road, Tainan City 701, Taiwan

e-mail: cpliu@mail.ncku.edu.tw

With the advent of global warming and energy crises, developing nanomaterial technologies into various nanodevices for energy harvesting has attracted a lot of attentions recently. Of which, nanogenerators by taking advantage of piezoelectric properties of nanowires (NWs) such as wurtzite compound semiconductors of ZnO [1], GaN [2], InN [3] and CdSe [4] can convert mechanical energy into electricity efficiently. When a GaN NW is bent by an atomic force microscopy (AFM) tip, an asymmetric strain is produced across the width of the NW. The output current is generated when the tip contacts the stretched side (negative piezoelectric potential side) of the NW as the working principle of a nanogenerator [1]. The key factors to the current generation process include the Schottky contact between metal electrode and GaN NWs and piezopotential created in NWs [5]. In order to deeply understand the role of the piezopotential, the free carrier screening effect [6] is studied by varying the doping concentration in GaN NW arrays on silicon (111) substrate by molecular beam epitaxy as shown in Figure 1 where undoped and Si-doped GaN NWs are prepared. Piezoelectric measurements were performed by AFM in contact mode using a Pt coated Si tip. As shown in Figure 2, while no output current is detected from the undoped GaN, a 0.07nA output current is harvested from the Si-doped GaN with a force of -3nN because of doping-induced lower resistivity. We also study the effect of strain on current-voltage characteristics of NWs by applying normal forces on tops of individual NWs with an AFM tip in Figure 3. With the normal force, the Schottky barrier height (SBH) at the Pt site is decreased but is increased at the Ag site due to the piezotronic effect. Consequently, this effect results in a current increase from 3.7 nA to 8.4 nA with strain at -4V bias and decrease from 1.12 nA to 0.04 nA at +7V bias at the Pt and Ag side, respectively, for the Si-doped GaN NWs. The lnI-$V^{1/4}$ curves derived from the I-V curves are fairly linear as shown in Figure 3(b), indicating that the thermionic emission diffusion model is the dominant carrier transport process and could be applied to calculate the SBH change from the I-V characteristics. The change of SBH is increased by 75 meV with normal force -3nN for undoped NW. However in the doped GaN NW, the change of SBH is increased by 65 meV with the same force. Apparently, due to the screening effect, external forces can generate higher piezo-field for undoped GaN by piezotronic effect. In conclusion, GaN NWs based piezoelectric nanogenerators have been demonstrated. We investigate the influence of carrier concentration on the energy harvesting and piezotronic effect of doped and Si-doped GaN NWs by AFM. The results can help design high performance piezoelectric nanogenerators and piezotronic devices in the future.

References

[1] Z.L. Wang, J.H. Song, Science 312 (2006) 242-246.
[2] C.T. Huang, J.H. Song, W.F. Lee, Y. Ding, Z.Y. Gao, Y. Hao, L.J. Chen, Z.L. Wang, Journal of the American Chemical Society 132 (2010) 4766-4771.
[3] N.J. Ku, J.H. Huang, C.H. Wang, H.C. Fang, C.P. Liu, Nano Letters 12 (2012) 562-568.
[4] Y.S. Zhou, K. Wang, W.H. Han, S.C. Rai, Y. Zhang, Y. Ding, C.F. Pan, F. Zhang, W.L. Zhou, Z.L. Wang, Acs Nano 6 (2012) 6478-6482.
[5] J. Liu, P. Fei, J.H. Song, X.D. Wang, C.S. Lao, R. Tummala, Z.L. Wang, Nano Letters 8 (2008) 328-332.

[6] Y. Gao, Z.L. Wang, Nano Letters 9 (2009) 1103-1110.

Figures

1.

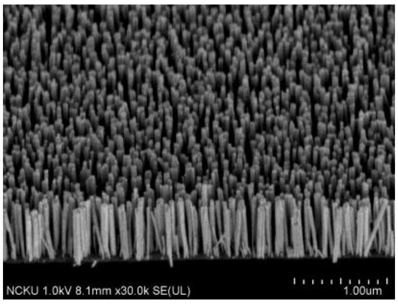


Figure1: Vertically aligned GaN NW array grown on the Si substrate. Side-view SEM images.

2.

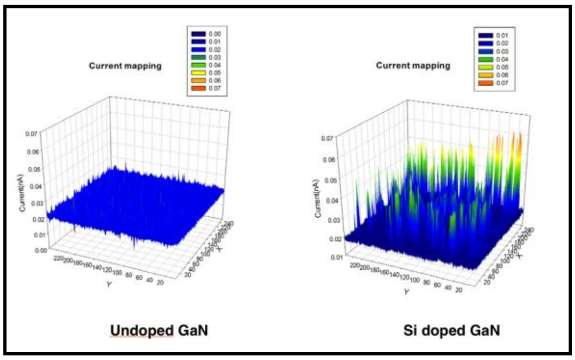
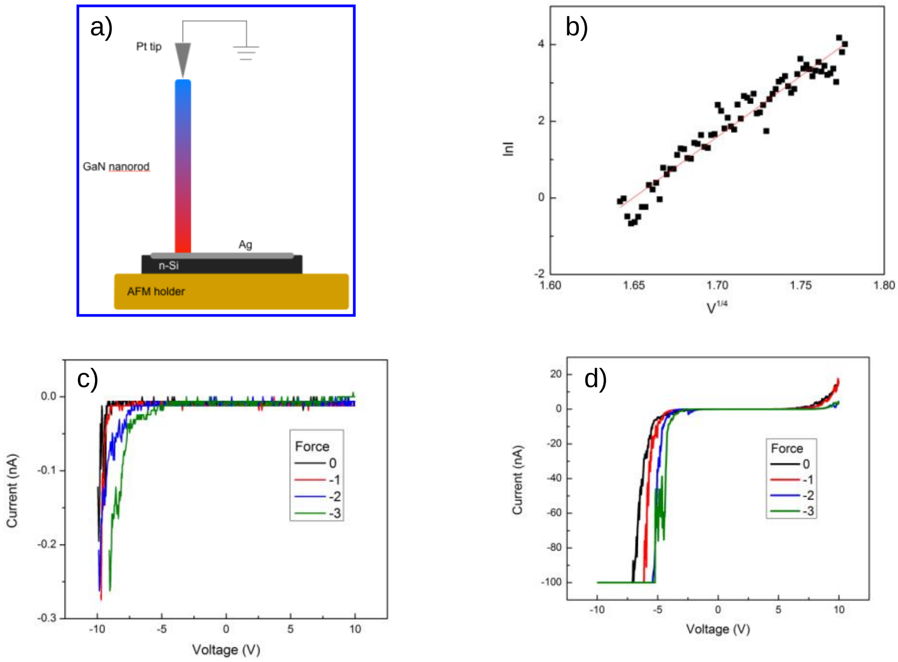


Figure2: Compare different doping concentration piezoelectric output current shown in the 3D graph.

3.



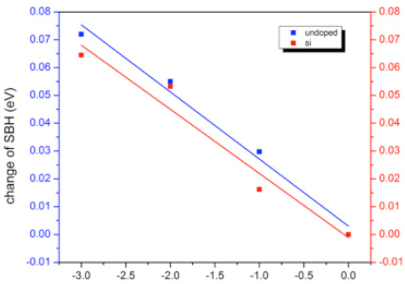


Figure3:
(a)Schematics of experimental setup for measuring I-V characteristics of a single GaN NW by an AFM tip under various normal applied forces; (b) plot of ln I as a function of V (for si doped GaN sample) (c) I-V curves of undoped GaN; (d) I-V curves of Si doped GaN ; (e) calculated change in Schottky barrier height from the measured I-V curves in (c) and (d).