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ZnO nanorods for electronic nanodevice applications

Gyu-Chul Yi, Won Il Park, J. Yoo, H.-J. Kim and C.-H. Lee

[1]National CRI Center for Semiconductor Nanorods and Department of Materials Science and Engineering, POSTECH, Pohang, Gyeongbuk 790-784, Korea
Phone: +82-54-279-2155 Fax : +82-54-279-8635 E-mail: gcyi@postech.ac.kr

1. Introduction

ZnO semiconductor nanorods are attractive components for nanometer-scale electronic and photonic device applications.[1] Recently, ZnO nanorods and nanowires are utilized in a wide variety of nanodevices including field-effect transistors (FETs) [2], ultraviolet photodetectors, Schottky diodes, and light emitting device arrays [3]. However, most of reported ZnO nano-FETs have exhibited poor transistor characteristics due to high impurity concentration, large contact resistances or surface mediated effects. Here, we report fabrications of high performance ZnO nanorod metal-oxide-semiconductor field effect transistors (MOSFETs) by coating polymer thin films on surfaces of ZnO and employing top-gate geometry.

2. Results and discussion

ZnO nanorod MOSFETs

ZnO nanorod MOSFETs were fabricated by using high quality ZnO nanorods and e-beam lithography. Single crystal ZnO nanorods with low defect concentration were prepared by catalyst-free metalorganic vapor phase epitaxy (MOVPE).[4] We investigated current-voltage (I_{ds}-V_{ds}) characteristic curves as a function of V_g for the back-gate ZnO nanorod MOSFETs prepared without any intentional surface treatment.[5]

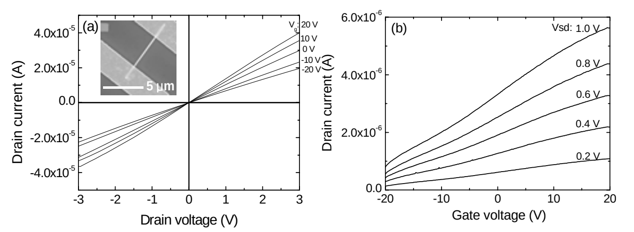

Fig. 1 (a) Typical I_{ds}-V_{ds} characteristic curves as a function of V_g (inset) a FE-SEM image (b) I_{ds}-V_g curves for back-gate ZnO nanorod MOSFETs.

As shown in Fig. 1(a), linear and symmetric behavior in I_{ds}-V_{ds} curves were observed at various gate voltages (V_g), indicating that ohmic contacts were formed between ZnO and Ti metal layers. From the Fig. 1(b), transconductance, g_m (= dI_{ds}/dV_g) is calculated to be 190 nS ($g_m/W \approx 1.9$ µS/µm) for V_{ds} = 1.0 V. From electrical characteristics of more than ten nanorod MOSFETs, we observed transconductance values in the range of 0.5~2 µS/µm. This may be attributed to high crystallinity and purity of ZnO nanorods prepared using catalyst-free MOVPE and low resistance ohmic contacts. Meanwhile, the conductance response to gate-bias voltage of ZnO nanorod MOSFETs was still weak, attributed in part to the surface-mediated effects.

Dual-gate ZnO nanorod MOSFETs

Dual-gate nanorod MOSFETs with an additional SiO_2 layer as a top-gate oxide were also fabricated and their electrical characteristics were investigated in order to compare device characteristics depending on gate geometry. [6] Fig. 2(a) shows typical I_{ds}-V_{ds} characteristic curves obtained at several different V_g values top-gate mode operation. ZnO nanorod MOSFETs were completely turned off at V_g = -10V. Meanwhile, Fig. 2(b) shows the I_{ds}-V_g characteristic curves for top-gate mode which exhibited sharp switching response unlike the back-gate MOSFETs. Upon using the top-gate, the switch ON/OFF ratio of ZnO nanorod MOSFETs was in the range 10^5~10^7. Transconductance, one of key transistor characteristics, was also enhanced by top-gate mode operation with normalized transconductance was 2.4 µS/µm at V_{ds} = 1.0 V. All these results indicate that the top-gate mode operation can enhance the device performance significantly in spite of using the identical channel. The enhanced device performance can be explained in terms of geometric field enhancement and resulting efficient gating effect for the top-gate mode geometry.

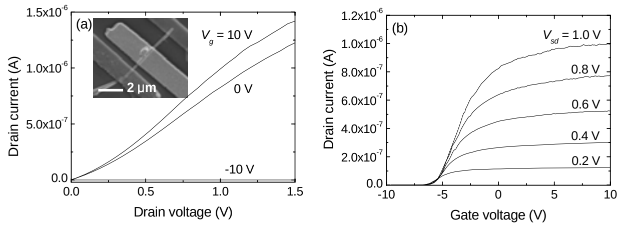

Fig. 2 (a) Typical I_{ds}-V_{ds} characteristic curves as a function of V_g.(inset) a FE-SEM image (b) I_{ds}-V_g curves for dual-gate ZnO nanorod MOSFETs under top-gate mode operation.

Surface passivation by a polymer coating

The electrical characteristics of ZnO nanorod MOSFETs were significantly improved by coating polyamide (n-methoxy methylated nylon) [5] and TWEEN20 (polyoxyethylene sorbitan monolaurate) on ZnO nanorod surfaces. After the polymer coating, as shown in Fig. 3(a), I_{ds}-V_g curves of ZnO nanorod FETs exhibit excellent conductance response to V_g: ZnO nanorod FETs were fully turned off at V_g in the range of -5.5 and -5 V and transconductance exhibited the maximum values in the range of 1~1.9 µS at V_g = 2.3 V (in case of V_{ds} = 1.0 V).

The maximum values of transconductance after polyamide and TWEEN20 coating were thirteen and five times higher than those for as-grown ZnO nanorod FETs, respectively. In addition, the I_{ds}-V_g curves after the coating showed drastic decreases of drain current below threshold voltage (V_{th}) and exhibited a large current ON/OFF ratio of 10^4-10^7. A subthreshold swing (S) of ~1.4 V/decade with a maximum ON state current of 7.5 and 18 μA were also obtained after polyamide and TWEEN20 coating, respectively.

We further analyzed carrier mobility in ZnO nanorod MOSFETs using capacitance given by equation for cylinders using an infinite plate model. Fig. 3(b) shows the electron-mobility versus V_g plots. The maximum value of electron-mobility of as-grown ZnO nanorod FETs (300 cm^2/Vs) was much higher than that of ZnO-based thin film transistors (0.01-10 cm^2/Vs). The high carrier mobility of ZnO nanorod MOSFETs results presumably from high crystallinity and low defect concentration of single crystal ZnO nanorods due to the catalyst-free growth method employed in this research. Furthermore, the mobility value of nanorod MOSFETs was increased to 2800 cm^2/Vs by TWEEN20 coating.

Reproducibility of the polymer passivation effect on the device performance was also investigated measuring *I-V* characteristic curves of thirteen different ZnO nanorod MOSFETs before and after polymer coating. Before polymer coating, most of samples showed the relatively weak conductance response to V_g and they were not fully turned off with applied negative V_g to -20 V. In contrast, the conductance responses to the V_g were significantly enhanced with polymer coating, and all of the samples were fully turned off in the range of $-15\ V < V_g < -5\ V$. Moreover, the field-effect mobility value of ZnO nanorod MOSFETs was drastically increased from 40-300 cm^2/Vs with mean value of 150 cm^2/Vs for the as-grown ZnO nanorod MOSFETs before coating to 120-2800 cm^2/Vs with mean value of 1060 cm^2/Vs after coating. The highest mobility value of 2800 cm^2/Vs in ZnO nanorod MOSFETs is even higher than those of the state-of-the-art planar Si MOSFETs (less than 1000 cm^2/Vs) and comparable to well-established single-wall carbon nanotube FETs (1000-20000 cm^2/Vs).

As for the origin of enhanced ZnO nanorod MOSFET characteristics after polymer coating we make the following suggestions. First, the chemisorption process which decreases transistor gain may be suppressed with polymer coating. Second, modification of ZnO surfaces with polymers may contribute to passivation of defects which deteriorate transistor characteristics by trapping and scattering carriers. Last, the enhanced mobility of polymer-coated nanorod MOSFETs may result from formation of a gate structure surrounded with dielectrics, or low-dimensional electron gas formed by band-bending at the ZnO/polymer interfaces.

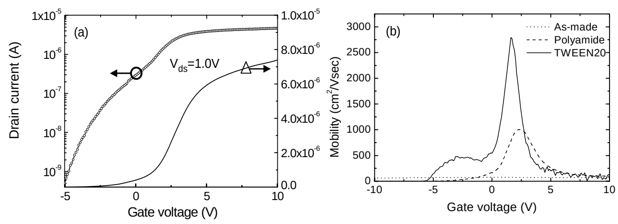

Fig. 3 (a) I_{ds}–V_g curves as a function of V_{ds} and log scale plot of I_{ds}–V_g (V_{ds}=1.0 V) for a ZnO single nanorod MOSFET after polyamide coating on the device. (b) Electron mobility vs. V_g plots of ZnO nanorod FETs before and after polyamide and TWEEN 20 coating.

3. Conclusion

In this research, high quality and single crystalline ZnO nanorods were employed as building blocks for fabrication of high-performance ZnO nanorod MOSFETs. The electrical characteristics of ZnO nanorod MOSFETs were significantly enhanced by top-gate mode operation and polymer coating. In addition, controlled metal/oxide semiconductor junction characteristics to either good ohmic or Schottky contacts on ZnO nanorods further ensured fabrications of high performance Schottky diodes, MESFETs, and logic gates. [7] These electronic devices based on metal/semiconductor nanorods junction can be used for more complex and functional electronic circuits.

Acknowledgements

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