Vol 17 No 10, October 2008
1674-1056/2008/17(10)/3875-05

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Electrical characteristics and optoelectronic properties of metal–semiconductor–metal structure with zinc oxide nanowires across Au electrodes*

Wang Ding-Qu(王鼎渠)†, Zhou Zhao-Ying(周兆英), Zhu Rong(朱 荣), and Ye Xiong-Ying(叶雄英)

State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments and Mechanology, Tsinghua University, Beijing 100084, *China*

(Received 27 March 2008; revised manuscript received 21 April 2008)

This paper reports on a method of assembling semiconducting ZnO nanowires onto a pair of Au electrodes to construct a metal–semiconductor–metal (MSM) structure by dielectrophoresis and studying on its electrical characteristics by using current-voltage ($I-V$) measurements. An electronic model with two back to back Schottky diodes in series with a semiconductor of nanowires was established to study the electrical transport of the MSM structures. By fitting the measured $I-V$ characteristics using the proposed model, the parameters of the Schottky contacts and the resistance of nanowires could be acquired. The photoelectric properties of the MSM structures were also investigated by analysing the measurements of the electrical transports under various light intensities. The deduced results demonstrate that ZnO nanowires and their Schottky contacts with Au electrodes both contribute to photosensitivity and the MSM structures with ZnO nanowires are potentially applicable for photonic devices.

Keywords: ZnO nanowire, MSM structure, Schottky barrier, optoelectronic property

PACC: 7230, 6140M, 7340S

1. Introduction

Low dimensional structures such as quantum dots, nanotubes, nanowires, and nanobelts are the fundamental materials for building nanodevices and nanosystems[1−3] that are in possession of potential superior performances. Studies on one dimensional (1D) nanostructures such as zinc oxide (ZnO) nanowires/nanobelts provide us the opportunity to advance our knowledge on their attractive and intrinsic properties. In general, most measurements of semiconducting nanowires are directly or indirectly carried out by recurring to metal electrodes, which form metal–semiconductor–metal (MSM) structures and ineluctably introduces two back-to-back and series-wound Schottky diodes at the metal/semiconductor interface.[4,5] Consequently, the measurements via electrical transports would be affected by the existent contact barriers.

In this paper, we report on a method of assembling semiconducting ZnO nanowires onto a pair of Au electrodes to construct a MSM structure by dielectrophoresis and study its electrical characteristics by using current-voltage ($I-V$) measurements. The $I-V$ characteristics of the MSM structure illuminated at different powers of light intensities were analysed to demonstrate a hybrid photosensitivity of ZnO nanowires and Schottky contacts.

2. Experiments

In our study, Au electrodes were patterned on a thin insulated SiO_2 film covering on a silicon substrate. The ZnO nanowires that have single crystal structures were synthesized by thermal evaporation of ZnO powders without the presence of catalyst.[6] The synthesized nanowires were casted into ethanol solution and ultrasonicated for twenty minutes to disperse them from bundles to individuals. An AC dielectrophoresis method[7] was then employed to trap and align the nanowires onto the electrodes, and thus formed a MSM structure. A droplet of the nanowires suspension was then dripped on the pre-fabricated electrodes; an alternating electrical current was applied on the electrode pairs for trapping and aligning the nanowires onto the electrodes. Through vast experiments, we found that the desirable frequency

*Project supported by the National Natural Science Foundation of China (Grant No 50575113) and Program for NCET.
†E-mail: dqwang99@mails.tsinghua.edu.cn

and peak-to-peak amplitude of the applied AC amplitude were 5–20 MHz and 2–20 V, respectively for trapping and aligning the nanowires. Generally multiple nanowires were trapped between electrode pair so as to form nanowires bunch MSM structure.

Electrical transport properties and the optoelectronic effect of the MSM structure were studied by using a pico-amperometer (Keithley, Source Measure Unit 237) at room temperature in the air ambient with a xenon arc lamp source. The two electrodes were connected to the ground and output of the electric source respectively.

3. Results and discussion

In the experiments, a total of over 40 similar MSM structures assembled with nanowire bundles were measured. The data showed that about 70% of them own infinite impedance behaviour, about 25% were asymmetric, and the others were symmetric. Figure 1 shows the three typical $I-V$ characteristics observed in the experiments. The inset of Fig.1 is the scanning electron microscope (SEM) image of one sample.

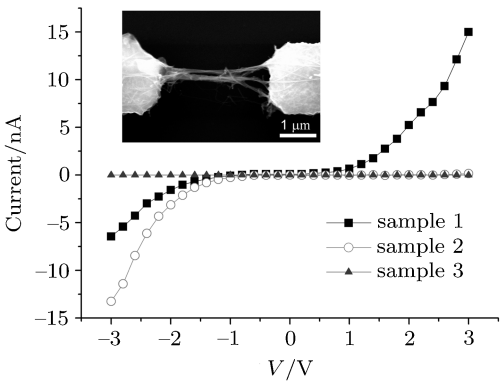


Fig.1. Three typical current-voltage characteristics of different nanostructures. Sample 1 shows symmetry; sample 2 shows asymmetry; and sample 3 shows infinite impedance behaviour. The inset is the SEM image of one sample.

The rectifying behaviour of the $I-V$ characteristics has been reported and explained by other researchers. As proposed by Harnack *et al*,[8] the reason was possibly due to asymmetric interfacial barrier properties, for example, different Schottky barrier heights on two ends of the aligned nanowires. Lao *et al*[9] considered that the formation of the Schottky diodes was suggested due to the asymmetric contacts formed in the dielectrophoresis aligning process. We suppose to give reasonable explanations for the observed $I-V$ behaviours. The MSM structure can be characterized by an electronic model with two back to back Schottky diodes in series with a semiconductor of nanowires, which is schematically shown in Fig.2. In general, the Schottky barriers on both ends are high, the two contacts are poor and infinite impedance behaviour is exhibited. If the barrier of one end of the nanowire bundle owns a good contact and the other is poor, then the asymmetry (rectifying behaviour) would be observed. Once either end of them possess similar contacts with approximate lower barrier heights or the barriers are lowered via a technical process (e.g. focus iron beam deposition) during fabrication so as to form approximate ohmic contacts, the symmetric characteristics can be attained.

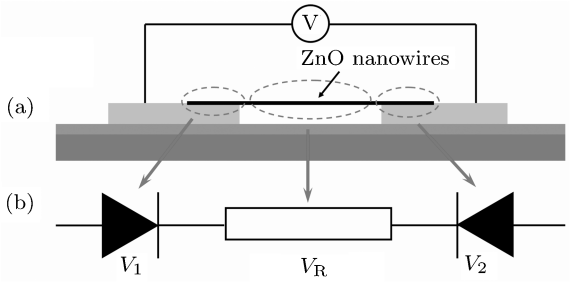


Fig.2. Schematic drawing of the MSM structure (a) and its electronic model (b).

For the MSM structure characterized by the electronic model with two back to back Schottky diodes in series with a semiconductor of nanowires, the electrical transport in the MSM structure is investigated mathematically. When a negative voltage V is applied on the right electrode of the MSM structure, Schottky Contact 1 is forward biased and Schottky Contact 2 is reverse biased. Denoting the bias voltages on Contact 1, the nanowire, and Contact 2 as V_1, V_R, and V_2, respectively, there was $V = V_1 + V_R + V_2$. The current through the forward biased Schottky Contact can be modelled by the classic thermionic emission equation[4]

$$J_1(V_1, \phi_b) = A^* T^2 \exp\left(-\frac{q\phi_b}{kT}\right)\left\{\exp\left(\frac{qV_1}{kT}\right) - 1\right\}, \tag{1}$$

where A^* is the Richardson constant of the semiconductor, ϕ_b is the Schottky barrier height, k is the Boltzmann constant, q is the magnitude of electronic charge, and T is the absolute temperature.

For the reverse Contact, the analysis is based on the thermionic-field emission model of Padovani and Stratton,[10] where the tunnelling current is mainly

the thermionic-field emission current and the current density through Schottky Contact 2 is given by

$$J_2\left(V_2,\phi_{\mathrm{b}}\right)=J_{\mathrm{s}}\exp\left[V_2\left(\frac{q}{kT}-\frac{1}{E_0}\right)\right], \qquad (2)$$

where J_{s} is a slowly varying function of applied bias, and

$$E_0=E_{00}\coth\left(\frac{qE_{00}}{kT}\right), \qquad (3)$$

with

$$E_{00}=\frac{\hbar}{2}\left[\frac{N_{\mathrm{d}}}{m^*\varepsilon_{\mathrm{s}}}\right]^{1/2}, \qquad (4)$$

where N_{d} is the donor density at the metal / semiconductor interface, m^* and ε_{s} are the effective mass of electron and permittivity of the semiconducting nanowire, respectively.

Based on the fact that the currents through the three serial components of the MSM structure are equal, we can figure out numerically the bias voltages V_1, V_{R}, V_2 and the corresponding current and clarify the electrical model of the MSM structure. The computed results for a case of the measurement are shown as the solid lines in Fig.3(a). The electrical model can be further utilized to predict the bias voltages on the contacts and nanowires at a large applied voltage, which are shown as the dotted lines in Fig.3(a). As shown in Fig.3(b), it can be seen that the curves fitted by the model are well accorded with the experimental data. By fitting the model, we can educe the barrier heights of the two contacts and the resistance of the semiconductor.

The resistance of the semiconductor can be also estimated by a simple approximative method. As shown in Fig.3(a), at a large bias, the incremental voltage is applied mostly on the nanowires, while the barrier voltages V_1 andV_2 vary slowly with the bias voltage V. In this region, the $I-V$ curves rise almost linearly and can be differentiated to obtain the resistance of the nanowires[5]

$$R=\frac{\mathrm{d}V_{\mathrm{R}}}{\mathrm{d}I}=\frac{\mathrm{d}V}{\mathrm{d}I}-\frac{\mathrm{d}V_2}{\mathrm{d}I}-\frac{\mathrm{d}V_1}{\mathrm{d}I}\approx\frac{\mathrm{d}V}{\mathrm{d}I}. \qquad (5)$$

We estimated the resistances of nanowires by using this approximate method and found that the nanowires used in our measurements were all in the MΩ range.

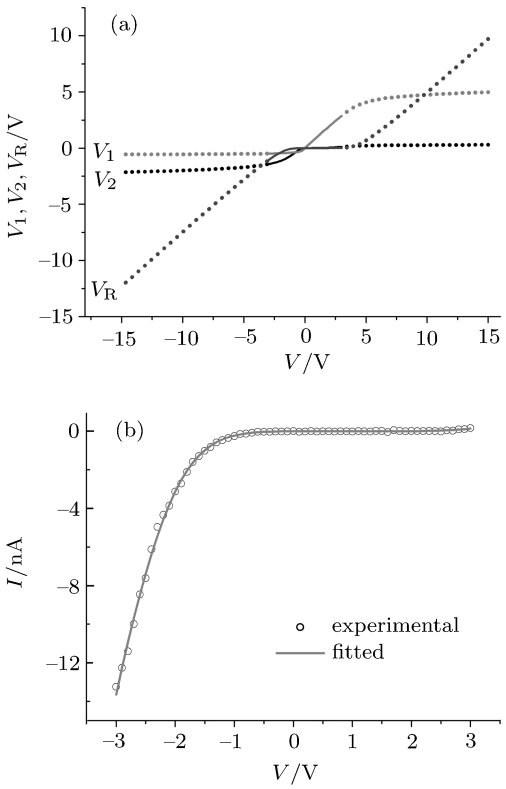


Fig.3. (a) Variations of V_1, V_2 and V_{R} versus the applied voltage V. The solid curves represent the bias voltages derived from the experimental data and the dotted curves are the bias voltages predicted by the developed electric model. (b) Model-fitted and experimental $I-V$ characteristics of the MSM structure.

Optoelectronic behaviour of 1D semiconducting ZnO nanowires is another one of the most important properties that dictate their applications for photonic devices. Optical devices based on ZnO nanowires are typical MSM structures, such as ultraviolet (UV) photodetector,[11,12] UV photodiode,[13,14] photoluminescence,[15,16] and light emitter,[17] which have been demonstrated. However, the photosensitivities of MSM structures were mostly attributed to the one action of the ZnO nanowires[11,12,16] or the Schottky contacts[13,14,17] separately. There has been few considerations on the photosensitivity from the view of the both effects of ZnO nanowires and Schottky contacts. In this paper, we study both the optoelectronic effects of ZnO nanowires and contacts with electrodes by using the proposed MSM structure model.

Figure 4(a) gives the $I-V$ characteristics of the MSM structure illuminated at different powers of light intensities by using a xenon arc lamp source at room temperature. The inset of Fig.4(a) shows an assembled MSM structure with ZnO nanowires bundle. The proposed electrical model is utilized to simulate the $I-V$ characteristics of the MSM structure. By fitting the model, we can estimate the barrier heights of the two contacts. The estimated results for the cases under different illuminations are listed in Table 1. It is obvious that the barrier heights of the contacts decrease with the increase of the light power.[18] Figure 4(b) gives the photocurrents $I_{\rm p}$ pertaining to the light intensity P at three different bias voltages of –3 V, –2 V, and –1 V.

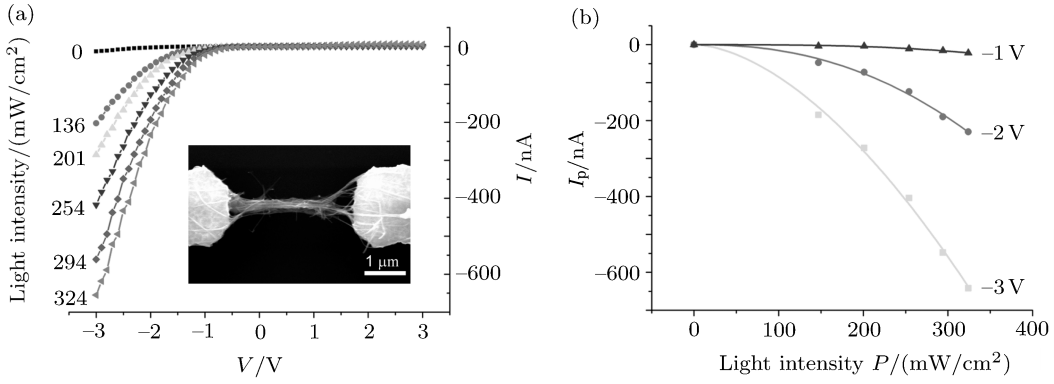


Fig.4. Rectifying $I-V$ characteristics of the MSM structure illuminated upon various light intensities from 0 to 324 mW/cm^2. The inset is the SEM image of the measured MSM structure. (b) The fitting curves of photocurrent $I_{\rm p}$ versus light intensity P at three different bias voltages of –3 V, –2 V, and –1 V. The fitting expression is $I_{\rm p} \propto P^{1.7}$.

We further estimated the photoresistance of the nanowires by using the proposed approximate method. To avoid collapse in the Schottky barriers, in our measurements the applied bias voltage was limited in the range of $-3--3$ V. We selected the measurement data in the range of $-3--2$ V for estimating the resistance of the nanowires. Though the voltage in the range of $-3--2$ V is not strictly as a large bias, the coarse resistances of nanowires could be estimated by using Eq.(5). The accurate resistances of nanowires could be educed by fitting the electrical model shown in Fig.2. Table 1 also gives a list of the coarse and accurate resistances of ZnO nanowires under the illumination with different light intensities.

Table 1. Estimated parameters of the MSM structure illuminated under different light intensities.

Light density P/(mW/cm^2)	0	147	201	254	294	324
Barrier height of Schottky Contact 1/eV	0.62	0.55	0.53	0.51	0.50	0.49
Barrier height of Schottky Contact 2/eV	0.82	0.81	0.80	0.78	0.76	0.75
Nanowire resistance R/MΩ, (Estimated from (5), coarse)	93.3	6.52	4.72	3.42	2.63	2.34
Nanowire resistance R/MΩ, (Educed from the electrical MSM model, accurate)	42.1	3.51	2.64	2.12	1.65	1.62
Electron concentration change $\Delta n/10^7$cm^{-1}	0	3.56	4.73	5.90	7.58	7.72

Consider that the photoconductivity of semiconductor (ZnO nanowires) can be modelled as,[19]

$$\Delta\sigma = q(\Delta n\mu_{\rm n} + \Delta p\mu_{\rm p}), \qquad (2)$$

where $\mu_{\rm n}$, $\mu_{\rm p}$ are the electron mobility and hole mobility respectively, and Δn, Δp are the changes in the electron concentration and the hole concentration induced by illumination respectively. Consider that the ZnO nanowires used in our measurements are n-type.[20] Assuming that the semiconducting ZnO has electron mobility $\mu_{\rm n}$=20 cm^2/Vs,[20] we estimate the electron concentration change of ZnO nanowires Δn

that is induced by illumination which is also listed in Table 1.

From the above analysis, it can be concluded that the photoconductivity of the MSM structure is hybrid effects of the ZnO nanowires and the Schottky contacts.

4. Conclusions

In conclusion, we prepared MSM structures with semiconducting ZnO nanowires across Au electrodes and measured the electrical transports of the structures with different interfacial properties. An electronic model of the MSM structure was established for acquiring the parameters of the Schottky contacts and the resistance of nanowires and predicting entire $I-V$ characteristics. The hybrid photosensitivity of ZnO nanowires and their Schottky contacts with Au electrodes were investigated by analysing $I-V$ characteristics. The results demonstrate that the ZnO nanowires and their Schottky contacts with Au electrodes both contribute to photosensitivity and that the MSM structure with ZnO nanowires is potentially applicable for photonic devices.

Acknowledgements

The authors want to thank Z. Y. Zhang in Peking University, China for his technical assistance and thank Professor Zhonglin Wang in the Georgia Institute of Technology, USA, for providing samples of nanowires for this work.

References

[1] Fennimore A M, Yuzvinsky T D, Han W Q, Fuhrer M S, Cumings J and Zettl A 2003 *Nature* **424** 408

[2] Sazonova V, Yaish Y, Ustunel H, Roundy D, Arias T A and McEuen P L 2004 *Nature* **431** 284

[3] Wang Z L and Song J H 2006 *Science* **312** 242

[4] Rhoderick E H and Williams R H 1998 *Metal–Semiconductor Contact* (Oxford: Clarendon) p11

[5] Zhang Z Y, Jin C H, Liang X L, Chen Q and Peng L M 2006 *Appl. Phys. Lett.* **88** 073102

[6] Pan Z W, Dai Z R and Wang Z L 2001 *Science* **291** 1947

[7] Wang D Q, Zhu R, Zhou Z Y and Ye X Y 2007 *Appl. Phys. Lett.* **90** 103110

[8] Harnack O, Pacholski C, Weller H, Yasuda A and Wessels J M 2003 *Nano Lett.* **3** 1097

[9] Lao C S, Liu J, Gao P, Zhang L, Davidovic D, Tummala R and Wang Z L 2006 *Nano Lett.* **6** 263

[10] Padovani F A and Stratton R 1966 *Solid-State Electron.* **9** 695

[11] Kind H, Yan H, Messer B, Law M and Yang P D 2002 *Adv. Mater.* **14** 158

[12] Keem K, Kim H, Kim G. T, Lee J S, Min B, Cho K, Sung M Y and Kim S 2004 *Appl. Phys. Lett.* **84** 4376

[13] Heo Y W, Tien L C, Norton D P, Pearton S J, Kang B S, Ren F and LaRoche J R 2004 *Appl. Phys. Lett.* **85** 3107

[14] Newton M C, Firth S and Warburton P A 2006 *Appl. Phys. Lett.* **89** 072104

[15] Tang B, Deng H, Shui Z W, Wei M, Chen J J and Hao Xin 2007 *Acta Phys. Sin.* **56** 5176 (in Chinese)

[16] Yang P, Yan H, Mao S, Russo R, Johnson J, Saykally R, Morris N, Pham J, He R and Choi H J 2002 *Adv. Funct. Mater.* **12** 323

[17] Wang Y X, Zhang Q F, Sun H, Chang Y L and Wu J L 2008 *Acta Phys. Sin.* **57** 1141 (in Chinese)

[18] Ham M H, Choi J H, Hwang W, Park C, Lee W Y and Myoung J M 2006 *Nanotechnology* **17** 2203

[19] Bube R H 1960 *Photoconductivity of Solids* (New York: Wiley) p32

[20] Arnold M S, Avouris P, Pan Z W and Wang Z L 2003 *J. Phys. Chem.* B **107** 659