Plasmonic welding of hybrid Au-ZnO nanostructure

Z Y Chen, H B Yang, P Ghosh, Q Li and M Qiu

1State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou, 310027, China

E-mail: qiangli@zju.edu.cn

Abstract. We report that 532 nm CW laser can be used to obtain non-wetting metal-semiconductor (Au-ZnO) Schottky heterojunctions by plasmonic welding. Single crystal Au and n-type ZnO nanowires are placed on gold (Au) and titanium (Ti) electrodes, respectively, and the junction welding is realized. The current-voltage (I-V) characteristic curve of the single Schottky rectifier is also measured.

1. Introduction

One-dimensional metal/semiconductor nano-materials have received widespread attention for their potential applications in micro/nano-electronics and -photronics. Metal/semiconductor Schottky junction with nonlinear electrical response can be applied in integrated circuits, including high-speed switches [1] and rectifier units [2]. The condition of Schottky junction formation is a large bias between the work function of the metal and the fermi level of the semiconductor. Different sizes and doping concentration can lead to different barrier heights.

The metal/semiconductor Schottky junction are generally achieved with two different methods: (1) chemical growth methods (including chemical vapor deposition [3], thermal vapor deposition [4, 5, 6], self-assembly [7], and liquid phase method [9]) and (2) nano-welding technology (including chemical [9], electrical joule heat [10, 11], thermal annealing [12], and photothermal welding [13]). Chemical growth methods have disadvantages such as complex operations and strict reaction conditions, including high vacuum and high temperature. In contrast, nanoscale welding method provides possibilities for building complex structures, reducing barrier height, enhancing mechanical strength, and increasing conductivity.

2. Experiment

2.1. Experimental setup

The length of n-type ZnO nanowire ranges from 30 μm to 100 μm, and its diameter is about 150 nm. The length of single-crystal Au nanowire ranges from 20 μm to 30 μm, and its diameter is about 200 nm. Figure 1 is the schematic of the experimental set-up for photothermal nano-welding. A Nd: YAG laser is used as the light source. The operating wavelength is 532 nm. An attenuator is placed next to the laser to control the laser intensity. To regulate the exposure time, a shutter is used. Here, the exposure time is set as 4 ms. For uniform heating, circularly polarized light is used. A CCD is used to monitor the nanomanipulation by two fiber probes.
2.2. Results and analysis
A single crustal Au nanowire is placed on top of a n-type ZnO nanowire using a nano-manipulator. The circularly polarized laser beam of wavelength 532 nm is focused on the top of the nanowire junction using a microscope objective (100 X). The scanning electron microscope (SEM) images are used to observe the quality of the welded junction. Figure 2 shows the welded junction of the single crystal Au and n-type ZnO nanowires.

Figure 1. Schematic of experimental set-up for photothermal nano-welding.

Figure 2. SEM image of the welded junction of the single crystal Au and n-type ZnO nanowires.
We studied electrical property of this structure towards further probing the quality of the welded junction. In order to obtain the characteristic current-voltage (I-V) curve, the single crystal Au and n-type ZnO nanowires were placed on Au and Ti electrodes, respectively. We welded three junctions: (1) single crystal Au nanowire on Au electrode, (2) single crystal Au and n-type ZnO nanowires, and (3) n-type ZnO nanowire on Ti electrode (see figure 3.a). Junction 1 and 3 are ohmic contacts because the barrier height, which is the difference between work function of Ti (4.1 eV) and Fermi level of ZnO (4.3 eV), is less than 1.0 eV. On the other hand, junction 2 is Schottky contact due to the large barrier height between single-crystal Au (work function is 5.2 eV) and n-type ZnO nanowires. The I-V characteristic curve (see figure 3.b) shows that the current remains about zero when the applied bias voltage is below +0.7 V, and it starts increasing beyond this voltage. The maximum current is about 1 A at bias voltage 3 V. This is typical behavior of single Schottky rectifier. It can be concluded that good quality junction is realized by plasmonic welding.

3. Conclusion
Our experimental results demonstrate the feasibility of the nano-scale device fabrication of metal-semiconductor (Au-ZnO) Schottky heterojunctions by photothermal welding technique. It has great significance in large-scale integration applications such as high-speed switches and rectifier units.

Acknowledgment
This work is supported by the National Natural Science Foundation of China (grant nos 6142503, 61575177 and 61235007).

References
[1] Hara E, Machida S and Ikeda M 1981 A high speed optoelectronic matrix switch using heterojunction switching photodiodes IEEE. J. Quant. 17 1539-46
[2] Polyakov A Y, Milnes A G, Govorkov A V, Druzhinina L V and Tunitskaya I V 1995 Band offsets in heterojunctions of InGaAsSb and AlGaAsSb Solid-Stat. Electron 38 525–9
[3] Jung S W and Park W I 2002 Time-resolved and time-integrated photoluminescence in ZnO epilayers grown on Al_{2}O_{3}(0001) by metalorganic vapor phase epitaxy Appl.Phys.Lett. 80 1924-6
[4] Hu J, Bo Y, Zhan J, Li C and Golberg D 2007 Mg_{3}N_{2}-Ga: Nanoscale Semiconductor-Liquid Metal Heterojunctions inside Graphitic Carbon Nanotubes Adv. Mat. 19 1342–6
[5] Hu J, Bo Y, Zhan J, Xu F, Sekiguchi T and Golberg D 2004 Growth of Single-Crystalline Cubic GaN Nanotubes with Rectangular Cross-Sections Adv.Mat. 16 1465–8
[6] Hu J, Bo Y and Golberg D 2005 Sn-Catalyzed Thermal Evaporation Synthesis of Tetrapod-Branched ZnSe Nanorod Architectures Small 1 95-9
[7] Yang J, Levina L, Sargent E H and Kelley S O 2006 Heterogeneous deposition of noble metals on semiconductor nanoparticles in organic or aqueous solvents J. Mater. Chem 16 4025-8
[8] Wen B, Liu C and Liu Y 2005 Bamboo-shaped ag-doped TiO$_2$ nanowires with heterojunctions. Inorganic Chemistry 44 6503-5
[9] Lee J, Lee P, Lee H B, Hong S, Lee I and Yeo J 2014 Room-temperature nanosoldering of a very long metal nanowire network by conducting-polymer-assisted joining for a flexible touch-panel application Adv. Funct. Mater. 23 4171-6
[10] Peng Y, Cullis T and Inkson B 2009 Bottom-up nanoconstruction by the welding of individual metallic nanoobjects using nanoscale solder Nano. Lett. 9 91-6
[11] Song T B, Chen Y, Chung C H, Yang Y M, Bob B and Duan H S 2014 Nanoscale joule heating and electromigration enhanced ripening of silver nanowire contacts Acs Nano 8 2804-11
[12] Gu Z, Ye H, Gracias D H and Gracias D 2005 The bonding of nanowire assemblies using adhesive and solder Jom 57 60-4
[13] Li Q, Liu G, Yang H, Wang W, Luo S and Dai S 2016 Optically controlled local nanosoldering of metal nanowires Appl. Phys. Lett. 108 193101