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Short communication

Realization of nitride–oxide based p–n heterojunctions with the n-VO_2/p-GaN/sapphire structure

Xiaoxuan Li[a], Jiming Bian[a,b,*], Minhuan Wang[a], Lihua Miao[a], Hongzhu Liu[a], Fuwen Qin[a], Yuzhi Zhang[b], Yingmin Luo[a]

[a] Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China
[b] Key Laboratory of Inorganic Coating Materials, Chinese Academy of Sciences, Shanghai 200050, China

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ABSTRACT

The nitride–oxide based p–n heterojunctions with the n-VO_2/p-GaN/sapphire structure was realized by sputtering deposition of VO_2 films on p-GaN/sapphire substrates. The structure and electrical properties of the as-grown VO_2/p-GaN/sapphire heterostructure were investigated systematically. The distinct reversible semiconductor-to-metal transition (SMT) with resistance change up to nearly two orders of magnitude was observed for the sample deposited at the optimized conditions. Moreover, the clear rectifying current–voltage characteristics originated from the n-VO_2/p-GaN interface were demonstrated both before and after SMT of VO_2 over layer, which were attributed to the p–n junction behavior and Schottky contact character, respectively. Our present finding demonstrated the feasibility of integrating correlated oxide and wide bandgap nitride semiconductors, and will further motivate research in novel devices with combined functional properties of both kinds of materials.

1. Introduction

Vanadium dioxide (VO_2) undergoes an abrupt reversible transition at a critical temperature (T_c) of 341 K, known as semiconductor-to-metal (SMT) or metal-to-insulator transition (MIT) first-order transition [1]. At temperatures below T_c, VO_2 is in semiconducting state with monoclinic structure, in which the V atoms pair open an energy gap of 0.6 eV. At temperatures above T_c, VO_2 is in metallic state with tetragonal structure, in which overlap between the Fermi level and the V_{3d} band eliminates the band gap [2–4]. This transition in crystal symmetry and electronic band structure, which can be triggered by temperature or voltage, was usually accompanied by an abrupt change in its resistivity and optical transmittance especially in the infrared region [3–5]. With these unique properties, VO_2 thin-film has been studied extensively for its numerous potential applications in ultrafast electrical and optical switches devices, data storage devices as well as smart window coatings [6–10].

On the other hand, gallium nitride (GaN) has been emerging as the most important wide bandgap semiconductor, due to its wide band gap (3.39 eV) and some other inherent properties [11]. Some applications with conventional Si and GaAs are currently being replaced by GaN-based optoelectronic and microelectronic devices, due to its advantages such as higher reliability, longer lifetime and lower power consumption [11,12]. Especially, the recently demonstration of high quality VO_2 films on n-type GaN/sapphire epitaxial substrate greatly intensified the interest in VO_2/GaN based nitride–oxide heterostructure, as it may provide new opportunities for novel device architectures in solid-state electronics and opto-electronics, which combine desirable functional properties of both classes of materials [13]. However, for various practical applications, nitride–oxide based p–n heterojunctions are essential elements since they are the building blocks for multiple devices. Unfortunately there have been very limited researches on this subject since its early stage of development, much works are needed to fully understand the physical mechanism behind the exotic characteristics of VO_2/p-GaN heterostructure [14,15]. Especially, the growth of high quality VO_2/p-GaN heterostructure was rather difficult due to the great discrepancy in preferred growth conditions between oxide and nitride.

In this study, the nitride–oxide based p–n heterojunctions with the n-VO_2/p-GaN/sapphire structure was successfully realized by sputtering depositing of VO_2 films onto p-GaN/sapphire substrates.

* Corresponding author at: Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China.
Fax: +86 411 84707865.
E-mail address: jmbian@dlut.edu.cn (J. Bian).

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The crystal structure and electrical properties of the as-grown VO_2/*p*-GaN/sapphire heterostructure were investigated systemically as a function of O_2 flow rate during sputtering deposition process. Our achievements will be helpful for understanding the physical mechanism behind the exotic characteristics of VO_2/*p*-GaN heterostructure, and further motivate researches in novel devices with combined functional properties of both correlated oxide and wide bandgap nitride semiconductors.

2. Experiments details

Commercially available Mg-doped GaN epitaxial layers (*p*-type, hole concentration $\sim 1.3 \times 10^{17}$ cm^{-3}) were employed as substrates, which were grown on c-plane sapphire substrates by metal organic chemical vapor deposition (MOCVD). The VO_2/*p*-GaN/sapphire heterostructure was achieved by sputtering deposition of VO_2 films on *p*-GaN/sapphire substrates. Prior to the deposition, the substrates were cleaned ultrasonically in ethanol, acetone and deionized water followed by drying with nitrogen. For the deposition process, argon and oxygen gases were introduced into the chamber by separate controllers after the vacuum chamber was evacuated down to a base pressure of $\sim 10^{-4}$ Pa. In order to remove contaminants on the surface, the VO_2 ceramic target (99.99%) was presputtered in argon atmosphere for 10 min. The total gas pressure during deposition was $\sim 10^{-1}$ Pa and the substrates temperature was kept at 400 °C. The distance between the target and the substrate was 11 cm. The O_2 flow rate was varied from 1.0 to 10.0 standard-state cubic centimeter per minute (sccm), while the Ar flow rate and radio frequency (RF) power were maintained at 80 sccm and 120 W, respectively. After the depositions, the samples were cooled down to the room temperature under the same deposition atmosphere in the chamber.

The surface and cross-section morphology of the VO_2/*p*-GaN/sapphire samples were analyzed by field effect scanning electron microscopy (FESEM) on Nov Nano SEM 450, while the crystallographic properties of the thin films were determined by X-ray diffraction (XRD) using LabX XRD-6000 (CuK_{a1}: $\lambda = 0.154056$ nm). The diffraction photons were collected by the diffractometer from 10 to 80° with a 0.02° step size. The temperature-driven phase transition behavior was investigated by measuring the electrical resistance during heating and cooling process using the conventional electrical method by Keithley 2635 A source meter. The samples were kept on a temperature controlled stage, and heated from room temperature to 100 °C in air by a heater at the backside of the substrate, the heating and cooling rates for the measurement are approximately 10 °C/min for heating and 1 °C/min for cooling. Details of the electrical measurements can be found in our previous report [4].

3. Results and discussion

Fig. 1 shows the XRD patterns of the VO_2/*p*-GaN/sapphire heterostructures grown with the O_2 flow rate ranging from 1.0 to 10.0 sccm. From the lower pattern in Fig. 1(a), the sample deposited with O_2 flow of 1.0 sccm exhibit the well-defined diffraction peak corresponding to the monoclinic VO_2 (1 2 1) at ~52.9°, accompanied with three high intensity diffraction peaks from sapphire (0 0 6), GaN (0 0 2) and GaN (0 0 4), respectively. VO_2 (4 0 0) at 31.12 was observed in the intermediate pattern, while the top pattern obtained at the highest O_2 flow rate of 10.0 sccm reveals V_3O_5 and a small amount of VO_2 (4 0 0). Remarkably, these results demonstrated that the valence states of V in the VO_2/*p*-GaN/sapphire heterojunctions are very sensitive to the O_2 partial pressure during the sputtering process, thus high quality pure phase VO_2 films could be achieved only under a narrow window of

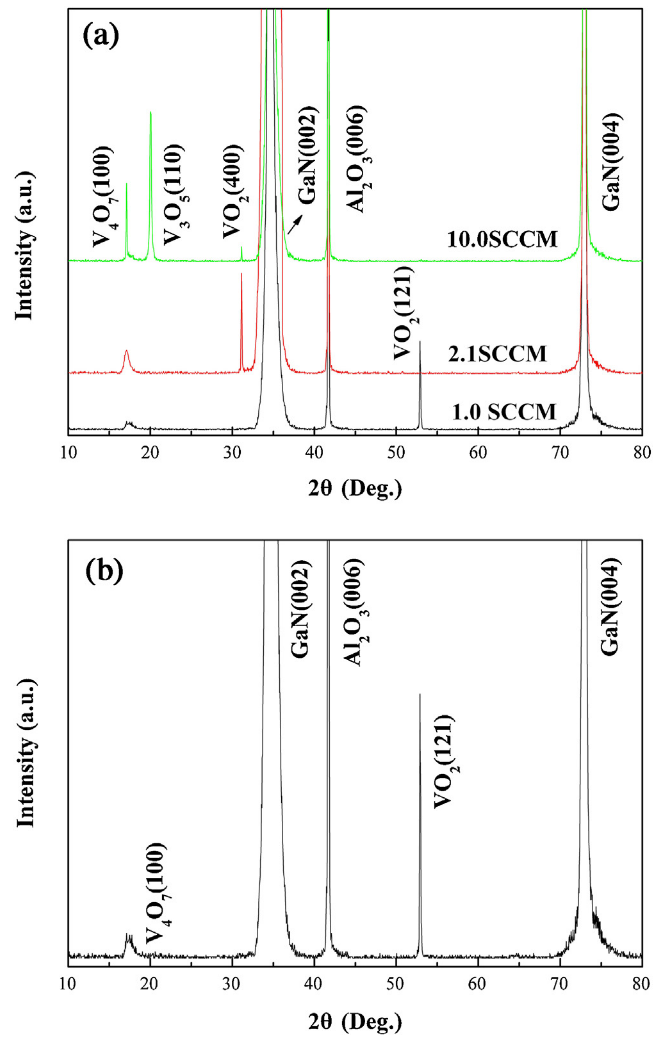

Fig. 1. XRD patterns of the as-grown VO_2/*p*-GaN/sapphire heterostructures. (a) Samples deposited at various O_2 flow rates; (b) typical XRD spectra for the optimized sample.

the optimized O_2 flow rate. To clearly demonstrate the crystallographic quality of VO_2/*p*-GaN/sapphire heterostructures, the XRD patterns of samples under optimized condition was shown in Fig. 1(b). The diffraction peak from GaN (0 0 2) at $2\theta = 34.74°$ appears broad just because of its extremely high intensity, which was more than 100 times stronger than that from VO_2 (1 2 1). So it can be concluded that the crystallinity of *p*-GaN under layer did not degrade at any detectable level during the high temperature deposition of VO_2 over layer, which is essential for eventual device applications [12].

Fig. 2(a)–(c) shows the SEM surface images of the VO_2/*p*-GaN/sapphire heterojunctions as a function of O_2 flow rate, as can be seen, the relatively smooth and flat surface with uniform grains distribution was obtained only for the sample under the optimized O_2 flow rate. As the O_2 flow rate get higher, irregular particles with various sizes were observed from Fig. 2(b) and (c). This phenomenon can be understood considering the decreased energy of particles arriving at heterojunction surface, which was resulted from the more collisions between the sputtering particles and O_2 as the O_2 flow rate getting higher. This was in well agreement with the XRD analysis. In addition, for the optimized sample, a well-defined interface between the VO_2 and *p*-GaN layer with VO_2 layer thickness around 200 nm can be observed from the corresponding