Microelectronics Reliability 78 (2017) 374–378

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Temperature dependence of current–voltage characteristics of MoS_2/Si devices prepared by the chemical vapor deposition method

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ARTICLE INFO

Article history:
Received 22 August 2017
Received in revised form 3 October 2017
Accepted 3 October 2017
Available online xxxx

Keywords:
Molybdenum disulfide
Temperature dependence
Heterojunction
Electrical properties
Diode
Si

ABSTRACT

Layers of MoS_2 are directly deposited on the n-type Si (n-Si) substrate by chemical vapor deposition for fabricating a MoS_2/n-Si heterojunction device. The rectification current–voltage (I–V) characteristics of MoS_2/n-Si devices were measured in the temperature range from 80 to 300 K in steps of 20 K. The temperature-dependent forward-bias I–V characteristics can be explained on the basis of the thermionic emission theory by considering the presence of the interfacial inhomogeneous barriers at the MoS_2/n-Si interfaces. The dominance of the induced carrier capture/recombination by states at the MoS_2/n-Si interface that lead to the formation of the inhomogeneous barriers serves to influence the photo-response at room temperature. The fabricated MoS_2/n-Si devices exhibit reversible switching between high and low current densities, when the simulated sunlight is turned on and off. The sensitivity of the I–V characteristics to temperature provides an opportunity to realize stable and reliable rectification behaviors in the MoS_2/n-Si devices. It is found that the electron mobility in the n-Si layer reduces as temperature increases, which leads to the noticeably increased value of the series resistance of MoS_2/n-Si devices.

1. Introduction

Promoted by the discovery of graphene and its fascinating properties in the past few years, graphene-like layered transition metal dichalcogenides (LTMDs) have been the subject of intense investigation due to their unique properties, which can be employed in many applications, such as electronic and optoelectronic devices. Of these LTMDs, MoS_2 has been extensively studied because it has good electrical and optical properties [1]. In addition, heterojunction device is playing an important role in electronics and optoelectronics. The integration of MoS_2 on Si could lower the cost of electronic and optoelectronic devices and multifunctional devices would be possible [2,3]. A heterojunction that is composed of MoS_2 and Si has many potential applications in electronic and optoelectronic devices and allows study of the interface effect in nanoscale and evolution of electrical transporting mechanisms. Interface states play key roles on the electrical output of the MoS_2/Si device. Due to lattice mismatch or defect segregation, the interface between two heteropartners can exhibit a higher defect density than the bulk of each partner [4]. MoS_2 is prepared by a variety of techniques such as an adhesive-tape-based micromechanical cleavage technique, lithium-based intercalation, chemical vapor deposition (CVD), metal-organic chemical vapor deposition, and thermal evaporation deposition [5–16]. The preparation process and the equipment for these methods are very complex. In order to fabricate large-scale MoS_2–based transistors, MoS_2 that was prepared using CVD was developed [5,9,13–16]. The fabrication of large-area heterostructures is of fundamental and technological interest. The CVD growth of MoS_2 is observed on bare Si surfaces in this study. The entire process for MoS_2/Si devices that is demonstrated requires no transfer processing, which minimizes cost and leverages the existing Si manufacturing infrastructure to maximize performance. The investigation of the temperature-dependent current-voltage (I–V) characteristics of MoS_2/n-type Si (n-Si) devices to find the interfacial inhomogeneous barrier is developed in this study. Correlation effects were evaluated using the well-known expressions for thermionic emission (TE) [2,17–20]. To investigate the effect of the interfacial inhomogeneous barrier on the device performance, the photo-response measurement is performed on the MoS_2/n-Si device. In addition, the sensitivity of the I–V characteristics to temperature provides an opportunity to realize stable and reliable rectification behaviors in the MoS_2/n-Si devices.

2. Experimental procedure

Four-inch 525 μm-thick n-Si (100) wafers with an electrical resistivity of about 3 Ω cm (Guv Team International Co., Ltd.) were used in the experiment. The n-Si samples were cleaned in chemical cleaning solutions of acetone and methanol. The n-Si sample was then chemically etched using a diluted HF solution for 1 min, rinsed with de-ionized water and blow-dried with N_2 (referred to as as-cleaned n-Si samples).

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https://doi.org/10.1016/j.microrel.2017.10.002
0026-2714/

The as-cleaned n-Si samples were then dipped in a $(NH_4)_2S_x$ solution (with 6% S, Nippon Shiyaku Co., Ltd.) for 10 min at room temperature and dried in nitrogen. The MoS_2 thin film was grown on the as-cleaned n-Si samples with $(NH_4)_2S_x$ treatment using the CVD method. The detailed CVD-grown process is shown in Refs [21–23]. The MoS_2 area was 1.0×0.5 cm^2. The structural properties of the MoS_2 films were determined using Raman spectroscopy (Ramboss 500i, DongWoo Optron). A 532-nm laser was used for excitation. The morphologies of the MoS_2 films were studied using field emission scanning electron microscopy (FESEM). X-ray photoelectron spectroscopy (XPS) was used to identify the chemical bonding state of the samples. XPS measurements were performed using a monochromatic Al $K\alpha$ X-ray source. These were calibrated by using the C 1 s peak as a reference. The electrical properties of the MoS_2 and n-Si films were measured by the Van der Pauw method with a four-point contact configuration. In order to determine the electrical properties of MoS_2/n-Si samples, gold (Au) ohmic contacts with a square pattern were deposited onto the MoS_2 surface using a sputter coater and indium (In) ohmic contacts with a square pattern were deposited onto the n-Si surface using a sputter coater. The current–time (I–t) and I–V curves were measured, using a Keithley Model-4200 semiconductor characterization system. The I–V characteristics of the devices were measured in the temperature range from 80 to 300 K in steps of 20 K using a temperature controlled cryostat. The photo-response for the devices was measured at an illumination intensity of 100 mW/cm^2, using a 150 W solar simulator with an AM 1.5G filter. The photo-response was measured by recording the current versus time and the simulated sunlight was turned on and off using a shutter.

3. Results and discussion

Fig. 1(a) shows the Raman spectra for MoS_2 films that were deposited on the n-Si substrate. The multilayer flakes show characteristic A_{1g} and E^1_{2g} Raman modes located at around 407 cm^{-1} and 383 cm^{-1}, respectively. In the E^1_{2g} mode, both S and Mo atoms vibrate along in-plane direction, whereas the S atoms vibrate in the perpendicular-to-plane direction in the A_{1g} mode. Our Raman spectrum result is consistent with the result shown in Ref. [24]. The frequency difference between the A_{1g} and E^1_{2g} peaks was about 24 cm^{-1}, suggesting that few layers of MoS_2 were formed [21–24]. The full width at half maximum for the Raman peak the E^1_{2g} (A_{1g}) peak is about 10 (11) cm^{-1}. The calculated values are similar to the reported values [25].

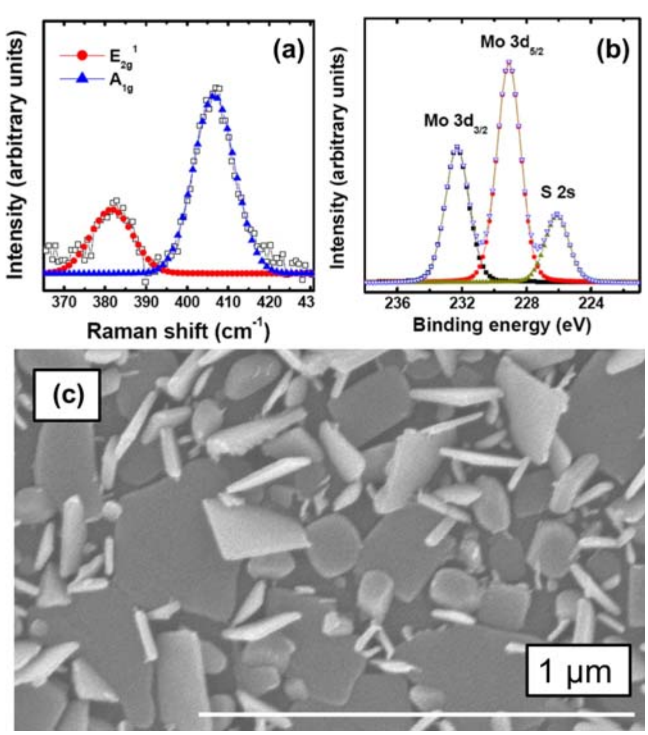

Fig. 1. (a) Raman spectra and (b) Mo 3d and S 2 s XPS spectra for MoS_2/n-Si samples and (c) a FESEM image of MoS_2 films that were deposited on the n-Si substrate.

The carrier concentration, carrier mobility and conduction types for MoS_2 samples were obtained from Hall-effect measurements. The Van der Pauw-Hall measurements (SWIN Hall8686 Hall Effect Measurement System) were performed at room temperature. The MoS_2 thin film that is deposited on the Si substrate exhibits p-type behavior. The hole concentration and mobility for MoS_2 films are respectively determined to be 2.0×10^{20} cm^{-3} and 354 cm^2 V^{-1} s^{-1}. Fig. 1(b) shows the Mo 3d and S 2 s XPS spectra for MoS_2 films that were deposited on Si substrates. The XPS core-level peaks are deconvolved into their various components using an interactive least-squares computer program. Mixed Gaussian–Lorentzian peaks were used in this analysis. The peak for Mo $3d_{5/2}$ was measured at about 229.1 eV and the peak for S 2 s was measured at about 226.0 eV. These binding energies are in good agreement with the reported values for p-type MoS_2 samples [25]. Both p-type and n-type conductivities have been reported in the MoS_2 layers deposited on different substrates [2,6,12,15,21,22,25]. MoS_2 shows both n- and p- type conductivities dependent on the experimental process [26]. The n-type and p-type conductivities have been reported in ultrathin MoS_2 layers deposited on SiO_2 [5,26,27–31]. It is worth noting that no intentional doping was introduced in these experiments. A relationship between the presence of large variations in the sulfur concentrations of MoS_x and the conduction type has been reported [32,33]. McDonnell et al. [34] showed that MoS_2 can exhibit both p-type and n-type conductivity at different positions on the same sample, which they attributed to variations in the local stoichiometry of MoS_2 due to surface defects. Fig. 1(c) shows the FESEM image of MoS_2 films. The scale bar is 1 μm. It is seen the shape of flake, indicating that MoS_2 films were deposited on the n-Si substrate.

The schematic of the MoS_2/n-Si device with Au/In contacts is shown in Fig. 2(a). Fig. 2(b) shows the rectification |I|–V characteristics for MoS_2/n-Si devices at 300 K in the dark. This result demonstrates direct and simple growth of p-type MoS_2 on n-Si, which can be of high importance in future electronic and optoelectronic applications. Fig. 2(b) shows that the ratio of the forward to reverse current at a bias voltage of ± 2 V is 128. For p-type MoS_2/n-Si heterojunctions, the rectification conduction mechanism usually involves TE. According to TE theory, the rectification I–V characteristic is given by [2,17–20,35].

$$I = \mathrm{I_s}\left[\exp\left(\frac{qV - I\mathrm{R_s}}{\eta kT}\right) - 1\right] \tag{1}$$

where I_s is the reverse-bias saturation current, R_s is the series resistance, q is the elementary charge, T is the absolute temperature, k is the Boltzmann constant, and η is the ideality factor. Based on TE theory, the forward-bias fitting curve is shown in Fig. 2(b). η is determined from the slope of the linear region of the forward bias ln (I)–V characteristics at low voltages. The derived value for η is 2.7. MoS_2/n-Si devices exhibit non-ideal TE behaviors because of $\eta > 2$. This deviation can be attributed to the presence of the inhomogeneous barrier at the MoS_2/n-Si interface that plays an important role in the conduction process. Due to lattice mismatch or defect segregation, the interface between two heteropartners can exhibit a higher defect density than the bulk of each partner [4].

In order to obtain a greater understanding of the rectification I–V characteristics, the photo-response measurements were performed on the MoS_2/n-Si device. Fig. 2(c) shows the time-resolved response for the current to repeated light switching for cycling times between 0 and 130 s and for voltages from 0 to 1 μV. For Keithley Model-4200-SCS semiconductor characterization system, it is difficult to observe the I–t characteristics for a constant voltage. However, the I–t characteristics could be easily obtained for applying V varied from 0 to 1 μV. The