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Research Article

Poole-Frenkel Conduction in Cu/Nano-SnO_2/Cu Arrangement

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It is well known that metal/Tin-dioxide/metal sandwich structures exhibit a field-assisted lowering of the potential barrier between donor-like center and the conduction band edge, known as the Poole-Frenkel effect. This behavior is indicated by a linear dependence of Iog J on $V^{1/2}$, where J is the current density, and V is the applied voltage. In this study, the electrical properties of Cu/nano-SnO_2/Cu sandwich structures were investigated through current-voltage measurements at room temperature. Also, an attempt to explore the governing current flow mechanism was tried. Our results indicate that noticeable feature appearing clearly in the current-voltage characterization is the Poole-Frenkel and space-charge-limited conduction mechanisms.

1. Introduction

Nanocrystalline materials with average grain size of less than 50 nm have attracted considerable scientific interest because of their unusual physical and chemical properties [1]. The microstructure of nanocrystalline materials depends upon the method of preparation. Tin dioxide (SnO_2), a wide band gap (3.6 eV) n-type semiconductor, is one of the most important materials for gas sensors [2]. It is well known for its application in gas sensors and dye-based solar cells [3]. Because of their relatively low operating temperature and as oxidizing gases, SnO_2 nanoparticles have been extremely studied [4]. As a transparent conducting oxide (TCO), it has been widely used as optoelectronic devices such as flat panel displays and thin film solar energy cells [5]. As an n-type semiconductor, tin dioxide has been actively explored as the functional component in detecting combustible gases such as CO, H_2, and CH_4 [6]. Most of these studies concentrated on devices, which were fabricated with polycrystalline films as the sensing units [7]. Nanostructures of SnO_2 could also be employed to detect various gases [8, 9].

In some of these applications, the mechanism of electronic conduction strongly affects the device characteristics. Therefore, one needs to understand conduction mechanism. The type of electronic conduction mechanism depends on several factors, in particular, the nature of the metallic contact to the semiconductor (either ohmic or blocking), the level of voltage applied across the sample, surface roughness, and grain size and its temperature. Metal-semiconductor (MS) structures (or Schottky diodes) have been studied extensively because of the very importance and critical components in integrated circuit technology. Moreover, it is a very attractive tool for the characterization of semiconductor materials [10–13].

In the present work, We examine the mechanisms, which control carrier transport in Cu/nano-SnO_2/Cu sandwich structures. These include the study of gate voltage dependence of device leakage current.

2. Experimental Details

SnO_2 nanoparticles were synthesized by a simple sol-gel method which its details reported elsewhere [14]. SnO_2 nanopowder Pellets were made by applying a uniaxial pressure of 312.92 atmospheres on the powder sample. Polarization measurements were performed on the Cu/nano-SnO_2/Cu sequence system using a computer-controlled AUTOLAB potentiostat and galvanostat.

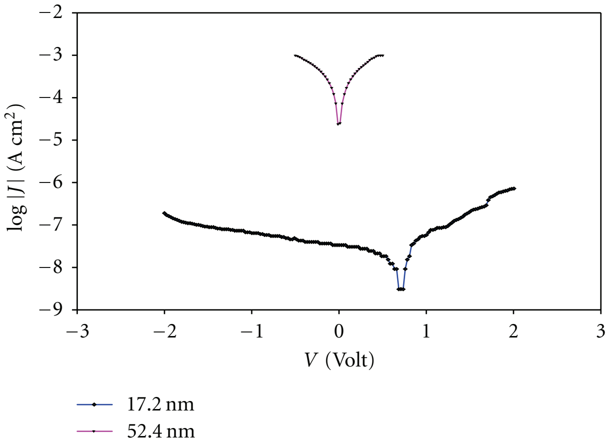

Figure 1: log $|J|$ versus V characteristic of nano-SnO_2 with different grain sizes.

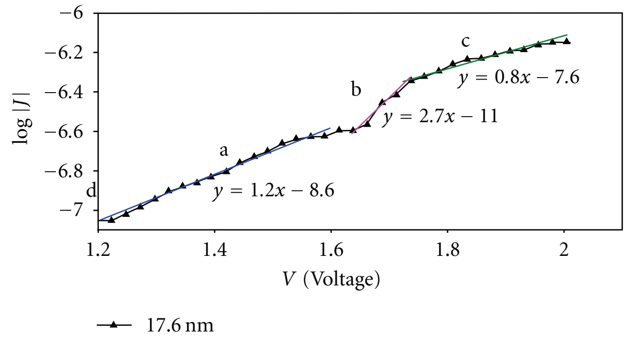

Figure 2: Forward bias log $|J|$-V plot of the Cu/nano-SnO_2/Cu arrangement with a grain size of 17.6 nm.

3. Results and Discussion

3.1. Polarization Study. A typical forward bias semilogarithmic log $|J|$ versus V characteristic of Cu/nano-SnO_2/Cu sandwich structures is shown in Figure 1. The leakage current can be affected by the surface roughness and grain size. The smaller grain size produces more grain boundaries and causes more leakage current [15]. Hence, it is suggested that the decrease of the leakage current of specimens can be attributed to the reduction of the surface roughness. The log $|J|$-V characteristics show also no double blocking behavior (see Figure 1). We assume that the copper electrode as a back contact does not block the current in reverse direction, which is especially the case for very low barriers. So the current transport through the Cu contact dominates the log $|J|$-V characteristic for positive voltages. Schottky emission, Poole-Frenkel, space-charge-limited conduction (SCLC), and so forth, are the possible conduction mechanisms in the studied junctions [16]. The governing conduction mechanism in Cu/nano-SnO_2/Cu Schottky diodes at hand can be figured out from the power of log $|J|$-V curve. Power of the curve greater than 2 ($m > 2$) indicates SCLC mechanism whereas being equal to 1 ($m = 1$) imply ohmic character. When the power lies between 1 and 2 imposing either Schottky or Poole-Frenkel conduction mechanism. The linear sections of the curve could be interpreted in terms of either the Schottky emission or Poole-Frenkel emission. For the Schottky emission, the current density J is expressed as follows [17]:

$$J = A^* T^2 \exp\left(\frac{-\varphi}{kT}\right) \exp^{(e\beta_s V^{1/2}/kTd^{1/2})}, \quad (1)$$

where A^* is the effective Richardson constant, φ is the Schottky barrier height at the electrode contact, and β_s is the Schottky field lowering constant. For Pool-Frenkel emission, the current density is given by

$$J = J_{\text{pf0}} \exp^{(\beta_{\text{pf}} V^{1/2} q/kTd^{1/2})}, \quad (2)$$

where β_{pf} is the Pool-Frenkel coefficient. The theoretical values of these coefficients are given by

$$2\beta_s = \beta_{\text{pf}} = \left(\frac{e}{\pi\varepsilon\varepsilon_0}\right)^{1/2}. \quad (3)$$

For Schottky diodes, thermionic emission (TE) model suggests the following J-V relationship:

$$J = J_0 \exp^{(eV/n\kappa T)}, \quad (4)$$

where V, κ, T, n and J_0 are the applied voltage, Boltzman constant, temperature, ideality factor, and saturation current density, respectively. The saturation current density is given by

$$J_0 = A^* T^2 \exp^{(-e\varphi_b/\kappa T)}, \quad (5)$$

where A^*, φ_b, and e are the Richardson constant, barrier height, and electron charge, respectively. The parameters J_0 and φ_b for SnO_2 nanoparticles with a grain size of 17.6 nm were calculated 8.6472×10^{-4} A and 0.6015 eV, and for SnO_2 nanoparticles with a grain size of 52.4 nm were obtained 0.0312 A and 0.5073 eV, respectively, using the above equations.

As shown in Figure 2, three linear regions are eventual in the log $|J|$-V characteristic of the Cu/nano-SnO_2/Cu sandwich structure. One of them is in the lower-voltage region ($1.2 < V < 1.6$), where the power is equal to 1.2, imposing either Schottky or Poole-Frenkel conduction mechanism. In the second region, with increasing voltage, more electrons injected from electrode into the film and current density originates from the SCLC mechanism, where the power is equal to 2.7. Abrupt increment of the current density is characteristic of the SCLC mechanism due to the trapped carriers. As the applied voltage is increased further, strong injection of electrons takes place and causes an increase in the density of filled trapping sites and leading to an increase of film conduction. An abrupt increase in leakage current appeared which follows a trap-filled limited law. For this conduction, the increasing slop indicates that the I-V correlations are determined by another distributed trap type [18].

In the higher voltage region (Section 3), less slope is observable and the "quasisaturation" of the current may be

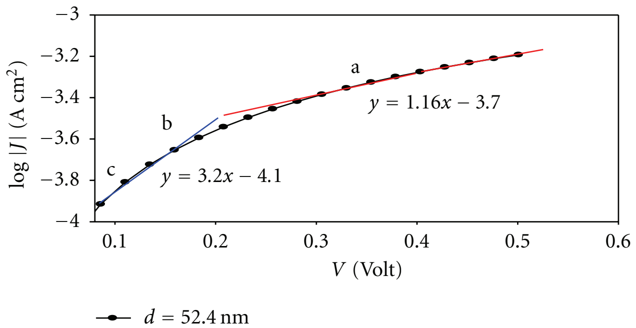

Figure 3: Forward bias log $|J|$-V plot of the Cu/nano-SnO_2/Cu arrangement with a grain size of 52.4 nm.

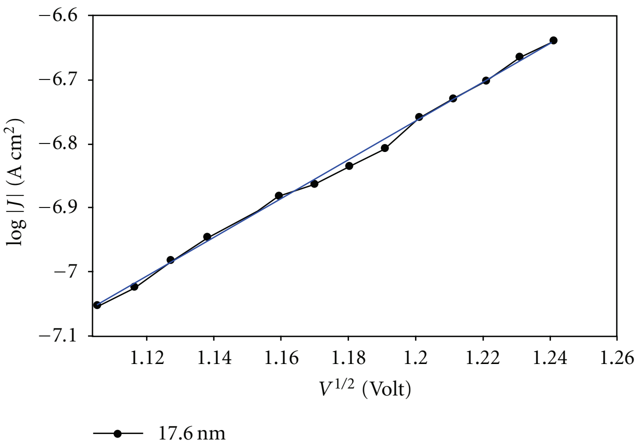

Figure 4: Log J-$V^{1/2}$ plot of the Cu/nano-SnO_2/Cu arrangement with a grain size of 17.6 nm.

caused by the charge trapping. Consequently, an internal electric field is created, which is opposed to the external electric field, limiting the carriers flow. As can be seen in the Figure 3, similar analysis is carried out for nanostructure SnO_2 with a grain size of 52.4 nm.

The other possibility for the nonlinear J-V characteristics is bulk-limited Poole-Frenkel emission. Figure 4 shows the plot of $\ln |J|$ versus $V^{1/2}$ for Cu/nano-SnO_2/Cu arrangement with a grain size of 17.6 nm, which clearly yields a linear section of the curve, could be interpreted in terms of either Schottky emission or Pool-Frenkel emission. Corresponding experimental value of β calculated from the slope of the linear region of Figure 4 was found to be $3.63 \times 10^{-5}\,\mathrm{eV\,m^{1/2}\,V^{-1/2}}$. The experimental value of β for SnO_2 nanoparticles with a grain size of 52.4 nm, derived from the slope of the linear section of Figure 5, was found to be $3.42\times10^{-5}\,\mathrm{eV\,m^{1/2}\,V^{-1/2}}$. Theoretical values of β_s and β_{pf} were found to be $1.88 \times 10^{-5}\,\mathrm{eV\,m^{1/2}\,V^{-1/2}}$ and $3.76 \times 10^{-5}\,\mathrm{eV\,m^{1/2}\,V^{-1/2}}$, respectively. Experimental value for β in the both nanoparticle is nearly agreement with the theoretically calculated value of β_{pf}. Hence, we can conclude that the conduction mechanism in our nanocrystalline film is controled by the Poole-Frenkel effect and the Schottky effect is probably masked by the Poole-Frenkel emission from some

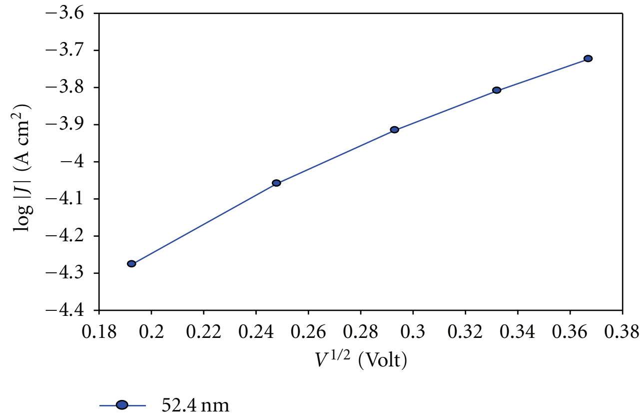

Figure 5: Log J-$V^{1/2}$ plot of the Cu/nano-SnO_2/Cu arrangement with a grain size of 52.4 nm.

shallow traps at grain boundaries. The adsorbed oxygen atoms at the grain boundary produce defect states which trap carriers and create a potential barrier. By applying an applied field, the barrier height is diminished and electrons can flow from interfacial states, thus it can be reason of the existence of the Poole-Frenkel mechanism [19].

4. Conclusion

The tetragonal tin dioxide nanoparticles were obtained by using sol-gel technique with thermal treatments. Possible mechanism for leakage current conduction in the Cu/nano-SnO_2/Cu sequence system showed characteristics of typical Schottky-barrier devices. The Poole-Frenkel effect has been observed in nanotin oxide thick film. This effect depends on the electron transport phenomenon through grain boundaries. Nanostructured SnO_2 films with a large number of grain boundaries contain a considerable number of trap states.

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