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Impact of metal electrode on charge transport behavior of metal-Gd_2O_3 systems

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ABSTRACT

In this paper, we have grown an 80 nm thick Gd_2O_3 thin film by electron beam evaporation on glass substrate and fabricated different metal (Al, Cu, Cr and Au) electrodes on grown sample under same condition. To investigate the charge transport mechanism in these metal-semiconductor systems, the electrical conductivities and current–voltage (I–V) measurements have been measured over temperature range of 250–400 K. We have found that Mott variable range hopping (VRH) is responsible for conduction behavior in all systems for entire temperature range. A strong correlation between transport properties and metal work function has been observed. A space charge model successfully explained the decreasing trend of conductivity with increasing the metal work function. The conductivity decreased from 2.9×10^{-5} to 1.8×10^{-11} S/cm as the metal work function increased from 4 to 5.1 eV for Al to Au metals respectively. The ideality factor also increased from 1.67 to 2.2 with metal work function from Al to Au metal. The observed result can be explained as; high work function metal forms higher depletion layer as compared to metal having low work function, which compensate the empty sites available for hopping and consequently decreased the hopping conductivity.

1. Introduction

Gd_2O_3 is emerging as today's research material due to its amazing optical, physical, chemical and mechanical properties [1]. It has wide band gap (5.4 eV), high dielectric constant ($k = 18$) and high refractive index ($n = 2$) [2,3], therefore can be used for sensors, optoelectronics, data storage devices and luminescence applications [4–6]. Apart from optical, mechanical and chemical properties, Gd_2O_3 has rich chemistry of intrinsic defects such as oxygen vacancies and Gd interstitials [7]. Therefore it is of crucial importance to understand charge transport processes in both crystalline and amorphous Gd_2O_3. In this regard, the temperature dependent electrical conductivity measurements can reveal the underlying charge transport mechanism. Previously, temperature dependent behaviors of electrical properties of oxide semiconductors such as CeO_2, ZnO and $SrTiO_3$ have been reported in the literature [7,8]. However, no report has been found in the literature about the hopping conduction mechanism of Gd_2O_3 with different metal electrodes according to the best of our knowledge. Therefore understanding of conduction mechanism in gadolinium oxide semiconductor will provide more comprehensive information of the system and transport properties of this class of material.

In this paper, we have investigated the effect of metal electrodes (Al, Cu, Cr and Au) on the transport properties of Gd_2O_3 thin film grown by electron beam evaporation. The conductivity and I–V data suggested that all metal-semiconductor-metal system exhibit the hopping conduction in the temperature range from 250 to 400 K. The measured values of conductivity are strongly dependent on the tail states created at the interface due to difference between metal work function and electron affinity of Gd_2O_3.

2. Experimental

Metal-Semiconductor structures were fabricated using electron beam evaporation system. In first step, Gd_2O_3 layer was fabricated

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and in second step metal electrodes were deposited on glass substrate. Deposition parameters are shown in Table 1. For evaporation of each metal, a separate graphite crucible was used to avoid any contamination effect. Metals and Gd_2O_3 of evaporation grade having purity 99.99% (Sigma–Aldrich) were used for fabrication. The thickness was monitored by FTM-7 thickness meter which uses quartz crystal as standard. After deposition, thickness was reconfirmed by using ellipsometer. An error of <±6%> is observed in thickness as compared to FTM thickness. Deposition rate was controlled by continues monitoring and changing the value of e-beam current.

Before electrical measurement, X-Ray Diffraction (XRD) and Energy Dispersive X-Ray Spectroscopy (EDX) studies were performed to check the structure and purity of films. EDX studies confirmed that the films have no impurities other than as mentioned in data sheet (MSDS) of supplied material.

Then dc current (I) as a function of applied potential difference (V) across each sample was recorded in temperature range 250 K–400 K with the help of Kiethely 4200 Semiconductor Characterization System (4200-SCS). The applied voltage across each device was varied from 0 to 20 V with 0.05 V interval in sweeping voltage mode of SCS-4200 and corresponding dc current was measured. To minimize the random error in our current–voltage data each current value was averaged over 10 readings for each voltage step before it was recorded, by making use of the assisted facility available in the aforesaid equipment i.e. Keithley 4200SCS.

3. Results and discussion

Fig. 1 shows the variation of dc conductivity of examined metal-semiconductor systems (Al, Cu, Cr and Au) in temperature range 250 K–400 K. To calculate the activation energies, we have used Arrhenius expression of conductivity [9,10].

$$\sigma = \sigma_0 \exp(-E_a/k_B T) \quad (1)$$

where σ_0 pre-exponential factor, E_a is the activation energy and k_B is Boltzmann's constant. The activation energies were calculated from the slope of Arrhenius plot and are shown in Table 2. The measured values of pre-exponential factor and activation energy suggested the hopping conduction mechanism in all investigated systems. As the hopping conduction is associated with the electron jumping from occupied donor to empty ones, and therefore the presence of empty donors are necessary. The hopping conductivity governed by the hopping probability between impurity sites. The hoping conduction reflects a high lattice disorder in the observed systems. This disorder stimulates localization of the charge carriers favoring the hoping conduction in general.

Temperature dependence of conductivity and charge transport mechanism in disordered materials can be described by means of Mott's variable–range hopping model [11,12].

$$\sigma T^{1/2} = \sigma_0 \exp\left[-(T_0/T)^{1/4}\right] \quad (2)$$

where σ_0 is the pre-exponential factor and T_0 is the degree of disorder. The characteristic Mott temperature in 3D is given by Ref. [13]:

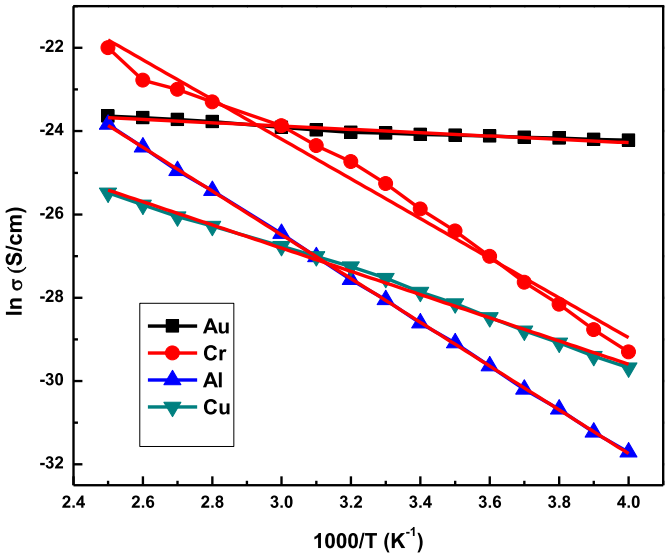

Fig. 1. Variation of dc conductivity with temperature for all metal-semiconductor-metal systems according to Arrhenius formulism in the temperature range 290–380 K. The red straight lines represent the linear fit in entire temperature range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$T_0 = \lambda\alpha^3/k_B N(E_F) \quad (3)$$

$N(E_F)$ is the density of localized states at Fermi level, λ is a dimensionless constant ~ 16 [14] and $\alpha = 10^7\ cm^{-1}$ represents the degree of localization. The expressions for the range of hopping and the activation energy for hopping in three dimensions are given by Ref. [15];

$$R_{hop}(T) = \left\{\frac{9}{8\pi\alpha k_B T N(E_F)}\right\}^{1/4} \quad (4)$$

$$W_{hop} = 3/(4\pi R^3 N(E_F)) \quad (5)$$

It is observed that variation of $Ln\alpha_{dc}$ with $T^{-1/4}$ is a straight line (Fig. 2) indicating the 3D charge transport mechanism may be dominated charge transport mechanism. The values of T_{Mott} are given by the slope of the straight line for all systems and are shown in Table 2.

A linear dependence in each case confirms the presence of hopping type conduction in low field regions. This hopping conduction originates due to the region of localized states. When the charge carriers are localized due to random electric fields, instead of band conduction, charge transport takes place via phonon-assisted hoping between localized sites [16]. Since the localized states have quantized energies extending over a certain range, activation energy is required for each hop. Hopping occurs either near the Fermi level or near the maximum of the density of states. Generally, an electron prefers to hop to a more remote site than to the nearest-neighbor one, in order to reduce the energy required for hopping [17].

Table 1
Growth parameters for the growth of Gd_2O_3 thin film and different metal electrodes.

Deposition parameters	Thin film	Metal electrodes			
	Gd_2O_3	Al	Cu	Cr	Au
Substrate temperature (°C)	100	26	26	26	26
Pressure (Torr)	2.0×10^{-5}	1.7×10^{-5}	3.0×10^{-5}	1.5×10^{-5}	3.2×10^{-5}
Deposition rate (nm/sec)	0.15	0.22	0.13	0.16	0.34