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Power spectral densities and polaron hopping conduction parameters in carbon films embedded by nickel nanoparticles

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ABSTRACT

In this work, the fractal dimensions and electric properties of carbon films embedded by nickel nanoparticles annealed at different temperature 300, 500 and 800 °C were investigated. A detailed analysis in terms of small polaron hoping (SPH) parameters is used to correlate electrical transport properties with annealing temperature in the range 150–300 K. It can be seen that with increasing annealing temperature up to 500 °C the polaron radius (r_p) decrease and has a minimum value 4.58×10^{-8} cm then from 500 °C to 800 °C it increased to 6.13×10^{-8} cm. The polaron hopping energy (W_H) at 500 °C has minimum value 0.017 eV while the density of states $N(E_F)$ at the Fermi level has maximum value 5.43×10^{21} eV^{-1} cm^{-3}. It can be seen that polaron hopping energy, density of state at Fermi energy and carrier mobility of films correlate with fractal dimensions of films which obtained from the power spectral densities (PSDs) analyses. It can be seen that there are a fluctuation in the polaron mass (m_p) and at 500 °C which correspond to maximum value of fractal dimension, has minimum value. With increasing fractal dimensions, carrier mobility of films decreases and have minimum value 1.2×10^{-10} s^{-1} V^{-1} cm^2.

1. Introduction

Recently, nano-composite thin films have attracted attention due to their many technological applications in physics and material have increasing properties with respect to industrial applications as protective coatings compared to single-phase coatings [1–3]. The presence of metal or metal carbide phase in carbon metal composite films coatings can enhance the cohesion, wear, and friction properties of films [4]. A combination of pure amorphous carbon films with metallic nanoparticles can enhance certain physical properties in a carbon based composite films [5]. Our special deposition conditions including room temperature and the non-hydrogenated deposition are prerequisites for applications in optical and electronic device [6]. Amorphous carbon films embedded by metals nanoparticles (Au, Ag, Cu, Mn, etc.) have many applications as coating materials in biomedical, electronic, mechanic and optics [7–9,4]. There are few reports about electrical properties of carbon–nickel composite films; however it has been paid less attention to the conduction mechanism carbon–nickel composite films. In the previous reports, we have studied the effect of deposition time and annealing temperature on magnetic and optical properties of the carbon–nickel films [10–12]. Following these studies, an attempt is made here to in order to obtain effect of annealing temperature on small polaron hoping (SPH) parameters the carbon–nickel composite films.

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Table 1
Different SPH parameters of the C–Ni films annealed at different temperatures 300, 500, and 800 °C.

Annealing temperature (°C)	W (eV)	σo ($\times 10^{-5}$ Ω^{-1} cm^{-1})	R ($\times 10^{-7}$ cm)	rp ($\times 10^{-8}$ cm)	εp	WH (eV)	J (eV)	$N(E_F)$ ($\times 10^{21}$ eV^{-1} cm^{-3})	γ_p
300	0.034	9.9	1.34	5.43	19.2	0.02	0.034	2.85	9.96
500	0.03	148	1.13	4.58	26	0.017	0.029	5.43	8.72
800	0.049	25	1.52	6.13	11.9	0.029	0.048	1.38	14.2

2. Experimental details

The films were grown at room temperature by RF-magnetron sputtering (VAS model) on glass substrates using a mosaic target in a deposition chamber evacuated to a base pressure in order of 0.01 Pa, and then the constant Ar working pressure of in order of 2 Pa was settled and maintained by throttle valve. Deposition was done in constant RF power regime 400 W. The films were prepared at the same deposition times of 10 min and then annfealed at 300, 500, and 800 °C under ambient atmospheric pressure in a furnace for 2 h. The field emission scanning electronic microscopy (FESEM) images were used for the morphological characterization. The Rutherford backscattering (RBS) spectra were obtained using incident ions (^{4}He) with energy of 2 keV for Ni concentration measurement. AFM analysis on non-contact mode was used to obtain surface morphology properties. The direct current electrical conductivity was measured by cooling samples in a continues He flow in a cryogenic units (optical low temperature model CCS 450 USA) in a thermostatic chamber in the temperature range 15–300 K. ORTEC (456, USA, 0–3 kV) high voltage power supply, Metrix VX102A (FRANCE) and Keithley 196 system DMM (USA) electrometers at temperatures range 150–300 K, were used for voltage and current measurements, accordingly.

3. Results and discussions

The small polaron hopping (SPH) conduction based on a single phonon approach to the present films in the high temperature region ($T > (1/2)\Theta_D$) and dependence of transition metal concentration on the conduction can be explained. The conductivity based of SPH in non-adiabatic region under strong electron–phonon interaction is expressed by [13]

$$\sigma = \frac{1}{KT} e^2 R^2 \nu_{ph} NC(1-C)\exp(-2\alpha R)\exp\left(-\frac{W}{KT}\right) = \frac{\sigma_o}{T}\exp\left(-\frac{W}{KT}\right) \tag{1}$$

with

$$W = W_H + \frac{1}{2}W_D \quad \text{for} \quad (T > \Theta_D/2), \quad W = W_H \quad \text{for} \quad (T < \Theta_D/4)$$

where ν_{ph} is the optical phonon frequency (generally $\nu_{ph} \sim 10^{13}$ s^{-1}), N the transition metal ion density, C the fraction of reduced transition metal ion, R the average spacing between transition metal ions (=$(1/N)^{1/3}$); α the tunneling factor (the ratio of the wave function decay), W_H the hopping energy and W_D is the disorder energy defined as the difference of electronic energies between two hopping sites and is given by

$$W_D = \left(\frac{e^2}{\varepsilon_S R}\right)k, \tag{2}$$

where ε_S is the static dielectric constant, and k is a constant of order 0.3. With definition the pre-exponential factor as

$$\sigma_o = \frac{1}{K} e^2 R^2 \nu_{ph} NC(1-C)\exp(-2\alpha R) \tag{3}$$

and considering cases of the adiabatic region, αR becomes negligible. Since, $\exp(-2\alpha R) = 1$, the conductivity is described in this region as follows

$$\sigma = \frac{1}{KT} e^2 R^2 \nu_{ph} NC(1-C)\exp\left(-\frac{W}{KT}\right) \tag{4}$$

where, $\nu_{ph}\exp(-2\alpha R)$ can be calculated using the experimental values and apart from this, we evaluate ν_{ph} in $\nu_{ph}\exp(-2\alpha R)$ according to $K\Theta_D = h\nu$ (h is the Planck's constant), so that Θ_D can be calculated from $T > \Theta_D/2$ the temperature at which the onset of the change of the slope of $\ln(\sigma T)$ with $1/T$ curve is confirmed.

Fig. 1(a)–(d) shows the values of $\ln(\sigma T)$ with $1/T$ for films annealed at different temperature 300, 500 and 800 °C in temperature range 15–300 K and their best fit in temperature range 150–300 K, respectively. It can be seen that relationship $\ln(\sigma T)$ against $1/T$ is almost linear in the chosen temperature range, which indicates that the conduction mechanism of films is dominated by the thermally activated hopping small polarons. With considering, in the adiabatic case $\exp(-2\alpha R)$ reduced to 1, the values of W and σ_o can be calculated using the fits at Fig. 1(b)–(d) and reported in Table 1.

Fig. 2 shows two basic metaphorical ideas describe the transfer of a particle from site to site on an atomic scale, hopping and tunneling. The transfer probability for tunneling due to thermal expansion stated by $\Gamma = c\exp(-2\alpha S)$ where c, S (=$R(1+PT)$), R and P are a constant independent of temperature, the temperature dependent of width between two identical potential