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# Influence of lithium phosphate concentration and temperature on the electrical conduction of $(76V_2O_5-24P_2O_5)_{1-X}(Li_3PO_4)_X$ glasses

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## Abstract

Characterization of the  $(76V_2O_5-24P_2O_5)_{1-X}(Li_3PO_4)_X$ , where  $X = 0.0, 0.01, 0.02, 0.10$  and  $0.15$ , glass has been done using X-ray diffraction and differential thermal analysis (DTA). The dc conductivity of the glass samples was studied over a temperature range from 300 to 593 K. The temperature dependence of dc conductivity shows two regions. One at relatively high temperature range, above  $\theta_D/2$ , and the other at relatively low temperature range, below  $\theta_D/2$ . The  $I-V$  characteristics of the glasses have been studied as a function of both temperature and  $Li_3PO_4$  content. The  $I-V$  characteristics exhibits threshold switching with differential negative resistance. It's found that both the threshold voltage ( $V_{th}$ ) and threshold current ( $I_{th}$ ) are dependent on the temperature and lithium phosphate concentration.  
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## 1. Introduction

The history of glass is a very old one, which of its scientific understanding is very new, however, during few decades, many efforts have been made in order to investigate and identify types of glasses from the scientific point of view. Without a thorough knowledge of the relationship between the structure and glass properties, no important progress is any longer. Semiconducting glasses [1,2] have attracted a great attention because of their intriguing electrical properties and technological applications. The electrical conduction in oxide glasses containing transition metal ions (TMI) has two different oxidation states takes place by means of small polaron hopping [3,4]. Many authors have studied the effect of additives on electrical properties of vanadium phosphate glasses [5–8]. These previous studies showed that the electrical conduction of these glasses could be greatly controlled by varying the reduction/oxidation ratio of the transition metal (vanadium) and/or by increasing the vanadium fractional in the glasses. However, the present work aims to study the influence of the addition of lithium phosphate in order to

reduce the vanadium  $V^{+5}$  to  $V^{+4}$  and its reflection on the electrical conduction and dielectric properties of the glasses.

## 2. Experimental work

### 2.1. Preparation of the glass samples

The glasses were prepared on the basis of percentage molar composition,  $76V_2O_5-24P_2O_5$ . The desired amounts of  $V_2O_5$  and  $P_2O_5$  were mixed and introduced in a muffle at temperature of 593 K for 3 h to illuminate  $P_2O_5$  to sublimate. Then the temperature of the muffle was raised to 1123 K for 5 h. The melt was shocked periodically to ensure complete homogeneity and then poured on an iron plate and left to cool down to room temperature in normal atmosphere. The samples were cut to form discs of diameter  $\sim 10$  mm and thickness of  $\sim 1$  mm.

A master batch was obtained from the quenched samples by grinding them with a mortar and pestle to reach a powder of particle size 0.07 mm. Weighted amount of the dopant  $Li_3PO_4$  were introduced to the master batch to obtain different glass samples and then melted again at 1123 K for 5 h. The melt was then poured on an iron plate and left to cool down to room temperature in the normal atmosphere and then all samples were kept in a desiccator. The samples

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Table 1

The values of the glass transition temperature  $T_g$  for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses

X	0.00	0.01	0.02	0.10	0.15
$T_g$ (K)	596	606	621	634	636

were prepared according to the formula  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3P_4)_x$  ( $X = 0.00, 0.01, 0.02, 0.10$  and  $0.15$ ).

## 2.2. Characterization of the samples

### 2.2.1. X-ray diffraction patterns

X-ray diffraction patterns for the virgin glassy samples were recorded by using Shimadzu XD-3 diffractometer. The lack of any sharp peaks for the virgin and the annealed samples indicated the amorphous nature of the samples and no indication of any microcrystals forming.

### 2.2.2. Differential thermal analysis (DTA)

The DTA were recorded simultaneously at heating rate of 20 K/min in the temperature range of 300–673 K using  $\alpha-Al_2O_3$  as a reference material by using DT-30 Shimadzu thermal analyzer. The DTA thermograms of all samples showed the glass transition temperature  $T_g$ . The values of  $T_g$  are shift towards higher temperatures with increasing lithium phosphate content (Table 1).

## 2.3. Electrical measurements

### 2.3.1. Conductivity measurement

The electrical conductivity measurements were carried out from room temperature to 593 K for all samples. The circulating current was measured by using a Keithley 617 °C programmable electrometer. Copper–constantan thermocouple was used for reading the sample temperature.

### 2.3.2. I–V characteristic measurements

I–V characteristic curves for different thickness and at different temperature were traced using a point contact method.

## 3. Results and discussions

Oxide glasses containing TMI show semiconducting behavior due to the presence of TMI in multivalent states in the glasses (e.g.  $V^{+4}$  and  $V^{+5}$  in vanadium glasses). It is generally agreed that the dc electrical conduction in these glassy semiconductors takes place by the hopping movement of small polarons between TMI sites of different valence states. The dc electrical conductivity of the vanadium phosphate glasses and the lithium doped glasses sample was studied over the temperature range (300–593 K). Fig. 1 represents Semi-logarithmic plot of  $\sigma T$  against  $10^3/T$  for all investigated samples. It is found that

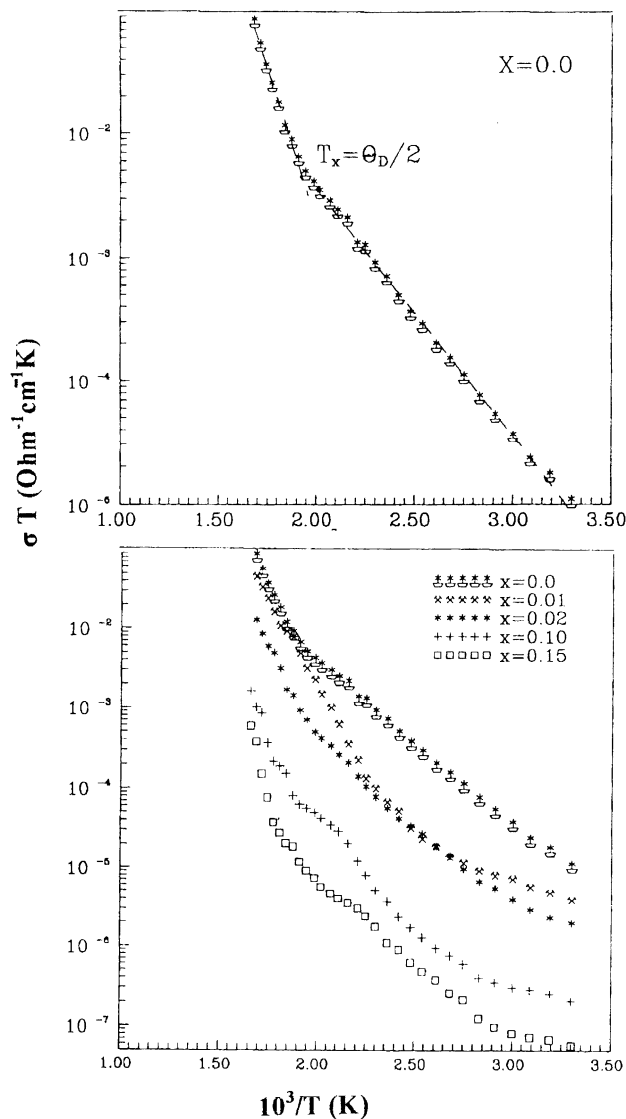


Fig. 1. Temperature dependence of dc conductivity for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses.

the electrical conductivity increases with increasing temperature obeying Mott and Davis relation [9]

$$\sigma = \nu_0 R^2 N c (1 - c) / K_B T [\exp(-E/K_B T)] \quad (1)$$

where  $N$  is the number TMI sites per unit volume,  $R$  is the average TMI site spacing,  $\nu_0$  is a jump frequency,  $c$  is the ratio of the TMI concentration in the low valence state to the total TMI concentration,  $(1 - c)$  represents the fraction of empty sites ( $V^{+5}$ ),  $K$  is the Boltzmann's constant and  $E$  is the activation energy for conduction processes.

The general behavior shows two regions in  $\sigma T$  vs.  $1/T$  relation, one at relatively low temperature range, where the other one appears at the higher temperature range. In addition, it shows a transition region at which the conduction process may change. The two regions intersect at definite temperature ( $T = T_x$ ) which can be obtained by using the equation  $\sigma_{01} \exp(-E_1/K_B T_x) = \sigma_{02} \exp(-E_2/K_B T_x)$ ,

Table 2  
The obtained activation energy values  $E_1$  and  $E_2$  and  $T_x$  as well as  $\theta_D$  for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glass samples

$X$	$E_1$ (eV)	$E_2$ (eV)	$T_x$	$\theta_D$ (K)
0.0	0.370	0.982	509.8	1019.6
0.01	0.212	0.828	409.1	818.2
0.02	0.366	0.848	485.2	970.4
0.10	0.115	1.088	443.9	887.9
0.15	0.129	1.446	472.5	945.0

where  $\sigma_{01}$  and  $\sigma_{02}$  are fitting parameters. The obtained values of  $T_x$  and subsequently ( $\theta_D = 2T_x$ ) are listed in Table (2). The transition point (the intersection of both conduction regions) is shifted towards the lower temperature range with increasing  $Li_3PO_4$  content in the glasses except the case of 0.15  $Li_3PO_4$ . This shows that, Debye temperature is shifted towards the lower temperature range [10]. Auston and Mott [11] assumed that a strong electron phonon interaction exists, the activation energy  $E$  is the result of polaron formation with binding energy  $E_H$  and the energy difference  $E_D$  which might exist between the initial and final sites due to variations in the total arrangements of ions, they suggested an expression for activation energy ( $E$ ) in the small polaron models as

$$E = E_H + E_D/2 \quad \text{for } T > \theta_D/2$$

$$E = E_H \quad \text{for } T < \theta_D/4$$

where  $E_H$  is the polaron hopping energy and  $\theta_D$  is the characteristic Debye temperature defined by  $\hbar\omega = k_B\theta_D$

The obtained values of the activation energies  $E_1$  and  $E_2$  are listed in Table 2.

It is noticed that the values of  $E_2$  lie in the range of 0.828–1.44 eV which refer the conduction beyond  $\theta_D/2$  for the preset glasses in addition they increase with increasing the  $Li_3PO_4$  content. The values of  $E_1$  lie in the range of

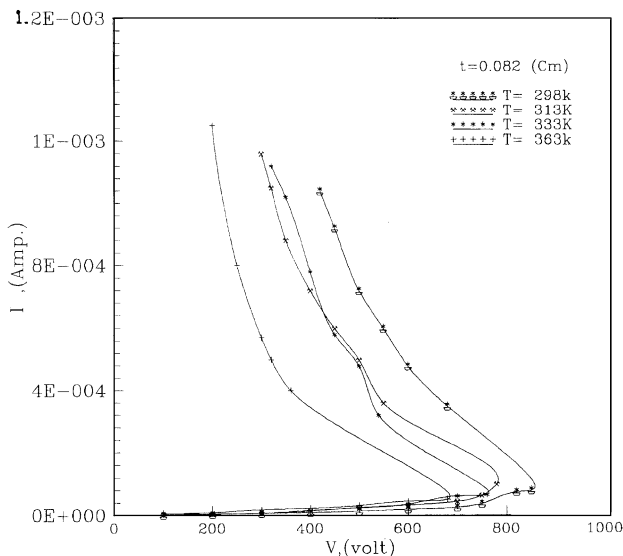


Fig. 2.  $I$ - $V$  characteristic curves for  $(76V_2O_5-24P_2O_5)$  glass sample at different temperatures.

Table 3  
The switching data as a function of temperature for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses

$X$	$T_a$	$\Delta T$ (K)	$V_{th}$ (V)	$I_{th}$ (A)	$P_{th}$ (mW)
0.00	298	22.24	780	$8.5 \times 10^{-5}$	66.30
	313	25.63	580	$1.5 \times 10^{-4}$	87.00
	363	33.54	390	$1.8 \times 10^{-4}$	70.20
0.01	383	37.53	269	$2.0 \times 10^{-4}$	42.00
	298	41.20	870	$8.0 \times 10^{-5}$	69.60
	313	45.76	780	$1.0 \times 10^{-4}$	78.00
	333	52.29	755	$8.0 \times 10^{-5}$	83.05
0.02	363	63.03	700	$6.0 \times 10^{-5}$	91.00
	298	22.50	885	$7.3 \times 10^{-5}$	64.60
	313	24.92	680	$8.85 \times 10^{-5}$	60.10
	333	28.35	590	$9.4 \times 10^{-5}$	55.50
	363	33.55	320	$2.8 \times 10^{-4}$	48.00
0.10	383	37.98	290	$2.20 \times 10^{-4}$	63.80
	313	53.83	1140	$1.71 \times 10^{-4}$	194.90
	333	61.61	940	$1.68 \times 10^{-4}$	180.50
	363	74.45	633	$2.2 \times 10^{-4}$	139.30
0.15	383	83.83	400	$3.5 \times 10^{-4}$	82.50
	333	47.72	1800	$8.2 \times 10^{-5}$	147.60
	363	57.45	1670	$1.2 \times 10^{-4}$	200.40
	383	64.51	880	$8.0 \times 10^{-5}$	149.60

0.369–0.129 eV, these values refer to the conduction at the transition region between  $\theta_D/4$  and  $\theta_D/2$ .

The increase of the activation energies with the increasing lithium phosphate content may be caused by an increase of the average distance between pairs of  $V^{5+}$  to  $V^{4+}$  by the increase of  $Li_3PO_4$  content ionization of Li atoms, and electron trapping by  $V^{5+}$  centers [12].

The activation energy for the dc conductivity should, therefore, exhibits a break in the vicinity of half the Debye temperature as the conduction mechanism changes from the low to high temperature regions. The higher of activation energies indicate a higher polaronic binding energy due to a greater amount of disorder causing a smaller polaronic radius at the high temperature range (above  $T > \theta_D/2$ ). The mechanism process is dominated by thermally activated nearest-neighbor hopping of small polarons [9,13]. At the intermediate temperature (above  $\theta_D/4$ ) the variable range hopping conduction appears.

The addition of lithium phosphate to vanadium phosphate glasses can be understood as follows: (i) an increase of phosphate in glass matrix reduces the vanadium fraction and

Table 4  
(4) The deduced activation energies  $E_v$  and  $E_r$ , fitting parameters  $V_0$  and  $R_0$  at the threshold point for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses

$X$	$V_0$	$E_v$	$R_0$	$E_r$
0.00	209.09	0.162	$5.28 \times 10^5$	0.247
0.01	152.80	0.161	$2.50 \times 10^5$	0.237
0.02	145.40	0.164	$1.15 \times 10^5$	0.238
0.10	148.77	0.172	$2.26 \times 10^4$	0.240
0.15	103.22	0.182	$7.70 \times 10^7$	0.337

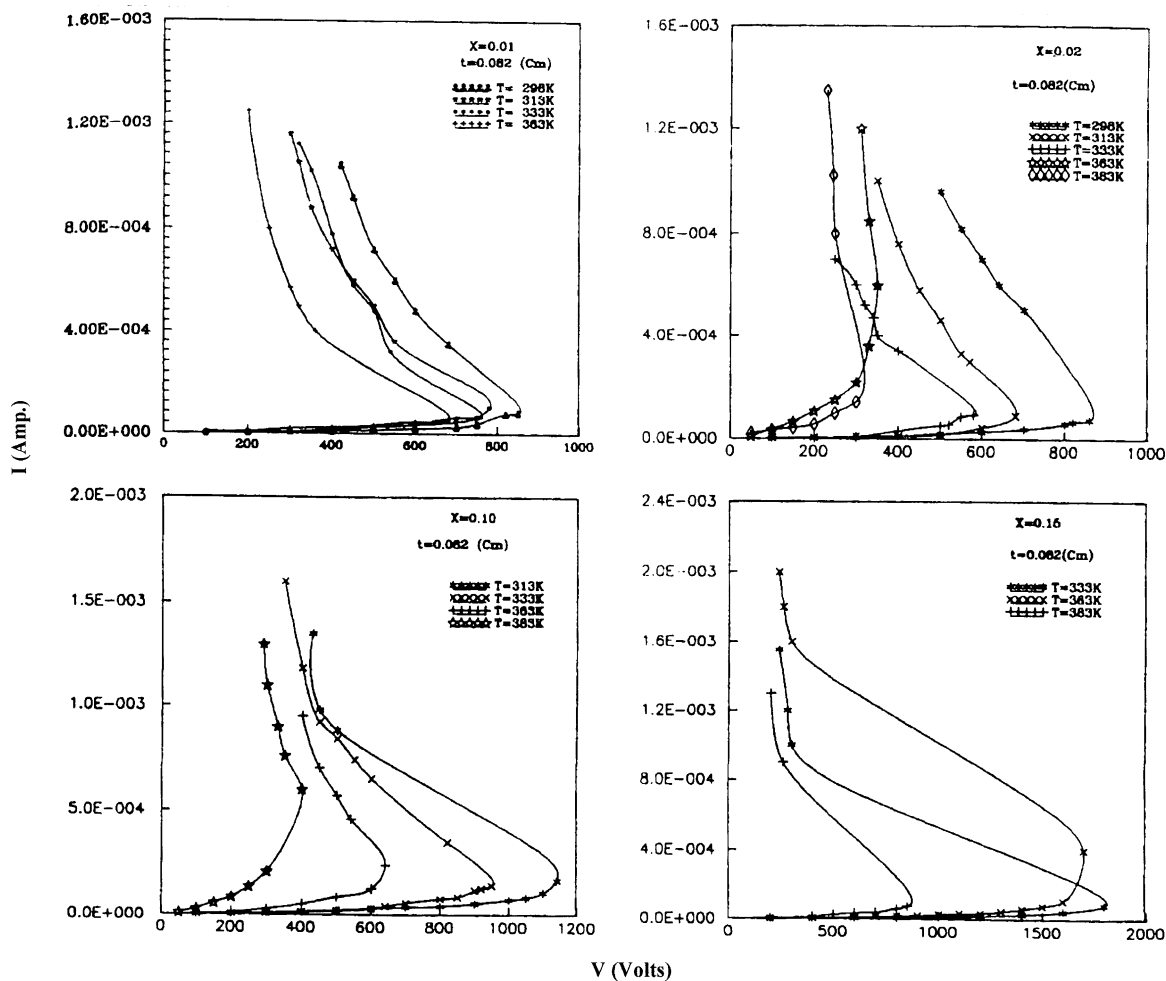


Fig. 3.  $I-V$  characteristic curves for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glass samples at different temperatures.

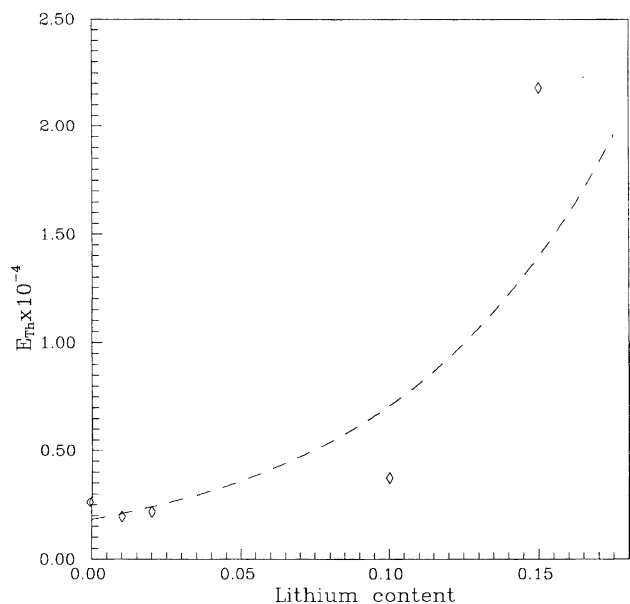


Fig. 4. Composition dependence of the threshold field for glass samples  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$ .

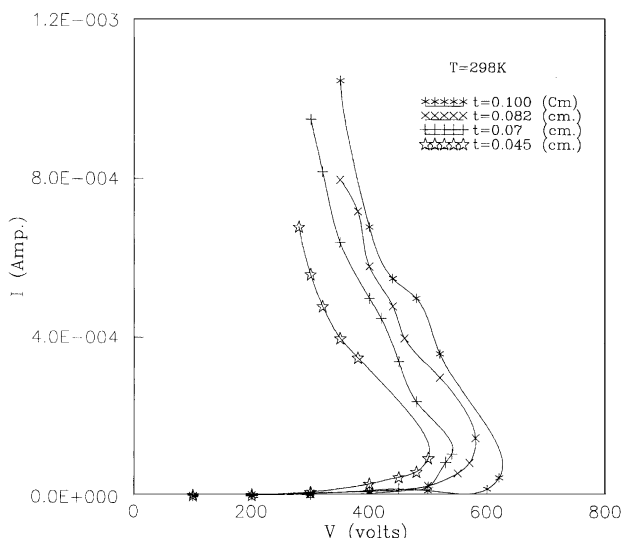


Fig. 5.  $I-V$  characteristic curves for  $(76V_2O_5-24P_2O_5)$  glass sample at different thickness.

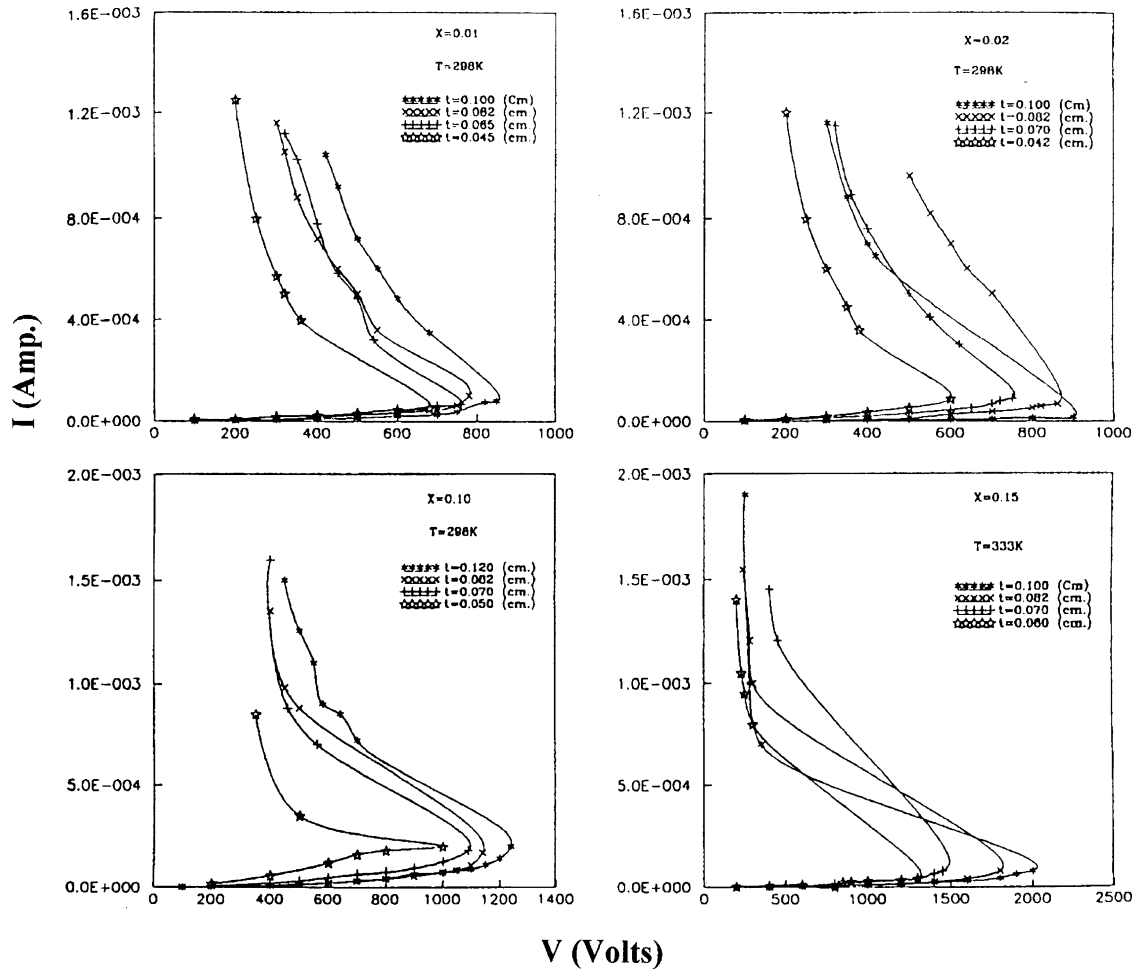


Fig. 6.  $I-V$  characteristic curves for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glass samples at different thickness.

subsequently the electrical conductivity; (ii) it also enhances the glass hydration, which increases the protonic condition [14]; (iii) it also leads to an increase of lithium ion contribution in conduction process, and (iv) the increase of  $Li_3PO_4$  content reduces the  $V^{+4}/V^{+5}$  fraction.

### 3.1. $I-V$ Characteristic

Fig. 2 illustrates the  $I-V$  characteristic curves for  $(76V_2O_5-24P_2O_5)$  glass that are studied at different temperatures from room temperature to 383 K. It is clear that the general behavior is characterized with a turn over point separates two states; the off state and negative resistance state. In addition, the voltage and current at the turnover point are defined as the threshold voltage  $V_{th}$  and threshold current  $I_{th}$ , respectively. The off state extends from zero voltage and zero current to the turn point ( $V_{th}, I_{th}$ ), including two regions; the quasi-ohmic one and the other is the pre-threshold region. In the case of  $(76V_2O_5-24P_2O_5)$  glasses, the values of  $V_{th}$  shift towards lower value with increasing temperature obeying the electro thermal

Table 5

The Switching data as a function of sample thickness for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses

X	T (cm)	$V_{th}$ (V)	$I_{th}$ (A)	$\rho_{th}$ (A)
0.00	0.110	620	$5.10 \times 10^{-5}$	2.07
	0.082	580	$8.78 \times 10^{-5}$	
	0.070	520	$9.40 \times 10^{-5}$	
	0.045	500	$1.30 \times 10^{-4}$	
0.01	0.100	850	$6.0 \times 10^{-5}$	2.01
	0.082	780	$1.6 \times 10^{-4}$	
	0.065	740	$8.0 \times 10^{-5}$	
	0.045	690	$1.0 \times 10^{-4}$	
0.02	0.110	900	$8.00 \times 10^{-5}$	2.40
	0.082	860	$1.00 \times 10^{-4}$	
	0.070	750	$1.20 \times 10^{-4}$	
	0.040	600	$1.15 \times 10^{-4}$	
0.10	0.120	1250	$2.0 \times 10^{-4}$	2.06
	0.082	1150	$2.2 \times 10^{-4}$	
	0.070	1100	$2.5 \times 10^{-4}$	
	0.050	1000	$3.0 \times 10^{-4}$	
0.15	0.100	2000	$8.1 \times 10^{-5}$	2.30
	0.082	1800	$9.0 \times 10^{-5}$	
	0.070	1450	$1.5 \times 10^{-4}$	
	0.060	1300	$4.0 \times 10^{-5}$	

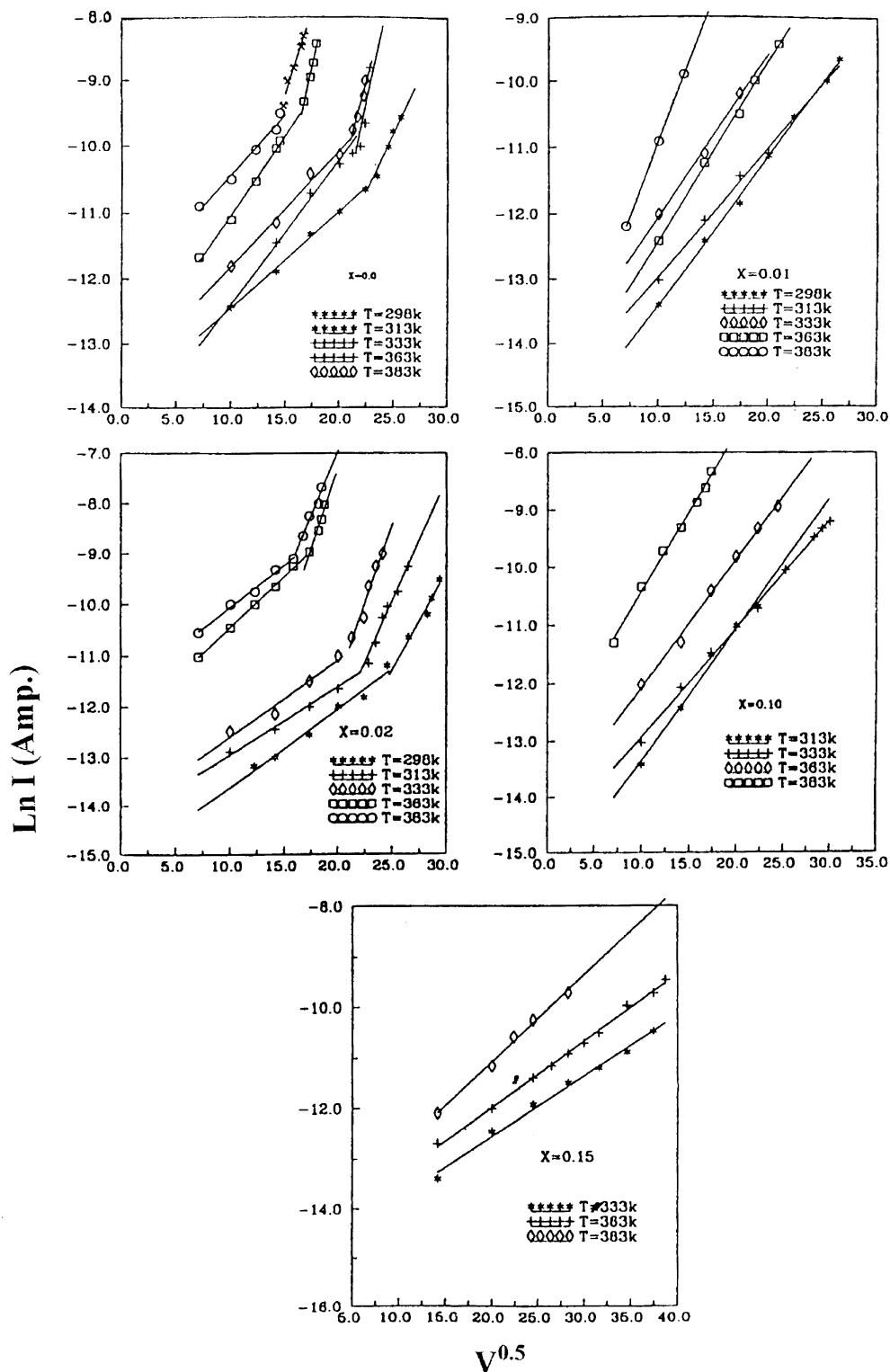


Fig. 7. Plots of  $\ln(I)$  vs.  $V^{0.5}$  for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glass samples at different temperatures.

model [15].

$$(V_{th}/T) = V_0 \exp(E_v/K_B T) \tag{2}$$

where  $V_0$  is the temperature independent parameter,  $E_v$  is an activation energy term concerning the attenuation of

the condition path temperature ( $T = T_a + \Delta T$ ), where  $T_a$  is the rise of conduction path temperature due to joule heating [16] and given by

$$\Delta T = (K_B T_a^2)/(E - K_B T_a) \tag{2'}$$

Table 6  
The obtained values of  $d$  (Å) for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses at different temperatures

$T$ (K)	$X$				
	0.0	0.01	0.02	0.10	0.15
298	1.92	3.35	2.63	–	–
313	2.42	4.05	1.84	25.11	–
333	2.76	2.09	6.75	18.79	15.5
363	1.11	1.29	5.87	12.71	6.06
383	0.93	0.40	2.36	11.05	1.76

where  $E$  is the low field activation energy. The calculated values of  $\delta T$  are listed in Table 3. Semi-logarithmic plot of  $(V_{th}/T)$  against  $(10^3/T)$  for  $(76V_2O_5-24P_2O_5)$  glass that fits Eq. (2) gives the value of  $E = 0.162$  eV for vanadium phosphate glass which found to be lower than that obtained at low field,  $E = 0.369$  eV. This can be attributed to the condition enhancement of both field and self-joule heating. The value of  $V_{th}$  is also found to shift towards lower voltage and higher current with increasing in temperature for  $76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses obeying the electro thermal model.

The Semi-logarithmic plots of  $(V_{th}/T)$  vs.  $(10^3/T)$  show straight lines for all compositions. The value of  $V_0$  and  $E_v$  are obtained and listed in Table 4. It is noticed that the values of  $E_v$  are nearly unchanged in the case of low content of  $Li_3PO_4$ , while an irregular variation has been obtained at the higher content of lithium phosphate.

In addition, the value of  $E_v$  is lower than one half that obtained at low field. This confirms the expectation that the electric field enhances conduction. The values of  $E_v$  in the case of 0.1 and 0.15%  $Li_3PO_4$ , are closer to that for  $E_{dc}$ , which obtained at low field. This can be attributed to the influence of  $Li_3PO_4$  as follows: (a) an increase of lithium ions contribution in the glass matrix; (b) the increase in phosphate group ( $PO_4$ ) in glass matrix reduces the vanadium fraction, which leads to a reduction in  $V^{4+}/V_{tot}$ ; (c) it also enhances the glass hydration that increases the protonic conduction.

The path resistance  $R_{th}(=V_{th}/I_{th})$  for all samples of  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  was calculated at different temperatures. The results show that  $R_{th}$  decreases with increasing temperature obeying Arrhenius relation [12]

$$R_{th}/T = R_0 \exp(E_r/k_B T) \quad (3)$$

where  $R_0$  is independent temperature parameter and  $E_r$  is the activation energy for conduction process. The values of  $E_r$  are obtained and listed in Table 4.

### 3.2. Influence of lithium phosphate and temperature on the turnover point

The effect of different content of  $Li_3PO_4$  in the present glass is also considered. Fig. 3 illustrates  $I-V$  characteristic curves at different temperatures. The turnover point shifts,

in general, towards higher current and voltage when  $Li_3PO_4$  content was increased. Also as the temperature increases, the values of  $V_{th}$  decrease. The corresponding threshold field  $E_{th}(=V_{th}/t)$ , where  $t$  is the sample thickness) is obtained and plotted against the  $Li_3PO_4$  content (Fig. 4). It is noticed that  $E_{th}$  increases exponentially with increasing  $Li_3PO_4$  content obeying the following relation

$$E_{th} = E_0 \exp(f/f_0) \quad (4)$$

Where  $E_0$  is the threshold field ( $1.8 \times 10^4$  V/cm) at  $f = 0$ , which is higher than that for the  $(76V_2O_5-24P_2O_5)$  glass. This may be attributed to the effect of sample hydrated;  $f_0$  is a characteristic concentration equal to 0.074.

### 3.3. Effect of thickness on $I-V$ characteristic of $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$ glasses

The effect of thickness on  $I-V$  characteristic of the investigated samples has been studied at 298 K. All samples showed similar behavior for the convenient  $I-V$  characteristic for vanadium phosphate glass (Fig. 5). The typical plots of the effect of thickness on the  $I-V$  characteristic of the glass samples  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  are shown in Fig. 6. The results show a direct relationship for the dependence of both  $V_{th}$  and  $R_{th}$  on the sample thickness. In addition, the slope of  $R_{th}$  against sample thickness is equal to  $\rho/A$  where  $\rho$  is the sample resistivity and  $A$  is the area of the conduction bath filament cross-section (Table 5). The linearity of  $R_{th}$  vs. thickness means that the filament cross-section areas are the same for different thicknesses. It is also found that the value of  $\rho/A$  increases with increasing lithium phosphate content that means an increase of  $\rho$ , which in agreement with low field study.

### 3.4. Switching mechanism

The conduction in the off state region (below the turn point) could be divided into two regions. The first is ohmic region whereas the second is field dependent. The later one could be explained according to the field emission of  $V^{4+}$  electrons which is based on Pool-Frenkel effect, the voltage dependence of conduction is given by Eq. (5) [17]

$$I = I_0 \exp(\beta V^{1/2}/k_B T) \quad (5)$$

where  $\beta = (e^3/4\pi\epsilon\epsilon_0 d)$ ,  $\epsilon$  and  $\epsilon_0$  are the relative and space permittivity, respectively, and  $d$  is the average jumping distance separating filled and empty states.

Semi-logarithmic plots of  $I$  versus  $V^{1/2}$  for the glass samples are shown in Fig. (7). Since the onset of emission in semiconductors initiates at field of about  $10^6$  V/cm, thus this statement is considered to explain the non-linearity in  $I-V$  curves by assuming the electron emission which occur between filled and nearest empty states. Accordingly, the values of  $d$  are obtained using the least square fitting of Eq. (5) and listed in Table 6. It is found

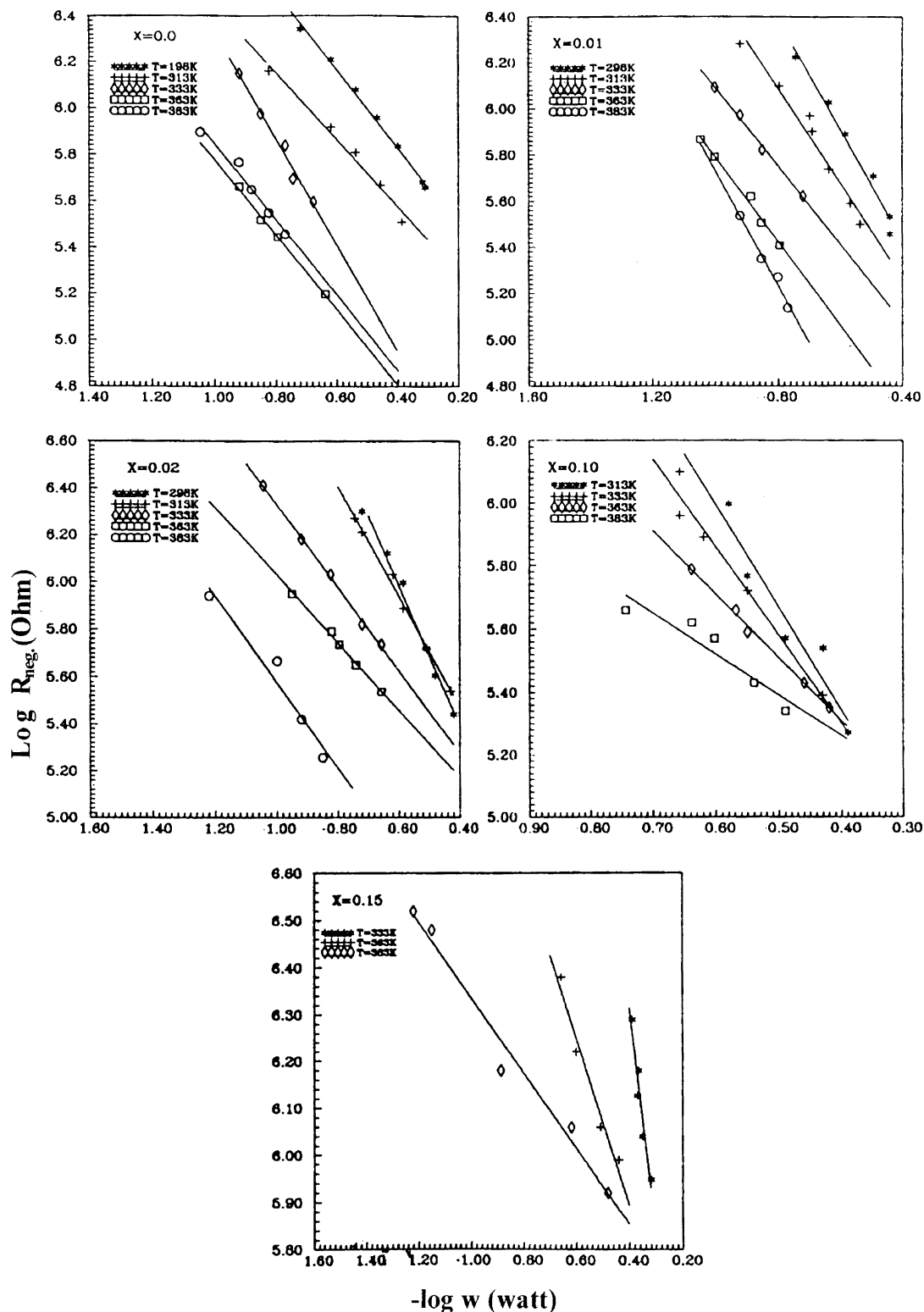


Fig. 8. Plots of negative resistance against power for glass  $(76\text{V}_2\text{O}_5-24\text{P}_2\text{O}_5)_{1-X}(\text{Li}_3\text{PO}_4)_X$  glass samples at different temperatures.

that the values of  $d$  lie in range between 0.4 and 25 Å, which was in agreement with published data<sup>9,17</sup> except the values lower than 3–4 Å.

The lower value of  $d$  ( $<3$  Å) could be attributed to the abnormal large values of the dielectric constant due to both

the interfacial and the ionic polarization in the present glasses.

Additionally, some deviation in  $\ln I-V^{1/2}$  plots are observed as the field approaches the threshold value at the turn over point. This in turn, leads to the reduction in

Table 7  
The obtained values of the power  $m$  for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glasses at different temperatures

T (K)	X				
	0.0	0.01	0.02	0.10	0.15
298	1.69	2.37	3.91	–	–
313	1.43	2.13	2.30	3.16	–
333	2.12	1.71	1.74	2.77	5.46
363	1.6	1.91	1.37	2.11	1.74
383	1.67	2.56	1.85	1.37	0.80

conduction path resistance. Resistance will enhance the field emission as a result of the presence of joule heating. The ultimate conduction is attained when the applied voltages approach the  $V_{th}$  value (zero differential resistance ( $\delta V/\delta I = 0$ )) and then conduction path switches to the negative differential resistance region. The estimation of the differential negative resistance  $R_{neg}$  with the applied field neglecting the influence of the joule heating arises in conduction path filament. The dissipated power in the thermally isolated filament plays a significant role in reducing the value of the negative resistance (Fig. 8).

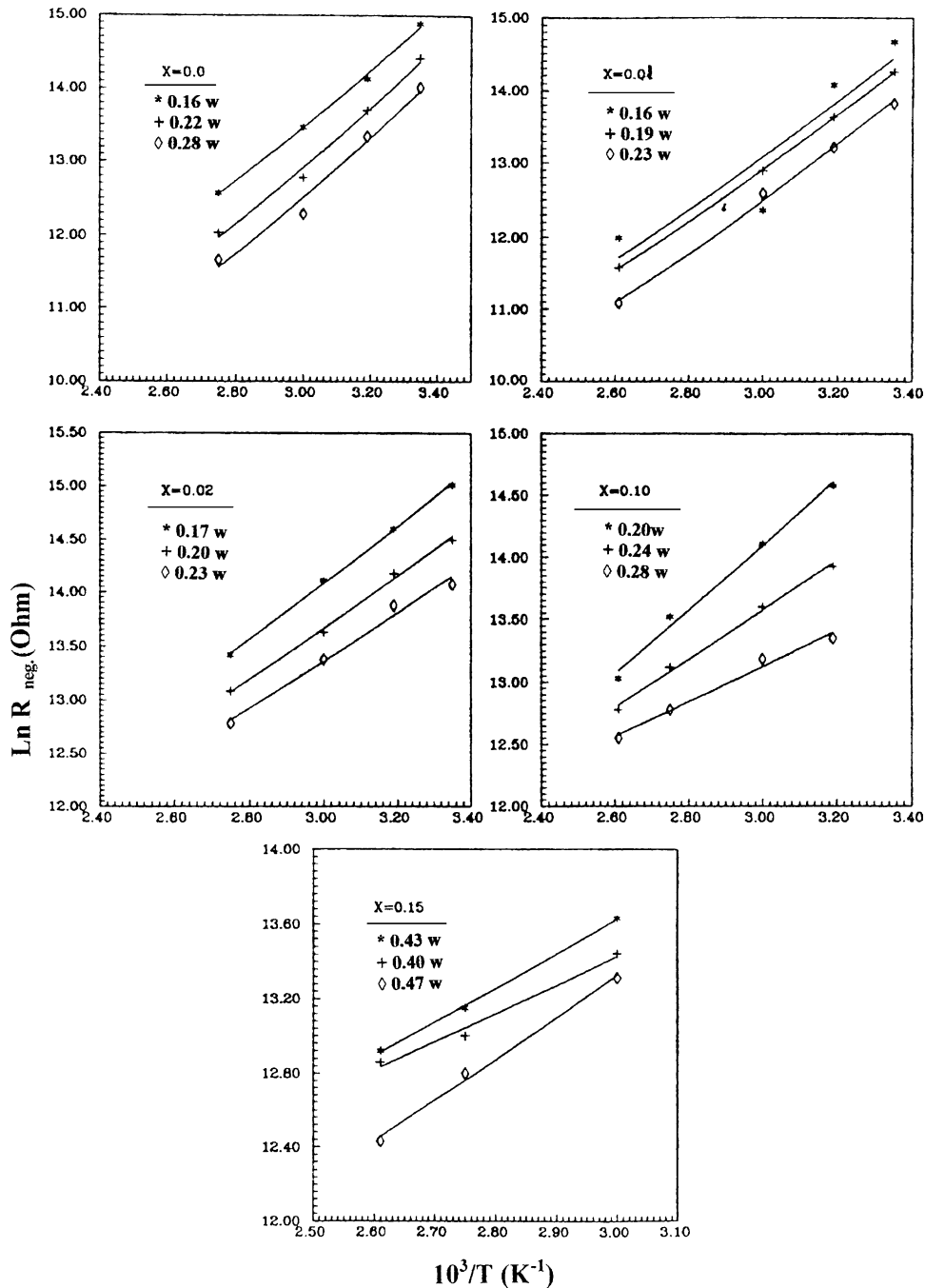


Fig. 9. The temperature dependence of negative resistance at different power for  $(76V_2O_5-24P_2O_5)_{1-x}(Li_3PO_4)_x$  glass samples.

The following empirical relation can describe this behavior

$$R_{\text{neg}} = R_0(W_0/W)^m \quad (6)$$

where  $R_0$  is the conduction bath resistance when  $W_0 = W$  (the ultimate power initiating the On-state and  $m$  is a power.

The values of the power  $m$  are obtained using the least square fitting and listed in Table 7. It is clear, in general, that  $m$  is larger than unity indicating that the rise of conduction in the differential resistance region is not due to a simple thermal effect. The conduction level in the mentioned region is generally influenced by the following [18]: (i) the temperature of the conduction filament leading to the presence of the phonons to conserve energy required for the electron hopping. (ii) The effective electric field assisting the electron hopping, the effect of the electric field ( $F$ ) is to modify the energy of hop between two sites I and j separated by a distance  $d_{ij}$  by an amount of ' $eFd_{ij} \cos \theta$ ' where  $\theta$  is the angle between  $F$  and  $d_{ij}$ . (iii) The presence of the negative resistance in the circuit of measurements results in a generation of a very high frequency signal assisting the electron hopping between the localized states at the Fermi level (Fig. 9).

#### 4. Conclusion

From the obtained results and discussion it may be concluded that

1. Increasing lithium phosphate content in the vanadium phosphate glasses reduces the phase separation.
2. The dc conductivity decreases with increasing lithium phosphate content in these glasses. The obtained values of dc conductivity lie in the range of the semiconductor materials.

3. The  $I$ – $V$  characteristics of the glasses illustrate non-linear relationship. They exhibit switching between high resistance state and negative resistance region passing through a turnover point.
4. The threshold voltage ( $V_{\text{th}}$ ) and the threshold current ( $I_{\text{th}}$ ) were found to strongly depend on lithium phosphate content. The  $V_{\text{th}}$  decreases with the ambient temperature while it shifts towards higher value with increasing lithium phosphate content.

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