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RESPONSIVITY IMPROVEMENT OF PHOTOCONDUCTIVE INFRARED DETECTROS

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ABSTRACT

Lead Sulfide (PbS) in thin film form is used in many applications as an infrared detector . In this work amorphous lead sulfide films was prepared using different thermal evaporation techniques . Electrical and structural measurements were done upon the as grown films. In order to enhance the electrical and structural characteristics, several heat treatment processes were done at temperatures of 250, 350, 420 ^{O}C . This study showed a great improvement in the detector responsivity due to the performed heat treatments which can be simulated in other types of detector materials.

KEY WORDS infrared , lead sulfide , detectors .

INTRO DUCTION

Photoconductive materials in thin solid film form are widely used as detectors in the region extending from the near infrared (0.7 μm wavelength) to the far infrared (30 μm wavelength) . The operating wavelength is dependent on the detector material and the temperature of operation . This study is concerned with the lead sulfide film detectors, which operate in the near and short wavelength of the infrared region (0.9-3.1 μm) [1]. These detectors are widely used in the searching, tracking and thermal imaging applications.

Different figures of merit were used to compare between similar detectors [2] , especially the detector responsivity. For lead sulfide detectors the max voltage responsivity at the cut off wavelength reaches $5*10^3$ V/W [3] . Voltage responsivity improvement can be achieved using the suitable heat treatment processes that affect the material resistivity [4] . The effect of heat treatment of the as grown samples on the responsivity will be manipulated.

THEORETICAL MODELING

The voltage responsivity of a photoconductive detector is defined as the output detector voltage per 1 watt incident radiation power;

$$R_v = V_o / P_\lambda$$

For an intrinsic photoconductive infrared detector ,if the detector surface is irradiated with beam of infrared photons , the DC generated photocurrent will be given by[5] :

$$I_s = Aq\eta\varphi G \qquad (2)$$

If the beam is modulated with a modulating reticle , then the frequency response of equation (2) will be:

$$i_s = \frac{Aq\eta\varphi G}{\sqrt{1+(2\pi f\tau)^2}} \qquad (3)$$

Where

φ ... Incident photon flux density (photons/cm^2.s)
q ... Carrier charge
η ...Quantum efficiency (number of excess carriers produced per absorbed photon).
A ... Detector area
f ... Modulating frequency
τ ... Carrier life time
G ... Internal photoconductive gain .

the phtoconductive gain(G) is the number of electrons, which flow through the external circuit for each absorbed photon .

$$G = \frac{(\mu_n + \mu_p)\tau V}{l^2} \qquad (4)$$

Where

μ_n ... Electron mobility
μ_p ... Hole mobility.
V ... Bias voltage
l ... Detector length.

For a photon of energy (hc/λ) ; the radiation power at the detector surface (P_λ) is given by :

$$P_\lambda = (hc/\lambda).A\varphi \qquad (5)$$

for such a detector , the voltage spectral responsivity is given by :

$$R_v(\lambda, f) = \frac{i_s R_d}{P_\lambda} = \frac{Aq\eta\varphi G R_d}{hcA\varphi\sqrt{1+(2\pi f\tau)^2}} \qquad (6)$$

$$R_v(\lambda, f) = \frac{\eta\lambda q G R_d}{hc\sqrt{1+(2\pi f\tau)^2}} \qquad (7)$$

where

h... Planck's constant
c... Speed of light
R_d.. Detector resistance = ρl/A (8)
ρ... Detector material resistivity

The idea of increasing the detector responsivity is based on the increase of the detector resistivity from eq.(8) through the different heat treatment processes as will be seen in the following.

Sample preparation and measurements

Two techniques were used for preparing as grown samples of lead sulfide films ; the resistive and the electron beam gun thermal evaporation techniques. For the first technique , an (EDWARDS E306) type thermal evaporation machine was used to produce the films deposited onto glass substrates. Different trials were performed to optimize the evaporation conditions to produce consistent homogeneous films. It was found that the following conditions produce consistent , good locking and sticking as grown films :

Vacuum pressure:	10^{-5}Torr
Filament material:	Tungsten
Boat material :	molybdenum
Deposition rate :	4 A°/s
distance between boat and substrate (d):	10Cm

For the second technique , an (EDWARDS BRV25) type elecron beam gun deposition system was used for depositing the lead sulfide films onto the glass substrates using the conditions :

Vacuum pressure:	10^{-5} Torr
Filament material:	Tungsten
Boat material :	Carbon
Voltage	2.5Kv
Current	300mA
Distance between boat and substrate :	10 Cm

For exploring the structure of the produced as grown samples , two structural analyzing techniques were used . X-ray florescence (XRF) spectroscopy were used performing a qualitative and quantitative analysis. An energy dispersive spectrometer Silicon Lithium (SiLi) detector XRF system has been used to perform the x-ray analysis for the produced specimens. The result is shown in figure (1).

As shown in the figure besides the peaks corresponding to Lead and Sulfur elements , there are others that correspond to the elements found in the glass substrate such as Silicon which is the basic element constituting the glass substrate beside the other impurities. From the figure it is clear that the peaks of sulfur and Lead corresponding

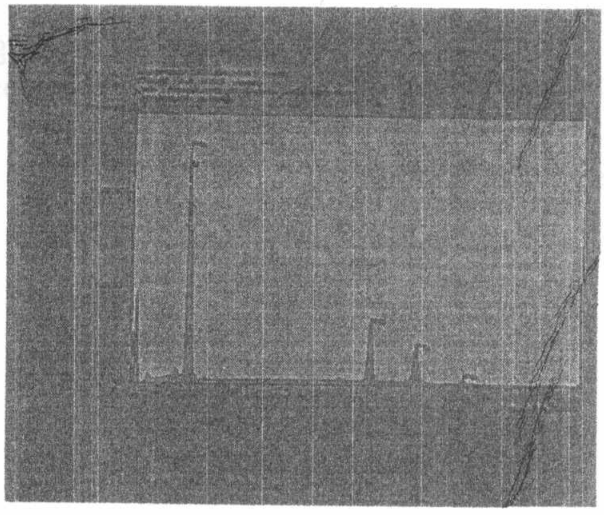

Fig.(1) XRF analysis

to the energy 2.3kev. is hardly separated . Studying the x-ray transition distribution for Lead and sulfur[6] shown in table (1) , we find that the difference in the (K) transitions of Sulfur and the(M) transitions of Lead is always less than 90ev. , since the maximum resolution of the SiLi detector is 99ev (which is the best resolution for such systems till now) thus the two peaks must appear as one peak as found in figure(1) ; which is known as a famous overlap in the x-ray field[7].

Transition		Lead (Pb) (kev)	Sulfur (S) (kev)
K	$K_{\alpha 1}$		2.30784
	$K_{\alpha 2}$		2.30664
M	M_{IV}	2.399	
	$M_{\alpha 1}$	2.3455	
	$M_{\alpha 2}$	2.3397	
L	$L_{\gamma 1}$	14.7644	
	$L_{\gamma 3}$	14.553	
	$L_{\beta 2}$	14.442	
	$L_{\gamma 5}$	14.3075	
	$L_{\beta 9}$	13.377	
	$L_{\beta 10}$	13.275	
	L_{III}	13.03444	
	$L_{\beta 15}$	12.945	
	L_{μ}	12.8968	
	$L_{\gamma 8}$	12.72	
	$L_{\beta 17}$	12.127	
	L_{η}	11.3492	
	$L_{\alpha 2}$	10.4495	

Table(1) Lead and Sulfur x-ray transitions.

From figure(1), it is clear that the (L) transitions of Lead appear at the standardized energies . quantitative study showed that the amount of sulfur is a little higher than the standard ratio(~1:6) due to the existence of some Sulfur in the glass substrate.

An imagination about the internal structure of the as grown specimens was an indeed requirement, so X-ray diffraction (XRD) spectroscopy performed using a (SHIMADZYU XD-D1) type XRD system . Figure (2) shows the resulted XRD pattern for the as grown samples.

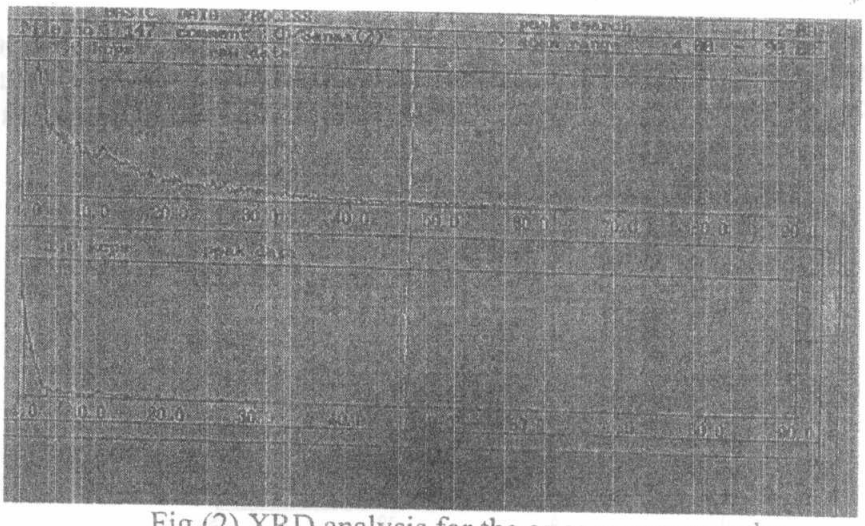

Fig.(2) XRD analysis for the as as grown samples.

It is clear that the specimens produced have an amorphous structure .Now it is obvious that heat treatment processes are required in order to get a polycrystalline structure.

Treatment processes and measurements

For treating the lead sulfide with annealing processes , a study of its thermal behavior was required , so a differential thermal analysis (DTA) was performed using a (SHIMADZU DT-50) type DTA system with temperature testing range up to 700°C . The resulted DTA diagram is shown in figure (3).

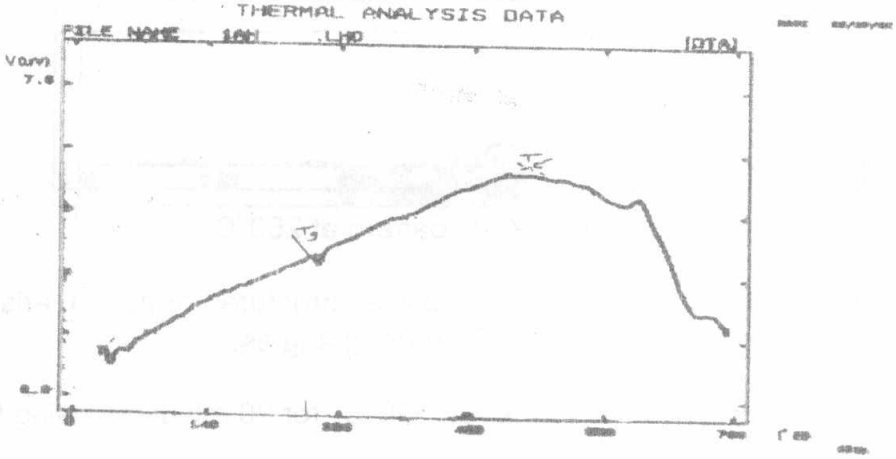

Fig.(3) DTA pattern for the lead sulfide.

The DTA curve shown in figure(3) continues in an approximately rectilinear manner , until the test material undergoes some physical or chemical change , the curve begins to deviate from the baseline . The intersection of the base line and the extrapolation of the straight part of the adjacent side of the peak is at 250°C temperature , which might be the glass transition(T_G) . The curve begins to deviate from the baseline forming what might be the crystallization peak (T_C) at temperature of 450°C . The effect of these temperatures on the samples crystallity will be assured using heat treatment and x-ray diffraction (XRD) analysis that will be studied in the following.

According to this thermal analysis a number of treatment processes will be performed and measured. Beginning with the annealing at 250°C for one hour using the annealing cycle shown in figure (4) , the resulted XRD pattern is shown in figure (5).

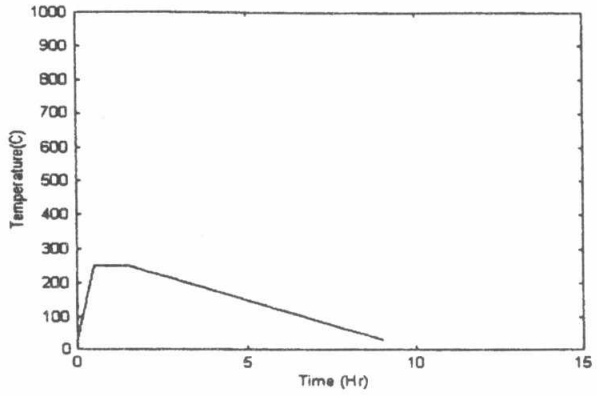

Fig.(4) Annealing cycle at 250°C

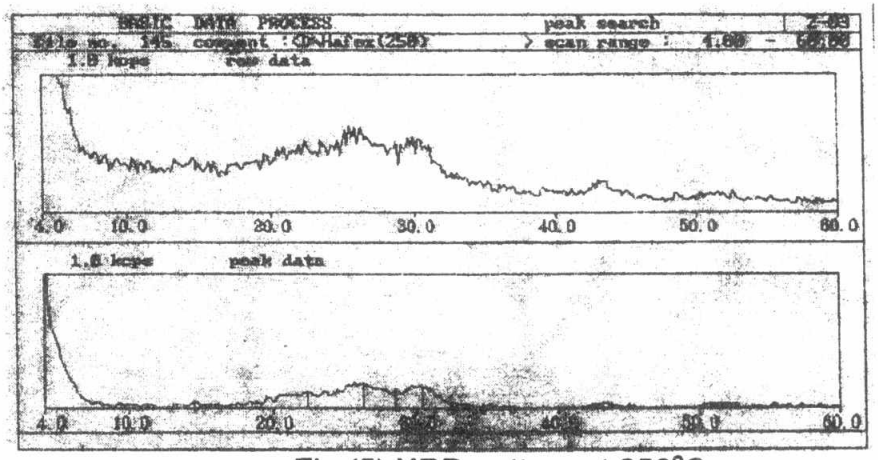

Fig.(5) XRD pattern at 250°C

Figure (5) illustrates that the polycrystalline structure formation arising from the appearance of 8 crystalline peaks at different 2θ angles.

Another annealing process is done at 350°C for 90 minutes , using the annealing cycle shown in figure (6)

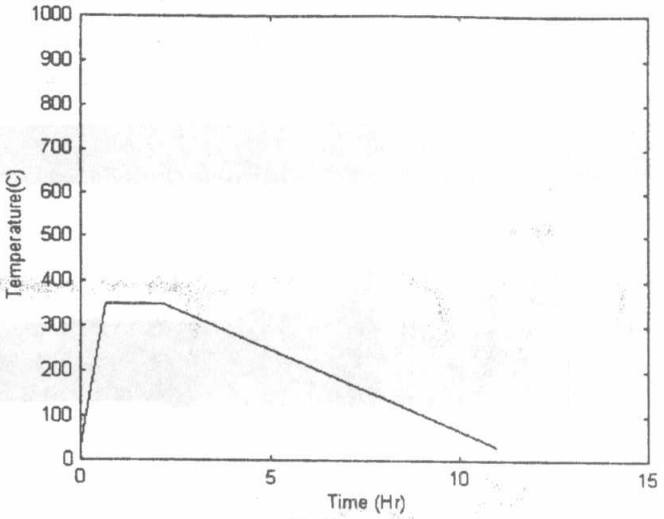

Fig.(6) Annealing cycle at 350°C

The resulted XRD pattern is shown in figure(7) .

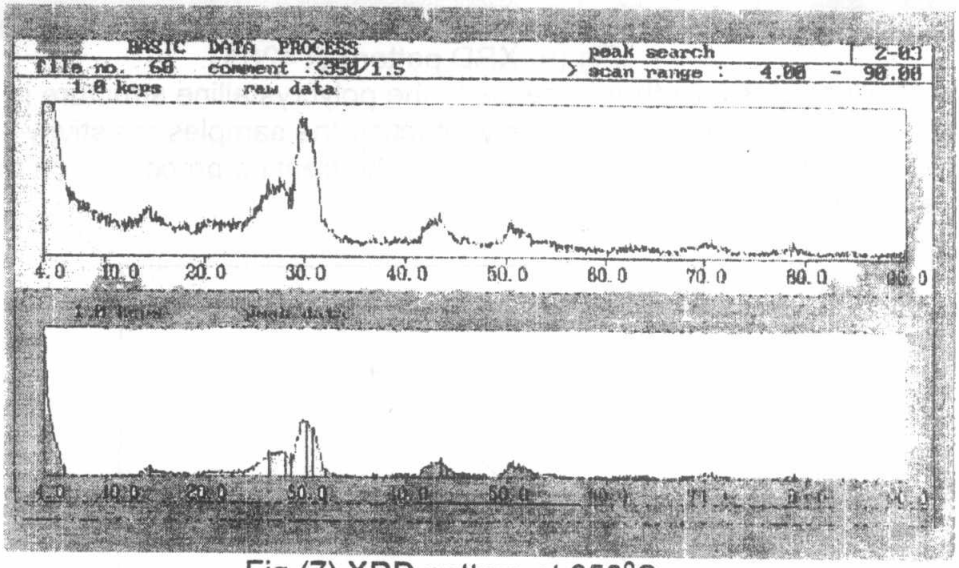

Fig.(7) XRD pattern at 350°C

Figure (7) illustrates the enhancement of the polycrystalline structure arising from the increased number of crystalline peaks and the increase in the amplitude at certain directions.

For further improvement of the polycrystalline structure , another heat treatment process is done at 420°C for one hour using the annealing cycle show in figure(8) .

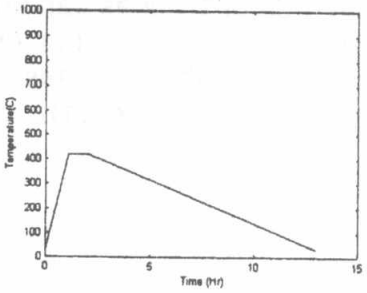

Fig.(8) Annealing cycle at 420°c.

The resulted XRD pattern is shown in figure(9).

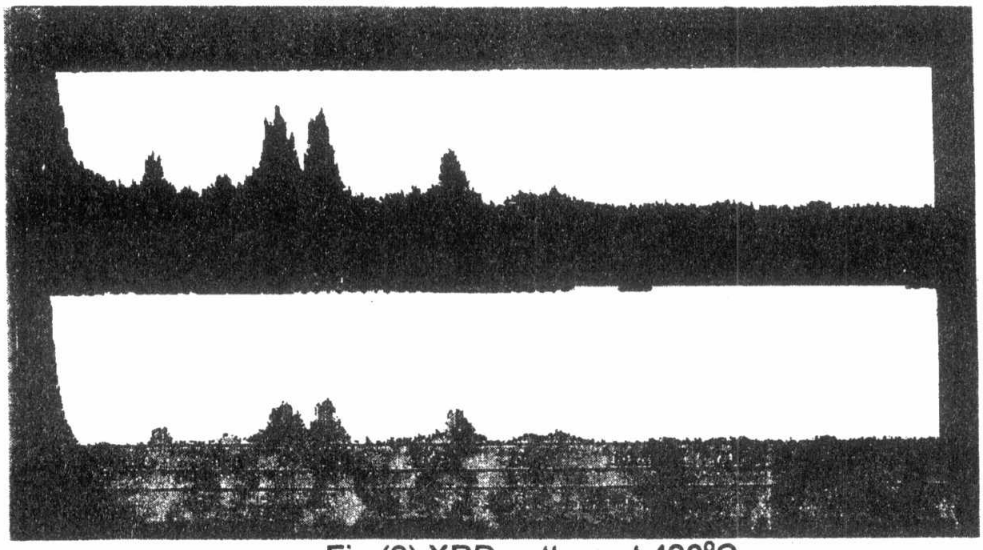

Fig.(9) XRD pattern at 420°C.

Figure (9) illustrates a further increase in the polycrystalline structure is reached . These treatment processes are highly affecting the samples resistivity . Studying this effect, figure (10) illustrates the influence of the treating processes on the measured samples resistivity .

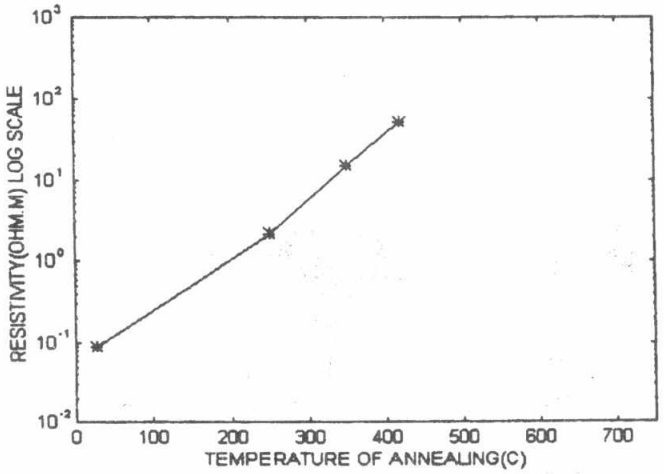

Fig.(10) Resistivity variation with temperature of annealing.

From figure(10) it is clear that increasing the annealing temperature will tend to increase the samples resistivity , this resistivity increase will of course plays a major part in increasing the sample responsivity as can be concluded from equations(7,8) . The maximum voltage responsivity at the cut off wavelength of lead sulfide (3.1 microns) is calculated for each annealing process , compared to the max responsivity of the non treated samples , shown in figure(11).

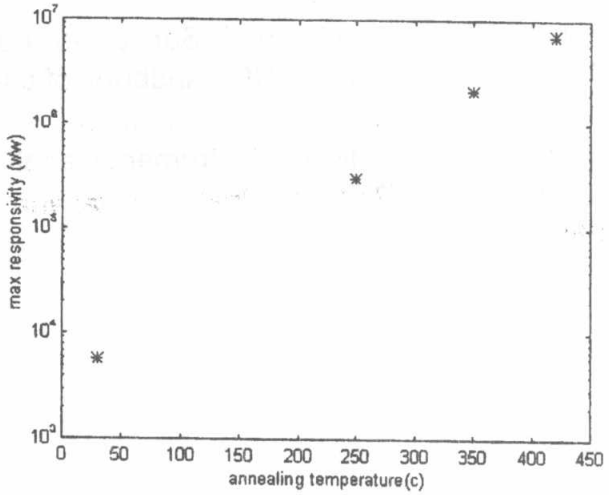

Fig.(11) Max. responsivity versus annealing temperature.

It is clear that best results were achieved by treatment at 420°C to give max. responsivity of ($8*10^6$ V/W). The same processes can be performed for most of the other photoconductive materials such as PbSe, PbTe, .. etc.

The last results were a theoretical estimation and calculated under the following conditions:

- The heat treatment processes do not hardly affect the photoconductive gain (G).
- The heat treatment processes do not hardly affect the carriers life time (τ) .

The experimental verification of these results could not be measured due to the lag of equipment and instrumentation, the practical improvement may be less than the calculated results .

The effect of heat treatment processes on the other detector figures of merit such as detectivity and response time will be published in other study.

CONCLUSION

Heat treatment processes for the as grown samples of Lead Sulfide at temperatures of 250°C,350°C,420°C will usefully cause an increase in its polycrystalline structure causing an increase in the material resistivity which will result in a great increase in the detectors responsivity . This phenomenon can be applied for most of the photoconductive materials.

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