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MBE-Grown Lead Tin Telluride Infrared Devices

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ABSTRACT

An attempt was made to examine the performance of the $Pb_{0.82}Sn_{0.18}Te$ films grown by Molecular Beam Epitaxy (MBE) technique as infrared (IR) band pass filter and photoconductive IR detector. Films of required thickness for these purposes were precalculated and were grown by controlling the growth time. The fabricated band-pass filters were with Full Width at Half Maximum (FWHM) of 20-25 per ent centred at 6.5, 8 and 10 microns. The measured detectivity of the film was of the order of 10^8 cm $Hz^{1/2}$ W^{-1} for 500 K black body temperature with 800 Hz chopping frequency and 10 per cent electrical bandwidth at 77 K. All these films were grown on freshly cleaved KCl (100) substrates.

1. INTRODUCTION

Infrared imaging and monitering systems have gained strategic importance in recent years both for civilian and military applications. In these systems the main components are IR source, IR detector and IR band-pass filter which are apart from the optical components required for focussing and directing the beams. Even though, IR wavelengths were varying from 7/10th of micron to several microns, the atmosphere which contain different kinds of molecules, allow only a few narrow regions for IR transmission. These are technically known as 'atmospheric windows[1]'. Among them 8-14 micron range window is given importance for IR communications because of its relatively broad nature. It is with transmittance more than 80 per cent (Fig. 1). Hence, the materials which are to be used for preparing the components for IR imaging systems should meet the conditions required for 8-14 micron signal transmission and

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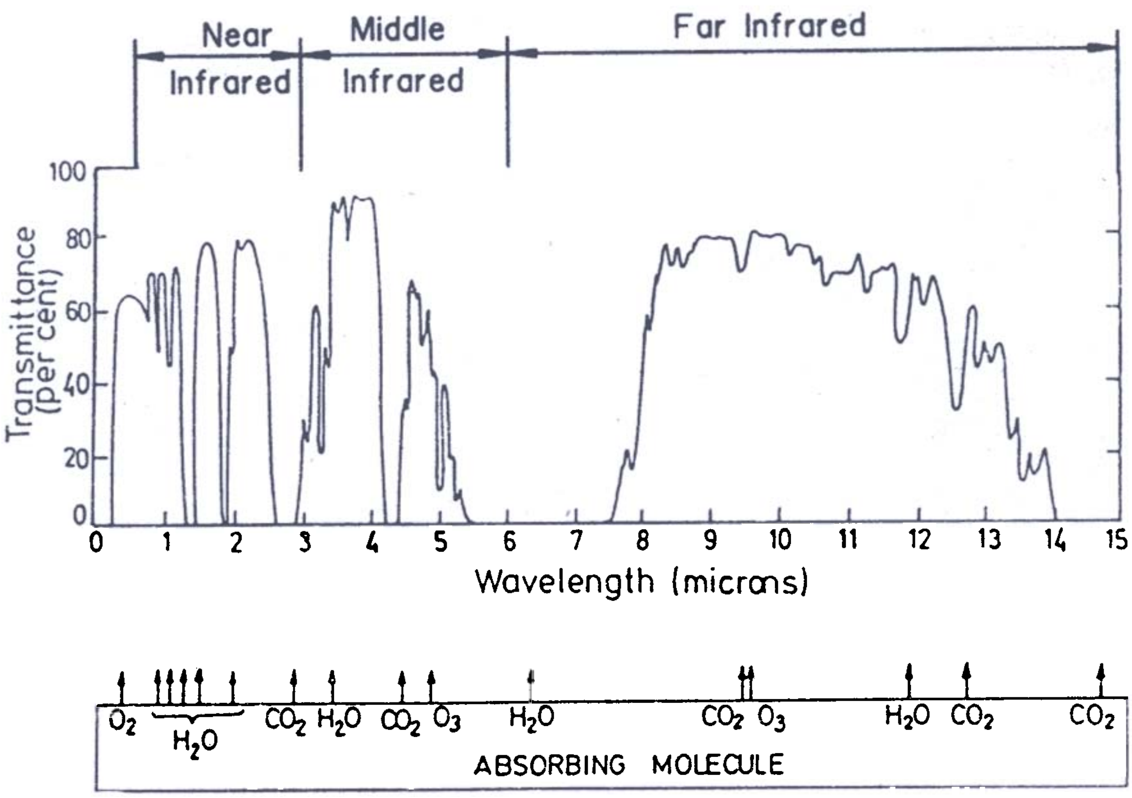


Figure 1. **Transmittance of the atmosphere for a 6000 ft. horizontal path at sea level containing 17 mm of precipitable water (after [1]).**

detection. $Pb_{1-x}Sn_xTe$ with $x < 0.2$ and $Hg_{1-x}Cd_xTe$ are the two material systems which are very important for the fabrication of detectors in 8-14 micron region. Of those two, because of the relatively easy preparation technique and moderately high operating temperature, $Pb_{1-x}Sn_x Te$ is used for the commercial preparation of IR sources (diode lasers) and detectors. In this paper we report the results obtained from the characteristic study of the MBE grown $Pb_{0.82}Sn_{0.18}Te$ films as IR band-pass filter and photoconductive IR detector.

2. EXPERIMENTAL DETAILS

The $Pb_{0.82}Sn_{0.18}Te$ alloy was prepared by melting elemental 5N pure *Pb*, *Sn* and *Te* powders in weighed stoichiometric proportions in an evacuated quartz ampule and the alloy composition was confirmed using x-ray technique, applying Vegard's law as described earlier[2-4]. The alloy was loaded in the Knudsen cell of the MBE system (MBE system installed at Indian Institute of Technology (IIT), Madras was imported from Vacuum Generaters (VG), England. Freshly cleaved *KCl* (100) single crystals were used as the substrates for the growth of films because of their least lattice mismatch (2.2 per cent) and higher IR transmittance[2,3] (96 per cent). The substrate temperature was optimized for the source temperature of 600°C as 375°C in order to obtain the most perfect single crystal films with fast growth rate[3]. The optimization of the substrate temperature was done using x-ray, electrical and optical methods[3]. The film grown at this substrate had a narrow line width in the x-ray (100) peaks, higher electrical mobility and low value of the optical absorption coefficient at the band edge compared to those of other films with different substrate temperatures[3]. The required optical parameters such as energy band gap, refractive index, extinction coefficient and optical absorption coefficient for fabricating filters and detectors were calculated from the transmittance spectra of the films as explained earlier[2-4].

3. IR BAND-PASS FILTERS

The simplest type of band-pass filter is a combination of longwave and shortwave pass filters. But because of the difficulty in producing either longwave or shortwave pass components with steep edges, a completely different approach based on the Fabry Perot interferometer is used for the commercial band-pass filters.

In this work, a bare substrate of the same size as that of the substrate was placed on the film with *KCl* (100) substrate to make a substrate-film-substrate system, similar to the fabry perot setup, and studied for the filter properties.

For this system, which contains a film of thickness, d, refractive index, n, absorption coefficient, a, and reflectance at the film-substrate interface, r_∞, with the substrate of transmittance T_{as} and refractive index, n_s, the expression for the normal incidence transmitted intensity is given[2,5&6].

$$T \quad \frac{T_{as}^2 \sinh^2 \gamma}{\sinh^2(ad/2 + \gamma) + \sin^2 \delta}$$

where

$\gamma = 0.5 \ ln\ (1/r_\infty)$

$\delta = 2\pi n/n_s d\bar{v}$

$\bar{v} = 1/\lambda$, the wave number in cm^{-1} and λ is the free space wavelength in cm.

From Eqn. (1), the derived expressions for the peak wave number $\bar{v}_{max}$ and the bandwidth $\Delta\bar{v}$ of the transmittance of a filter[2] are :

$$\bar{v}_{max} = \frac{m}{4(n/n_s)d}$$

and

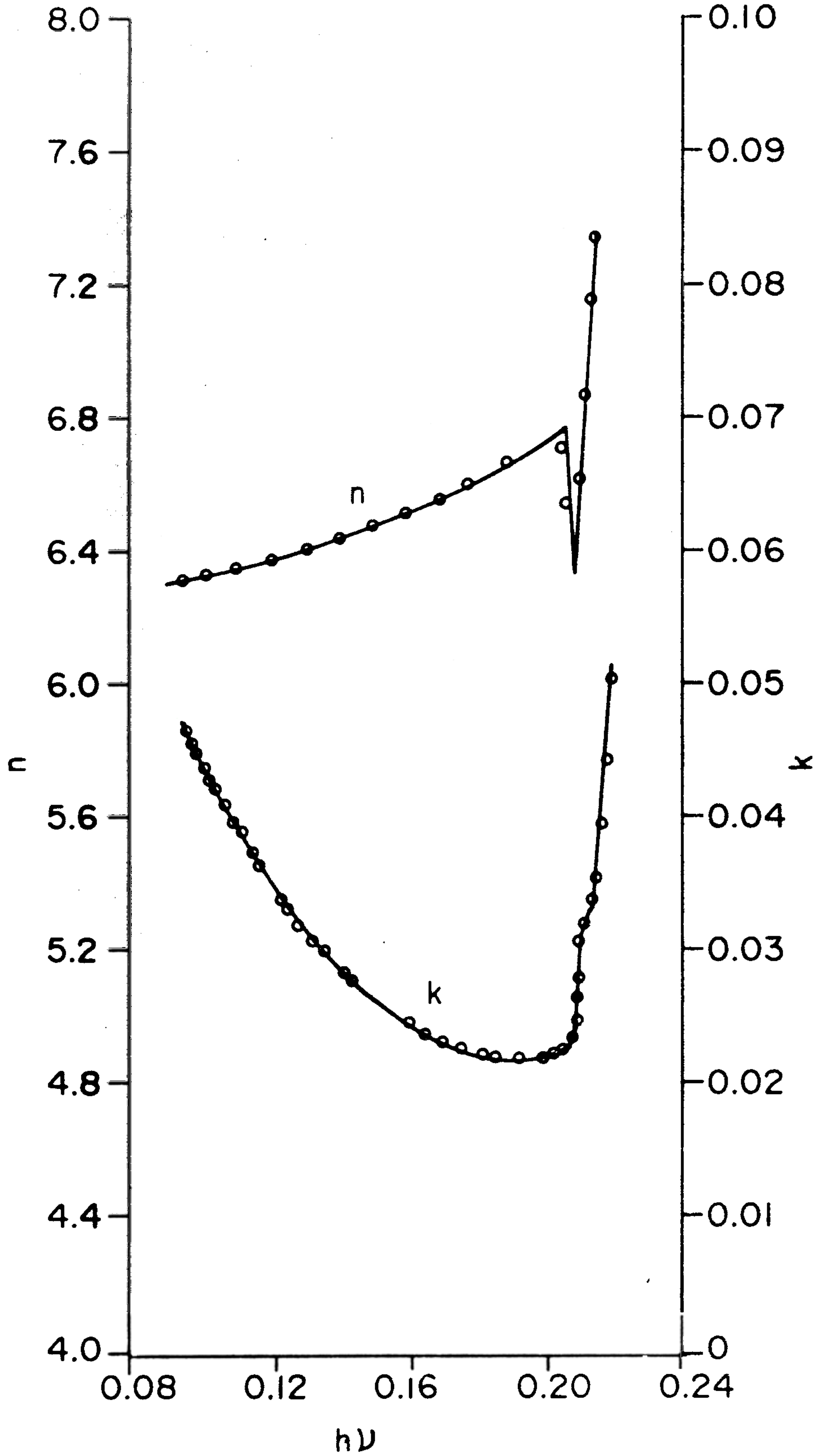
$$\Delta\,\bar{v} = \frac{4 \sinh\,(ad/2 + \gamma)\bar{v}_{max}}{m\,\pi\ .} \tag{3}$$

where m is the order of the interference peak.

Hence, from Eqn. (3) it is clear that $\Delta\bar{v}$ decreases with increasing m. But to increase the value of m at a particular peak wavenumber (wavelength), thickness of the active layer (film) of the filter should be increased. In effect the transmittance value at the peak wavenumber will be reduced and the transmittance outside the pass-band will be increased[2], according to Eqn. (1). Hence to fabricate band-pass filters using materials with minimum but not negligible absorption below the band edge, m should be chosen as the least value.

In this work, *IR* band-pass filters with peak wavenumbers (wavelengths) of 950 cm^{-1} (10.5 μm), 1250 cm^{-1} (8 μm) and 1600 cm^{-1} (6.25 μm) were fabricated using

$Pb_{0.82}Sn_{0.18}Te$ which are to be operated at room temperature. The required thickness of the active layers were calculated using the known values of n and k of $Pb_{0.82}Sn_{0.18}Te$ (Fig. 2) at room temperature[2] for the least value of $m = 2$. These values were substituted in Eqns. (2) and (3) for determining $\bar{\nu}_{max}$ and $\Delta\bar{\nu}$. They are shown in Table 1.



Variations of real and imaginary parts of the refractive index of $Pb_{0.82}Sn_{0.18}Te$ with photon energy (after [2]).

The transmitted intensities of the filters, made up of $Pb_{0.82}Sn_{0.18}Te$ films on *KCl* (100) substrates prepared by MBE technique, are shown in Fig. 3. The measured $\bar{\nu}_{max}$ and $\Delta\bar{\nu}$ *s* from these transmitted spectra are also shown in Table 1. The calculated and observed $\Delta\bar{\nu}$ *s* are varying from 20-30 per cent of $\bar{\nu}_{max}$. For these filters 20 per cent transmittance outside the passband is observed (the transmittance spectra were recorded using Perkin-Elemer spectrophotometer, Model 983 at RSIC, IIT Madras).

Table 1. Interference band-pass filter characteristics

Calculated

λ_{Max} (microns)	$\bar{\nu}_{max}$ (cm^{-1})	m		n/n_s	d (microns)	$\Delta\bar{\nu}$ cm^{-1}	Bandwidth (%)
6.25	1600	2	0.44	4.56	0.685	463	28.9
8.00	1250	2	0.46	4.42	0.850	379	23.6
10.53	950	2	0.47	4.35	1.210	295	31.0

Experimental

d (microns)	m	λ_{max} (microns)	$\bar{\nu}_{max}$ (cm^{-1})	$\Delta\bar{\nu}$ (cm^{-1})	Bandwidth (%)	Minimum transmittance outside the pass band (%)
0.680	2	6.10	1640	460	28.0	18
0.855	2	8.06	1240	440	35.5	28
1.190	2	10.64	940	320	34.0	20

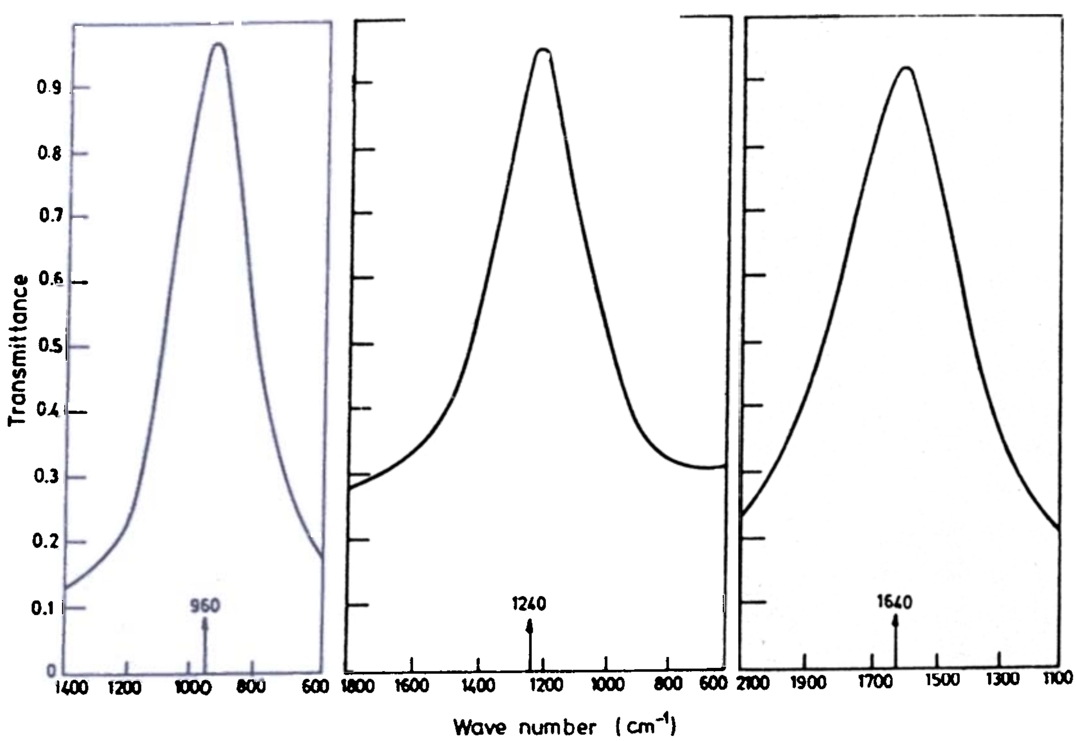


Figure 3. Interference band-pass filters.

4. IR PHOTOCONDUCTIVE DETECTOR

The performance of the photoconductor is evaluated by means of responsivity, *R*, detectivity, D^* and Noise Equivalent Power (NEP), which are known as figures of merit of the detectors[2,7&8]. The expressions for these figures of merit are given as[2,7&8].

$$R = \frac{V_s}{HA}$$

$$NEP = \frac{V_n}{R\,(\Delta f)^{1/2}}$$

$$D^* = \frac{R}{V_n}(A\,\Delta f)^{1/2} \tag{6}$$

where

V_s, V_n are the signal and noise voltages

H is the irradiance of the black body

A is the area of the detector and

Δf is the electrical bandwidth.

Further, *R* can also be expressed in terms of the material parameters as[2]

$$R = \frac{\eta\, V_0 \tau}{\quad} \tag{7}$$

where

η is the quantum efficiency

V_0 is the applied bias voltage

$h\gamma$ is the photon energy

τ is the carrier life time and

n_0 is the carrier concentration.

Hence to achieve maximum *R* as well as D^*, one must have lower carrier concentration, optimum bias voltage, optimum thickness, long carrier life time and maximum quantum efficiency.

Maximum quantum efficiency will be for the thickness of the film when it is equal to the skin depth of the material at a particular wavenumber (wavelength). That is when $d = 1/a$, η will be maximum.

For $Pb_{0.82}Sn_{0.82}Te$, a is nearly equal to 2.5 (10^3 cm^{-1}) at wavelength close to the band edge. So the thickness value of 4 μ_m is suitable for good response detector. Here, $Pb_{0.82}Sn_{0.18}Te$ film of 4.3 μ_m thick was prepared using MBE technique for photoresponse measurement at 77°K.

5. BLACK BODY RESPONSE MEASUREMENT

To measure the photoresponse, metal Indium was evaporated at the edge of the film for electrode purpose with effective detector area of 0.03 cm^2. The measurement was done with 10 per cent electrical bandwidth at 90° field of view for the black body temperature of 500K and chopping frequency of 800 Hz. The resistance of the film at 77°K was 120 ohms. The bias voltage was optimized to give maximum signal to noise ratio with one kilo ohm load resistance in the series (this measurement was done at SSPL, New Delhi).

6. RESULTS

The variations of signal voltage, noise voltage and their ratio as a function of bias current at the temperature of 77 K are shown in Fig. 4. From this figure it is observed that the optimum bias current is 0.5 mA. The parameters for the black body response measurement are given in Table 2. By substituting these parameters in Eqns. (4) to (6) the figures of merit were calculated for the optimum bias current. The results are shown in Table 3. The measured detectivity, D^* (500, 800, 10 per cent) is of the order 10^8 cm $Hz^{1/2}W^{-1}$. The detectivity can be further increased by reducing the reflectivity of the film surface. This can be done by suitable antireflection coating.

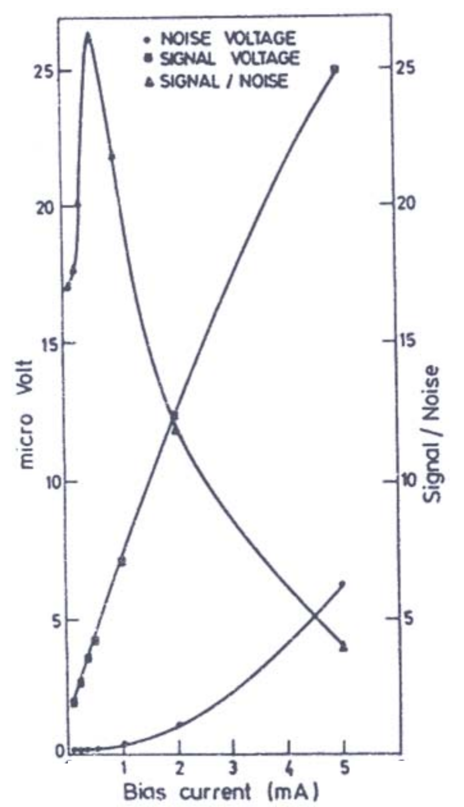


Figure 4. Determination of optimum bias current for $Pb_{0.82}Sn_{0.18}Te$ photoconductor at 77 K.

7. CONCLUSION

The prepared films of $Pb_{0.82}Sn_{0.18}Te$ by MBE technique were checked for IR band-pass filter and photoconductive detector applications and satisfactory results were obtained.

Table 2. Conditions for black body response measurement

Black body temperature	T(K)	=	500
Aperature area	a(10^{-2} cm^2)	=	3.3
Distance of the source from detector	D(cm)	=	10
Irradiance	H(μW cm^{-2})	=	9.31
Chopping frequency	f(Hz)	=	800
Electrical bandwidth	Δf(%)	=	10
Field of view		=	90°
Load resistance	(10^3 ohms)	=	1.00
Area of the detector	(10^{-2} cm^2	=	3
Detector temperature	(K)	=	77
Ambient temperature	(K)	=	297
Optimum bias current	(mA)	=	0.5
Resistance of the detector at 77°K	(ohms)	=	100
Thickness	(micrometers)	=	4.3

Table 3. Figures of merit of the detector

Responsivity	R	=	15	(V W^{-1})
Detectivity	D^*	=	1.47	(10^8 cm Hz$^{1/2}$W^{-1})
NEP (500, ou0, 10%)		=	1.054	(10^{-8} W Hz$^{-1/2}$)

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