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Properties of HgCdTe for Infrared Detector Applications

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Abstract: ***Mercury Cadmium Telluride (HgCdTe, also known as MCT) is a leading semiconductor material for high-performance infrared detector applications due to its tunable band gap and excellent optoelectronic properties. This review examines its structural, electronic, and transport characteristics relevant to short-wave, mid-wave, and long-wave infrared detection. Detector architectures, including photoconductive, photovoltaic, and metal-insulator-semiconductor configurations, are discussed. The influence of alloy composition on band gap, carrier concentration, mobility, and lattice properties is evaluated. HgCdTe remains highly attractive for thermal imaging, remote sensing, surveillance, and aerospace applications, although challenges related to surface stability and passivation remain.***

Keywords: HgCdTe; Mercury Cadmium Telluride; Infrared Detectors; Band Gap Engineering; Photovoltaic Detectors; Thermal Imaging; Semiconductor Materials; Infrared Sensors.

1. Introduction

Infrared detectors are used to detect infrared radiation, i.e., thermal radiation that all objects emit above absolute zero temperature• Thus, it is possible to detect an object by detecting its IR emission, rather than detecting reflected radiation from an illuminating source. In the infrared, the source of radiation is the object itself, and thus detection can be entirely passive. For this reason, infrared (IR) sensors will always play an important role in tactical and strategic military systems used for target acquisition, identification and tracking. These various IR applications include missile seekers, laser radars, infrared search and track (IRST), forward-looking infrared (FLIR), thermal imaging and space-based surveillance systems. When detection is made through the atmosphere, there are certain regions in the IR spectrum that are transparent due to the lack of molecular absorption by H_2O and CO_2. These windows occur in short wave length (SWIR), middle wave length (MWIR) and long wave length (LWIR) regions at 1-2μm, 3-5μm, and 8-14μm, respectively. For most objects at ambient temperature (300K), the IR emission peaks around 10 μm. As the object temperature increases, its emission shifts to shorter wavelengths. Thus as a general rule, LWIR is preferred for the detection of near ambient temperature targets such as ground vehicles like tanks, convoys etc. and MWIR is preferred for the detection of elevated temperature targets such as hot plume or jet exhaust. The key component of any IR detection system is the IR sensor or detector arrays. The infrared detector converts the incident radiation into an electrical signal which can be utilised for various applications mentioned above. There are two broad classes of detectors, viz. Photon detectors and thermal detectors. In case of photon detectors, the incident radiation excites carriers in the material, which are then used for detection. Some common IR materials used for photon detectors are listed below . In case of thermal detectors, the radiation from the object is absorbed by the detector lattice, thereby increasing the lattice temperature and changing the electronic property of the detectors. Thermal detectors are very much less sensitive than photon detectors, but have the advantage of operating at room temperature. One of the most versatile materials for photon detectors in IR region. Mercury cadmium telluride is often abbreviated as HgCdTe or MCT. This material of special interest consists of a mixture of the wide gap semiconductor CdTe (Eg ~1.6 eV) with a semimetallic compound, HgTe, which can be thought as a semiconductor having a " negative energy gap" of about 0.3 eV. The gap in the MCT alloy varies almost linearly with composition (x) between the two endpoint values, so that it passes through zero at an intermediate composition (x ~ 15) and has a value 0.1eV at x ~ 0.2 at 77 K. Thus the MCT material is suitable for intrinsic infrared detectors and can be obtained simply by making an appropriate alloy of HgTe and CdTe in Table .1

Table 1

Material	Wavelength (μm)	Temperature (K)
Si	0.1- 1.1	300
Pbs	1-3	300
PbSe	1-4	77
InSe	3-5	77
MCT	3-5	77/200
MCT	8-14	77

2. Literature Review

The initial incentive for HgCdTe was provided around 1960 by the need for detectors sensitive in the 8-14 um range, atmospheric transmission "window". Previously, only extrinsic detectors, like Si: Ga, Ge: Cu, Si: In, etc., had been available with high performance in the wavelength interval, but they have the disadvantage of being operated at very low temperatures 4.2K, An intrinsic detector offered the possibility of higher operating temperatures because of the fact that relatively little thermal excitation of carriers occurs across an energy gap at temperatures high enough for substantial excitation from an impurity level of the same energy to take place. The basic problem was to find a suitable semiconductor having an energy gap of about 0.09eV corresponding to the desired long wavelength cut-off limit of 10μm for detector response as obtained from the following equation

$$E_g = hc_0 / \lambda$$

$$E_g\,(\mathrm{eV}) = 1.24 / \lambda\ \mu\mathrm{m} \quad \text{-----(1)}$$

Where Eg--- energy gap
and λ - wavelength

No elemental or compound semiconductor with this energy gap was known, so it was necessary to develop the technology of an alloy system, the property of which could be tuned to the 8-14µm interval by adjusting the alloy composition. $Hg_{1-x}Cd_x$ Te with x ~ 0.2 was found to be a promising material for infrared detectors operable at 77K with efficient performance. Most of the effort on $Hg_{1-x}Cd_xTe$ to date has focused on the x~0.2 alloy and on photovoltaic detectors based on it, operated at 77 K. The main interest in $Hg_{1-x}Cd_xTe$ (x ~0.2) was as a semiconductor with a narrow energy gap suitable for an 8-14µm intrinsic infrared detector. The potentialities of $Hg_{1-x}Cd_xTe$ as an infrared detector have been proven by various researchers (1-4). The mercury cadmium telluride $Hg_{1-x}Cd_xTe$ with (x~ 0.2) semiconductor alloys system is a widely applicable high-performance infrared (IR) detector material in the 8-14 um wavelength range. During the last decade, there has been an enormous increase in the research effort devoted to various aspects of the science and technology of mercury cadmium telluride (MCT) IR detectors (1-4). These devices may be classified into three categories shown in fig, 1.

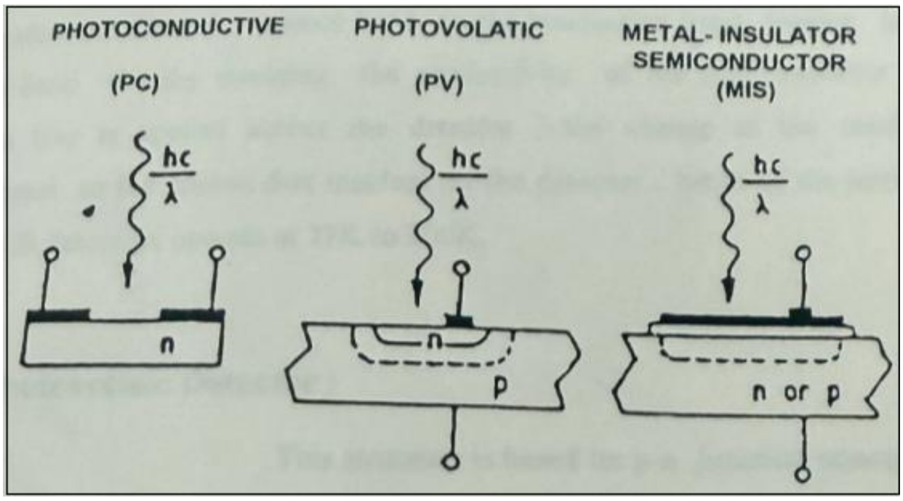

Figure 1: Shematic Cross-Section of PC, PV and MIS (HgCdTe) IR Detector

Photoconductive Detector: This is the simplest type of detector structure. It can be made from intrinsic or extrinsic semiconductors. The photon energy must be greater than the band gap energy for the semiconductor to absorb the photon. The absorption excites electrons from the valence band to the conduction band leaving holes in the valence band, thereby changing the conductivity of the semiconductor. When a constant bias is applied across the detector, the change in the conductivity is proportional to the photon flux incident on the detector. Most of the intrinsic LWIR and MWIR detectors operate at 77K to 200K.

Photovoltaic Detector: This structure is based on the p-n junction concept. Incident photons generate electron-hole pairs by intrinsic photon absorption and minority carriers diffuse to the junction where they are swept across by the built- in field in the reverse current direction. Because they are junction devices, IR detectors exhibit I-V curves similar to p-n junction. A photovoltaic detector operated in short circuit voltage mode operation with charge stored in the photo-diode causes a change in the junction capacitance, leading to non-linear saturation effects. Thus, the short circuit current mode is the preferred operating mode.

Metal-Insulator-Semiconductor (MIS) Detectors: The MIS structure consists of a transparent metal gate, a thin insulator layer and a doped semiconductor. Because of its inherent simplicity and its successful use in visible imaging CCD's, considerable effort has been made to use this technology with infrared detector materials. The device is operated by applying a voltage pulse to the gate which creates a depletion region in the semiconductor that acts potential well. Incident infrared photons create electron-hole pairs in the semiconductor. The minority carriers remain in the potential well near the surface, while the majority carriers are forced into the bulk of the device. This minority carrier charge stored is detectable.

Material Properties of Mercury Cadmium Telluride:
The chemical combination of elements from group II (atoms A) and group VI (atoms B) of the periodic table is characterised by the presence of four valence electrons per atom. This leads to a crystal lattice in which each atom A (or B) is surrounded symmetrically by four nearest neighbour atoms B or A), thus giving a tetrahedral lattice. In the geometric centre of each tetrahedron of atoms A (or B) is an atom belonging to the other group, i.e. B(or A). Two kinds of crystal structures conform to this arrangement of atoms, viz.:

1) The Zincblende structure and
2) The Wurtzite structure.

In case of HgCdTe and CdTe, both of these have a zincblende structure. The zincblende structure is composed of two interpenetrating face-centred cubic sublattices displaced by (¼ a_o, ¼ a_o, ¼ a_o) along the cubic body diagonal, where a_o is the lattice constant. If we represent the II- VI compounds generically as AB, the A atoms (cations) occupy the sites on one of these FC sublattices and the B atoms (anions) sits on the other. The MCT crystal structure is shown in fig.2.

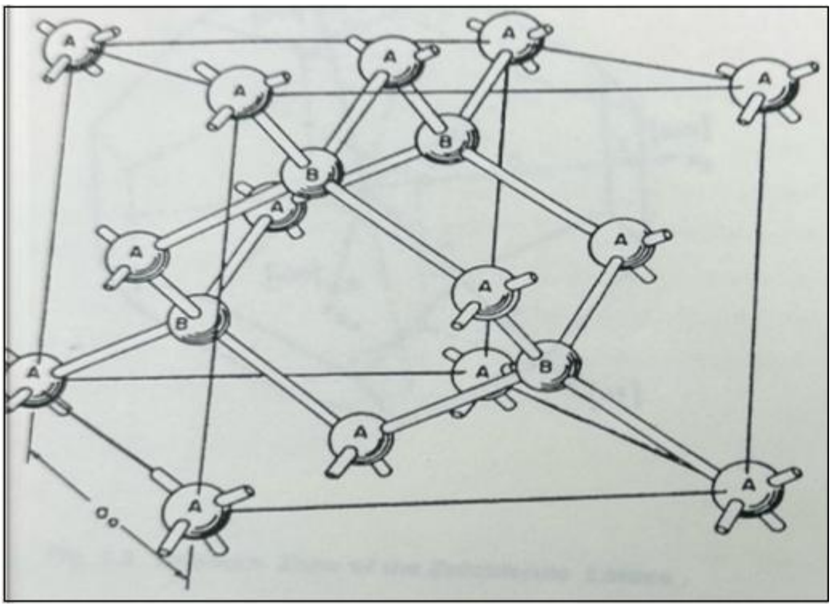

Figure 2: Zincblende Crystal Lattice

The Brillouin zone of the zincblende structure is a polyhedron obtained by truncation of an octahedron, as shown in the figure. 3

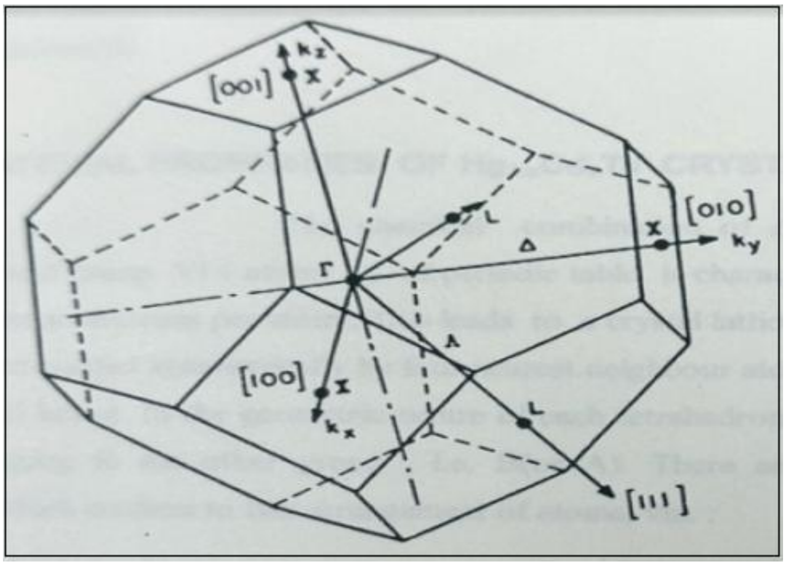

Figure 3: Brillouin Zone the Zincblende Lattice

In the figure, the basic points and axes of symmetry are marked, characterising translation properties in K- space. The F point is the centre of the zone (K=0). A indicates axes in [11I] directions. L shows the points of the intersection on the A axes with the surface of the zone, 4 the axes in the [100] [010]and [001] directions and the points marked & show the intersection of the axes with surface of the zone, 4 the axes in the [100] [010Jand [001] directions and the points marked X show the intersection of the 4 axes with surface of the zone. The work reported by a large number of workers on the phase diagram between CdTe-HgTe indicates the possibility of growing solid solutions of the HgCdTe system over the complete composition range. The phase diagram, as calculated by Schmit and Speerschneider (9), is illustrated in fig. 3

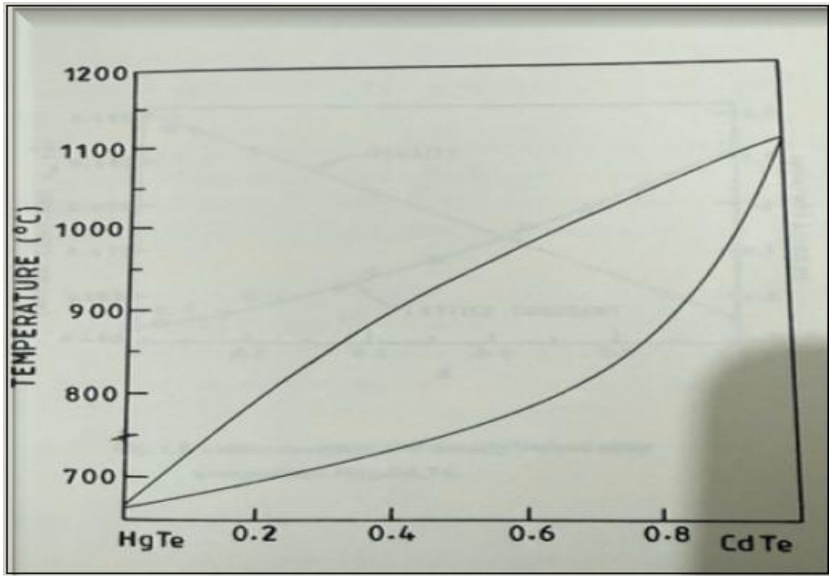

Figure 4: Phase diagram for $Hg_{1-x}Cd_xTe$

It shows a wide separation between liquidus and solidus curves in the pseudo- binary CdTe - HgTe phases. This indicates a large value of segregation coefficient and large vapour pressure of mercury at the higher temperatures. The dependence of the lattice constant 'ao' on composition' x' for the alloy system of $Hg_{1-x}Cd_xTe$ was experimentally measured by Woolley, Blair and Newnham (11). The resulting curves are shown in fig. 5. The curves showed a deviation from Vegard's law, i.e., a nonlinearity of the 'a_o' versus 'x' variation. The density versus composition curve of $Hg_{1-x}Cd_xTe$, determined gravimetrically by Blair and Newnham, is reproduced in Fig. 5.

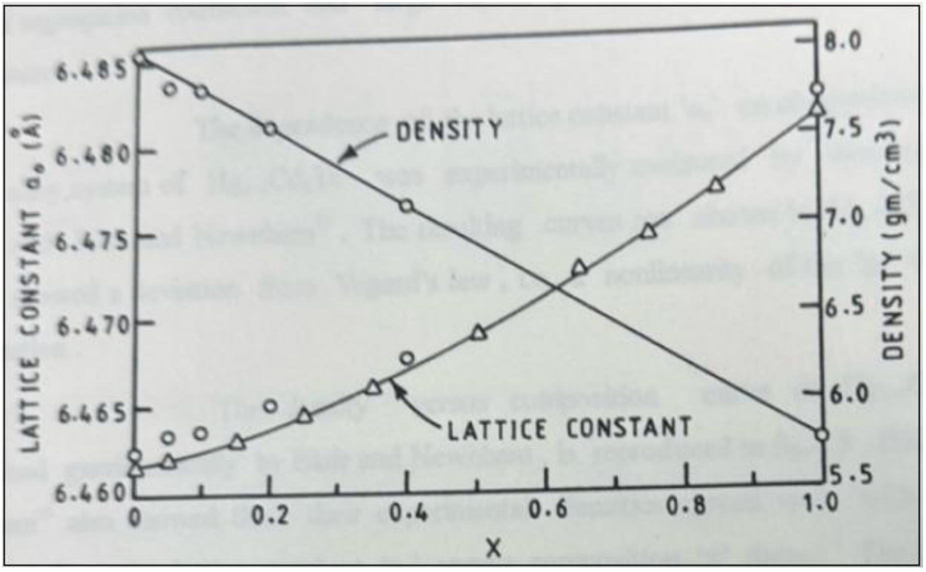

Figure 5: Lattice constant and density Versus alloy Composition $Hg_{1-x}Cd_xTe$

Blair and Newnham also showed that their experimental densities agreed well with those calculated from the lattice constant 'a_o' versus composition 'x' data. The lattice constant 'a_o' and density as a function of 'x' are given below:

Lattice constant (Å) = $6.4 + 00.0084x + 0.000168\times - 0.0057x$

And Density d (gm/cm^3) = $8.0765 - 2.226x$

Some important parameters of HgTe, CdTe and these interpolated for $Hg_{0.8}Cd_{0.2}Te$ are tabulated in Table 2

Table 2

S. No.	Parameter	Temperature (K)	Expt. Values HgTe	Expt. Values CdTe	Interpolated $Hg_{0.8}Cd_{0.2}Te$
1	Crystal Structure[8]	-	Zincblende	Zincblende	Zincblende
2	Lattice Constant[11, 77]	-	6.461	6.481	6.463
3	Dielectric Constant [12, 13, 14]	-	20	10.6	18.1
4	Thermal Expansion Coefficient [11, 16, 17]($^0K^{-1}$)	77 298	2×10^{-6} 4×10^{-6}	5.5×10^{-6}	4.3×10^{-6}
5	Thermal Conductivity 18 ($wcm^{-1}\,{}^0K$)	77	0.15	0.4	0.2

Semiconducting Properties of MCT:

MCT alloy can be formed by mixing binary alloys HgTe and CdTe when proper solid solubility conditions exist for the desired compositions. The binary constituents are preferably expected to have compatibility of structure and chemical formula as to achieve smooth restructuring of energy band structures. Ternary alloy (MCT) of HgTe and CdTe semiconductors can thus be treated as an additional class of semiconductors in which the energy band parameters could be varied as per requirement by appropriate solution of the constituents HgTe and CdTe and their relative concentrations .Thus the $Hg_{1-x}Cd_xTe$ alloy provides the possibility of tailoring its properties and hence projects itself as an important semiconducting material in the fabrication of IR detectors, light emitting diodes, solar cells etc. The band structures of the components (viz. HgTe and CdTe) of the MCT alloy system can be said to blend to give the band structures of the MCT mixed alloy. Consistent with the zinc blende structure semiconductors, CdTe has the valence band maximum at Γ_8 and the conduction band minimum Γ_6. The E Vs k plot for CdTe in the vicinity of its energy gap (8) k = 0 are shown in fig.1.6.

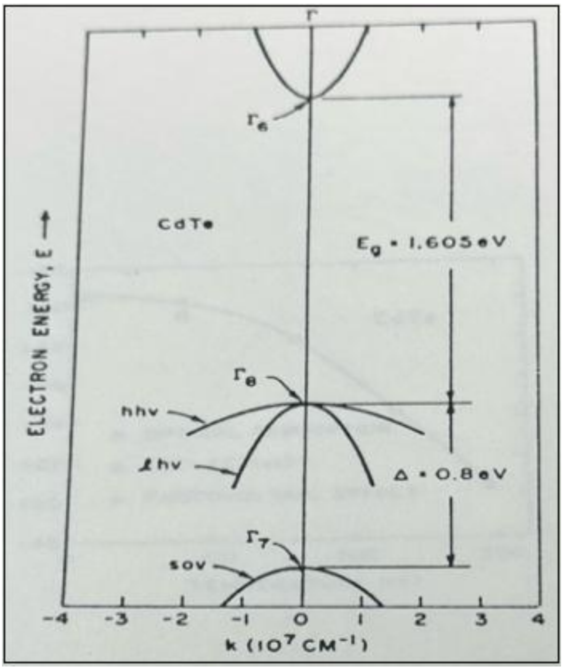

Figure 6: Energy Band Structure of CdTe

It may be observed that Cdle has a direct band gap of 1.605 eV and valence band spin orbit splitting energy is 6.8 eV at 0° K The temperature Vs. The energy gap curve for CdTe as given by Long (8) is also shown in fig. 7.

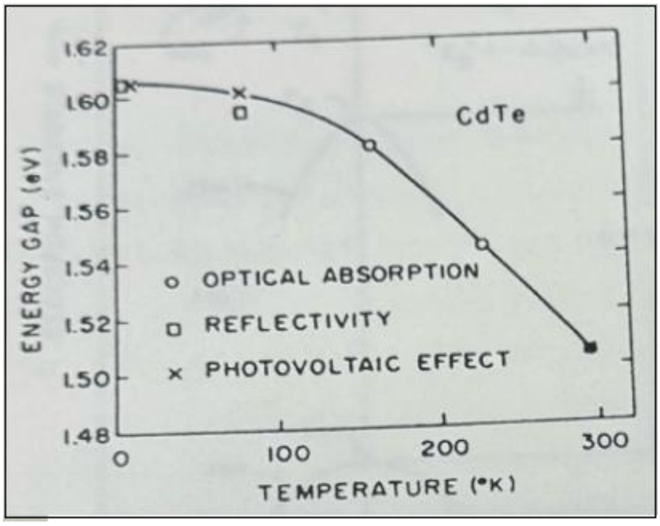

Figure 7: Temperature dependence of the energy gap in CdTe

In the case of HgTe, however, the Γ_6 state, which is normally the conduction band minimum in zincblende structure compounds, happens to lie at a lower energy than Γ_8 valence band maximum, as can be seen from the E Vs. k plot for HgTe in

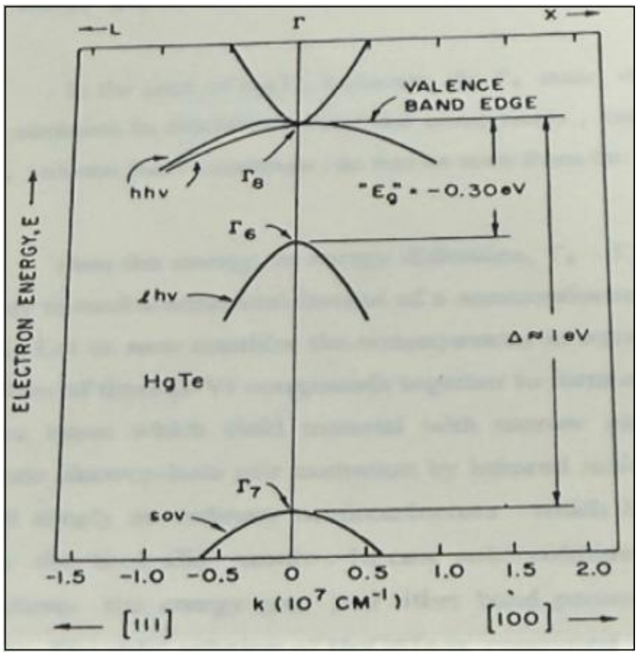

Figure 8: Energy band structure of HgTe

Thus, the energy or energy difference,Γ_6- Γ_8 is negative in HgTe and so HgTe may termed a semimetal instead of a semiconductor, with an energy gap® of -0.3eV at 0°K. Let us now consider the consequences in terms of energy band structure of mixing of two of these II-VI compounds together to form an alloy The alloy systems of interest are those which yield material with narrow gaps, in the range corresponding to intrinsic electron-hole pair excitation by infrared radiation. The mixed crystals can be treated simply as ordinary semiconductors which have a continuously variable adjustable gap due to their alloy nature. In case a solid solution of two material have same band structures the energy gap and other band parameters should vary smoothly, in fact, linearly. The solid solution of HgCdTe is composed of wide band gap semiconductor CdTe (Eg=1.6eV) and a semimetal HgTe (Eg= -0.3eV) and results in the band gap of alloy varying with composition between two end point values. Though CdTe falls well outside the range of narrow band gap materials, the mixed system CdTe - HgTe gives rise to cross over between valence and conduction bands and energy gap passes through zero at an intermediate composition of x ~ 0.15 as shown in fig. 9.

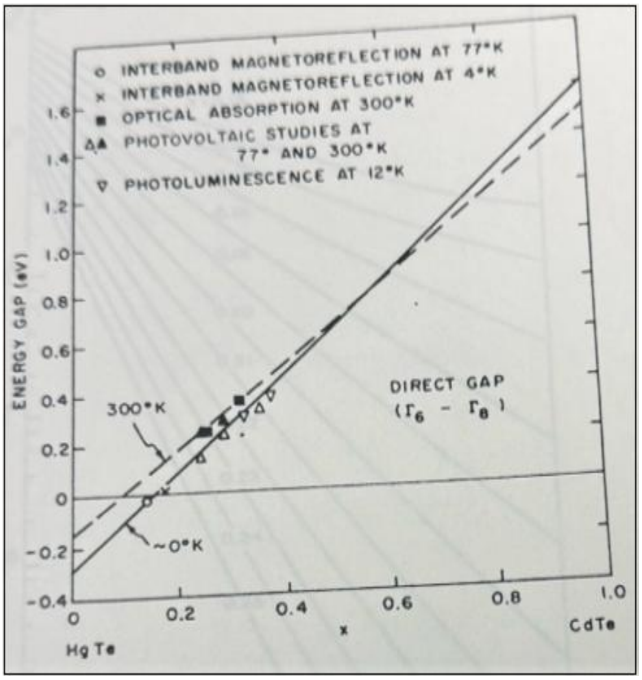

Figure 9: Energy Gap Vs Composition in $Hg_{1-x}Cd_xTe$

Electrical Properties:

Study of the electrical properties of semiconductor materials and justifying them for the requirements for device fabrication is very important. In MCT technology, the study of variation of carrier concentration and mobility with composition and temperature are crucial for the photoconducting and photovoltaic infrared detectors. Determining the carrier concentration and mobility data useful for analysis of intrinsic detector properties of various alloy compositions and thereby their wavelength responses is thus of great interest. The variation of intrinsic carrier concentration versus temperature in $Hg_{1-x}Cd_xTe$ alloy system for various values of 'x' is shown in fig. 10.

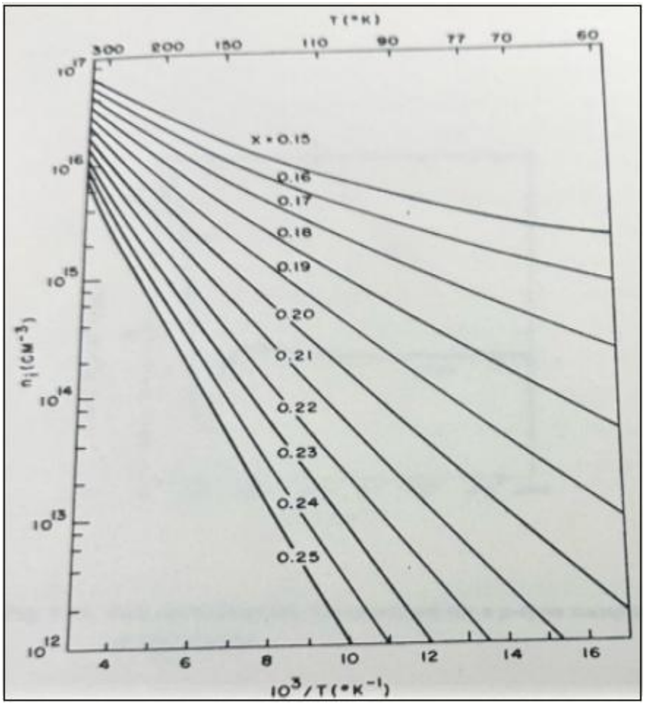

Figure 10: Intrinsic carrier concentration vs. temperature in $Hg_{1-x}Cd_xTe$ for various alloy compositions

The results of the Hall coefficient versus temperature for a p-type $Hg_{0.8}Cd_{0.2}Te$ are shown in fig. 11.

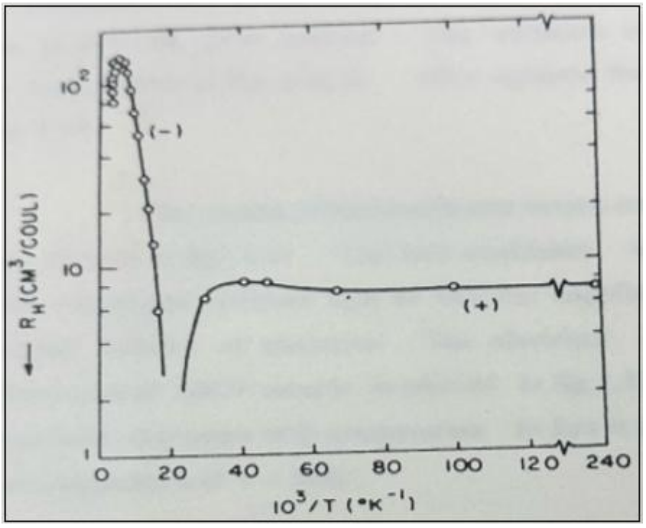

Figure 11: Hall Coefficient vs Temperature for p-type Sample of $Hg_{1-x}Cd_xTe$

The hall coefficient is positive in low temperature, extrinsic range and reverses sign to become negative in the intrinsic range because of higher mobility of electrons. The electrical resistivity versus temperature data from a typical MCT sample is plotted in fig.12

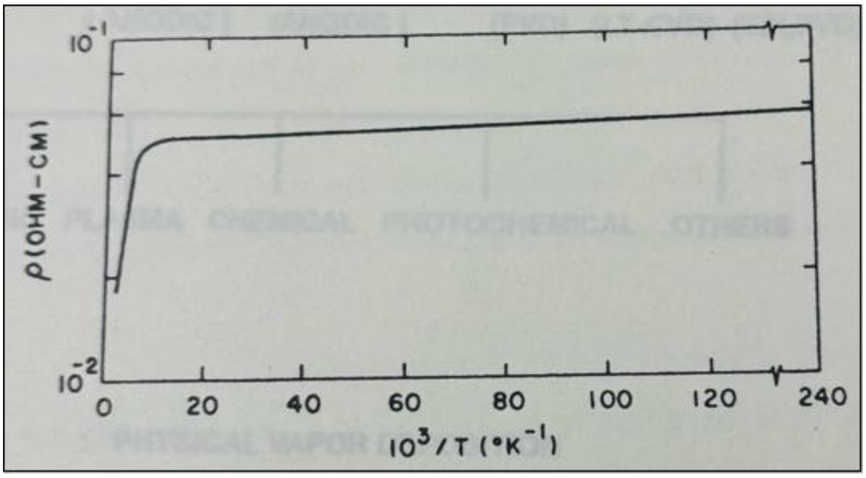

Figure 12: Electrical Resistivity Vs Temperature for a p- type sample of $Hg_{1-x}Cd_xTe$

The results show that the mobility magnitude decreases with temperature. In fact it is low and becomes almost independent of temperature at T< 30K.

3. Conclusions

HgCdTe remains one of the most versatile semiconductor materials for infrared detection because of its tunable electronic properties, strong sensitivity, and wide spectral applicability. Its continued importance in thermal imaging, defense, aerospace, and sensing technologies is well established. However, challenges involving material stability, defect control, and surface passivation continue to limit optimal performance. Future advances in fabrication and interface engineering are expected to further improve device reliability and detector efficiency.

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