Electrical and thermal transport properties of CdO and CdMgO alloys grown using PA-MBE technique

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Introduction

- **Oxide semiconductors are promising candidates for optoelectronic applications because of advantages like large bandgap energy, and high mechanical and chemical stability.**
- **CdO is one of the oldest known semiconductor oxides that have been studied widely because of its high electron concentration, high transparency, high electron mobility, low resistivity, and high exciton binding energy.**
- **Development of advanced growth techniques and in situ characterization methods allowed not only to grow high-quality CdO layers but also related ternary alloys (such as ZnCdO and CdMgO) which in turn can be used in many wide spectral range applications.**
- **Plasma-assisted molecular beam epitaxy (PA-MBE) allows the most precise control of growth parameters, such as growth rate, and flux of Cd, which could be monitored by a variety of in situ characterization techniques such as flux monitor, laser reflectometry, and desorption mass spectroscopy.**
- **In this work, we have investigated a series of CdO and CdMgO layers grown on m-plane sapphire and quartz substrate using PA-MBE technique.**

Methodology

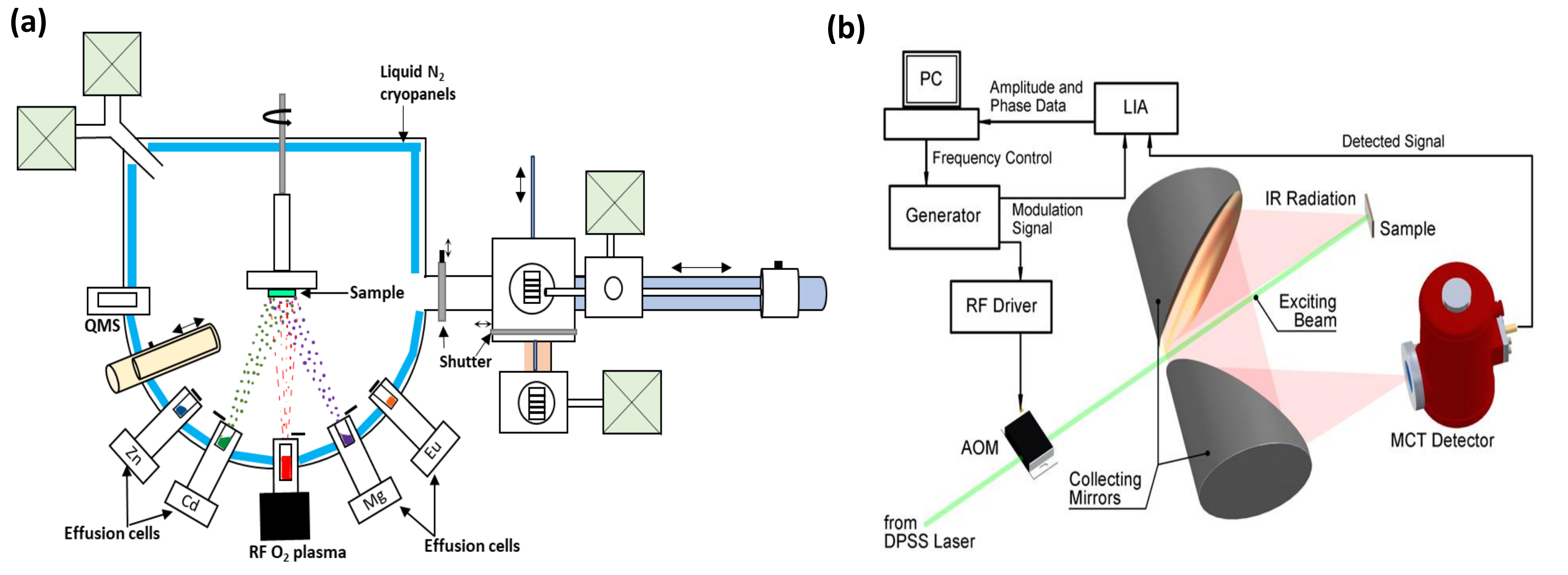

Fig.1. Schematic representation of (a) oxide MBE setup (b) photothermal radiometry setup

- **CdO and CdMgO random alloys were grown using plasma-assisted MBE technique (PA-MBE) on *m*- plane sapphire and quartz substrates respectively**
- **The following characterization were performed:**
  - ☐ **Optical study → UV-Vis spectroscopy**
  - ☐ **Electrical study→ Hall measurement**
  - ☐ **Thermal study→ Photothermal infrared radiometry**

Results and Discussion

1. Optical study

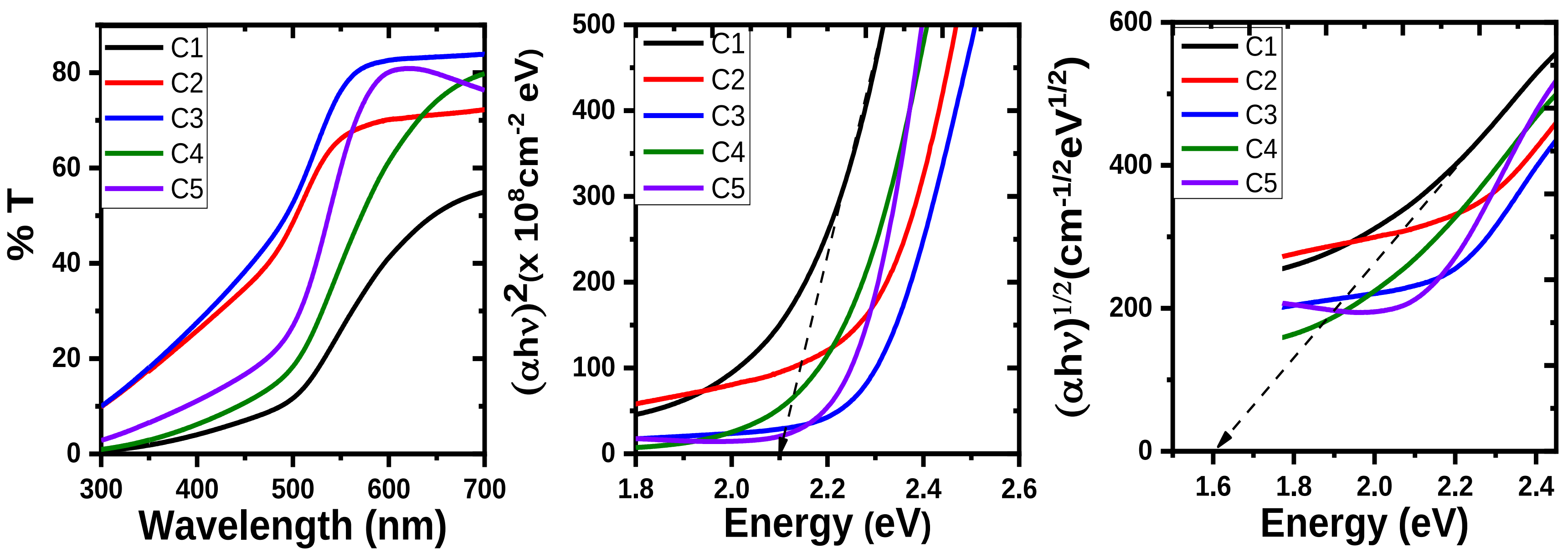

Fig.2. (a) transmittance spectra(b) α² plot as a function of energy (hv), and (c) α^1/2 plot as a function of energy (hv) for CdO alloys on the quartz substrate.

- **Absorption coefficient,**

$$\alpha = -\frac{1}{d} ln(T)$$

- **Tauc relation,**

$$\alpha h\nu = A\,(h\nu - E_{g,o})^{n}$$

where n=1/2 and 2 for direct & indirect transition

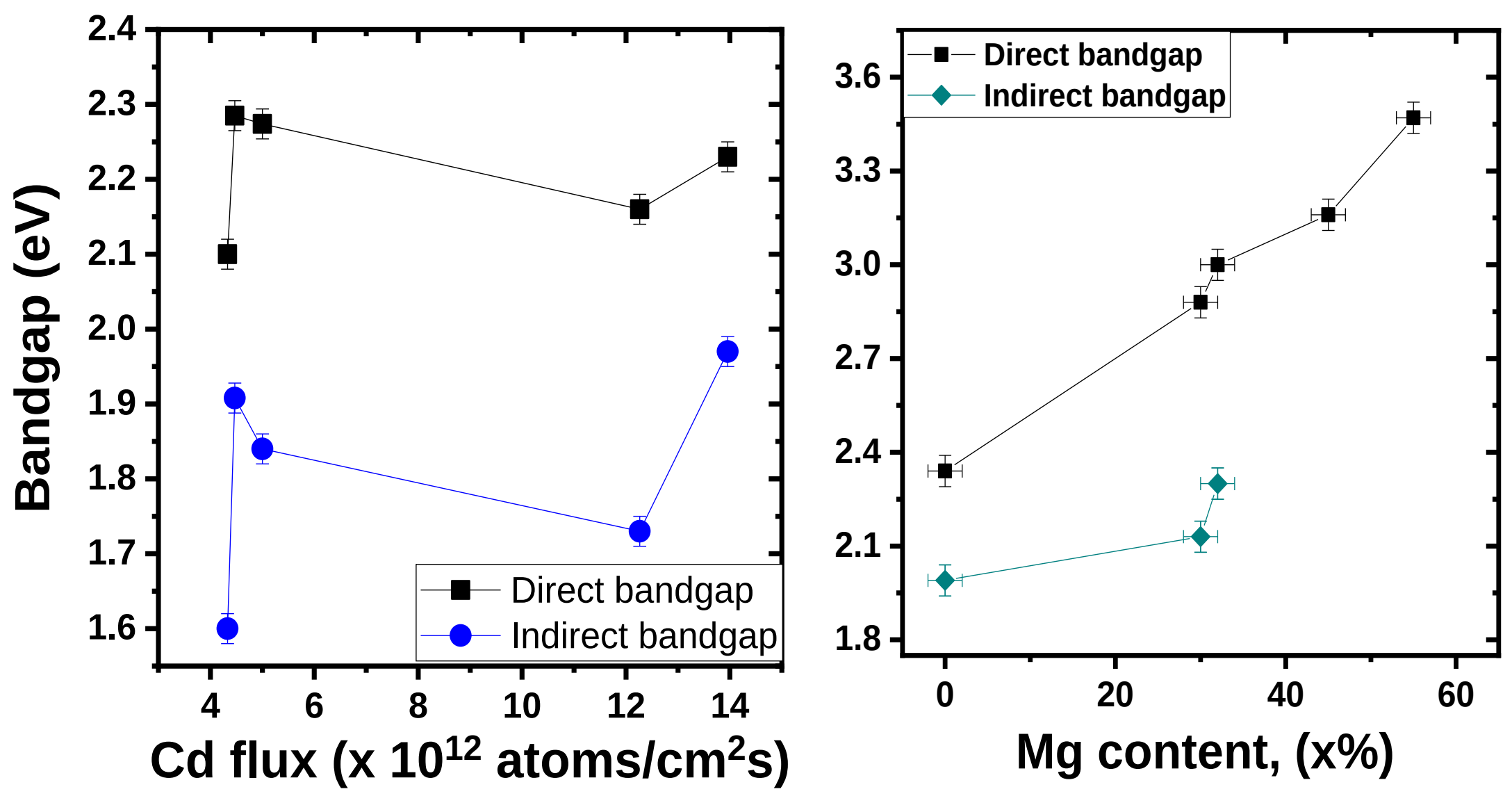

Fig.3. Variation of bandgap with (a)Cd flux in CdO, and (b) Mg content in CdMgO alloys.

2. Electrical study

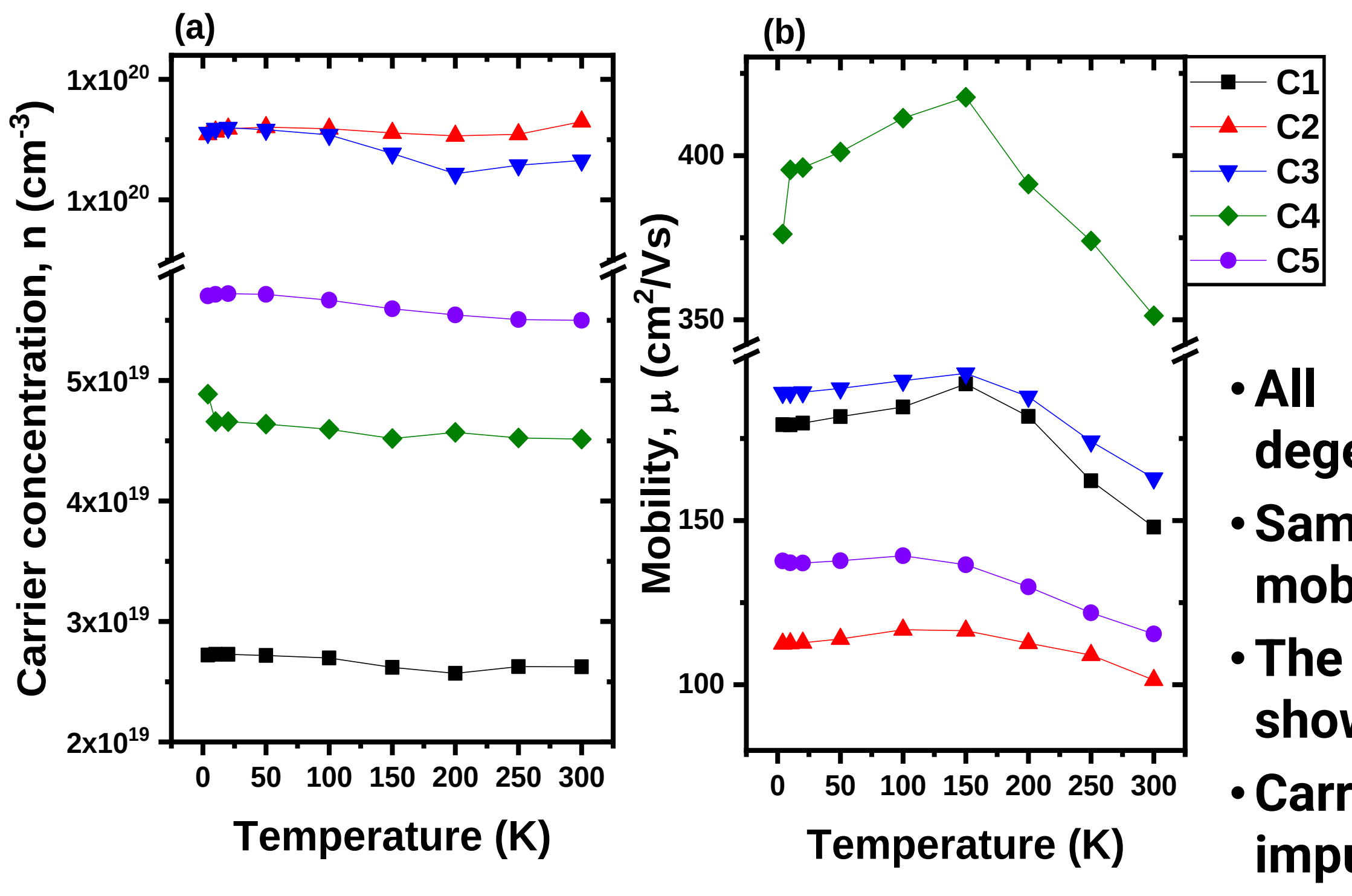

Fig.4. Variation of (a) carrier concentration and (b) electron mobility with temperature of CdO/m-Al$_2$O$_3$

- **Carrier concentration,**

$$n = \frac{IB}{U_{Hall}ed}$$

- **Mobility,** $\mu = \frac{1}{ne\rho}$

- **All the grown CdO layers are degenerate in nature**
- **Sample C4 shows the highest carrier mobility of 352 cm^{2}V^{-1}s^{-1}**
- **The sample with a higher n (C2) shows the lowest μ**
- **Carrier scattering causes by ionized impurities scattering and lattice scattering**

$$E_{g,opt} = E_{g,0} + \Delta E_{BM} - \Delta E_{BGN}$$

$$\Delta E_{BGN} = \Delta E_{e-i} + \Delta E_{e-e}$$

$$\Delta E_{BM} = \frac{\hbar^2 k_f^2}{2\mu^*}$$

$$\Delta E_{e-i} = \frac{4\pi n e^2}{\epsilon_o a_o \lambda^3} = \frac{e\hbar}{2}\sqrt{\frac{\pi^3 n}{\epsilon_o \mu}}$$

$$\Delta E_{e-e} = \frac{2e^2 k_f}{\pi\epsilon_o} + \frac{e^2\lambda}{2\epsilon_o}[1 - \frac{4}{\pi}tan^{-1}(\frac{k_f}{\lambda})]$$

Sample	n (cm^{-3})	ΔE_{BM} (meV)	ΔE_{BGN} (meV)	
			ΔE_{e-i}	ΔE_{e-e}
C1	2.62 x 10^{19}	146.94	35.39	0.98
C2	1.07 x 10^{20}	374.06	71.31	1.55
C3	1.03 x 10^{20}	362.46	70.23	1.53
C4	4.51 x 10^{19}	211.01	46.42	1.17
C5	5.49 x 10^{19}	240.73	51.25	1.25

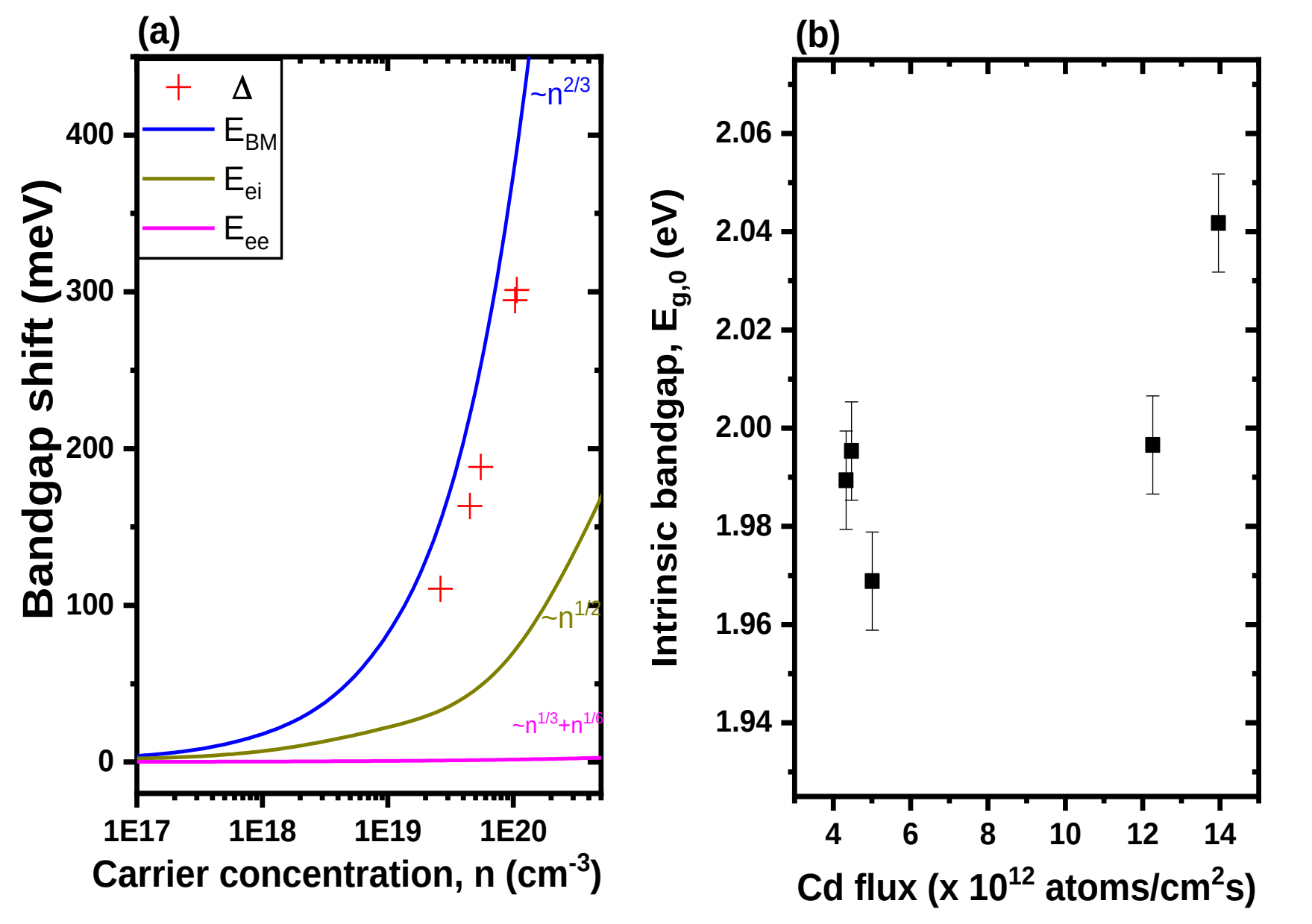

Fig.6. (a)Bandgap shift as a function of carrier concentration (b) Intrinsic bandgap with change in Cd flux

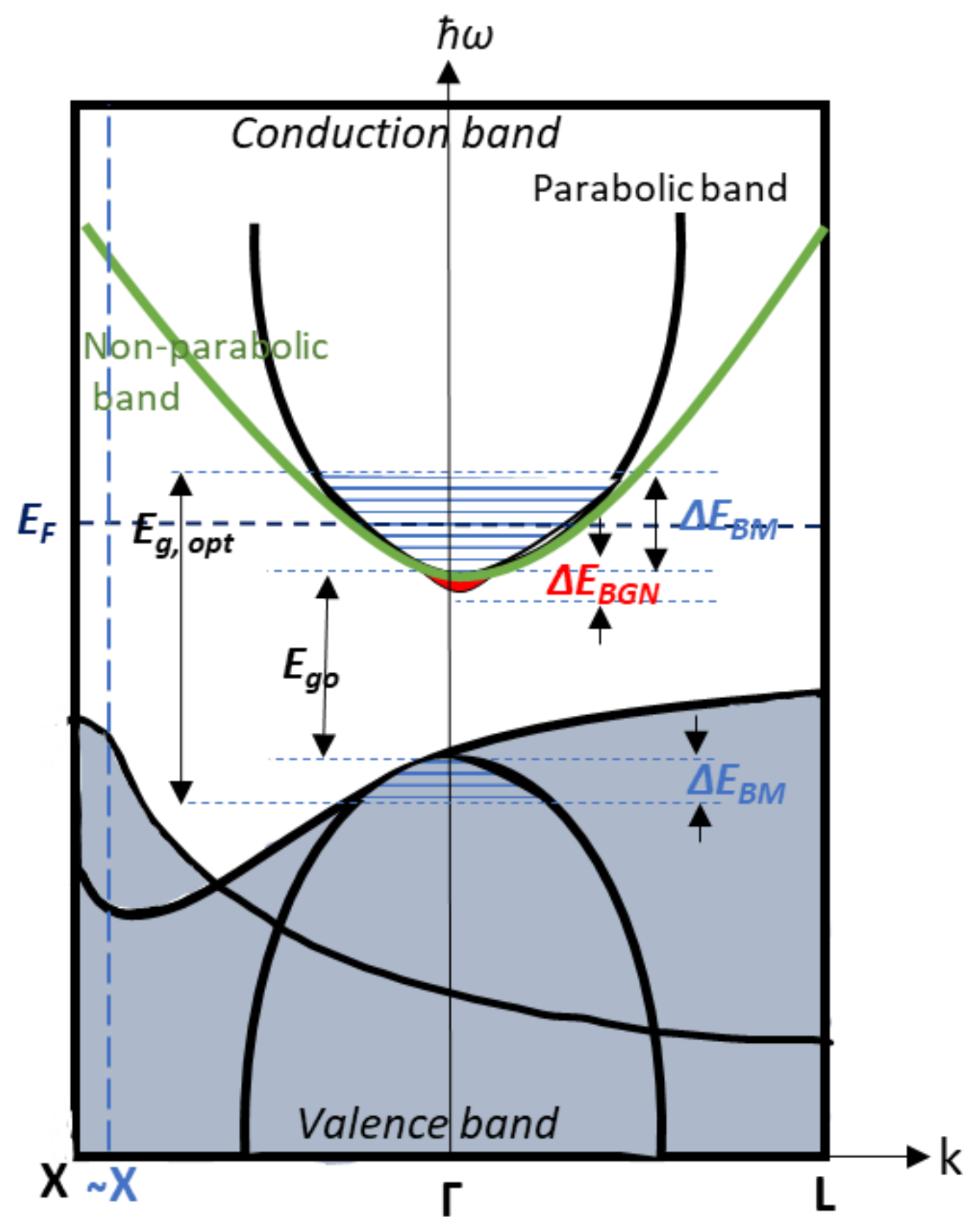

Fig.5. Schematic bandgap representation of degenerate CdO

- **In degenerate CdO layers, electron occupation in the CBM and VBM causes bandgap widening**
- **Random distributions of impurities cause electron-ion interaction whereas the electron-electron interaction is due to Columbic charge carriers in the semiconductor band**
- ***ΔE$_{e-e}$* values are much lower compared to *ΔE$_{e-i}$***

3. Thermal study

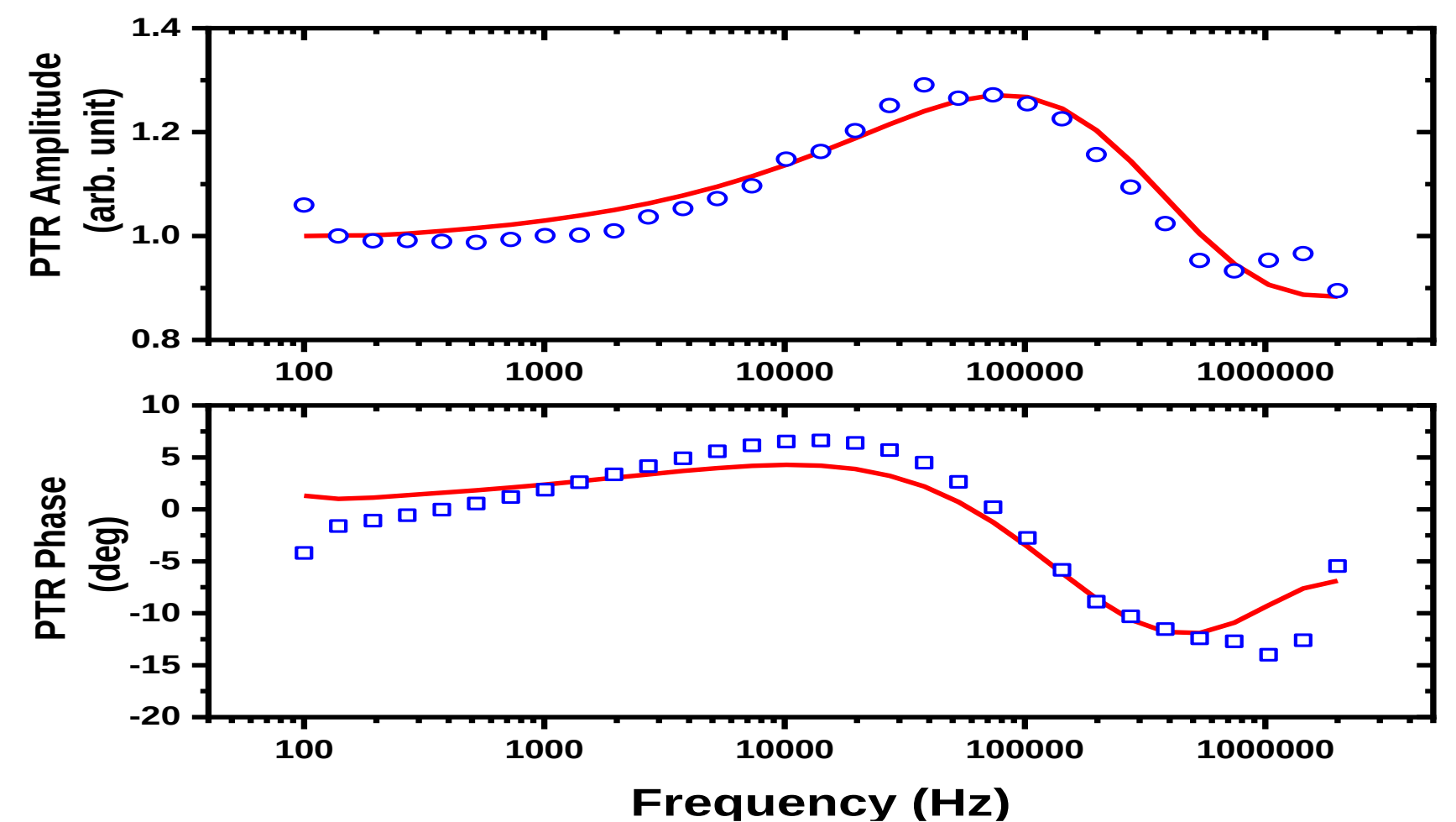

Fig.7. Normalized PTR amplitude and phase of CdMgO alloys

$$\theta(0) = \left(\frac{(1-R)I_o}{2k_1\sigma_1}\right)\left(\frac{1+y_1}{1-y_1}\right)$$

$$y_n = e^{-2L_n\sigma_n}\left(\frac{U_+^1}{U_-^1}\right), \sigma_n = \sqrt{i\omega/\alpha_n}\,, \alpha_n = k_n/\rho_n C$$

$$U_\pm^1 = (1+y_2) - R_{12}k_2\sigma_2(y_2-1) \pm \left(\frac{k_2\sigma_2}{k_1\sigma_1}\right)(y_2-1)$$

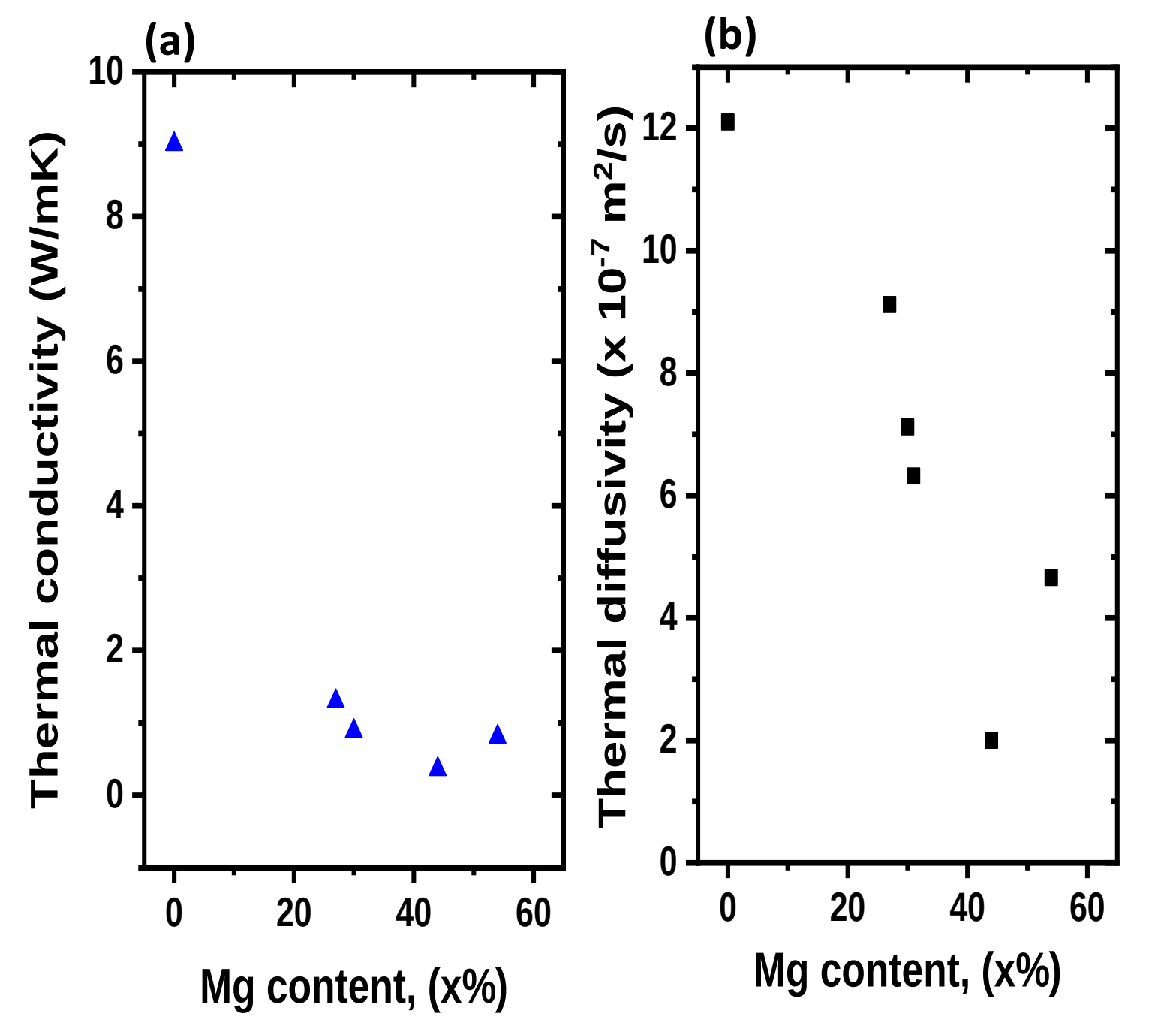

Fig.8. Variation of (a)thermal conductivity and (b)thermal diffusivity with change in Mg content in CdMgO alloys

Conclusions

- ✓ **Pure CdO layer and CdMgO layers were grown on m-plane sapphire and quartz substrate using PA-MBE technique.**
- ✓ **The direct bandgap varies from 2.1 eV to 2.33 eV whereas the indirect bandgap varies from 1.6 eV to 1.97 eV for pure CdO layers with a change in Cd flux**
- ✓ **The shifting of bandgap toward higher energies depends upon n and is acquired by combining the effect of bandgap widening (BGW) and bandgap narrowing (BGN) effects.**
- ✓ **C2 shows maximum n of 1.06 x 10^{20} cm^{-3} and C6 shows maximum μ of 352 cm^{2}V^{-1}s^{-1}**
- ✓ **Optical bandgap (both direct and Indirect bandgap) increases with an increase in Mg concentration in CdMgO alloys.**
- ✓ **Thermal conductivity and diffusivity decreases with increases in Mg content up to 50% in CdMgO alloys and started to increase above 50 %, as expected for bulk crystal.**

References

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