BAPVC Annual Project Report

Project Title: Ideal transparent conductors for full spectrum photovoltaics

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Summary:

The group has developed high mobility Cadmium oxide (CdO) thin films using conventional radio frequency magnetron sputtering methods on low cost glass substrates with electrical and optical properties comparable to films grown by pulsed laser deposition on sapphire. Optimized CdO films suitable for full spectrum PVs with resistivity in the mid 10^{-5} Ω-cm and >85% transmittance in the range of 400-1300 nm were achieved. The group also explored alloying CdO with MgO with the energy gap of 7.8 eV to upward shift the absorption edge and improve the UV transmittance of the resulting CdMgO alloys.

Key Accomplishments:

Previously the group has demonstrated high mobility Cadmium oxide thin films using pulsed laser deposition (PLD) method. In the past year, they have achieved CdO films with similar electrical and optical properties using scalable RF magnetron sputtering methods on low cost glass substrates. Fig. 1 shows the electron mobility of undoped and doped (In and Ga) CdO films deposited on glass using the RF sputtering technique. Sputtered deposited films on glass substrate with electron concentration up to 10^{21}cm^{-3} and mobility approaching 200 cm^2/Vs (ρ~4x10^{-5} Ω-cm) have been achieved. Systematic studies of the doping and annealing of CdO were carried out. The group found that as-grown In and Ga doped films show similar electrical properties. However a thermal annealing under N_2 of In doped CdO films results in a more stable material with improved mobility. In contrast some degradation of electrical properties and reduction of electron concentration is observed in Ga doped CdO when the films are annealed at temperatures higher than 400^{o}C. The different behavior of those two dopants can be attributed to the smaller size difference between In and Cd atoms compared with Ga and Cd atoms. Figure 2 shows the transmittance and reflectance measurements from CdO films doped with In and Ga. These results represent films with resistivity <10^{-4} Ω-cm that were optimally doped with ~3-4% of Ga or In and annealed. A wide transmission window of 400-1300 nm is observed in both types of films.

A drawback of these CdO based TCOs is their relatively small bandgap that limits the ultraviolet (UV) transmittance edge to only ~400 nm that is not sufficient

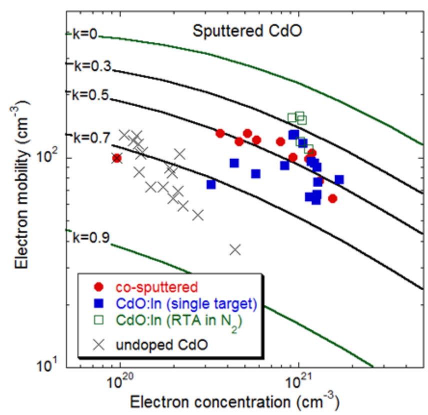

Fig. 1 Electron mobility of sputter-deposited CdO films undoped and doped with In and Ga on glass substrates. Calculated mobilities of CdO with different compensation ratio k are also shown.

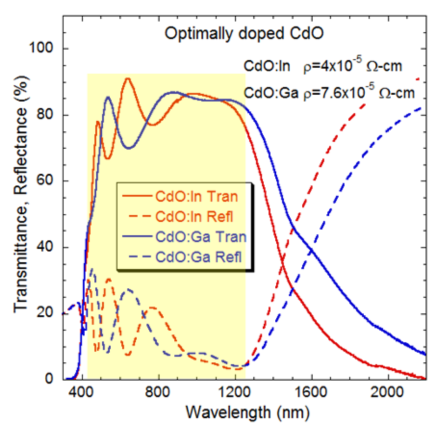

Fig. 2. Transmittance and reflectance from optimally doped CdO films with In and Ga showing a wide transmission window from 400 to 1300 nm,

for an efficient utilization of the UV part of the solar spectrum. The UV absorption edge of the doped CdO is determined by the intrinsic direct gap of ~2.2 eV and the Burstein-Moss shift associated with the high location of the Fermi energy in the conduction band resulting from the large concentration of electrons in the material. In the past year, the group has also explored alloying CdO with MgO that has a much larger energy gap of 7.8 eV. They have synthesized and characterized a series of $Cd_{1-x}Mg_xO$ thin films with substitutional Mg content x up to 0.28 by co-sputtering from CdO and MgO targets. The synthesized material shows significant decrease in the grain size with increasing Mg concentration. The reduction of the electron concentration and mobility in these undoped samples was explained by a rapid upward shift of the conduction band edge with increasing Mg concentration. Alloying ~10% of MgO with CdO increases the intrinsic bandgap by ~400 meV resulting in a desirable shift of the optical absorption edge to higher energies. However, a significant reduction of electron mobility to ~20 cm^2/Vs was also observed. CdMgO films (~6% Mg) with electron concentration of $10^{21}/cm^3$ and mobility of 40 cm^2/Vs were achieved with In doping and thermal annealing,. The films properties are comparable to standard TCOs and the relatively low mobility results in strong IR absorption. Hence, it was concluded that alloying CdO with MgO is not an appropriate route for achieving a TCO for full spectrum PVs.

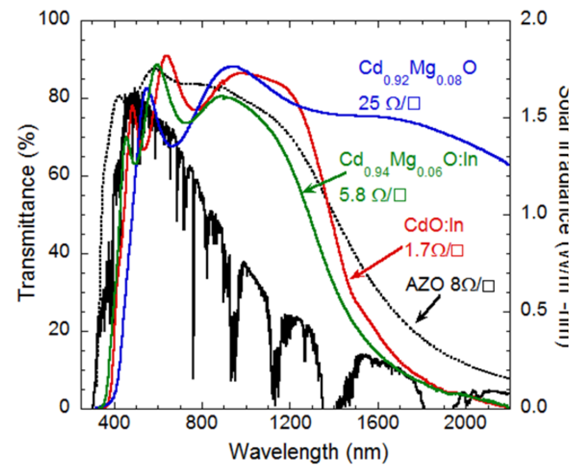

Fig. 3 Transmittance of CdMgO films undoped and doped with In. Transmittance curves from a conventional Al doped ZnO (AZO) and a In doped CdO film are also shown.

Future Work:

The group has identified several areas that are essential for the further development of CdO based materials as transparent conductors for full spectrum PVs.

1. The group has previously shown that the structural mismatch between ZnO and CdO creates two distinct regimes of optical and electrical behavior of CdxZn1-xO alloys. , The wurtzite phase alloys exhibit a reduction in the absorption edge energy across the visible spectrum from 3.3 to 1.9 eV with x increasing from 0 to 0.69. A phase transition to the rocksalt structure is observed above x=0.69, along with an abrupt step-like increase in the electron mobility up to 90 cm^2/Vs and an intrinsic gap to 2.6 eV. They are conducting systematic studies of the rocksalt CdZnO phase regime as these materials offer a potential of larger intrinsic optical gap without any detrimental effect on the electrical properties.
2. To explore the potential of using IR transparent CdO based TCOs the group will investigate the vertical transport and minority carrier recombination of CdO interfaces with Si, GaAs, CIGS and CZTS.
3. Performance of solar cells using CdO TCOs will be evaluated. This effort will focus on technologies that require top contacts with good infrared transmittance such as Si, CIGS or 3-junction tandems.
4. Since CdO-based TCOs show very low metallic-like resistivities the group will explore the feasibility of using TCO grid structure as a top contact to Si PVs..
5. The large, high frequency dielectric constant of CdO offers an interesting possibility of using this material for antireflective coating. The group will study reflectivity of CdO films deposited on materials used for thin film PVs including CdTe.