BAPVC Annual Project Report

Project Title: New P-type Transparent Conductors, in Thrust *Photon management and transparent conductors*
PI: Joel Ager
E-mail: JWAger@lbl.gov

Summary:

All transparent conductors ("TCOs") used in solar cells are n-type (electron conducting); the field of p-type transparent conductors is far less advanced. It was discovered recently that Cu-alloyed ZnS can produce performance, both in terms of transparency and conductivity, that is close to the best ever reported for p-type TCOs. It is the goal of this work to expand the technological readiness level of p-type conductors, both in terms of manufacturability and performance.

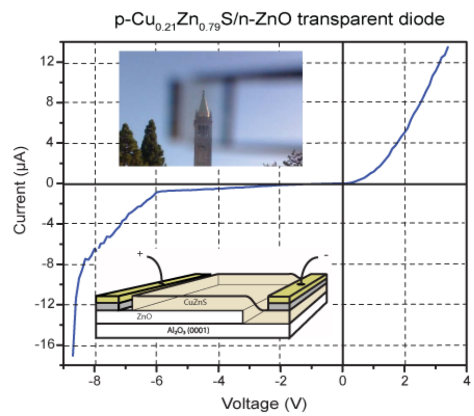

Fig. 1. I–V curve of Cu-alloyed ZnS-based diode structure and schematic of the diode structure. Clear rectifying behavior is seen and current blocking is observed to 6 V in reverse bias. The on/off ratio is 75 at ±3 V.

Key Accomplishments:

The key characteristics of Cu-alloyed ZnS are shown in Fig. 1 The conductivity of the film is p-type as shown by thermopower and the peak conductivity, 54 S cm^{-1}, is comparable to some of the highest values in literature for p-type transparent conductors. The material has conductivity greater than 20 S cm^{-1} for a range of Cu contents, although a value of 20% appears to be optimal for maximizing conductivity. There are some tradeoffs between transparency and conductivity which are under investigation.

As shown in Fig. 2, the x-ray photoelectron analysis was employed to show (1) that Cu is in the +1 oxidation state, which is expected for its position as an acceptor on the Zn site in ZnS lattice and (2) that the surface valence band has very low binding energy, which is consistent the behavior of a degenerately hole-doped material. This is consistent with our initial band structure calculations which suggest that Cu can form a band just above the ZnS valence band and that the concentration of compensating donors could be mitigated by synthesis under S-rich conditions.

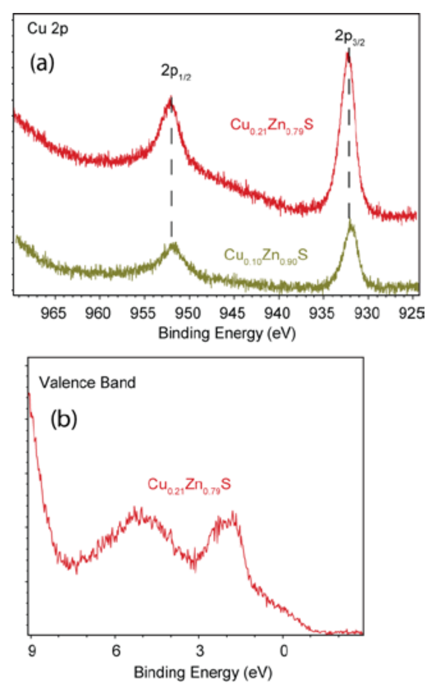

Fig. 2. High-resolution XPS showing that Cu is in the desired +1 oxidation state (a) and (b) that the binding energy of VB is low, consistent with metallic p-type doping.

Future Work:

The performance of our current p-type conductor is close to "world record" but is less than desirable for a high performance solar cell. The project

performance goal is to produce p-CuZnS films with a conductivity of >100 S/cm and a transparency of >75% at 550 nm with a sheet resistance of <200 Ω/□, which would represent a factor of 5 improvement from present results. It is relevant to understand the practical limits of conductivity in these new materials. The collaborative study of the relationship between Cu content and structure on the hole transport, which will be supported by *an ab-initio* band structure and a quantitative hole scattering model, will be completed. This work will set the upper performance bounds for p-CuZnS and related materials. P-CuZnS will be synthesized by methods which are translatable to manufacturing: initial work will be performed with electrochemical deposition and reactive sputtering. Towards the goal of using p-TCOs as interconnection layers in tandem designs, ohmic contacts to
p-type absorbers (e.g. CdTe, CIGS) will be investigated.