Title: New Approach Towards the Deposition of I-III-VI Thin Films

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

To order the complete compilation report, use: ADA405047

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP012585 thru ADP012685
NEW APPROACH TOWARDS THE DEPOSITION OF I-III-VI THIN FILMS

Mohammad Afzaal, David Crouch, Paul O'Brien and Jin-Ho Park

The Manchester Materials Science Centre and Department of Chemistry, University of Manchester, Oxford Road, Manchester, M13 9PL, UK.
E-mail: jin-ho.park@man.ac.uk; paul.obrien@man.ac.uk

ABSTRACT

The ternary chalcopyrite semiconductor Cu(In/Ga)(Se/S)\textsubscript{2} is currently used as an absorber layer in high efficiency thin film solar cells. In this study, various types of I-III-VI (I = Cu, III = Ga or In, VI = S or Se) thin films (CuGaS\textsubscript{2}, CuInS\textsubscript{2} and CuInSe\textsubscript{2}) were prepared from a series of organometallic precursors, M\{\[S/Se\]\textsubscript{2}CNMeR\} \textsubscript{n} (M = Cu, In, Ga; R = alkyl), which are pyrophoric, the precursors are easy to synthesize by one-pot reactions and are air stable. The optimum growth temperature for the preparation of these films on glass substrates using aerosol-assisted chemical vapour deposition (AACVD) was found to be above 400 °C in terms of crystallinity, although deposition does occur at lower temperatures. The films have been characterised using XRPD, SEM and EDS. SEM analyses show all films are microcrystalline. XRPD results show evidence of the crystalline nature of theses films. The results of this comprehensive study are presented and discussed.

INTRODUCTION

Ternary compound semiconductors such as copper indium/gallium disulfide/diselenide (CuInS\textsubscript{2}, CuGaS\textsubscript{2} or CuInSe\textsubscript{2}) are promising materials for use in high efficiency solar cells. There have been only a few reports of the deposition of CuME\textsubscript{2} by CVD methods. A halogen transport VPE method[1] has been used to grow single crystals. CuInSe\textsubscript{2} films contaminated with In\textsubscript{2}Se\textsubscript{3} have been deposited by MOCVD using copper(II) hexafluoroacetylacetonate mixed with trimethylamine, triethyl indium and hydrogen selenide.[2,3] A plasma enhanced process using both hexafluoroacetylacetonate copper and indium complexes and a novel selenium source 4-methyl-1,2,3-selenadiazole has also been used.[4] Chichibu has reported[5] the growth of heteroepitaxial layers of CuInSe\textsubscript{2} using cyclopentadienylcoppertriethylphosphine, trimethyl indium and diethylselenide as the precursors; the first successful MOVPE results.

There are also some initial reports concerning the use of single-source organometallic precursors for the deposition of CuInS\textsubscript{2} films.[6,7] Recently Hollingsworth et. al. reported spray CVD of CuInS\textsubscript{2} films using a single-source precursor, (Ph\textsubscript{3}P)\textsubscript{2}Cu(\textmu-SEt)\textsubscript{2}ln(SEt)\textsubscript{2}. In their study, highly orientated CuInS\textsubscript{2} was deposited on Si(111) substrates at 600 °C.[8]

We have been developing a range of dithio- and diseleno-carbamato complexes of various metals which have been successfully used to deposit a wide range of semiconductor materials.[9] One particularly successful modification to the sulfur/selenium containing ligands has been to develop compounds in which the parent amine is asymmetrically substituted and involves a bulky or extended alkyl substituent.[10,11] Compounds with these ligands are air stable and sufficiently volatile for the deposition of thin films of materials such as CuE\textsubscript{2}, InE\textsubscript{3}, GaE\textsubscript{3}, ZnE
and CdE (E = S or Se).[12-13] Success with the binary parents of CuInE₂ has encouraged us to deposit the ternary phase. In this paper we report a simple AACVD process for copper indium/gallium disulfide/diselenide thin films.

EXPERIMENTAL DETAILS

Precursor Synthesis

The precursors were prepared by literature methods[14] and analyzed by CHN, NMR, Mass Spec. and TGA.


**In(S₂CNMe°Hex)₃ (2):** Yield 67%, m. p. 100 °C, Elemental analysis: C₂₄H₃₆S₆In. Calculated: C: 42.02, H: 6.91, N: 5.88%. Found: C: 42.27, H: 6.73, N: 6.01%. ¹H NMR (δ, C₆D₆, 300 MHz): 0.86 (t, 9H, -NCH₂CH₂CH₂CH₂CH₂CH₂), 1.18 (m, 18H, -CH₂CH₂CH₂CH₂CH₂CH₂), 1.38 (m, 6H, -NCH₂CH₂CH₂CH₂CH₂CH₂), 2.8 (s, 9H, -NCH₃), 3.3 (t, 6H, -NCH₂CH₂CH₂CH₂CH₂CH₂).

**Cu(Se₂CNMe°Hex)₂ (3):** Yield 70%, Elemental analysis: C₁₆H₃₆Se₄N₂Cu. Calculated: C: 30.45, H: 5.07, N: 4.44%. Found: C: 30.84, H: 4.97, N: 4.40%. Mass Spectrum: m/z significant peaks, [CuSe₂CNCH₅C₆H₁₅] 288, [CuSe₂CNCH₅CH₂CH₃] 300, [CuSe₂CNCH₅CH₂CH₃] 314.

**In(Se₂CNMe°Hex)₃ (4):** Yield 57%. Elemental analysis: C₂₄H₃₆Se₆In. Calculated: C: 29.81, H: 4.96. N: 4.35%. Found: C: 30.84, H: 4.97, N: 4.40%. ¹H NMR (δ, C₆D₆, 300 MHz): 0.55 (t, 9H, -NCH₂CH₂CH₂CH₂CH₂CH₂), 0.77 (in, 18H, -CH₂CH₂CH₂CH₂CH₂CH₂), 1.00 (m, 6H, -NCH₂CH₂CH₂CH₂CH₂CH₂), 2.4 (s, 9H, -NCH₃), 2.9 (t, 6H, -NCH₂CH₂CH₂CH₂CH₂CH₂).

**Ga(Se₂CNMe°Hex)₃ (5):** Yield 68% m. p. 85 °C. Elemental analysis: C₃₂H₄₈N₆Se₆Ga. Calculated: C: 44.99, H: 7.55, N: 6.56% Found: C: 44.78, H: 8.14, N: 6.58%. ¹H NMR (δ, C₆D₆, 300 MHz): 0.92 (t, 9H, -NCH₂CH₂CH₂CH₂CH₂CH₂), 1.18 (m, 18H, -CH₂CH₂CH₂CH₂CH₂CH₂), 1.40 (m, 6H, -NCH₂CH₂CH₂CH₂CH₂CH₂), 2.8 (s, 9H, -NCH₃), 3.4 (t, 6H, -NCH₂CH₂CH₂CH₂CH₂CH₂).

Deposition of films and characterizations

**Aerosol Assisted Chemical Vapour Deposition (AACVD):** Approximately 0.25g of precursor was dissolved in 30ml Toluene (or THF) in the round-bottomed flask. Six glass substrates (1 x 2 cm) were placed inside the reactor tube. The carrier gas flow rate was controlled by Platon flow gauges. The solution in the flask is placed in a water bath above the piezoelectric modulator of a humidifier, where aerosol droplets are generated and transferred by the carrier gas into a hot-wall zone. Then both the solvent and the precursor evaporate and the precursor vapour reaches the heated substrate surface where thermally induced reactions and film deposition take place. This homemade aerosol-assisted chemical vapour deposition kit consists of a two-neck flask, a PIFCO ultrasonic humidifier (Model No. 1077) and a CARBOLITE furnace.
**Film characterizations:** X-ray diffraction studies were performed using Cu-Kα radiation on a Philips X’Pert MPD diffractometer. The sample was mounted flat and scanned from 20 - 80° in steps of 0.04° with a count time of 2 s. Samples were carbon coated before electron microscopic analysis. All EDS and electron microscopy was then carried out in a Jeol Superprobe 733 microscope.

**RESULTS AND DISCUSSION**

**Copper Indium Sulfide by AACVD**

Films of CuInS$_2$ were successfully grown on glass at 350 - 450 °C by AACVD. It is interesting to note that employing AACVD can reduce deposition temperature for the growth of CuInS$_2$ to 350 °C as compared to those grown by LP-MOCVD.[15] All films grown using compounds 1 and 2 (1:1 ratio) gave narrow and strong peaks in the X-ray powder diffraction and show characteristic tetragonal phase of CuInS$_2$ (Fig. 1). The XRPD patterns of the films grown at various growth temperatures show a preferred orientation along the (112) plane regardless of growth temperature. EDS analysis of films grown at 450 °C peaks corresponding to Cu, In and S and ratio was found to be close to 1:1:2.

SEM analysis for the as-deposited CuInS$_2$ films on glass indicates slightly different features in terms of their morphology compared to those grown by LP-MOCVD. Films grown at 450 °C show that particles are formed as randomly orientated flakes ca. 0.2 μm thick as compared to the relatively thick width (ca. 1 μm) crystallites grown by LP-MOCVD and particles grown by AACVD are laid down horizontally on the glass substrate. Also the shape of particles are very similar to those prepared on fused silica using (Ph$_3$P)$_2$CuIn(SEt)$_4$ by spray CVD.[8]

![Fig. 1. XRPD patterns of CuInS$_2$ on glass (using compounds 1 and 2 by AACVD (temperatures indicate growth temperatures)) and SEM images of the films grown at 450 °C.](image-url)
In 2 hour growth, films were found to be ca. 1 μm thick with 0.5 μm/h growth rate. At lower growth temperature (350 °C), a mixture of morphologies can be seen. Particle size is found to be between 0.5 - 1.6 μm.

Various ratios of compounds 1 and 2 were also utilized in order to investigate stoichiometric change of CuInS₂ films. XRPD patterns of as-deposited films grown with different ratios show that there is no evidence to trace any by-products such as indium sulfide or copper sulfide and indicate no effect on stoichiometry of CuInS₂, in contrast to the LP-MOCVD work.

**Copper Indium Selenide by AACVD**

CuInSe₂ films have been also deposited on glass using compounds 3 and 4 by AACVD. In this case, only a 1:1 molar ratio of compounds 3 and 4 was used. Films were grown at 425 - 475 °C with constant argon flow rate of 180 sccm. XRPD analyses (Fig. 2) suggest that as-deposited films have tetragonal phase with a preferred orientation along (112) direction in all cases.

SEM images of the films show (Fig. 2) that the deposited layer is not homogenous and mainly consist of several different shapes of particles with a poor coverage at lower growth temperature (425 °C). The heterogeneous morphology on thin film layer can be altered by using single crystalline substrates such as InP(111) and Si(111) which may lead to homogenous growth process. The observation of homogenous growth was found in the LP-MOCVD study.[16]

**Copper Gallium Sulfide by AACVD**

In the growth of CuGaS₂, stoichiometric amount of compounds 1 and 5 were employed and dissolved in THF (30ml). In initial experiments, Cu/In ratio was maintained at 1:1 and growth time was kept constant for 2 hours (180 sccm/flow rate).

![Fig. 2. XRPD patterns of CuInSe₂ films on glass by AACVD and SEM images of CuInSe₂ on glass using compounds 3 and 4 by AACVD [(a) 425 °C; (b) 450 °C; (c) and (d) 475 °C].](image-url)
Fig. 3. XRPD patterns of CuGaS$_2$ films on glass by AACVD and SEM images of CuGaS$_2$ on glass using compounds 1 and 5 by AACVD [(a) 300 °C; (b) 400 °C; (c) and (d) 450 °C].

XRPD patterns (Fig. 3) show that deposited films by AACVD have chalcopyrite structure with a preferred orientation along (112) direction (JCPDS 27-0279). It is also conclusive that at high temperatures, the crystallinity of deposited film is highly indicated by the sharpness of peaks, whilst at low temperature (350 °C) XRPD pattern exhibits weak reflections indicating poorly crystalline films. Similar results are obtained for the films grown at lower argon flow rate (120 sccm).

SEM analysis (Fig. 3) shows that the material consists of clusters of randomly orientated platelets to the surface for films grown at 400 and 450 °C (180 sccm/flow rate). The films deposited are dense but are uneven. Growth rates are approximately 500 nm/h for films grown at 350 °C and 1 μm/h at 450 °C. As growth temperature decrease, the growth of CuGaS$_2$ is significantly reduced. EDS analysis shows films are slightly copper rich with Cu 30%, Ga 24% and S 46%. However, when flow rate of argon as a carrier gas was reduced to 120 sccm, the clusters formed tended to be denser but some individual platelets can also be seen. In 2 hour growth at 450 °C, films with ca. 1.5 μm thickness were deposited on the glass substrate (growth rate, ca. 0.75 μm/h). EDS elemental atomic percent for CuGaS$_2$ films was found to be 29%, 23% and 48% respectively.

CONCLUSIONS

The results described herein demonstrate that AACVD using organometallic precursors results in stoichiometric CuME$_2$ (M = In or Ga, E = S or Se) films, and the quality (e.g., morphology or preferred orientations) of films are dependent on experimental parameters. Furthermore, films grown on glass by AACVD show similar XRPD patterns regardless deposited materials. It is evident that the AACVD approach leads to the deposition of I-III-IV films from the precursors used in this work. As a result, it is shown to be that a series of asymmetrical alkylthiocarbamate metal complexes can be used as precursors for the deposition of I-III-VI class films by CVD techniques.
ACKNOWLEDGEMENTS

POB acknowledges the support of Sumitomo/STS as visiting Professor of Materials Chemistry at Imperial College, London, UK. Authors thank the EPSRC, UK for the grants that have made this research possible.

REFERENCES