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Crystal Growth and Characterization of the Solid Solutions $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe)

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Polycrystalline samples of members of the systems $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe) were prepared by direct combination of the elements. The difference between the solubility characteristics of $CuMS_2$ (M = Al, Ga, or In) in ZnS and that of $CuFeS_2$ in ZnS is discussed. Single crystals of members of the systems $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe) (nominal composition x = 0, 0.05, 0.01) have been grown by chemical vapor transport using iodine as the transport agent. They all crystallize with the zincblende structure. Their IR transmission range is narrower than that observed for pure ZnS, but all, except for the $ZnS-CuInS_2$ system, still show good transmission in the long-wavelength IR range. The addition of small amounts of $I-III-VI_2$ modifies the hardness and the thermal stability of ZnS.

Introduction

ZnS has been studied extensively because it offers a variety of unique device applications. ZnS crystallizes with the cubic zincblende structure below 1020 °C and with the hexagonal wurtzite structure above this phase transition temperature. The ternary chalcogenides, $CuMS_2$ (M = Al, Ga, In, or Fe) crystallize with the chalcopyrite structure, which is closely related to the cubic zinceblende structure. In the chalcopyrite structure, there is an ordering of Cu(I) and M(III) (M = Al, Ga, In, or Fe), which results in a doubling of the c-axis. There have been relatively few studies[1-4] carried out on the preparation and characterization of solid solutions formed between ZnS and $CuMS_2$ (M = Al, Ga, In, or Fe). Apple[1] and Robbins et al.[2] have investigated the extent of the solid solutions $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, Ga, or In) and have determined their optical properties. It was noted that the ternary chalcopyrites $CuMS_2$ (M = Al, Ga, or In) were totally miscible with ZnS. In the $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, Ga, or In) systems, the cubic zincblende structure was the stable structure for substitution of up to 30 mol % $CuAlS_2$, 40 mol % $CuGaS_2$, or 50 mol % $CuInS_2$, respectively. Moh[3] and Sugaki et al.[4] have reported the phase relations between ZnS and $CuFeS_2$ above 300 °C. In the pseudobinary $ZnS-CuFeS_2$ system, the maximum $CuFeS_2$ in ZnS is approximately 1.6 mol % at 800 °C.

ZnS is used as an IR window material because of its wide transmission range in the far-infrared. However, ZnS is soft, which limits its suitability for some applications. Previous work[5] reported that single crystals of members of the system $(ZnS)_{1-x}(CuGaS_2)_x$ (x = 0.053, 0.103) showed good transmission in the far-infrared range and were much harder than ZnS. Therefore, it should be possible to modify the properties of ZnS using the other chalcopyrites, $CuMS_2$ (M = Al, In, or Fe), as components.

The chemical vapor transport method has been widely and conveniently applied to grow single crystals of ZnS and $CuMS_2$ (M = Al, Ga, or In).[6-9] In a recent study,[5] single crystals of the solid solutions formed between ZnS and $CuGaS_2$, suitable for characterization, were grown by chemical vapor transport using iodine as the transport agent. Therefore, this method is extended in this study to grow single crystals of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, of Fe). Polycrystalline samples were also prepared by the direct combination of zinc, copper, aluminum, indium, or iron and sulfur. This study concerns itself with the preparation and characterization of the systems $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe) for both powder and single-crystal samples. Attention is focused on such problems as the different solubility characteristics between $CuMS_2$ (M = Al, Ga, or In) and $CuFeS_2$ in ZnS and the magnetic behavior of Fe(III) in a tetrahedral site, as well as the IR transmission, thermal stability and hardness of the materials.

Table I. Growth Conditions and Crystal Size for Single Crystals of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe)

M	nominal comp (x)	charge temp (°C)	growth temp (°C)	cryst size (mm)
	0.00	950	925	10 × 6 × 2
Al	0.05	870	830	3 × 3 × 2
Al	0.10	880	850	3 × 7 × 2
In	0.05	840	810	4 × 3 × 1
In	0.10	840	810	10 × 5 × 1
Fe	0.10	840	800	13 × 6 × 1

Experimental Section

Preparation of Polycrystalline Samples. Members of the systems $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe) were prepared by the following procedure: polycrystalline samples with different compositions were prepared by using stoichiometric amounts of zinc (Gallard and Schlesinger, 99.9995%) sublimed prior to use, copper (Johnson Matthey, 99.9995%), or iron (Leico 46987) prereduced in Ar/H_2 (85/15) and sulfur (Gallard and Schlesinger, 99.999%). The appropriate weights of the reactants to give a total weight of 1 or 2 g of product were sealed in evacuated 12 mm i.d. × 60 mm silica tubes. To complete the reaction between the metal and sulfur without exploding the sample tubes, the tubes were heated to 400, 500, 600, and 700 °C and held for 24 h at each temperature. They were finally heated to 800 °C and held at the temperature for 72 h. The samples were then ground under a nitrogen atmosphere and reheated for 24 (Al, In) or 48 h (Fe) at 800 °C. The samples were intimately mixed after each heat treatment. Finally, the samples were cooled in the furnace to room temperature before removal.

Crystal Growth. Single crystals of ZnS and $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe) were grown by chemical vapor transport using iodine as the transport agent. Polycrystalline samples were introduced into a silica tube (14 mm o.d., 12 mm i.d. × 300 mm) which had been previously heated to near its melting point in order

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to minimize any nucleation sites. The tube was evacuated to 10^{-5} Torr, and freshly sublimed iodine (Deepwater Chemical Co., Std. ACS reagent 99.9%) was introduced as the transport agent at a concentration of 5 mg/mL. The tube was sealed off and enclosed in a tightly wound Kanthal coil (to even out temperature gradients), and the whole assembly was placed in a three-zone furnace. The crystal growth temperature program consisted of setting the furnace to back transport mode for 1 day, equilibrating the furnace to the maximum temperature for 3 h, and finally cooling the growth zone at 1 °C/h to the growth temperature.[10] Optimum crystal growth for ZnS took place when the charge zone was maintained at 950 °C and the growth zone at 925 °C. The optimum growth conditions for single crystals of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, In, or Fe) are summarized in Table I. The transport process was carried out for 1 week. The typical sizes of different compositional crystals are also given in Table I. The actual composition of each single crystal of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) was determined from cell parameter measurements of known polycrystalline samples. The compositions of the $(ZnS)_{1-x}(CuFeS_2)_x$ single crystals were estimated from magnetic measurements of single crystals.

Characterization of Products. X-ray powder diffraction patterns of samples were obtained using a Philips diffractometer and monochromated high intensity Cu Kα_1 radiation (λ = 1.5405 Å). For qualitative phase identification, diffraction patterns were taken over the range $12° < 2\theta < 80°$ with a scan rate of 1° 2θ/min, while cell parameters were determined from scans taken at 0.25° 2θ/min. Precise lattice parameters were obtained from the diffraction peaks using a least-squares refinement program which corrects for the systematic errors of the diffractometer.

Single crystals were polished on opposite faces with progressive suspensions of 1-, 0.5-, and 0.3-μm alumina on α-A polishing cloth (Mark V Laboratory) using a Minimet polisher. Optical measurements were performed at room temperature on a Perkin-Elmer 580 double-scanning infrared spectrophotometer. The measurements were carried out in the transmission mode over the range 2.5–50 μm. Transmission through the sample was normalized to the signal obtained in the absence of the sample.

Microhardness measurements (Knoop indenter) were made on polished single crystals using a Kentron microhardness tester. The results were obtained using a diamond indenter with a 25-g load. The stability of these compounds toward oxidation was determined by grinding a small crystal and heating the resulting powder in flowing oxygen (60 mL/min) and monitoring the change in weight during the heating period. The decomposition temperature was determined as the temperature where the weight of the sample began to change. Magnetic susceptibilities were measured from liquid nitrogen temperature (77 K) to 720 K using a Faraday balance at a field strength of 10.4 kOe. Honda–Owens (field dependency) plots were also made, and all magnetic susceptibility data were corrected for diamagnetism.

Results and Discussion

$CuAlS_2$ and $CuInS_2$ crystallize with the same structure as $CuGaS_2$, and they show similar chemical and physical properties. Therefore, the characterization of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) systems has been analyzed similarly to the $(ZnS)_{1-x}(CuGaS_2)_x$ system, which was previously reported.[5] Polycrystalline samples of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) where $x \leq 0.3$ were prepared directly from the elements. X-ray diffraction analyses indicated that $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) polycrystalline samples were all single phase with the cubic zincblende structure. These results are in good agreement with previous studies[1,2] which have reported the extent of the solid solutions $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, Ga, or In). Because of similarities in structure, unit cell dimensions, and bond type, the ternary sulfides $CuMS_2$ (M = Al, Ga, or In) were found to be totally miscible with ZnS.

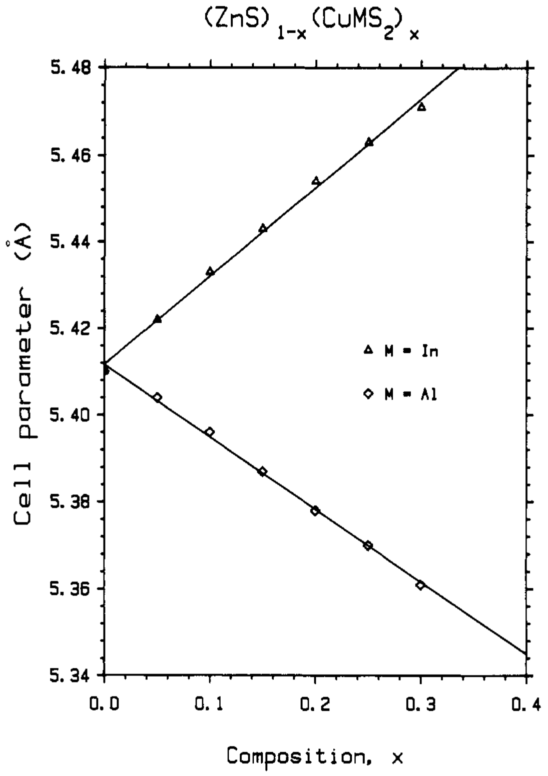

Figure 1. Variation of cell parameter with $CuAlS_2$ and $CuInS_2$ composition in $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In).

Table II. Properties of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al, Ga, In, or Fe) Single Crystals

M	nominal comp (x)	cryst comp (x)	cell param (Å)	Knoop hardness (kg/mm^2)	dec temp (°C)	IR trans range (μm)
	0.0	0.0	5.410 (2)	153 (10)	570	2.5–14
Al	0.05	0.027	5.407 (2)	206 (20)	580	4.0–10
Al	0.10	0.069	5.400 (2)	275 (35)	595	4.0–10
Ga[a]	0.05	0.053	5.403 (2)	250 (10)	670	4.5–13
Ga[a]	0.10	0.103	5.397 (2)	298 (20)	680	4.5–13
In	0.05	0.051	5.422 (2)	211 (20)	480	*b*
In	0.10	0.105	5.433 (2)	254 (20)	450	*b*
Fe	0.10	0.022	5.412 (2)	226 (15)	530	5.0–14

[a] Reference 5. [b] The transmission of single crystals with 0.01-cm thickness is less than 30% in the range 2.5–50 μm.

The cell parameters of the polycrystalline samples are plotted as a function of chalcopyrite concentration for $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) in Figure 1. At chalcopyrite concentrations less than 30.0 mol %, the cell parameters decrease linearly with increasing amounts of substituted chalcopyrite in the aluminum system and increase linearly in the indium system in accordance with Vegard's law. The cell parameter data are in good agreement with those reported by previus papers.[2,11] The composition of unanalyzed single crystals, which are grown by chemical vapor transport, can be obtained from the linear relationship between the cell parameter and the concentration of substituted chalcopyrite.

Single crystals of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In; x = 0.05 or 0.10) were grown by chemical vapor transport using iodine as the transport agent. All single crystals grown crystallized with the cubic zincblende structure. The properties of these compounds are summarized in Table II. The results of the ZnS–$CuGaS_2$ system were given in a previous paper.[5] The compositions of $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) single crystals were determined by comparing their cell parameters with those obtained from a

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plot of cell parameter vs composition for the standard polycrystalline materials (Figure 1). The results of these determinations for $(ZnS)_{1-x}(CuMS_2)_x$ (M = Al or In) are given in Table II. It can be seen that the actual composition of some of the transported crystals deviated from their nominal composition. Hence, the comparison of single-crystal cell parameters with those of known standards is essential for determining composition.

The hardness values, as determined by the Knoop method, are given in Table II. The measured hardness of pure ZnS is 153 kg/mm^2, which is in good agreement with previous investigations.[12-14] It is noted that the hardness values of the crystals containing chalcopyrite substitution show a significant increase compared to the value of the pure end member. From previous studies,[9,15] it has been reportd that chalcopyrites (I-III-VI_2) are much harder than II-VI compounds and that the hardness of chalcopyrites decreases from $CuAlS_2$ to $CuInS_2$. The substitution of $CuAlS_2$ results in a relatively larger increase in the hardness of ZnS than an equivalent substitution of $CuGaS_2$ or $CuInS_2$. These results are in agreement with those reported by He et al.[15] in which the measured value of the hardness of $CuAlS_2$ is greater than that of $CuGaS_2$. Shay and Wernick[9] have speculated that as the atomic number increases in the same family, atoms are most polarizable and hence a decrease in the measured hardness would be anticipated. Even at the low concentrations of chalcopyrite substituted for ZnS in this study, the effective increase in the hardening by $CuAlS_2$ can be observed (Table II).

The IR transmission data are also summarized in Table II. The results indicate that pure ZnS transmits in the range of 1.5–14 μm, which is in good agreement with previous reports.[12-14] $CuAlS_2$ causes a marked decrease in the upper end of the transmission of ZnS, and $CuGaS_2$ does narrow the transmission range particularly at the low end. However, these materials still show good transmission in the long-wavelength IR range. In the range 2.5–50 μm, $CuInS_2$ reduces the magnitude of IR transmission by less than 30%. The thermal stability data, taken in a flowing oxygen atmospheres, show that the chalcopyrites $CuAlS_2$ and $CuGaS_2$ increase the decomposition temperatures of pure ZnS (Table II). For the ZnS–$CuInS_2$ systems, the onset temperature of decomposition is lower than that of pure ZnS.

The electrical and optical properties of the $CuMS_2$ compounds (M = Al, Ga, or In) have been reported by Tell et al.[16] In early studies, Shay et al.[17-19] have indicated that many of the electronic properties can be explained if the valence band is assigned considerable d-character. This can result from the hybridization of copper 3d orbitals and anion sp states. In a more recent paper, Jaffe and Zunger[20] have calculated the electronic structure of these ternary chalcopyrite semiconductors. They reported that almost all of the copper d electrons occupy the upper valence band and there are empty group III metal states in the conduction band. The electronic structure of the upper valence band consists primarily of copper 3d–sufur 3p hybrid wave functions which interact most strongly for $CuAlS_2$. The empty conduction band is composed of unoccupied group III–group VI anion states. The filled group III–group VI anion valence band lies below the copper 3d–sulfur 3p band.

It is, therefore, not surprising that $CuFeS_2$ shows physical and chemical properties different from those of the other $CuMS_2$ (M = Al, Ga, or In) I–III–VI_2 compounds. $CuFeS_2$, chalcopyrite, is the only compound which contains a magnetic ion among these tetrahedrally coordinated semiconductors. With respect to the measured electrical properties, there is little difference between chalcopyrite and the nonmagnetic analogs. However, the observed Hall mobility for chalcopyrite of 35 cm^2/V s at 80 K[19] is small, which suggests some effect of the unpaired iron 3d electrons on the electrical properties. Furthermore, from optical measurements, Goodman and Austin[21,22] reported that the absorption edge of 0.5 eV for $CuFeS_2$ is much smaller than the value of 2.5 eV measured for $CuGaS_2$. The difference in the absorption edge of $CuFeS_2$ may also be related to the delocalization of Fe(III) 3d electrons.

The magnetic properties of $CuFeS_2$ show the effect much more clearly. Neutron diffraction[23] and static magnetic measurements[19] have shown that $CuFeS_2$ is antiferromagnetic with T_N = 550 °C. The effective magnetic moment associated with Fe(3d^5) was only 3.85 μB. This moment cannot be interpreted with an assignment of Fe(III)3d^5 which would be consistent with Mössbauer studies, which assign iron as a trivalent species.[24-25] Finally, it was shown by Sato and Teranishi[26] that for the systems $CuFe_xAl_{1-x}S_2$ and $CuFe_xGa_{1-x}S_2$ the iron 3d electrons are localized when the iron concentration is small but undergo a transition to the delocalized state at a critical value of x. These results are consistent with those obtained by Sainctavit et al.[27] from XANES spectra. They reported that for $CuFeS_2$ there is additional strong hybridization of anion 3p and delocalized iron 3d states.

For the system $(ZnS)_{1-x}(CuFeS_2)_x$ where $0.025 \le x \le 0.3$, X-ray diffraction patterns of polycrystalline samples indicated that there were two phases present, namely, the cubic zincblende structure and the tetragonal chalcopyrite structure. This is consistent with the report by Moh[3] that the maximum solubility of $CuFeS_2$ in ZnS was approximately 1.6 mol % at 800 °C. Undoubtedly, the narrow solubility limit of $CuFeS_2$ in ZnS is related to their differences in bonding. For $CuFeS_2$, there is at least a partial participation of the iron unpaired 3d electrons with the uppermost sulfur valence bands. This is also consistent with the evidence previously discussed which supports the delocalization of 3d electrons over the bonding bands. Furthermore, the cell dimensions of $CuFeS_2$ (a = 5.29 Å, c = 10.43 Å) are smaller than those of $CuGaS_2$ (a = 5.36 Å, c = 10.49 Å) even though the radius of Fe(III) (r = 0.49 Å) is larger than that of Ga(III) (r = 0.47 Å). This is consistent with the concept of increased metal–sulfur bonding in $CuFeS_2$ resulting from partial delocalization of Fe(III) 3d electrons and admixture with anion p states.

The composition of $(ZnS)_{0.978}(CuFeS_2)_{0.022}$ single crystals grown by chemical vapor transport was determined by

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Chem. Mater. 1992, 4, 1017-1020

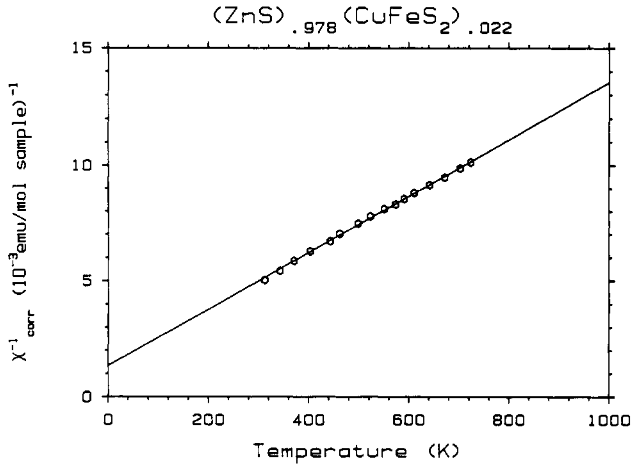

Figure 2. Variation of magnetic susceptibility with temperature for a single crystal of $(ZnS)_{0.978}(CuFeS_2)_{0.022}$.

magnetic measurements. The phase crystallized with the zincblende structure. Magnetic susceptibility measurements were made as functions of both field and temperature. Two separate crystals were measured and showed paramagnetic behavior without any field dependency at either room temperature or at liquid nitrogen temperature.

The reciprocal magnetic susceptibility of $(ZnS)_{0,978}(CuFeS_2)_{0,022}$ is plotted versus temperature in Figure 2 and approaches Curie–Weiss behavior with a Weiss constant of −110 K. The Curie constant obtained from the linear dependence of x^{-1} vs T shown in Figure 2 was standardized against a polycrystalline sample with 2.5 mol % $CuFeS_2$. Comparison with this standard gave a composition of 2.2 mol % $CuFeS_2$ for the single crystal. This composition is above the solubility limit of $CuFeS_2$ in ZnS single crystals reported by Moh.[3] This fact implies the presence of small clusters of an iron-rich phase, which would be consistent with the observed Weiss constant.

The properties of $(ZnS)_{0.978}(CuFeS_2)_{0.022}$ single crystals are summarized in Table II. They give the same IR transmission at the long-wavelength end, but there appears to be a cutoff at 5.0 μm. The microhardness and thermal stability data show that $CuFeS_2$ increases the hardness of pure ZnS and decreases the decomposition temperature.

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Registry No. $(ZnS)_{1-x}(CuAlS_2)_x$ (x = 0.027), 143120-96-1; $(ZnS)_{1-x}(CuAlS_2)_x$ (x = 0.069), 143120-97-2; $(ZnS)_{1-x}(CuInS_2)_x$ (x = 0.051), 143120-98-3; $(ZnS)_{1-x}(CuInS_2)_x$ (x = 0.105), 143120-99-4; $(ZnS)_{1-x}(CuFeS_2)_x$ (x = 0.022), 143121-00-0; ZnS, 1314-98-3.

Electrochromic Properties of Langmuir–Blodgett Films of Bisphthalocyanine Complexes of Rare Earth Elements

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The electrochromic behavior observed in the series of lanthanide bisphthalocyanine complexes with *tert*-butyl substituents $LnPc^t_2$ ($Pc^t = R_4Pc$, R = *tert*-butyl, Ln = Pr, Sm, Eu, Tb, Ho, Er, Tm, and Lu) is reported. The splitting of the first oxidation potential due to the proximity of the two phthalocyanine (Pc) rings was resolved in the voltammograms of Langmuir–Blodgett (LB) films. The LB films formed on ITO glass electrodes were more stable to repetitive cycling than cast films. Electrochromism was observed with LB and cast films electrodes in aqueous $KClO_4$ solution.

Introduction

The potential application of electrochromic materials, in multicolor electrochromic devices, has stimulated the investigation of the spectroelectrochemical properties of lanthanide (Ln) bisphthalocyanine derivatives.[1,2] Electrochromism of Langmuir–Blodgett (LB) films of unsubstituted bisphthalocyanine complexes of lanthanide elements ($LnPc_2$) has been studied for $LuPc_2$,[3] an octaalkoxymethyllutetium bisphthalocyanine,[4] and $YbPc_2$.[5] The electrochemical properties of the $LnPc_2$ complexes (Ln = Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Tm, Er, Yb, Lu) in solution have also been reported.[6,7] The electrochromic properties of octa-*tert*-butylbisphthalocyanine complexes ($LnPc^t_2$, Ln = Er, Lu) deposited as LB films were recently documented by Liu et al.[1] The advantage of $LnPc^t_2$ materials over the unsubstituted $LnPc_2$ complexes is their enhanced solubility in organic solvents suitable for LB work. The synthesis of $LnPc^t_2$ or $LnPc_2$ can lead to a green

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