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- (71) Applicant (for all designated States except US): **E. I. DU PONT DE NEMOURS AND COMPANY** [US/US];
1007 Market Street, Wilmington, Delaware 19898 (US).
- (72) Inventor; and
- (75) Inventor/Applicant (for US only): **IONKIN, Alex, Sergey** [US/US]; 402 Brentford Road, Kennett Square, Pennsylvania 19348 (US).
- (74) Agent: **SANTOPIETRO, Lois, A.**; E. I. du Pont de Nemours and Company, Legal Patent Records Center, 4417 Lancaster Pike, Wilmington, Delaware 19805 (US).
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(54) Title: PREPARATION OF COPPER ZINC TIN SULFIDE

(57) Abstract: The present invention relates to synthesis of copper zinc tin sulfide, $\text{Cu}_2\text{ZnSnS}_4$. Copper zinc tin sulfide is useful as an absorber material in a thin film solar cell application.

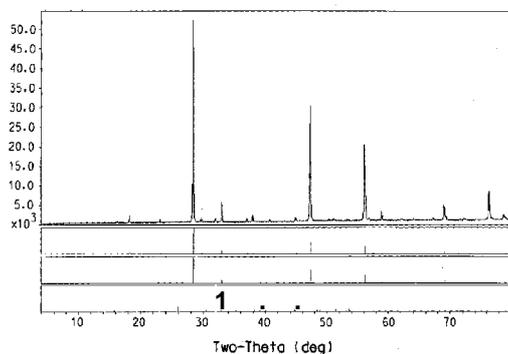


FIG. 1A

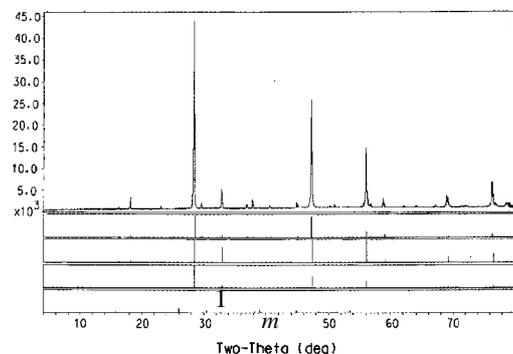


FIG. 1B

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TITLE

PREPARATION OF COPPER ZINC TIN SULFIDE

CROSS REFERENCE TO RELATED APPLICATIONS

5 This application claims priority under 35 U.S.C. § 119(e) from, and claims the benefit of, the following U.S. Provisional Application: No. 61/264409 filed on November 25, 2009, and which is by this reference incorporated in its entirety as a part hereof for all purposes.

FIELD OF THE INVENTION

10 The present invention relates to synthesis of copper zinc tin sulfide, $\text{Cu}_2\text{ZnSnS}_4$. Copper zinc tin sulfide is useful as an absorber material in a thin film solar cell application.

BACKGROUND

15 Solar cells, also termed photovoltaic or PV cells, and solar modules convert sunlight into electricity. These electronic devices have been traditionally fabricated using silicon (Si) as a light-absorbing, semiconducting material in a relatively expensive production process. To
20 make solar cells more economically viable, solar cell device architectures have been developed that can inexpensively make use of thin-film, light-absorbing semiconductor materials such as copper-indium-gallium-sulfodi-selenide, $\text{Cu}(\text{In}, \text{Ga})(\text{S}, \text{Se})_2$, also termed CIGS. This class of solar cells
25 typically has a p-type absorber layer sandwiched between a back electrode layer and an n-type junction partner layer. The back electrode layer is often Mo, while the junction partner is often CdS. A transparent conductive oxide (TCO) such as zinc oxide doped with aluminum is formed on the junction partner layer and is typically used as a transparent
30 electrode.

Despite the demonstrated potential of CIGS in thin-film solar cells, the toxicity and low abundance of indium and selenium are major impediments to the widespread use and acceptance of CIGS in

commercial devices. An attractive alternative for absorber layers of thin film solar cells are quaternary chalcogenide, particularly copper zinc tin sulfide, $\text{Cu}_2\text{ZnSnS}_4$ (CZTS). It has a direct bandgap of about 1.5 eV and an absorption coefficient greater than 10^4 cm^{-1} . In addition, CZTS does not include any toxic or nonabundant elements.

Thin films of CZTS have been prepared via sputtering of Cu, SnS, and ZnS precursors, hybrid sputtering, pulsed laser deposition, spray pyrolysis of halides and thiourea complexes, electrodeposition / thermal sulfurization, E-beam Cu/Zn/Sn / thermal sulfurization, and sol-gel deposition, followed by thermal sulfurization.

Bulk quantities of CZTS have been prepared in evacuated quartz ampoules at temperatures between 400 °C to 1150 °C. Bulk quantities have also been prepared in a furnace with a source of sulfur, such as H_2S .

There is a need for a safe, robust process to produce CZTS in bulk quantities for non-vacuum based thin-film photovoltaics.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A and 1B are x-ray powder diffraction patterns of the CZTS prepared in one embodiment.

DETAILED DESCRIPTION

Disclosed herein is a method, comprising the steps of:

- a) providing a precursor mixture comprising:
 - i) a copper sulfide, a zinc sulfide, and a tin sulfide;
 - ii) a copper tin sulfide and a zinc sulfide;
 - iii) a copper zinc sulfide and a tin sulfide; or
 - iv) a zinc tin sulfide and a copper sulfide;
- wherein the precursor mixture has a total molar ratio of Cu:Zn:Sn:S of about 2:1 :1 :4; and
- b) heating the precursor mixture in an inert atmosphere to a temperature of about 300 °C to about 1000 °C.

The method can prepare CZTS. Herein, the term "CZTS" refers to $\text{Cu}_2\text{ZnSnS}_4$, and further encompasses copper zinc tin sulfide compositions with a range of stoichiometries, such as but not limited to

5 $\text{Cu}_{1.94}\text{Zn}_{0.63}\text{Sn}_{1.3}\text{S}_4$. That is, the molar ratio of the elements can vary from strictly 2 Cu: 1 Zn: 1 Sn: 4S and can also be doped by small amounts of other elements such as sodium or iron.

In one embodiment, the heating is carried out in an open container. By "open container " is meant a container which is open to the

10 atmosphere, that is, contains at least one opening which allows a free vapor communication between the precursor mixture and ambient pressure, thus maintaining the precursor mixture essentially in equilibrium with the ambient pressure. The open container can be made out of any material that is inert to the precursor mixture, such as alumina, aluminum

15 nitride, magnesia, magnesia with alumina, zirconia, zirconia with yttrium oxide, carbon graphite, platinum, and alloys of platinum, gold and rhodium. The open container can be of any shape or size such as combustion boats, crucibles, incineration trays, incineration dishes, and the bottom floor of a oven or furnace.

20 The precursor mixture can be prepared by combining the individual components either before or after being placed in the container used for heating. The precursors components can be pre-milled separately or after combining. The combining can be done by any means as long as the individual components are homogenized. Suitable combining methods

25 include grinding, shaking, and ball milling. Typically, the particle sizes of precursors are between 350 mesh size and 5 mesh size, or between 200 and 325 mesh. After combining, the precursor mixture can be in powder form or formed into any shape, such as a pressed pellet.

The precursor mixture comprises: i) a copper sulfide, a zinc sulfide,

30 and a tin sulfide; ii) a copper tin sulfide and a zinc sulfide; iii) a copper zinc sulfide and a tin sulfide; or iv) a zinc tin sulfide and a copper sulfide.

By "a copper sulfide" it is meant a composition consisting of copper and sulfur, such as copper (I) sulfide or copper (II) sulfide, or a mixture thereof.

By "a zinc sulfide" it is meant a composition consisting of zinc and sulfur, such as zinc (II) sulfide, or a mixture thereof.

By "a tin sulfide" it is meant a composition consisting of tin and sulfur, such as tin (II) sulfide or tin (IV) sulfide, or a mixture thereof.

By "a copper tin sulfide" it is meant a composition consisting of tin, copper and sulfur, such as a Cu_2SnS_3 .

By "a copper zinc sulfide" it is meant a composition consisting of zinc, copper and sulfur.

By "a zinc tin sulfide" it is meant a composition consisting of zinc, tin and sulfur.

In one embodiment, the precursor mixture comprises a copper sulfide, a zinc sulfide, and a tin sulfide. In another embodiment, the precursor mixture comprises a copper tin sulfide and a zinc sulfide.

The precursor mixture has a total molar ratio of Cu:Zn:Sn:S of about 2:1 :1 :4, where the ratio of the Cu, Zn, and Sn can deviate by about 20 molar %. This can occur when some of the Cu, Sn, or Zn metal ions are replaced by a different Cu, Sn, or Zn ion, but only to the extent that the composition remains neutral. For example, the Zn content can be enriched by decreasing the Cu content, producing a Cu:Zn:Sn:S ratio of 1.8:1 .2:1 :4.

After combining, the precursor mixture is heated in an inert atmosphere. By "inert atmosphere" it is meant an atmosphere that is inert to the precursor mixture, such as helium, neon, argon, krypton, xenon, nitrogen and mixtures thereof. In particular, the inert atmosphere should not contain water, oxygen, or H_2S . The inert atmosphere may be streamed or flowed over the open container during the heating step.

The heating is typically carried out at ambient atmospheric pressure.

The total heating time is not critical and depends on the temperature and desired conversion, but is typically from about 0.25 hr to several days. Suitable heating times include 0.25 hr, 1 hour, 2 hours, 6

hours, 12 hours, 24 hours, 2 days, 3 days and 5 days, and any time interval inbetween.

The precursor mixture is heated to a temperature of about 300° C to about 1000 °C, about 400 °C to about 800 °C, or about 600 °C to about 800 °C. The heating can be performed in any manner, such as in one step, ramping or stepping to the upper temperature, or cycling between the lower and the upper temperature. The heating can be performed using any means, such as in a tube furnace. The precursor mixture can be heated starting at ambient temperature or placed directly at the lower or upper temperature.

The $\text{Cu}_2\text{ZnSnS}_4$ product is typically cooled to ambient temperature under inert atmosphere to prevent oxidation or hydrolysis. The method can further comprised isolating $\text{Cu}_2\text{ZnSnS}_4$. This can be done by any known means, including etching with a solvent, typically an acid such as 10% HCl, followed by filtration to remove insoluble impurities, for example SnS.

The CZTS prepared by the method described above can be useful in the fabrication of electronic devices such as photovoltaics.

EXAMPLES

Copper(II) sulfide 200 mesh powder, copper(I) sulfide 200 mesh powder, zinc(II) sulfide 325 mesh powder, tin (II) sulfide 8 mesh powder were purchased from Alfa Aesar (26 Parkridge Rd, Ward Hill, MA). Tin(IV) sulfide was purchased from Pfaltz & Bauer Inc. (172 E. Aurora St., Waterbury, CT). Copper tin sulfide was prepared from Cu(II) sulfide and Sn(IV) sulfide, according to the procedure described in Fiechter, S.; Martinez, M.; Schmidt, G.; Henrion, W.; Tomm, Y. Hahn-Meitner-Institute, Berlin, Germany. Journal of Physics and Chemistry of Solids (2003), 64(9-10), 1859-1862.

X-ray diffraction patterns were compared to standard patterns of CZTS available from International Centre for Diffraction Data (ICDD), located in Newtown Square, PA.

EXAMPLE 1

Copper (II) sulfide (4.35 g, 0.0455 mol), zinc (II) sulfide (2.22 g, 0.0228 mol) and tin(IV) sulfide (4.16 g, 0.0228 mol) were mixed together by shaking for 15 minutes, then placed into a 20 ml alumina boat. The alumina boat was then put into a tube furnace, with a nitrogen flow at ambient temperature. The boat was heated from ambient temperature to 800 °C over 15 minutes, and kept at this temperature for 1 day. The sample was cooled to ambient temperature and ground. The ground sample was placed back into the boat and the tube furnace under nitrogen flow. The heating cycle was then repeated. This procedure was repeated 4 times, for a total heating time of 5 days.

The sample was analyzed by XRD (x-ray powder diffraction) after each heating cycle. The results are shown in Figures 1A and 1B. The resulting powder diffraction patterns showed the presence of CZTS in good purity.

EXAMPLE 2

Copper (II) sulfide (3.26 g, 0.0341 mol), zinc (II) sulfide (1.65 g, 0.0169 mol) and tin(II) sulfide (3.21 g, 0.0213 mol) were mixed together and placed into a 20 ml alumina boat. The boat was then placed in a tube furnace with nitrogen flow at ambient temperature. The boat was heated from ambient temperature to 600 °C over 15 minutes, and kept at this temperature for 1 day. The sample was cooled to ambient temperature and analyzed by XRD. The resulting powder diffraction patterns showed the presence of CZTS in good purity.

EXAMPLE 3

Copper (II) sulfide (8.7 g, 0.091 mol), zinc (II) sulfide (4.44 g, 0.0456 mol), and tin(IV) sulfide (8.32 g, 0.0456 mol) were mixed together and pressed into 8 pellets, which were then placed into two 20 ml alumina
5 boats and into a tube furnace with nitrogen flow. The boat was heated from ambient temperature to 600 °C over 15 minutes and kept at 600 °C for 3 days. The sample was cooled and analyzed by XRD, which showed the presence of CZTS in good purity.

10

EXAMPLE 4

Example 3 was repeated using zinc (II) sulfide (2.29 g, 0.0235 mol) and copper tin sulfide (Cu_2SnS_3 , 8.037 g, 0.0235 mol). The resulting sample was analyzed by XRD, which showed the presence of CZTS in
good purity.

15

CLAIMS

What is claimed is:

1. A method, comprising the steps of:
 - 5 a) providing a precursor mixture comprising:
 - i) a copper sulfide, a zinc sulfide, and a tin sulfide;
 - ii) a copper tin sulfide and a zinc sulfide;
 - iii) a copper zinc sulfide and a tin sulfide; or
 - iv) a zinc tin sulfide and a copper sulfide;
 - 10 wherein the precursor mixture has a total molar ratio of Cu:Zn:Sn:S of about 2:1 :1 :4; and
 - b) heating the precursor mixture in an inert atmosphere to a temperature of about 300 °C to about 1000 °C.
- 15 2. The method of Claim 1, further comprising isolating $\text{Cu}_2\text{ZnSnS}_4$.
3. The method of Claim 1, wherein the precursor mixture is heated to a temperature of about 600 °C to about 800 °C.
- 20 4. The method of Claim 1, wherein the precursor mixture is heated for about 6 hours to about 5 days.
5. The method of Claim 1, wherein the precursor mixture comprises a copper sulfide, a zinc sulfide, and a tin sulfide.
- 25 6. The method of Claim 1, wherein the precursor mixture comprises a copper tin sulfide and a zinc sulfide.
7. The method of Claim 1, wherein in step b) the inert atmosphere is
30 flowed over the precursor mixture.
8. The method of Claim 1, wherein the heating is carried out at ambient atmospheric pressure.

9. The method of Claim 1, wherein the heating is carried out in an open container.

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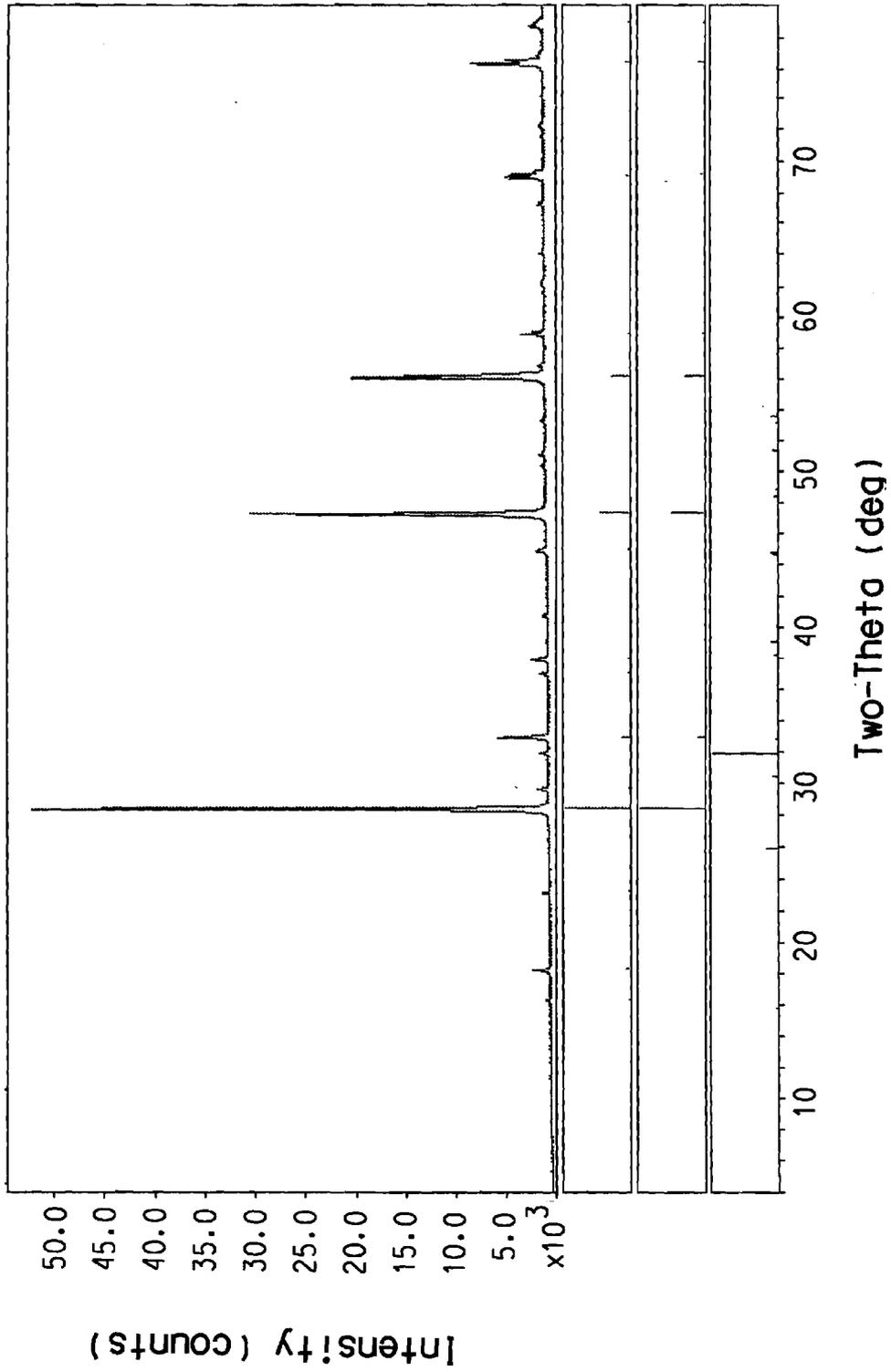


FIG. 1A

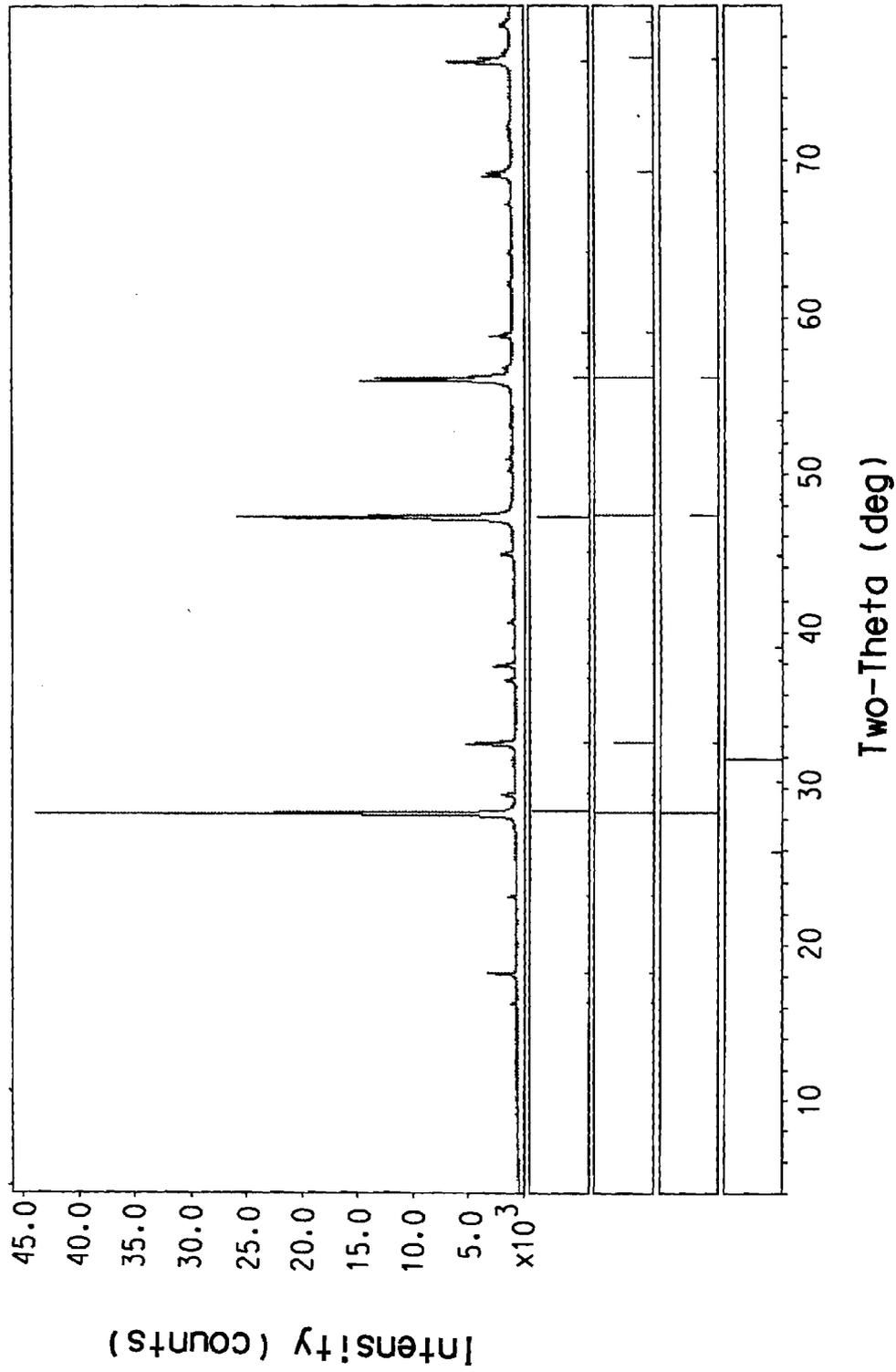


FIG. 1B

INTERNATIONAL SEARCH REPORT

International application No PCT/US2010/057562
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A. CLASSIFICATION OF SUBJECT MATTER
INV. C01G19/00
 ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C01G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal , CHEM ABS Data, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>SCHORR S ET AL: "In-si tu investi gati on of the kesteri te formati on from bi nary and ternary sul phi des" , THIN SOLID FI LMS, ELSEVI ER-SEQUOIA S.A. LAUSANNE, CH, vol . 517, no. 7, 2 February 2009 (2009-02-02) , pages 2461-2464, XP025928658, ISSN: 0040-6090, DOI : DOI : 10. 1016/J .TSF. 2008. 11.053 [retri eved on 2008-11-13] the whol e document</p> <p style="text-align: center;">----- -/- .</p>	1-9

Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents :

<p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&" document member of the same patent family</p>
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Date of the actual completion of the international search 16 February 2011	Date of mailing of the international search report 22/02/2011
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Corri as, M
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INTERNATIONAL SEARCH REPORT

International application No

PCT/US2010/057562

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>TODOROV T ET AL: "Cu₂ZnSnS₄ films deposited by a soft-chemistry method", THIN SOLID FILMS, ELSEVIER-SEQUOIA S.A. LAUSANNE, CH, vol . 517, no. 7, 2 February 2009 (2009-02-02) , pages 2541-2544, XP025928679 , ISSN: 0040-6090, DOI : DOI : 10.1016/J.TSF.2008.11.035 [retrieved on 2008-11-08] "Experimental part"</p> <p style="text-align: center;">-----</p>	1-9
A	<p>JP 2007 269589 A (UNIV NAGAOKA TECHNOLOGY) 18 October 2007 (2007-10-18) * abstract</p> <p style="text-align: center;">-----</p>	1-9
A	<p>SHANNON C RIHA ET AL: "Solution-Based Synthesis and Characterization of Cu₂ZnSnS₄ Nanocrystals", JOURNAL OF THE AMERICAN CHEMICAL SOCIETY, AMERICAN CHEMICAL SOCIETY, US, vol . 131, no. 34, 2 September 2009 (2009-09-02) , pages 12054-12055 , XP002615607 , ISSN: 0002-7863 , DOI : DOI : 10.1021/JA9044168 [retrieved on 2009-08-12] the whole document</p> <p style="text-align: center;">-----</p>	1-9

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2010/057562

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2007269589	A	NON E	
