Pure phase synthesis of Cu$_3$PS$_4$ and Cu$_6$PS$_5$Cl for semiconductor applications†

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We have achieved the first reported pure phase synthesis of two new nanoparticle materials, Cu$_3$PS$_4$ and Cu$_6$PS$_5$Cl. We have achieved this through learning about the potential reaction pathways that CuCl$_2$, P$_2$S$_5$, and 1-dodecanethiol can take. This study has shown that the key variable to control is the state of the phosphorus source when the CuCl$_2$ is added. If P$_2$S$_5$ is added together with the CuCl$_2$ to dodecanethiol then the reaction will follow a path to Cu$_3$PS$_4$, but if it is dissolved in dodecanethiol prior to the addition to CuCl$_2$ then the reaction will produce Cu$_6$PS$_5$Cl. The formation of these two different phases can occur simultaneously, yet we have found sets of conditions that manipulate the reaction system to form each phase exclusively. These nanoparticles could have broad semiconductor or solid electrolyte applications.

There is a need to explore new thin film photovoltaic absorbers, as many of the current thin film technologies have challenges associated with them. The high efficiency materials such as CuIn$_{1-x}$Ga$_x$Se$_2$ (ref. 1–5) and CdTe,†‡ require the use of the less-abundant elements indium and tellurium. To rectify this shortcoming, materials that use earth abundant elements such as Cu$_3$ZnSnSe$_4$ (CZTSe) and amorphous-Si have been explored. This class of materials has been unable to reach the efficiencies of the CuIn$_{1-x}$Ga$_x$Se$_2$ and CdTe cells that are necessary to become an economic alternative to fossil fuel based energy. Specifically in the case for CZTSe, the issue is caused by intrinsic defect formation, leading to band tails in the material. This defect is caused by the zinc on copper site (Cu$_{2z}$) and the accompanying copper on zinc (Zn$_{2c}$) site. This is due to the similar sizes of the Cu$^{+1}$ and the Zn$^{+2}$ ions.

Because of the uncertainties regarding the limitations and future of previously developed earth abundant materials for solar cells, it is necessary to investigate new materials that avoid the pitfalls that have hampered the previous technologies. It has been proposed to use a Cu$_3$V–VI$_4$ (V = P, As, Sb; VI = S, Se) structured material to address these issues. This class of materials uses earth abundant cations to allow for production on a terawatt scale. They also avoid the cation switching that has hampered the efficiencies of CZTSe devices, due to the mismatch between the sizes of V$^{+5}$ and Cu$^{+1}$ cations.

Some work examining the phosphorus member of the Cu$_3$V–VI$_4$ material family and its potential use as a solar absorber material has been reported in the literature. The reported calculations have estimated that the band gap of the selenide material is within the ideal range of 1.0–1.5 eV, and they have potential for the power conversion efficiencies to be greater than that of CuInSe$_2$. Experimental studies have confirmed the band gap of Cu$_3$PSe$_4$ to be 1.35 eV. On the other hand, Cu$_3$PS$_4$ with a higher band gap is a potential candidate for a top cell in a tandem cell. Both of the materials have shown a photoelectric response and could be attractive materials for photovoltaic devices.

In the past, crystals of Cu$_3$PS$_4$ have been synthesized either using chemical vapor transport and temperatures in excess of 850 °C for long periods of time such as 24 hours or heating elemental powders of copper, phosphorus and sulfur in sealed evacuated fused silica tubes at high temperatures for extended time periods. While these techniques produce crystals of Cu$_3$PS$_4$, that could be used for fundamental characterization, they are not suitable for fabrication of thin films of Cu$_3$PS$_4$. There is a need to pursue and develop new solution based techniques for the synthesis of Cu$_3$PS$_4$, if it is to be competitive with other thin film technologies. Using nanoparticles as a method for forming thin films has been employed for a variety of other materials for PV applications.

The previous solution-based method, to synthesize Cu$_3$PS$_4$ nanoparticles has faced significant obstacles. This method is based on reducing both copper and phosphorus to a neutral state and reacting them together to form Cu$_3$P nanoparticles. These nanoparticles are then reacted with thiourea in a separate reaction. While this procedure does produce Cu$_3$PS$_4$ nanoparticles, they are not pure phase. There is the presence of a phosphorus rich phase that is altering the composition and effecting the photoluminescence. If Cu$_3$PS$_4$ nanoparticles are to be used a precursor to a solar absorber, they will need to be free of any contaminants that could adversely affect a final film.
For this contribution we have examined copper–phosphorus–sulfide system. This material can occur in two main phases, the $\text{Cu}_6\text{PS}_5\text{Cl}$ enargite phase and the $\text{Cu}_2\text{PS}_6$ argyrodite phase. The argyrodite structure also has a chloride phase compound $\text{Cu}_4\text{PS}_5\text{Cl}$. The enargite phase is of more interest for photovoltaic applications, as either a top material for a multi-junction device or for use in high band gap electronic devices.

Argyrodites, while they may not be useful as solar absorbers, have been explored for use as solid electrolytes.\textsuperscript{33–35} $\text{Cu}_4\text{PS}_5\text{Cl}$ has been of particular interest due to its high performance and copper mobility.\textsuperscript{16,37} This material has shown better conductivities than other materials in the same family. In a similar case to the enargite materials, synthesis of the argyrodites is done in sealed ampule or vacuum based methods.\textsuperscript{34–37}

## Experimental

### Co-addition of CuCl\textsubscript{2} and P\textsubscript{2}S\textsubscript{5} powders at room temperature for solvothermal nanoparticle synthesis

In a nitrogen filled glovebox, copper(II) chloride (Sigma-Aldrich, ≥99.995% trace metals basis, CuCl\textsubscript{2}) and phosphorus pentasulfide (Acros Organics, 98%+, P\textsubscript{2}S\textsubscript{5}) are added to a reaction flask in either stoichiometric amounts or 50% excess phosphorus (Cu : P 2 : 1) content followed by 4 mL of 1-dodecanethiol (Sigma-Aldrich, ≥98%, DDT). This flask is heated to 250 °C under an argon atmosphere and held at that temperature for 1 hour. Then the flask is allowed to cool to room temperature in ambient conditions. After nanoparticles reach room temperature, they are dispersed in a hexane and isopropanol mixture (V : V 1 : 5) and precipitated using centrifugation at 14k rpm for 5 minutes. This washing is done three times and afterwads the nanoparticles are dried under dry nitrogen.

### Phosphorus pentasulfide pre-dissolution nanoparticle reaction

P\textsubscript{2}S\textsubscript{5} and 1-dodecanethiol are added to a reaction flask under a nitrogen atmosphere, and the flask heated under an argon atmosphere to 250 °C and is held for 1 hour. Then it is cooled to ambient temperature. The flask is opened in a nitrogen atmosphere, and CuCl\textsubscript{2} is added to the flask, which is resealed. The flask is heated to 250 °C under argon and is held for 1 hour, then is cooled to room temperature. The particles are dispersed in a hexane and isopropanol mixture (V : V 1 : 5) and are precipitated out by centrifuging at 14k rpm for 5 min. This is done three times, and then the nanoparticles are dried in nitrogen.

### Characterization

X-ray diffraction data was gathered using a Rigaku SmartLab diffractometer with a Cu Kz X-ray source. Raman spectra were acquired using a Horiba/Jobin-Yvon LabRAM HR 800 confocal microscope with a 633 nm He:Ne laser. Samples for XRD and Raman spectroscopy were made by drop casting the particles in hexane onto soda-lime glass. UV-Vis was collected by an Agilent Technologies Cary 60 spectrophotometer. Scanning electron microscopy energy dispersive X-ray spectroscopy data (SEM-EDS). Transmission electron microscopy (TEM) for the $\text{Cu}_3\text{PS}_4$ nanoparticles was done on a Hitachi 2700-C, and for the $\text{Cu}_6\text{PS}_5\text{Cl}$ nanoparticles s FEI Talos F200X was used.

## Results and discussion

We wanted to design a single pot synthesis to simplify the $\text{Cu}_3\text{PS}_4$ synthesis and to avoid complications from having multiple steps. For this material in particular there have been issues with residual phosphorus staying on the nanoparticles after an earlier reaction that stays with the nanoparticles through subsequent reactions. Other reaction pathways that use multiple steps could have possibilities for other impurities to be left behind. This means that we need to have our copper, phosphorus, and sulfur source all present and active in our initial reaction.

### Synthesis of $\text{Cu}_3\text{PS}_4$

We synthesized pure phase $\text{Cu}_3\text{PS}_4$ nanoparticles by the novel co-addition of CuCl\textsubscript{2} and P\textsubscript{2}S\textsubscript{5} powders (Cu : P 2 : 1) at room temperature for nanoparticle synthesis method. The PXRD and Raman spectra are shown in Fig. 1. All peaks seen in those spectra can be assigned to $\text{Cu}_3\text{PS}_4$. The phase purity of nanoparticles was confirmed by Rietveld refinement (see ESI†), which found no evidence of the presence of $\text{Cu}_4\text{PS}_5\text{Cl}$ and did not find any unexplained peaks. The composition for the nanoparticles was examined through SEM-EDX (see Table 1), and it showed that the nanoparticles are very close to the expected composition but are slightly phosphorus rich and copper poor. The near stoichiometric composition of 3 : 1 Cu : P produced by this synthesis demonstrates an improvement over the 1 : 1 Cu : P ratio seen in previous studies.\textsuperscript{33} This extreme phosphorus excess was hypothesized to be caused by a presence of elemental phosphorus on the surface of the nanoparticles. We attribute the lack of the extra phosphorus in our synthesis to the final solubility of the P\textsubscript{2}S\textsubscript{5} in the dodecanethiol. Since the P\textsubscript{2}S\textsubscript{5} remained soluble at room temperature any excess can be removed with the solvent using a washing step. Typically this washing is done using isopropanol to remove any excess species from the nanoparticles.

### Synthesis of $\text{Cu}_6\text{PS}_5\text{Cl}$

We were also able to synthesize pure phase $\text{Cu}_6\text{PS}_5\text{Cl}$ nanoparticles by the phosphorus pentasulfide pre-dissolution nanoparticle reaction. The amount of P\textsubscript{2}S\textsubscript{5} pre-dissolved in DDT and added CuCl\textsubscript{2} lead to Cu : P of 2 : 1. The PXRD data in Fig. 1 matches known spectra for this material. When this spectra was examined using Rietveld refinement, it reported >99% $\text{Cu}_6\text{PS}_5\text{Cl}$ and <1% $\text{Cu}_3\text{PS}_4$. We attribute this to experimental error, as the analysis was placing the peaks only within the noise of the spectra (see ESI†), and no $\text{Cu}_3\text{PS}_4$ was observable in the Raman spectra. The SEM-EDS shows that the nanocrystals have approximately the correct atomic ratios of Cu, P, and S. We suspect the particles do not have the exact composition because of a few reasons. This synthesis procedure seems to make copper poor nanoparticles as seen in the $\text{Cu}_3\text{PS}_4$...
synthesis, and the dodecanethiol could be attached to the surface of the nanoparticles causing them to be sulfur rich. Being chlorine poor could be explained by a shortage of chlorine in the reaction \( \text{HCl} \) since we know that \( \text{HCl} \) gas is produced during the initial part of the reaction. We have also taken Raman spectra for this material (see Fig. 1), but we do not have a known standard for it, but based on the previously shown data, we are confident that these nanoparticles are Cu$_6$PS$_5$Cl. We will be using this Raman spectra to identify this phase in other samples. The nanoparticles were also examined under TEM to see their size and shape (see Fig. 2b). The nanoparticles vary widely in shape and size, with sizes ranging from 5–30 nm in calliper diameter. The shapes range from nearly spherical to irregular. The \( d \)-spacings for these particles was examined from an HR-TEM image and found the correct spacing of 0.28 nm for the \{222\} plane (see ESI†).

From the TEM images of the Cu$_3$PS$_4$ nanoparticles (see Fig. 2a), we can examine their size and shape. We have found them to be about 3–15 nm in diameter and are irregularly shaped. We also examined the plane spacing as well, and found the (002) plane with a \( d \)-spacing of 0.30 nm (see ESI†). We did not see any evidence of a phosphorus layer on the outside of the nanoparticles. This is in agreement with the SEM-EDX.

The band gap was measured using UV-Vis spectroscopy (see Fig. 2). After examining the absorption curve, we found an indirect transition at 2.15 eV. It compares favourably with the previous work report for this material having an indirect band gap at 2.3 eV. Photoluminance data for Cu$_3$PS$_4$ also shows the band gap to be around 2.3 eV, close to our measured band gap for nanoparticles synthesized by an earlier method.

The state of phosphorus and how it leads to different reaction products

We have found that the state of the phosphorus source is a determining factor for the nanoparticle phase formed. P$_3$S$_5$ reacts with thiols to from thiophosphate esters, and these dissolve in the remaining excess thiol. We have observed the

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**Table 1** SEM-EDS composition data from the Cu$_3$PS$_4$ and Cu$_6$PS$_5$Cl nanoparticles, given as elemental ratios with respect to phosphorus

| Element | Cu | P  | S   | Cl |
|---------|----|----|-----|----|
| Cu$_3$PS$_4$ | 2.84 | 1  | 3.81 | 0  |
| Cu$_6$PS$_5$Cl | 5.42 | 1  | 5.48 | 0.44 |

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**Fig. 1** (a) PXRD spectra (Cu$_3$PS$_4$ standard JCPDS: 01-071-3306, Cu$_6$PS$_5$Cl standard JCPDS: 01-073-5736) and (b) Raman spectra of the Cu$_3$PS$_4$ and Cu$_6$PS$_5$Cl nanoparticles.

**Fig. 2** (a) TEM HAADF image of the Cu$_3$PS$_4$ nanoparticles (b) TEM HAADF image of the Cu$_6$PS$_5$Cl nanoparticles UV-Vis absorption data for the Cu$_3$PS$_4$ nanoparticles shows an indirect band gap at 2.15 eV.
dissolution of the P₂S₅ to occur in 1-dodecanethiol at elevated temperatures, starting around 100 °C and finishing around 165 °C. Based on this and the other findings shown in this contribution we propose the following reaction pathways for the formation of either Cu₃PS₄ or Cu₆PS₅Cl (see Fig. 3). Different reaction conditions effected the pathway that the reaction would follow and would have a significant impact on the composition of the reaction products. Knowledge of this reaction scheme was what guided us to developing both pure phase syntheses previously described.

To test the significance of the CuCl₂ to P₂S₅ ratio, we first added stoichiometric quantities of CuCl₂ and P₂S₅ (Cu : P is 3 : 1) to the DDT at room temperature in the flask. This mixture was heated to 250 °C and held there for 1 hour. During heat up, aliquots of samples were collected from the reaction flask and analyzed for composition by Raman spectroscopy, and the results are shown in Fig. 4a. It seems that the reaction of the P₂S₅ with the CuCl₂ and DDT happen concurrently. When we compared the two phases of Cu₃PS₄ and Cu₆PS₅Cl nanoparticles present during the heating ramp as well as the final product from the synthesis we saw a shifting composition. As the reaction temperature increased, the Cu₆PS₅Cl phase began to form in a greater amount than the Cu₃PS₄. The final composition was a mixture of both phases.

When the reaction is modified so excess amounts of P₂S₅ are added (Cu : P was 2 : 1) initially at room temperature to the reaction flask, we observed a different end result from the previous stoichiometric case. The beginning of the reaction remained similar with both phases present throughout the reaction period. Although the relative quantity of Cu₃PS₄ was now higher with respect to Cu₆PS₅Cl but then end product was not the same (see Fig. 4b). Due to the excess amounts of P₂S₅ added, all of the Cu₆PS₅Cl phase converted into the Cu₃PS₄ phase. We have tested this conversion in a separate reaction by using Cu₆PS₅Cl as a replacement for the CuCl₂ (Cu : P 2 : 1) and observed the phase change to Cu₃PS₄. This occurs at 250 °C but does not happen at 150 °C. The temperature dependence was why the Cu₆PS₅Cl phase appears at low temperatures only to disappear at higher temperatures.

To examine the changes that may occur with the state of phosphorus during the reaction, three experiments were done where the CuCl₂ was added to P₂S₅ and DDT mixture at different points in the reaction. While P₂S₅ was added to DDT at room temperature and heated, the CuCl₂ with Cu : P of 2 : 1 was added prior to heating, just after reaching 250 °C, and after 1 hour at 250 °C. The composition of the product nanoparticles shifted from Cu₆PS₅Cl rich to Cu₃PS₄ rich as the CuCl₂ was added later (see Fig. 5). We suggest that this shift is caused by the reaction history between the P₂S₅ and the DDT. It seems that after P₂S₅ is dissolved in DDT, there are two types of phosphorus species that are present in the solution. The first type reacts with Cu-species to directly form Cu₃PS₄ while the second type reacts to form Cu₆PS₅Cl. At a high temperature of 250 °C, the first type of phosphorus species further reacts with Cu₆PS₅Cl to form Cu₃PS₄. While in this study we have not delineated each type of phosphorus species, it is likely that the first type of phosphorus species are simply dissolved P₂S₅ molecules in DDT (we denote it P₂S₅* in Fig. 3), and the second type of phosphorus species are by-products of P₂S₅ reaction with DDT such as (RS)₃PS and (RS)₃PSSH. An increase in the second type of phosphorus species seems to occur with reaction time at 250 °C leading to favorable formation of Cu₆PS₅Cl over Cu₃PS₄. In another possibility, the reaction of P₂S₅ with DDT may itself provide the two types of phosphorus species.

To isolate the injection process as a possible variable, the synthesis was repeated with DDT heated alone to 250 °C and then injected CuCl₂ and P₂S₅ (Cu : P of 2 : 1) powders together at 250 °C. As with the solvothermal reaction in Fig. 4b a time dependent evolution of the composition is seen. The composition shifts from initially being Cu₆PS₅Cl rich to only Cu₃PS₄ over the hour long reaction (see Fig. 6). This demonstrates that when the CuCl₂ and the P₂S₅ are added together either at room temperature or at 250 °C, the reaction will eventually produce Cu₃PS₄ free of Cu₆PS₅Cl. However it is interesting to compare initial reaction products in Fig. 4b at a lower temperature of 150 °C with that in Fig. 6 after 1 minute of injection. We find that while at lower temperatures Cu₃PS₄ is favored, at a high temperature of 250 °C Cu₆PS₅Cl is initially favored. It seems at the temperature of 250 °C, not only the second type of phosphorus species is quick to form but its kinetic rate to form Cu₆PS₅Cl is much higher than corresponding rate with the first type of phosphorus species to form Cu₃PS₄. With co-injection of P₂S₅ and CuCl₂ at 250 °C, we have enough first type of phosphorus species to eventually convert all the Cu₆PS₅Cl to Cu₃PS₄.
The conversion of Cu₆PS₅Cl to Cu₃PS₄

To see if the Cu₆PS₅Cl could directly be converted to Cu₃PS₄, a series of reactions was performed using Cu₆PS₅Cl as the only copper source. These reactions were done under three different conditions. Two that used the solvothermal method, whereby Cu₆PS₅Cl and P₂S₅ are added to DDT at room temperature and the mixture is heated to the reaction temperature of either 150 °C or 250 °C (Fig. 7b and a respectively). In the third experiment, the Cu₆PS₅Cl is added after the P₂S₅ has been heated in DDT for 1 hour at 250 °C (Fig. 7c). The Cu₆PS₅Cl : P₂S₅ in all three experiments was 2 : 3 which is close to the Cu : P

Fig. 4 Raman spectra taken during the temperature ramp for the solvothermal reaction at two different composition loadings, (a) Cu : P 3 : 1, (b) Cu : P 2 : 1. The data at 250 °C represents the sample when the reaction attains 250 °C and the final data is after 1 hour.

Fig. 5 Final Raman spectra taken after reactions where the CuCl₂ is added at different times in the reaction (Cu : P 2 : 1). In (a) the reaction was terminated after 1 hour at 250 °C, while (b) and (c) reactions were terminated after 1 hour following the addition of CuCl₂.

Fig. 6 Raman spectra taken from a synthesis where both CuCl₂ and P₂S₅ are both injected as powders at 250 °C (Cu : P 2 : 1) at different points in the reaction (a) 1 minute after injection and (b) 1 hour after injection.
ratio of 2 : 1 used in earlier experiments. For the solvothermal reactions, there was significant conversion at 250 °C but very little if any at 150 °C (see Fig. 7). This shows that the rate of reaction between the first type of phosphorus species and Cu₆PS₅Cl to form Cu₃PS₄ at lower temperatures (≤150 °C) is quite slower and one needs higher temperatures for this reaction rate to become appreciable. This temperature dependence on the conversion is the reason that in our Cu₃PS₄ synthesis shown in Fig. 4b), Cu₆PS₅Cl is present during early stages of the reaction at lower temperatures and only converts to Cu₃PS₄ later on after the reaction has reached 250 °C. When the P₂S₅ was reacted for an hour with the DDT at 250 °C prior to adding the Cu₆PS₅Cl, the conversion to Cu₃PS₄ was stopped. This is consistent with the possibility that at 250 °C with time there is a decrease in the amount of the first type of phosphorus species and after one hour, the predominant phosphorus species is the second type which does not lead to the formation of Cu₃PS₄. This is consistent with our Cu₆PS₅Cl nanoparticle synthesis recipe where P₂S₅ is first heated at 250 °C in DDT for an hour, the mixture is then cooled to room temperature to add CuCl₂ and run the solvothermal synthesis of the nanoparticles.

When the original reaction conditions are used (using CuCl₂ and P₂S₅ added together at room temperature to DDT and then heating to reaction temperature and holding for 1 hour) but using temperatures lower than 250 °C, we did not get the desired single phase product (see Fig. 8). We observed similar compositions during the temperature ramp to the previously discussed reactions, where there was a mixture of the Cu₃PS₄ and Cu₆PS₅Cl phases, when the temperature is below 250 °C (Fig. 4b). This was consistent with our findings on the effect of temperature on the conversion from Cu₆PS₅Cl to Cu₃PS₄ and the postulate that there are two types of phosphorus species in the solution with different reaction rates. At lower temperatures, reaction rate between first type of phosphorus species and Cu₆PS₅Cl is low and therefore, one sees a preference for more Cu₆PS₅Cl as the temperature increases.

Conclusions

Understanding and being able to control the process of the phase change was the important step to achieving each single phase product of Cu₃PS₄ and Cu₆PS₅Cl. High temperatures facilitate the conversion, but it is necessary to add excess P₂S₅ to make sure there is enough phosphorus to complete it. The conversion to Cu₃PS₄ can be completely stopped if the phosphorus is dissolved in the thiol at high temperature of 250 °C before adding the copper, because in this state it will not react with the Cu₆PS₅Cl.

In order to explain the experimental observations and tailor the reaction when P₂S₅ and CuCl₂ are reacted in DDT, we invoke the presence of two types of phosphorus species in the solution. The first type of phosphorus species is favoured when excess phosphorus is added to the solution and solution temperatures are low. This first type of phosphorus species reacts directly with copper precursors in the solution to for Cu₃PS₄, and also with Cu₆PS₅Cl to form Cu₃PS₄. Although for the reaction rates to be meaningful with Cu₆PS₅Cl, higher temperatures (T ∼ 250 °C) are needed. The second type of phosphorus species exclusively reacts with copper precursors in the solution to Cu₆PS₅Cl, and the abundance of this phosphorus species increases as temperature of the reaction is increased. At T ∼ 250 °C, after a period of about one hour, all of the phosphorus seems to be present as the second type of phosphorus species. It is likely that when P₂S₅ is added to DDT and heated, initial phosphorus...
species are of the first type which eventually convert to the second type at the higher temperatures. Once the second type of phosphorus species is present in the solution, it reacts rapidly with copper to form Cu₄PS₅Cl. However, if reaction temperatures are high enough and first type of phosphorus is present in the solution, Cu₄PS₅Cl will react to form Cu₃PS₄. A reaction temperature of 250°C ensures the absence of the product Cu₆PS₅Cl to Cu₃PS₄. A reaction temperature of 250°C is required for the absence of the first type of phosphorus species to Cu₃PS₄. A reaction temperature of 250°C with co-injection of P₅S₅ and CuCl₂ fulfills this condition. It insures that all the by-product Cu₄PS₅Cl is converted to Cu₃PS₄ before the first type of phosphorus species disappears from the solution phase (by perhaps conversion to the second type of phosphorus species). Similarly, pure phase synthesis of Cu₆PS₅Cl requires the absence of the first type of phosphorus species from the solution phase. This is achieved by preheating the P₅S₅ with DDT at 250°C for one hour. This ensures that there is little of the first type of phosphorus species in the solution phase. Addition of CuCl₂ to this solution results in exclusively the formation of Cu₆PS₅Cl.

In summary, we have shown a new synthesis method for synthesizing copper phosphorus sulfide nanoparticles. Our new synthesis is only a single step reaction that produces a phase pure product, making it advantageous to previous methods that have used multiple reactions and lead to a multiphase product. We have determined that controlling the reaction of the phosphorus pentasulfide with the solvent is the key to determining the phase of the final product. We have tested this using different reaction conditions. These nanoparticles are expected to have applications as a precursor for solar absorber films and other thin-film electronic devices.

Statement of data access

The data associated with this manuscript can be found at the project’s website: https://datacenterhub.org/groups/dmref1534691.

Conflicts of interest

There are no conflicts to declare.

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References

1. S. M. Mcleod, C. J. Hages, N. J. Carter and R. Agrawal, Prog. Photovoltaics, 2015, 23, 1550–1556.
2. P. Jackson, R. Wuerz, D. Hariskos, E. Lotter, W. Witte and M. Powalla, Phys. Status Solidi RRL, 2016, 10, 583–586.
3. T. Todorov, T. Gershon, O. Gunawan, Y. S. Lee, C. Sturdevant, L. Y. Chang and S. Guha, Adv. Energy Mater., 2015, 5, 1–6.
4. D. Keller, S. Buecheler, P. Reinhard, F. Pianezzi, B. Bissig, R. Carron, F. Hage, Q. Ramasse, R. Erni and A. N. Tiwari, Appl. Phys. Lett., 2016, 109(15), 152103.
5. R. L. Garris, L. M. Mansfield, B. Egaas and K. Ramanathan, IEEE J Photovolt., 2016, 7, 281–285.
6. D. Kuciauskas, P. Dippo, Z. Zhao, L. Cheng, A. Kaneve, W. K. Metzger and M. Gloeckler, IEEE J Photovolt., 2016, 6, 313–318.
7. R. W. Crisp, M. G. Panthani, W. L. Rance, J. N. Duenow, P. a Parilla, R. Callahan, M. S. Dahney, J. J. Berry, D. V Talapin and J. M. Luther, ACS Nano, 2014, 8, 9063–9072.
8. D. E. Swanson, J. R. Sites and W. S. Sampath, Sol. Energy Mater. Sol. Cells, 2017, 159, 389–394.
9. C. K. Miskin, W.-C. Yang, C. J. Hages, N. J. Carter, C. S. Joglekar, E. A. Stach and R. Agrawal, Prog. Photovoltaics, 2015, 23, 654–659.
10. W. Wang, M. T. Winkler, O. Gunawan, T. Gokmen, T. K. Todorov, Y. Zhu and D. B. Mitzi, Adv. Energy Mater., 2014, 4, 1301465.
11. K. Rudisch, Y. Ren, C. Platzer-Björkman and J. Scragg, Appl. Phys. Lett., 2016, 108(23), 231902.
12. T. Mise, S. Tajima, T. Fukano, K. Higuchi, T. Washio, K. Jimbo and H. Katagiri, Prog. Photovoltaics, 2016, 24, 1009–1015.
13. T. Matsui, H. Sai, K. Saito and M. Kondo, Prog. Photovoltaics, 2013, 21, 1363–1369.
14. C. J. Hages, N. J. Carter and R. Agrawal, J. Appl. Phys., 2016, 119(1), 014505.
15. T. Gokmen, O. Gunawan, T. K. Todorov and D. B. Mitzi, Appl. Phys. Lett., 2013, 103(10), 103506.
16. C. J. Hages, N. J. Carter, R. Agrawal and T. Unold, J. Appl. Phys., 2014, 115(23), 234504.
17. J. E. Moore, C. J. Hages, R. Agrawal, M. S. Lundstrom and J. L. Gray, Appl. Phys. Lett., 2016, 109, 1–5.
18. F. Hong, W. Lin, W. Meng and Y. Yan, Phys. Chem. Chem. Phys., 2016, 18, 4828–4834.
19. K. Biswas, S. Lany and A. Zunger, Appl. Phys. Lett., 2010, 96, 1–4.
20. J. V. Marzik, a. K. Hsieh, K. Dwight and a. Wold, J. Solid State Chem., 1983, 49, 43–50.
21. R. B. Balow, E. J. Sheets, M. M. Abu-omar and R. Agrawal, Chem. Mater., 2015, 27, 2290–2293.
22. V. Itthibenchapong, R. S. Kokenyesi, A. J. Ritenour, L. Zakharov, S. Boettcher, J. Wager and D. Keszler, J. Mater. Chem. C, 2013, 657–662.
23 E. J. Sheets, W.-C. Yang, R. B. Balow, Y. Wang, B. C. Walker, E. A. Stach and R. Agrawal, J. Mater. Res., 2015, 30, 3710–3716.
24 L. Yu, R. S. Kokenyesi, D. A. Keszler and A. Zunger, Adv. Energy Mater., 2013, 3, 43–48.
25 I. Repins, N. Vora, C. Beall, S.-H. Wei, Y. Yan, M. Romero, G. Teeter, H. Du, B. To, M. Young and R. Noufi, Mater. Res. Soc. Symp. Proc., 2011, 1324, 97–108.
26 T. Shi, W. Yin, M. Al-jassim, Y. Yan, T. Shi, W. Yin, M. Al-jassim and Y. Yan, Appl. Phys. Lett., 2013, 103(15), 152105.
27 M. Schulte-Kellinghaus and V. Krämer, Thermochim. Acta, 1978, 27, 141–149.
28 R. B. Balow, C. K. Miskin, M. M. Abu-Omar and R. Agrawal, Chem. Mater., 2017, 29, 573–578.
29 R. Nitsche and P. Wild, Mater. Res. Bull., 1970, 5, 419–423.
30 D. H. Foster, V. Jieratum, R. Kykyneshi, D. a. Keszler and G. Schneider, Appl. Phys. Lett., 2011, 99, 181903.
31 B. K. Graeser, C. J. Hages, W. C. Yang, N. J. Carter, C. K. Miskin, E. A. Stach and R. Agrawal, Chem. Mater., 2014, 26, 4060–4063.
32 S. A. McClary, J. Andler, C. A. Handwerker and R. Agrawal, J. Mater. Chem. C, 2017, 5, 6913–6916.
33 M. Chen and S. Adams, J. Solid State Electrochem., 2015, 19, 697–702.
34 W. F. Kuhs, R. Nitsche and K. Scheunemann, Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem., 1978, 34, 64–70.
35 I. P. Studenyak, M. Kranjcec, R. Y. Buchuk, V. O. Stephanovich and S. Kokenyesi, Semicond. Phys., Quantum Electron. Optoelectron., 2013, 16, 259–264.
36 W. F. Kuhs, R. Nitsche and K. Scheunemann, Mater. Res. Bull., 1979, 14, 241–248.
37 A. Gagor, A. Pietraszko and D. Kaynts, J. Solid State Chem., 2008, 181, 777–782.
38 L. Maier and J. R. Van Wazer, J. Am. Chem. Soc., 1962, 84, 3054–3058.