Hybrid polymer solar cells: From the role colloid science could play in bringing deployment closer to a study of factors affecting the stability of non-aqueous ZnO dispersions

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Abstract

The development and deployment of large-scale, cost-effective, renewable energy is becoming increasingly important. A cost reduction of about an order of magnitude in solar derived electricity is required to enable widespread deployment. This requires an alternative type of solar cell prepared using solution-processing techniques. In recent years hybrid polymer solar cells containing inorganic nanoparticles (e.g., CdSe, ZnO or PbS) blended with semiconducting polymers have been investigated. These solar cells offer great promise because both components can in principle harvest light. The highest power conversion efficiency (PCE) values reported for these solar cells to date is 2.8%. However, PCE values of at least 10% are required for commercialisation to be viable. One of the major problems restricting the PCE for hybrid polymer solar cells is colloidal in nature. The photoactive layers for these solar cells are prepared using a three component blend of inorganic nanoparticles, conjugated polymer and organic solvent. Solvent evaporation during film formation results in extensive phase separation. This produces relatively large polymer-rich domains between nanoparticle aggregates within the photoactive layer, which promotes recombination of the photogenerated charge carriers. This article aims to show how colloid and interface science could enable major PCE improvements for hybrid polymer solar cells. We also present experimental data concerning the dispersion stability of ZnO nanoparticles under conditions similar to those used for photoactive layer preparation within hybrid solar cells. The data indicate that the improved stability of ZnO dispersions in co-solvent blends containing methanol (MeOH) is due to hydrogen-bonding of MeOH to the ZnO surface. Furthermore, turbidity data also suggest that depletion aggregation of ZnO nanoparticles is likely under conditions used to prepare hybrid solar cells. The article concludes with proposals for colloidal studies that may enable improvement of the PCE for hybrid solar cells.

Keywords: hybrid solar cells; ZnO nanoparticles; morphology.

1. Introduction

Solar cells transform incident photons into direct current. This article focuses on a new generation of solar cells, which are termed hybrid polymer solar cells. These cells have a photoactive layer that consists of interconnected semiconducting nanoparticles dispersed within a solid semiconducting polymer phase. (The photoactive layer is the part of the solar cell that harvests light and transforms it into mobile charges.) It is because the nanoparticles have at least one dimension within the range of 1 nm to ca. 100 nm that they can be considered as colloids. A key development for organic solar cells came from Tang when he demonstrated the concept of bringing two semiconductors into contact to increase the power conversion efficiency (PCE). The interface is known as a heterojunction. The first solar cell containing a dispersed polymer heterojunction (termed a bulk heterojunction, BHJ) was demonstrated by Yu et al. in 1994. These solar cells have not yet been commercialized, which is in large part due to their low PCE values. This article aims to show how colloid science could enable the PCEs of hybrid polymer solar cells to be increased. In addition, results concerning the colloidal stability of a representative dispersion used for preparation of hybrid polymer solar cells are presented.

Silicon based PVs currently comprise the overwhelming majority of the solar cell market. Commercial crystalline silicon solar cells typically achieve a PCE of about 15%. There are several important disadvantages for silicon-based PVs including high-
Photons with energy greater than the band gap are absorbed by the photoactive layer to create a neutral exciton by promotion of an electron from the HOMO to the LUMO of the light harvesting polymer. An exciton consists of a bound electron (\(e^-\)) – hole (\(h^+\)) pair. The average length over which the exciton can diffuse within the polymer before recombination of the hole and electron occurs is the exciton diffusion length, (ca. 10 nm for poly(3-hexylthiophene, P3HT)). This is a distance of critical importance to the PCE. Exciton dissociation can occur at a heterojunction provided that recombination does not compete. (Recombination, which is the process whereby an electron and hole combine, results in annihilation of the charge carrier.) After dissociation the charges migrate to their respective electrodes.

Fig. 1(a) shows a diagram of a typical hybrid polymer solar cell. The PCE, which is the key parameter characterizing cell performance, is the ratio of the maximum power output to incident light power. The challenge for hybrid polymer solar cell researchers is to increase the PCE to levels of at least 10 %. In colloid terms the BHJ is a bicontinuous solid dispersion where both the nanoparticle and polymer phases are semiconducting. The morphology of the ideal nanoparticle-polymer photoactive layer is similar to that present within bicontinuous microemulsions. This is depicted in Fig. 1(a). The ideal morphology may be thought of as an inter-penetrating nanoparticle network whose connected nanoparticle segments are separated by a curved polymer phase. This structure extends in three dimensions and the polymer domains should not exceed a thickness of ca. 10 nm.

The starting point for preparing a photoactive layer is a dispersion of inorganic nanoparticles within a solvent containing dissolved conjugated polymer. (The solvent is often a co-solvent mixture.) The final point is the solid nanoparticle-in-polymer dispersion. The process of solvent evaporation is depicted in Fig. 1(b). A key challenge for the preparation of the photoactive layers is to achieve the optimum morphology depicted in Fig. 1(a). This is difficult because it is not permissible to use an adsorbed, stabilizing, layer for the nanoparticles because such a layer tends to make inter-particle hopping of the charges energetically demanding, which reduces the PCE. It can be seen from published images for inorganic nanoparticle-polymer solar cells that phase separation occurs during solvent evaporation. This is because a phase instability line is crossed. Unfortunately, the phase diagrams have not been reported which means that the locations of the instability lines are not known. One of the key challenges from the colloid science perspective is to move the phase separation boundaries in directions that improve the morphology of the nanoparticle-polymer films that result (e.g., to regions of lower solvent volume fractions).

Hybrid polymer solar cells have involved a number of different inorganic nanoparticles and polymers. Examples which have given the highest PCE values include poly(phenylene vinylene) (PPV) or poly(3-hexylthiophene) (P3HT) with CdSe nanorods and also PPV with ZnO nanocrystals. These solar cells have given efficiencies of 2.8, 2.6 and 1.6 %, respectively. It is noteworthy that the highest PCE values have been obtained using nanorods, which is presumably due to less interparticle hopping. The hypothesis that is being investigated within the BRS group is that improved morphological control within the photoactive layer will originate from improved control of dispersion stability during solvent evaporation. Unfortunately, the factors controlling the dispersion stability of non-aqueous dispersions containing inorganic nanoparticles is not an area that has received a great deal of attention within the colloid science community. There have been some seminal reviews written a number of years ago in the area of non-aqueous dispersion stability. Furthermore, the interactions of ZnO (and other nanoparticles) with short chain stabilizing species (capping agents) have been investigated to a limited extent. Moreover, the conformations of conjugated polymers within solutions is also not an area that has been comprehensively studied. Consequently, the study of stability for dispersions of inorganic (quantum-sized) nanoparticles within conjugated polymer solutions is in its infancy.

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**Fig. 1.** (a) Diagram of a hybrid solar cell. An ideal morphology for the photoactive layer is illustrated. The average distance of a polymer domain (hole transporting phase) should be less than or equal to ca. 10 nm for efficient charge transport. (b) Depiction of a ternary phase diagram for a polymer / nanoparticle / solvent mixture. The parameters \(\phi_{\text{solv}}\), \(\phi_{\text{pol}}\) and \(\phi_{\text{np}}\) are the volume fractions of solvent, polymer and nanoparticles, respectively.
2. Colloidal aspects governing stability of dispersions used to prepare hybrid solar cells

The two-particle interaction energy \( G(h) \) between neighbouring semiconducting nanoparticles (interparticle separation of \( h \)) dispersed in a non-adsorbing polymer solution (e.g., P3HT in CHCl\(_3\)) can be described by the following equation\(^1\).

\[
G(h) = G_E(h) + G_A(h) + G_S(h) + G_{\delta}(h) + G_{\text{dipole}}(h) \tag{1}
\]

Where \( G_E(h) \) is the electrostatic repulsion term. Although well understood in aqueous dispersions this term is complicated for charged particles dispersed in organic solvents due to the low dielectric constants\(^12\). The parameter \( G_A(h) \) is the van der Waals attraction term. \( G_S(h) \) will remain negative (attractive) during solvent evaporation and will increase in magnitude as the process continues. The term \( G_{\delta}(h) \) in equation (1) represents the steric interaction. This is significant when a stabilising polymer (or a short chain ligand capping layer, e.g., trioctyl phosphine oxide, TOPO) is present. In the case of nanoparticle/polymer/solvent mixtures depletion flocculation due to non-adsorbed (free) polymer should also be considered. The term \( G_{\text{dipole}}(h) \) in equation (1) represents the attractive inter-particle interaction due to depletion. The term \( G_{\text{dipole}}(h) \) represents attractive dipole-dipole interactions. This term is only significant for nanoparticles that possess a significant permanent dipole moment. It is important for CdSe nanorods\(^13\). Unfortunately, with the exception of \( G_E(h) \) and \( G_A(h) \), each term in equation (1) provides a negative contribution to dispersion stability. As mentioned above the use of steric stabilizing agents is a disadvantage from the viewpoint of high PCE values. In addition to \( G(h) \) an entropic contribution originating from the combinations possible for the nanoparticles (\( \Delta G_{\text{ent}} \)) will oppose flocculation at low particle volume fraction \( (\phi_{np}) \) values. Because \( \Delta G_{\text{ent}} \) will decrease with increasing \( \phi_{np} \) that term should become insignificant as solvent evaporation proceeds. The challenge, then, with this system is to design approaches that improve dispersion stability during photoactive layer formation, whilst optimizing PCE values.

The key term that favours colloidal stability in non-aqueous media is \( G_S(h) \). Fig. 2(a) depicts the two-particle interaction curve for nanocrystals capped with TOPO. Dispersion stability is favoured by the steric stabilising layer. However, a low PCE can be expected for the resulting photoactive layer. The approach developed to compensate for this in the case of CdSe nanorods was to exchange long chain capping agents with pyridine\(^14\). The advantage of this is that the pyridine-coated particle surface is hydrophobic and the pyridine layer can be subsequently removed from the film using annealing. The disadvantage appears to be that significant aggregation of the nanorods occurs within the photoactive layers\(^1\). Nevertheless, very respectable PCE values (above) have been obtained using these systems (above). The colloidal reason for the poor stability of the pyridine capped nanorods is probably due to the absence of steric stabilisation (depicted in Fig. 2(b)). The challenge is to design systems that have two-particle interaction curves like that in Fig. 2(a) without leaving the nanoparticles encapsulated with a non-conducting layer.

![Illustration of the two particle potential curves for the nanoparticle dispersions stabilized by (a) TOPO and (b) pyridine.](image)

3. Experimental details

In the present work we examined ZnO nanocrystals or nanorods. We selected those materials as they have been used to prepare hybrid polymer solar cells with reasonable PCE values\(^11\). Also, the nanocrystals or nanorods are convenient to prepare in a reliable manner.

ZnO nanoparticle preparation

The nanocrystals were prepared by the method of Beek et al.\(^15\) This involved dissolving zinc acetate dihydrate (Aldrich, 2.95 g) in methanol (125 mL) at about 60 °C. A solution of KOH (1.48 g) in methanol (65 mL) was then added with stirring. The heater and stirrer were removed after 135 min. The precipitate was washed, with the aid of centrifugation, with methanol (MeOH, 50 mL). After the final centrifugation step the sediment was dispersed in CHCl\(_3\) or chlorobenzene (CBZ).

ZnO nanorods were prepared by continuing the nanocrystal synthesis from the point at which the reaction had proceeded for 135 min. The reaction mixture was then concentrated by a factor of ten using rotary evaporation at ca. 30 °C. The solution, which was clear at this point, was heated at 60 °C for 15 to 20 h. Methanol was added upon cooling to room temperature and the mixture was washed as described above. Addition of the nanorods to either CHCl\(_3\) or CBZ containing 2 % n-propylamine resulted in stable dispersions.
Physical methods

UV-visible spectroscopy measurements were conducted using a Hitachi U-1800 spectrophotometer. For these measurements the nanocrystals or nanorods were initially dispersed in CBZ or CHCl₃ and then diluted with the appropriate co-solvent being tested. The particle concentration used was 0.5 wt.% The depletion flocculation studies were performed by dissolving linear polystyrene (PS) in CBZ. PS was used as a model polymer for the reasons described in the text (later).

TEM measurements were performed using a Philips CEM 200 operating at 200 keV. Optical micrographs were obtained using an Olympus microscopy using transmitted light. Wide-angle x-ray diffraction data on powdered samples were obtained using a Philips X’pert system and Cu Kα radiation.

4. Results and Discussion

ZnO nanoparticle characterization

ZnO is a semiconductor and the nanocrystals are of a sufficiently small size that the extent of the electronic wave function is limited by the physical size of the nanocrystals. This gives a size-dependent UV-visible spectrum. The wavelength at half of the absorption maximum for the excitonic peak (\(\lambda_{1/2}\)) provides a convenient measure of particle size and a calibration curve relating particle size to \(\lambda_{1/2}\) has been reported. The spectrum for the ZnO nanocrystals is shown in Fig. 3(a). The \(\lambda_{1/2}\) value (352 nm) indicated a nanocrystal size of 3.8 nm.

The particle size for the nanocrystals was also estimated using x-ray diffraction (Fig. 3(b)). The diffractogram showed evidence of a wurtzite-type crystalline phase. The peaks are broadened because of the fine particle size. Application of the Scherrer equation gave an average diameter of 4.2 nm. The nanocrystals were also examined using TEM (Fig. 3(c)). It was difficult to achieve complete dispersion. This can also be seen from related TEM of other ZnO nanocrystals. The TEM data suggest a relatively broad particle size distribution with particle sizes in the range of 3 to 8 nm. The number average particle size was 5.1 nm with a coefficient of variation (CV) of 26%. This is consistent with the data obtained using UV-visible spectroscopy and XRD data. TEM is more useful for assessing the polydispersity of the particle size distribution.

Nanorods are potentially attractive for use within hybrid solar cells because they provide an opportunity for less interparticle hopping. This, in turn, increases electron mobility and decreases the likelihood of recombination. The TEM images of the nanorods showed clearly defined rods. The images gave an average length of 21 nm (CV = 37%) and a width of 7 nm (CV = 16%). The average length and width of the nanorods prepared here are similar to those reported by Beek et al. It is noted that the nanocrystal dispersions have a tendency to age, although this can be reduced by low temperature-storage. The nanorods appeared to be more stable in this regard.

![Fig. 3. Characterisation data for ZnO nanocrystals and nanorods. (a) An UV-visible spectrum for the nanocrystals at a concentration of 0.01 wt.% in CHCl₃. (b) Powder x-ray diffractogram for the nanocrystals. (c) A TEM image for the nanocrystals. (d) A TEM image for the nanorods.](image-url)
Origin of ZnO dispersion stability within co-solvent blends containing methanol

The construction of a hybrid solar cell is challenging because of the need to find a solvent system in which the polymer (which is invariably hydrophobic) is soluble and the nanoparticles (which are hydrophilic) can be dispersed. Solvents that are commonly used to dissolve the polymers are CHCl₃ or CBZ. ZnO nanoparticles do not disperse well in these solvents. However, it has been reported that the use of a co-solvent of CHCl₃ or CBZ containing a MeOH volume fraction \( \phi_{\text{MeOH}} \) of 0.10 gives good nanoparticle dispersion. However, the reasons for this have not been given. Small molecules, such as MeOH, can be removed from dried nanocomposite films by annealing. They are seen as good co-solvents for preparation of hybrid solar cells containing ZnO. It is important to understand the reasons for this behaviour in more detail than what has been reported to date.

We investigated the stability for the ZnO dispersions in co-solvent blends using turbidity measurements at 600 nm. This region was chosen because it is well away from the absorption maximum for ZnO (cf. Fig. 3(a)) and the intensity in this region originates from particle scattering and not absorption. Data for the nanocrystals or nanorods dispersed in CBZ/MeOH are shown in Fig. 4(a). The nanorods contain a small amount of \( n \)-propylamine which is why the optical density (OD) values are lower than those for the nanocrystals for dispersions containing \( \phi_{\text{MeOH}} \) of ca. 0.05. It can be seen from the data that a minimum in the OD occurs at around 0.2. However, this could extend to higher values (up to 0.5). The minimum indicates good dispersion of the nanorods or nanocrystals. At higher values of \( \phi_{\text{MeOH}} \) the particles aggregated excessively and precipitated.

The data from Fig. 4(a) are consistent with the reports that CBZ/MeOH co-solvent blends containing \( \phi_{\text{MeOH}} = 0.10 \) give good dispersion of nanocrystals or nanorods. But what is the origin of this effect? Two explanations can be put forward. The first attributes this to hydrogen bonding of the MeOH molecules onto the ZnO particle surface. This would transform the hydrophilic surface to a hydrophobic one and aids dispersion. The second is that it is a result of an increased dielectric constant of the dispersion medium which increases the effectiveness of electrostatic repulsion. Electrostatic effects are generally weak in organic solvents with low dielectric constants. However, they can become stronger if the dielectric constant increases.

In order to distinguish between these two possibilities nanocrystals were dispersed in CBZ containing different volume fractions of CH₂Cl₂ (See Fig. 4(b)). These dispersions were prepared by diluting a parent mixture of nanocrystals dispersed in CH₂Cl₂ with CBZ. CH₂Cl₂ has a higher dielectric constant (9.08) than CBZ (5.6). Furthermore, it cannot hydrogen bond with ZnO. It can be seen from the data that the OD increases with increasing \( \phi_{\text{CH₂Cl₂}} \) and therefore the extent of aggregation increases. Trace amounts of MeOH (from the preparation method) are believed to be responsible for the OD values being a minimum at \( \phi_{\text{CH₂Cl₂}} = 0.056 \). As a further test, MeOH was added to a sample of the parent mixture of nanocrystals dispersed CH₂Cl₂. The OD value at \( \phi_{\text{MeOH}} = 0.15 \) was lower than for all of the dispersions containing CBZ and CH₂Cl₂. As a final test a \( n \)-propylamine was added to a nanocrystal dispersion in CH₂Cl₂. The OD also decreased strongly.

The results described above provide strong support for the view that MeOH (and \( n \)-propylamine) provide dispersion stability to ZnO mixtures through hydrogen-bonding. They are not consistent with a mechanism that relies on an increase in the dielectric constant of the dispersion medium. Thus, once a critical \( \phi_{\text{co-solv}} \) is achieved, at which the ZnO surface is covered by hydrophobic alkyl groups, dispersion of nanocrystals or nanorods can be considered in terms of dispersing hydrophobic nanoparticles in a hydrophobic solvent (e.g., hydrophobic silica in toluene). The process is favoured by enthalpic and entropic contributions to the total free energy change that follows dispersion.

**Evidence for depletion flocculation for nanoparticle / polymer mixtures**

It is reasonable to expect that the stability of the nanoparticle / polymer / co-solvent dispersion during spin coating will control the photoactive layer morphology. Spin-coating removes solvent through evaporation and therefore the nanoparticle (\( \phi_{\text{np}} \) and...
polymer (\(\phi_\text{pol}\)) volume fractions must increase. Aggregation can be expected as the composition moves towards a dry nanocomposite films (Fig. 1(b)). The polymers used to prepare hybrid polymer cells are not usually designed to adsorb onto the nanoparticles in the dispersed state. They can be considered as free polymers. In such circumstances depletion flocculation can be expected provided the nanoparticle size is significantly greater than that for the polymer chains.

Turbidity measurements are normally a good means for assessing dispersion stability provided the polymer chains do not absorb. Fig. 5(a) shows the structure of a hole transporting polymer developed at Manchester for potential use in hybrid solar cells\(^7\). The polymer is extensively conjugated (cf. polystyrene, Fig. 5(b)). The UV-visible spectrum is shown in Fig. 5(c) and it can be seen that this poly(triarylamine) (PTAA) polymer absorbs light strongly at wavelengths lower than 440 nm. Unfortunately, the polymer absorbs far too strongly at 600 nm to enable turbidity measurements to be used to probe stability of ZnO / PTAA / co-solvent mixtures (Fig. 5(d)). We used PS as a model polymer system to enable turbidity measurements to be used to probe stability. PS is a reasonable model for hole transporting polymer chains because it has a solubility parameter\(^18\) (17.52 MPa\(^{1/2}\)) that is similar to that of poly(3-hexylthiophene) (18.0 MPa\(^{1/2}\)). (The solubility parameter for our PTAA has not yet been measured.) The PS used here had a molar mass of 10,000 g mol\(^{-1}\) and a polydispersity of xx [\*RR to provide data*].

![Fig. 5. Structures of (a) PTAA and (b) PS. (c) The UV-visible spectrum for PTAA. (d) The variation of OD with \(\phi_\text{pol}\) for PTAA or PS with 0.5 wt.% ZnO present is shown as well as that for pure PS solution.](image)

The turbidity of nanocrystal or nanorod dispersions containing PS was investigated (Fig. 6(a)). The data for the nanorods show that aggregation occurs when the \(\phi_\text{pol}\) value reached 0.05. This is taken as the critical polymer volume fraction for aggregation, \(\phi_\text{pol}^*\). The value for \(\phi_\text{pol}^*\) was 0.06 for the nanocrystals. The general order of the values would suggest that the nanocrystals are smaller than the nanorods and this is expected based on their estimated particle sizes (above). It should be noted that the turbidity increases shown in Fig. 6(a) were not the result of PS precipitation because the parent solutions were optically transparent (Fig. 6(a)).

Depletion flocculation is, by definition, a reversible process. Dilution of the aggregates would be expected to result in re-dispersion if the process was reversible. However, it can be seen from Fig. 6(a) that dilution of the nanorods simply decreased the turbidity in proportion to the nanorod concentration. The polymer triggered aggregation was not reversible. This implies that the aggregates correspond to a primary minimum. It can be postulated that some of the capping agents (\(n\)-propylamine and / or MeOH) desorbed. The dispersions also showed clear visual changes on triggered aggregation and this can be seen from Fig. 6(b) where micrometer–sized aggregates are evident. In order to illustrate the consequences for photoactive layer films we show an SEM (obtained using back scattered radiation) for a photoactive layer prepared using PTAA (\(M_n = 7,200\) and\(^17\) PD = 2.84) and ZnO nanocrystals. The back scattered electrons are more sensitive to the ZnO phase compared to the polymer. The image shows that aggregation of the nanocrystals has occurred within the film. The aggregates are not likely to be an efficient structure for charge transport as there are polymer-rich parts between them which are several tens of nanometers in size. A challenge, therefore, is to prevent the nanoparticle aggregation through depletion from occurring in the first place.

The data presented here show that depletion aggregation can occur for ZnO nanoparticle / polymer mixtures. This must be seen as a contributing factor to the aggregation that is evident within the photoactive layers of hybrid polymer solar cells. The
depletion interaction energy scales with particle size. Therefore, one method to reduce depletion effects should be to decrease the particle size. This could be achieved through synthetic manipulation to prepare smaller particles. This illustrates the challenges that are present within this area. A large particle size (longer rods) is beneficial from the viewpoint of PCE, but renders the dispersion more susceptible to depletion aggregation, which in turn will produce larger polymer domains within the nanocomposite films. What is required is a method to reduce depletion effects whilst using large particle sizes. It is noted that the depletion interaction energy decreases with increasing chain size due to an increase in osmotic pressure of the polymer solution. The use of longer hole transporting polymer chains could be advantageous for morphology control.

Fig. 6. (a) Effect of added polystyrene on the optical density at 600 nm for ZnO nanocrystals (closed circles) or nanorods (open squares) dispersed in CHCl3/MeOH co-solvent mixture. The co-solvent mixture containing \( \phi_{\text{MeOH}} = 0.10 \). Data points for a PS solution are also shown (open circles). The nanorod dispersion was also diluted (closed squares) to test the reversibility of aggregation. (b) An optical micrograph for the nanorods dispersed in CHCl3/MeOH containing \( \phi_{\text{pol}} = 0.06 \) of PS. (c) SEM obtained using back scattered radiation for a PTAA/ZnO nanocrystal film prepared from a CHCl3/MeOH co-solvent.

5. Conclusions and suggested areas for future work

There is a strong need for low cost solar cells. Hybrid solar cells have potential to provide efficiencies that would facilitate commercialization. However, major improvements in PCE values are needed. Chemists continue to develop improved new materials (hole transporting polymers and quantum dots) that comprise the photoactive layers. Physicists continue to improve solar cell design and improve the theoretical understanding of their performance. However, the colloid science community has not yet engaged in this important area. The optimum PCE values cannot yet be achieved because the methods to allow morphology control, and the principles that underpin them, have not been developed. Colloid scientists, with some notable exceptions, have traditionally avoided non-aqueous dispersions containing inorganic nanoparticles and hydrophobic polymers. It is hoped that more attention to the challenges that underpin this area will follow. An important step would be measurement of the phase diagrams for the nanoparticle / polymer / co-solvent dispersions for the most promising hybrid polymer solar cell systems.

The results for the ZnO dispersions shown here reveal that co-solvent composition can be used to control the interfacial structure and improve nanoparticle dispersion. Further, depletion aggregation looks to be a barrier to achieving optimum morphologies for the nanocomposite photoactive layers. What is now needed are the fundamental insights, followed rapidly by practical approaches, to enable moderately large nanorods to be distributed within hole transporting polymer films without using methods that result in the nanoparticles being encapsulated by a non-conducting layer. It is here that colloid scientists can provide the essential skills at the chemistry / physics interface to help solve a major challenge that has considerable importance.

6. Acknowledgements

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7. References