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Published in:
Acs Nano

DOI:
10.1021/nn2001118

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2011

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Download date: 22-11-2018
Infrared Emitting and Photoconducting Colloidal Silver Chalcogenide Nanocrystal Quantum Dots from a Silylamide-Promoted Synthesis

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teresting perspectives on colloidal nanocrystal quantum dots (NCs) for infrared applications1,2 were first demonstrated with PbS- and HgTe-based ultrasensitive photodetectors3,4 and photodiodes,3 as well as with CdTe/CdSe core/shell NCs with a staggered type-II band alignment,5 which were applied as luminescence labels for cancer detection.6 While the performance of NC-based devices are competitive with those based on epitaxial semiconductor heterostructures,3,4 the potential for more environmentally benign alternatives for infrared active nanocrystal materials is currently being explored in order to avoid the use of the heavy metals Pb, Hg, or Cd. Such attempts include, for example, the synthesis of Bi or Sn chalcogenides,7,8 of InAs-based NCs10,11 of Cu2Se,12 and CuInS2,13 compounds, and here we introduce a relatively unexplored class: silver chalcogenide (Ag2X, X = S, Se, Te) NCs.

Ag2Xs exhibit different crystal structures, dependent on growth conditions and temperature. In their low-temperature structure, referred to here as β-phase, Ag2Xs represent narrow band gap semiconductors with fundamental absorption edges at 0.15 eV for Ag2Se, 0.67 eV for Ag2Te, and 0.85 eV for Ag2S.14,15 Thus, heterostructures of Ag2Xs are candidates for applications in infrared optical devices operating at wavelengths covering the telecommunication spectral regions as well as the technologically important atmospheric windows in the mid-infrared region. In addition, slight deviations from stoichiometric compositions in bulk Ag2Te and Ag2Se cause large magnetoresistance effects in these materials,16,17 making them applicable also as megagauss sensors.18 Due to these appealing properties of bulk Ag2Xs, several attempts to obtain these materials in the form of colloidal NCs have been reported.19–26 With respect to the infrared activity of Ag2Xs, pioneering work has been performed by the Murray group, who demonstrated an excitonic absorption peak at about 1.15 μm wavelength for monodisperse Ag2Te NCs.

KEYWORDS: silver chalcogenides · semiconductor colloidal nanocrystals · photoconductivity · infrared emission · silylamide-promoted synthesis

ABSTRACT Here, we present a hot injection synthesis of colloidal Ag chalcogenide nanocrystals (Ag2Se, Ag2Te, and Ag2S) that resulted in exceptionally small nanocrystal sizes in the range between 2 and 4 nm. Ag chalcogenide nanocrystals exhibit band gap energies within the near-infrared spectral region, making these materials promising as environmentally benign alternatives to established infrared active nanocrystals containing toxic metals such as Hg, Cd, and Pb. We present Ag2Se nanocrystals in detail, giving size-tunable luminescence with quantum yields above 1.7%. The luminescence, with a decay time on the order of 130 ns, was shown to improve due to the growth of a monolayer thick ZnSe shell. Photoconductivity with a quantum efficiency of 27% was achieved by blending the Ag2Se nanocrystals with a soluble fullerene derivative. The co-injection of lithium silylamide was found to be crucial to the synthesis of Ag chalcogenide nanocrystals, which drastically increased their nucleation rate even at relatively low growth temperatures. Because the same observation was made for the nucleation of Cd chalcogenide nanocrystals, we conclude that the addition of lithium silylamide might generally promote wet-chemical synthesis of metal chalcogenide nanocrystals, including as-yet unexplored materials.

Published online April 18, 2011
10.1021/nn2001118

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Received for review January 11, 2011 and accepted April 18, 2011

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results and discussion

Ag2Se Nanocrystal Synthesis. The published synthetic strategies regarding Ag2Se-based spherical NCs of different quality include transformation from CdSe or ZnS NCs by complete cation exchange,19-20 the treatment of Ag NCs by Se,21 a positive microemulsion method,22,23 and double jet precipitation.22 Ag2Se nanowires have also been demonstrated, synthesized by template-engaged synthesis strategies.24-26 Although Ag2Se NCs with orthorhombic crystal structure (low-temperature β-phase) as well as cubic crystal structure (high-temperature α-phase) have been obtained, to date, no infrared optical activity has been reported. We studied quantities such as photoluminescence quantum yield, luminescence decay time, and quantum efficiency in photoconductivity as a measure for the quality of the obtained semiconductor NCs and in order to test their potential for applications in infrared optical devices. The latter are of importance because Ag-based NCs can be expected to cause less environmental impact than the NC materials currently used in infrared optical devices, which contain toxic heavy metals.

As a general trend, a decrease of photoluminescence intensity with increasing size is observed in all infrared emitting NCs.29-31 Therefore, to obtain photoluminescent Ag2Se NCs, we developed a novel solution phase synthesis that resulted in especially small NC sizes. In our preliminary experiments, we followed the recently suggested concept of a quasi-seeded growth by cation exchange-mediated nucleation. This concept was demonstrated for PbSe NCs making use of SnSe intermediate nuclei.29 In fact, the proposed mechanism was developed following the observed correlation between final NC size and concentration of the applied Sn precursor, tin(II) bis[bis(trimethylsilyl)amide], (Sn[N(SiMe3)2]2). For Ag2Se NCs, we adapted the given recipe for PbSe NCs by replacing the Pb precursor with an appropriate Ag precursor, in our case, silver(I) trifluoroacetate (AgTFA). Oleylamine (OLA) was used as a coordinating solvent and trioctylphosphine selenide (TOPSe) as the Se source. To guarantee that the obtained NCs exhibited the orthorhombic crystal structure (low-temperature modification), we restricted the nucleation temperature to values below 100 °C. Within this temperature limit, a direct reaction between AgTFA and TOPSe showed only a very slow nucleation after injection, and eventually very large Ag2Se particles were obtained (Figure S1 in Supporting Information), likely due to insufficient reactivity of the precursors. However, the co-injection of Sn[N(SiMe3)2]2, the precursor used for the formation of SnSe seeds,29 together with the TOPSe resulted in an instantaneous nucleation and growth of Ag2Se NCs. These NCs exhibit photoluminescence with a peak at 1060 nm, which is red-shifted with respect to the absorption edge found at 770 nm (Figure S2). Even though the chosen synthesis route appears to be successful, in that luminescent Ag2Se NCs were achieved, the underlying mechanism seems to differ from that reported for PbSe.29 In contrast to the case of PbSe, for the Ag2Se NCs, the amount of Sn[N(SiMe3)2]2 does not influence the final size of the obtained NCs. The NC size depends neither on reaction temperature, varied between room temperature and 100 °C, nor on growth time.

In order to cross-check these observations, we repeated the synthesis by replacing the Sn[N(SiMe3)2]2 with another highly reactive silylamide. Specifically, with lithium bis(trimethylsilyl)amide, (Li[N(SiMe3)2]), Ag2Se NCs were also obtained, excluding the relevance of any cation exchange processes from SnSe nuclei for the present synthesis. Moreover, the Ag2Se NCs obtained by the addition of Li[N(SiMe3)2] outperformed even those obtained with Sn[N(SiMe3)2]2 with respect to colloidal stability, photoluminescence quantum efficiency, and synthesis yield, typically found to range between 70 and 90%.32 We thus conclude that the presence of the silylamide [N(SiMe3)2] groups is the essential factor in speeding up the nucleation rate of this synthesis process. In particular, we suggest that the Ag2Se NC synthesis follows a route as sketched in Scheme 1.

In the first step, a metathesis reaction between the silver salt (AgTFA) and the lithium silylamide results in the generation of short-lived silver silylamide complexes, depicted as [Ag][N(SiMe3)2] in Scheme 1.
subsequent decomposition of these silver silylamide complexes provides active silver centers [Ag0], which instantly react with TOPSe to form Ag2Se NCs. This overall scheme takes into account the following considerations: (i) The metathesis reaction between AgTFA and Li[N(SiMe3)2] is driven by the higher ionization potential of silver (\( I_1(Ag) = 731 \text{ kJ/mol} \)) as compared to that of lithium (\( I_1(Li) = 520.2 \text{ kJ/mol} \)). This difference in ionization potential results in a more favorable coordination of silver by N(SiMe3)2 groups in solution; in other words, the creation of covalent Ag–N bonds results in less dissociative silver silylamide. In addition, the subsequent decomposition of the silver silylamide complex ensures the irreversibility of this process. (ii) The metathesis reaction suggested above is supported by the similar reaction between potassium silylamide and silver chloride previously used to ex situ synthesize silver silylamide as bulk crystals. This ex situ synthesized bulk silver silylamide has a tetramer crystal structure \( \{[Ag(\mu-N(SiMe3)2)]_2\}_4 \) and is thermally robust up to its melting point at approximately 275 °C. However, it cannot be used as Ag precursor in our synthesis because, surprisingly, it is insoluble in hydrocarbons. (iii) The decomposition of the silver silylamide to silver in oleylamine environment is plausible because attempts to solve the bulk \( \{[Ag(\mu-N(SiMe3)2)]_2\}_4 \) in hot tetrahydrofuran or pyridine have resulted in its decomposition to silver. (iv) The tendency of silylamides to thermally decompose has been observed for several other silylamides, and it has actually been used for the synthesis of elemental Pb, Bi, and Ge NCs. (v) The hypothesis that the reaction between silylamide derivatives and TOP chalcogens includes reduction to active metal centers as intermediate species was originally proposed by Polking et al., who described the synthesis of GeTe. We proved this hypothesis by performing a synthesis identical to that of Ag2Se NCs, but without the addition of Se, resulting in metallic Ag NCs. These are easily identified by a narrow absorption peak found at 410 nm, due to the well-known plasmon resonance of Ag NCs at this wavelength as well as by energy-dispersive X-ray spectroscopy (Figure S3 in Supporting Information). (vi) The reaction of TOPSe with Ag to Ag2Se NCs is not surprising because the strategy of treating synthesized Ag NCs by chalcogens in order to obtain Ag2X NCs has been reported previously.

In the present synthesis of Ag2Se NCs, the processes described in Scheme 1 are very fast and result therefore in exceptionally small sizes of NCs, in the range between 2 and 4 nm, as will be shown.

The Ag2Se NCs obtained by the co-injection of lithium silylamide exhibit excitonic absorption features in the near-infrared region (Figure 1A), which can be tuned by size. For 2.0 nm Ag2Se NCs, an excitonic absorption peak is observed close to 750 nm, while 3.4 nm NCs exhibit a shoulder at 1000 nm and an absorption onset at 1300 nm. The size of the NCs is mainly controlled by the Se to Ag ratio while increasing the growth time even results in a size focusing (Figures S4 and S5 in Supporting Information). For both sizes of NCs, luminescence can also be observed, with maxima at 1030 and 1250 nm, respectively. Thus there is a considerable Stokes shift on the order of 200 nm for both NC sizes, indicating the presence of (surface) defects, which also restrict the quantum yield, measured at 1.76% for the 2.0 nm Ag2Se NCs. With increasing NC size, the intensity decreases, which is also observed for all other NC systems with infrared emission. The situation can be improved by growing an inorganic shell around the Ag2Se cores. To accomplish this, we injected zinc acetate solved in oleylamine into the as-grown Ag2Se NC solution, containing an excess of Se, to obtain the ZnSe shell. ZnSe
function of Ag₂Se nanocrystals before (black) and after (gray) growth of a ZnSe shell, as deduced from SAXS experiments (Figure S11 in Supporting Information). Further, the composition of the Ag₂Se and Ag₂Se/ZnSe core/shell NCs is proven by energy-dispersive X-ray spectroscopy (Figure S9), confirming the expected 2 to 1 ratio between the Ag and Se, respectively, and a shell thickness corresponding to approximately 1 monolayer of ZnSe around the Ag₂Se NCs. The small NC sizes and their low crystal symmetry inhibit an accurate determination of their lattice parameters by wide-angle X-ray scattering (WAXS). The WAXS spectrum of the Ag₂Se NCs shows only a broad peak between 2θ angles of 30 and 45°, due to the overlap of a number of size broadened diffraction peaks (Figure S10).

Small-angle X-ray scattering (SAXS) analysis (Figure S11 in Supporting Information) provides accurate measures of size distributions of large ensembles of NCs. In particular, for the smallest Ag₂Se NCs, the size distribution function (see Figure 2D), weighted by particle volume as computed by generalized indirect Fourier transformation,41 shows a NC diameter of 2.0 nm and a standard deviation of 19%. When the same analysis is applied after the growth of a ZnSe shell, a mean size of 2.2 nm is obtained, directly proving the crystallization of ZnSe on the Ag₂Se NC surface, similar to what has been reported for CdSe/ZnSe NCs.42 In the distribution functions shown in Figure 2D, the scattering length contrast between Ag₂Se and ZnSe is not considered but can be taken into account by fitting the raw SAXS scattering curves by means of the GIFT-NG software with a spherical core, or core/shell model. From the data shown in Figure S11, we derive an Ag₂Se core diameter of 1.92 nm and a shell thickness of 0.22 nm. This results in a total outer diameter of the Ag₂Se/ZnSe NCs of 2.4 nm and a size distribution of 22%.

Ag₂Se Nanocrystals as Sensitizers in Photodetectors. Most importantly, the obtained NCs are useful in infrared optical devices, such as photodetectors. To obtain photocconductivity in NC assemblies, two strategies were chosen due to (i) its high band gap energy as compared to that of Ag₂Se, resulting in a type-I band alignment between core and shell; (ii) its low toxicity; and (iii) its chemical robustness. Even though there is a considerable mismatch between the lattices of ZnSe (zinc blende structure with a lattice constant \( a = 7.568 \) Å) and Ag₂Se (orthorhombic crystal structure with \( a = 4.337, b = 7.070, c = 7.773 \) Å),40 applying a ZnSe shell increases the PL intensity by up to 40% (Figure 1B). The Ag₂Se/ZnSe core/shell structure is also more stable than the core-only Ag₂Se NCs, and after a storing time of 6 months, the difference between PL intensities increases to a ratio of 5:1 (Figure S6). Growing a ZnSe shell results in a small red shift of the luminescence (Figure 1B), which is associated with the overall increase of the NC size. The PL decay time is only slightly affected: under 150 fs pulsed excitation, an almost monoeponential decay is observed with a characteristic decay time of 131 ns for the Ag₂Se core-only NCs and of 122 ns for the Ag₂Se/ZnSe core/shell NCs (Figure 1C,D). Both decay times are smaller than those observed with the same setup for the established infrared active NC materials PbS (2800 ns) and PbSe (1200 ns). However, the decay time is longer than for HgTe NCs (70 ns), which are well-known for their high quantum yields in both PL and photocconductivity experiments. Due to this lifetime, Ag₂Se might also be a promising candidate for photoconducting devices.4,31

The sizes and size distributions of the NCs were determined from overview images taken by transmission electron microscopy (TEM). Figure 2A shows a typical image achieved from the smallest Ag₂Se NCs. To obtain size histograms, at least 100 individual NCs were analyzed. Figure 2B shows size histograms from two batches with mean sizes of 2.0 ± 0.6 and 3.4 ± 0.7 nm, as determined from Gauss fits. Compared to previously reported Ag₂Se NCs, these obtained NCs are exceptionally small. The crystal structure of the NCs is determined by the indexing of selected area electron diffraction (SAED) rings (Figure S7 in Supporting Information), which confirmed that the NCs are Ag₂Se in its low-temperature \( \beta \)-modification (P2₁,2₁,2₁ structure group). This is also proven by the high-resolution TEM image in Figure 2C, showing an approximately 2.5 nm large NC oriented in the [012] direction and by the fact that the deduced lattice constants are in accordance with those expected for \( \beta \)-type Ag₂Se (a model NC of the same orientation is presented in Figure S8 of the Supporting Information). Furthermore, the composition of the Ag₂Se and Ag₂Se/ZnSe core/shell NCs is proven by energy-dispersive X-ray spectroscopy (Figure S9), confirming the expected 2 to 1 ratio between the Ag and Se, respectively, and a shell thickness corresponding to approximately 1 monolayer of ZnSe around the Ag₂Se NCs. The small NC sizes and their low crystal symmetry inhibit an accurate determination of their lattice parameters by wide-angle X-ray scattering (WAXS). The WAXS spectrum of the Ag₂Se NCs shows only a broad peak between 2θ angles of 30 and 45°, due to the overlap of a number of size broadened diffraction peaks (Figure S10).

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Ag₂Se Nanocrystals as Sensitizers in Photodetectors. Most importantly, the obtained NCs are useful in infrared optical devices, such as photodetectors. To obtain photocconductivity in NC assemblies, two strategies...
were employed. Photoconductivity can be obtained (i) by manipulating the NC ligand shell in order to
decrease the average NC distance in the film and thus
increasing conductivity,3–5,8 or (ii) by forming donor/
acceptor type bulk heterojunctions providing charge
separation within the film as well as sufficient charge
transport channels for electrons and holes.43 The latter
approach has the advantage that the protecting ligand
shell is fully restored, resulting in a higher stability in air,
as compared to the ligand-manipulated NC layers.
Such a donor/acceptor heterojunction is achieved by
blending the Ag2Se NCs with PCBM ([6,6]-phenyl-C61-
butyric acid methyl ester), a soluble derivative of C60.
The PCBM usually acts as efficient electron acceptor,
assuming that the work function of the NCs is smaller
than that of the PCBM (of approximately 4.3 eV).44 The
efficiency of the photoconducting device is also in-
creased by the addition of the PCBM because the
electron mobility in the PCBM is superior to that
typically observed in NC films. To measure the photo-
conductivity, a blend with a weight ratio of 1:4 Ag2Se
NCs/PCBM solved in chlorobenzene is drop-casted
onto interdigitated gold electrodes with a distance of
20 μm and an active area of 13.5 mm², fabricated on
glass substrates. The photosensitivity of this blend is
evidenced by the current/voltage characteristics,
showing a 7.3 times current increase under 4 mW/cm²
illumination with a broad-band infrared light source
(λ > 850 nm, Figure 3A). That this photosensitivity is
caused by absorption only in the Ag2Se NCs is evi-
denced by the fact that the measured response is
observed at wavelengths well below the absorption
onset of PCBM. The latter is found at a wavelength of
750 nm in absorbance as well as in photoconductivity
(Figure S12 in Supporting Information). Thus the
responsivity spectrum in Figure 3B, starting at a wave-
length of 900 nm, is also caused solely by absorbance
in the Ag2Se NCs. At this wavelength, the responsivity
amounts to 0.2 A/W, corresponding to a quantum
efficiency of 27%. While this value is not as good as
those reported for PbS/PCBM blends measured under
identical conditions,43 further optimizations are possi-
able. With the Ag2Se NCs/PCBM blends, a photore-
sponse is obtained up to a wavelength of 1300 nm
(Figure 3B). This wavelength is somewhat longer than
the cutoff wavelength of standard photodetectors
based on crystalline silicon, and it is within the spectral
region of minimum absorbance of human tissues and
blood, so that biomedical applications of Ag2Se NC
detectors could be feasible.

Other Ag Chalcogenide Nanocrystals and Generality of the
Silylamide-Promoted Synthesis. As shown in Scheme 1, the
described synthesis route is not necessarily restricted
to selenides but might also be applicable to tellurides
and sulfides. In fact, both Ag2S and Ag2Te could be
obtained by replacing TOPSe with the corresponding
TOPX. The absorption and PL spectrum of 3.1 nm Ag2S
are shown in Figure 4A. The energy band gaps (Eg) of
3.1 and 3.6 nm Ag2S NCs, deduced via the Bardeen or
Tauc equation, are found at approximately 1.45
and 1.35 eV, respectively. As expected, the band gap
energies are increased with respect to that of bulk
material (0.85 eV), in contrast to what has previously
been reported for larger sized Ag2S NCs.45 Ag2Te NCs
are also obtained, and for 3.2 nm large NCs, photolu-
minescence is found to peak at 1300 nm and to reach
up to 1500 nm (Figure 4C). The photoluminescence
from Ag2Te NCs has not been previously reported and
thus represents a novel materials system with potential for further applications in infrared devices. EDX spectra show the expected 2:1 Ag/Te ratio for the Ag₂Te NCs, whereas for the Ag₂S sample, an excess of Ag is detected (Figure S13 in Supporting Information). This might be caused by the low reactivity of TOPs, resulting in a mixture of Ag and Ag₂S NCs in the sample. The sizes of the Ag₂S and Ag₂Te NCs shown in Figure 4 were deduced from the TEM images in Figures S14 and S15.

Since lithium has very low ionization energy, the lithium-silylamide-promoted synthesis could serve as a general route toward metal chalcogenide NCs. We have also obtained good results for CdSe and CdTe NCs, as shown in Figure 4D,E. Their diameters were deduced from their optical transition energies by using an experimentally derived sizing formula reported by Yu et al.47 Furthermore, we performed successful synthesis with the same scheme for ZnSe, MnSe, PbSe, and Cu₂Se, proving that the in situ synthesis of metal silylamides is a powerful strategy for the one-pot synthesis of a large class of small sized chalcogenide NCs, including as-yet unexplored materials.

CONCLUSIONS

We demonstrated a high-yield wet-chemical synthesis of 2.0 to 3.4 nm β-type Ag₂Se NCs, with a size control given by the Ag to Se precursor ratio. The optical absorbance and photoluminescence spectra in the infrared region reveal strong confinement effects. While the growth of a ZnSe shell is proven to enhance the photoluminescence intensity, mixing the NCs with a fullerene results in photocconductivity signals up to a wavelength of 1200 nm. Due to the low toxicity of these materials, the Ag₂Se/ZnSe core/shell NCs might be used as an alternative to the standard infrared materials containing heavy metals such as Pb, Cd, and Hg. We found that a key to the synthesis of such small Ag₂Se NCs is the co-injection of a highly reactive silylamide, and we applied the same synthesis route to the synthesis of Ag₂Te, Ag₂S, and other nanocrystal materials, demonstrating the generality of this approach.

EXPERIMENTAL SECTION

Materials. Silver(I) trifluoroacetate (AgTFA, 98%), tin(II) bis[(trimethylsilylamide) (Sn[NSiMe₃]₂)₂], lithium bis[(trimethylsilyl)amide] (Li[NSiMe₃]₂), Zn(acetate)₂, cadmium(II) chloride (99.99%), lead(II) oxide (99.999%), hexamethyldisilathiane (purum grade), octadecene (90%, techn.), chloroform (99.9%), toluene (99.9%), tetrachloroethylene (99.9%), hexane (99%), ethanol, and methanol were purchased from Sigma-Aldrich; tri-n-octylphosphine (TOP, 97%) from Strem; selenium (99.999%) from Alfa Aesar; oleic acid (OLA, 90%), sulfur (99.998%), tellurium (99.99%), silver(I) trifluoroacetate (AgTFA, 98%), tin(II) bis[(trimethylsilylamide) (Sn[NSiMe₃]₂)₂], lithium bis[(trimethylsilyl)amide] (Li[NSiMe₃]₂), oleic acid (OA, 90%), sulfur (99.998%), tellurium (99.99%), zinc acetate (Zn(acetate)₂), cadmium(II) chloride (99.99+ %), lead(II) oxide (99.999%), hexamethyldisilathiane (purum grade), octadecene (90%, techn.), chloroform (99.9%), tetrachloroethylene (99.9%), hexane (99%), ethanol, and methanol were purchased from Sigma-Aldrich; tri-n-octylphosphine (TOP, 97%) from Strem; selenium (99.999%) from Alfa Aesar; oleic acid (OLA, 80–90%) from Acros. All were used without previous purification. The 10% (w/w) solutions of selenium or tellurium in TOP (TOPSe and TOPTe, respectively) and 5% (w/w) of sulfur (TOPS) were prepared by dissolving the appropriate amounts of chalcogens in TOP under N₂ atmosphere.

Synthesis of Ag₂Se Nanocrystals. All syntheses were carried out under oxygen-free and dry atmosphere using standard Schlenk-line technique. A recipe to produce the smallest (2.0 nm in size) Ag₂Se NCs is given below.

AgTFA (1 mmol) and OLA (10 mL) were heated up to 70 °C for dissolving and purification under vacuum for 1 h and then flushed with argon for 30 min. Li[NSiMe₃]₂ (0.4 g) was dissolved in 10% (w/w) TOPS (2.5 mL) with sonication and then swiftly injected. The reaction was continued for 1 h at constant temperature. After cooling, the NCs were isolated by a chloroform/methanol mixture and by centrifugation. The non-polar/polar washing procedure was repeated once, and the NCs were then solved in a common nonpolar solvent.

The average size of the produced NCs can be well controlled by the ratio between Se and Ag precursors (Figure 5 in Supporting Information). The reaction was tested in a temperature range between room temperature and 100 °C. The time of reaction is highly temperature dependent and lasts from 2 min to several days in order to achieve the optimal size dispersivity. The amount of silylamide does not essentially influence the final size of the NCs.

Synthesis of Ag₂Se/ZnSe Core/Shell Nanocrystals. Zn(acetate)₂ (1.5 mmol) was dissolved in dried OLA (5 mL) inside a glovebox by heating it to 100 °C for 1 h. The obtained zinc precursor was injected into an Ag₂Se NC solution, synthesized at 70 °C according to the procedure described above, and the temperature was kept constant for another 1 h. The NCs were cooled to RT and washed twice with a chloroform/methanol mixture and centrifugation, and then some amount of OA was added to improve the colloidal stability. The amount of 0.3 M Zn acetate solution (in OLA) was calculated to be equimolar to the Se excess, still remaining after Ag₂Se NC synthesis.

Syntheses of Other Materials. The Ag₂Te, Ag₂S, CdSe, and CdTe NCs were synthesized similarly to Ag₂Se, taking appropriate TOP chalcogenides and adjusting the reaction temperature.

Characterization of Nanocrystals. Linear absorption spectra were taken using a JASCO V670 spectrometer operating from 200 to 2700 nm. TEM and HRTEM images and electron diffraction patterns were obtained using JEOL 2011 FaSTEM microscope operating at an accelerated voltage of 200 kV. EDX elemental analyses were performed on a JEOL JSM-6400 SEM microscope. X-ray diffraction patterns were collected with a Siemens D501 powder diffractometer operating in Bragg–Brentano focusing geometry using Cu Kα radiation (1.5406 Å) and a graphite monochromator on the secondary side. Small-angle scattering (SAXS) data were measured using synchrotron radiation at the μ-Spot beamline of the BESSY II storage ring (Helmholtz-Zentrum Berlin fuer Materialien und Energie). Data were recorded with a 2D detector using the standard SAXS setup48 at an X-ray energy of 15 keV.

The excitation source for the photoluminescence measurements was a Spectra Physics continuous wave argon ion laser, model 163A 5216, emitting at a wavelength of 514 nm. The maximum emission power of 50 mW was utilized for the experiments. The exciting beam was chopped by a chopper wheel and focused on the cuvettes containing the NCs in solution. The photoluminescence was collected by two CaF₂ lenses and spectrally resolved by an Acton Research Corporation Spectra Pro 150 monochromator. The monochromatic light was detected by a nitrogen-cooled Judson J10-M204-B10 M InSb photodiode. This signal was amplified with a Judson PA-7 preamplifier and a Stanford Research System SR510 lock-in amplifier, which used the excitation source chopper frequency.
as a reference. A self-written program running on a personal computer operated the monochromator over the desired spectral range and evaluated the amplified signals at the different wavelengths to obtain the photoluminescence spectra. To quantify the efficiency, the incident and reflected laser power was measured and the luminescence was focused onto a high sensitivity pyrometer from Spectrum Detectors Inc. (STEP 49, calibrated by the National Institute of Standards and Technology (NIST)), placed in front of the entrance slit of the grating spectrometer. Losses at the lenses and the utilized RG 550 long path filter were taken into account. While the measurement collected the PL signal within a room angle of 0.236 sr, as given by the F-number of the collecting lens, the total emitted power was obtained by integration over a sphere.

Photocurrent measurements were carried out using the same optical elements, spectrometer, and lock-in amplifier as was used for the PL experiments. The I–V characteristics were measured with a Keithley 236 Source Measure Unit, and for illumination, a 40 W halogen lamp was used. To measure the illumination power, a high sensitivity pyrometer from Spectrum Detectors Inc. (STEP 49) was used.

Acknowledgment. The authors wish to thank the Austrian Science Fund FWF (Project SFB IR_ON) and the EU’s seventh Framework Programme (FP7/2007-2013, No. 226716) for financial support, as well as Prof. G. Knor for allowing us to use his equipment for linear absorbance measurements. We are also thankful to Dr. U. Monkovius, S. Minniberger, O. Fuchs, E. Pachinger (University Linz), and B. Aichmayer, S. Siegel, and C. L. MPI (of Colloids and Interfaces in Potsdam) for technical support.

Supporting Information Available: Supporting Figures S1–S15 with descriptions. This material is available free of charge via the Internet at http://pubs.acs.org.

REFERENCES AND NOTES


32. The amount of Ag2Se NCs was roughly estimated from balancing the solid remains from NC solutions with well-defined volumes, taking into account the amount of ligands (TOP is assumed as ligand), as determined from EDX spectra. The yield is the ratio between Ag2Se NCs obtained from the synthesis and total Ag2Se amount as calculated from the AgTFA reaction (Scheme 1).