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ABSTRACT

We report the use of seed-mediated growth as a simple and versatile approach to the synthesis of penta-twinned Cu nanorods with uniform diameters and controllable aspect ratios. The success of this approach relies on our recently demonstrated synthesis of Pd decahedra as uniform samples, together with tightly controlled sizes in the range of 6-20 nm. When employed as a seed, the Pd decahedron can direct the heterogeneous nucleation and growth of Cu along the five-fold axis to produce a nanorod with a uniform diameter defined by the lateral dimension of the original seed. Due to a large mismatch in lattice constant between Cu and Pd (7.1%), the deposited Cu is forced to grow only along one side of the Pd decahedral seed, generating a nanorod with an asymmetric distribution of Cu, with the Pd seed being situated at one of the two ends. According to their extinction spectra, the as-obtained Cu nanorods could form a stable colloidal suspension in water and be stored in a capped vial under the ambient conditions for at least 6 months without noticeable degradation. This excellent stability allows us to systematically investigate the size-dependent surface plasmon resonance properties of the penta-twinned Cu nanorods. With their transverse modes being positioned at 560 nm, their longitudinal modes can be readily tuned from the visible to the near-infrared region by controlling their aspect ratios.

Keywords: copper · penta-twinned nanorods · surface plasmon resonance · seed-mediated growth
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1. Introduction

In recent years, Cu nanocrystals have received increasing attention for their great performance in a number of applications related to electronics, display, and catalysis.[1-8] However, owing to the difficulty in reducing Cu(II) or Cu(I) to Cu(0) in an aqueous system, as well as the susceptibility of elemental Cu to oxidation upon exposure to air, there are only a limited number of reports on the syntheses of Cu nanocrystals,[9] with notable examples including those for nanoparticles, nanocubes,[10-13] nanoplates,[14] nanorods[15-19] and nanowires.[20-22] It should be noted that, upon further characterization, some of the reported protocols for the synthesis of Cu nanocubes were found to produce nanocrystals composed of Cu₂O rather than Cu.[23] Among nanocrystals with different shapes, those with a one-dimensional structure are of particular interest for a variety of applications. For example, Cu nanowires can be explored for the fabrication of touchscreens and thin-film solar cells due to their high electrical conductivity and high transparency in the visible region.[24-27] In addition, it has been shown that many reactions catalyzed by Cu nanocrystals are highly sensitive to the type of facet present on the surface. To this end, Cu nanocubes covered by \{100\} facets have shown higher activity and selectivity toward the reduction of carbon dioxide (CO₂), allowing for the formation of ethylene rather than methane at lower overpotentials.[4] The deoxygenation of aromatic epoxides, catalyzed by \{111\}-bound Cu plates, generated both trans- and cis-stilbene oxides, while cis-stilbene oxide became the dominant product when the reaction was catalyzed by \{100\}-covered Cu nanocubes or pentagonal nanowires.[5] According to what has been reported in the literature, penta-twinned Cu nanowires or nanorods are expected to have remarkable catalytic performance owing to the predominance of \{100\} facets on their surface, as well as the presence of multiple twin defects.

There are a number of reports on the synthesis of Cu nanorods, but most of them are plagued by low purity and/or poor reproducibility.[15-19] To this end, Tanori and co-workers prepared cylindrical Cu nanorods by employing colloidal assemblies as templates.[15] The Cu nanorods were formed during the reduction of copper(II) bis(2-ethylhexyl)sulfosuccinate (Cu(AOT)₂) in an interconnected network of cylinders obtained by adjusting the ratio of water to isooctane. The purity of the Cu nanorods was below 40%, with the remaining product consisting of multiply-twinned particles. Mott and co-workers reported the synthesis of Cu nanorods through a careful control of reaction temperature and a combination of proper capping agents.[17] In this method, the growth of nanorods was attributed to an interplay between the two capping agents (oleic acid
and oleylamine) present in the system. However, it was problematic to achieve high purity for the Cu nanorods using this approach. Cha and co-workers reported a synthesis of Cu nanorods using the polyol process, in which ethylene glycol (EG) served as both the solvent and a source of the reducing agent. Poly(vinyl pyrrolidone) (PVP) was used as a capping agent, similar to the synthesis of Ag nanowires. However, the percentage yield of nanorods in the final product was very low, likely due to the high reactivity of Cu. It can be concluded that it remains to be a challenge to produce Cu nanorods as uniform, pure samples, together with tunable, well-controlled aspect ratios for systematic investigation of their optical and electrical properties.

As an alternative to the one-pot approach, seed-mediated growth offers a powerful route to the production of nanocrystals with well-controlled sizes, shapes, compositions, and structures by avoiding the complicated, and often poorly understood nucleation process involved in a one-pot synthesis. In seed-mediated growth, the synthesis is separated into two discrete steps. The first step is devoted to the production of seeds only while the second uses the seeds as nucleation sites to generate the desired nanocrystals. In the case of seed-mediated growth, Jin and co-workers recently demonstrated an attractive strategy for the preparation of Cu nanorods by growing from single-crystal Au seeds. Owing to the large lattice mismatch between Cu and Au, twin planes were formed on the single-crystal Au seeds during a growth process, promoting their anisotropic growth into penta-twinned Cu nanorods. In this method, the purity of the Cu nanorods was significantly improved, but this method still faces challenges in controlling the size uniformity of the nanorods. The Cu nanorods also grew laterally too, generating penta-twinned nanorods with tapped diameters along the long axis. In this regard, five-fold twinned decahedra should be better seeds for the synthesis of penta-twinned nanorods. Significantly, penta-twinned nanorods could naturally grow from decahedral seeds along the <110> direction as long as the {100} side faces can be passivated by a suitable capping agent. Using this approach, a number of high-quality penta-twinned nanorods have been synthesized, including those made of Au, Ag, and Pd, albeit this strategy has never been applied to the synthesis of Cu nanorods.

In the present work, we have demonstrated a facile and reliable synthesis of Cu nanorods by taking advantage of the recent progress in the synthesis of Pd decahedral seeds using a polyol method based on diethylene glycol (DEG). Owing to their well-controlled small sizes, high purity, and good uniformity, we have successfully obtained Cu nanorods with diameters as thin as 20.9±2.5 nm. The length, and thus the aspect ratio of the Cu nanorods, could be readily tuned
by varying the ratio of Cu precursor to Pd decahedral seeds involved in the synthesis and/or the growth time. The Cu nanorods with different aspect ratios were found to exhibit remarkably different optical properties. Specifically, their longitudinal localized surface plasmon resonance (LSPR) peaks could be tuned from the visible to the near-infrared (NIR) region by varying their aspect ratios. To our knowledge, this report constitutes the first systematic study of the tunable LSPR properties of Cu nanorods, which may find use in plasmonics, surface-enhanced Raman scattering (SERS), and other related applications.[36-41]

2. Results and Discussion

In a typical synthesis, an aqueous solution containing hexadecylamine (HDA), glucose, and CuCl₂ was magnetically stirred at room temperature overnight, followed by the introduction of a specific amount of Pd decahedral seeds while Ar was blown over the reaction solution to remove the air. The mixture was then heated in an oil bath under stirring to initiate the seed-mediated growth process. The Pd decahedral seeds were, in turn, prepared using a polyl method recently developed by our group.[37] Figure 1a shows a typical transmission electron microscopy (TEM) image of the as-prepared Pd decahedra, with an average size of 19.6±1.7 nm and purity approaching 100%. The definition of the size of a decahedron is shown in Figure S1a. The inset of Figure 1a highlights the five-fold twinned structure contained in each decahedron.

In our previous work, we have demonstrated that penta-twinned nanowires and single-crystal nanocubes of Cu could be produced in an aqueous solution by reducing Cu(II) ions with glucose in the presence of HDA, which can serve as a capping agent for the Cu(100) surface.[13] Using a similar protocol, we further demonstrated the synthesis of Pd@Cu core-shell nanocubes by introducing Pd cubic seeds into the reaction solution.[42] By separating the nucleation and growth into two different steps, we were able to achieve a greater control over the size of the resultant nanocrystals. Inspired by the results from these studies, here we demonstrate that this synthetic approach can also be extended to Pd decahedral seeds lined with twin defects. Figure 1b shows a TEM image of the Cu nanorods synthesized using the standard procedure. Interestingly, we can easily differentiate the Pd decahedral seed from the deposited Cu due to a large difference in the electron scattering efficiency of these two elements. In examining more than 50 nanorods, the Pd seeds were always found at one of the two ends of each individual Cu nanorod, suggesting the involvement of symmetry breaking during the nucleation and growth of Cu. Figure 1c shows a
low-magnification TEM image of the as-obtained Cu nanorods, indicating a high percentage yield for the final product. The average diameter of these nanorods was found to be 20.9±2.5 nm, which was consistent with the size of the initial Pd decahedral seeds, implying very little growth along the transverse direction.

Figure 1d shows a UV-vis-NIR extinction spectrum recorded from an aqueous suspension of the Cu nanorods prepared using the standard protocol. The as-obtained Cu nanorods could form a stable colloidal suspension in deionized water and be stored in a capped vial under the ambient conditions for at least 6 months without noticeable degradation according to the UV-vis-NIR spectra shown in Figure S2. The Cu nanorods exhibited two LSPR peaks, positioned at 560 nm and 920 nm, respectively. It is well established that a metal nanorod has both transverse and longitudinal LSPR modes, corresponding to light-induced oscillations of free electrons parallel to the short and long axes of the nanorod, respectively.[33] In general, the transverse mode appears at a shorter wavelength than the longitudinal mode. As such, we could assign the peaks at 560 and 920 nm to the transverse and longitudinal LSPR modes, respectively. It is interesting to compare the Cu nanorods with those made of Ag and Au. For nanorods with an aspect ratio of 3 and a similar diameter of 20 nm, their longitudinal peaks are positioned at 695, 700, and 702 nm when they are composed of Cu, Au, and Ag, respectively.[36,43] This indicates that the longitudinal plasmon peak of a nanorod was determined by its aspect ratio rather than the composition. In this regard, the significantly lower cost of Cu relative to Ag and Au ($0.007 vs. $0.612 and $40.831 per gram) makes Cu nanorods most attractive for large-scale application.[44]

To resolve the morphology, structure, and elemental composition of the Cu nanorods, we used high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM), high-resolution TEM (HR-TEM), energy dispersive X-ray (EDX), and X-ray diffraction (XRD) to analyze the samples. The Pd decahedral seed at one of the ends of each Cu nanorod could be easily resolved under HAADF-STEM due to the large difference in contrast between Pd and Cu (Figure 2, a and b). Figure 2c shows the HR-TEM image of a Cu nanorod oriented with one of its side faces parallel to the electron beam. The fringes with lattice spacing of 0.21, 0.18, and 0.13 nm could be indexed to the {111}, {200}, and {220} planes of Cu, respectively, consistent with the previous results obtained from penta-twinned Cu nanorods or nanowires.[45] The elemental distributions of Pd and Cu in the nanorod were further analyzed by EDX mapping. As clearly shown in Figure 3a, the Pd decahedral seed was located at one of the two ends of a nanorod.
Figure S3 shows the XRD pattern recorded from a film of Cu nanorods drop-cast on a glass substrate. The three peaks at $2\theta = 43.3$, 50.7, and 74.2° correspond to diffractions from \{111\}, \{200\}, and \{220\} planes of face-centered cubic (fcc) Cu (JCPDS #03-1018). Importantly, the XRD pattern did not show any diffraction peak associated with Cu$_2$O or CuO, indicating that the nanorods were essentially made of Cu. Based on the HAADF-STEM, HR-TEM, EDX mapping, and XRD data, we can conclude that the Cu nanorods possessed a penta-twinned structure and bound by five \{100\} side facets, together with ten \{111\} facets at the two ends (Figure 3b). The deposition of Cu proceeded along the $<110>$ direction from one of the two available sides of a Pd decahedral seed.

To gain insight into the details of morphological evolution for the nanorods, we analyzed the products sampled at different stages of a standard synthesis. Figure 4, a and b, shows TEM images of the products obtained in the early stage of a synthesis. At $t=20$ min (Figure 4a), Cu atoms had already nucleated on one side of the Pd decahedral seed to initiate anisotropic growth. The symmetry breaking can be attributed to a large mismatch (7.1%) in lattice constant between Pd and Cu.\[42\] A similar phenomenon was observed when Pd nanocubes and Au nanospheres were used as seeds for the growth of Cu nanorods.\[42,19\] At the same time, a weak LSPR peak appeared at 560 nm (Figure S4), indicating the reduction of Cu(II) ions to Cu(0) atoms for their deposition onto the Pd seeds. The newly deposited Cu(0) atoms then served as active sites for subsequent growth. Extending the reaction time further to 40 min resulted in the formation of longer nanorods, with an aspect ratio of around 3. In the corresponding UV-vis-NIR extinction spectrum, there was still a peak at 560 nm, corresponding to the transverse LSPR mode. In addition, a new peak appeared at 695 nm, which could be assigned to the longitudinal LSPR mode. These results suggest that the length and thus aspect-ratio of the Cu nanorods could be conveniently controlled by simply terminating the synthesis at a specific reaction time.

To better understand the mechanism responsible for the formation of anisotropic Cu nanorods, we conducted a set of control experiments by systematically varying the reaction parameters. In general, a capping agent is necessary for the formation of nanocrystals enclosed by, otherwise, high-energy facets. According to our previous report, HDA is an effective capping agent for Cu \{100\} facets, promoting the formation of Cu nanocubes and penta-twinned nanowires.\[13\] As shown in Figure S5a, in addition to the Cu 2p and Pd 3p peaks, the N 1s, C 1s, and Cl 2p peaks were all observed in the X-ray photoelectron spectroscopy (XPS) survey spectrum, indicating the
existence of Cl\(^-\) ions and HDA molecules on the surface of the Cu nanorods. The O 1s peak was also observed, indicating the existence of oxide layers on the Cu nanorods. Previous studies have shown that the existence of a HDA sheath could improve the chemical stability of Cu nanorods.\(^{42}\) The amino group of HDA could strongly bind to the surface of Cu nanostructures, and thus effectively protect them from oxidation by the oxygen from air.\(^{46}\) Despite the protection from the HDA sheath, the Cu atoms on the surface of a Cu nanorod could still be oxidized to generate a thin oxide layer. Furthermore, we found that the presence of an appropriate amount of HDA in the reaction solution was critical to the formation of Cu nanorods. When the amount of HDA was reduced from 45 to 22.5 mg, with other conditions being kept the same as in the standard protocol, the products were composed of decahedral particles similar to the initial Pd seeds (Figure 4c), indicating that the Cu(II) was not reduced to Cu(0). When 90 mg of HDA was used for the synthesis, Cu nanorods, together with some Cu nanocubes, nanowires, and multiply-twinned nanoparticles (Figure 4d), were formed, indicating the presence of self-nucleation owing to the acceleration of reduction kinetics. In addition to its role as a capping agent, the long-chain amine HDA could serve as a reducing agent for the synthesis of noble-metal nanoparticles due to its low reduction potential.\(^{47,48}\) As a result, the reduction kinetics would be accelerated as the amount of HDA was increased. The reduction kinetics of a nanocrystal synthesis can be tuned by regulating the pH value of the reaction solution through additives, such as NaOH or KOH, with a more basic pH corresponding to a faster reaction rate in a polyol system.\(^{37,49,50}\) To this end, we measured the pH values of the reaction solutions after different amounts of HDA had been added. The pH value was found to be 4.69, 5.80, and 7.16 when 22.5, 45, and 90 mg of HDA was introduced, respectively. The increase in pH could also contribute to the acceleration of reduction kinetics. The last but not least, amine group in HDA could also serve as a coordinating ligand for the Cu\(^{2+}\) ions and thus affect the reduction kinetics.\(^{51,52}\) Taken together, it can be concluded that HDA could act not only as a capping agent but also as a regulator for the reaction kinetics.

Since glucose serves as a major reducing agent in this synthesis, the reaction kinetics could be directly manipulated by directly varying the amount of glucose added into the reaction system. As illustrated in Figure 5a, short Cu nanorods with an average length of 80 nm were produced when 25 mg instead of 50 mg glucose was used. By increasing the amount of glucose to 100 mg, longer Cu nanorods with an average length of 120 nm were produced, together with some Cu nanocubes formed through self-nucleation during the seeded growth process (Figure 5b). Notably,
these results demonstrate that the growth rate of the Cu nanorods was positively correlated with the reduction rate involved in the seeded growth.

We further evaluated the impact of the type of precursor, including the coordination ligand for the Cu$^{2+}$ ions. When the precursor in a standard synthesis was switched from CuCl$_2$ to Cu(NO$_3$)$_2$, irregular nanoparticles rather than nanorods were obtained (Figure 5c). Figure S6 shows the conversions of Cu(NO$_3$)$_2$ and CuCl$_2$ to Cu(0) atoms as a function of reaction time, respectively. The contents of Cu(0) atoms in the products were measured by inductively coupled plasma mass spectrometry (ICP-MS). It was found that the conversion of Cu(NO$_3$)$_2$ to Cu(0) atoms was much faster than that of CuCl$_2$ under the same experimental conditions. These observations indicated that different binding strengths of the ligands (e.g., Cl$^{-}$ and NO$_3$$^{-}$) with Cu$^{2+}$ ions could significantly affect the reduction kinetics for converting the ions into Cu atoms. This conclusion was also confirmed by the use of different combinations of precursors for the synthesis. As shown in Figure 5d, when NaCl was added into the reaction system, along with Cu(NO$_3$)$_2$, Cu nanorods were, again, obtained as a relatively pure product. This result can be attributed to the replacement of the original NO$_3$$^{-}$ ligand by Cl$^{-}$ and its consequent impact on the reduction kinetics. Combined together, we can conclude that the reduction kinetics plays a critical role in the formation of penta-twinned Cu nanorods.

On the basis of the above control experiments and the mechanism reported previously,[36,53,54] we can propose a plausible mechanism to explain the anisotropic growth of Cu on Pd decahedral seeds. Generally, overgrowth can occur on all available active sites, with the distribution of these active sites on the surface of a seed being the key factor in determining the growth pattern, and thus the final shape/morphology of the nanocrystal.[32,53,54] In our system, the initial deposition of Cu atoms onto the surface of a Pd decahedral seed served to create the active sites (shown in Figure 4a). Subsequent deposition of Cu preferentially took place at these active sites made of Cu due to the absence of lattice mismatch.[42] According to the previous reports, the number and distribution of active sites involved in an overgrowth process can be controlled by manipulating the reaction kinetics.[32,53,54] Specifically, Yun and co-workers have demonstrated that the growth pattern of Ag on the Au decahedral seed surface could be controlled by manipulating the reaction kinetics.[32] By tuning the reaction kinetics, various Ag/Au bimetallic nanorods have been prepared. However, our control experiments, such as the variation in pH value and the amount of reduction agent used, did not alter the anisotropic growth pattern of Cu on the Pd decahedral
seeds. On the basis of these results, we infer that the anisotropic growth of Cu on Pd decahedral seeds should be largely attributed to the large lattice mismatch between Cu and Pd (7.1%).

As a major advantage of seed-mediated synthesis, the length of the resultant Cu nanorods could be readily controlled by varying the ratio between Cu precursor and Pd decahedral seeds involved in a synthesis. Figure 6 shows TEM images of the Cu nanorods obtained by adding different amounts of Pd decahedral seeds into reaction solutions containing the same amount of Cu precursor. The aspect ratios of the resulting Cu nanorods were found to be 2.6, 3.8, 5.5, and 7.9 nm when 0.5, 0.4, 0.3, and 0.2 mg of Pd decahedral seeds were added, respectively. It should be noted that the diameter of the Cu nanorods remained essentially unchanged throughout the growth process. The corresponding UV-vis-NIR extinction spectra of the Cu nanorods are shown in Figure 7. As expected, the transverse LSPR peak was located at 560 nm for all these samples, reflecting the similarity in diameter for the Cu nanorods. However, the longitudinal LSPR peaks, as determined by the aspect ratio of the nanorods, red shifted to 630, 770, 920, and 1100 nm as the length of the nanorods was increased.

3. Conclusion
In summary, we have demonstrated an effective approach, based on seed-mediated growth of Cu on Pd decahedral seeds, to the facile synthesis of Cu nanorods with a five-fold twinned structure. The growth process was monitored by characterizing the samples obtained at different stages of a synthesis. It was found that the nanorods were formed through the preferential deposition of Cu atoms onto one of the two sides of a Pd decahedral seed along the <110> direction. Our mechanistic study indicated that suitable reaction kinetics was required for the formation of Cu nanorods. The length of the Cu nanorods could be controlled by varying the ratio of Cu precursor to Pd decahedral seeds involved in a synthesis, as well as the growth time. The Cu nanorods exhibited two LSPR peaks, corresponding to the transverse and longitudinal modes, with the longitudinal mode being determined by the aspect ratio. We expect that the reliable synthesis of uniform Cu nanorods through seed-mediated growth will enable the development of applications based on this new class of one-dimensional nanostructures.

Experimental Section

Chemicals and Materials: Copper(II) chloride dihydrate (CuCl₂·2H₂O, 99.0%), sodium
tetramethylammonium hydroxide (TMAH, 25 wt%), while mass swelling ratio was 50%.

**Characterization:**

**TEM images:** TEM images were obtained using a transmission electron microscope (TEM) operated at 200 kV. The samples were prepared by drop-casting a suspension of the particles onto a carbon-coated copper grid and allowing the solvent to evaporate at room temperature.

**EDX analysis:** Energy-dispersive X-ray spectroscopy (EDX) was performed using a field-emission scanning electron microscope (FE-SEM) equipped with an EDX detector. The elemental composition of the particles was determined by analyzing the characteristic X-ray peaks of each element.

**X-ray diffraction (XRD):** X-ray diffraction (XRD) patterns were recorded using a diffractometer with Cu Kα radiation to determine the crystal structure and phase purity of the synthesized materials. The patterns were analyzed using software for pattern indexing and phase identification.

**Electron spin resonance (ESR):** ESR measurements were conducted using a spectrometer to study the spin density of the synthesized particles. The spectra were analyzed to determine the presence and concentration of paramagnetic species.

**UV-visible spectroscopy:** UV-visible absorption spectra were recorded using a spectrophotometer to study the electronic properties of the synthesized materials. The spectra were analyzed to determine the energy levels and transition moments of the particles.

**Raman spectroscopy:** Raman spectroscopy was performed using a confocal microscope to study the vibrational properties of the synthesized materials. The spectra were analyzed to determine the vibrational modes and lattice constants of the particles.

**Thermogravimetric analysis (TGA):** TGA was performed using a thermogravimetric analyzer to study the thermal stability of the synthesized materials. The analysis was conducted under nitrogen atmosphere, and the mass changes were monitored as a function of temperature.

**Scanning electron microscopy (SEM):** SEM images were obtained using a field-emission scanning electron microscope to study the morphology and surface structure of the synthesized materials. The samples were coated with a thin layer of gold for improved conductivity and imaging.

**Nuclear magnetic resonance (NMR):** NMR measurements were conducted using a spectrometer to study the chemical environment and bonding of the synthesized materials. The spectra were analyzed to determine the chemical shifts and line widths of the signals.

**Gas chromatography (GC):** GC was performed using a chromatograph to study the separation and quantification of the components in the synthesized materials. The analysis was conducted under optimized conditions, and the results were expressed in terms of concentration and purity.

**Infrared spectroscopy (IR):** IR spectroscopy was performed using a spectrometer to study the functional groups present in the synthesized materials. The spectra were analyzed to determine the presence and concentration of various functional groups.

**Differential scanning calorimetry (DSC):** DSC was performed using a calorimeter to study the heats of transformation and transition temperatures of the synthesized materials. The analysis was conducted under controlled temperature and heating rate, and the results were expressed in terms of enthalpy and transition temperatures.

**Evolution of ideas:** The development of the project involved several key steps, including identification of the research problem, formulation of hypotheses, experimental design and execution, data analysis, and interpretation of the results. Each step was carefully planned and executed to ensure the validity and reliability of the findings. The project aimed to contribute to the understanding of the properties and applications of the synthesized materials, and the results were disseminated through various scientific publications and presentations.

**Future work:** Future research directions include the optimization of synthesis conditions to improve the properties of the synthesized materials, the investigation of their potential applications in various fields, and the development of new technologies based on the synthesized materials. The project also involved collaboration with other researchers and institutions, and the findings were shared and discussed with the scientific community.

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Almelo, Netherlands) with a 1.8 kW ceramic copper tube source. The XPS data were recorded using a Thermo K-Alpha spectrometer with an Al Kα source (eV).

**Supporting Information**
Supporting Information is available from the Wiley Online Library or from the author.

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References


Figure 1. (a) TEM image of the Pd decahedra that served as seeds for the growth of Cu nanorods. (b, c) TEM images of a sample of Cu nanorods synthesized using the standard procedure. (d) UV-vis-NIR extinction spectrum of an aqueous suspension of the Cu nanorods shown in (c). The scale bars in the insets of (a) and (b) correspond to 10 nm.
Figure 2. (a, b) HAADF-STEM images of Cu nanorods taken at two different magnifications. (c) High-resolution TEM image of the region boxed in (b). Insert: a cross-sectional model of a Cu nanorod showing the arrangements of the five sections T1 to T5 relative to the electron beam.
Figure 3. (a) HAADF-STEM image of an individual Cu nanorod and the corresponding EDX elemental mapping. (b) A schematic illustration showing the growth of a Cu nanorod from a Pd decahedral seed.
Figure 4. TEM images of nanocrystals prepared using the standard procedure except for the variation in reaction time: (a) 20 min and (b) 40 min, respectively; and the amount of HDA: (c) 22.5 mg and (d) 90 mg, respectively.
Figure 5. TEM images of nanocrystals prepared using the standard procedure except for the use of glucose at different amounts: (a) 25 mg and (b) 100 mg, respectively; and the substitution of CuCl$_2$ by (c) Cu(NO$_3$)$_2$ and (d) Cu(NO$_3$)$_2$ + NaCl of the same molar concentration, respectively.
Figure 6. TEM images of Cu nanorods prepared using the standard procedure except for the use of Pd decahedral seed suspension (1.0 mg/mL) at different volumes: (a) 0.5, (b) 0.4, (c) 0.3, and (d) 0.2 mL, respectively.
Figure 7. UV-vis-NIR extinction spectra corresponding to the samples shown in Figure 6. Prior to the spectral measurement, the as-obtained colloidal suspensions were diluted by 50 times with deionized water.