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Inorganic Particles

Michael Köhler

17.1

Introduction

The large surface area-to-volume ratio of microchannels and microreactors makes their application more feasible for homogeneous than for heterogeneous systems. Complications can arise from sedimentation of particles, from aggregation and blocking and from more or less specific adsorption at the wall surfaces. Despite these difficulties, the generation and handling of solid particles and suspensions were early considered for application of chip devices and microfluidic systems, such as miniaturized parallel synthesis and screening [1, 2]. The great attraction of microreactors lies in the controlled reaction conditions and make them an interesting tool for heterogeneous systems and in particular of the synthesis and modification of nanomaterials.

Whereas the manipulation of aerosols and similar disperse systems in the gas phase is difficult, the generation and manipulation of emulsions and suspensions can be realized in microreactors (Figure 17.1). In particular, the well-controlled conditions of mixing and temperature control brought microreactors into the focus of interest for the generation of nanoparticles, and they were applied for the synthesis of dielectric particles of inorganic [3–5] and polymer [6] materials. Quantum dots consisting of compound semiconductors can also be prepared by using microreactors [7, 8]. For some years, microreactor arrangements have also been under investigation for the preparation of metal nanoparticles [9]. Thus a wide range of nanomaterials have been handled in microreactors. The investigations show that microreaction technology can be applied for the synthesis of very different types of nanoparticles (Figure 17.2).

There are some general demands for the fabrication of nanoparticles independently of the material. For this purpose, the control of size and shape is one of the most important quality features for nanoparticles. The suppression of a large distribution of sizes is also a general challenge in nanoparticle synthesis. In addition, microreaction technology seems to be particularly suited for the generation of complex nanoparticles of well-defined composition.

Heterogeneous systems in micro channels

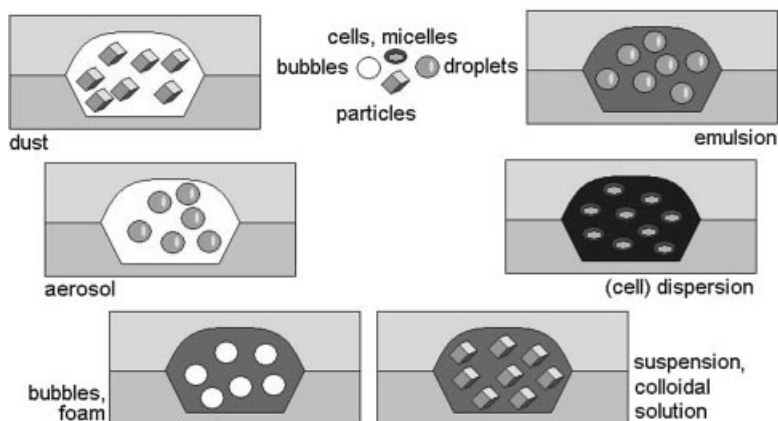


Figure 17.1 Dispersed systems in microreaction technology.

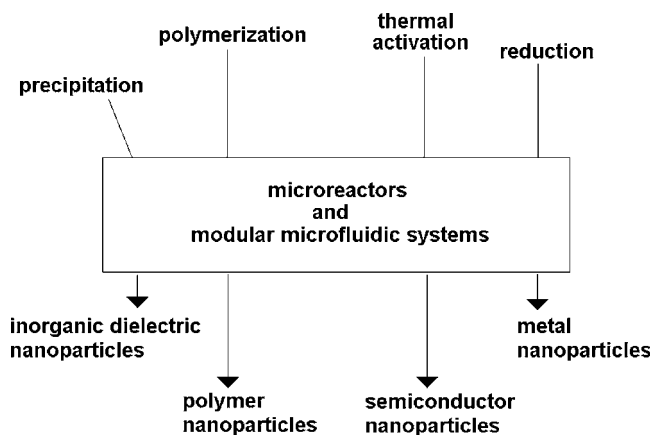


Figure 17.2 Reactions for generation of nanoparticles of different materials in microreactors and in modular microfluidic arrangements.

17.2 Dielectric Nanoparticles

The formation of dielectric salt-like nanoparticles can be realized by precipitation. Essential problems in the application of microreactors to precipitation reactions are particle aggregation, particle sticking on the walls and clogging of microchannels. Schenk *et al.* applied a segment flow tubular reactor for the generation of CaCO_3 nanoparticles in a microflow-through system [3]. The embedding of the reaction mixtures in fluid segments and the separation of the reaction mixture from the wall of

the reactor tube led to the suppression of particle deposition on the reactors walls. The whole system consisted on a mixer/segmenter unit for the formation of fluid segments and mixing of reactants, a reactor tube, a separator unit and a back-flow unit for the separation liquid. An interdigital static micromixer with a triangular mixing chamber was found to be best suited for mixing in this system.

Microreactors can also be applied for high-temperature gas processes of nanoparticle synthesis. A tube reactor (diameter 2 mm) was used for the generation of TiO_2 nanoparticles. The main size of nanoparticles could be shifted between 31.7 and 9.0 nm by controlling the reaction temperature in the range 1000–500 °C [5]. In addition to real microreactors, spontaneously formed microdroplets, compartments and micellar systems have been applied for the generation of dielectric nanoparticles. TiO_2 nanoparticles [10–12], NiO nanoparticles [13] and various nanoparticles of metal oxides [14] are formed in droplets or in a micellar environment. Cottam *et al.* reported a microfluidic synthesis of small nanorods of titanium oxide by fast mixing of an oleic acid solution of tetraisopropoxytitanium (TTIP) with trimethylamine *N*-oxide dihydrate (TMAO) [15]. Both reaction solutions were mixed by a Y-shaped micro channel structure and conducted through a 40 cm microchannel with an internal channel width of 100 μm . As a result, bunched assemblies of rod-like titanium dioxide were obtained. The length of the bundles was more than 100 nm and the diameter of the single rods was less than 10 nm.

Polymer nanoparticles are formed, in general, during an emulsion polymerization process. This technology has long been known and is usually performed in large batch reactors. In a miniaturized setup, a chip device can be used for the efficient preparation of the emulsion consisting of an aqueous phase. This phase contains the water-soluble initiator and the surfactant and a dispersed organic phase containing the monomer. During the polymerization, polymer particles are formed by growing macromolecules. The whole polymerization can be designed as a microflow-through process by connecting the micromixer with a longer residence loop. The tube coil is thermostated at elevated temperature for completion of polymerization. As a result, polymer nanoparticles with diameters between about 60 and 120 nm are obtained [6]. Figure 17.3 shows the experimental arrangement and the polystyrene nanoparticles produced which are prepared by microflow-through synthesis and partially metalized by gold.

17.3

Semiconductor Nanoparticles

Semiconductor nanoparticles are of particular importance due to their optical properties. They act as quantum dots and can be applied as components in optically active materials, as optically active labels for biomolecules and cells and as components in miniaturized optoelectronic devices [16]. Compound semiconductor nanoparticles can be prepared by liquid-phase processes. Several groups have investigated the preparation of CdSe particles. The fluorescence emission of these particles is strongly dependent on the particle size. The realization of well-controlled reaction

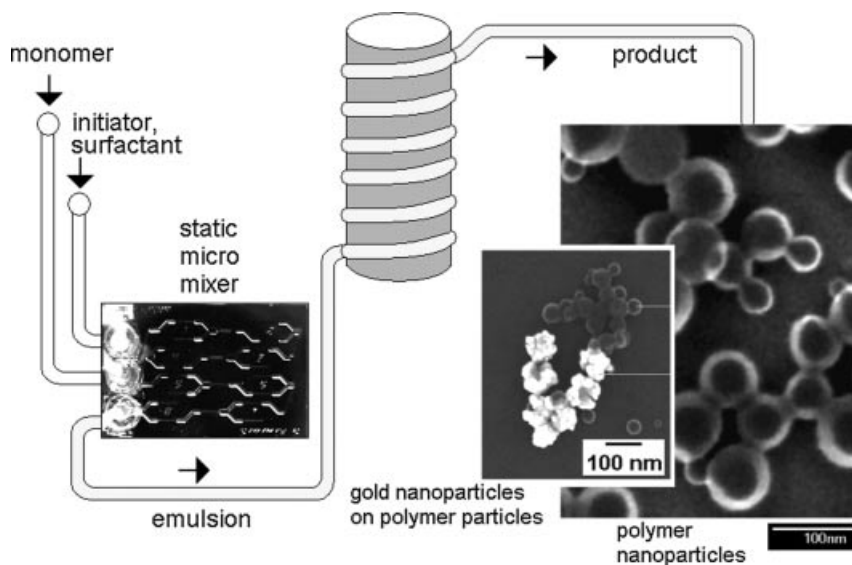


Figure 17.3 Generation of polymer nanoparticles and metal-coated polymer nanoparticle aggregates by use of a microflow-through arrangement consisting of syringe pumps, a static micromixer for emulsification and reaction initiation and a thermostated residence loop.

conditions in microreactors promised a narrow size distribution of produced particles, which means high optical quality of the product.

Nakamura and coworkers found a shift in particle size between 2.8 and 4.2 nm depending on flow rate in a microflow-through process [7, 17]. Chan *et al.* succeeded in the preparation of CdSe nanoparticles of controlled size between 2.44 and 2.69 nm by temperature control [18]. They applied a glass wafer micro-channel reactor. Fast mixing in micro fluid segments supports the formation of homogeneous products in the synthesis of CdS nanoparticles by a time control in the millisecond range [19]. The precise control of reaction temperature, reactant ratio and flow rate in the flow-through process allows very fine steps in the variation of the absorption maximum and the emission wave length maximum [20, 21]. In particular, these syntheses of semiconductor nanoparticles demonstrate clearly the advantage of microreactors for the generation of special products with well-defined physical properties [22].

17.4 Metal Nanoparticles

Metal nanoparticles are of particular interest from very different points of view. First, they possess a size-dependent optical absorption band. Sharp bands in optical spectra are due to plasmon absorption, which is in the short-wavelength range

of the visible spectrum for silver (about 450 nm) and in the longer wavelength range for gold (about 625 nm), for example. The bands can be shifted bathochromically, if particle growth or aggregates arise. The chemical interaction between differently surface-modified nanoparticles leads to a change in the optical spectrum [23–28] and this optical shift can be used for indication of electronic interactions. Hence metal nanoparticles are under consideration as nanolabels and nanopigments [29, 30].

Finally, metal nanoparticles are under investigation as elements in future electronic nanodevices: they can be used as nanowires, nanoislands and as electron confinements in single electron tunneling devices [33–35]. Therefore, the fabrication of nanoparticles with very well-defined sizes and surface properties is particularly important. Molecular films at particle surfaces are essential for specific interactions between nanoparticles and macromolecules, between nanoparticles and substrates and for the positioning of nanoparticles inside nanoelectrode arrangements. Nanoparticles are also of interest for nano-optoelectronic applications due to their specific optical properties. For this purpose, the synthesis of nanoparticles with very small distributions in chemical composition, size and shape in microreactors is under investigation.

Nanoparticles in the form of colloidal solutions (nanosuspensions) can be prepared by the reduction of metal salt or metal complex solutions in the liquid phase. Noble metals can easily be obtained by reduction of their solutions in the aqueous phase, if a suitable reducing agent is used. The preparation of gold nanoparticles by reduction of tetrachloroaurate by citric acid at high temperature is a long-known method of nanoparticle preparation. The formation of metal nanoparticles by chemical reduction of a salt or complex solutions consists of two main steps. In both steps electrons must be transferred from the reducing agent to the metal in order to bring its oxidation number to zero.

The first main step is the nucleation. Thereby, a small group of metal atoms must be formed and aggregate to a stable core. This is a rather complex process, because several individual ions or complex molecules and sufficient molecules of the reducing agent must be involved (Figure 17.4a). Therefore, several elementary reactions must be connected: decomposition of complexes, electron transfer and interaction of primarily formed metal atoms. This first step can be regarded as a homogeneous phase reaction, because the educts involved are supplied from a molecular dispersion inside the liquid. However, the result of the first step is a metal cluster or nucleus, which makes necessary an introduction of a new interface into the system. The second main step is the particle growth. This can be described by the mechanism of a complex electrochemical open-circuit process. The primarily formed nucleus acts as a complex electrode with formation of a mixed potential. There is no outer current, but a local current can flow between a cathodic and an anodic site of the small particle. The further reduction of metal ions to the metal state (oxidation number zero) represents the anodic partial current. The oxidation of the reducing agent represents the anodic partial current (Figure 17.4b). Both processes are coupled only by the electrode potential or – related to this – to the electrical charge of the growing particle. Hence particle growth is also a complex

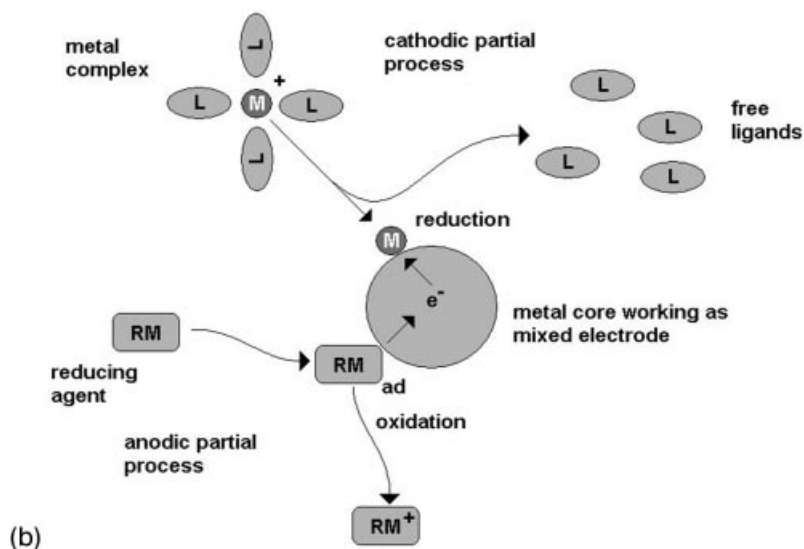
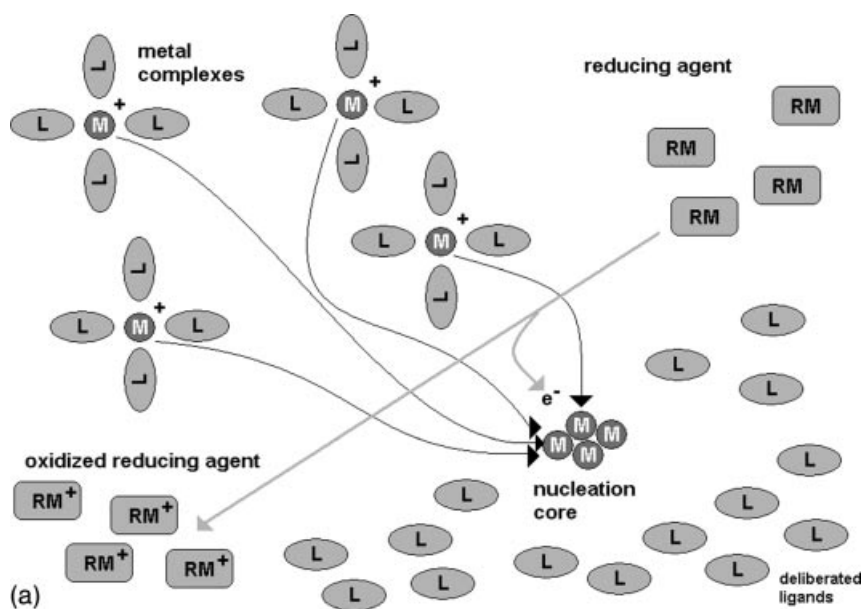


Figure 17.4 Processes during the formation of metal nanoparticles. (a) Complex process of nucleation: several metal-containing molecules must be reduced in close spatial contact in order to form a stable nucleus. (b) Particle growth: the process can be described by two partial processes coupled only by electrochemical potential of growing particle.

process, but less complex than the nucleation. The spatial decoupling of oxidation and reduction is the most important feature of particle growth, in contrast to nucleation.

The kinetics of nanoparticle formation reaction, size and size distribution of the colloidal product solution depend strongly on the rate of nucleation and particle growth and the concentration dependence of both rates. Homogeneous particle sizes (narrow size distribution) are expected, if three conditions are fulfilled:

1. The mixing of reactant solutions occurs very quickly in order to obtain homogeneous concentration conditions at the beginning.
2. The nucleation rate is high at the beginning.
3. The nucleation rate depends strongly on the concentration of a non-excess reactant, so that a critical concentration for nucleation (nucleation threshold) is passed by the consumption of this reactant during the nucleation process.

Conditions 2 and 3 ensure that particle growth can be approximately neglected during the nucleation phase. Fast nucleation is followed by slow particle growth. As a result, all cores are formed nearly simultaneously and all particles grow in parallel. Under the assumption of a homogeneous distribution of educts, the rates of cathodic and anodic partial processes should be the same for all particles and particles of equal size are obtained as a result.

The application of microreactors for the generation of metal nanoparticles is motivated from two aspects: On the one hand, static micromixers allow very quick mixing of metal salt (complex) and reducing agent solution. On the other, rapid changes in temperature, pH or other parameters can be used for switching between nucleation and particle growth.

It could be shown that gold nanoparticles (GNPs) can be prepared in a microflow-through process using static micromixers at room temperatures with the use of ascorbic acid as reducing agent [9]. The size and the optical properties of GNPs can be shifted over a certain range by changing the flow rates (Figure 17.5). Increasing flow rate leads to a certain reduction in particle size. This effect could be explained through

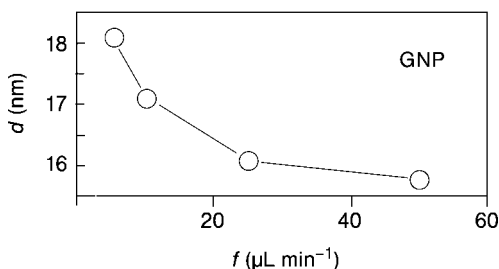


Figure 17.5 Flow rate effect of the mean size of gold nanoparticles prepared in a microflow-through reduction of tetrachloroauric acid with ascorbic acid (measurement of size by centrifugal sedimentation spectroscopy).

faster mixing in the case of a higher flow rate, which leads to the formation of an increasing number of cores during the nucleation phase. Under optimized conditions, the improved mixing leads to a significant reduction in the size distribution. The microflow-through processes can lead to a significant improvement in size distribution in the case of a high excess of reducing agent [36]. Probably, a high nucleation rate after fast mixing, rapid reduction of the metal complex concentration and a sharp transition from the nucleation to the growth phase are responsible for the narrowing of the size distribution.

A strong reduction in the absolute size of gold nanoparticles can be achieved by the application of reducing agents with particularly high nucleation power. This can be achieved at room temperature using sodium borohydride instead of ascorbic acid. Fast mixing of tetrachloroaurate solution and reducing agent solution leads to a further acceleration of nucleation. As a result, Au nanoparticles of 5 nm diameter and below were found in flow-through reactions [37]. The mean particle diameter and the size distribution of gold and silver nanoparticles can be influenced by the optimization of flow rates of educts and flow rate ratios [38]. The size and size distribution of larger Ag nanoparticles synthesized with initial formation of gold seeds and higher concentrations of silver nitrate depends strongly on the absolute flow rates. A shift from rather homogeneously distributed smaller nanoparticles (100 nm diameter) to heterogeneous products was observed on enhancement of the carrier solution in three-step mixing procedures using slug flow. A change in the size distribution of silver-rich precipitates also took place in the case of a general flow rate enhancement under a constant ratio of reactant and carrier flow rates (Figure 17.6). Strong effects of flow rates on the particle size and size distribution were also found in a four-step mixing regime under similar conditions. The formation of very large silver particles could be suppressed by an enhancement of flow rates without changing the reactant ratios (Figure 17.7). Microfluid systems were also successfully applied for the synthesis of surface-modified gold nanoparticles [33]. The optimization of flow rates of reactants allows the control of particle size in the case of alkythiolated monolayer-protected colloids (MPCs) in a microfluidic device [39].

Microflow-through processes are well suited for the generation of nanoparticles with special shape. Thus, the formation of Au nanorods succeeded by a micro flow-through synthesis [40, 41]. The nanorods showed a very homogeneous distribution in size and shape. The shape of gold nanorods generated by mixing a seed solution with a growth solution (tetrachloroauric acid, ascorbic acid and CTAB) is influenced by the volume flow rate ratio of the reactant solutions and by the reaction temperature [42]. The diameter of particles increases with increase in temperature and is accompanied by a shift of the absorption spectrum (Figure 17.8). In the case of fast mixing of tetrachloroauric acid and silver nitrate with ascorbic acid solution, the formation of star-like nanoparticles with four branches was observed [43]. The product quality and the optical spectra of the colloidal solution depend on the absolute flow rates. A shift from the dominance of larger star-like particles (170 nm) at medium reactant flow rates [(1 + 0.5) mL min⁻¹] to smaller particles (about 90 nm) at higher flow rates [(4 + 2) mL min⁻¹] was observed (Figure 17.9).

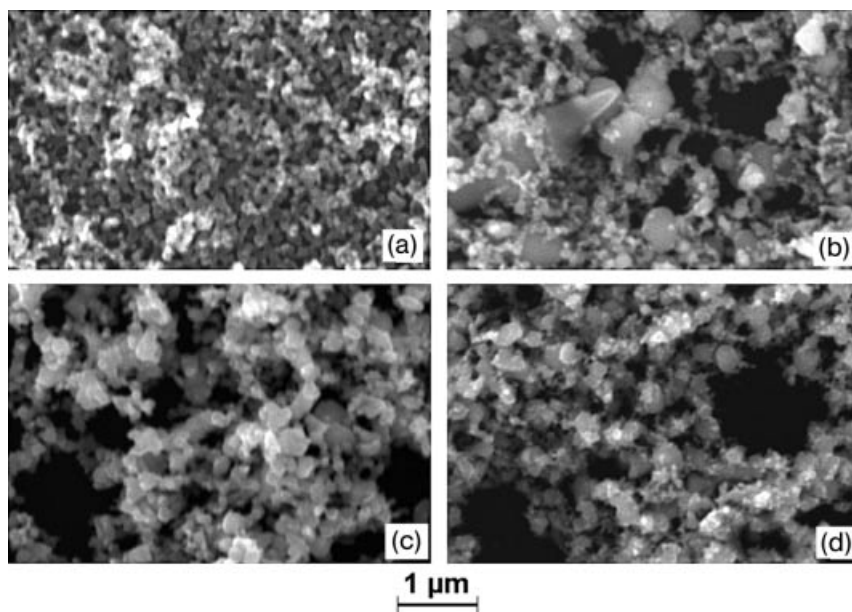


Figure 17.6 Formation of larger silver nanoparticles in a slug-flow process (with tetradecane) with three mixing steps in an arrangement with 4 T-junctions connected by three PTFE knot mixers with the following input channels: (a) 1, tetradecane 1 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 1 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 1 mL min^{-1} ; 4, AgNO_3 (0.05 mol L^{-1}) 1 mL min^{-1} ; (b) 1, tetradecane 5 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 1 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 1 mL min^{-1} ; 4, AgNO_3 (0.05 mol L^{-1}) 1 mL min^{-1} ; (c) 1, tetradecane 0.2 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 0.2 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 0.2 mL min^{-1} ; 4, AgNO_3 (0.05 mol L^{-1}) 0.2 mL min^{-1} ; (d) 1, tetradecane 2 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 2 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 2 mL min^{-1} ; 4, AgNO_3 (0.05 mol L^{-1}) 2 mL min^{-1} .

Microflow-through processes can be applied for the surface modification of metal nanoparticles. Two- and multi-step arrangements are particularly suitable for the application of molecular effectors either before, during or after the nanoparticle formation. Surface-active molecules can cause stabilization of nanoparticles, they can reduce the growth rate of particles or can lead to aggregation in the case of compensation of electrical charges or by establishing attractive molecular interactions between surface layers. In the presence of water-soluble synthetic macromolecules such as PVA and in the presence of proteins, different types of nanoparticle aggregates were found after the preparation of gold nanoparticles in two- and three-step microflow-through processes [44, 45].

Two- and three-step arrangements of micromixers are also of interest for the generation of nanoparticles of binary and complex composition. They can be realized for continuous flow processes and for segmented flow applications (Figure 17.10). The order of reactant application, the flow rates and flow rate ratios determine the properties of the colloidal product solution obtained. Strong dependences of the

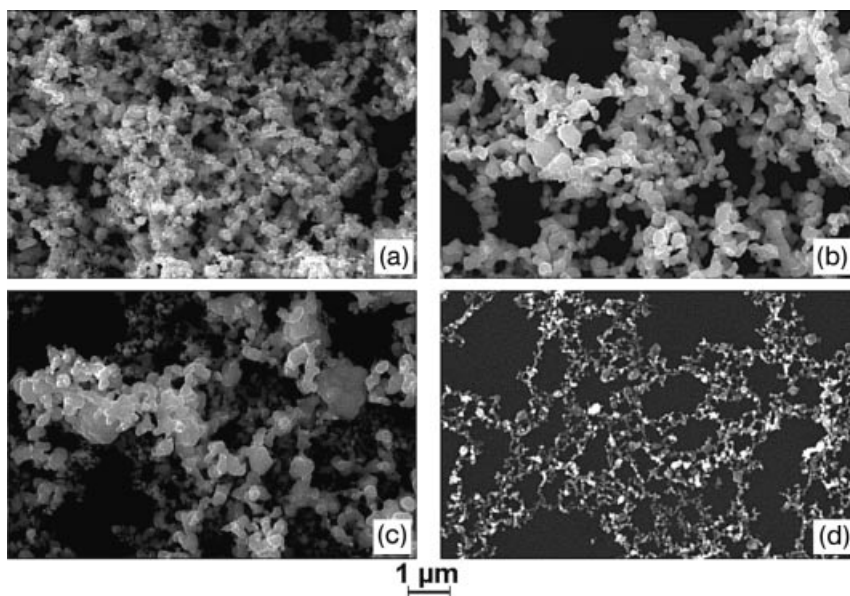


Figure 17.7 Formation of larger silver nanoparticles in a slug-flow process (with tetradecane) with four mixing steps in an arrangement with 5 T-junctions connected by four PTFE knot mixers with the following input channels: (a) 1, tetradecane 1 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 1 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 1 mL min^{-1} ; 4, AgNO_3 (0.005 mol L^{-1}) 1 mL min^{-1} ; 5, AgNO_3 (0.05 mol L^{-1}) 1 mL min^{-1} ; (b) 1, tetradecane 3 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 1 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 1 mL min^{-1} ; 4, AgNO_3 (0.005 mol L^{-1}) 0.2 mL min^{-1} ; 5, AgNO_3 (0.05 mol L^{-1}) 0.2 mL min^{-1} ; (c) 1, tetradecane 0.2 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 0.2 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 0.2 mL min^{-1} ; 4, AgNO_3 (0.005 mol L^{-1}) 0.2 mL min^{-1} ; 5, AgNO_3 (0.05 mol L^{-1}) 0.2 mL min^{-1} ; (d) 1, tetradecane 2 mL min^{-1} ; 2, ascorbic acid (0.1 mol L^{-1}) 2 mL min^{-1} ; 3, HAuCl_4 (1 mmol L^{-1}) 2 mL min^{-1} ; 4, AgNO_3 (0.005 mol L^{-1}) 2 mL min^{-1} ; 5, AgNO_3 (0.05 mol L^{-1}) 2 mL min^{-1} .

optical properties of nanoparticles on flow rates (Figure 17.11) were found in the two- and three-step microflow-through syntheses of Au/Ag nanoparticles by the use of static micromixers [38].

The suppression of reactor fouling is one of the most important problems in all systems containing macromolecules, particles or cells. The attractive interaction between particles and walls can be decreased or overcompensated repulsive forces generated by electrical charging. Negatively charged nanoparticles are pushed away through anionic groups at the wall surface. Another way to avoid sticking of polar and hydrophilic particles consists in the hydrophobization of walls, for example the alkylsilanization of glass or silicon surfaces [39]. Perfluoroalkylsilanized surfaces show a low gettering activity against nanoparticles. The embedding of nanoparticles in droplets inside emulsions or in fluid segments represents a further strategy for avoiding reactor fouling.

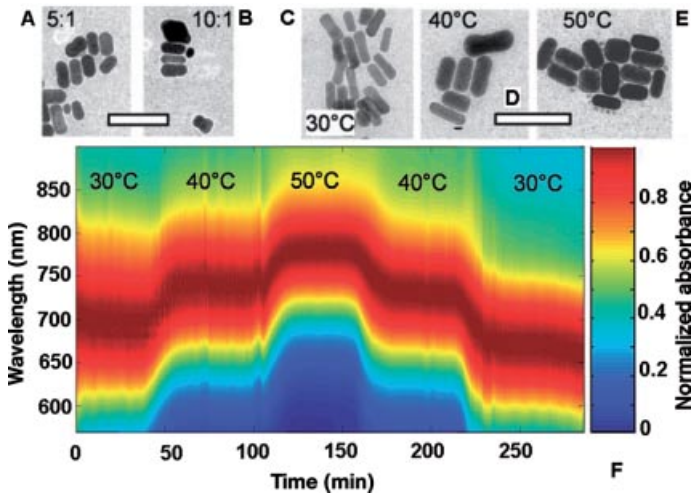


Figure 17.8 Gold nanorods obtained by the reduction of tetrachloroauric acid with ascorbic acid in the presence of CTAB at elevated temperature (courtesy of C. Sönnichsen). (a) Particles obtained at a ratio of seed solution to growth solution of 5 : 1; (b) ratio of seed solution to growth solution of 10 : 1; (c), (d), (e) particles obtained at increasing temperature (scale bars: 100 nm); (f) shift of optical absorption band in experiments with stepwise varied temperature (absorption coded by color scale).

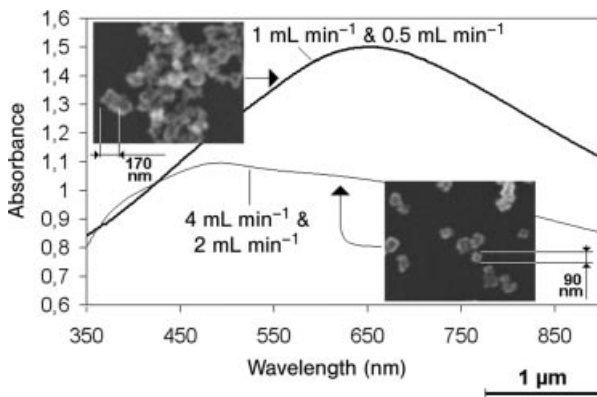


Figure 17.9 Formation of star-like Au/Ag particles under continuous flow conditions with a single step mixing: above, premixed aqueous solution of 0.45 mM AgNO_3 and 0.275 mM HAuCl_4 at 1 mL min^{-1} and ascorbic acid (0.1 M) at 0.5 mL min^{-1} ; below, premixed aqueous solution of 0.45 mM AgNO_3 and 0.275 mM HAuCl_4 at 4 mL min^{-1} and ascorbic acid (0.1 M) at 2 mL min^{-1} (room temperature).

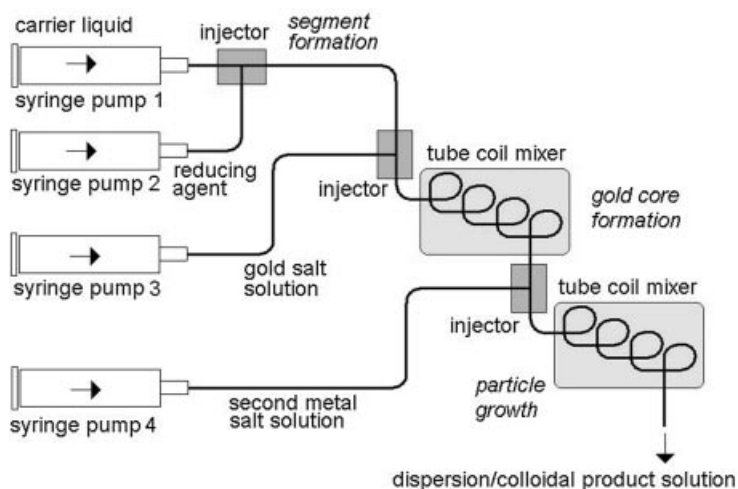


Figure 17.10 Modular arrangement for a segmented-flow two-step process for generation of composite metal nanoparticles.

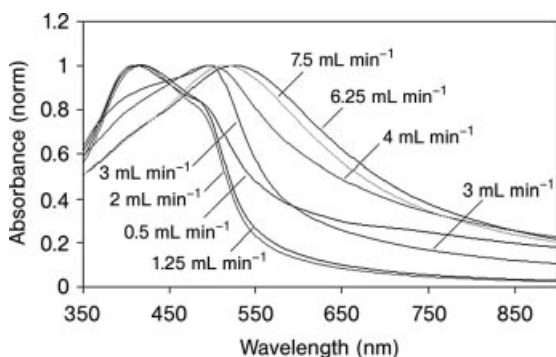


Figure 17.11 Flow rate dependence of optical spectra of colloidal product solutions obtained by a flow-through two-step synthesis of Au/Ag nanoparticles (constant ratio of reactants).

17.5

Transport Conditions in Nanoparticle Formation

The residence time and, therefore, the reaction behavior of particles depend on the transport conditions of particles in the laminar flow, if homogeneous fluids are applied. The non-linear velocity gradients inside microchannels cause unsymmetrical shear forces. As a result, particles are not only brought to rotation, but are also transported to the central region of the microchannel (Magnus effect). Therefore, the fluid transport behavior leads to an enhancement of particle concentration in the center of microchannels and to a lowering of their concentration near the walls.

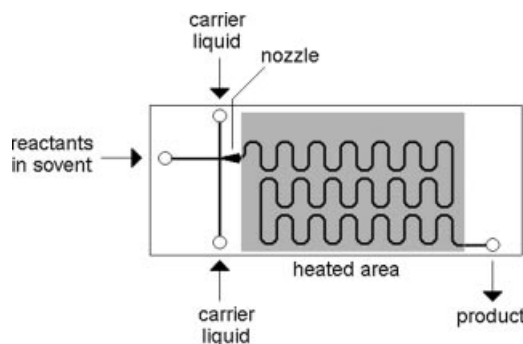


Figure 17.12 Experimental arrangement for the thermally activated synthesis of semiconductor nanoparticles by use of a segmented flow process [50].

Further, the differences in the transport of particles by velocity gradients can be used for the manipulation and for the separation of micro- and nanoparticles. Hence mixtures of particles can be separated into several classes of sizes in a microlaminar streaming system [48].

The advantages of fluid segment application for liquid transport were demonstrated with the application of a segmented flow tubular reactor for the preparation of nanoparticles of calcium carbonate and calcium oxalate [5]. It can also be applied for the generation of compound semiconductor nanoparticles such as CdS and CdSe [49–51]. The segmented flow principle is combined, therefore, with thermal activation by integrated thin-film heaters (Figure 17.12). Meandering microchannels cause strong excitation of segment internal convection, resulting in very efficient mixing of reactants. Hence efficient mixing can be realized in milliseconds. The clogging problem in the formation of precipitates can be suppressed by the use of a microsegmented flow [44]. The sticking of precipitates on the inner wall surface is suppressed if the contact angle of segment liquids is near 180° .

17.6

Applications of Nanoparticles in Microreactors

The application of microflow-through devices is of particular interest for continuous heterogeneous catalysis with nanoparticles. The advantages of nanoparticles are their special surface properties on the one hand and the high specific surface area on the other.

The application of solid catalysts in microreactors has been studied for different processes. Automated laboratory systems were applied for catalyst screenings [53, 54]. Ag/Al and Ag/Al₂O₃ were applied in microflow-through reactors for the partial oxidation of ethylene [55]. For catalytic applications, a microflow-through arrangement with a static micromixer was used to prepare Au/Ag nanoparticles [56]. Microfluid segments are also of interest for catalytic reactions in microreactors [57].

It is expected that nanoparticles will play an increasing role in future microcatalytic applications. Therefore, different strategies for the introduction of nanoparticles into the reaction system are possible: first, the nanoparticles can be presynthesized and precipitated or immobilized inside the reactor. Second, the presynthesized nanoparticles can be added as a colloidal solution, resulting in a process similar to a homogeneous phase reaction. Finally, the nanoparticles can be prepared *in situ* in a first reaction step inside a multi step reaction chain. More complex constructed microflow-through arrangements including different reactors should be particularly suited to this technology.

17.7

Conclusion

Nanoparticles of different sizes and materials can be prepared and manipulated in microreactors. The range of materials includes inorganic dielectrics, organic polymers and metallized polymer particles, semiconductors and metallic nanoparticles. In addition to pure materials, composite nanoparticles were prepared. The size of nanoparticles prepared in microsystems ranges from cluster-like particles through small nanoparticles a few nanometers in diameter up to larger particles of several hundred nanometers. Microreactors allow rapid mixing and a well-reproducible change in concentrations during nucleation and particle growth. Therefore, microreactors are particularly suitable for the generation of nanomaterials with narrow size distributions. In addition, microreactor arrangements can be applied for two- and multi-step reactions and for the synthesis of nanoparticles of complex composition.

References

- 1 A. Schober, A. Schwienhorst, J. M. Köhler, M. Fuchs, R. Günther, M. Thürk, Microsystems for independent parallel chemical and biological processing, *Microsyst. Technol.* **1995**, *1*, 168.
- 2 G. Mayer, K. Wohlfart, A. Schober, J. M. Köhler, Nanotiterplates for screening and synthesis, in *Microsystem Technology: a Powerful Tool for Biomolecular Studies* (eds J. M. Köhler, T. Mejevaia, H.-P. Saluz), Birkhaeuser Basel, **1999**, p. 75.
- 3 R. Schenk, M. Donnet, V. Hessel, Ch. Hofmann, N. Jongen, H. Löwe, in *IMRET 5*, Strasbourg, **2001**, p. 489.
- 4 V. Hessel, H. Löwe, *Chem. Ing. Tech.* **2002**, *74*, 17 and 185.
- 5 R. Schenk, V. Hessel, N. Jongen, V. Buscaglia, S. Guillemet-Fritsch, A.-G. Jones, Nanopowders produced using microreactors, in *Encyclopedia of Nanoscience and Nanotechnology* (ed. H. S. Nalwa), American Scientific Publisher ASP, Valencia, USA, **2004**, Vol. 10.
- 6 P. M. Günther, J. Wagner, G. A. Gross, J. M. Köhler, in *9th International Conference on Miniaturized Systems μ -TAS*, 9–13 October 2005, Boston, **2005**, pp. 918–920.
- 7 H. Nakamura, Y. Yamaguchi, M. Miyazaki, M. Uehara, H. Maeda, P. Mulvaney, Continuous preparation of CdSe

- nanocrystals by a microreactor, *Chem. Lett.* **2002**, 1072–1073.
- 8 I. Shestopalov, J. D. Tice, R. F. Ismagilov, *Lab Chip* **2004**, *4*, 316–321.
 - 9 J. Wagner, T. Kirner, G. Mayer, J. Albert, J. M. Köhler, *Chem. Eng. J.* **2004**, *101*, 251.
 - 10 R. B. Zhang, L. Gao, *Mater. Res. Bull.* **2002**, *37*, 1659–1666.
 - 11 H. Wang, H. Nakamura, M. Uehara, M. Miyazaki, H. Maeda, *Chem. Commun.* **2002**, 1462.
 - 12 M. Takagi, T. Maki, M. Mivahara, K. Mae, *Chem. Eng. J.* **2004**, *101*, 269.
 - 13 B. Xia, I. W. Lenggorgo, K. Okuyama, *Chem Mater.* **2002**, *14*, 2623–2627.
 - 14 D. G. Shhukin, G. B. Sukhorukov, *Adv. Mater.* **2004**, *16*, 671–682.
 - 15 B. F. Cottam, S. Krishnadasan, A. de Mello, J. C. de Mello, M. S. P. Shaffer, *Lab Chip* **2007**, *7*, 167–169.
 - 16 W. J. Parak, L. Manna, F. Ch. Simmel, D. Gerion, P. Alivisatos, in *Nanoparticles* (ed. G. Schmid), Wiley-VCH Verlag GmbH, Weinheim, **2004**, pp. 4–49.
 - 17 H. Nakamura, A. Tashiro, Y. Yamaguchi, M. Miyazaki, T. Watari, H. Shimizu, H. Maeda, Application of a microfluidic reaction system for CdSe nanocrystal preparation: their growth kinetics and photoluminescence analysis, *Lab Chip* **2004**, *4*, 237–240.
 - 18 E. M. Chan, R. A. Mathies, A. P. Alivisatos, Size-controlled growth of CdSe nanocrystals in microfluidic reactors, *Nano Lett.* **2003**, *3*, 199–201.
 - 19 I. Shestopalov, J. D. Tice, R. F. Ismagilov, *Lab Chip* **2004**, *4*, 316–321.
 - 20 B. K. H. Yen., N. E. Stott, K. F. Jensen, M. G. Bawendi, *Adv. Mater.* **2003**, *15*, 1858–1862.
 - 21 B. K. H. Yen, A. Gunther, M. A. Schmidt, K. F. Jensen, M. G. Bawendi, *Angew. Chem. Int. Ed.* **2005**, *44*, 5447–5451.
 - 22 J. DeMello, A DeMello, *Lab Chip* **2004**, *4*, 11N–15N.
 - 23 S. Link, Z. L. Wang, M. A. El-Sayed, *J. Phys. Chem.* **1999**, *103*, 3529–3533.
 - 24 C. Sönnichsen, A. P. Alivisatos, *Nano Lett.* **2005**, *5*, 301–304.
 - 25 S. Link, M. A. El-Sayed, *J. Phys. Chem.* **1999**, *103*, 8410–8426.
 - 26 G. Schmid, L. F. Chi, *Adv. Mater.* **1998**, *10*, 515–526.
 - 27 A. Rai, A. Singh, A. Ahmad, M. Sastry, *Langmuir* **2006**, *22*, 736–741.
 - 28 M. Moskovitch, I. Srnová-Sloufová, B. Vlckova, *J. Chem. Phys.* **2002**, *116*, 10435–10446.
 - 29 W. Fritzsche, *Rev. Mol. Biotechnol.* **2001**, *82*, 37.
 - 30 S. J. Park, T. A. Taton, Ch. A. Mirkin, *Science* **2002**, *195*, 1503–1506.
 - 31 M. Haruta, *Nature* **2005**, *437*, 1098.
 - 32 M. D. Hughes, *et al.*, *Nature* **2005**, *437*, 1132
 - 33 D. L. Klein, P. L. McEuen, J. E. B. Katari, R. Roth, A. P. Alivisatos, *J. Appl. Phys.* **1996**, *68*, 2574.
 - 34 U. Simon, *Adv. Mater.* **1999**, *10*, 1487.
 - 35 U. Simon, in *Nanoparticles* (ed. G. Schmid), Wiley-VCH Verlag GmbH, Weinheim, **2004**, pp. 328–362.
 - 36 J. Wagner, J. M. Köhler, *Nano Lett.* **2005**, *5*, 685.
 - 37 J. Wagner, T. R. Tshikhudo, J. M. Köhler, in *9th International Conference on Microreactor Technology, IMRET 9*, 6–8 September 2006, Potsdam, **2006**, p. 128.
 - 38 J. Wagner, T. R. Tshikhudo, J. M. Köhler, *Chem. Eng. J.* **2008**, *135S*, S104–S109.
 - 39 D. Shalom, R. C. R. Wootton, R. F. Winkle, B. F. Cottam, R. Vilar, A. de Mello, C. P. Wilde, *Mater. Lett.* **2007**, *61*, 1146–1150.
 - 40 C. Sönnichsen, A. P. Alivisatos, *Biophys. J.* **2005**, *88*, 364A–365A.
 - 41 H. C. Soennichsen, presented at the 3rd Ilmenauer Workshop “Mikrolabortechnik”, 22–24 February **2006**, Elgersburg.
 - 42 J. Boleininger, A. Kurz, V. Reuss, C. Sönnichsen, *Phys. Chem. Chem. Phys.* **2006**, *8*, 3824–3827.
 - 43 J. M. Köhler, H. Romanus, U. Hübner, J. Wagner, *J. Nanomater.* **2007**, Art. No. 98134.
 - 44 J. M. Köhler, J. Wagner, J. Albert, *J. Mater. Chem.* **2005**, *15*, 1924.
 - 45 J. M. Köhler, J. Wagner, G. Mayer, U. Hübner, *Chem. Ing. Tech.* **2005**, *77*, 567.

- 46 J. M. Köhler, U. Hübner, J. Wagner, M. Held, presented at the AIChE Spring National Meeting/5th World Congress on Particle Technology, April 2006, Orlando, FL, paper 98c.
- 47 J. Wagner, T. Kirner, G. Mayer, J. Albert, J. M. Köhler, *Chem. Eng. J.* **2004**, *101*, 251.
- 48 J. Tagaki, M. Yamada, M. Yasuda, M. Seki, *Lab Chip* **2005**, *5*, 778–784.
- 49 I. Shestopalov, J. D. Tice, R. F. Ismagilov, *Lab Chip* **2004**, *4*, 316–321.
- 50 E. M. Chan, A. P. Alivisatos, R. A. Mathies, *J. Am. Chem. Soc.* **2005**, *127*, 13854.
- 51 L. H. Hung, K. M. Choi, W. Y. Tseng, Y. C. Tan, K. J. Shea, A. P. Lee, *Lab Chip* **2006**, *6*, 174–178.
- 52 S. L. Poe, M. A. Cummings, M. P. Haaf, D. T. McQuade, *Angew. Chem.* **2006**, *118*, 1574–1578.
- 53 T. Zech, P. Claus, D. Hönicke, *Chimia* **2002**, *56*, 611–620.
- 54 T. Zech, G. Bohner, J. Klein, *Catal. Today* **2005**, *110*, 58–67.
- 55 A. Kursawe, D. Hönicke, in *International Conference on Microreaction Technology, IMRET 5*, **2001**, pp. 240–251.
- 56 J. M. Köhler, J. Wagner, J. Albert, G. Mayer, in *5th International Conference on Unsteady-state Processes in Catalysis*, 22–26 November 2006, Suita, Japan, **2006**, pp. 43–44.
- 57 N. Aoki, K. Mae, in *5th International Conference on Unsteady-state Processes in Catalysis*, 22–26 November 2006, Suita, Japan, **2006**, pp. 29–30.