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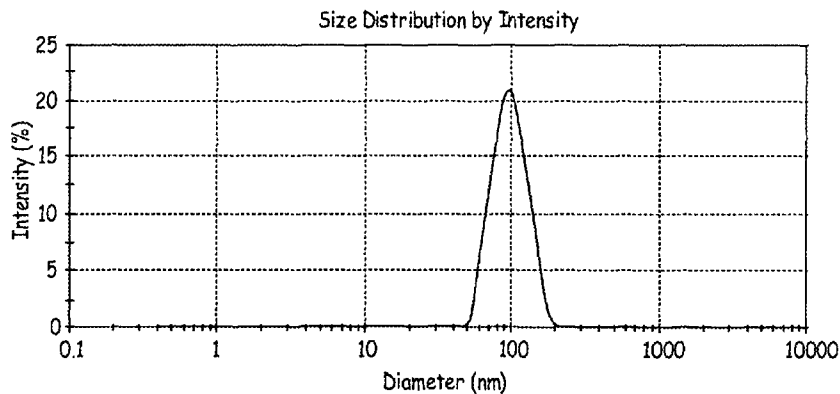
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(54) Title: NANOPARTICLE INKS BASED ON SILICON/GERMANIUM, DOPED PARTICLES, PRINTING AND PROCESSES FOR SEMICONDUCTOR APPLICATIONS

	Diam (nm)	% Intensity	Width (nm)
Z-Average (nm):	91.82	Peak 1: 95.5	100
PDI:	0.131	Peak 2: 0	0
Intercept:	0.926	Peak 3: 0	0



(57) Abstract: Highly uniform silicon/germanium nanoparticles can be formed into stable dispersions with a desirable small secondary particle size. The silicon/germanium particles can be surface modified to form the dispersions. The silicon/germanium nanoparticles can be doped to change the particle properties. The dispersions can be printed as an ink for appropriate applications. The dispersions can be used to form selectively doped deposits of semiconductor materials such as for the formation of photovoltaic cells or for the formation of printed electronic circuits.

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**NANOPARTICLE INKS BASED ON SILICON/GERMANIUM, DOPED
PARTICLES, PRINTING AND PROCESSES FOR SEMICONDUCTOR
APPLICATIONS**

5 CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to copending U.S. provisional patent application serial number 60/878,239 filed on January 3, 2007 to Hieslmair et al., entitled "Doped Dispersions and Processes for Doping Semiconductor Substrates," incorporated herein by reference.

10

FIELD OF THE INVENTION

The invention relates to dispersions/inks of silicon/germanium particles or silica/germania particles, such as doped particles. The invention further relates to inks that are suitable for inkjet printing. Additionally, the invention relates to the use of doped
15 silicon/germanium particles or silica/germania particles for the formation of doped structure and/or domains along semiconductor substrates.

BACKGROUND OF THE INVENTION

The formation of semiconductor devices generally involves the formation of doped
20 regions in which the dopants alter the electrical conduction properties or other desired properties. Through the selected doping process different domains can be formed in the material that provide functionalities for particular semiconductor devices. For example, some dopants provide excess electrons that can populate the conduction bands, and the resulting materials are referred to as n-type semiconductors. Other dopants provide holes
25 and are used to form p-type semiconductors. Additional dopants can provide other functionalities. Through appropriate doping, a wide range of devices can be formed, such as transistors, diodes and the like.

With increasing costs and undesirable environmental effects from the use of fossil fuels and other non-renewable energy sources, there are growing demands for alternative
30 forms of energy. Various technologies are available for the formation of photovoltaic cells, i.e., solar cells. A majority of commercial photovoltaic cells are based on silicon. Increased commercialization of alternative energy sources relies on increasing cost effectiveness through lower costs per energy unit. Thus, for a photovoltaic cell, the

objective would be to increase energy conversion efficiency for a given light fluence and/or to lower the cost of producing a cell.

SUMMARY OF THE INVENTION

5 In a first aspect, the invention pertains to a dispersion of silicon/germanium nanoparticles comprising a liquid and at least about 0.1 weight percent silicon/ germanium nanoparticles. The doped silicon/germanium nanoparticle can have an average primary particle size of no more than about 100 nm and a volume-average secondary particle size of no more than about three times that average primary particle size.

10 In a further aspect, the invention pertains to a method for surface modifying silicon/germanium nanoparticles in which the method comprises blending the surface modifying composition into a dispersion of the silicon/germanium nanoparticles in a dispersing liquid wherein the silicon/germanium nanoparticles have a volume-average secondary particle size of no more than about a factor of 5 times the average primary
15 particle size, wherein the silicon/germanium nanoparticles have an average primary particle size of no more than about 100 nm. In some embodiments, the surface modifying composition chemically bonds with the silicon/germanium particle surfaces to form surface modified nanoparticles with a surface modification moiety chemically bonded to the nanoparticle surfaces.

20 In another aspect, the invention relates to a method for depositing silicon/germanium nanoparticles. The method comprises printing an ink comprising a dispersing liquid and silicon/germanium particles in which the silicon/germanium nanoparticle have an average particle size of no more than about 75 nm and a volume-average secondary particle of no more than about 150 nm. The ink can have a viscosity of no more than
25 about 400 mPa·s at room temperature.

 In other aspects, the invention relates to a printed substrate comprising a substrate surface having a selected pattern covering no more than about 90 percent of the surface area in which the pattern comprises silicon/germanium nanoparticles, the nanoparticles having an average primary particle size of no more than about 100 nm. In some
30 embodiments, the silicon/germanium nanoparticles have a distribution of primary particle sizes such that at least about 95 percent of the primary particles have a diameter greater than about 40 percent of the average diameter and less than about 160 percent of the average diameter.

Additionally, the invention relates to a dopant ink composition suitable for ink jet printing, the ink comprising a stable dispersion of silica/germania nanoparticles in a dispersing liquid with a concentration of silica/germania nanoparticles from about 0.1 weight percent to about 20 weight percent. The silica/germania nanoparticles can have an average primary particle size of no more than about 100 nm, and the dopant ink generally has a viscosity from about 0.1 mPa·s to about 100 mPa·s.

In a further aspect, the invention relates to a dispersion comprising a liquid and doped silica/germania nanoparticles. In some embodiments, the doped silica/germania nanoparticles having an average primary particle size from about 1 nm to about 100 nm and a volume-average particle size of no more than about 500 nm. The dispersion can have a concentration of doped silica/germania nanoparticle from about 0.1 weight percent to about 20 weight percent doped silica/germania nanoparticles. The silica/germania nanoparticles can comprise a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon atoms of the silica/germania nanoparticles.

In another aspect, the invention relates to a method for forming a dispersion in which the method comprises blending a collection of doped silica/germania nanoparticles with a liquid and the liquid and nanoparticles are selected to be compatible with each other. The nanoparticles have an average primary particle size from about 1 nm to about 100 nm and a volume-average secondary particle size no more than about 500 nm following mixing. In some embodiments, the silica/germania nanoparticles comprise a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon/germanium atoms of the silica/germania nanoparticles.

In other aspects, the invention relates to a method for forming a deposit of silica/germania particles on a substrate surface in which the method comprises inkjet printing a pattern of an ink. The ink generally comprises silica/germania particles having an average primary particle size from about 1 nm to about 100 nm and a volume-average secondary particle size no more than about 500 nm.

Moreover, the invention pertains to a method for doping a semiconductor substrate comprising silicon or germanium in which the method comprises heating a deposit in contact with substrate to drive dopant into the substrate. The deposit generally comprises doped silica/germania particles in which the doped silica/germania particles comprise a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon/germanium atoms of the silica/germania particles. The particles can have an average primary particle size from about 1 nm to about 100 nm and an average second

particle size no more than about 500 nm based on a dispersion formed with the particles prior to forming a coating.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Fig. 1 is a top perspective view of a printed substrate.

Fig. 2 is a plot of particle size distribution by dynamic light scattering (DLS) of a silicon particle dispersion for nanoscale silicon particles in methanol at 0.5 weight percent.

Fig. 3 is a plot of particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles in propylene glycol at 0.5 weight percent.

10 Fig. 4 is a plot of particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles with a surface modification in gamma butyrolactone at 1.0 weight percent.

Fig. 5 is a plot of the particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles with a surface modification in ethyl lactate at 1.0
15 weight percent.

Fig. 6 is a plot of the particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles with and without surface modification in ethyl lactate at 1.0 weight percent.

Fig. 7 is a plot of the particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles with a surface modification in ethyl acetate
20 formed at 5 weight percent concentration and diluted to 1.0 weight percent for the DLS measurement.

Fig. 8 is a plot of the particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles with or without a surface modification in
25 methanol at 0.5 weight percent.

Fig. 9 is a plot of the particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles without surface modification in gamma butyrolactone at 1.0 weight percent.

Fig. 10 is a plot of the particle size distribution by DLS of a silicon particle dispersion for nanoscale silicon particles with a surface modification in ethyl acetate at
30 1.0 weight percent following performance of the surface modification in gamma-butyrolactone.

Fig. 11 is an x-ray micrograph of silica particles synthesized using laser pyrolysis with an aerosol tetraethoxysilane precursor in which the micrograph is taken at a first magnification.

5 Fig. 12 is an x-ray micrograph of the sample of Fig. 11 taken at a greater magnification.

Fig. 13 is a plot of the size distribution of a dispersion of silica nanoparticles in methylethylketone liquid using dynamic light scattering to make the measurement.

Fig. 14 is a plot of the size distribution of a dispersion of silica nanoparticles in isopropanol liquid using dynamic light scattering to make the measurement.

10

DETAILED DESCRIPTION OF THE INVENTION

Versatile processes for the delivery of silicon and/or germanium nanoparticles or correspondingly of silica and/or germania can be based upon the ability to form high quality dispersions of nanoparticles along with the ability to produce silicon/silica
15 nanoparticles with desirable properties. In some embodiments, the silicon/silica particles have selected dopants to provide desired properties for the particles. As described herein, the dispersions of the silicon/silica particles generally have highly uniform silicon/silica particles that can be dispersed well such that the resulting dispersions have a small secondary particle size with high uniformity. Flow-based methods are described that can
20 effectively form silicon/silica nanoparticles with high particle uniformity as well as a selected dopant concentration. Since the dispersions can be formed with appropriate properties, the dispersions can be used to formulate inks suitable for inkjet printing, which provides for efficient and precise deposition of the inks. In embodiments relating to doped silicon/silica particles, the dispersions and inks can be used to place deposits of doped
25 silicon/silica at selected locations along a semiconductor substrate. The doped silicon particles can be used to form doped layers or domains along the semiconductor materials. Also, dopants from silica particles can be driven into the semiconductor materials to correspondingly dope the semiconductors at selected locations.

Silicon is an important material for a range of applications. In particular, silicon is
30 a widely used semiconductor material for the formation of electrical circuits. Also, silicon can be selectively doped to influence the electrical properties of the silicon. Germanium can be used similarly as semiconductors from electrical circuit formation. For some applications, mixtures or blends of silicon and germanium may be useful. To simplify the discussion in the detailed description of the invention, the term silicon is used to refer to

silicon, germanium, combinations, e.g., alloys, thereof and mixtures thereof, unless otherwise stated or otherwise clearly limited in context, such as with respect to the description of chemical precursors. With respect to the claims, silicon shall refer only to silicon, and silicon/germanium shall refer to silicon, germanium, combinations/alloys
5 thereof and mixtures thereof.

Silica, i.e., silicon dioxide or SiO_2 , is also an important material for a range of applications. For example, silica can be used to form transparent optical materials useful for the transmission of light. In addition, silica is a useful dielectric for applications in electronics. Silica can be used as a dielectric with silicon based semiconductors since
10 silica particles can be produced such that the material does not provide any contaminants that can negatively impact the performance of a silicon based semiconductor if the contaminants migrate into the silicon based semiconductor. Also, silica can be selectively doped to influence the properties of the silica. As described further below, the doped silica particles can be used to deliver dopants to a silicon based semiconductor without
15 providing undesirable contaminants. Germania can be used similarly with respect to germanium-based semiconductors as silica is used for silicon-based semiconductors. For some applications, mixtures or blends of silica and germania may be useful. To simplify the discussion in the detailed description of the invention, the term silica is used to refer to silica, germania, combinations, e.g., alloys, thereof and mixtures thereof, unless otherwise
20 stated or otherwise clearly limited in the context, such as with respect to the description of chemical precursors. Furthermore, in the detailed description silicon/silica shall refer to silicon, germanium, silica, germania and appropriate combinations and alloys thereof. With respect to the claims, silica shall refer only to silica, and silica/germania shall refer to silica, germania, combinations/alloys thereof and mixtures thereof.

Dispersions of particular interest comprise a dispersing liquid and silicon/silica particles dispersed within the liquid along with optional additives. The dispersion can be stable with respect to avoidance of settling over a reasonable period of time, generally at least an hour, without further mixing. A dispersion can be used as an ink, i.e., the dispersion can be printed. The properties of the ink can be adjusted based on the particular
25 printing method. For example, in some embodiments, the viscosity of the ink is adjusted for the particular use, such as inkjet printing, and particle concentrations and additives provide some parameters to adjust the viscosity. The availability to form stable dispersions with small secondary particle sizes provides the ability to form certain inks. Other additives can be used to formulate a range of inks with appropriate properties.

The ability to form good dispersion is related to the ability to synthesize silicon/silica particles, including doped silicon/silica particles, with appropriate particle properties relating to the particle size, uniformity and surface chemistry. Flow based synthesis methods have been discovered to be very versatile with respect to synthesizing desired silicon/silica particles with or without dopants. In flow based methods, such as laser pyrolysis and flame pyrolysis, the product particles are collected as a powder. These flow-based approaches are particularly versatile with respect to forming doped silicon/silica particles.

Furthermore, it is desirable for the silicon/silica particles to be uniform with respect to particle size and other properties. Specifically, it is desirable for the particles to have a uniform primary particle size and for the primary particles to be substantially unfused. Then, the particles generally can be dispersed to yield a smaller more uniform secondary particle size in the dispersion. Secondary particle size refers to measurements of particle size within a dispersion. The formation of a good dispersion with a small secondary particle size can be facilitated through the matching of the surface chemistry of the particles with the properties of the dispersing liquid. The surface chemistry of particles can be influenced during synthesis of the particles as well as following collection of the particles. For example, the formation of dispersions with polar solvents is facilitated if the particles have polar groups on the particle surface.

In general, desirable silicon/silica particles for dispersions and corresponding inks are submicron. In other words, the particle collections have an average primary particle diameter of no more than about 1 micron, which is equal to 1000 nanometers (nm), and in some embodiments the average primary particle diameter is no more than about 100 nm. In some embodiments, the particles are very uniform in particle size. Also, the particle can have appropriate surface properties to form good dispersions for inks and other uses. Suitable submicron particles can be formed, for example, by vapor-based flow processes, such as flame pyrolysis or laser pyrolysis. Laser pyrolysis is a desirable approach for the formation of the particles since the resulting particles are generally highly uniform and can be well dispersed, which can involve surface modification of the particles, as described further below. In addition, laser pyrolysis is also desirable due to its flexibility with respect to product particle composition, such as a wide range of ability to introduce dopants.

As described herein, suitable approaches have been found to disperse dry nanoparticle powders, perform surface modification of the particles in a dispersion and form inks and the like for deposition. Using one or more of the processing approaches

described herein, inks can be formed that can be deposited using inkjet printing and other convenient printing approaches. Thus, the advantages of vapor-based particle synthesis can be combined with desirable solution based processing approaches with highly dispersed particles to obtain desirable dispersions and inks, which can be formed with
5 doped particles.

In some embodiments of particular interest, the particles are synthesized by laser pyrolysis in which light from an intense light source drives the reaction to form the particles. Laser pyrolysis is useful in the formation of particles that are highly uniform in composition and size. The ability to introduce a range of precursor compositions facilitates the formation
10 of silicon/silica particles with selected dopants, which can be introduced at relatively high concentrations.

Laser pyrolysis has been successfully used for the synthesis of a wide range of complex inorganic particles, including, for example, compositions with multiple metal/metalloid elements as well as doped materials. For example, the synthesis of highly
15 uniform silica particles is described in U.S. Patent 6,471,930 to Kambe et al., entitled "Silicon Oxide Particles," and U.S. Patent 6,726,990 to Kumar et al., entitled "Silicon Oxide Particles," both of which are incorporated herein by reference. A wide range of dopants for introduction into silica particles is described, for example, in U.S. Patent 6,849,334 to Horne et al., entitled "Optical Materials and Optical Devices," incorporated
20 herein by reference.

In the laser pyrolysis process, the dopant element(s) are introduced into the reactant stream such that the elements can be incorporated into the product particles. The dopant elements can be delivered into the reactant stream as a suitable composition. The reactant stream can comprise vapor precursor and/or aerosol precursors. For the doping of
25 semiconductor substrates, desirable dopants include, for example, B, P, Al, Ga, As, Sb and combinations thereof.

With respect to silicon/silica dispersions, the dispersions can have concentrations from low concentrations to about 30 weight percent. In general, the secondary particles size can be expressed as a cumulant mean, or Z-average particle size as measured with
30 dynamic light scattering (DLS). The Z-average particle size is an intensity average based on the scattered light measurements, and the scattering intensity based particle size distribution can be converted to volume distributions that can be used to evaluate a volume-average size. Generally, the volume-average particle size is no more than about 2

microns and in some embodiments, no more than about 250 nm. Additionally, in some embodiments it is desirable for the secondary particle size distribution to be narrow.

In general, the surface chemistry of the particles influences the process of forming the dispersion. In particular, it is easier to disperse the particles to form smaller secondary particle sizes if the dispersing liquid and the particle surfaces are compatible chemically, although other parameters such as density, particle surface charge, solvent molecular structure and the like also directly influence dispersability. In some embodiments, the liquid may be selected for to be appropriate for the particular use of the dispersion, such as for a printing process. The surface properties of the particles can be correspondingly be adjusted for the dispersion. For silicon synthesized using silanes, the resulting silicon generally is partially hydrogenated, i.e., the silicon includes some small amount of hydrogen in the material. It is generally unclear if this hydrogen or a portion of the hydrogen is at the surface as Si-H bonds. However, the presence of a small amount of hydrogen does not presently seem particularly significant.

In general, the surface chemistry of the particles can be influenced by the synthesis approach, as well as subsequent handling of the particles. The surface by its nature represents a termination of the underlying solid state structure of the particle. This termination of the surface of the silicon particles can involve truncation of the silicon lattice. This termination of the surface of the silica particles can involve the formation of single bonds, such as Si-O-H, or strained bonds, such as Si-O-Si that introduce surface strain along the surface. The termination of particular particles influences the surface chemistry of the particles. The nature of the reactants, reaction conditions, and by-products during particle synthesis influences the surface chemistry of the particles collected as a powder during flow reactions. In some embodiments, the silicon particles can become surface oxidized, for example through exposure to air. For these embodiments, the surface can have bridging oxygen atoms in Si-O-Si structures or Si-O-H groups if hydrogen is available during the oxidation process. The presence of OH bonds provide for alternative surface modification approaches.

The stability of particle dispersions can be improved at higher concentrations of particles through surface modification of the particles. In general, the surface properties of the particles influence the dispersion of the particles. The surface properties of the particles generally depend on the synthesis approach as well as the post synthesis processing. Some surface active agents, such as many surfactants, act through non-bonding interactions with the particle surfaces. In some embodiments, desirable properties

are obtained through the use of surface modification agents that chemically bond to the particle surface. The surface chemistry of the particles influences the selection of surface modification agents.

For surface oxidized silicon particles and silica particles, suitable surface
5 modification agents include, for example, alkoxysilanes, which chemically bond to metal oxide and metalloid oxide particles. Specifically, the alkoxysilanes bond through an Si-O-Si bond. In particular, trialkoxysilanes can form three bonds with the oxidized particle surface, which stabilizes the bonds with the particle. The fourth side group of the trialkoxysilane that does not bond with the oxidized particle surface influences the
10 resulting properties of the surface modified particles that relate with the interaction with fluids.

In general, silicon can be oxidized upon exposure to air. Therefore, the oxide coated particles can form the basis for further modification. The oxide coating can be reacted with NH_4^+F or HF to replace Si-O-H bonds with Si-H bonds that can be further
15 reacted. In particular, the hydrogenated surfaces with Si-H groups provide for the organic functionalization of the silicon surface. Functionalization of silicon surfaces is described further in U.S. Patent 5,429,708 to Linford et al., entitled "Molecular Layers Covalently Bonded to Silicon Surfaces," incorporated herein by reference.

For silicon particles without an oxidized surface, the surface can be functionalized,
20 for example, with halogens, such as Cl_2 to form Si-Cl bonds. Organic compounds with nucleophilic groups, such as $-\text{NH}_2$, $-\text{OH}$, $=\text{NH}$, $-\text{SH}$, $-\text{SeH}$, TeH and $-\text{PH}_2$, can be reacted with the Si-Cl groups to form bonds with the silicon atom through a nucleophilic substitution. These reactions are described further in U.S. Patent 6,403,382 to Zhu et al.,
25 entitled "Attachment Chemistry for Organic Molecules to Silicon," incorporated herein by reference. These reactions should not be altered in the presence of a dopant.

When processing a dry, as-synthesized powder, it has been found that forming a good dispersion of the particles prior to surface modification involving chemical bonding facilitates the surface modification process and results in particles with a higher degree of surface modification. The dispersion of the as-synthesized particles generally comprises
30 the selection of a solvent that is relatively compatible with the particles based on the surface chemistry of the particles. Shear, sonication or other appropriate mixing conditions can be applied to facilitate the formation of the dispersion. In general, it is desirable for the particles to be well dispersed, although the particles do not need to be

stably dispersed if the particles are subsequently surface modified with a chemically bonded composition.

If the particles are dispersed prior to performing the surface modification, the surface modification agent can be added to the dispersion in a solvent that is soluble or
5 miscible with dispersing liquid of the particle dispersion. Appropriate mixing can be applied to combine the surface modifying composition with the dispersed particles. The surface modifying compound can chemically bond with the dispersed particles to form a dispersion of surface modified particles.

The silicon/silica inks can be deposited onto the substrate using any suitable
10 process, such as a selected coating process, for example, spray coating, and/or printing. While various printing approaches can be effective, inkjet printing is desirable in some embodiments due to resolution and speed that can be achieved. Suitable inkjet heads are available commercially or can be constructed in simple forms using basic technology, although new designs can be used that are more suitable for a particular application.

15 Printing processes can effectively coat large areas very quickly and efficiently. For semiconductor applications, the use of the printing techniques described herein can eliminate one or more photolithography steps. For circuit formation, the substrate can comprise semiconductor materials, such as silicon, germanium or alloy thereof, or in other embodiments, a polymer substrate. A printing process can deposit the ink at specific
20 locations along the substrate surface. This allows the selective placement of silicon/silica particles with or without a dopant along the substrate, such as for circuit formation or other application. Other patterning approaches can be used alone or combined with a printing approach, or no patterning can be used, as appropriate for a specific application.

For printed circuit applications, once a doped silicon ink is deposited at selected
25 locations, the particles can be sintered or otherwise fused at the deposited position on the substrate to form a corresponding structure or domain. This can be done by heating the substrate in an oven to relatively high temperatures, such as 750°C to 1250°C to obtain a solid mass from the particles in intimate contact with the substrate surface. Nanoparticles melt or flow at lower temperatures than larger particles so that the use of nanoparticles can
30 facilitate the process with oven based heating. These temperatures are still below the melting point of bulk silicon, so that rapid thermal annealing can be used on silicon substrates and other relatively high temperature substrates. However, improved control of the process as well as energy saving can be obtained through the application of light energy, such as from a laser or incoherent light source, to melt the particles at the

deposited position along the substrate without generally heating the substrate or only heating the substrate to lower temperatures. This photonic curing process may be suitable for some lower melting substrates.

For semiconductor doping applications, once a doped silica ink is deposited at
5 selected locations, the dopant can be driven into the substrate to dope the surface layer of the substrate. This can be done by heating the substrate in an oven to relatively high temperatures, such as 750°C to 1100°C to obtain the desired diffusion profile for the dopant. Nanoparticles melt or flow at lower temperatures than larger particles so that the use of nanoparticles can facilitate the doping process with oven based heating. A faster
10 process involves rapid thermal anneal in which higher temperatures of 1000°C to 1250°C are reached for short times, such as from about 20 seconds to about 120 seconds. These temperatures are still below the melting point of silicon, so that rapid thermal annealing is still a solid state diffusion process. However, improved control of the resulting doped substrate as well as energy saving can be obtained through the application of light energy,
15 such as from a UV light source, using a laser or incoherent light source, to melt just the surface of the substrate without generally heating the substrate or only heating the substrate to lower temperatures. After the dopant is driven into the substrate surface, the residual oxide material can be etched off of the substrate, such as using wet etching or plasma etching.

20 In general, the deposition approaches described herein can be applied to any appropriate electric circuit applications. Thus, the dopant approaches described herein can be used in the formation of integrated circuits and other electrical and electro-optical devices, such as microelectromechanical (MEMS) devices. In particular, these processing approaches can be effectively used in the formation of photovoltaic devices, i.e., solar
25 cells. The processes herein are well suited for large area semiconductors such as photovoltaic panels as well as other large area applications, such as display circuits. Similarly, through the printing process the doped silicon/silica particles can be used to form dopant domains to corresponding select locations on the substrate surface so that printed electronics can be formed. Printed electronics can be an effective approach for the
30 formation of semiconductor devices with moderate resolution of electrical components at a lower cost than photolithography.

For solar cell applications, the use of doped silica particles to dope corresponding sections of silicon semiconductors has been known for some time. Screen printing of doped silica sol-gel solution to dope a semiconductor for a solar cell is described in U.S.

Patent 4,104,091 to Evans, Jr. et al., entitled "Application of Semiconductor Diffusants to Solar Cells by Screen Printing," incorporated herein by reference. Once the silica is printed to place the silica at desired locations, the printed structure is heated to drive the dopants from the silica into the adjacent semiconductor.

5 The formation of desirable solar cell elements on a thin silicon foil is described further in copending U.S. Provisional patent application 60/902,006 to Hieslmair et al. filed February 16, 2007, entitled "Photovoltaic Cell Structures, Solar Panels and Corresponding Structures," incorporated herein by reference. This provisional application describes forming shallow doped regions in some embodiments. These shallow doped
10 regions can be conveniently formed by printing the doped silicon and using heat and/or light, such as from a laser or flash lamp, to fuse the doped silicon into corresponding doped contacts, as described further below. These shallow doped regions can be conveniently formed by printing the doped silica and using laser light to drive in the dopants, as described further below. In other embodiments, thicker junctions may be
15 desirable.

Printed circuit applications of particular interest include, for example, display circuits in which electrical connections for display elements cover a relatively large area while involving moderate resolution to distinguish the elements. The display circuits can be formed through the printing process and subsequent processing to form the circuitry for
20 controlling the display element.

Optical applications of particular interest for silica particles include, for example, displays in which display elements can be formed through the printing process and subsequent processing to form the display element. For example, phosphor particles can be coated with silica to stabilize the phosphor properties. The resulting silica coated
25 particles can be dispersed as described herein to deposit the phosphor particles. The deposited phosphor particles can be heated to fuse the particles into a mass that forms a display element. Boron, phosphorous and/or germanium dopants can be used to lower the flow temperature of the silica particles. Also, rare earth dopants can be added into phosphors to form active materials that can emit light under appropriate activating
30 conditions. Thus, the printing process can be effective to form display structures with desired optical material at selected locations within the structure in which the optical materials incorporate particular dopants to influence the optical and/or physical properties of the material.

In other applications, silica particles can be deposited to form waveguides and the like, which can be useful for optical communications applications. The silica dopants can be selected to adjust the index-of-refraction of the particles. The index-of-refraction of the resulting optical structure following fusing of the particles can be altered through the adjustment of the index-of-refraction of the particles. The index-of-refraction of the waveguides is selected to provide for total internal reflection of selected wavelengths of light. The waveguide can be printed to follow a selected optical pathway.

As described herein, high quality dispersions of silicon/silica, with or without dopants, provides the ability for effective printing of the silicon/silica to form higher resolution structures. Due to the enhanced ability to control the properties of the inks, the silicon/silica particles can be printed rapidly and with relatively high resolution, for example, using inkjet printing or other desired approach. The ability to introduce selected dopants over a wide range of compositions provides the ability to form a corresponding wide range of devices based on the silicon particles. The dopants can be selected based on the particle device to be formed and the corresponding desired electrical properties for the element. Using the printing process, silicon/silica particles with different dopants can be selectively placed at different locations along the substrate surface.

Particle Synthesis and Properties

The desirable dispersions described herein are based in part on the ability to form highly uniform silicon/silica nanoparticles with or without dopants. Laser pyrolysis is a particularly suitable approach for the synthesis of highly uniform silicon/silica particles. Also, laser pyrolysis is a versatile approach for the introduction of desired dopants at a selected concentration. Also, the surface properties of the silicon/silica particles can be influenced by the laser pyrolysis process, although the surface properties can be further manipulated after synthesis to form desired dispersions. Small and uniform silicon/silica particles can provide processing advantages with respect to forming dispersions/inks.

In some embodiments, the particles have an average diameter of no more than about one micron, and in further embodiments it is desirable to have particles with smaller particle sizes to introduce desired properties. For example, nanoparticles with a small enough average particle size are observed to melt at lower temperatures than bulk material, which can be advantageous in some contexts. Also, the small particle sizes provide for the formation of inks with desirable properties, which can be particularly advantageous for inkjet printing since larger particles may clog some inkjet heads. Generally, the dopants and the dopant

concentration are selected based on the desired electrical properties of the subsequently fused material or material that receive transferred dopants. In the formation of optical material, for example, the optical properties, such as index-of-refraction and/or emission, of the silica particles can be selected through the addition of dopants.

5 Suitable submicron and nano-scale particles can be formed, for example, by laser pyrolysis, flame synthesis, combustion approaches or solution-based approaches, such as sol-gel processes. While laser pyrolysis is a desirable approach for particle production, submicron particles can be produced using a flame production apparatus such as the apparatus described in U.S. Patent 5,447,708 to Helble et al., entitled "Apparatus for
10 Producing Nanoscale Ceramic Particles," incorporated herein by reference. Furthermore, submicron particles can be produced with a thermal reaction chamber such as the apparatus described in U.S. Patent 4,842,832 to Inoue et al., "Ultrafine Spherical Particles of Metal Oxide and a Method for the Production Thereof," incorporated herein by reference.

In particular, laser pyrolysis is useful in the formation of particles that are highly
15 uniform in composition, crystallinity, when appropriate, and size. Laser pyrolysis involves light from an intense light source that drives the reaction to form the particles. Due to the versatility of laser pyrolysis as an excellent approach for efficiently producing a wide range of nanoscale particles with a selected composition and a narrow distribution of average particle diameters, laser pyrolysis can be used to form doped silicon/silica particles with a
20 wide range of selected dopants or combinations of dopants. For convenience, light-based pyrolysis is referred to as laser pyrolysis since this terminology reflects the convenience of lasers as a radiation source and is a conventional term in the art. Laser pyrolysis approaches discussed herein incorporate a reactant flow that can involve gases, vapors, aerosols or combinations thereof to introduce desired elements into the flow stream. The versatility of
25 generating a reactant stream with gases, vapor and/or aerosol precursors provides for the generation of particles with a wide range of potential compositions.

A collection of submicron/nanoscale particles may have an average diameter for the primary particles of less than about 500 nm, in some embodiments from about 2 nm to about 100 nm, alternatively from about 2 nm to about 75 nm, or from about 2 nm to about 50 nm.
30 A person of ordinary skill in the art will recognize that other ranges within these specific ranges are covered by the disclosure herein. Primary particle diameters are evaluated by transmission electron microscopy.

As used herein, the term "particles" refer to physical particles, which are unfused, so that any fused primary particles are considered as an aggregate, i.e. a physical particle. For

particles formed by laser pyrolysis, the particles can be generally effectively the same as the primary particles, i.e., the primary structural element within the material. Thus, the ranges of average primary particle sizes above can also be used with respect to the particle sizes. If there is hard fusing of some primary particles, these hard fused primary particles form correspondingly larger physical particles. The primary particles can have a roughly spherical gross appearance, or they can have rod shapes, plate shapes or other non-spherical shapes. Upon closer examination, crystalline particles may have facets corresponding to the underlying crystal lattice. Amorphous particles generally have a spherical aspect. Diameter measurements on particles with asymmetries are based on an average of length measurements along the principle axes of the particle.

Because of their small size, the particles tend to form loose agglomerates due to van der Waals and other electromagnetic forces between nearby particles. Even though the particles may form loose agglomerates, the nanometer scale of the particles is clearly observable in transmission electron micrographs of the particles. The particles generally have a surface area corresponding to particles on a nanometer scale as observed in the micrographs. Furthermore, the particles can manifest unique properties due to their small size and large surface area per weight of material. These loose agglomerates can be dispersed in a liquid to a significant degree, and in some embodiments approximately completely to form dispersed primary particles.

The particles can have a high degree of uniformity in size. Laser pyrolysis generally results in particles having a very narrow range of particle diameters. Furthermore, heat processing under suitably mild conditions generally does not significantly alter the very narrow range of particle diameters. With aerosol delivery of reactants for laser pyrolysis, the distribution of particle diameters is particularly sensitive to the reaction conditions. Nevertheless, if the reaction conditions are properly controlled, a very narrow distribution of particle diameters can be obtained with an aerosol delivery system. As determined from examination of transmission electron micrographs, the particles generally have a distribution in sizes such that at least about 95 percent, and in some embodiments 99 percent, of the particles have a diameter greater than about 35 percent of the average diameter and less than about 280 percent of the average diameter. In additional embodiments, the particles generally have a distribution in sizes such that at least about 95 percent, and in some embodiments 99 percent, of the particles have a diameter greater than about 40 percent of the average diameter and less than about 250 percent of the average diameter. In further embodiments, the particles have a distribution of diameters such that at least about 95 percent,

and in some embodiments 99 percent, of the particles have a diameter greater than about 60 percent of the average diameter and less than about 200 percent of the average diameter. A person of ordinary skill in the art will recognize that other ranges of uniformity within these specific ranges are contemplated and are within the present disclosure.

5 Furthermore, in some embodiments essentially no particles have an average diameter greater than about 5 times the average diameter, in other embodiments about 4 times the average diameter, in further embodiments 3 times the average diameter, and in additional
10 embodiments 2 times the average diameter. In other words, the particle size distribution effectively does not have a tail indicative of a small number of particles with significantly larger sizes. This is a result of the small reaction region to form the inorganic particles and
15 corresponding rapid quench of the inorganic particles. An effective cut off in the tail of the size distribution indicates that there are less than about 1 particle in 10^6 has a diameter greater than a specified cut off value above the average diameter. High particle uniformity can be
20 exploited in a variety of applications.

15 In addition, the submicron particles may have a very high purity level. Furthermore, crystalline nanoparticles, such as those produced by laser pyrolysis, can have a high degree of crystallinity. Similarly, the crystalline nanoparticles produced by laser pyrolysis can be
20 subsequently heat processed to improve and/or modify the degree of crystallinity and/or the particular crystal structure. Impurities on the surface of the particles may be removed by heating the particles to achieve not only high crystalline purity but high purity overall.

 The size of the dispersed particles can be referred to as the secondary particle size. The primary particle size, of course, is the lower limit of the secondary particle size for a particular collection of particles, so that the average secondary particle size can be
25 approximately the average primary particle size if the primary particles are substantially unfused and if the particles are effectively completely dispersed in the liquid.

 The secondary or agglomerated particle size may depend on the subsequent processing of the particles following their initial formation and the composition and structure of the particles. In particular, the particle surface chemistry, properties of the dispersant, the application of disruptive forces, such as shear or sonic forces, and the like can influence the
30 efficiency of fully dispersing the particles. Ranges of values of average secondary particle sizes are presented below with respect to the description of dispersions. Secondary particles sizes within a liquid dispersion can be measured by established approaches, such as dynamic light scattering. Suitable particle size analyzers include, for example, a Microtrac UPA instrument from Honeywell based on dynamic light scattering, a Horiba Particle Size

Analyzer from Horiba, Japan and ZetaSizer Series of instruments from Malvern based on Photon Correlation Spectroscopy. The principles of dynamic light scattering for particle size measurements in liquids are well established.

5 A basic feature of successful application of laser pyrolysis for the production of desirable silicon/silica particles is the generation of a reactant stream containing one or more silicon precursor compounds and, in some embodiments, a radiation absorber and/or a secondary reactant. The secondary reactant can be a source of atoms for the product particles and/or can be an oxidizing or reducing agent to drive a desired product formation. A secondary reactant may not be used if the precursor decomposes to the desired product under
10 intense light radiation, which can be the situation for silicon particles. Similarly, a separate radiation absorber may not be used if the silicon precursor absorbs the appropriate light radiation to drive the reaction. Dopant precursors can be introduced into the reactant flow for incorporation into the silicon/silica particles.

The reaction of the reactant stream is driven by an intense radiation beam, such as a
15 light beam, e.g., a laser beam. In some embodiments, CO₂ lasers can be effectively used. As the reactant stream leaves the radiation beam, the inorganic particles are rapidly quenched with particles in present in the resulting product particle stream, which is a continuation of the reactant stream. The concept of a stream has its conventional meaning of a flow originating from one location and ending at another location with movement of mass between
20 the two points, as distinguished from movement in a mixing configuration.

A laser pyrolysis apparatus suitable for the production of commercial quantities of particles by laser pyrolysis has been developed using a reactant inlet that is significantly elongated in a direction along the path of the laser beam. This high capacity laser pyrolysis apparatus, e.g., 1 kilogram or more per hour, is described in U.S. Patent 5,958,348, entitled
25 "Efficient Production Of Particles By Chemical Reaction," incorporated herein by reference. Approaches for the delivery of aerosol precursors for commercial production of particles by laser pyrolysis is described in copending and commonly assigned U.S. Patent 6,193,936 to Gardner et al., entitled "Reactant Delivery Apparatus," incorporated herein by reference. With respect to combined vapor and aerosol delivery approaches, a silicon precursor can be
30 delivered as a vapor, while one or more dopant precursors is delivered as an aerosol. However, for many desirable dopants, suitable dopant precursors can be delivered as a vapor.

In general, nanoparticles produced by laser pyrolysis can be subjected to additional processing to alter the nature of the particles, such as the composition and/or the crystallinity. For example, the nanoparticles can be subjected to heat processing in a gas atmosphere prior

to use. Under suitably mild conditions, heat processing is effective to modify the characteristics of the particles, such as removal of carbon contaminants, without destroying the nanoscale size or the narrow particle size distribution of the initial particles. For example, heat processing of submicron vanadium oxide particles is described in U.S. Patent 5,989,514 to Bi et al., entitled "Processing Of Vanadium Oxide Particles With Heat," incorporated herein by reference.

A wide range of simple and complex submicron and/or nanoscale particles have been produced by laser pyrolysis with or without additional heat processing. Specifically, the inorganic particles can include, for example, elemental metal or elemental metalloid, i.e. un-ionized elements such as silver or silicon, metal/metalloid oxides, metal/metalloid nitrides, metal/metalloid carbides, metal/metalloid sulfides or combinations thereof. In addition, uniformity of these high quality materials can be substantial. These particles generally can have a very narrow particle size distribution. In particular, laser pyrolysis for the formation of silicon particles is described in Cannon et al., "Sinterable Ceramic Powders from Laser-Driven Reaction: I, Process Description and Modeling," *J. Am. Ceramic Society* 65 (7), 324 (1982), and Cannon et al., "Sinterable Ceramic Powders from Laser-Driven Reaction: II, Powder Characteristics and Process Variables," *J. Am. Ceramic Society* 65 (7), 330 (1982), both of which are incorporated by reference. Laser pyrolysis methods and uniform silica particles formed by laser pyrolysis are described further in U.S. Patent 6,471,903 to Kambe et al., entitled "Silicon Oxide Particles," and U.S. Patent 6,726,990 to Kumar et al., entitled "Silicon Oxide Particles," both of which are incorporated herein by reference. Doped silica particles formed using laser pyrolysis process are described in U.S. Patent 6,849,334 to Horne et al., entitled "Optical Materials and Optical Devices," incorporated herein by reference. The production of a range of particles by laser pyrolysis is described further in published U.S. Patent Application 2003/203205A to Bi et al., entitled "Nanoparticle Production and Corresponding Structures," incorporated herein by reference.

Submicron and nanoscale particles can be produced with selected dopants using laser pyrolysis and other flowing reactor systems. Dopants can be introduced at desired concentrations by varying the composition of the reactant stream. A dopant element or a combination of dopant elements are introduced into the silicon host material by appropriately selecting the composition in the reactant stream and the processing conditions. Thus, submicron particles incorporating selected dopants, including, for example, complex blends of dopant compositions, can be formed. Generally, the conditions in the reactor should be sufficiently reducing to produce the elemental silicon or alloys for the product nanoparticles.

The doped particles can be either amorphous solid state blends with the dopant composition dissolved in the host material. However, generally the silicon particles are crystalline, and the dopant can be an intercalation or alloying element. On the other hand, silica particles can be amorphous, and the dopant can be in the form of a solid state blend. In some
5 embodiments, one or more dopants can be introduced in concentrations in the particles from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon atoms, in further embodiments from about 1.0×10^{-5} to about 5.0 atomic percent and in further embodiments from about 1×10^{-4} to about 1.0 atomic percent relative to the silicon atoms. A person of ordinary skill in the art will recognize that additional ranges within the explicit dopant level
10 ranges are contemplated and are within the present disclosure.

Dopants can be introduced to vary properties of the resulting particles. For example, dopants can be introduced to change the electrical properties of the particles. In particular, As, Sb and/or P dopants can be introduced into the silicon particles to form n-type semiconducting materials in which the dopant provide excess electrons to populate the
15 conduction bands, and B, Al, Ga and/or In can be introduced to form p-type semiconducting materials in which the dopants supply holes. Also, dopants can be introduced to change the optical properties of the particles, such as the index-of-refraction, or dopants can introduce fluorescent or phosphorescent properties to the particles such that they can function as phosphors. Dopants can also be introduced to alter the processing properties of the material,
20 such as by lowering the softening temperature. Furthermore, dopants can also interact within the materials. For example, some dopants are introduced to increase the solubility of other dopants. Also, as described below, the dopants can be used to transfer dopants to an adjacent material, such as a semiconductor substrate.

In some embodiments, the one or plurality of dopants are rare earth metals or rare
25 earth metals with one or more other dopant elements. Rare earth metals comprise the transition metals of the group IIIb of the periodic table. Specifically, the rare earth elements comprise Sc, Y and the Lanthanide series. Other suitable dopants comprise elements of the actinide series. For optical glasses, the rare earth metals of particular interest as dopants comprise, for example, Ho, Eu, Ce, Tb, Dy, Er, Yb, Nd, La, Y, Pr and Tm. Generally, the
30 rare earth ions of interest have a +3 ionization state, although Eu^{+2} and Ce^{+4} are also of interest. Rare earth dopants can influence the optical absorption properties that can enable the application of the materials for the production of optical amplifiers and other optical devices. Suitable non-rare earth dopants for various purposes include, for example, Bi, Sb,

Zr, Pb, Li, Na, K, Ba, B, Si, Ge, W, Ca, Cr, Ga, Al, Mg, Sr, Zn, Ti, Ta, Nb, Mo, Th, Cd and Sn.

In general, any reasonable element can be introduced as a dopant to achieve desired properties. Suitable silicon precursors for elemental silicon particle formation include, for example, silane (SiH_4), disilane (Si_2H_6), trisilane (Si_3H_8), silicon tetrachloride (SiCl_4), trichlorosilane (SiCl_3H), and SiCl_2H_2 . Silane, SiH_4 , is a convenient precursor for laser pyrolysis since it absorbs infrared light from a CO_2 laser and decomposes to form crystalline silicon particles upon decomposition. The higher order silanes similarly decompose to form elemental silicon, i.e. Si^0 , silicon in its elemental state. Thus, with silane as a precursor, a secondary reactant source may not be used, and a separate infrared absorber is not needed. Corresponding germanes (GeH_4 and Ge_2H_6) can be used as precursors. An inert gas can be used to moderate the reaction. Suitable inert gases include for example, Ar, He N_2 or mixtures thereof.

Suitable precursors for B, Al, Ga, P, As, Sb and other dopants are described explicitly in the '334 patent. Suitable precursors for aerosol delivery of gallium include, for example, gallium nitrate ($\text{Ga}(\text{NO}_3)_3$). Arsenic precursors include, for example, AsCl_3 , which is suitable for vapor delivery, and As_2O_5 , which is suitable for aerosol precursor delivery in aqueous or alcohol solutions. Suitable boron precursors comprise, for example, diborane (B_2H_6), BH_3 , and the like, and suitable combinations of any two or more thereof. Suitable aluminum precursors include, for example, aluminum hydride (AlH_3), aluminum s-butoxide ($\text{Al}(\text{OC}_4\text{H}_9)_3$), trimethyl aluminum ($\text{Al}(\text{CH}_3)_3$), trimethyl ammonia aluminum $\text{Al}(\text{CH}_3)_3\text{NH}_3$, and the like, and suitable combinations of any two or more thereof. Suitable phosphorous precursor compositions for vapor delivery comprise, for example, phosphine (PH_3), phosphorus trichloride (PCl_3), phosphorous pentachloride (PCl_5), phosphorus oxychloride (POCl_3), $\text{P}(\text{OCH}_3)_3$, and the like, and suitable combinations of any two or more thereof. Suitable antimony precursors include, for example, stibine (SbH_3) and antimony trichloride (SbCl_3), which is soluble in alcohol.

Surface Modification and Dispersion Process

The submicron silicon/silica particles generally are dispersed for further processing or use. In some embodiments, the dispersion can be further stabilized by surface modifying the silicon/silica particles. The surface modifying agents of particular interest can form chemical bonds with the particle surface. Through appropriate selection of the dispersing liquid and the particle surface properties, stable dispersions can be formed at

reasonable concentrations. The dispersions can be delivered through suitable coating approaches or printed with the dispersion used as an ink. The surface modification process can involve a switch of dispersants.

The surface modification of inorganic particles, e.g., silicon/silica particles, can improve stability of the particle dispersions and provide for dispersion of the particles in a wider range of liquids and potentially at higher concentrations. While some surface modifiers can merely coat the surface, improved stability of the coated particles may be accomplished with surface modifiers that are chemically bonded to the surface. For convenience of terminology, a surface modifying compound refers to a compound that adds at least 3 atoms to the particle surface when it bonds to the particle surface, to distinguish compositions, that modify the surface of a silicon particle or silicon oxide surface coating of the particle such as through the introduction of an Si-OH group or an Si-Cl group. In general, it is expected that the presence of a dopant does not significantly alter the surface modification process or chemistry. A range of surface modifying compounds can be used to chemically bond to the silicon particle surfaces. Suitable functional groups for bonding to inorganic particles with different compositions are described in U.S. Patent 6,599,631 to Kambe et al, entitled "Polymer-Inorganic Particle Composites," incorporated herein by reference.

In particular, alkoxysilanes react with silicon oxides at the surface of silicon particles to form Si-O-Si- bonds to form a stable surface coating with the release of a corresponding compound from the displaced alkoxy silane functional group. For bonding with some surface modification agents, an improved surface coating can be achieved with improved -OH functional group coverage on the surface of the silicon/silica particles.

In particular, trialkoxysilanes provide very stable bonding to oxidized particle surfaces with potentially three points of bonding. The fourth side chain of the trialkoxysilanes provides the ability to influence the dispersability and other surface properties of the surface modified inorganic particles. Specifically, the fourth side chain of the silane can be selected to improve dispersability in a selected solvent and/or to provide a reactive functional group for further processing. Similarly, polydialkoxysiloxane silanes provide stable bonding with the ability of each monomer unit to form two bonds to the particle. The siloxane polymer can wrap around the particles during the bonding process. In addition to alkoxy silanes, chemical compounds with other functional groups can form bonds to an oxidized surface of silicon particles. Specifically, compounds with chlorosilicate (-SiCl) groups, some amine groups, carboxylic acid groups and hydroxide

groups can also bond to oxidized silicon particle surfaces. Additional functional groups of these compounds can be similarly selected to yield desirable properties for the resulting surface modified particles.

With respect to the alkoxy side chains of silanes, methoxy groups and ethoxy groups have been found to be effective in reacting with inorganic oxide particle surfaces, and a range of compounds with these functional groups are commercially available. Suitable fourth functional groups for the trialkoxy silanes include, for example, alkyl groups, epoxide groups $-(\text{CH}_2)_n\text{CHCH}_2\text{O}_{\text{bridge}}$, methacryloxyalkyl $-(\text{CH}_2)_n\text{OOC}=\text{CH}_2$, isocyanate $-(\text{CH}_2)_n\text{NCO}$, thiol $-(\text{CH}_2)_n\text{SH}$, acetyl $-(\text{CH}_2)_n\text{OOCCH}_3$, hydroxybenzophenyl $-(\text{CH}_2)_n\text{OC}_6\text{H}_5(\text{OH})\text{COC}_6\text{H}_5$, allyl $-\text{CH}_2\text{CH}=\text{CH}_2$, and phenethyl $-(\text{CH}_2)_n\text{C}_6\text{H}_5$. In general, the surface modifying compound can be coated at a coverage from less than a monolayer to four or more monolayers as well as values between. The amount of coverage can be estimated based on the surface area of the particles and the amount of compound that can be expected to pack along the particle surface.

Other surface modification approaches for silicon particles are described above. In particular, oxidized silicon particle surfaces can be reacted to form hydrogenated surfaces, and the resulting Si-H groups can be functionalized with organic compounds. In other embodiments, un-oxidized silicon particle surfaces can be reacted with Cl_2 to form Si-Cl bonds that are susceptible to nucleophilic substitution to provide desired functionalization of the silicon particle surface.

One of at least two processes can be used to perform the surface modification. In one approach, an unstable, higher concentration dispersion can be formed with the silicon/silica particles, and the surface modification is performed to stabilize the higher concentration dispersion. However, better particle dispersions generally are obtained through first forming a dilute, relatively stable dispersion of the particles without surface modification and then performing the surface modification.

In the direct approach, the liquid is selected to balance the dispersion of the unmodified particles, the solubility of the surface modifying compound unbound to the particles and the dispersion of the particles following surface modification. Generally, the liquid is not a particularly good dispersant for the unmodified particles. Similarly, the liquid may not be a good solvent for the surface modifying agent. But if the surface modifying agent is somewhat soluble in the liquid and the unmodified particles can be dispersed with mixing, the surface modification reaction can be performed. As the particles become surface modified, the dispersion may stabilize as the reaction proceeds.

Better dispersion results generally can be obtained if the inorganic particles without a surface modifier are first stably dispersed with a desirably small average secondary particle size. Alcohols and water/alcohol blends generally are good dispersants for silicon particles with surface oxidation as well as for unmodified silica particles as synthesized by some approaches. The surface modifying compound can be added directly into the dispersing liquid if it has some solubility, or the surface modification compound can be dissolved into a solvent that is miscible with or soluble in the liquid of the particle dispersion. After the surface modification is complete, the particles can be transferred to a different dispersing liquid as described below. The surface modified particles can be stored or shipped in a liquid suitable for further processing.

In general, to change dispersing liquids, it has been found effective to settle the particles by forming a liquid mixture in which the stability of the dispersion is lost. Centrifugation or filtration can be used to efficiently separate the particles from the liquid once they are no longer stably dispersed. If the particles are centrifuged, the liquid is decanted from the precipitated particles. The particles can be washed one or more times with a selected dispersing liquid to remove residual amounts of the original liquid. Then, the particles can be redispersed in the selected liquid. In this way, the liquid can be changed for a later processing step through the selection of a surface modifier that facilitates dispersion in the selected liquid.

Following surface modification and/or at other stages of the dispersion process, the dispersion can be filtered to remove contaminants and or any stray unusually large particles. Generally, the filter is selected to exclude particulates that are much larger than the average secondary particle size so that the filtration process can be performed in a reasonable way. In general, the filtration processes have not been suitable for overall improvement of the dispersion quality. Suitable commercial filters are available, and can be selected based on the dispersion qualities and volumes.

Properties and Formation of the Dispersions and Inks

The dispersions can be formulated for a selected application. The dispersions can be characterized with respect to composition as well as the characterization of the particles within the dispersions. In general, the term ink is used to describe a dispersion that is subsequently deposited using a printing technique, and an ink may or may not include additional additives to modify the ink properties.

The dispersions comprise a liquid and the dispersed silicon/silica particles, which may or may not be surface modified. In general, silicon/silica particles formed by laser pyrolysis can be well dispersed in a polar organic liquid at moderate concentrations with no surface modification, although higher concentration dispersions generally can be formed with surface modification. Suitable alcohols include, for example, small aliphatic alcohols, such as methanol, ethanol, propylene glycol, butanediol, mixtures thereof and the like. Upon surface modification, the silicon particles can be dispersed in a broader range of solvents and solvent blends through the matching of the chemical properties of the surface modifying agent with the liquid. Thus, following surface modification, the particles can be well dispersed in a range of less polar solvents, such as ethyl lactate, n-methyl pyrrolidinone, gamma-butyl lactone and the like.

Better dispersions are more stable and/or have a smaller secondary particle size indicating less agglomeration. As used herein, stable dispersions have no settling without mixing after one hour. In some embodiments, the dispersions exhibit no settling of particles without mixing after one day and in further embodiments after one week, and in additional embodiments after one month. In general, dispersions with well dispersed particles can be formed at concentrations of at least up to 30 weight percent inorganic particles. Generally, for some embodiments it is desirable to have dispersions with a particle concentration of at least about 0.05 weight percent, in other embodiments at least about 0.25 weight percent, in additional embodiments from about 0.5 weight percent to about 30 weight percent and in further embodiments from about 1 weight percent to about 20 weight percent. A person of ordinary skill in the art will recognize that additional ranges of stability times and concentrations within the explicit ranges above are contemplated and are within the present disclosure.

The dispersions can include additional compositions besides the silicon/silica particles and the dispersing liquid or liquid blend to modify the properties of the dispersion to facilitate the particular application. For example, property modifiers can be added to the dispersion to facilitate the deposition process. Surfactants can be effectively added to the dispersion to influence the properties of the dispersion.

In general, cationic, anionic, zwitter-ionic and nonionic surfactants can be helpful in particular applications. In some applications, the surfactant further stabilizes the particle dispersions. For these applications, the selection of the surfactant can be influenced by the particular dispersing liquid as well as the properties of the particle surfaces. In general, surfactants are known in the art. Furthermore, the surfactants can be selected to influence

the wetting or beading of the dispersion/ink onto the substrate surface following deposition of the dispersion. In some applications, it may be desirable for the dispersion to wet the surface, while in other applications it may be desirable for the dispersion to bead on the surface. The surface tension on the particular surface is influenced by the surfactant. Also, blends of surfactants can be helpful to combine the desired features of different surfactants, such as improve the dispersion stability and obtaining desired wetting properties following deposition. In some embodiments, the dispersions can have surfactant concentrations from about 0.01 to about 5 weight percent, and in further embodiments from about 0.02 to about 3 weight percent. A person of ordinary skill in the art will recognize that additional ranges of surfactant concentrations within the explicit ranges above are contemplated and are within the present disclosure.

The use of non-ionic surfactants in printer inks is described further in U.S. Patent 6,821,329 to Choy, entitled "Ink Compositions and Methods of Ink-Jet Printing on Hydrophobic Media," incorporated herein by reference. Suitable non-ionic surfactants described in this reference include, for example, organo-silicone surfactants, such as SILWETTM surfactants from Crompton Corp., polyethylene oxides, alkyl polyethylene oxides, other polyethylene oxide derivatives, some of which are sold under the trade names, TERGITOLTM, BRIJTM, TRITONTM, PLURONICTM, PLURAFACTM, IGEPALTM, and SULFYNOLTM from commercial manufacturers Union Carbide Corp., ICI Group, Rhone-Poulenc Co., Rhom & Haas Co., BASF Group and Air Products Inc. Other nonionic surfactants include MACKAMTM octylamine chloroacetic adducts from McIntyre Group and FLUORADTM fluorosurfactants from 3M. The use of cationic surfactants and anionic surfactants for printing inks is described in U.S. Patent 6,793,724 to Satoh et al., entitled "Ink for Ink-Jet Recording and Color Ink Set," incorporated herein by reference. This patent describes examples of anionic surfactants such as polyoxyethylene alkyl ether sulfate salt and polyoxyalkyl ether phosphate salt, and examples of cationic surfactants, such as quaternary ammonium salts.

Viscosity modifiers can be added to alter the viscosity of the dispersions. Suitable viscosity modifiers include, for example soluble polymers, such as polyacrylic acid, polyvinyl pyrrolidone and polyvinyl alcohol. Other potential additives include, for example, pH adjusting agents, antioxidants, UV absorbers, antiseptic agents and the like. These additional additives are generally present in amounts of no more than about 5 weight percent. A person of ordinary skill in the art will recognize that additional ranges

of surfactant and additive concentrations within the explicit ranges herein are contemplated and are within the present disclosure.

For electronic applications, it can be desirability to remove organic components to the ink prior to or during certain processing steps such that the product materials are effectively free from carbon. In general, organic liquids can be evaporated to remove them from the deposited material. However, surfactants, surface modifying agents and other property modifiers may not be removable through evaporation, although they can be removed through heating at moderate temperature in an oxygen atmosphere to combust the organic materials.

The use and removal of surfactants for forming metal oxide powders is U.S. Patent 6,752,979 to Talbot et al., entitled "Production of Metal Oxide Particles with Nano-Sized Grains," incorporated herein by reference. The '979 patent teaches suitable non-ionic surfactants, cationic surfactants, anionic surfactants and zwitter-ionic surfactants. The removal of the surfactants involves heating of the surfactants to moderate temperatures, such as to 200°C in an oxygen atmosphere to combust the surfactant. Other organic additives generally can be combusted for removal analogously with the surfactants. If the substrate surface is sensitive to oxidation during the combustion process, a reducing step can be used following the combustion to return the surface to its original state.

In general, if processed appropriately, for dispersions with well dispersed particles, the average secondary particle size can be no more than a factor of four times the average primary particle size, in further embodiments no more than about 3 times the average primary particle size and in additional embodiments no more than about 2 times the average primary particle size. In some embodiments, the volume-average particle size is no more than about 1 micron, in further embodiments no more than about 250 nm, in additional embodiments no more than about 100 nm, in other embodiments no more than about 75 nm and in some embodiments from about 5 nm to about 50 nm. With respect to the particle size distribution, in some embodiment, essentially all of the secondary particles can have a size no more than 5 times the volume-average secondary particle size, in further embodiments no more than about 4 times the volume-average particle size and in other embodiments no more than about 3 times the average particle size. Furthermore, the DLS particle size distribution by volume can have in some embodiments a full width at half-height of no more than about 50 percent of the volume-average particle size. Also, the secondary particles can have a distribution in sizes such that at least about 95 percent of the particles have a diameter greater than about 40 percent of the average particle size and less

than about 250 percent of the average particle size. In further embodiments, the secondary particles can have a distribution of particle sizes such that at least about 95 percent of the particles have a particle size greater than about 60 percent of the average particle size and less than about 200 percent of the average particle size. A person of ordinary skill in the art will
5 recognize that additional ranges of particle sizes and distributions within the explicit ranges above are contemplated and are within the present disclosure.

The Z-average particle sizes can be measured using dynamic light scattering. The Z-average particle size is based on a scattering intensity weighted distribution as a function of particle size. Evaluation of this distribution is prescribed in ISO International
10 Standard 13321, Methods for Determination of Particle Size Distribution Part 8: Photon Correlation Spectroscopy, 1996. The Z-average distributions are based on a single exponential fit to time correlation functions. However, small particles scatter light with less intensity relative to their volume contribution to the dispersion. The intensity weighted distribution can be converted to a volume-weighted distribution that is perhaps
15 more conceptually relevant for evaluating the properties of a dispersion. For nanoscale particles, the volume-based distribution can be evaluated from the intensity distribution using Mie Theory. The volume-average particle size can be evaluated from the volume-based particle size distribution. Further description of the manipulation of the secondary particle size distributions can be found in Malvern Instruments - DLS Technical Note
20 MRK656-01, incorporated herein by reference.

The viscosity of the dispersion/ink is dependent on the silicon particle concentration as well as the other additives. Thus, there are several parameters that provide for adjustment of the viscosity. The viscosity is particularly relevant for inkjet printing although other printing and coating processes may have desired viscosity ranges.
25 For some embodiments, the viscosity can be from 0.1 mPa·s to about 100 mPa·s and in further embodiments from about 0.5 mPa·s to about 25 mPa·s. For some embodiments, the dispersions/inks can have a surface tension from about 2.0 to about 6.0 N/m² and in further embodiments from about 2.2 to about 5.0 N/m² and in additional embodiments form about 2.5 to about 4.5 N/m². A person of ordinary skill in the art will recognize that
30 additional ranges of viscosity and surface tension within the explicit ranges above are contemplated and are within the present disclosure.

The dispersions/inks can be formed using the application of appropriate mixing conditions. For example, mixers/blenders that apply shear can be used and/or sonication can be used to mix the dispersions. The particular additives can be added in an

appropriate order to maintain the stability of the particle dispersion. In general, appropriately selected surfactants and some property modifiers can stabilize the particle dispersion. A person of ordinary skill in the art can select the additives and mixing conditions empirically based on the teachings herein.

5

Printing and Other Deposition Approaches

The dispersions/inks can be deposited for using a selected approach that achieves a desired distribution of the dispersion on a substrate. For example, coating and printing techniques can be used to apply the ink to a surface. Using selected printing approaches, patterns can be formed with high resolution. Following deposition, the deposited material can be further processed into a desired device or state.

Suitable coating approaches for the application of the dispersions include, for example, spin coatings, dip coating, spray coating, knife-edge coating, extrusion or the like. Coating approaches generally are used to cover a substrate, although a mask or the like can be used to limit the deposition locations following removal of the mask. In general, any suitable coating thickness can be applied, although in embodiments of particular interest, coating thickness can range from about 50 nm to about 500 microns and in further embodiments from about 100 nm to about 250 microns. A person of ordinary skill in the art will recognize that additional ranges of thicknesses within the particular ranges above are contemplated and are within the present disclosure.

Similarly, a range of printing techniques can be used to print the dispersion/ink into a pattern on a substrate. Suitable printing techniques include, for example, screen printing, inkjet printing, lithographic printing, gravure printing and the like. Suitable substrates include, for example, polymers, such as polysiloxanes, polyamides, polyimides, polyethylenes, polycarbonates, polyesters, combinations thereof, and the like, ceramic substrates, such as silica glass, and semiconductor substrates, such as silicon or germanium substrates. The composition of the substrates influences the appropriate range of processing options following deposition of the dispersion/ink.

While various coating and printing approaches are suitable, inkjet printing offers desirable features with respect to speed, resolution and versatility with respect to real time selection of deposition patterning while maintaining speed and resolution. Practical deposition using inkjet printing with inorganic particles requires dispersion properties that involve both the techniques to form high quality silicon/silica nanoparticle along with the improved ability to form high quality dispersions from these particles. Thus, the particles

produced using laser pyrolysis combined with the improved surface modification approaches and dispersion techniques provides for the formation of inks that are amenable to inkjet deposition.

In general, following deposition, the liquid evaporates to leave the particles and any other non-volatile components of the inks remaining. If the substrate tolerates suitable temperatures and if the additives have been properly selected, the additives can be removed through the addition of heat in an appropriate oxygen atmosphere to remove the additives, as described above. Similarly, with suitable substrates, the silicon/silica particles can then be melted to form a cohesive mass of the silicon/silica deposited at the selected locations. If the heat treatment is performed with reasonable control over the conditions, the deposited mass does not migrate significantly from the deposition location, and the fused mass can be further processed into a desired device.

Solar Cell and Other Semiconductor Applications

For solar cell and other semiconductor applications, silicon particles can be used to form doped contacts that can form a portion of a particular device. For silica particles, the particles can be used to form dielectric components and/or to deliver dopants to semiconductor substrates. A representative printed substrate is shown in Fig. 1. In this embodiment, substrate 100 has a surface coating 102 with windows 104, 106 through coating 102 to expose a portion of the substrate surface. Silicon/silica ink is printed to form deposits 108, 110 on the substrate surface. The substrate comprises silicon, germanium or an alloy thereof. Suitable substrates include, for example, high purity silicon wafers and the like. In other embodiments, suitable substrates include silicon/germanium foils, as described in copending U.S. Patent application serial number 11/717,605 filed on March 13, 2007 to Hieslmair et al., entitled "Thin Silicon or Germanium Sheets and Photovoltaics Formed From Thin Sheets," incorporated herein by reference. A silicon dispersion/ink can be applied over the surface using the coating or printing techniques described above.

Some specific embodiments of photovoltaic cells using thin semiconductor foils and back surface contact processing is described further in U.S. Provisional patent application serial number 60/902,006 filed on February 16, 2007 to Hieslmair, entitled "Photovoltaic Cell Structures, Solar Panels, and Corresponding Processes," incorporated herein by reference. In some embodiments, the silicon/silica ink is applied through pre-established windows to the substrate surface. The doped ink is printed within the substrate

windows. Other patterning or no patterning can be used as desired for a particular application.

To form a device component from the silicon/silica particle deposit, the material is heated. For example, the structure can be placed into an oven or the like with the temperature set to soften the particles such that fuse into a mass. The time and temperature can be adjusted to yield a desired fusing and corresponding electrical properties of the fused mass as well as dopant migration for silica particle embodiments. Alternative approaches can be used to heat the surface of the substrate with the deposit. A thermal process based on taking advantage of reduced melting temperatures for silicon nanoparticles with a particle size no more than roughly 10 nm is described in U.S. Patent 5,576,248 to Goldstein, entitled "Group IV Semiconductor Thin Films Formed at Low Temperature Using Nanocrystal Precursors," incorporated herein by reference. This reference describes films that are no thicker than about 20 nm. Higher temperatures or light based fusing can be used to achieve thicker deposits. A rapid thermal anneal for the general drive in of a dopant into a semiconductor material is described further in U.S. Patent 6,287,925 to Yu, entitled "Formation of Highly Conductive Junctions by Rapid Thermal Anneal and Laser Thermal Process," incorporated herein by reference. The material can be heated to a temperature of under 1000°C for an appropriate period of time to allow for dopant migration.

However, improved control of the resulting doped substrate as well as energy saving can be obtained through the use of light to melt the silicon particles without generally heating the substrate or only heating the substrate to lower temperatures or to melt only the surface of the substrate to provide for dopant migration. Local high temperatures on the order of 1400°C can be reached to melt the surface layer of the substrate as well as the silicon particles on the substrate. Generally, any intense source selected for absorption by the particles can be used, although excimer lasers or other lasers are a convenient UV source for this purpose. Eximer lasers can be pulsed at 10 to 300 nanoseconds at high fluence to briefly melt a thin layer, such as 20 nm to 1000 nm, of the substrate. Longer wavelength light sources such as 1 micron wavelength light sources can also be used.

Thermal and light based fusing of silicon particles is described further in published U.S. Patent Application 2005/0145163A to Matsuki et al., entitled "Composition for Forming Silicon Film and Method for Forming Silicon Film," incorporated herein by reference. In particular, this reference describes the alternative use of irradiation with a

laser or with a flash lamp. Suitable lasers include, for example, a YAG laser or an excimer laser. Noble gas based flash lamps are also described. The heating generally can be performed in a non-oxidizing atmosphere.

5 Following the fusing of the silicon particles into a solid structure, additional processing steps can be performed to incorporate the resulting structure into the device. For photovoltaic applications, the fused deposit can comprise a doped silicon material that forms a p-doped or n-doped contact. The contacts are then connected to appropriate current collectors to provide for harvesting of the power from the photovoltaic cell.

10 For silica embodiments, following the drive in of the dopant, it may or may not be desirable to remove the silica. For photovoltaic applications it is generally desirable to remove the silica to expose the doped semiconductor for the application of conductive electrical contacts. To remove the silica, the oxide can be etched, for example, using conventional approaches, such as using wet (chemical) etching or plasma etching. Suitable chemical etching compositions include, for example, tetramethyl ammonium
15 hydroxide solution, or HF. Once the oxide is removed, the substrate can be further processed. These same heating approaches can be used to process the silica particles into a solid dielectric mass. The particles may or may not be doped for these embodiments.

Integrated Circuit Applications

20 The ability to print appropriate silicon inks provides for the formation of circuit components at moderate resolution and high efficiency. The printing process can effectively be used to form large area structures. If the particles can be fused at appropriately low temperatures, the deposits can be formed on polymer substrates. In these embodiments, the powders can be used to form flexible electronics.

25 In particular, the silicon inks can be used to form one or more structures within a display, which can be a flexible display and which can have a small area or a large area. For example, Aveso, Inc. is marketing smart credit cards with small printed displays. This technology is described further, for example, in published PCT Application WO 2006/0227523A to Pennaz et al., entitled "Layered Structure With Printed Elements,"
30 incorporated herein by reference.

Thin film transistors (TFTs) can be used to gate new display structures including, for example, active matrix liquid crystal displays, electrophoretic displays, and organic light emitting diode displays (OLED). Appropriate elements of the transistors can be printed using conventional photolithographic approaches or for moderate resolution using

inkjet printing or other suitable printing techniques. The substrates can be selected to be compatible with the processing temperatures for the ink.

The TFTs comprise doped semiconductor elements and corresponding interfaces. Thin film transistors used as electronic gates for a range of active matrix displays are described further in Published U.S. Patent Application number 2003/0222315A to Amundson et al., entitled "Backplanes for Display Applications, and Components for use Therein," incorporated herein by reference. An n-type doped polycrystalline or amorphous silicon TFT active element with an anode common structure with an organic LED element is described further in U.S. Patent 6,727,645 to Tsujimura et al., entitled "Organic LED Device," incorporated herein by reference. OLED display structures are described further, for example, in published U.S. Patent Application 2003/0190763 to Cok et al., entitled "Method of Manufacturing a Top-Emitting OLED Display Device With Desiccant Structures," incorporated herein by reference. Conventional photolithography techniques for the formation of TFTs is described further in U.S. Patent 6,759,711 to Powell, entitled "Method of Manufacturing a Transistor," incorporated herein by reference. These conventional photolithography approaches can be replaced with the printing approaches described herein. US 6,759,711 further describes integration of TFTs with an active matrix liquid crystal display. The silicon nanoparticle inks described herein can be effectively used to print elements of a TFT with selected dopants.

Biochips are growing in use for diagnostic medical purposes. U.S. Patent 6,761,816 to Blackburn et al., entitled "Printed Circuit Boards With Monolayers and Capture Ligands," incorporated herein by reference. These biochip arrays have electrical circuits integrated with biological components so that automatic evaluations can be performed. The functional inks described herein can be used to form electrical components for these devices while biological liquids can be printed or otherwise deposited for the other components.

Radio-Frequency Identification (RFID) tags are gaining widespread use for loss prevention. These devices are desired to be small for less obtrusiveness and low cost. The silicon inks described herein can be used effectively to print RFIDs or components thereof. Systems for printing RFIDs on a roll-to-roll configuration are described further in published U.S. Patent Application serial number 2006/0267776A to Taki et al., entitled "RFID-Tag Fabricating Apparatus and Cartridge," incorporated herein by reference.

In coating deposition approaches, the silicon ink deposition and fusing of the particles can be used as a relatively direct replacement for CVD process with the potential

of having lower cost and less capital expenditure since high vacuum equipment is not needed. Also, liquid coating and printing processes can be performed on large substrates that are difficult to handle with CVD equipment.

5 For inkjet printing applications, the use of materials is significantly reduced due to deposition only where the material is needed. Inkjet printing with existing equipment can achieve the moderate resolution that is presently needed for many applications. As inkjet technology improves further, the resolution of the printing process can be improved further. Inkjet printing can be effectively used for very large substrates. For processing approaches with appropriately low temperature cures, the printing can be performed onto a
10 range of flexible substrates.

Optical Applications

For optical applications, generally the deposited silica is melted or sintered to form a solid mass from the particles to reduce scattering at the particle surfaces. Dopants can be
15 introduced to alter the processing properties, such as the softening temperature for the particles, or the optical properties, such as the index-of-refraction or optical emission properties. The approaches described above for semiconductor processing can be adapted for optical applications. In general, for optical applications, the silica inks can be deposited to form particular optical structures, such as display elements or waveguides.

20 For example, in some embodiments, the inks can be printed at particular locations along a structure for the formation of a display. Then, the deposits can be cured at the printed locations. The dopants can be varied to alter the optical properties at different locations along the display. In some embodiments, the particles can comprise phosphor materials coated with silica. The coating of phosphor particles with silica is described
25 further in U.S. Patent 5,908,698 to Budd, entitled "Encapsulated Electroluminescent Phosphor and Method for Making Same," and in U.S. Patent 5,599,529 to Cowie, entitled "Dispersions," both of which are incorporated herein by reference. The coated particles can be dispersed and deposited according to the description of other silica particles described herein. The core phosphor particles can be formed, for example, as described in
30 U.S. Patent 6,692,660 to Kumar, entitled "High Luminescent Phosphor Particles and Related Particle Compositions," incorporated herein by reference. Different phosphor materials can be deposited at different locations to form a desired display device. While many display structures are known or can be subsequently developed in the art, and example of a display structure is found in U.S. Patent 5,651,712, entitled "Multi-Chromic

Lateral Field Emission Devices With Associated Displays and Methods of Fabrication," incorporated herein by reference.

Waveguides can be used to transmit optical signals, for example, in connection with telecommunication signals. Waveguides can take the form of optical fibers, planar waveguides or the like. The printing approaches described herein can be used to form optical waveguides through the deposition of silica particle dispersions and the subsequent fusing of the particles into an optical structure. The approaches described herein are alternatives to chemical vapor deposition combined with photolithography and to Light Reactive Deposition (LRDTM), as described in WO 02/32588 to Bi et al., entitled "Coating Formation by Reactive Deposition," incorporated herein by reference. The deposition approaches described herein can be used to form the waveguide cores that can be covered with a lower index-of-refraction cladding material, for example, using chemical vapor deposition or LRDTM. With respect to alternative approaches to planar waveguide formation, the formation of planar waveguides by flame hydrolysis is described in U.S. Patent 3,934,061 to Keck et al., entitled "Method of Forming Planar Optical Waveguides," incorporated herein by reference.

EXAMPLES

Example 1 - Dispersion of silicon particles in alcohols

This example demonstrates that silicon particles generated using laser pyrolysis can be well dispersed in alcohols.

The silicon particles were synthesized using laser pyrolysis with an apparatus essentially as shown in Fig. 8 of U.S. provisional patent application serial number 60/961,429 to Holunga et al. filed July 20, 2007, entitled "Laser Pyrolysis with In-Flight Particle Manipulation for Powder Engineering," incorporated herein by reference. Inert quenching gas was introduced into the system to cool the product particles. The particles were synthesized using silane as the precursor and argon as an inert moderating gas. The silane decomposes under intense laser light to form the silicon. The powders used in this example had a BET surface area of 69.9 m²/g.

A 0.3 portion of the silicon powder was blended with 60 grams of alcohol to form a 0.5 weight percent dispersion. The particle size distributions were obtained with dynamic light scattering (DLS) using a Malvern ZetaSizerTM instrument. The results for methanol dispersing liquid are plotted in Fig. 2, and the results for propylene glycol are plotted in Fig. 3. The dispersion in propylene glycol had a smaller Z-average particle size,

91.8 nm versus 114.9, and a narrower particle size distribution. The dispersions were stable for at least a month.

Example 2 - Dispersions of Surface Modified Silicon Particles

5 This example demonstrates that surface modified silicon particles can be dispersed at higher concentrations with reasonable stability and transferred between liquids.

The silicon particles were synthesized using laser pyrolysis as described above with respect to Example 1. These powders for this example had a BET surface area of 77 m²/g. Initially, 500 mg of the unmodified particles were mixed with 50 g of gamma
10 butyrolactone liquid, and the mixture was sonicated for 1 h with an ultrasonic probe sonicator.

Then, 155 mg of methacryloxypropyl trimethoxysilane (Z6030, Dow Corning.) was added to the dispersion, and the sample was placed in an ultrasonic bath for 4.5hr. The size distribution of the resulting 1 weight percent dispersion was measured by DLS,
15 and the lot of the particle size distribution is shown in Fig. 4. The distribution had a Z-average particle size of 72.0 nm with two peaks, with a smaller peak at 17.9 nm and a larger peak at 108 nm.

A 30 ml aliquot of the dispersion in gamma butylactone was mixed with 60 ml of hexane and 60 ml of acetone to destabilize the dispersion. The sample was then
20 centrifuged at 5000 rpm for 60 minutes. The supernatant was discarded, and the precipitate was redispersed in ethyl lactate using 20 minutes in an ultrasonic bath. Ethyl lactate dispersions at 15, 10 and 5 weight percent seemed to be stable. Due to the darkness of the dispersions, the properties of the dense dispersions could not be evaluated in any detail. No settling could be observed, and after weeks there were no visible changes to the
25 dispersions suggesting that the dispersion were stable for at least several weeks. These concentrations were not amenable to DLS particle size distribution measurements due to the high optical density. DLS measurements at 1 weight percent are presented in Fig. 5. The particle size distribution had a Z-average particle size of 62.6 nm and also had two peaks, with one at 18.3 nm and a larger peak at 86.2 nm.

30

Example 3 - Surface Modification of Silicon Particles in Ethyl Acetate

In this example, the particles are directly surface modified in ethyl lactate at two different concentrations.

A 500 mg quantity of silicon particles (surface area $74 \text{ m}^2/\text{g}$ as measured by BET) were mixed with 50 g of ethyl lactate and sonicated in a bath sonicator for 2 hrs to form a 1 weight percent dispersion. Then, 143 mg of methacryloxypropyltrimethoxysilane surface modification agent was added, and the resulting dispersion was sonicated for another 2 hours. The intensity-based particles size distributions obtained by DLS both before (A) and after (B) surface modification are shown in Fig. 6. After surface modification, the intensity average particle size distribution is smaller than before surface modification.

A 1 g quantity of silicon particles (surface area $69 \text{ m}^2/\text{g}$ as measured by BET) were mixed with 20 g of ethyl lactate and sonicated in a bath sonicator for 2 hrs to form a 5 weight percent mixture. Then, 275 mg of methacryloxypropyltrimethoxysilane surface modification agent was added, and the resulting mixture was sonicated for another 2 hours. The high optical density of the sample prohibited acquisition of DLS data at such a high concentration. Visual inspection of the samples after sitting overnight revealed that fewer particles settled at the bottom of the sample bottles for the surface modified samples relative to samples that did not involve surface modification. To obtain DLS measurements, the samples were diluted to 1 weight percent. The intensity-based particles size distributions obtained by DLS for the diluted sample both without surface modification (A) and with surface modification (B) are shown in Fig. 7.

20

Example 4 - Comparison of Surface Modification in Methanol and Gamma Butyrolactone

This example compares the resulting particle size distributions for samples surface modified in methanol versus gamma butyrolactone.

In sample 1, 150mg of silicon particles (surface area $68 \text{ m}^2/\text{g}$ as measured by BET) were mixed with 30g of methanol to form a 0.5 weight percent dispersion. The sample was then bath sonicated for 2hrs. A 40 mg quantity of methacryloxypropyl trimethoxysilane silane surface modification agent was added, and the sample was sonicated for another 4hrs. The intensity-based particle size distribution measured by DLS at 0.5 wt% concentration is shown in Fig. 8 before surface modification (A) and after surface modification (B).

30

In sample 2, 1g of silicon particles (surface area $68 \text{ m}^2/\text{g}$ as measured by BET) were mixed with 20g of methanol to form a 5 weight percent dispersion. The sample was then bath sonicated for 2hrs. A 275mg quantity of methacryloxypropyltrimethoxysilane was added, and the sample was sonicated for another 4hrs. A 100g quantity of hexane was

added to destabilize the dispersion, and the sample was centrifuged at 4000rpm for 20 min. The precipitate was redispersed in 200g of methanol via bath sonication for 20 min. The intensity-based particle size distribution measured by DLS at 0.5% concentration is shown also in Fig. 8 (C).

5 In another sample, a 500 mg quantity of silicon particles (surface area of 77 m²/g as measured by BET) were mixed with 50 g of gamma butyrolactone to form a 1 weight percent dispersion and sonicated with an ultrasonic probe sonicator (Hielscher, model UP200S) for 1 h at 60% amplitude and 0.5 cycle. Then, a 155 mg quantity of methacryloxypropyltrimethoxysilane silane was added to the dispersion, and the sample
10 was place in an ultrasonic bath for 4.5 h at 65 DEG C. The intensity-based particle size distribution measured by DLS is shown in Fig. 9. A 30 mL aliquot of the dispersion in gamma butyrolactone was mixed with 60 mL of hexanes and 60 mL of acetone to destabilize the dispersion. The sample was centrifuged at 5000 RPM for 60 min. The supernatant was discarded, and the precipitate was redispersed in ethyl lactate by a 20
15 minutes sonication in an ultrasonic bath. Dispersions at 15, 10, and 5 wt% appeared mostly stable for over a day, but the high optical density of the sample prohibited acquisition of DSL data at such high concentrations. The intensity-based DLS particle size distribution at 1% concentration in ethyl lactate is plotted in Fig. 10.

20 Example 5 - SiO₂ dispersion in Methyl Ethyl Ketone (MEK)

This example demonstrates the dispersion and surface modification of silica particles synthesized using laser pyrolysis.

SiO₂ was produced by laser pyrolysis aerosol) with Tetraethoxysilane (TEOS) as the silicon precursor. The silicon precursor was delivered with as an aerosol with a
25 mixture of ethylene, oxygen and an inert gas serving as the carrier gas. The apparatus was similar to the apparatus in Figs. 6-8 of U.S. Patent 6,849,334 to Horne et al., entitled "Optical Materials and Optical Devices," incorporated herein by reference. The SiO₂ particles had a primary particle size as determined using a transmission electron micrograph of 10 – 20 nm. Transmission electron micrographs at two magnifications are
30 shown in Figs. 11 and 12, respectively, for a representative SiO₂ nanoparticle sample made from TEOS using laser pyrolysis.

SiO₂ powder (13.6 g, with a BET surface area > 236.5 m²/g) was added to methylethylketone (MEK) to make a 5% wt mixture. The mixture was sonicated with a probe sonicator for 1 - 4 hours. Then, methacryloxypropyl trimethoxysilane (Z6030, 3.0g

– 17.9 g, Dow Corning.) was added to the dispersion, and sonication was continued for 1-3hr. The resultant secondary particles sizes were evaluated with dynamic light scattering (DLS) using a Malvern ZetaSizer™ instrument. The distribution of the size of the particles revealed from DLS measurement is shown in Fig. 13 where about 66% of the secondary particles had a diameter of 362.6 nm and 34% of the particles had a peak secondary particle size of about 28.1 nm. SiO₂ particles therefore form a good dispersion in MEK at 5% wt after modification with methacryloxypropyl trimethoxysilane.

Example 6 - SiO₂ dispersion in Isopropanol

10 This example demonstrated the dispersion of SiO₂ nanoparticles in isopropanol as an alternative dispersing liquid. The SiO₂ nanoparticles for this example had the same property as the nanoparticles in Example 5.

SiO₂ powder (1.0 g, with a BET surface area 214.0 m²/g) was added to isopropanol to make a 1% wt mixture. The mixture was sonicated in a bath sonicator for 1 - 4 hours. 15 Then, N-(2-aminoethyl)-3-aminopropyltrimethoxysilane (0.32g – 1.94 g, Gelest, Inc.) was added to the dispersion and continue sonication for 1-7hr at a temperature of 25 °C– 60 °C. The resultant secondary particles sizes were evaluated with dynamic light scattering (DLS) using a Malvern ZetaSizer™ instrument. The distribution of the size of the particles revealed from DLS measurement is shown in Fig. 14 where the particles had an average secondary particle size of about 99.7 nm. SiO₂ particles therefore form good dispersion in 20 IPA at 1% wt after modification with N-(2-aminoethyl)-3-aminopropyltrimethoxysilane methacryloxypropyl trimethoxysilane.

The embodiments above are intended to be illustrative and not limiting. Additional 25 embodiments are within the claims. In addition, although the present invention has been described with reference to particular embodiments, those skilled in the art will recognize that changes can be made in form and detail without departing from the spirit and scope of the invention. Any incorporation by reference of documents above is limited such that no subject matter is incorporated that is contrary to the explicit disclosure herein.

What is claimed is:

1. A dispersion of silicon/germanium nanoparticles comprising a liquid and at least about 0.1 weight percent silicon/germanium nanoparticles, wherein the silicon/germanium nanoparticle have an average primary particle size of no more than about 100 nm, and a volume-average secondary particle size of no more than about three times that average primary particle size.
2. The dispersion of claim 1 wherein the silicon/germanium nanoparticles have a distribution of secondary particle sizes such that at least about 95 percent of the secondary particles have a particle size greater than about 40 percent of the average diameter and less than about 250 percent of the average particle size.
3. The dispersion of claim 1 wherein the silicon/germanium particles in the dispersion have a DLS particle size distribution by volume with a full width at half-height of no more than about 50 percent of the volume-average particle size.
4. The dispersion of claim 1 wherein effectively no secondary particle sizes are greater than about five times the volume-average particle size as determined by DLS measurements
5. The dispersion of claim 1 wherein the dispersion comprises at least about 5 weight percent silicon/germanium particles.
6. The dispersion of claim 1 wherein the nanoparticles have a surface modification moiety chemically bonded to the surface of nanoparticles.
7. The dispersion of claim 1 wherein the liquid comprises an organic liquid.
8. The dispersion of claim 1 wherein the silicon nanoparticles comprise a dopant a concentration of at least about 1.0×10^{-7} atomic percent of the material.

9. A method for surface modifying silicon/germanium nanoparticles, the method comprising blending the surface modifying composition into a dispersion of the silicon/germanium nanoparticles in a dispersing liquid wherein the silicon/germanium nanoparticles have a volume-average secondary particle size of no more than about a factor of 5 times the average primary particle size, wherein the silicon/germanium nanoparticles have an average primary particle size of no more than about 100 nm and wherein the surface modifying composition chemically bonds with the silicon/germanium particle surfaces to form surface modified nanoparticles with a surface modification moiety chemically bonded to the nanoparticle surfaces.
10. The method of claim 9 wherein the blending comprises adding the surface modifying agent dissolved in a solvent that is soluble in the dispersing liquid.
11. The method of claim 9 wherein the volume-average particle size is no more than about 200 nm.
12. The method of claim 9 wherein the dispersion has a concentration of at least about 1 weight percent silicon/germanium nanoparticles.
13. The method of claim 9 further comprising forming a more concentrated dispersion of the surface modified nanoparticles.
14. A method for depositing silicon nanoparticles, the method comprising printing an ink comprising a dispersing liquid and silicon/germanium particles, the silicon/germanium nanoparticle having an average particle size of no more than about 75 nm and a volume-average secondary particle of no more than about 150 nm and wherein the ink has a viscosity of no more than about 400 mPa·s at room temperature.
15. The method of claim 14 wherein the printing is performed with an inkjet printer.
16. The method of claim 14 wherein the ink has a viscosity of no more than about 300 mPa·s at room temperature.

17. The method of claim 14 wherein the ink has a concentration of at least about 2 weight percent silicon/germanium particles and wherein the silicon/germanium particles have a surface modification moiety chemically bonded to their surface.
18. The method of claim 17 wherein the surface modification moiety is formed through the reaction of a surface modification compound with the particle, the surface modification compound comprising an alkoxysilane.
19. The method of claim 14 wherein the ink comprises a viscosity modifying organic composition and an organic surfactant.
20. The method of claim 14 wherein the ink has a surface tension from about 2.0 N/m² to about 6.0 N/m².
21. A printed substrate comprising a substrate surface having a selected pattern covering no more than about 90 percent of the surface area, the pattern comprising silicon/germanium nanoparticles, the nanoparticles having an average primary particle size of no more than about 100 nm, wherein the silicon/germanium nanoparticles have a distribution of secondary particle sizes such that at least about 95 percent of the secondary particles have a particle size greater than about 40 percent of the average particle size and less than about 250 percent of the average particle size.
22. The printed substrate of claim 21 wherein the pattern comprises a plurality of discrete and isolated islands.
23. The printed substrate of claim 21 wherein the silicon/germanium nanoparticles are doped.
24. The printed substrate of claim 21 wherein the nanoparticles have an average primary particle size of no more than about 50 nm.
25. The printed substrate of claim 21 wherein the nanoparticles have a surface modification moiety chemically bonded to the surface or the particles.

26. A dopant ink composition suitable for inkjet printing, the ink comprising a stable dispersion of silica/germania nanoparticles in a dispersing liquid with a concentration of silica/germania nanoparticles from about 0.1 weight percent to about 20 weight percent, wherein the silica/germania nanoparticles have an average primary particle size of no more than about 100 nm and wherein the dopant ink has a viscosity from about 0.1 mPa·s to about 100 mPa·s.
27. The dopant ink of claim 26 wherein the silica/germania nanoparticle have an average particle size from about 1 nm to about 50 nm.
28. The dopant ink of claim 26 wherein the silica/germania nanoparticle have a volume-average secondary particle size of no more than about 500 nm.
29. The dopant ink of claim 26 wherein the collection of silica/germania nanoparticles have effectively no primary particles with a diameter greater than about 4 times the average primary particle size.
30. The dopant ink of claim 26 wherein the silica/germania nanoparticles comprise a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon/germanium atoms of the silica/germania nano-particles.
31. The dopant ink of claim 30 wherein the dopant is B, P, Al, Ga, As, Sb or combinations thereof.
32. A dispersion comprising a liquid and doped silica/germania nanoparticles, the doped silica/germania nanoparticles having an average primary particle size from about 1 nm to about 100 nm and a volume-average particle size of no more than about 500 nm, the dispersion having a concentration of doped silica/germania nanoparticle from about 0.1 weight percent to about 20 weight percent doped silica/germania nanoparticles, wherein the silica nanoparticles comprise a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon/germanium atoms of the silica/germania nanoparticles.

33. The dispersion of claim 32 wherein the volume-average particle size is no more than about 250 nm.
34. The dispersion of claim 32 wherein the concentration of doped silica/germania nanoparticles is from about 1.0×10^{-5} weight percent to about 1 weight percent.
35. The dispersion of claim 32 wherein the secondary particle size distribution has a majority peak with a full width at half maximum of no more than about 50% of the volume-average secondary particle size.
36. The dispersion of claim 32 wherein the collection of silica/germania particles have an average primary particle size from about 1 nm to about 100 nm.
37. The dispersion of claim 32 wherein the silica/germania particles have a surface modification composition selected to be compatible with the liquid.
38. A method for forming a dispersion, the method comprising blending a collection of doped silica/germania nanoparticles with a liquid wherein the liquid and nanoparticles are selected to be compatible with each other, the nanoparticles having an average primary particle size from about 1 nm to about 100 nm and a volume-average secondary particle size no more than about 500 nm following mixing, wherein the silica/germania nanoparticles comprise a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon/germanium atoms of the silica/germania nanoparticles.
39. The method of claim 38 wherein the blending comprises sonication.
40. The method of claim 38 wherein the blending comprises the application of shear using a mixing element.
41. The method of claim 38 wherein the silica/germania particles have a surface modifying composition selected to be compatible with the liquid.

42. A method for forming a deposit of silica/germania particles on a substrate surface, the method comprising inkjet printing a pattern of an ink comprising silica/germania particles having an average primary particle size from about 1 nm to about 100 nm and a volume-average secondary particle size no more than about 500 nm.
43. The method of claim 42 wherein the ink has a concentration of silica/germania particles from about 0.1 to about 30 weight percent.
44. The method of claim 42 wherein the ink has a viscosity from about 0.1 mPa·s to about 100 mPa·s.
45. The method of claim 42 wherein the silica/germania particles comprise a dopant.
46. The method of claim 45 wherein the dopant is B, P, Al, Ga, As, Sb or combinations thereof.
47. A method for doping a semiconductor substrate comprising silicon or germanium, the method comprising heating a coating in contact with substrate to drive dopant into the substrate, wherein the coating comprises doped silica/germania particles, the doped silica/germania particles comprising a dopant element from about 1.0×10^{-7} to about 15 atomic percent relative to the silicon/germanium atoms of the silica/germania particles, the particles having an average primary particle size from about 1 nm to about 100 nm and an average second particle size no more than about 500 nm based on a dispersion formed with the particles prior to forming a coating.
48. The method of claim 47 wherein the heating is performed with a laser.
49. The method of claim 47 wherein the heating is performed with a light source.
50. The method of claim 47 wherein the heating is performed in an oven.
51. The method of claim 47 further comprising removing at least some of the silica/germania following the driving of the dopant into the substrate.

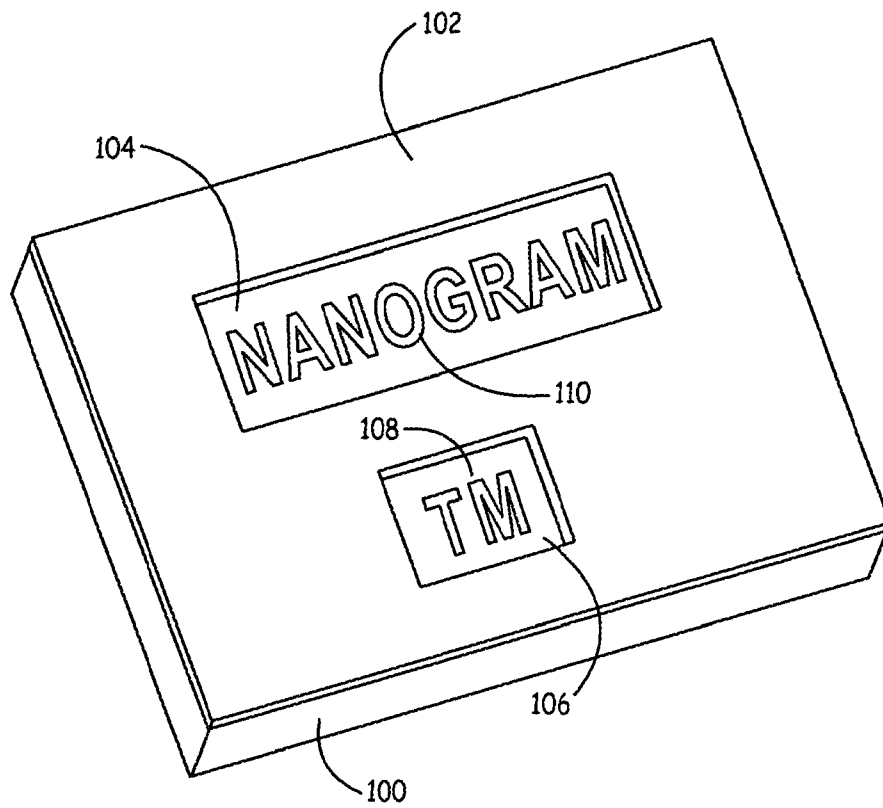


FIG. 1

	Diam (nm)	% Intensity	Width (nm)
Z-Average (nm): 114.9	Peak 1: 167.1	100	103.2
PDI: 0.277	Peak 2: 0	0	0
Intercept: 0.8087	Peak 3: 0	0	0

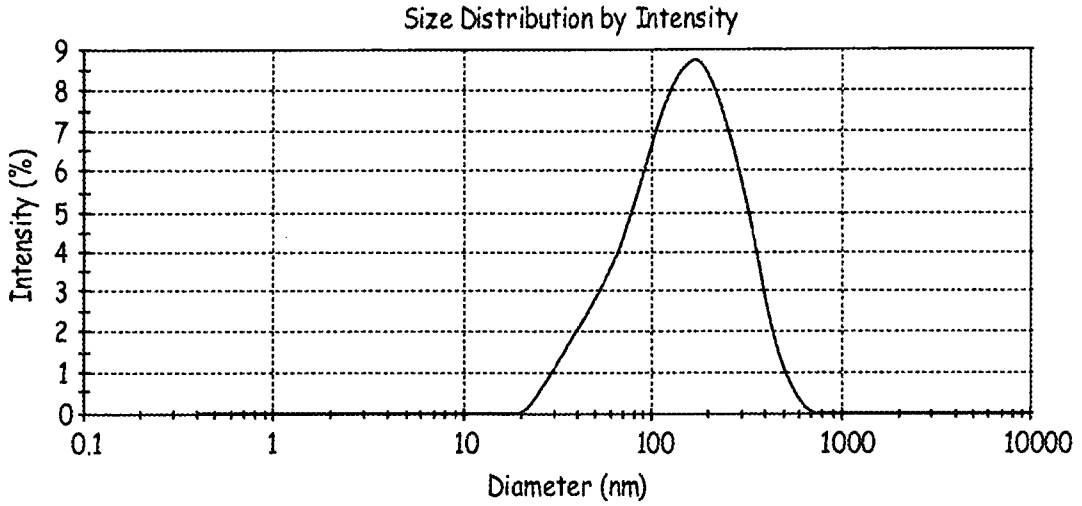


FIG. 2

	Diam (nm)	% Intensity	Width (nm)
Z-Average (nm): 91.82	Peak 1: 95.5	100	24.34
PDI: 0.131	Peak 2: 0	0	0
Intercept: 0.926	Peak 3: 0	0	0

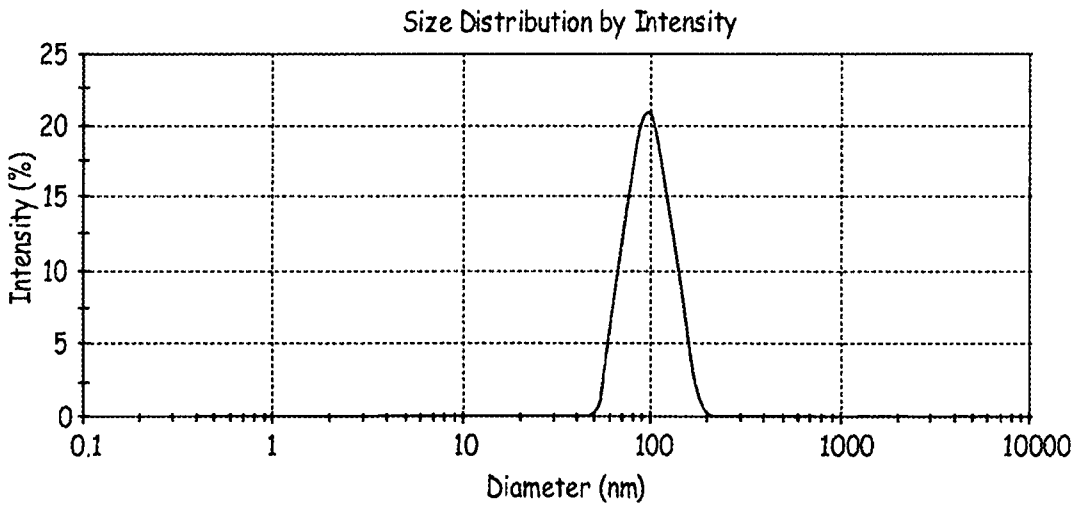


FIG. 3

	Diam (nm)	% Intensity	Width (nm)
Z-Average (nm): 72.0	Peak 1: 108	90.3	44.7
PDI: 0.282	Peak 2: 17.9	9.7	3.73
Intercept: 0.890	Peak 3: 0.00	0.0	0.00

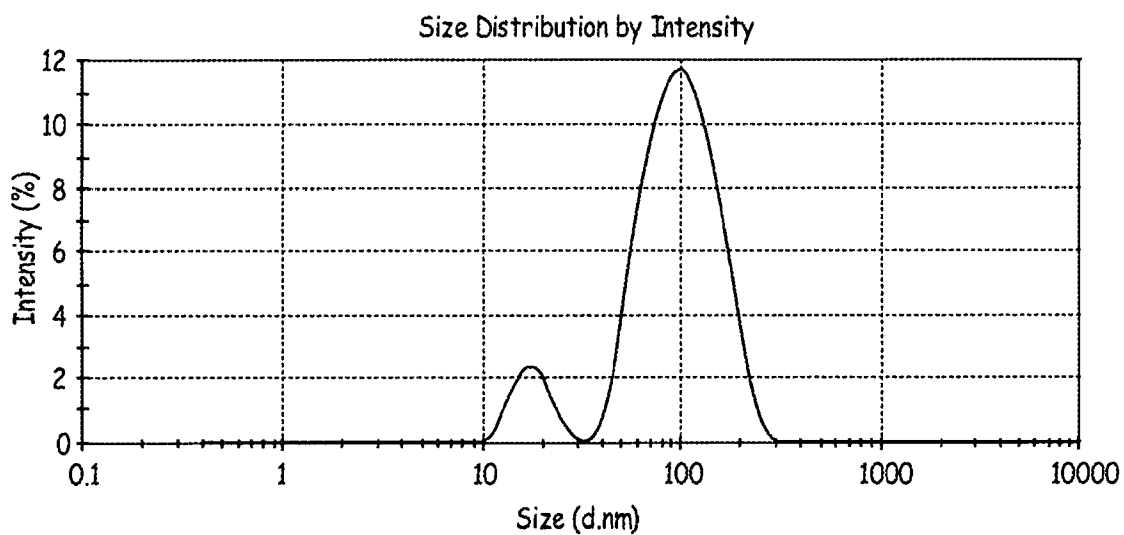


FIG. 4

	Diam (nm)	% Intensity	Width (nm)
Z-Average (d.nm): 62.6	Peak 1: 88.2	92.5	39.8
PDI: 0.254	Peak 2: 18.3	7.5	3.81
Intercept: 0.917	Peak 3: 0.00	0.0	0.00

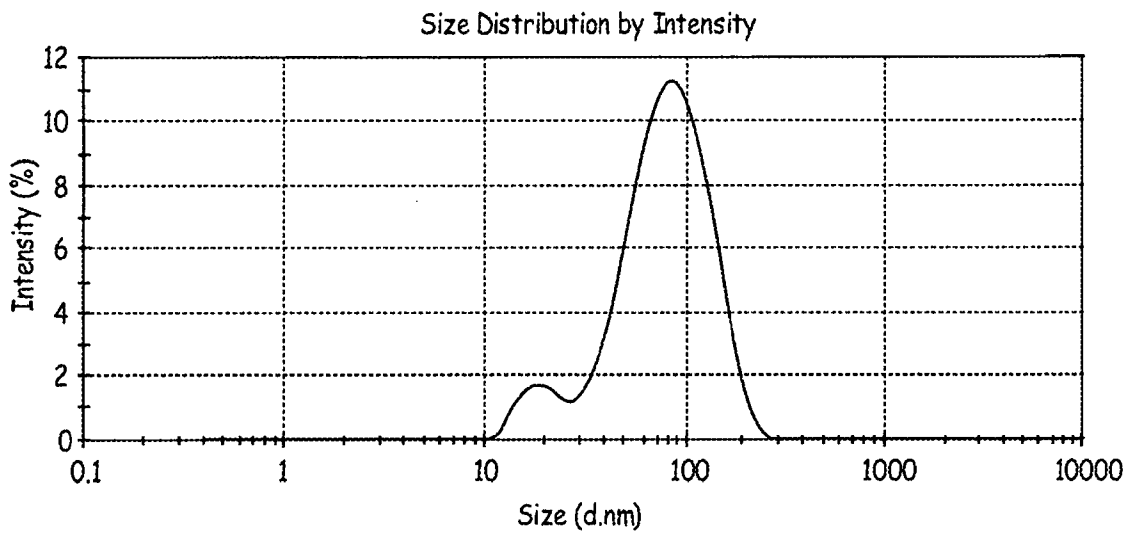


FIG. 5

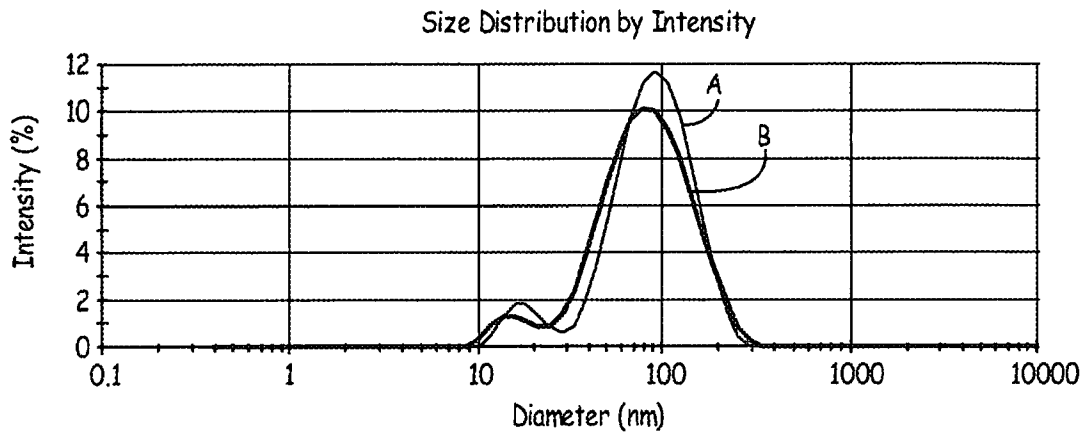


FIG. 6

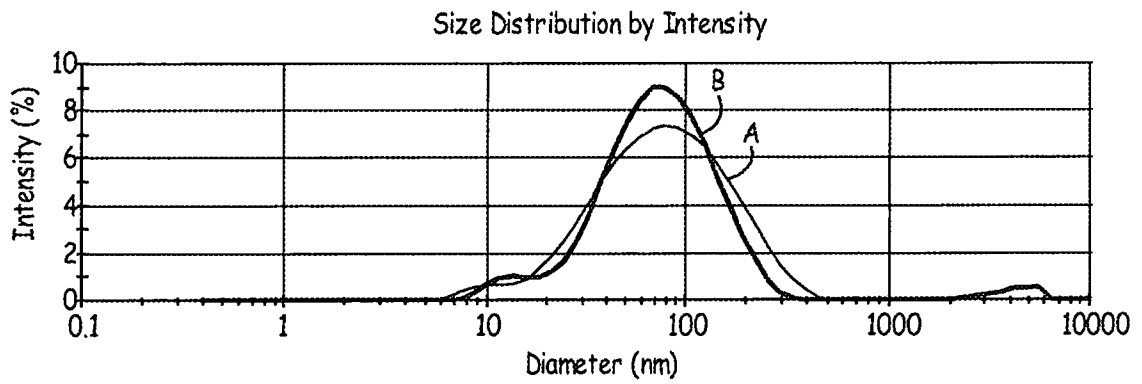


FIG. 7

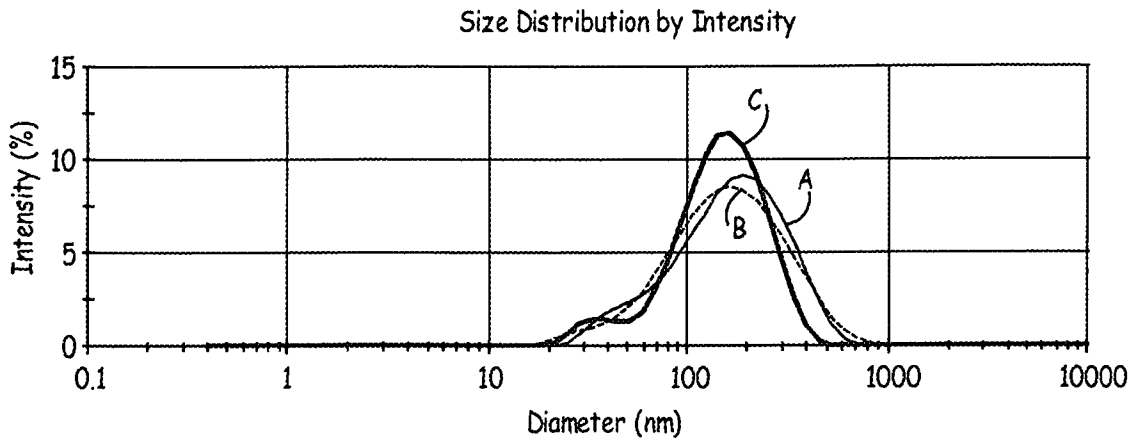


FIG. 8

	Diam (nm)	% Intensity	Width (nm)
Z-Average (d.nm): 72.0	Peak 1: 108	90.3	44.47
PDI: 0.282	Peak 2: 17.9	9.7	3.73
Intercept: 0.890	Peak 3: 0.00	0.00	0.00

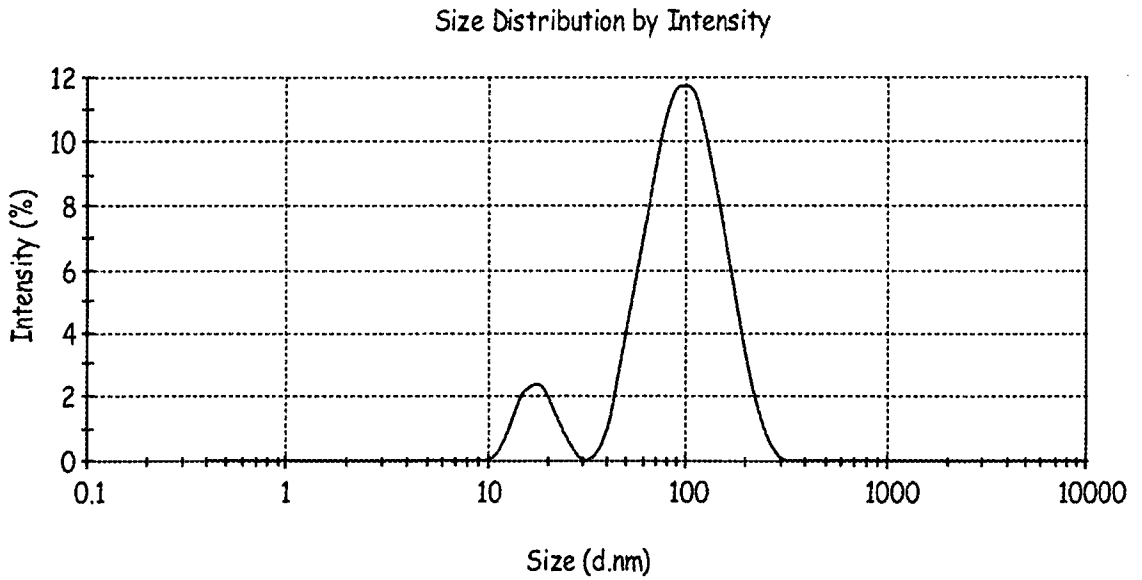


FIG. 9

	Diam (nm)	% Intensity	Width (nm)
Z-Average (d.nm): 62.6	Peak 1: 88.2	92.5	39.8
PDI: 0.254	Peak 2: 18.3	7.5	3.81
Intercept: 0.917	Peak 3: 0.00	0.0	0.00

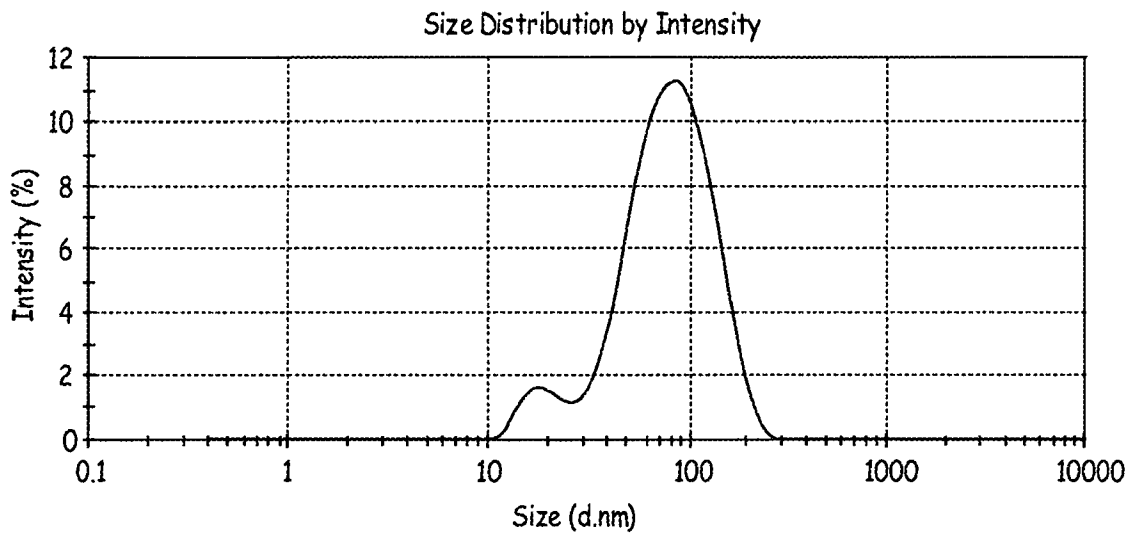


FIG. 10

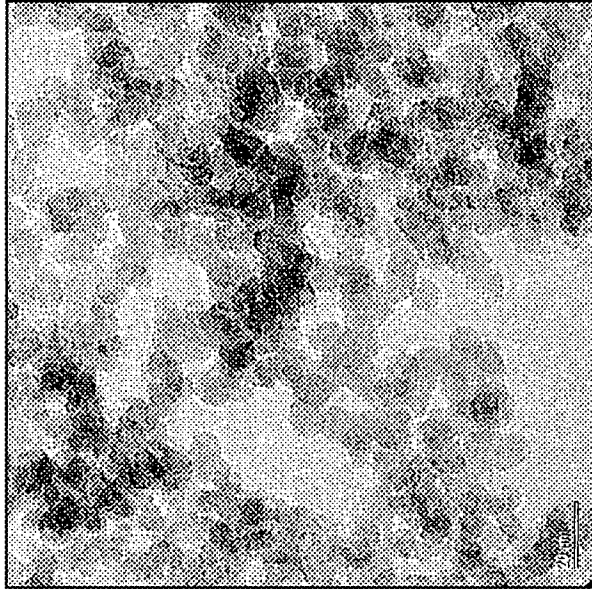


FIG. 12

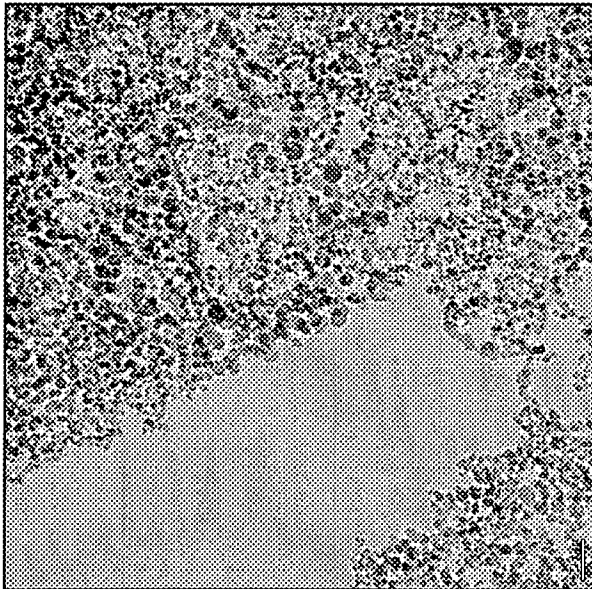


FIG. 11

	Diam (nm)	% Intensity	Width (nm)
Z-Average (nm):	67.33		
PDI:	0.874		
Intercept:	0.9573		
Peak 1:	362.6	66.76	231.3
Peak 2:	28.14	33.24	14.55
Peak 3:	0	0	0

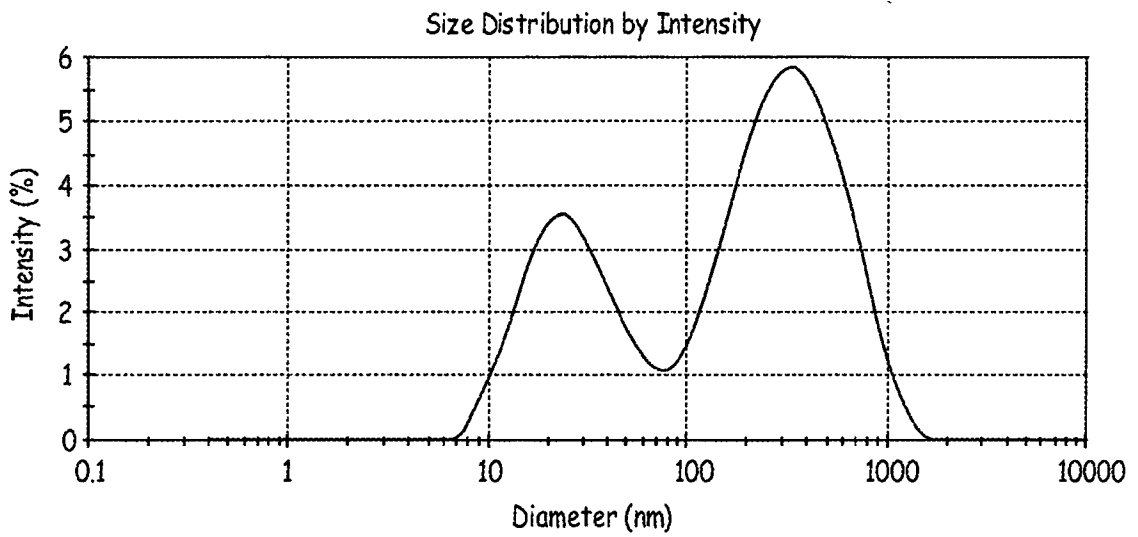


FIG. 13

	Diam (nm)	% Intensity	Width (nm)
Z-Average (nm):	99.72	100	32.67
PDI:	0.077	0	0
Intercept:	0.9593	0	0
Peak 1:	108.7	100	32.67
Peak 2:	0	0	0
Peak 3:	0	0	0

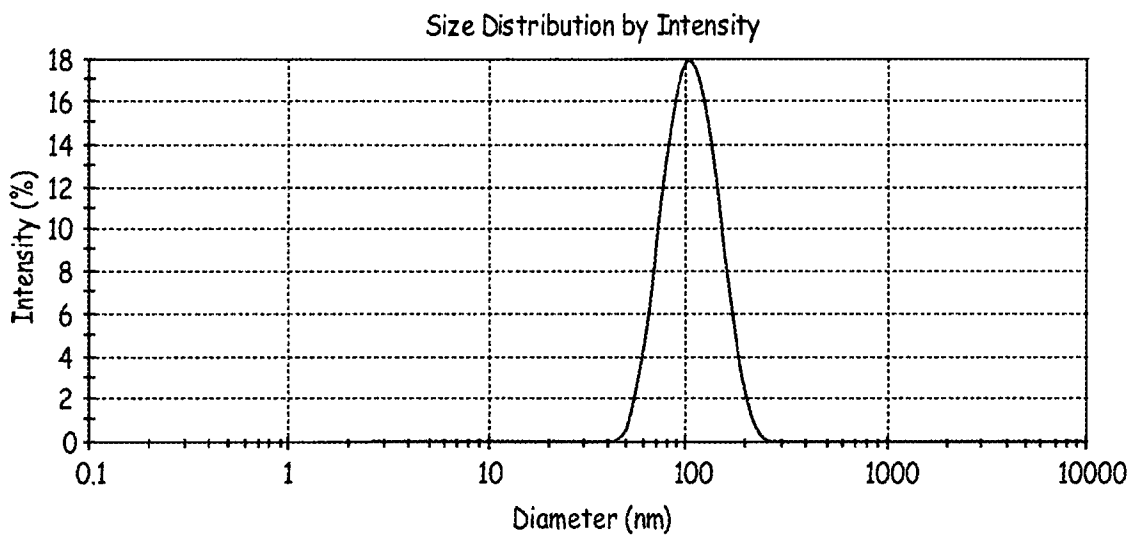


FIG. 14

A. CLASSIFICATION OF SUBJECT MATTER*C09D 11/00(2006.01)i, C09C 1/28(2006.01)i*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 8 C09D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CAS(ONLINE), DELPHION, eKIPASS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2006/0137567 A1 (NANO PRODUCTS CORP.) 29 Jun. 2006 See the abstract and claims 1-20	1-51
A	US 7078276 B1 (KOVIO INC.) 18 Jul. 2006 See the whole document	1-51
A	US 6712999 B2(DAIMLERCHRYSLER AG) 30 Mar. 2004 See the whole document	1-51
A	US 2006/0237719 A1(HEWLETT-PACKARD CO.) 26 Oct. 2006 See the whole document	1-51
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 Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

29 MAY 2008 (29.05.2008)

Date of mailing of the international search report

29 MAY 2008 (29.05.2008)

Name and mailing address of the ISA/KR



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SIHN, YOUNG SIHN

Telephone No. 82-42-481-8162



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2008/000004

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