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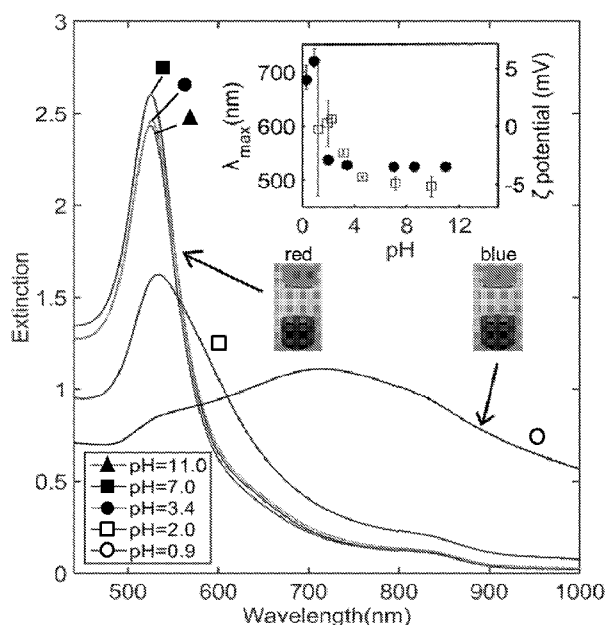


FIG. 1

(57) Abstract: The present disclosure relates to microcapsules comprising a hollow or non-hollow core, and a rigid or flexible shell, wherein a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, is embedded in said shell. Methods for making the microcapsules and uses thereof are also described.

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MICROCAPSULES HAVING METALLIC NANOPARTICLES, METHODS FOR MAKING MICROCAPSULES HAVING METALLIC NANOPARTICLES, AND USES THEREOF

5 Cross Reference to Related Applications

This application claims the priority of U.S. Provisional Application Nos. 62/485,535, filed April 14, 2017, and 62/596,284, filed December 8, 2017, both of which are hereby incorporated by reference in their entireties.

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Field of the Invention

The present disclosure relates to microcapsules comprising a hollow or non-hollow core, and a rigid or flexible shell, wherein a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, is embedded in said shell. The applications of the microcapsules of the present disclosure are diverse. Applications may include, but are not limited to, renewable energy, such as solar energy harvesting; biology and medicine, such as cancer therapy, antibacterial therapy, and drug delivery; and sensor technology in the aerospace, automotive, and civil engineering industries.

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Background

Metallic nanoparticles, such as gold nanoparticles (Au NPs), have been investigated for use in a multitude of applications due to their unique optical, physical and biocompatible properties. For example, a striking feature of Au NPs lies in the potential for tuning their localized plasmon resonance maximum by adjusting their shape, size, surrounding environment and interparticle distance. Such strong plasmonic effects have been widely used in areas such as solar energy harvesting, cancer therapy, and drug delivery for accurate transport and delivery of medications. More recently, studies have shown that metallic nanoparticles may be useful in controllable optical sensors. For example, a pregnancy test based on Au NPs is

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well-known. The test is based on the color change of the solution due to the aggregation of Au NPs mediated by components in the urine. A positive is red when the nanoparticles are stabilized by human chorionic gonadotropin (hCG), a hormone produced by the embryo after implantation. A negative test turns blue upon the nanoparticles aggregation in absence of hCG. Other examples of plasmonic-based sensors rely on the aggregation of nanoparticles triggered by a change in pH, temperature or even charge destabilization. However, to the inventors' knowledge, no plasmonic-based microcapsule sensors have been developed that are capable of sensing external mechanical stress.

There is an ongoing need for the development of materials that are capable of sensing various external stimuli. Polymeric materials are used in many different applications (coatings, plastics, composites, among others). However, such materials can deform and crack due to external stresses during their lifetime. A direct in-situ visual method to detect those defects within the materials would allow early repair before further damage can occur and/or would indicate when replacement of the affected part is necessary before an unsafe situation arises. Such a sensory device would have wide application in small structures, for instance, mechanical parts, and in large structures, such as dams, bridges, etc. Materials that are capable of sensing various external stimuli would also find use in the field of food safety to detect rotten food or food toxins.

Summary of the Invention

In a first aspect, the present disclosure relates to a microcapsule comprising:
a hollow or non-hollow core; and
a rigid or flexible shell, wherein a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, is embedded in said shell.

In a second aspect, the present disclosure relates to a process for manufacturing microcapsules described herein, the process comprising:

a) forming an emulsion by mixing a first mixture comprising a first solvent and a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, and a second mixture comprising a second solvent, immiscible with the first solvent,

wherein the first mixture and/or the second mixture comprises one or more shell precursor compounds;

b) reacting the precursor compounds so as to form a rigid or flexible shell, thereby forming the microcapsules;

c) recovering the microcapsules formed in step b).

In a third aspect, the present disclosure relates to a film comprising a polymer matrix and a plurality of microcapsules described herein.

In a fourth aspect, the present disclosure relates to a method for detecting an external stimulus, the method comprising:

a) incorporating a plurality of microcapsules described herein into a substrate;

b) exposing the substrate to an external stimulus; and

c) observing a change in extinction or a change in optical fluorescence.

In a fifth aspect, the present disclosure relates to a method for inhibiting the growth of a microbe, the method comprising contacting the microbe with a plurality of microcapsules described herein, thereby inhibiting the growth of the microbe.

Brief Description of the Figures

FIG. 1 shows the plasmonic response of Au NPs solutions ($[Au]=0.57mM$) as a function of pH. Inset shows plasmonic peak maximum as a function of the pH (filled circular points) and Zeta potential of the Au NPs at $[Au]=0.57mM$ as a function of the pH (square unfilled points).

FIG. 2 shows a schematic representation of the formation of inventive gold-silica microcapsules.

FIG. 3 shows a) an optical microscope image of typical microcapsules at 0.02 M of gold; b) and c) SEM images of microcapsules obtained at 0.02M of gold, and d) an SEM image of a typical microcapsule surface covered by Au NPs.

FIG. 4 shows the position of the plasmonic peak maximum as the polymer is elongated. The dashed line corresponds to the wavelength of maximum extinction of the Au NPs in water. Inset shows optical response as a function of film elongation (extinction normalized at 400 nm).

FIG. 5 shows the optical response as a function of potential energy of impact (the extinction is normalized at 420 nm). Inset shows the position of the plasmonic peak maximum as the polymer is impacted.

Detailed Description

As used herein, the terms “a”, “an”, or “the” means “one or more” or “at least one” unless otherwise stated.

As used herein, the term “comprises” includes “consists essentially of” and “consists of.” Analogously, the term “comprising” includes “consisting essentially of” and “consisting of.”

The phrase “free of” means that there is no external addition of the material modified by the phrase and that there is no detectable amount of the material that may be observed by analytical techniques known to the ordinarily-skilled artisan, such as, for example, gas or liquid chromatography, spectrophotometry, optical microscopy, and the like.

Throughout the present disclosure, various publications may be incorporated by reference. Should the meaning of any language in such publications incorporated by reference conflict with the meaning of the language of the present disclosure, the meaning of the language of the present disclosure shall take precedence, unless
5 otherwise indicated.

As used herein, the terminology "Cx-Cy" in reference to an organic group, wherein x and y are each integers, means that the group may contain from x carbon atoms to y carbon atoms per group.

10 The microcapsules of the present disclosure comprise a hollow or non-hollow core, and a rigid or flexible shell, wherein a plurality of metallic nanoparticles is embedded in said shell.

15 The microcapsules may be hollow or non-hollow. When the microcapsule is non-hollow, a liquid is typically encapsulated within the microcapsule. The liquid encapsulated within the microcapsule is typically a hydrophobic liquid. Exemplary hydrophobic liquids include, but are not limited to, C₁₋₂₀ straight, branched, or cyclic alkanes, such as pentane, hexane, cyclohexane, dodecane, hexadecane, and
20 decalin; and C₁₋₂₀ aromatic hydrocarbons, such as benzene, xylene, and toluene; select alcohols, such as octanol; oils, such as silicon oil, animal, vegetable or other natural oils; alkyl esters, such as ethyl acetate and hexyl acetate; and mixtures thereof. In an embodiment, the core comprises toluene.

25 When the core of the microcapsule is non-hollow, the core may further comprise an active agent. As used herein, an active agent is a material that provides a beneficial effect. Suitable active agents include, but are not limited to, drugs or other pharmaceutical agents, such as antibacterial agents; fragrances, flavoring agents, dyes, fluorophores, and spiropyran derivatives.

30 The shell of the microcapsules of the present disclosure may be rigid or flexible depending on the material used to make the microcapsule. When the shell is rigid,

the shell typically comprises silicon. In an embodiment, the shell comprises silicon dioxide. When the shell is flexible, the shell typically comprises a polymer. In an embodiment, the polymer is a homopolymer or copolymer derived from ethylenically-unsaturated monomers. The copolymer may be a random copolymer or a block copolymer. Exemplary ethylenically-unsaturated monomers suitable for use in the shell of the microcapsules include, but are not limited to, (meth)acrylic ester monomers, including methyl acrylate, ethyl acrylate, butyl acrylate, 2-ethylhexyl acrylate, decyl acrylate, lauryl acrylate, methyl methacrylate, butyl methacrylate, ethyl methacrylate, isodecyl methacrylate, lauryl methacrylate, hydroxyethyl methacrylate, and hydroxypropyl methacrylate; (meth)acrylic amides, such as (meth)acrylamide, N-isopropyl(meth)acrylamide, and bis-acrylamide; styrene and substituted styrenes; butadiene; vinyl acetate, vinyl butyrate and other vinyl esters; vinyl monomers, such as vinyl chloride, vinyl toluene, vinyl benzophenone; vinylidene chloride, and mixtures thereof. In an embodiment, the shell comprises a homopolymer or copolymer derived from ethylenically-unsaturated monomers selected from the group consisting of methyl methacrylate, butyl acrylate, methyl acrylate, N-isopropyl(meth)acrylamide, bis-acrylamide, and mixtures thereof.

As used herein, the term "nanoparticle" refers to a particle having at least one dimension less than or equal to 1000 nm, typically less than or equal to 100 nm. The metallic nanoparticles used in the present disclosure may have any shape. Typically, the metallic nanoparticles are spherical or substantially spherical. Accordingly, in an embodiment, the mean diameter of the metallic nanoparticles is about 1 nm to about 100 nm, typically from about 1 to about 60 nm, more typically about 20 to about 60 nm, most typically about 40 nm.

Each metallic nanoparticle comprises or consists of a metal, or an alloy or intermetallic comprising a metal. Metals include, for example, alkali metals, such as, for example, lithium, sodium, potassium, and rubidium; main group metals such as, e.g., lead, tin, bismuth, antimony and indium; transition metals, such as gold, silver, copper, nickel, cobalt, palladium, platinum, iridium, osmium, rhodium, ruthenium, rhenium, vanadium, chromium, manganese, niobium, molybdenum, tungsten,

5 tantalum, titanium, zirconium, zinc, mercury, yttrium, iron and cadmium; as well as inner transition metals, also referred to rare earth elements, such as cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), samarium (Sm), scandium (Sc), terbium (Tb), thulium (Tm), and ytterbium (Yb).

In an embodiment, each metallic nanoparticle comprises at least one transition metal, typically gold or silver.

10 In an embodiment, the plurality of metallic nanoparticles comprises nanoparticles having the same metal, typically the same transition metal.

In another embodiment, the plurality of metallic nanoparticles comprises nanoparticles having different metals, typically different transition metals, more
15 typically gold and silver.

The metallic nanoparticles used in the microcapsules described herein are solid nanoparticles free of transition metal oxide and/or core/shell nanoparticles. Solid nanoparticles free of transition metal oxide are solid metallic nanoparticles that do
20 not contain any metal oxides. Representative metal oxides that the metallic nanoparticles do not contain include silver oxides, titanium oxides, such as titanium dioxide (TiO_2), and the like.

The term “core/shell nanoparticle” refers to a nanoparticle having a core that is
25 coated on the surface with another material, which forms a shell. Typically, the core of a core/shell nanoparticle comprises or consists of a metal, or an alloy or intermetallic comprising a metal. The thickness of the shell surrounding the core is not particularly limited. However, the shell thickness is typically from 1 nm to 40 nm.

30 The metallic nanoparticles may be in any form known to those of ordinary skill in the art. For example, the metallic nanoparticles may be in the form of nanocrystals, in which the atoms are in one or more crystalline arrangements, or in the form of

nanophosphors, which may be doped or undoped. Nanophosphors make up a class of optical materials having such properties as quantum cutting and photon upconversion and downconversion. Some doped nanophosphors, such as lanthanide-doped colloidal upconverting nanophosphors, are capable of converting long-wavelength near-infrared excitation into short-wavelength visible emission through the long-lived, metastable excited states of the dopant. The downconverting phosphors are capable of convert high energy photons (low wavelength) into several lower energy photons with energies above the band gap of the luminescent material.

The metallic nanoparticles used in the microcapsules described herein may comprise an organic capping agent. Suitable organic capping agents include, for example, phosphines; phosphine oxides; alkyl phosphonic acids; polymers, such as polyalkylpolyoxyalkyl polyacrylates, polyvinylpyrrolidones, such as PVP-10K and poly(diallyldimethylammonium-nitrate-co-1-vinylpyrrolidone) (PVP-DADMAN, Solvay®), polyvinyl acetates, poly(vinyl alcohol), polystyrene, and polymethacrylate; polymeric acids, such as polyacrylic acid; alkyl thiols, such as (C₄-C₁₂) thiols; alkyl amines, such as (C₄-C₁₂) amines; carboxylic acids, such as acetic acid, citric acid, and ascorbic acid; fatty acids, such as (C₆-C₂₄) fatty acids; surfactants; dendrimers, and salts and combinations thereof.

(C₄-C₁₂) thiols, include, but are not limited to, ethanethiol, propanethiol, butanethiol, and dodecanethiol.

(C₄-C₁₂) amines, include, but are not limited to, butylamine, sec-butylamine, isobutylamine, tert-butylamine, 3-methoxypropylamine, (2-methylbutyl)amine, 1,2-dimethylpropylamine, 1-ethylpropylamine, 2-aminopentane, amylamine, isopentylamine, pentylamine, tert-amylamine, 3-ethoxypropylamine, 3,3-dimethylbutylamine, hexylamine, 3-isopropoxypropylamine, heptylamine, 2-heptylamine, 1,4-dimethylpentylamine, 1,5-dimethylhexylamine, 1-methylheptylamine, 2-ethyl-1-hexylamine, octylamine, 1,1,3,3-tetramethylbutylamine, nonylamine, decylamine, dodecylamine, tridecylamine, tetradecylamine, hexadecylamine, oleylamine, and octadecylamine.

(C₆-C₂₄) fatty acids include, but are not limited to, hexanoic acid, heptanoic acid, octanoic acid, nonanoic acid, decanoic acid, undecanoic acid, dodecanoic acid, tridecanoic acid, myristic acid, pentadecanoic acid, palmitic acid, oleic acid,

5 heptadecanoic acid, stearic acid, nonadecanoic acid, arachidic acid, heneicosanoic acid, behenic acid, tricosanoic acid, lignoceric acid, pamoic acid, hexacosanoic acid, 8-methylnonanoic acid, 11-methylauric acid, 12-methyltridecanoic acid, 12-methyltetradecanoic acid, 13-methylmyristic acid, isopalmitic acid, 14-methylhexadecanoic acid, 15-methylpalmitic acid, 16-methylheptadecanoic acid, 17-methylstearic acid, 18-methylnonadecanoic acid, phytanic acid, 19-methylarachidic acid, and isostearic acid.

Surfactants include, for example, anionic surfactants, cationic surfactants, nonionic surfactants, amphoteric or zwitterionic surfactants.

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Anionic surfactants include, for example, alkyl sulfates (eg., dodecylsulfate), alkylamide sulfates, fatty alcohol sulfates, secondary alkyl sulfates, paraffin sulfonates, alkyl ether sulfates, alkylpolyglycol ether sulfates, fatty alcohol ether sulfates, alkylbenzenesulfonates, alkylphenol ether sulfates, alkyl phosphates; alkyl or alkylaryl monoesters, diesters, and triesters of phosphoric acid; alkyl ether phosphates, alkoxylated fatty alcohol esters of phosphoric acid, alkylpolyglycol ether phosphates (for example, polyoxyethylene octadecenyl ether phosphates marketed as LUBRHOPHOS® LB-400 by Rhodia), phosphonic esters, sulfosuccinic diesters, sulfosuccinic monoesters, alkoxylated sulfosuccinic monoesters, sulfosuccinimides, 25 α-olefinsulfonates, alkyl carboxylates, alkyl ether carboxylates, alkyl-polyglycol carboxylates, fatty acid isethionate, fatty acid methyltauride, fatty acid sarcoside, alkyl sulfonates (eg., 2-(methyloleoylamino)ethane-1-sulfonate, marketed as GEROPON® T77 by Solvay) alkyl ester sulfonates, arylsulfonates (eg., diphenyl oxide sulfonate, marketed as RHODACAL® DSB by Rhodia), 30 naphthalenesulfonates, alkyl glyceryl ether sulfonates, polyacrylates, α-sulfo-fatty acid esters, and salts and mixtures thereof.

Cationic surfactants include, for example, aliphatic, cycloaliphatic or aromatic primary, secondary and tertiary ammonium salts or alkanolammonium salts; quaternary ammonium salts, such as tetraoctylammonium halides and cetyltrimethylammonium halides (eg., cetyltrimethylammonium bromide (CTAB));
5 pyridinium salts, oxazolium salts, thiazolium salts, salts of amine oxides, sulfonium salts, quinolinium salts, isoquinolinium salts, tropylium salts.

Other cationic surfactants suitable for use according to the present disclosure include cationic ethoxylated fatty amines. Examples of cationic ethoxylated fatty
10 amines include, but are not limited to, ethoxylated oleyl amine (marketed as RHODAMEEN® PN-430 by Solvay), hydrogenated tallow amine ethoxylate, and tallow amine ethoxylate.

Nonionic surfactants include, for example, alcohol alkoxylates (for example,
15 ethoxylated propoxylated C₈-C₁₀ alcohols marketed as ANTAROX® BL-225 and ethoxylated propoxylated C₁₀-C₁₆ alcohols marketed as ANTAROX® RA-40 by Rhodia), fatty alcohol polyglycol ethers, fatty acid alkoxylates, fatty acid polyglycol esters, glyceride monoalkoxylates, alkanolamides, fatty acid alkylolamides, alkoxylated alkanol-amides, fatty acid alkylolamido alkoxylates, imidazolines,
20 ethylene oxide-propylene oxide block copolymers (for example, EO/PO block copolymer marketed as ANTAROX® L-64 by Rhodia), alkylphenol alkoxylates (for example, ethoxylated nonylphenol marketed as IGEPAL® CO-630 and ethoxylated dinonylphenol/nonylphenol marketed as IGEPAL® DM-530 by Rhodia), alkyl glucosides, alkoxylated sorbitan esters (for example, ethoxylated sobitan
25 monooleate marketed as ALKAMULS® PSMO by Rhodia), alkyl thio alkoxylates (for example, alkyl thio ethoxylates marketed as ALCODET® by Rhodia), amine alkoxylates, and mixtures thereof.

Typically, nonionic surfactants include addition products of ethylene oxide, propylene
30 oxide, styrene oxide, and/or butylene oxide onto compounds having an acidic hydrogen atom, such as, for example, fatty alcohols, alkylphenols or alcohols. Examples are addition products of ethylene oxide and/or propylene oxide onto linear

or branched fatty alcohols having from 1 to 35 carbon atoms, onto fatty acids having from 6 to 30 carbon atoms and onto alkylphenols having from 4 to 35 carbon atoms in the alkyl group; (C₆-C₃₀)-fatty acid monoesters and diesters of addition products of ethylene oxide and/or propylene oxide onto glycerol; glycerol monoesters and diesters and sorbitan monoesters, diesters and triesters of saturated and unsaturated fatty acids having from 6 to 22 carbon atoms and their ethylene oxide and/or propylene oxide addition products, and the corresponding polyglycerol-based compounds; and alkyl monoglycosides and oligoglycosides having from 8 to 22 carbon atoms in the alkyl radical and their ethoxylated or propoxylated analogues.

Amphoteric or zwitterionic surfactants include, but are not limited to, aliphatic quaternary ammonium, phosphonium, and sulfonium compounds, wherein the aliphatic radicals can be straight chain or branched, and wherein the aliphatic substituents contains about 6 to about 30 carbon atoms and at least one aliphatic substituent contains an anionic functional group, such as carboxy, sulfonate, sulfate, phosphate, phosphonate, and salts and mixtures thereof. Examples of zwitterionic surfactants include, but are not limited to, alkyl betaines, alkyl amidopropyl betaines, alkyl sulphobetaines, alkyl glycines, alkyl carboxyglycines; alkyl amphopropionates, such as cocoamphopropionate and caprylamphodipropionate (marketed as MIRANOL® JBS by Rhodia); alkyl amidopropyl hydroxysultaines, acyl taurates, and acyl glutamates, wherein the alkyl and acyl groups have from 6 to 18 carbon atoms, and salts and mixtures thereof.

In an embodiment, each metallic nanoparticle comprises an organic capping agent, typically a polyvinylpyrrolidone, more typically poly(diallyldimethylammonium-nitrate-co-1-vinylpyrrolidone).

The metallic nanoparticles used in the present disclosure may be obtained from commercial sources or synthesized according to methods known to those of ordinary skill in the art. Typically, the metallic nanoparticles are synthesized by reduction of a metal precursor compound with a reducing agent, optionally in the presence of an organic capping agent, such as those described herein.

Exemplary metal precursor compounds include silver nitrate, silver nitrite, silver oxide, silver fluoride, silver hydrogen fluoride, silver carbonate, silver oxalate, silver azide, silver tetrafluoroborate, silver acetate, silver propionate, silver butanoate, silver ethylbutanoate, silver pivalate, silver cyclohexanebutanoate, silver ethylhexanoate, silver neodecanoate, silver decanoate, silver trifluoroacetate, silver pentafluoropropionate, silver heptafluorobutyrate, silver trichloroacetate, silver 6,6,7,7,8,8,8-heptafluoro-2,2-dimethyl-3,5-octanedionate, silver lactate, silver citrate, silver glycolate, silver glyconate, silver benzoate, silver salicylate, silver phenylacetate, silver nitrophenylacetate, silver dinitrophenylacetate, silver difluorophenylacetate, silver 2-fluoro-5-nitrobenzoate, silver acetylacetonate, silver hexafluoroacetylacetonate, silver trifluoroacetylacetonate, silver tosylate, silver triflate, silver trispyrazolylborate, silver tris(dimethylpyrazolyl)borate, silver ammine complexes, trialkylphosphine and triarylphosphine derivatives of silver carboxylates, silver beta-diketonates, silver beta-diketonate olefin complexes and silver cyclopentadienides; platinum formate, platinum acetate, platinum propionate, platinum carbonate, platinum nitrate, platinum perchlorate, platinum benzoate, platinum neodecanoate, platinum oxalate, ammonium hexafluoroplatinate, ammonium tetrachloroplatinate, sodium hexafluoroplatinate, potassium hexafluoroplatinate, sodium tetrachloroplatinate, dihydrogen tetrachloroplatinate, potassium hexabromoplatinate, hexachloroplatinic acid, hexabromoplatinic acid, dihydrogen hexahydroxoplatinate, diammine platinum chloride, tetraammine 5 platinum chloride, tetraammine platinum hydroxide, tetraammine platinum tetrachloroplatinate, platinum(II) 2,4-pentanedionate, diplatinum trisdibenzylideneacetate, platinum sulfate and platinum divinyltetramethyldisiloxane; gold(III) acetate, gold(III) chloride, tetrachloroauric acid, gold azide, gold isocyanide, gold acetoacetate, imidazole gold ethylhexanoate and gold hydroxide acetate isobutyrate; palladium acetate, palladium propionate, palladium ethylhexanoate, palladium neodecanoate, palladium trifluoroacetate, palladium oxalate, palladium nitrate, palladium chloride, tetraammine palladium hydroxide, tetraammine palladium nitrate, chloropalladic acid (dihydrogen hexachloropalladate), and tetraammine palladium tetrachloropalladate; iron(II)

acetate, tetrachloroferric acid (HFeCl_4), iron(II) bromide, iron(III) bromide, iron(II) chloride, iron(III) chloride, iron(II) iodide, iron(II) oxalate, iron(III) oxalate, iron(II) sulfate, iron(III) sulfate, and potassium hexacyanoferrate(II). The above compounds may be employed as such or optionally as their hydrates.

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Reducing agents include, for example, polyols, such (alkylene)glycols (e.g., ethylene glycol, propylene glycol and the butylene glycols); hydrazine and derivatives thereof; hydroxylamine and derivatives thereof, monohydric alcohols such as, e.g, methanol and ethanol, aldehydes such as, e.g., formaldehyde, ammonium formate, formic acid, acetaldehyde, and propionaldehyde, or salts thereof (e.g., ammonium formate); hypophosphites; sulfites; tetrahydroborates (such as, e.g., the tetrahydroborates of Li, Na, K); lithium aluminum hydride (LiAlH_4); sodium borohydride (NaBH_4); polyhydroxybenzenes such as, e.g., hydroquinone, alkyl-substituted hydroquinones, catechols and pyrogallol; phenylenediamines and derivatives thereof; aminophenols and derivatives thereof; carboxylic acids and derivatives thereof such as, e.g., ascorbic acid, ascorbate salts, citric acid, citrate salts, erythorbic acid, erythorbate salts, and ascorbic acid ketals; 3-pyrazolidone and derivatives thereof; hydroxytetronic acid, hydroxytetronamide and derivatives thereof; bisnaphthols and derivatives thereof; sulfonamidophenols and derivatives thereof; and Li, Na and K.

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In an embodiment, the reducing agent is ascorbic acid. In another embodiment, the reducing agent is a polyol, typically ethylene glycol.

In accordance with the present disclosure, the metallic nanoparticles are embedded in the shell of the microcapsules described herein. Generally, the metallic nanoparticles are immobilized in the shell. In some embodiments, a portion of each metallic nanoparticle embedded in the shell is exposed on the surface of the shell.

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The surface area covered by nanoparticles in each microcapsule is from 0% to about 99%, typically 1% to about 90%, more typically from about 10% to 90%, more typically from about 50% to 90%.

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The present disclosure also concerns a process for manufacturing the microcapsules described herein, the process comprising:

a) forming an emulsion by mixing a first mixture comprising a first solvent and a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, and a second mixture comprising a second solvent, immiscible with the first solvent,

wherein the first and/or second mixtures each comprise one or more shell precursor compounds;

b) reacting the precursor compounds so as to form a rigid or flexible shell, thereby forming the microcapsules;

c) recovering the microcapsules formed in step b).

Initially, an emulsion is formed by mixing a first mixture comprising a first solvent and a plurality of the metallic nanoparticles described herein and a second mixture comprising a second solvent, immiscible with the first solvent. The first and/or second mixtures each comprise one or more shell precursor compounds. In an embodiment, the first mixture comprises one or more shell precursor compounds. In another embodiment, the second mixture comprises one or more shell precursor compounds. As used herein, the term "immiscible" means that no more than 1 g/L, no more than 0.9 g/L, no more than 0.6 g/L, or no more than 0.5 g/L of one solvent is dissolved in another solvent. As generally understood by the ordinarily-skilled artisan, an emulsion comprises a continuous phase and a dispersed phase resulting from the mixing of two or more liquids that are immiscible. The formation of emulsions is well known to those of ordinary skill in the art. The continuous phase may be formed from a hydrophilic or hydrophobic liquid as long as the dispersed phase is formed from a liquid immiscible with the liquid used to form the continuous phase. Thus, if the continuous phase is formed from a hydrophilic liquid, the dispersed phase is formed from a hydrophobic liquid, or vice versa.

Typically, the continuous phase is formed by the first mixture comprising a first solvent and a plurality of metallic nanoparticles. The first solvent comprises water and, optionally, one or more water-miscible organic liquids. Suitable water miscible organic liquids include polar aprotic organic solvents, such as, for example, dimethyl

sulfoxide and dimethyl 2- methylglutarate (marketed as Rhodiasolv® IRIS), polar protic organic solvents, such as, for example, methanol, ethanol, propanol, butanol, ethylene glycol, and propylene glycol, and mixtures thereof. The plurality of metallic nanoparticles is dispersed in the first solvent to provide the first mixture. In an
5 embodiment, the first mixture comprises a first solvent, a plurality of metallic nanoparticles, and one or more shell precursor compounds.

There is no particular limitation to the pH of the first mixture or second mixture.

However, the first mixture is typically acidic (i.e., pH less than 7). Thus, in an
10 embodiment, the first mixture further comprises an acid. Suitable acids include, but are not limited to, inorganic acids, such as, for example, hydrofluoric acid (HF), hydrochloric acid (HCl), hydrobromic acid (HBr), hydroiodic acid (HI), and solutions thereof; oxo acids, such as nitric acid (HNO₃), phosphoric acid (H₃PO₄), sulfuric acid (H₂SO₄), and solutions thereof; and carboxylic acids, such as acetic acid, citric acid,
15 trifluoroacetic acid, and solutions thereof. In an embodiment, the pH of the first mixture is less than or equal to 4.

Typically, the dispersed phase is formed by the second mixture comprising a second solvent, immiscible with the first solvent, and optionally one or more shell precursor
20 compounds. The second solvent typically comprises one or more hydrophobic organic liquids. Exemplary hydrophobic organic liquids suitable for use as the second solvent include, but are not limited to, C₁₋₂₀ straight, branched, or cyclic alkanes, such as pentane, hexane, cyclohexane, dodecane, hexadecane, and decalin; C₁₋₂₀ aromatic hydrocarbons, such as benzene, xylene, and toluene; select
25 alcohols, such as octanol; oils, such as silicon oil, animal, vegetable or other natural oils; alkyl esters, such as ethyl acetate and hexyl acetate; and mixtures thereof. In an embodiment, the second solvent is toluene.

Shell precursor compounds are compounds capable of undergoing a reaction, such
30 as a polymerization reaction, to form the shell of the microcapsule. Suitable precursor compounds include, but are not limited to, siloxanes, such as, for example, tetraethyl orthosilicate (TEOS), polydiethoxysiloxane (PEOS), and ethylenically-

unsaturated monomers. Exemplary ethylenically-unsaturated monomers include, but are not limited to, (meth)acrylic ester monomers, including methyl acrylate, ethyl acrylate, butyl acrylate, 2-ethylhexyl acrylate, decyl acrylate, lauryl acrylate, methyl methacrylate, butyl methacrylate, ethyl methacrylate, isodecyl methacrylate, lauryl methacrylate, hydroxyethyl methacrylate, and hydroxypropyl methacrylate; (meth)acrylic amides, such as (meth)acrylamide, N-isopropyl(meth)acrylamide, and bis-acrylamide; styrene and substituted styrenes; butadiene; vinyl acetate, vinyl butyrate and other vinyl esters; vinyl monomers, such as vinyl chloride, vinyl toluene, vinyl benzophenone; vinylidene chloride, and mixtures thereof.

In an embodiment, the one or more shell precursor compounds is polydiethoxysiloxane (PEOS), or an ethylenically-unsaturated monomer selected from the group consisting of methyl methacrylate, butyl acrylate, methyl acrylate, N-isopropyl(meth)acrylamide, bis-acrylamide, and mixtures thereof.

The first mixture and second mixture are subsequently combined and agitated to form the emulsion. Any method known to those of ordinary skill in the art may be used for agitation. For example, sonication may be used.

The emulsion formed according to the present disclosure is stable versus coarsening. This is achieved when the metallic nanoparticles in the continuous phase adsorb at the interface between the continuous and dispersed phases to form a so-called Pickering emulsion. Stable Pickering emulsions may be formed by satisfying the following various conditions.

The placement of the metallic NPs at the liquid/liquid interface should lead to a decrease in the total free energy. Equation (1) shows the free energy of desorption of a nanoparticle at the interface, where γ_{ow} is the interfacial tension; θ_{ow} is the three-phase contact angle between the solid and the interface; R is the radius of the nanoparticles. The adsorption of nanoparticles of radius ranging between 10 nm and 100 μm and with intermediate contact angle ($40^\circ \leq \theta_{ow} \leq 90^\circ$) induces a decrease in the energy of order of thousands of $k_B T$ per particle, where k_B is the Boltzmann

constant and T is the temperature. Thermal energy is thus not large enough to desorb the nanoparticles from the interface, and a single metallic NP is strongly and irreversibly bound to the interface.

$$\Delta G = -\pi R^2 \gamma_{ow} (1 - |\cos(\theta_{ow})|)^2 \quad (1)$$

Based on Equation (1), particles are best adsorbed at the interface for $\theta_{ow} = 90^\circ$, when particles have equal affinity for the continuous and dispersed phase. The metallic nanoparticles described herein may be tuned by using a suitable organic capping agent such that the particles have equal affinity for the continuous and dispersed phase.

The number of nanoparticles suitable for forming a stable Pickering emulsion can be estimated from Equation (2) where N_p is the number of NPs needed to fully cover droplets of diameter D with particles of diameter d , w_p is the total mass of the nanoparticles; ρ is the density of the nanoparticles; and V is the total volume of the dispersed phase.

$$N_p = \frac{w_p}{\rho V} \left(\frac{D}{d}\right)^3 \quad (2)$$

It was found that the reduction of electrostatic repulsions between metallic nanoparticles enabled good adsorption and high packing of the NPs at the interface.

The reaction step comprises a radical polymerization reaction, as in the case when ethylenically-unsaturated shell precursor compounds are used, or a polycondensation reaction, as in the case when polydiethoxysiloxane is used. Such radical polymerization reactions and polycondensation reactions are well-known to those of ordinary skill in the art. The metallic nanoparticles are adsorbed on the interface between the dispersed phase and the continuous phase. Following the reaction step, a shell is formed at the interface, which locks the plurality of metallic nanoparticles in the formed shell.

Recovering the microcapsules formed in the reaction step may be achieved using any method. For example, the microcapsules may be recovered using centrifugation, filtration, sedimentation, or a combination thereof.

- 5 The process described herein may further comprise drying the recovered microcapsules to remove any solvent, including solvent trapped in the core of the microcapsules. Drying may be achieved by any known method. For example, the microcapsules may be dried by subjecting the microcapsules to heat and/or low pressure atmosphere.

10

- The present disclosure concerns a film comprising a polymer matrix and a plurality of microcapsules described herein. The polymer matrix is not limited and may be any type of polymeric material known to those of ordinary skill in the art. Some exemplary polymer matrices include, but are not limited to, polyesters, polysulfones, polyethersulfones, polyarylates, polyimides, polyetherimides, polytetrafluoroethylenes, poly(ether ketone)s, poly(ether ether ketone)s, poly(butyl acrylate), poly((meth)acrylate)s, polycarbonates, polyolefins, polyvinyl alcohols, and mixtures thereof. A plurality of microcapsules may be dispersed in a solution comprising the polymer matrix. The solvent may then be removed to yield a film comprising the polymer matrix and the plurality of microcapsules. Alternatively, a plurality of microcapsules may be dispersed in a solution comprising monomers that are subsequently polymerized to form the polymer matrix, yielding a film in which the plurality of microcapsules is embedded in the polymer matrix. In an embodiment, a plurality of microcapsules is added to a solution of polymer matrix, typically polyvinyl alcohol (PVA) or acrylic polymer. Removal of the solvent results in a film comprising PVA or acrylic polymer and a plurality of microcapsules embedded therein.

- The film may be rigid or elastic. By choosing the appropriate glass transition temperature for the polymer matrix used, the elasticity of the obtained film can be tuned.

30

The present disclosure also relates to a method for detecting an external stimulus, the method comprising:

- a) incorporating a plurality of microcapsules described herein into a substrate;
- b) exposing the substrate to an external stimulus; and
- 5 c) observing a change in extinction or a change in optical fluorescence.

Incorporating a plurality of microcapsules described herein into a substrate may be achieved according to any method known to the ordinarily-skilled artisan. For example, the plurality of microcapsules may be introduced during the manufacture of
10 the substrate, which may subsequently be used to manufacture an article. The substrate may comprise, for example, a metal, a polymer, a glass, a paper, a ceramic material, or a combination thereof. Suitable polymers are polymers selected from polyesters, polysulfones, polyethersulfones, polyarylates, polyimides, polyetherimides, polytetrafluoroethylenes, poly(ether ketone)s, poly(ether ether
15 ketone)s, poly((meth)acrylate)s, polycarbonates, polyolefins, polyvinyl alcohols, and mixtures thereof.

Exposure of the substrate comprising the plurality of microcapsules described herein to an external stimulus, includes, but is not limited to, mechanical deformation,
20 change in temperature; adsorption of oil, organic solvent, and/or water; and change in pH, results in a change in extinction or a change in optical fluorescence. A change in extinction or a change in optical fluorescence typically manifests as a change in color or color intensity capable of being observed by the naked eye. A change in extinction or a change in optical fluorescence may also be observed with
25 the aid of devices known to be useful in detecting such changes, for example, by using a UV-vis spectrophotometer in accordance with methods known to those of ordinary skill.

In some embodiments, the removal of the external stimulus results in a return to the
30 condition before the exposure of the substrate to the external stimulus. That is to say, the change in extinction or a change in optical fluorescence due to the external stimulus, for example, mechanical deformation, change in temperature; adsorption of

oil, organic solvent, and/or water; and change in pH, is reversed when the external stimulus is removed.

5 The present disclosure relates to a method for inhibiting the growth of a microbe, the method comprising contacting the microbe with a plurality of the microcapsules described herein, thereby inhibiting the growth of the microbe.

10 The contacting of microbes with a plurality of the microcapsules inhibits the growth of the said microbes. Without wishing to be bound by theory, it is believed that the release of metal ions, typically silver ions, from the microcapsule shell in the vicinity of the microbes result in deleterious effects on the microbes, thus inhibiting their growth. Microbes whose growth may be inhibited include, but are not limited to, bacteria, viruses, yeast and other fungi, algae, plankton, and protozoa. In an embodiment, the microbe is bacteria, algae, or plankton. Thus, the microcapsules
15 may be used in wound care products, including, but not limited to, dressings, hydrogels, hydrocolloids, creams, gels, lotions, catheters, sutures, socks and bandages.

20 The microcapsules, methods and processes, and films according to the present disclosure are further illustrated by the following non-limiting examples.

Examples

25 The Au NPs used in this procedure were synthesized by reduction of HAuCl_4 with ascorbic acid in presence of PVP-DADMAN. A solution of 3.5×10^{-5} M PVP-DADMAN and 2.5×10^{-3} M HAuCl_4 was brought to boil. Then, 12.5 mL of ascorbic acid (0.39×10^{-3} M) was added. The solution protected from light by aluminum foil was stirred for 1 h at 97°C . After synthesis, the Au NPs were left to rest for one day to remove the biggest nanoparticles. The rest of the dispersion was centrifuged and
30 concentrated into a few milliliters solution.

The pH of solutions containing the gold nanoparticles was measured with a VWR Scientific digital pH temperature meter (model 8015). The Zeta potential of the gold nanoparticle solutions ($[\text{Au}^0] = 0.574 \text{ mM}$ and $[\text{NaCl}] = 10^{-2} \text{ M}$) as a function of the pH was measured on a Zetasizer Nano Series 200. FIG. 1 shows the evolution of the surface potential of the Au NPs as a function of pH. A surface potential jump at pH~4 was observed. Below pH = 4, Au NPs seemed to have no charge, whereas above pH = 4, they appear to be weakly negatively charged. This pH coincides with the pKa of ascorbic acid, and with the simultaneous change in the emulsion color. At relatively high pH, i.e., pH ~6, the emulsion droplets do not appear to present a very high packing fraction of the Au NPs on their surface, and thus the droplets appear pink. By decreasing the pH to a value below 4, the charges at the droplets surfaces are decreased, as does any subsequent electrostatic repulsion. In subsequent emulsion formation, droplets appear blue under the microscope, in agreement with dense packing at the surface. Thus, in the following examples, the pH was set below the pKa of the ascorbic acid.

Silver nanoparticles (Ag NPs) were synthesized by reduction of AgNO_3 using ascorbic acid in the presence of PVP-DADMAN or were obtained by reduction of AgNO_3 in ethylene glycol. Mixtures of gold and silver NPs were obtained by mixing the Au NPs and Ag NPs.

Scanning electron microscopy (SEM) was performed on JEOL 7500 HRSEM. The samples were prepared by air drying under ambient conditions a drop of microcapsules dispersion in water on an electron microscopy science carbon-coated copper grid. Transmission electron microscopy (TEM) was carried out on a JEOL JEM-1400 electro-microscope. The accelerating voltage was set at 120kV.

Optical microscopy images were acquired on an Olympus microscope in bright field and transmission mode. Optical extinction spectra were recorded in transmission mode using a Cary 5000 spectrophotometer.

Example 1. Synthesis of gold-silica microcapsules

0.2 g of PEOS was diluted in 1 mL of toluene. The water phase of the emulsion (4mL) contains a solution of Au NPs at $[Au^0]=0.02$ M with 0.2 mL of HCl and 0.1 mL of butanol. The oil and water phases were emulsified together with a Brandson 3210 ultrasonic bath at 30°C for 15 minutes. After 3 days, the silica shell was fully formed. The microcapsules were recovered, cleaned and concentrated by simple sedimentation.

FIG. 2 shows the schematic representation of the gold-silica microcapsules formed. FIG. 3 shows images of the dried microcapsules formed after 3 days. The color, aspect and size of the microcapsules are analyzed by optical microscopy (FIG. 3a) and SEM (Figs. 3b-3d). The microcapsules are spherical with dimensions ranging from several hundredths of nanometers to several tenths of micrometers (4-20 μ m). The microcapsules had a deep blue color, which comes from a monolayer of densely packed nanoparticles on their surface, as shown in Figure 3d. The silica shell thickness as measured from SEM images ranges between 30 and 60 nm.

Example 2. Synthesis of gold-acrylate microcapsules.

10 mg of azobisisobutyronitrile (AIBN) was dissolved in 0.5 mL of toluene containing diverse ratios of methylmethacrylate/methacrylate/butacrylate for a total mass of monomers equal to 0.2g. The water phase of the emulsion (4 mL) contained a solution of AuNPs at $[Au^0]=0.02$ M with 20 μ L of HCl. The oil and water phases were emulsified together with a Brandson 3210 ultrasonic bath at 30°C for 15 minutes. After 2 hrs at 60°C under inert atmosphere, the acrylate shells were fully formed. The microcapsules were recovered, cleaned and concentrated by simple sedimentation.

Example 3. Synthesis of gold-PNipam microcapsules.

10 mg of benzoyl peroxide was diluted in 0.8 mL of hexane. The water phase of the emulsion (3 mL) contained the AuNPs at $[Au^0]=0.02$ M with 10 mg of bis-acrylamide and 100 mg of N-isopropylacrylamide (Nipam). The oil and water phases were emulsified together with a Brandson 3210 ultrasonic bath at 30°C at the solution level for 15 minutes. The polymerization was carried out at 60°C for 2 hours under inert atmosphere. After that time, the PNipam shells were fully formed. The microcapsules were recovered, cleaned and concentrated by simple sedimentation.

Example 4. Silver-silica microcapsules.

0.2 g of PEOS was diluted in 1 mL of toluene. The water phase of the emulsion (5 mL) contains the Ag NPs (Ag wt% =0.2) with 150 μ L of HCl and 0.1 mL of butanol. The oil and water phases were emulsified together with a Brandson 3210 ultrasonic bath at 30°C for 15 minutes. After 3 days, the silica shell was fully formed. The microcapsules were recovered, cleaned and concentrated by simple sedimentation.

Example 5. PVA film preparation and stretching.

A solution of 10 wt% PVA in water was prepared and degassed. Then 1 g of the microcapsules made according to Example 1 were concentrated and dispersed in the PVA solution under gentle stirring to avoid the formation of air bubbles, which could make the final film inhomogeneous and more fragile. The final polymer-microcapsule solution was left to dry at room temperature for several days.

During the drying step, the silica crust provided blue microcapsules with enough rigidity to retain their spherical shape. Their intrinsic color confers to the resulting film a slight blue color. After drying, a uni-axial stretching of the polymer film is then performed. Stretching of the dried film was achieved using a vise upon mild heating of the film. A magnified view of the elongated polymer film displays pink stretched microcapsules. This color change is noticeable by naked eye on the film. It is

attributed to the deformation of the spherical microcapsules into an ellipsoid-like shape along with the increase of the interparticle distance. Indeed, during this anisotropic deformation, the distance between the Au NPs increases, thus entailing a color change. Further confirmation was providing by recording the film extinction curve by spectrophotometry for each stretching step. The maximum of each extinction curve, $\lambda_{\max}$, was plotted as a function of different elongations of the film, L_f/L_0 , where L_f is the length of the film after each stretching step and L_0 is the initial length of the film before mechanical deformation. FIG. 4 shows the position of the plasmonic peak maximum as the polymer was elongated, with the inset showing the UV response as a function of film elongation (the extinction is normalized at 400 nm). Results showed that for small elongations ($1 < L_f/L_0 < 1.3$), the film absorbs light in the red/infrared region ($\lambda \sim 850 - 900$ nm) of the visible spectrum, thus the film appears blue. As the amplitude of the elongations increased, the optical properties of the microcapsules embedded in the film change and the extinction is shifted towards the blue/green visible region of the spectrum ($\lambda \sim 540$ nm), thus the film appears red. $\lambda_{\max}$ reaches a plateau when the absorption of the stretched microcapsules ($\lambda \sim 540$ nm) is close to the absorption of the free Au NPs in solution ($\lambda = 536$ nm, see FIG. 1).

Example 6. PVA film impact and perforation tests

The optical response of PVA films made according to Example 5 was further tested for two other mechanical deformations, namely impact and perforation tests.

For the impact tests, a 0.91 kg weight is dropped from several different heights on top of the film. The extinction was recorded for each impact height and the maximum of the extinction peak is plotted versus the potential energy of the weight at impact. The plot is shown in FIG. 5. The graph shows that as the potential energy of the weight at impact increases, the extinction of the plasmonic peak shifts from the red/infrared region ($\lambda \sim 970$ nm) to the green/blue visible region of the spectrum ($\lambda \sim 540$ nm). Interestingly, at low impact energy, the analysis using the spectrophotometer exhibits a very small shift of the maximum of the plasmonic peak that cannot be detected by the human eye (circled in black on film at top of FIG. 5).

At higher impact energy, the human eye is capable of seeing the area of impact by noticing a red spot at the place of the impact zone as shown in the image at the bottom of FIG. 5.

- 5 The second test relates to perforating the film. As a hole was poked in the film, the polymer film underwent very large strains in the vicinity of the hole. Observations under an optical microscope showed that the microcapsules lying far from the hole remain undisturbed and spherical and thus displayed a blue color, whereas those located close to the edge of the perforation were likely deformed into an ellipsoidal
10 shape as indicated by their purple and/or pink color.

The PVA film comprising the microcapsules described herein were sensitive enough to enable the detection of a color change by spectrophotometry arising from very tiny deformations not detectable by the eye. The underlying industrial potential
15 applications are numerous. For instance, such mechanochromic shells mixed in paints, fabrics or polymers could be used to gather local and/or global information about the material they have been embedded in; such as the early detection of cracks or bullet/rock impact locations.

20 **Example 7. Acrylate latex film preparation and stretching.**

0.25 mL of the gold-acrylate microcapsules made according to Example 2 was mixed with 1.5mL of a water emulsion of commercially-available acrylate latex. The obtained mixture was then bar-coated on a plastic substrate and left to dry at room
25 temperature. After drying, the film was peeled off of the substrate.

The film was stretched and a change in color of the microcapsules was observed. The change of color was reversible when the stress was released.

Example 8. Gold/silver-silica microcapsules

Mixtures of gold and silver NPs were prepared by mixing gold and silver NPs that were prepared separately. Mixtures of gold and silver NPs having different proportions of gold nanoparticles and silver nanoparticles ($[Au^0]/[Ag^0] = 1/100, 50/50, 75/25, \text{ and } 100/0$) were then used to prepare microcapsules using the procedure described in Example 1.

This example shows that the synthesis method described herein is versatile as microcapsules comprising one or more types of nanoparticles embedded in silica shell can be easily synthesized. It is also possible to reduce different metal salts into nanoparticles at high concentration in metal salt.

It was found that the optical response of the final gold-silica microcapsules can be finely tuned with the ratio gold/silver NPs and that, therefore, the color of the microcapsules can be tuned by changing the ratio of gold/silver NPs in the microcapsules.

Example 9. Antibacterial properties of microcapsules

The antibacterial properties of the silver-silica (AgSi) microcapsules made according to Example 4 were investigated in a disk diffusion assay and a planktonic assay. In this example, the silver NPs were obtained by reduction of silver nitrate in ethylene glycol.

In the disk diffusion assay, wafers impregnated with the AgSi microcapsules were tested in both spread agar plates and overlay agar plates (broth used was 10^9 *E. coli* in TSB). The wafers were impregnated by dropping a dispersion containing the AgSi microcapsules on one side of the wafer (designated "top side"). The wafers were placed either disk up (top side up) or disk down (top side down) in the spread and overlay plates.

The disk diffusion experiments revealed that the AgSi microcapsules were capable of inhibiting the growth of *E. coli* in the plates.

In the planktonic assay, 10^8 *E. coli* in TSB broth was diluted to obtain 10^6 *E. coli* in TSB, to which the AgSi microcapsules concentrated and dispersed in DI water at pH~5 were added. Following shaking overnight, the mixture was diluted to obtain 10^{-4} , 10^{-5} , and 10^{-6} dilutions. 10 droplets of 10- μ L aliquots of each dilution was plated and incubated overnight. Bacteria were then counted.

- 10 The planktonic assay revealed that the AgSi microcapsules were capable of inhibiting the growth of *E. coli* in liquid medium.

Without wishing to be bound by theory, it is believed that the release of silver ions from the AgSi microcapsule shell in the vicinity of the bacteria result in deleterious effects on the bacteria, thus inhibiting their growth. The inventive AgSi microcapsules provide an efficient way to deliver antibacterial silver because they are easy to synthesize (2 steps), their spherical shape presents increased antibacterial surface, and are environmentally friendly due to easy recovery by physical methods, such as filtration or sedimentation.

Example 10. Detection of solvent by gold acrylate microcapsules

The gold-acrylate microcapsules made according to Example 2 were exposed to an excess of toluene. Before exposure to the toluene solvent, the gold-acrylate microcapsules exhibited a dark blue color. However, upon exposure to toluene, the dark blue microcapsules turned a blue color and then a purple-pink color over time.

The foregoing result shows that the inventive microcapsules may be used, for example, in visual detection of oil/solvent in mixture, visual detection of trapping/oil-solvent recovery, and kitchen grease trapping/detection in coatings.

When the gold-acrylate microcapsules made according to Example 2 were exposed to moisture, as during incorporation into PVA, it was observed that the microcapsules exhibit a change in color upon hydration.

- 5 Thus, the foregoing result shows that the inventive microcapsules may be used, for example, as a visual humidity sensor.

Example 11. Detection of pH

- 10 Gold-acrylate microcapsules were made according to Example 2 and suspended in an acidic solution. The acidic solution (pH ~1), containing the inventive gold-acrylate microcapsules, was observed under an optical microscope. At acidic pH, the gold-acrylate microcapsules appeared dark blue color in color. NaOH was then added to the acidic solution such that the NaOH was allowed to diffuse through the solution.
- 15 As the NaOH diffused through the solution, the color of the gold-acrylate microcapsules changed from dark blue to purple-pink, indicating a change in pH. The color of the gold-acrylate microcapsules was purple-pink in areas where the solution was basic while the color of the gold-acrylate microcapsules was dark blue in areas where the solution was still acidic. This observation indicates that the
- 20 inventive microcapsules are suitable for detecting local pH and local changes in pH.

- To investigate whether the process is reversible, the solution containing the inventive microcapsules was made completely basic (pH ~14). In basic solution, the microcapsules appeared purple-pink. HCl was added and allowed to diffuse through
- 25 the solution. The color of the gold-acrylate microcapsules was dark blue in areas where the solution was acidic while the color of the gold-acrylate microcapsules was purple-pink in areas where the solution was still basic. This result indicates that the color change due to pH is reversible. The pH can be increased and decreased over many cycles with the result that the color of the gold-acrylate microcapsules
- 30 alternates between dark blue and purple-pink.

WHAT IS CLAIMED IS:

1. A microcapsule comprising:
 - a hollow or non-hollow core; and
 - a rigid or flexible shell, wherein a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, is embedded in said shell.
2. The microcapsule according to claim 1, wherein each metallic nanoparticle comprises at least one transition metal, typically gold or silver
3. The microcapsule according to claim 1 or 2, wherein the plurality of metallic nanoparticles comprises nanoparticles having the same metal, typically the same transition metal.
4. The microcapsule according to claim 1 or 2, wherein the plurality of metallic nanoparticles comprises nanoparticles having different metals, typically different transition metals, more typically gold and silver.
5. The microcapsule according to any one of claims 1-4, wherein each metallic nanoparticle comprises an organic capping agent, typically a polyvinylpyrrolidone, more typically poly(diallyldimethylammonium-nitrate-co-1-vinylpyrrolidone).
6. The microcapsule according to any one of claims 1-5, wherein mean diameter of the metallic nanoparticles is about 1 nm to about 100 nm, typically from about 1 to about 60 nm, more typically about 20 to about 60 nm, most typically about 40 nm.
7. The microcapsule according to any one of claims 1-6, wherein the surface area covered by nanoparticles is from 0% to about 90%, typically from about 1% to 90%, more typically from about 50% to 90%.

8. The microcapsule according to any one of claims 1-7, wherein the shell of the microcapsule is rigid, typically comprising silicon, more typically comprising silicon dioxide.
9. The microcapsule according to any one of claims 1-7, wherein the shell of the microcapsule is flexible, typically comprising a polymer, more typically a homopolymer or copolymer derived from ethylenically-unsaturated monomers.
10. The microcapsule according to any one of claims 1-9, wherein the core of the microcapsule is non-hollow, typically comprising liquid, more typically comprising a hydrophobic liquid.
11. The microcapsule according to claim 10, wherein the core of the microcapsule further comprises an active agent.
12. A process for manufacturing microcapsules according to any one of claims 1-11, the process comprising:
 - a) forming an emulsion by mixing a first mixture comprising a first solvent and a plurality of metallic nanoparticles, wherein each metallic nanoparticle is a solid nanoparticle free of transition metal oxide or a core/shell nanoparticle, and a second mixture comprising a second solvent, immiscible with the first solvent,
wherein the first and/or second mixtures comprise one or more shell precursor compounds;
 - b) reacting the precursor compounds so as to form a rigid or flexible shell, thereby forming the microcapsules;
 - c) recovering the microcapsules formed in step b).
13. The process according to claim 12, further comprising drying the microcapsules recovered in step c).

14. The process according to claim 12 or 13, wherein the first solvent is an aqueous solvent, typically water.
15. The process according to any one of claims 12-14, wherein the second solvent is an organic solvent, typically hydrocarbon, more typically C1-20 straight, branched, or cyclic alkane or C1-20 aromatic hydrocarbon, most typically toluene.
16. The process according to any one of claims 12-15, wherein reacting the precursor compounds in step b) comprises a radical polymerization reaction or a polycondensation reaction between the precursor compounds.
17. The process according to any one of claims 12-16, wherein the first mixture further comprises an acid.
18. A film comprising a polymer matrix and a plurality of microcapsules according to any one of claims 1-11 or a plurality of microcapsules made according to the process of any one of claims 12-17.
19. A method for detecting an external stimulus, the method comprising:
- a) incorporating a plurality of microcapsules according to any one of claims 1-11 or a plurality of microcapsules made according to the process of any one of claims 12-17 into a substrate;
 - b) exposing the substrate to an external stimulus; and
 - c) observing a change in extinction or a change in optical fluorescence.
20. The method according to claim 19, wherein the external stimulus is a mechanical deformation, a change in temperature; an adsorption of oil, organic solvent, and/or water; or a change in pH.
21. A method for inhibiting the growth of a microbe, the method comprising contacting the microbe with a plurality of microcapsules according to any one of

claims 1-11 or a plurality of microcapsules made according to the process of any one of claims 12-17, thereby inhibiting the growth of the microbe.

22. The method according to claim 21, wherein metal ions, typically silver ions, are released from the microcapsule shell.

23. The method according to claim 21, wherein the microbe is bacteria, algae, or plankton.

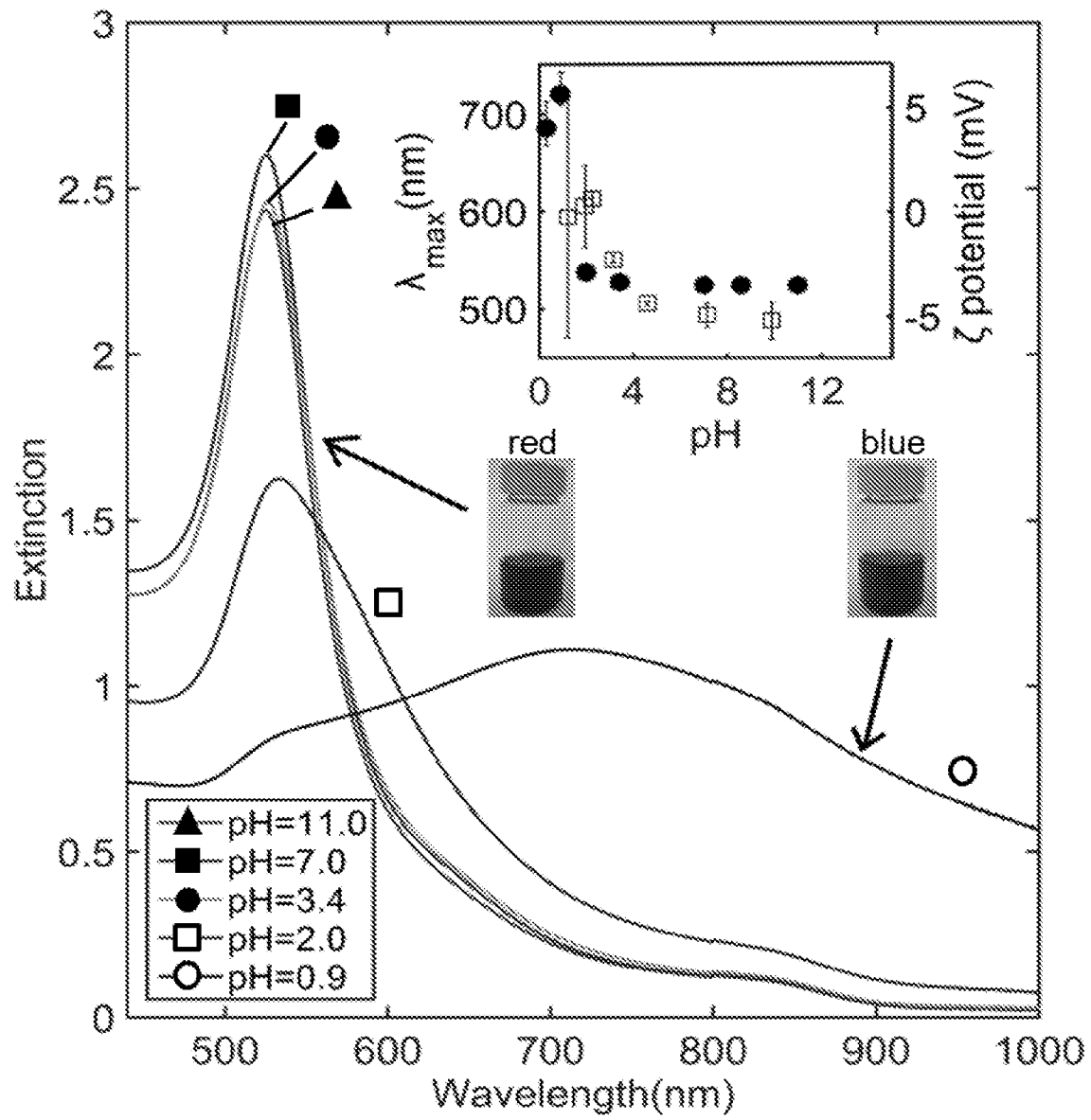


FIG. 1

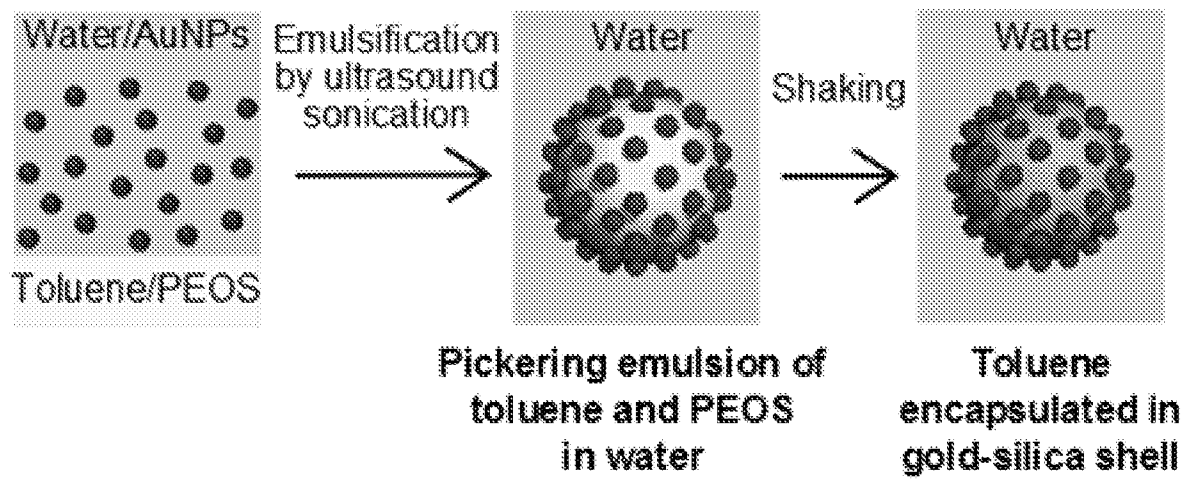


FIG. 2

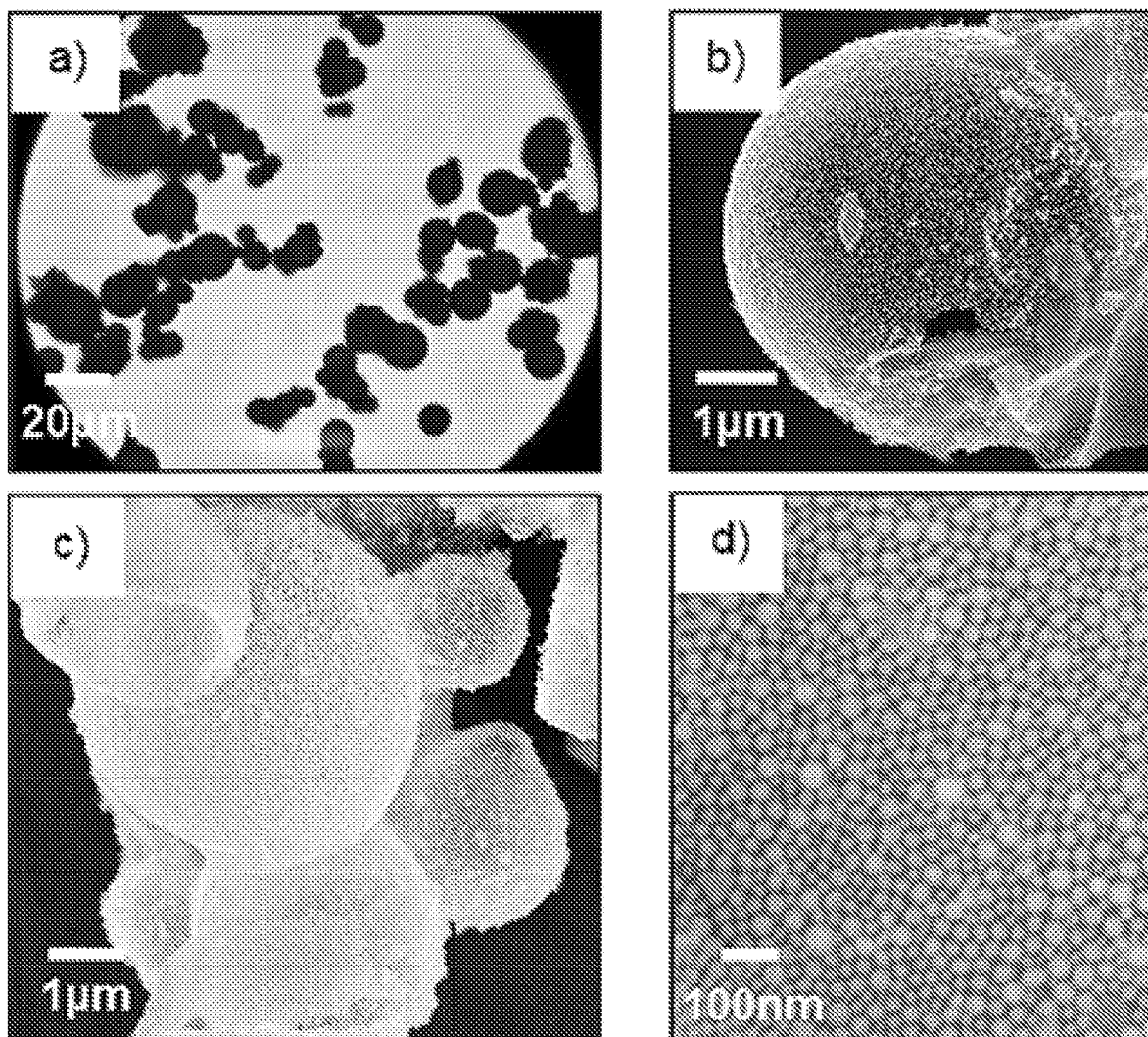


FIG. 3

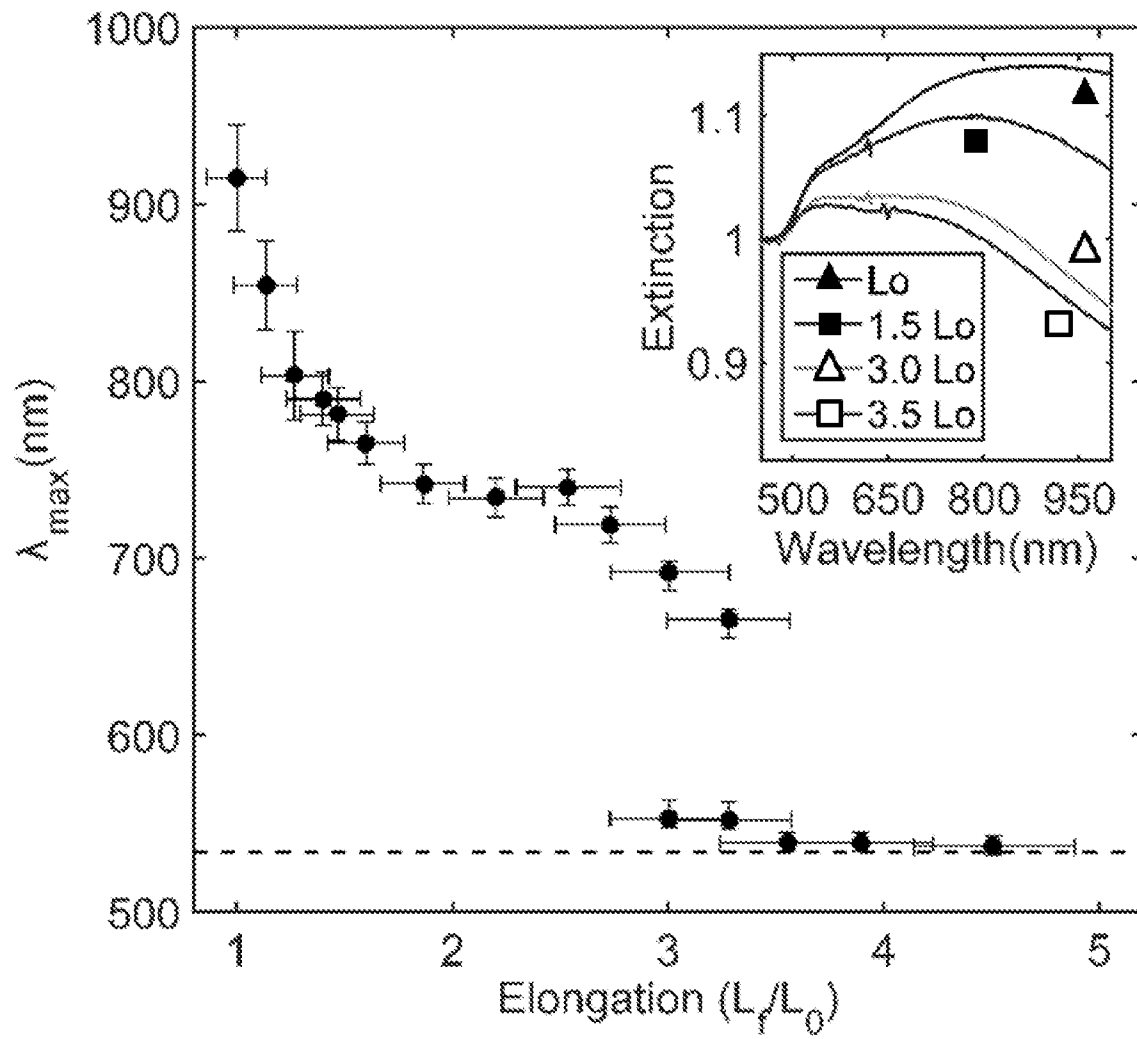


FIG. 4

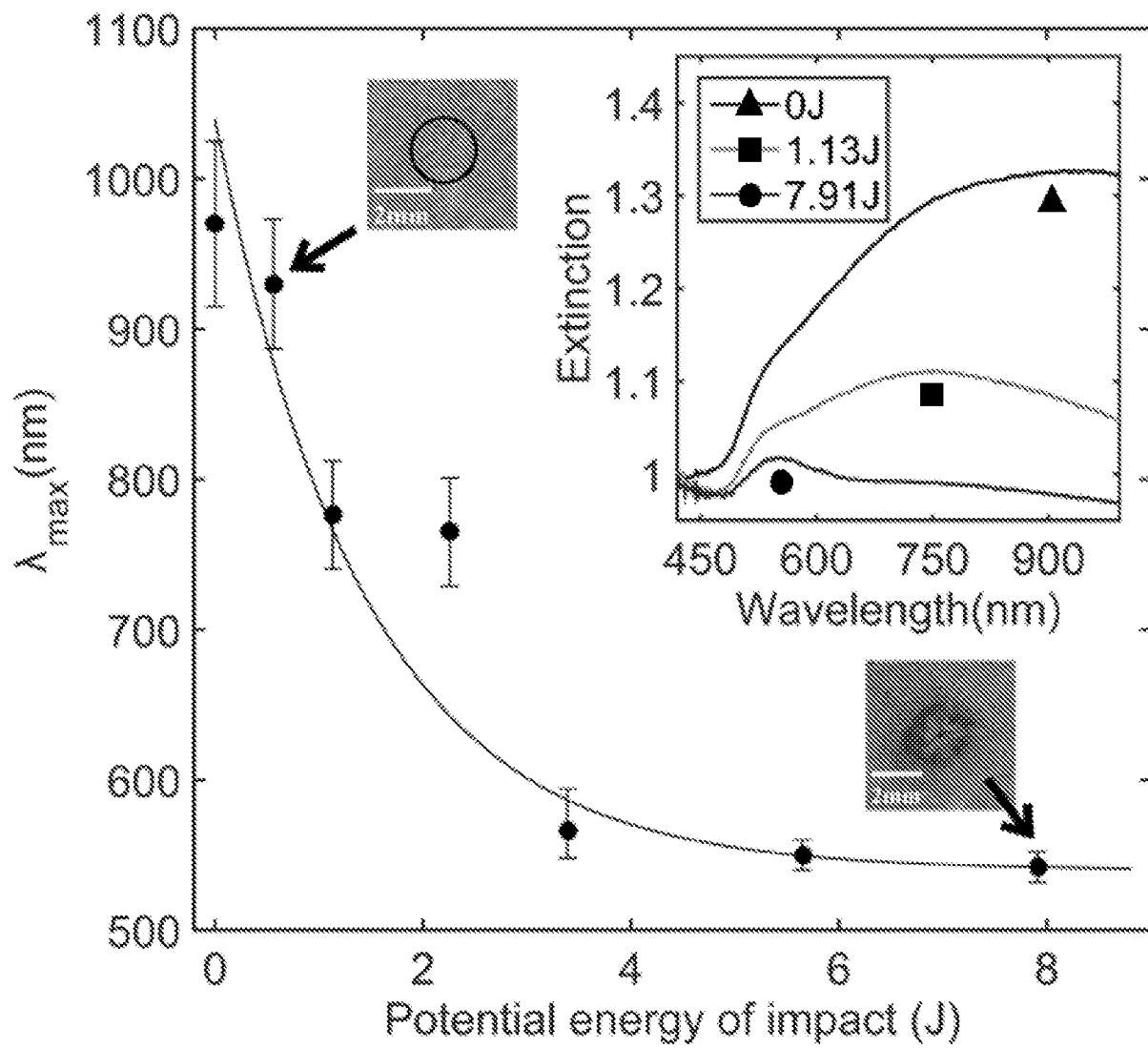


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2018/000461

A. CLASSIFICATION OF SUBJECT MATTER INV. B01J13/16 A61Q19/00 B01J13/18 B82Y30/00 C11D3/50 A23L27/00 ADD. 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) B01J A61Q B82Y C11D A23L 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) EPO-Internal, WPI Data														
C. DOCUMENTS CONSIDERED TO BE RELEVANT <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>X</td> <td>WO 2008/009216 A1 (NANO SPORTS TECHNOLOGIES LTD [CN]; LI YI [CN]; NEWTON EDWARD [CN]; SON) 24 January 2008 (2008-01-24) figures 2b, 8; examples 1, 3 -----</td> <td>1-23</td> </tr> <tr> <td>X</td> <td>US 2015/079504 A1 (FARRUGIA VALERIE M [CA]) 19 March 2015 (2015-03-19) paragraph [0049] - paragraph [0053]; figures 3, 4a; examples 1,2 -----</td> <td>1-18, 21-23 19,20</td> </tr> <tr> <td>A</td> <td>-/--</td> <td></td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X	WO 2008/009216 A1 (NANO SPORTS TECHNOLOGIES LTD [CN]; LI YI [CN]; NEWTON EDWARD [CN]; SON) 24 January 2008 (2008-01-24) figures 2b, 8; examples 1, 3 -----	1-23	X	US 2015/079504 A1 (FARRUGIA VALERIE M [CA]) 19 March 2015 (2015-03-19) paragraph [0049] - paragraph [0053]; figures 3, 4a; examples 1,2 -----	1-18, 21-23 19,20	A	-/--	
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X	WO 2008/009216 A1 (NANO SPORTS TECHNOLOGIES LTD [CN]; LI YI [CN]; NEWTON EDWARD [CN]; SON) 24 January 2008 (2008-01-24) figures 2b, 8; examples 1, 3 -----	1-23												
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A	-/--													
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.														
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Date of the actual completion of the international search 30 August 2018		Date of mailing of the international search report 06/09/2018												
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Mc Donnell, Shane												

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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X	O. KREFT ET AL: "Remote Control of Bioreactions in Multicompartment Capsules", ADVANCED MATERIALS, vol. 19, no. 20, 17 October 2007 (2007-10-17), pages 3142-3145, XP055503155, DE ISSN: 0935-9648, DOI: 10.1002/adma.200701977	1-11, 18-20
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A	examples 1,11	12-17, 19,20
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A	[0032, 0065]; claim 1	19-23
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Information on patent family members

International application No

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