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**Fears et al.**

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(54) **FABRICATION OF NANOPOROUS AEROGELS VIA FREEZE SUBSTITUTION OF NANOWIRE SUSPENSIONS**

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 141 days.

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(58) **Field of Classification Search**  
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See application file for complete search history.

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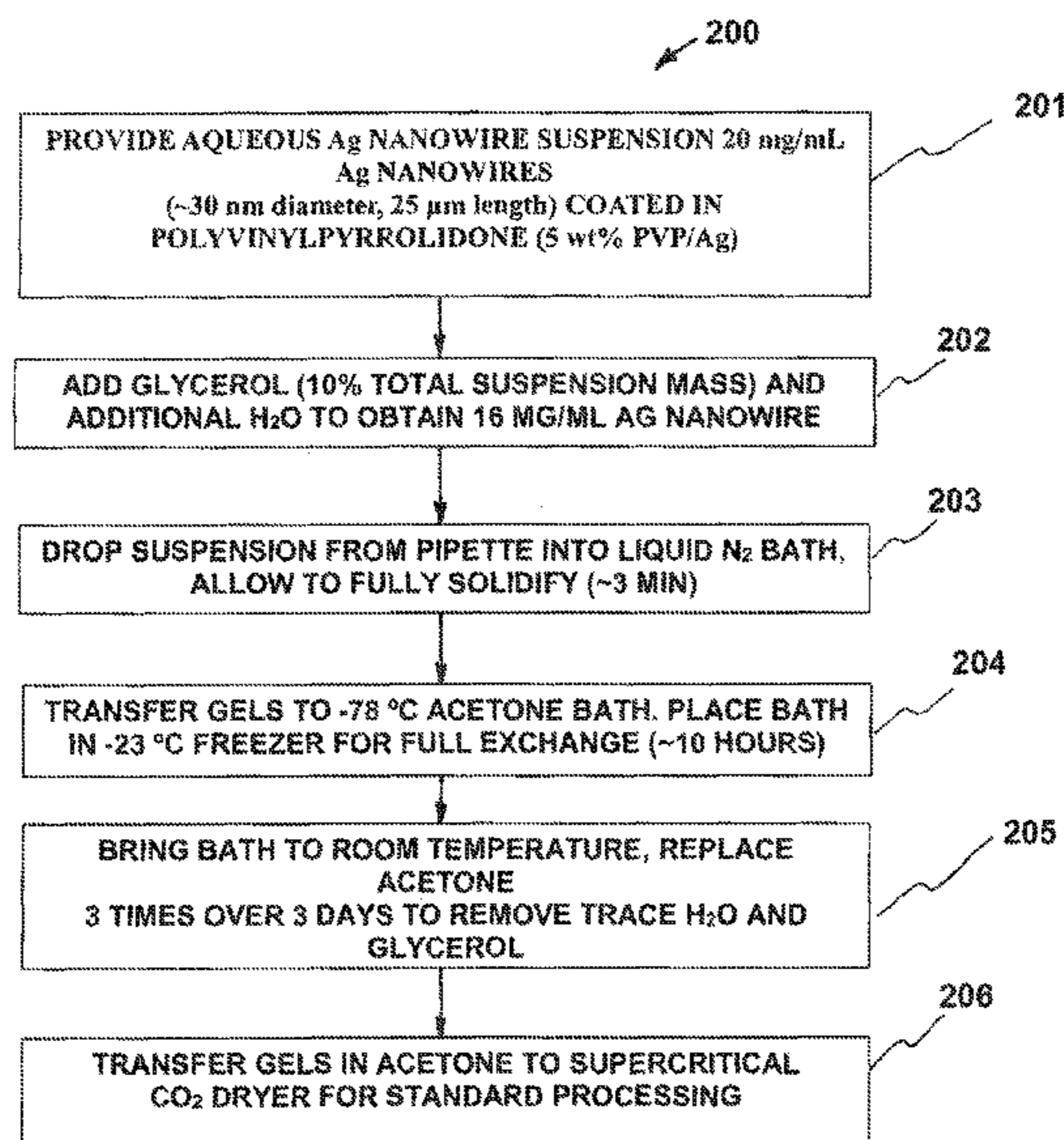
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(57) **ABSTRACT**

A method of making a nanoporous aerogel includes the steps of providing nanowire suspensions, freeze casting the nanowire suspensions to produce freeze-cast gels, extracting the frozen medium from the freeze-cast gels by freeze-substitution with a solvent to produce wet gels, modifying or functionalizing the wet gels as needed, and drying the wet gels to produce a nanoporous aerogel.

13 Claims, 7 Drawing Sheets



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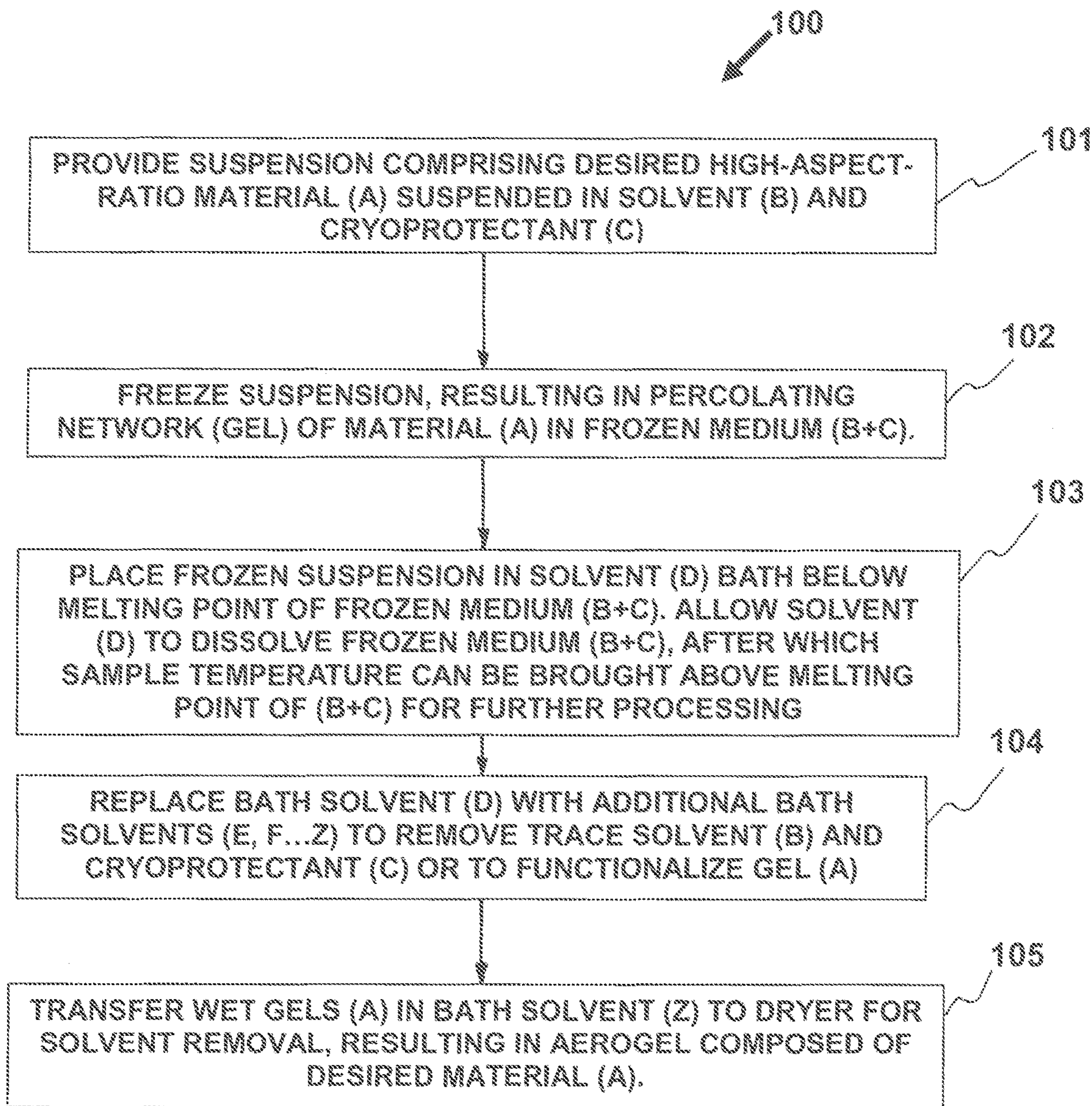


FIG. 1

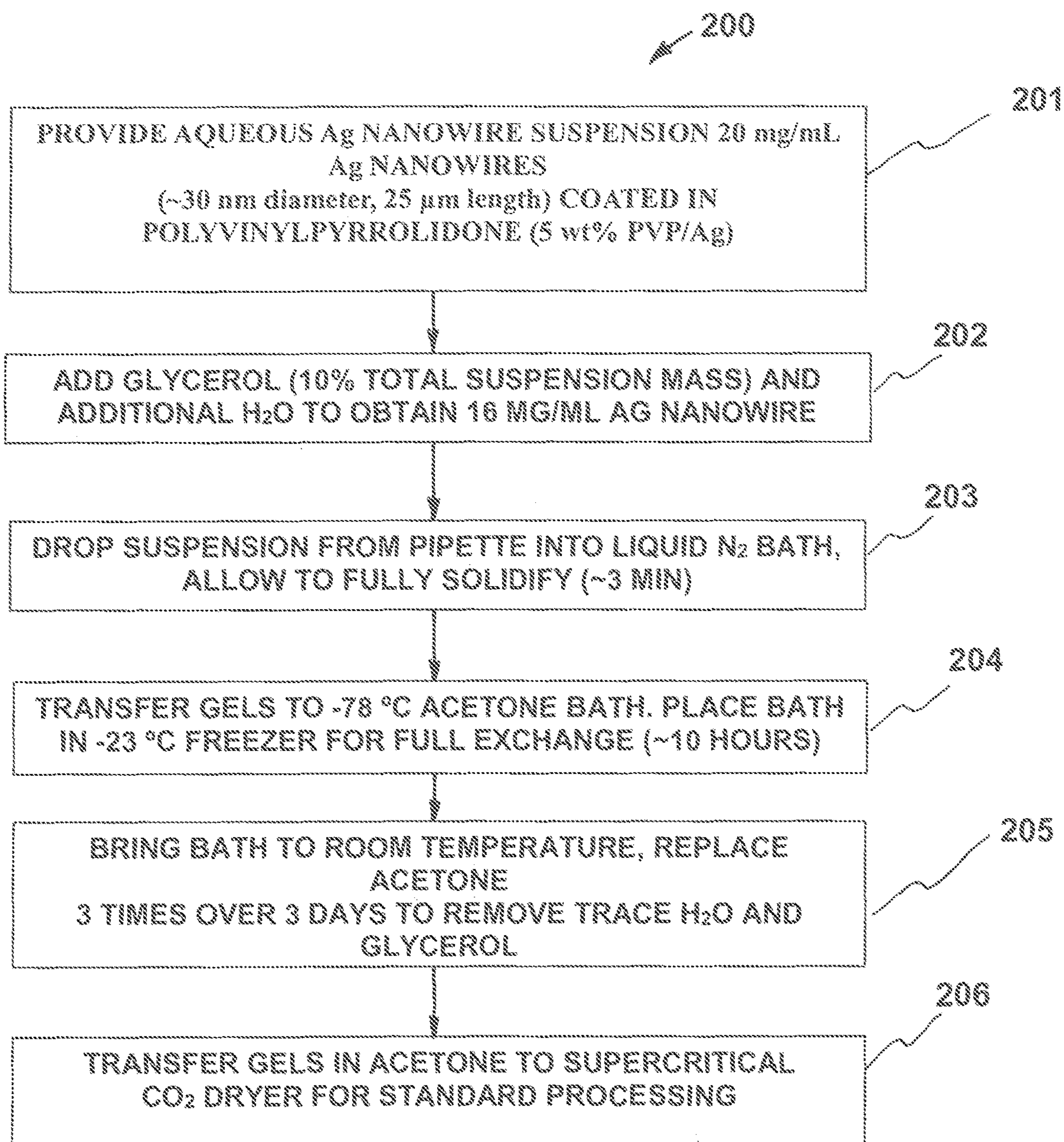


FIG. 2

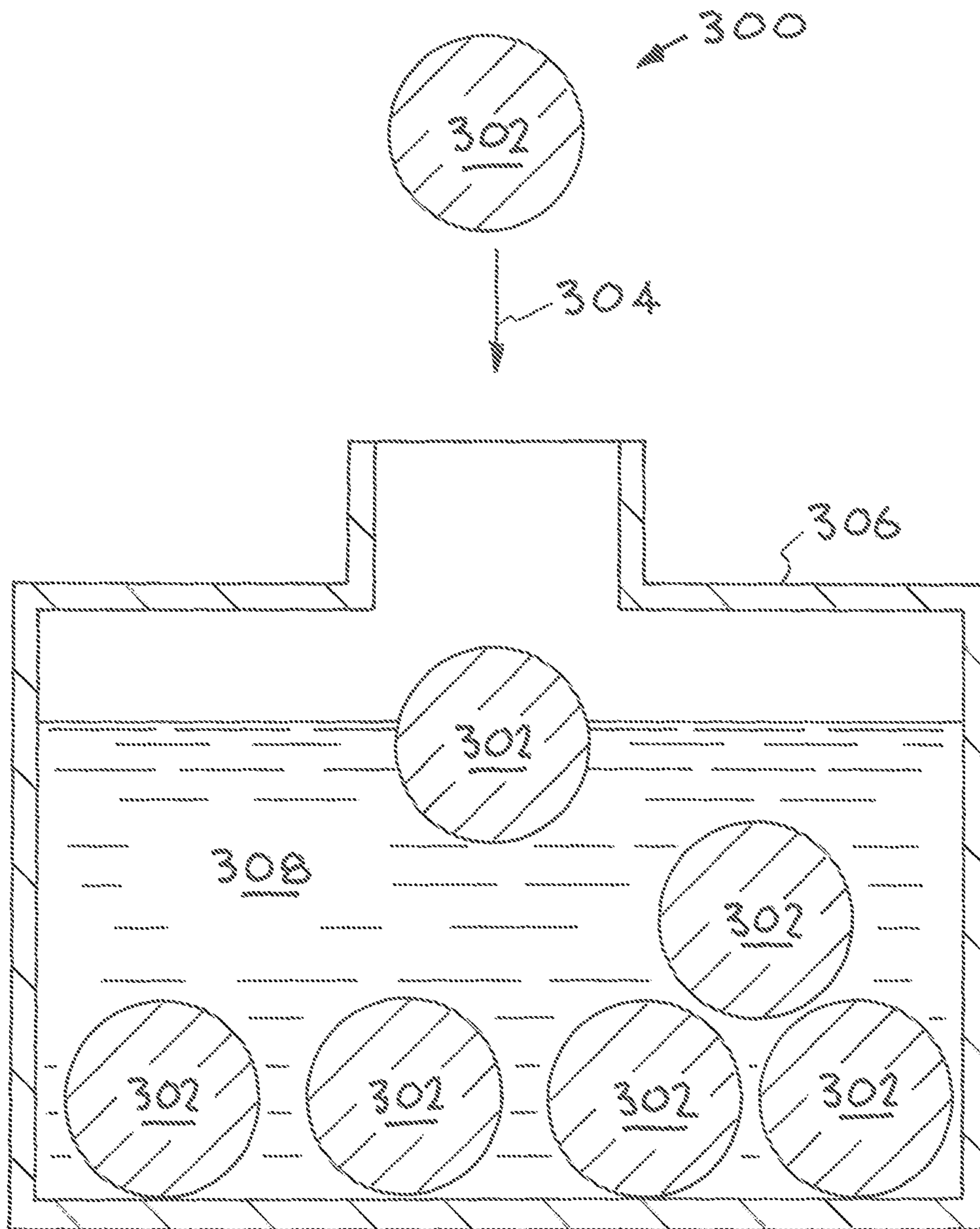


FIG. 3

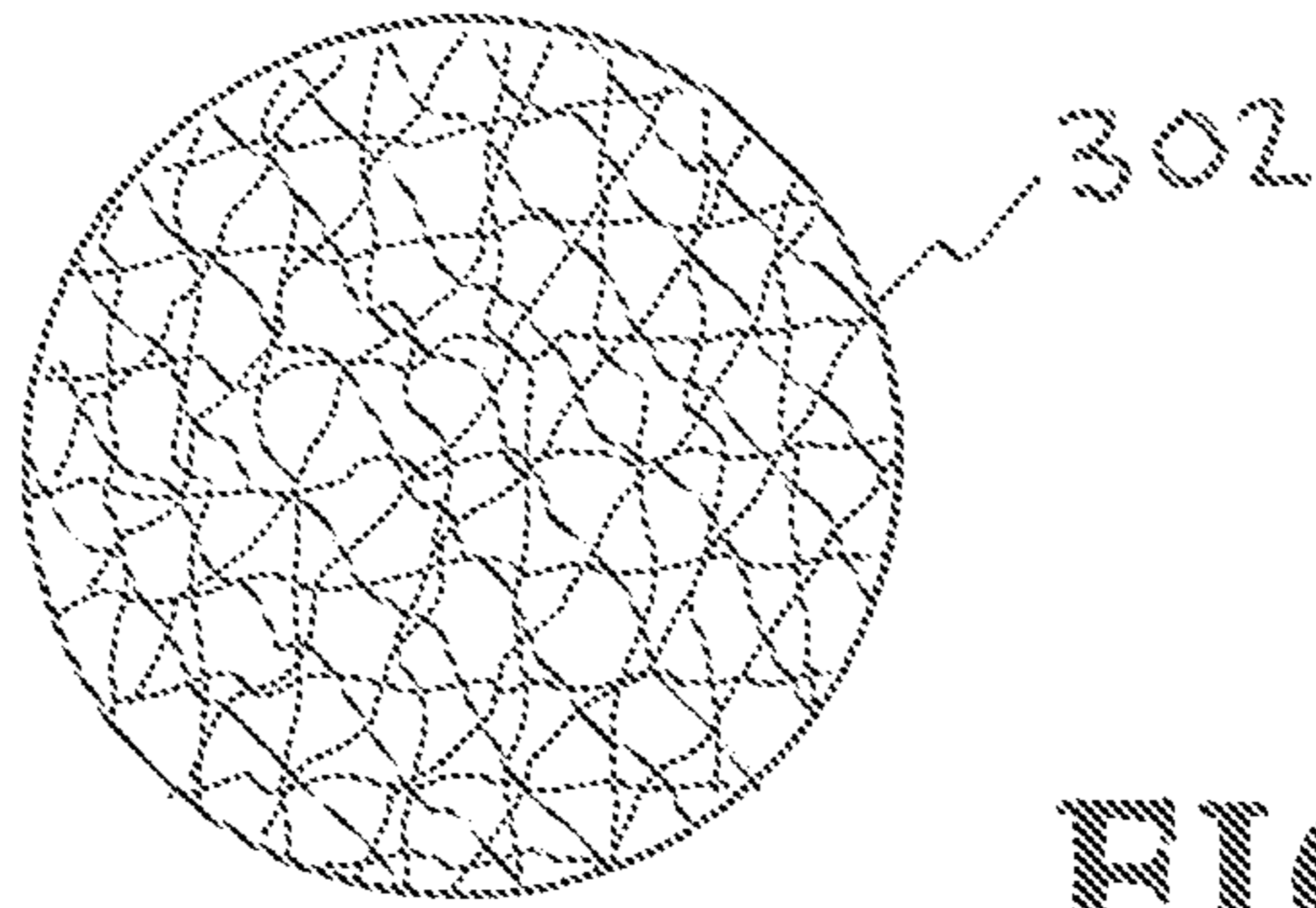


FIG. 4

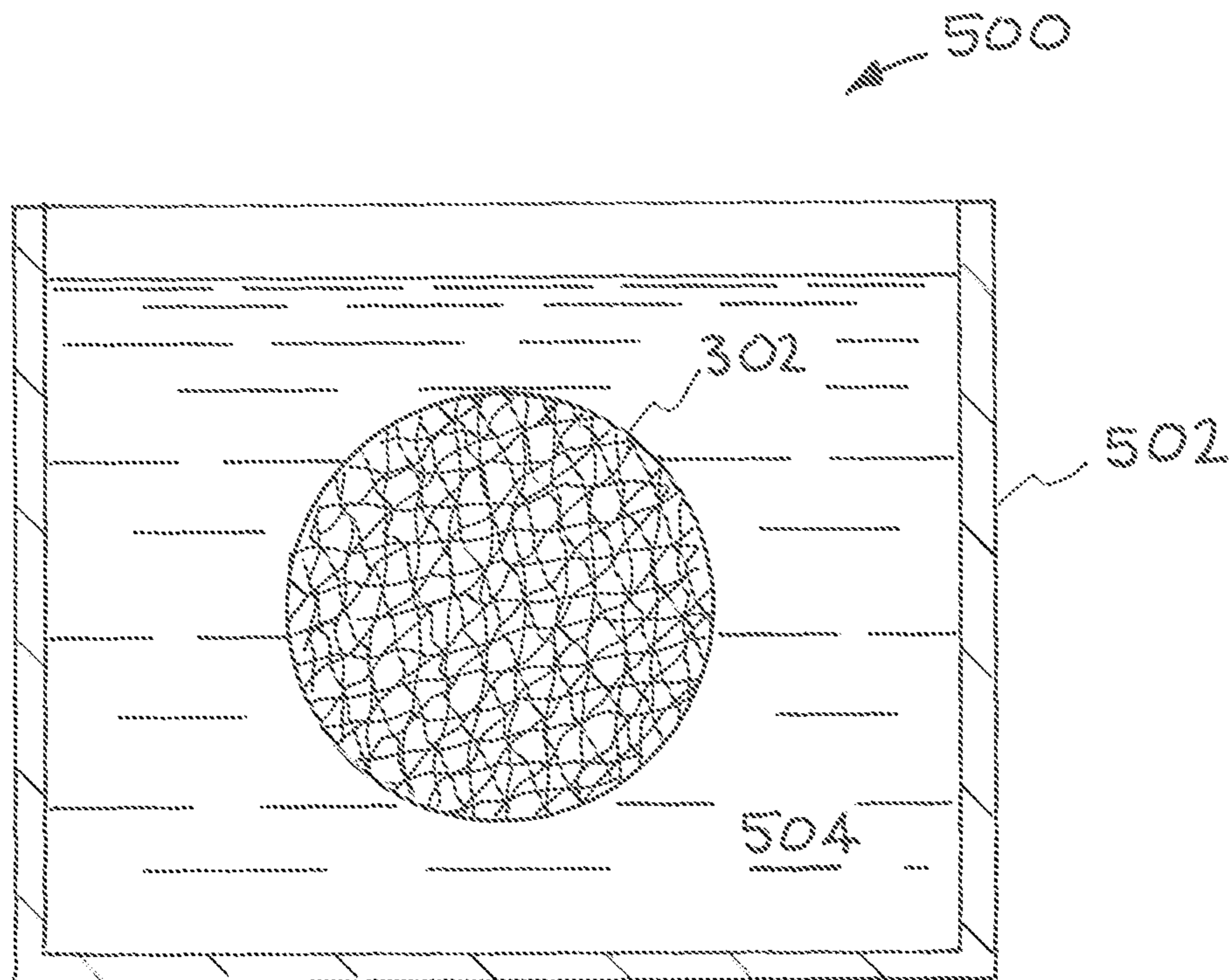


FIG. 5

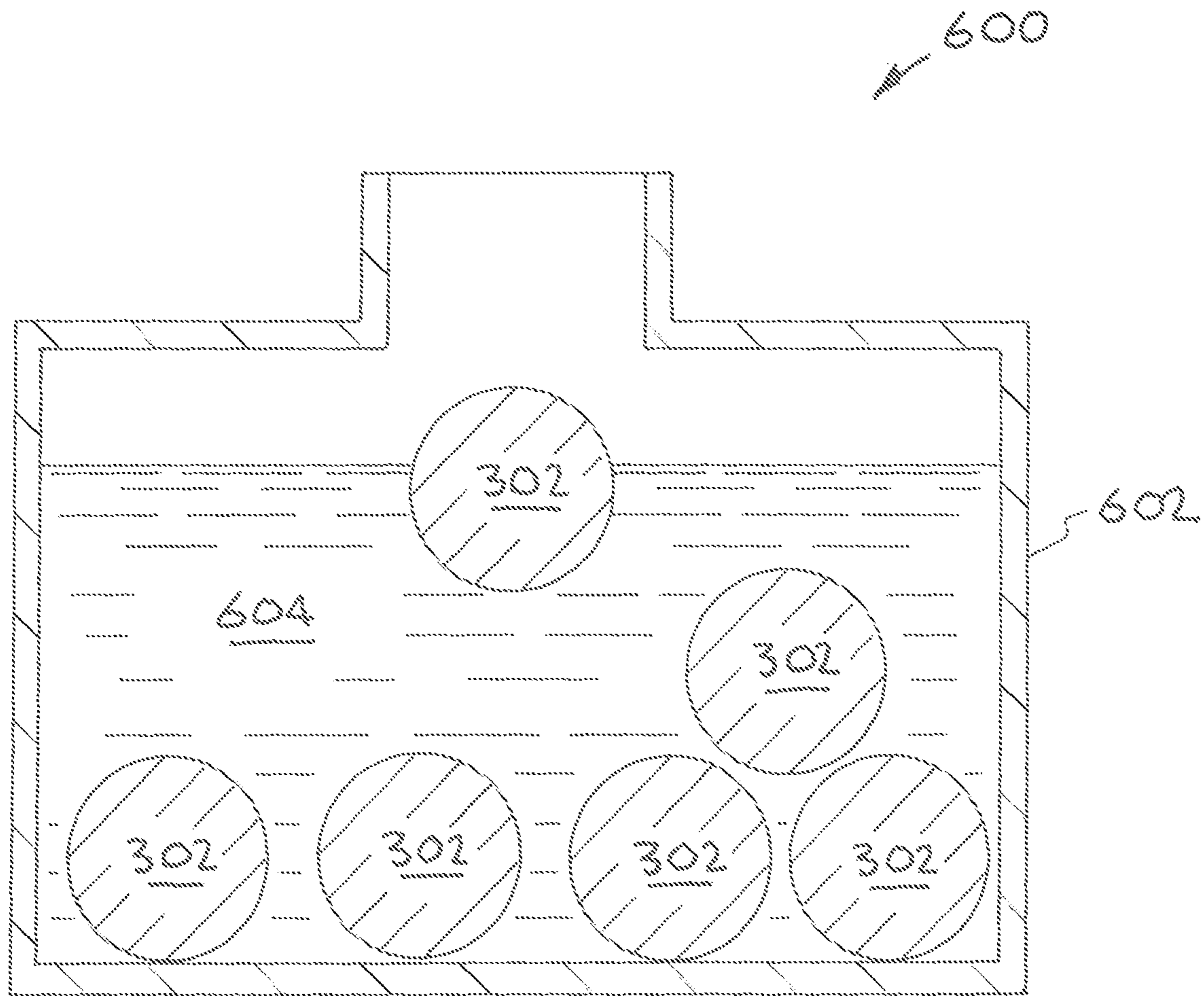


FIG. 6

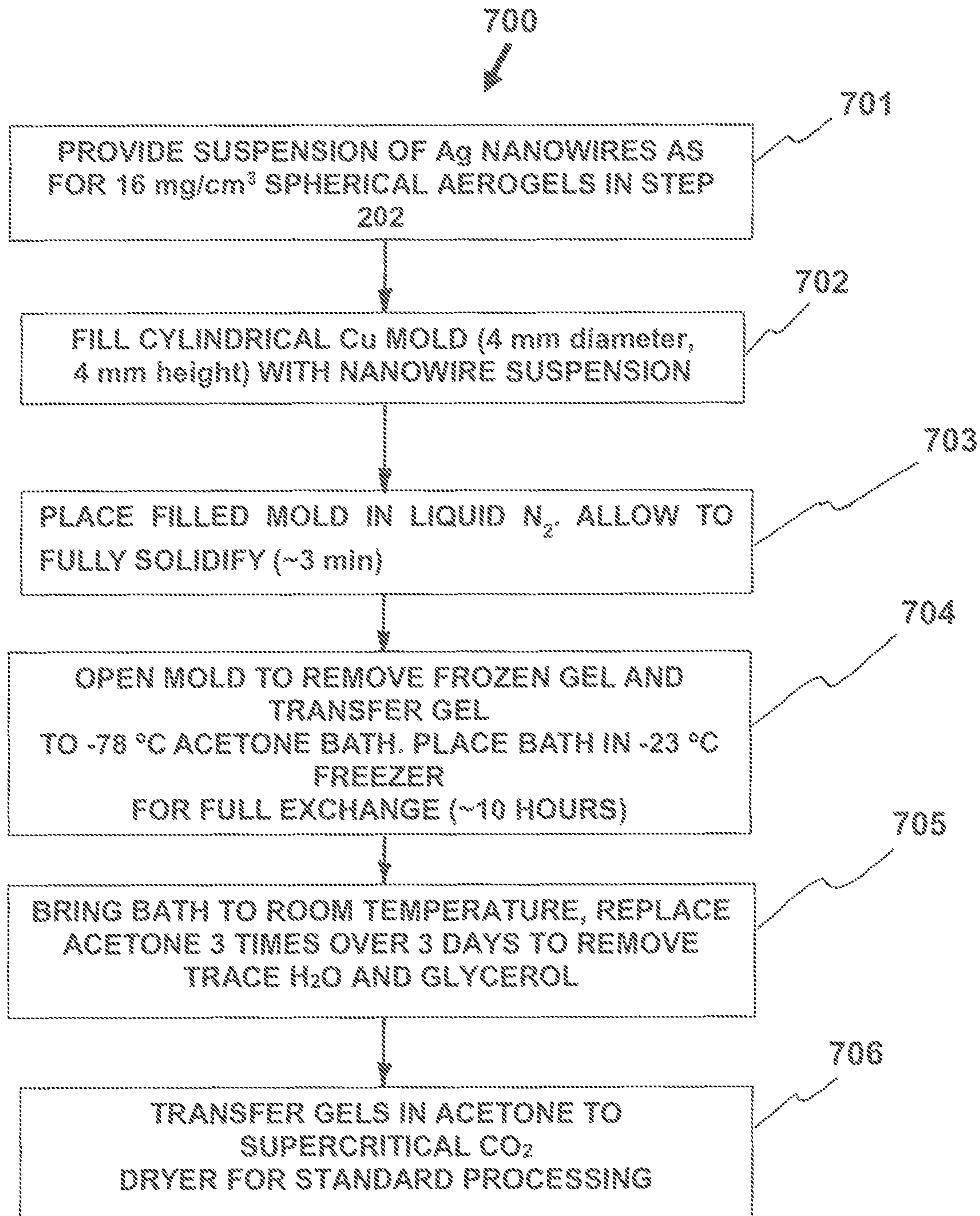


FIG. 7



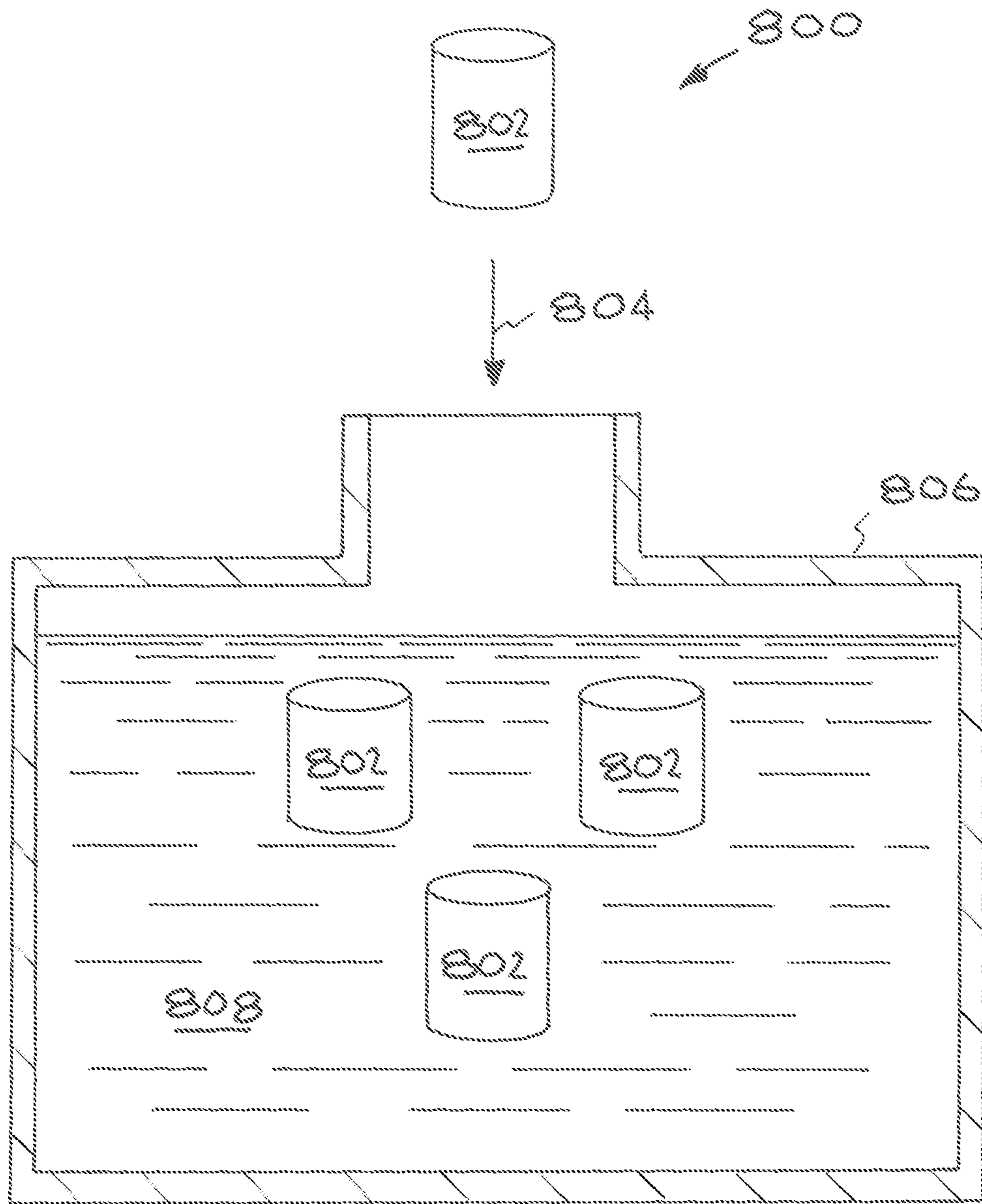


FIG. 8

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**FABRICATION OF NANOPOROUS  
AEROGELS VIA FREEZE SUBSTITUTION  
OF NANOWIRE SUSPENSIONS**

STATEMENT AS TO RIGHTS TO  
APPLICATIONS MADE UNDER FEDERALLY  
SPONSORED RESEARCH AND  
DEVELOPMENT

The United States Government has rights in this applica-  
tion pursuant to Contract No. DE-AC52-07NA27344  
between the United States Department of Energy and Law-  
rence Livermore National Security, LLC for the operation of  
Lawrence Livermore National Laboratory.

BACKGROUND

Field of Endeavor

The present application relates to nanowire suspensions  
and more particularly to fabrication of nanoporous aerogels  
via freeze substitution of nanowire suspensions.

State of Technology

This section provides background information related to  
the present disclosure which is not necessarily prior art.

U.S. Pat. No. 6,326,030 for a method for preparing a  
non-fibrous porous material issued Dec. 4, 2001 provides the  
state of technology information quoted below.

“A method for preparing a non-fibrous porous material  
essentially consisting of one or more hydrophilic polymers  
and/or pharmaceutical medicaments comprising forming an  
aqueous solution, sol or gel comprising one or more hydro-  
philic polymers and/or pharmaceutical medicaments, freez-  
ing the solution, sol or gel and extracting the frozen water  
selectively using a hydrophilic organic solvent being mis-  
cible with water at a temperature below 5° C. at which  
temperature the solvent is not able to dissolve the frozen  
solutes, leaving the non-fibrous material in a solid, porous  
form.”

SUMMARY

Features and advantages of the disclosed apparatus, sys-  
tems, and methods will become apparent from the following  
description. Applicant is providing this description, which  
includes drawings and examples of specific embodiments, to  
give a broad representation of the apparatus, systems, and  
methods. Various changes and modifications within the  
spirit and scope of the application will become apparent to  
those skilled in the art from this description and by practice  
of the apparatus, systems, and methods. The scope of the  
apparatus, systems, and methods is not intended to be  
limited to the particular forms disclosed, and the application  
covers all modifications, equivalents, and alternatives falling  
within the spirit and scope of the apparatus, systems, and  
methods as defined by the claims.

New methods are needed to produce nanoporous materi-  
als with new elemental compositions, new form factors, and  
reduced costs. Inventors' apparatus, systems, and methods  
utilize freeze-casting of nanowire suspensions to form  
freeze-cast gels followed by extraction of the frozen medium  
by freeze substitution with an appropriate solvent. The  
solvent in resultant wet gels is removed in the final drying  
step. In this disclosure, “nanowire” can refer to any high-  
aspect-ratio object such as elongated nanoparticles, fibers,

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and objects with more complex geometries. This method  
allows for the use of suspension media not amenable to  
conventional freeze drying and of nonvolatile solvent com-  
positions that are desirable to achieve superior foam mor-  
phologies and to reduce sample deformation and fracture  
during freeze-casting. In contrast to the limitations of the  
conventional freeze-drying method, in the method disclosed  
in this invention, freeze-cast gels and wet gels are not  
subject to damaging gravitational forces during freeze sub-  
stitution and solvent drying steps. Microstructural stresses  
are reduced during freeze-substitution as compared to freeze  
drying, resulting in negligible sample shrinkage and excel-  
lent mold replication. The freeze-substitution stage also  
allows for chemical modification and functionalization of  
the gels (such as ligand exchange) prior to drying. Such  
chemical modification and functionalization are not possible  
in traditionally freeze-dried gels.

Inventors' apparatus, systems, and methods include the  
following steps: providing nanowire suspensions, freeze  
casting the nanowire suspensions to produce freeze-cast  
gels, extracting the frozen medium from freeze-cast gels by  
freeze-substitution of the frozen medium with a solvent to  
produce wet gels, and drying the wet gels by one of the  
conventional gel drying methods to produce a nanoporous  
aerogel. Inventors' apparatus, systems, and methods have  
many advantages, including the following:

they produce a uniform aerogel,

they are applicable to a wide variety and elemental  
compositions of nanoporous aerogels, including pure  
metal aerogels and multicomponent aerogels made  
from nanowires with different elemental composition,  
complex geometries of parts are made possible via the use  
of molds that can also include soluble mold compo-  
nents removable during the solvent extraction step,  
the freeze-substitution step of the fabrication process  
allows the use of suspension media and nonvolatile  
components that not amenable to conventional freeze  
drying, and

before the drying step to remove the solvent from wet  
gels, chemical modification of aerogels can be per-  
formed, such as ligand exchange and surface function-  
alization; this is not possible in the conventional freeze  
drying process.

Inventors' apparatus, systems, and methods have many  
uses. For example, inventors' apparatus, systems, and meth-  
ods can be used to fabricate ultra-low-density nanoporous  
components of targets for laser-driven X-ray sources, laser-  
driven ion sources, and laser-driven neutron sources. Also,  
the inventors' apparatus, systems, and methods can be used  
for automotive lightweighting, energy absorption, thermal  
management, catalyst materials and supports, capacitors,  
and nanoporous material components of fuel targets for  
inertial confinement fusion energy applications. In one  
embodiment, the inventors' apparatus, systems, and meth-  
ods can be used for making silver aerogels for antimicrobial  
scaffolds in medical implants.

The apparatus, systems, and methods are susceptible to  
modifications and alternative forms. Specific embodiments  
are shown by way of example. It is to be understood that the  
apparatus, systems, and methods are not limited to the  
particular forms disclosed. The apparatus, systems, and  
methods cover all modifications, equivalents, and alterna-  
tives falling within the spirit and scope of the application as  
defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into  
and constitute a part of the specification, illustrate specific

embodiments of the apparatus, systems, and methods and, together with the general description given above, and the detailed description of the specific embodiments, serve to explain the principles of the apparatus, systems, and methods.

FIG. 1 is a flow chart illustrating one embodiment of the inventors' apparatus, systems, and methods for fabricating nanowire aerogels.

FIG. 2 is a flow chart illustrating a specific embodiment of the inventors' apparatus, systems, and methods for fabricating spherical Ag nanowire aerogels from an aqueous suspension of Ag nanowires.

FIG. 3 illustrates the steps of providing nanowires and freeze casting droplets of the nanowire suspension to produce spherical freeze-cast gels.

FIG. 4 is an illustration of a spherical freeze-cast gel.

FIG. 5 illustrates the step of extracting the frozen medium from freeze-cast gels by freeze-substitution with a solvent to produce wet gels.

FIG. 6 illustrates the step of supercritically drying the wet gels to produce nanoporous aerogels.

FIG. 7 is a flow chart illustrating another embodiment of the inventors' apparatus, systems, and methods for fabricating cylindrical Ag nanowire aerogels from an aqueous suspension of Ag nanowires.

FIG. 8 illustrates the steps of providing nanowires and freeze casting the nanowires to produce cylindrical freeze-cast gels.

#### DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Referring to the drawings, to the following detailed description, and to incorporated materials, detailed information about the apparatus, systems, and methods is provided including the description of specific embodiments. The detailed description serves to explain the principles of the apparatus, systems, and methods. The apparatus, systems, and methods are susceptible to modifications and alternative forms. The application is not limited to the particular forms disclosed. The application covers all modifications, equivalents, and alternatives falling within the spirit and scope of the apparatus, systems, and methods as defined by the claims.

Ultra-low-density (ULD) (<20 mg/cm<sup>3</sup>) materials with micron and submicron feature sizes are desirable for a variety of niche applications. There are few materials, however, that can be fabricated into useful geometries at such low densities with high uniformity and reproducibility. Prototypical ultra-low-density materials either rely on multistep chemical methods (SiO<sub>2</sub>) or the complex fabrication and removal of nanostructured scaffolds (C, NiP). Furthermore, these methods are intrinsically limited to a small number of materials with appropriate chemistries.

Suspensions of nanomaterials can be used to form aerogels by spontaneously gelling above their percolation threshold, which, for 1-D materials, is proportional to the inverse of their aspect ratio. In practice, for unknown reasons, this has proven difficult. Alternatively, a method based on freeze-casting of particulate suspensions followed by a freeze-drying step has been shown to be useful for fabricating porous materials with a wide variety of compositions, densities, and feature sizes. During the freeze-casting of a nanoparticulate suspension, a percolating particulate network (gel) assembles at grain boundaries formed during solvent crystallization. A nanoporous aerogel can then be made by removing the frozen medium via conventional

freeze-drying. ULD materials are still difficult to fabricate via this method as physical forces encountered during freeze drying often damage the necessarily fragile porous network. By utilizing suspensions of high aspect ratio nanowires and employing freeze-casting followed by low-temperature extraction of the frozen solvent by freeze-substitution and supercritical drying steps, the inventors have been able to fabricate monolithic, nanoporous Ag aerogels with monolith densities below 3 mg/cm<sup>3</sup>. The physical (rather than chemical) nature of this method suggests that it could be used to fabricate a number of desired, previously unrealized ULD materials. With this new method, the inventors have demonstrated the fabrication of aerogels from Ag, Cu, and Au nanowires.

Referring now to the drawings, and in particular to FIG. 1, a flow chart illustrates one embodiment of the inventors' apparatus, systems, and methods. This embodiment of the inventors' apparatus, systems, and methods is designated generally by the reference numeral 100. The embodiment 100 is a general process for fabricating freeze-cast nanowire aerogels with frozen medium extraction by freeze-substitution that includes the steps described below.

Step 101—Provide suspension comprising desired high-aspect-ratio material (A) suspended in solvent (B) and cryoprotectant (C).

Step 102—Freeze suspension, resulting in percolating network (gel) of material (A) in frozen medium (B+C).

Step 103—Place frozen suspension in solvent (D) bath below melting point of frozen medium (B+C). Allow solvent (D) to dissolve frozen medium (B+C), after which sample temperature can be brought above melting point of (B+C) for further processing.

Step 104—Replace bath solvent (D) with additional bath solvents (E, F . . . Z) to remove trace solvent (B) and cryoprotectant (C) or to functionalize gel (A).

Step 105—Transfer wet gels (A) in bath solvent (Z) to dryer for solvent removal, resulting in aerogel.

Referring now to FIG. 2, a flow chart illustrates another specific embodiment of the inventors' apparatus, systems, and methods. This embodiment of the inventors' apparatus, systems, and methods is designated generally by the reference numeral 200. The embodiment 200 is a process for fabricating 16 mg/cm<sup>3</sup> spherical Ag nanowire aerogels that includes the steps described below.

Step 201—Provide aqueous Ag nanowire suspension. 20 mg/mL Ag nanowires (~30 nm diameter, 25 μm length) coated in polyvinylpyrrolidone (5 wt % PVP/Ag).

Step 202—add glycerol (10% total suspension mass) and additional H<sub>2</sub>O to obtain 16 mg/mL Ag nanowire suspension.

Step 203—Drop suspension from pipette into liquid N<sub>2</sub> bath, allow to fully solidify (~3 min).

Step 204—Transfer gels to -78° C. acetone bath. Place bath in -23° C. freezer for full exchange (~10 hours).

Step 205—Bring bath to room temperature, replace acetone 3 times over 3 days to remove trace H<sub>2</sub>O and glycerol.

Step 206—Transfer gels in acetone to supercritical CO<sub>2</sub> dryer for standard processing.

Referring now to the FIGS. 3-6 of the drawings, the embodiment of the inventors' apparatus, systems, and methods 100 and 200 is illustrated and described in greater detail.

FIG. 3 shows the step of providing nanowire suspensions and the step of freeze casting the nanowires to produce spherical freeze-cast gels. FIG. 3 is designated generally by the reference numeral 300. In FIG. 3, the step of providing nanowire suspensions is illustrated by a liquid droplet of a

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nanowire suspension **302**. The nanowire suspension **302** is cryogenically cooled by being placed in a cryogenic bath **306**. The arrow **304** illustrates the nanowire suspension **302** being placed in a bath of cryogenic liquid **308** to produce freeze-cast gels **302**. The freeze-cast gels **302** are illustrated in FIG. 4.

FIG. 5 shows the step of extracting the frozen medium from freeze-cast spherical gels by freeze substitution in a solvent to produce wet gels. FIG. 5 is designated generally by the reference numeral **500**. In FIG. 5, the step of extracting the frozen medium from freeze-cast gels by freeze-substitution with a solvent is illustrated by the freeze-cast gel **302** being cooled in a container **502** of solvent **504**.

FIG. 6 illustrates the step of drying the wet gel to produce the nanoporous aerogel. Wet gels **302** are dried via one of the standard drying procedures. For example, during supercritical drying, wet gels **302** are placed in a pressure vessel **602** in a bath of flowing CO<sub>2</sub> **604** for solvent exchange followed by the venting of CO<sub>2</sub> **604** under supercritical conditions.

Referring now to FIG. 7, a flow chart illustrates another embodiment of the inventors' apparatus, systems, and methods in which cylindrical ULD Ag nanowire aerogels are fabricated from an aqueous suspension of Ag nanowires by freeze-casting in cylindrical molds with high thermal conductivity. This embodiment of the inventors' apparatus, systems, and methods is designated generally by the reference numeral **700**. The embodiment **700** includes the steps described below.

Step **701**—provide a Ag nanowire suspension as in Step **202**.

Step **702**—fill cylindrical molds with the said nanowire suspension.

Step **703**—freeze cast the said nanowire suspension by placing the molds in a cryogenic bath.

Step **704**—disassemble the molds to remove the freeze-cast gels and transfer said freeze-cast gels to a solvent bath for freeze-substitution of the frozen medium with the solvent to produce wet gels.

Step **705**—process wet gels in preparation for supercritical drying.

Step **706**—supercritically dry said wet gels to produce the nanoporous aerogels.

Referring now to FIG. 8 of the drawings, an embodiment of the inventors' apparatus, systems, and methods **800** is illustrated and described. This embodiment of the inventors' apparatus, systems, and methods is designated generally by the reference numeral **800**. FIG. 8 illustrates the step of freezing nanowire suspensions **802** in a mold having a desired shape such as cylindrical. The nanowire suspensions **802** are cryogenically cooled by being placed in a cryogenic bath **806**. The arrow **804** illustrates the nanowire suspensions **802** being placed in a bath **806** of cryogenic liquid **808** to produce a freeze-cast nanowire suspensions.

Additional embodiments of the above method include but are not limited to the use of high melting point (close to or above room temperature) solvents, non-elemental and composite nanowires, chemical modification of gels between the freeze substitution and solvent drying steps, and alternative drying strategies such as freeze drying or ambient drying. Another embodiment includes making parts via freeze-casting by injection molding and extrusion of nanowire suspensions with or without additives that modify the viscosity of the nanowire suspension. Another embodiment includes the omission of the final solvent drying step and the direct use of wet gels in applications that require wetted porous materials, e.g., porous electrodes and catalytic materials.

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Although the description above contains many details and specifics, these should not be construed as limiting the scope of the application but as merely providing illustrations of some of the presently preferred embodiments of the apparatus, systems, and methods. Other implementations, enhancements, and variations can be made based on what is described and illustrated in this patent document. The features of the embodiments described herein may be combined in all possible combinations of methods, apparatus, modules, and systems. Certain features that are described in this patent document in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination. Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments.

Therefore, it will be appreciated that the scope of the present application fully encompasses other embodiments which may become obvious to those skilled in the art. In the claims, reference to an element in the singular is not intended to mean "one and only one" unless explicitly so stated, but rather "one or more." All structural and functional equivalents to the elements of the above-described preferred embodiment that are known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the present claims. Moreover, it is not necessary for a device to address each and every problem sought to be solved by the present apparatus, systems, and methods, for it to be encompassed by the present claims. Furthermore, no element or component in the present disclosure is intended to be dedicated to the public regardless of whether the element or component is explicitly recited in the claims. No claim element herein is to be construed under the provisions of 35 U.S.C. 112, sixth paragraph, unless the element is expressly recited using the phrase "means for."

While the apparatus, systems, and methods may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the application is not intended to be limited to the particular forms disclosed. Rather, the application is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the application as defined by the following appended claims.

The invention claimed is:

1. A method of making a nanoporous aerogel, comprising: provide a liquid droplet of a nanowire suspension, provide a cryogenic bath, freeze cast said nanowire suspension by placing said liquid droplet of a nanowire suspension in said cryogenic bath to produce a spherical freeze-cast gel wherein said spherical freeze-cast gel contains a frozen medium,

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provide a container of solvent,  
 extract said frozen medium from said spherical freeze-  
 cast gel by freeze-substitution by cooling said spherical  
 freeze-cast gel in said container of solvent to produce  
 a spherical wet gel, and  
 dry said spherical wet gel to produce the nanoporous  
 aerogel.

2. The method of making a nanoporous aerogel of claim  
 1 wherein said step of drying said spherical wet gel com-  
 prises providing a pressure vessel containing a bath of  
 flowing carbon dioxide, placing said spherical wet gel in  
 said bath of flowing carbon dioxide, and venting said carbon  
 dioxide under supercritical conditions.

3. The method of making a nanoporous aerogel of claim  
 1 wherein said step of providing a liquid droplet of a  
 nanowire suspension comprises providing a liquid droplet of  
 a nanowire suspension comprising a nanowire suspension of  
 carbon nanotubes.

4. The method of making a nanoporous aerogel of claim  
 1 wherein said step of providing a liquid droplet of a  
 nanowire suspension comprises providing a liquid droplet of  
 a nanowire suspension comprising a nanowire suspension of  
 metal nanowires.

5. The method of making a nanoporous aerogel of claim  
 1 wherein said step of providing a liquid droplet of a  
 nanowire suspension comprises providing a liquid droplet of  
 a nanowire suspension comprising an aqueous metal  
 nanowire suspension.

6. The method of making a nanoporous aerogel of claim  
 5 wherein said step of providing a liquid droplet of a  
 nanowire suspension comprising an aqueous metal nanowire  
 suspension comprises providing a liquid droplet of a  
 nanowire suspension comprising an aqueous silver nanowire  
 suspension.

7. The method of making a nanoporous aerogel of claim  
 1 wherein said step of providing a liquid droplet of a  
 nanowire suspension comprises providing a liquid droplet of  
 a nanowire suspension comprising a non-aqueous metal  
 nanowire suspension.

8. The method of making a nanoporous aerogel of claim  
 7 wherein said step of providing a non-aqueous metal  
 nanowire suspension comprises providing a non-aqueous  
 gold nanowire suspension.

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9. The method of making a nanoporous aerogel of claim  
 7 wherein said step of providing a non-aqueous metal  
 nanowire suspension comprises providing a non-aqueous  
 copper nanowire suspension.

10. The method of making a nanoporous aerogel of claim  
 1 wherein said step of freeze casting said nanowire suspen-  
 sion to produce a spherical freeze-cast gel comprises placing  
 said liquid droplet of nanowire suspension in said cryogenic  
 bath comprises placing said liquid droplet of nanowire  
 suspension in a cryogenic liquid to produce a spherical  
 freeze-cast gel.

11. The method of making a nanoporous aerogel of claim  
 1 wherein said step of freeze casting said nanowire suspen-  
 sion to produce a spherical freeze-cast gel comprises placing  
 said nanowires liquid droplet of nanowire suspension in  
 liquid nitrogen to produce a spherical freeze-cast gel.

12. The method of making a nanoporous aerogel of claim  
 1 wherein said step of extracting said spherical freeze-cast  
 gel in a solvent to produce a spherical wet gel comprises  
 extracting said spherical freeze-cast gel in acetone below  
 -20° C. to produce a spherical wet gel.

13. A method of making a nanoporous Ag aerogel, com-  
 prising:

provide aqueous Ag;

add glycerol and water to said aqueous Ag;

provide a liquid droplet of said aqueous Ag, glycerol, and  
 water to produce an aqueous Ag, glycerol, and water  
 suspension;

provide a cryogenic bath;

freeze cast said aqueous Ag, glycerol, and water suspen-  
 sion to produce a spherical freeze-cast Ag gel by  
 placing said aqueous Ag, glycerol, and water suspen-  
 sion in said cryogenic bath;

extract said water and said glycerol from said spherical  
 freeze-cast Ag gel by freeze substitution with acetone  
 to produce a spherical Ag wet gel and  
 supercritically dry said spherical Ag wet gel to produce  
 the nanoporous Ag aerogel.

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