US011214862B2

(12) **United States Patent**
Wang et al.

(10) **Patent No.: US 11,214,862 B2**
(45) **Date of Patent: *Jan. 4, 2022**

(54) **FORMING IRON NITRIDE HARD MAGNETIC MATERIALS USING CHEMICAL VAPOR DEPOSITION OR LIQUID PHASE EPITAXY**

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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 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **16/446,487**

(22) Filed: **Jun. 19, 2019**

(65) **Prior Publication Data**

US 2019/0316253 A1 Oct. 17, 2019

Related U.S. Application Data

(62) Division of application No. 15/501,670, filed as application No. PCT/US2015/043812 on Aug. 5, 2015, now Pat. No. 10,358,716.

(60) Provisional application No. 62/035,245, filed on Aug. 8, 2014.

(51) **Int. Cl.**

C23C 16/34	(2006.01)
C23C 16/56	(2006.01)
C23C 16/448	(2006.01)
C23C 16/50	(2006.01)

(52) **U.S. Cl.**

CPC ***C23C 16/34*** (2013.01); ***C23C 16/4488*** (2013.01); ***C23C 16/50*** (2013.01); ***C23C 16/56*** (2013.01)

(58) **Field of Classification Search**

CPC C23C 16/34; C23C 16/4488; C23C 16/50; C23C 16/56

See application file for complete search history.

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(57) **ABSTRACT**

The disclosure describes techniques for forming hard magnetic materials including α''-$Fe_{16}N_2$ using chemical vapor deposition or liquid phase epitaxy and hard materials formed according to these techniques. A method comprises heating an iron source to form a vapor comprising an iron-containing compound; depositing iron from the vapor comprising the iron-containing compound and nitrogen from a vapor comprising a nitrogen-containing compound on a substrate to form a layer comprising iron and nitrogen; and annealing the layer comprising iron and nitrogen to form at least some crystals comprising α''-$Fe_{16}N_2$.

14 Claims, 7 Drawing Sheets

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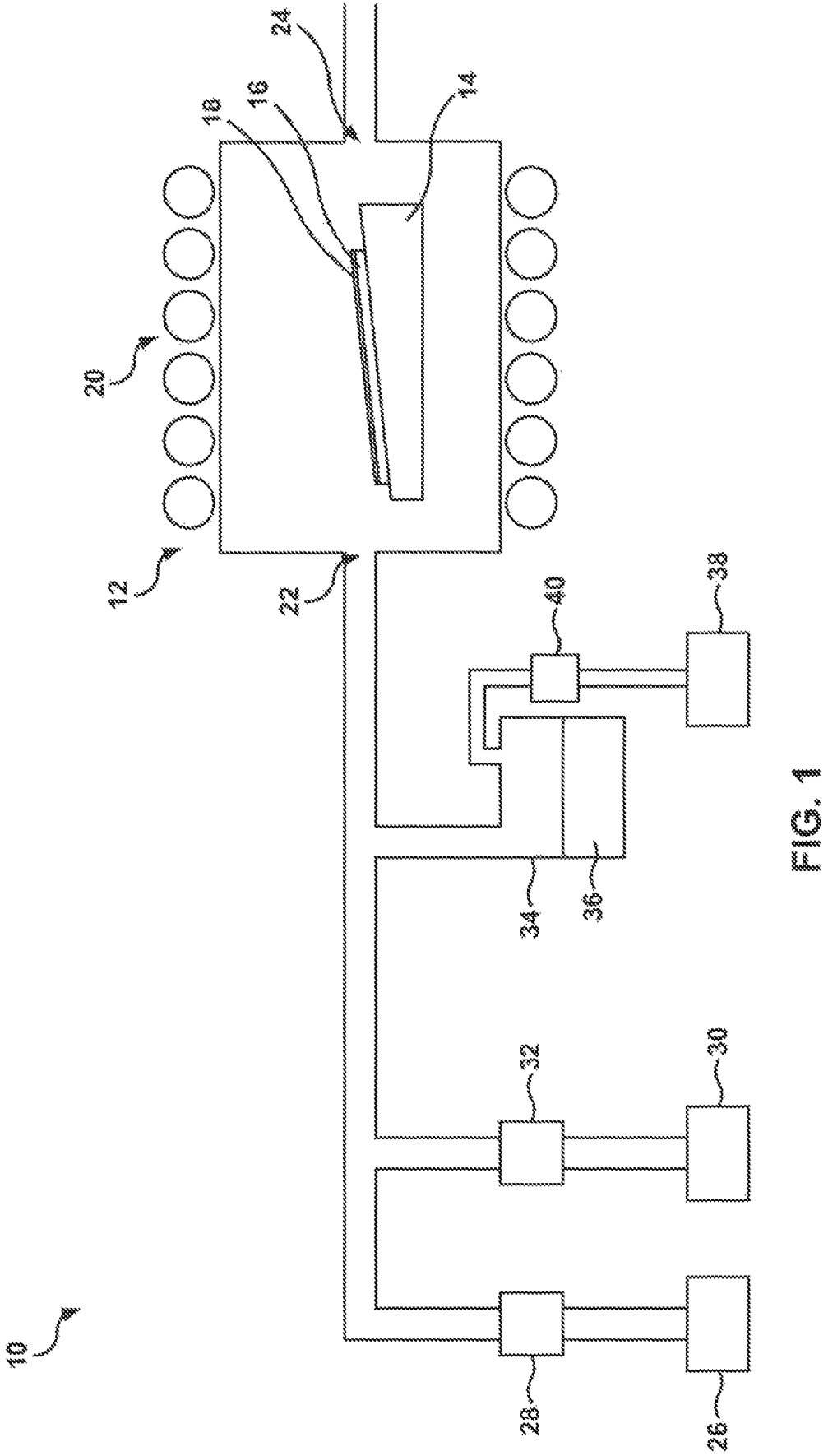
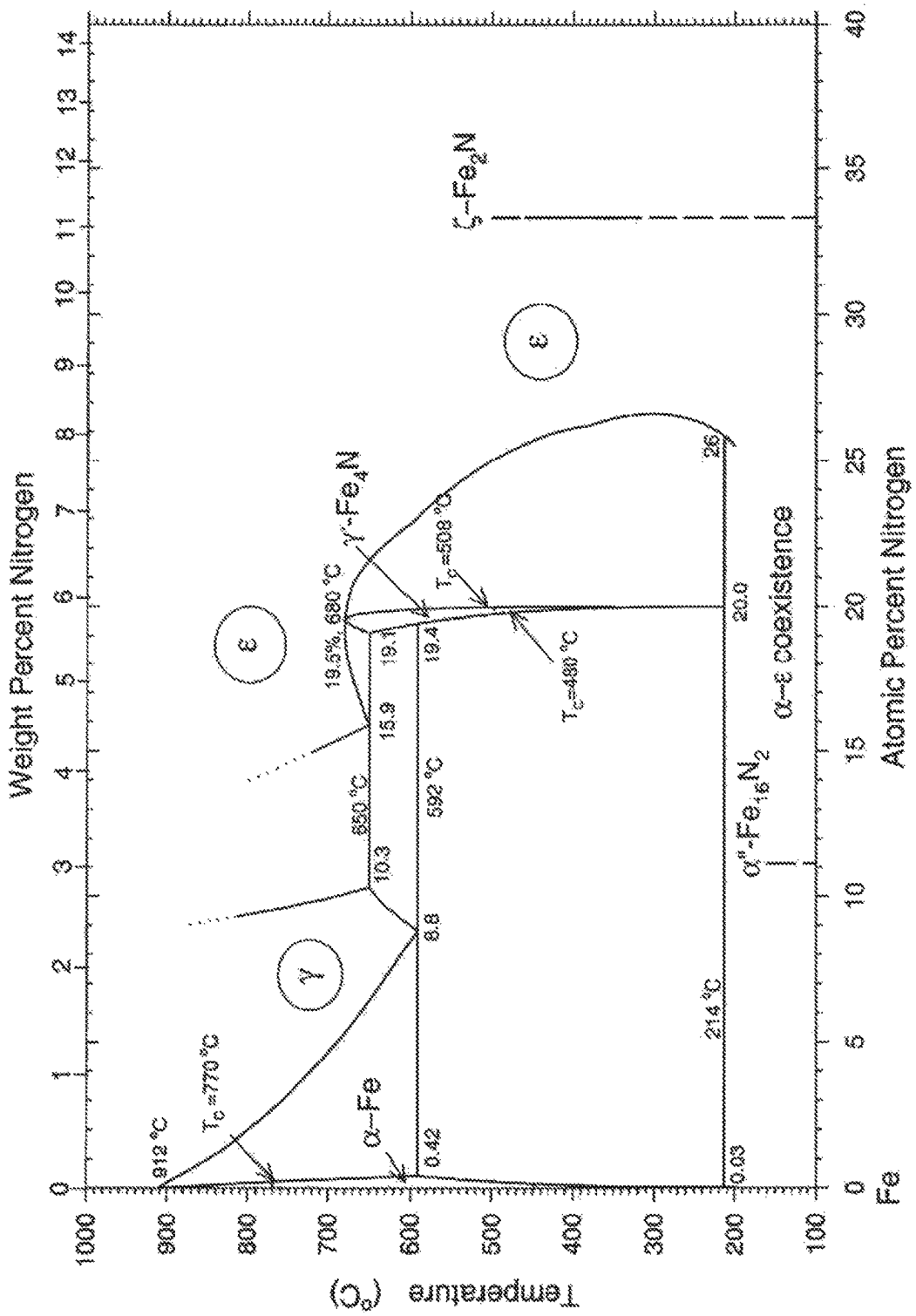


FIG. 1


Weight Percent Nitrogen
Atomic Percent Nitrogen
Temperature (°C)
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ε
γ
α–Fe
ζ–Fe2N
γ'-Fe4N
α"-Fe16N2
α–ε coexistence
912 °C
Tc=770 °C
650 °C
592 °C
214 °C
Tc=508 °C
Tc=488 °C
19.57%, 680 °C
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8.8
0.42
15.9
19.1
19.4
20.0
26
0.03

FIG. 2

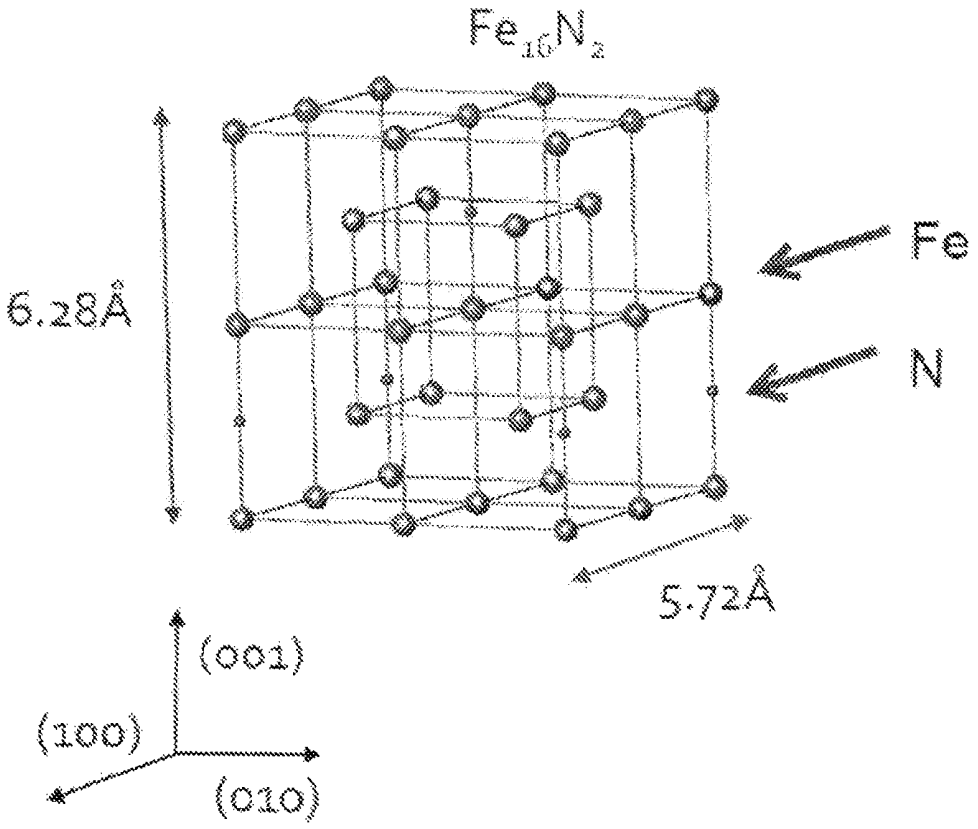


FIG. 3

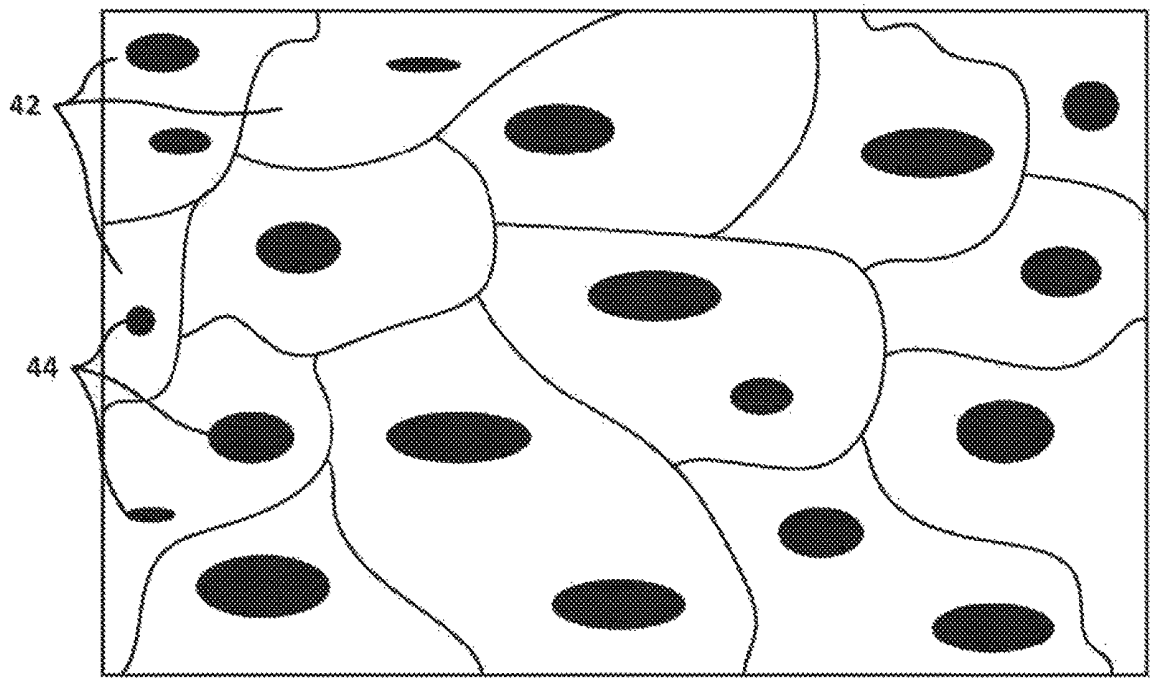


FIG. 4

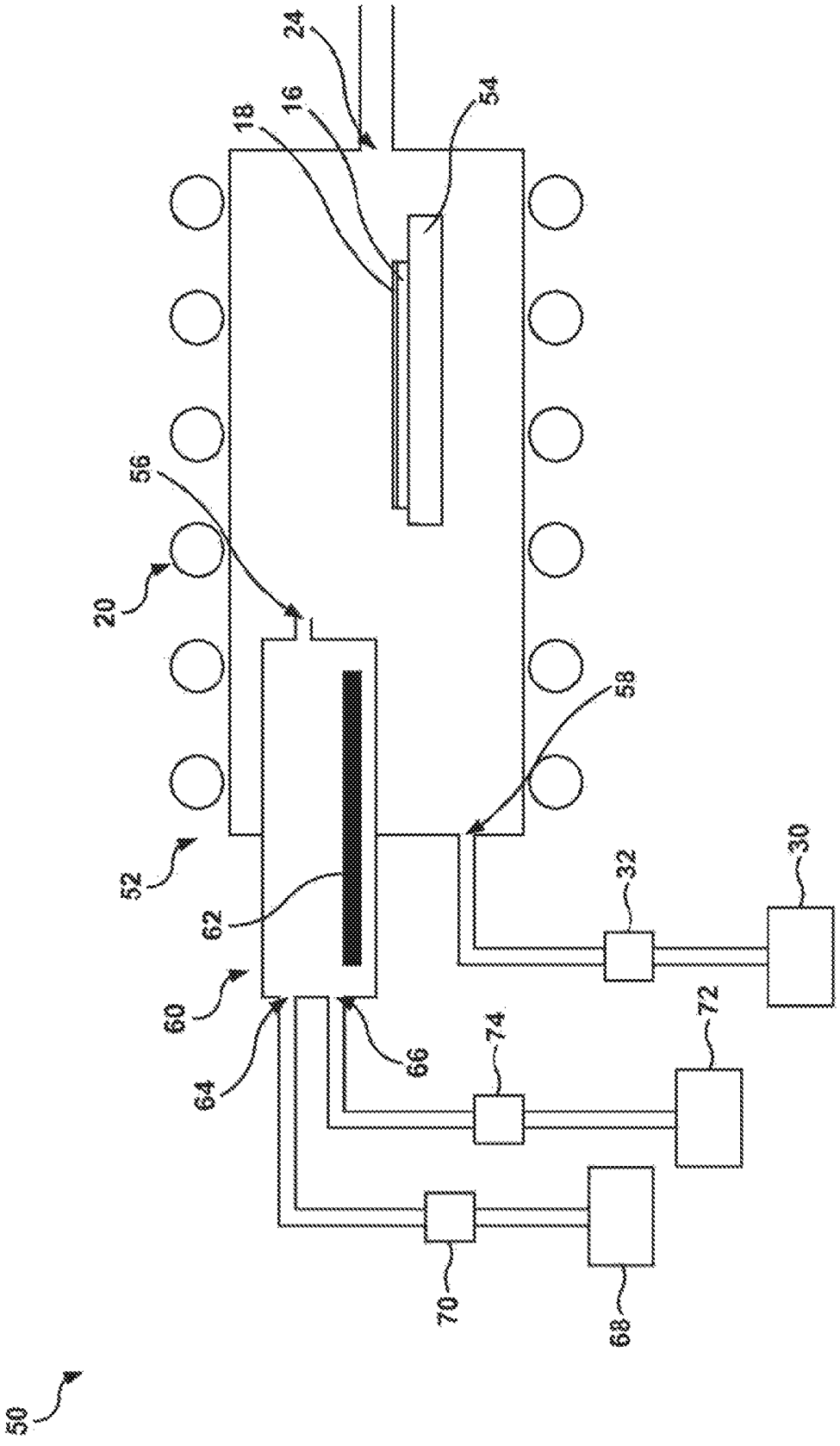


FIG. 5

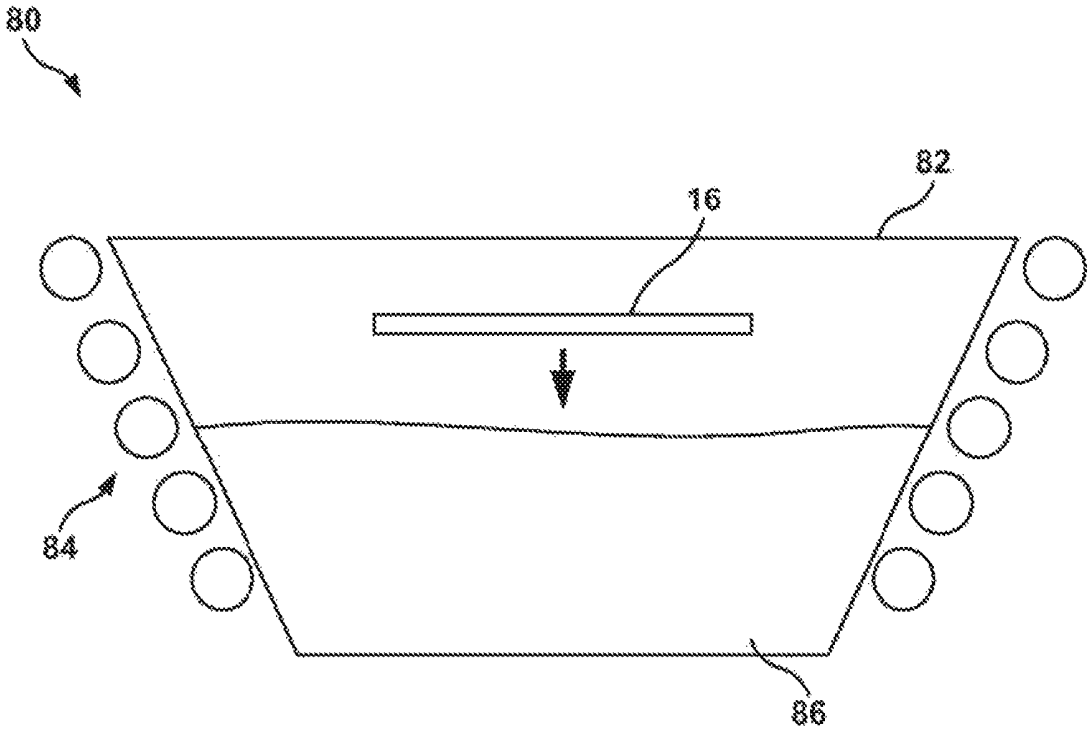
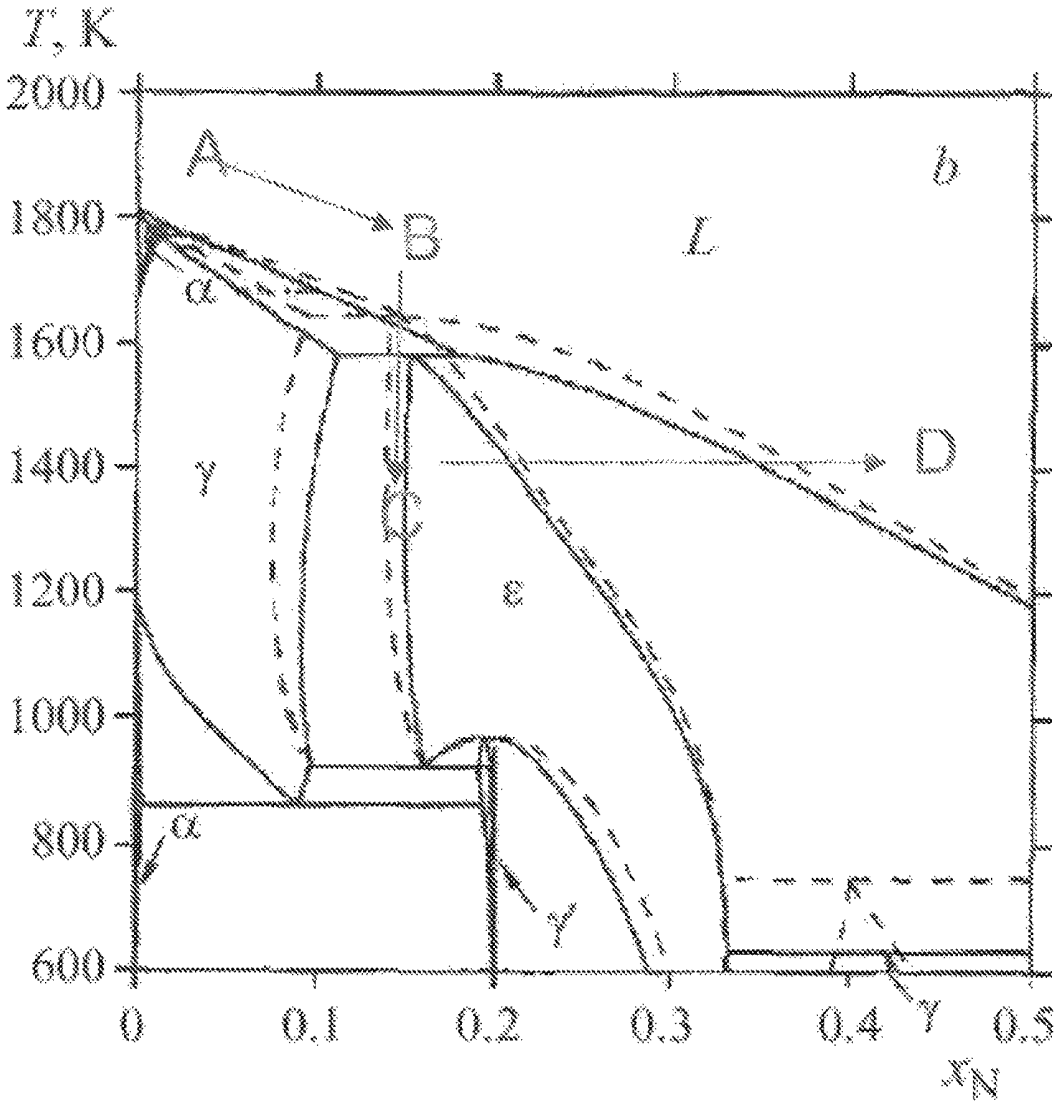


FIG. 6


T, K
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1800
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1200
1000
800
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A
B
L
b
α
γ
C
ε
D
α
γ
γ
0
0.1
0.2
0.3
0.4
0.5
x_N

FIG. 7

FORMING IRON NITRIDE HARD MAGNETIC MATERIALS USING CHEMICAL VAPOR DEPOSITION OR LIQUID PHASE EPITAXY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 15/501,670; filed Feb. 3, 2017, which is a national stage entry under 35 U.S.C. § 371 of International Application No. PCT/US2015/043812, filed Aug. 5, 2015, which claims the benefit of U.S. Provisional Patent Application No. 62/035,245, filed Aug. 8, 2014. The entire contents of U.S. patent application Ser. No. 15/501,670, International Application No. PCT/US2015/043812 and U.S. Provisional Patent Application No. 62/035,245 are incorporated herein by reference.

GOVERNMENT RIGHTS

This invention was made with Government support under contract number DE-AR0000199 awarded by the DOE, Office of ARPA-E. The Government has certain rights in this invention.

TECHNICAL FIELD

The disclosure relates to hard magnetic materials and techniques for forming hard magnetic materials.

BACKGROUND

Permanent magnets play a role in many electromechanical systems, including, for example, alternative energy systems. For example, permanent magnets are used in electric motors or generators, which may be used in vehicles, wind turbines, and other alternative energy mechanisms. Many permanent magnets in current use include rare earth elements, such as neodymium, which result in high energy product. These rare earth elements are in relatively short supply, and may face increased prices and/or supply shortages in the future. Additionally, some permanent magnets that include rare earth elements are expensive to produce. For example, fabrication of NdFeB and ferrite magnets generally includes crushing material, compressing the material, and sintering at temperatures over 1000° C., all of which contribute to high manufacturing costs of the magnets. Additionally, the mining of rare earth can lead to severe environmental deterioration.

SUMMARY

The disclosure describes hard magnetic materials including α''-$Fe_{16}N_2$ and techniques for forming hard magnetic materials including α''-$Fe_{16}N_2$ using chemical vapor deposition (CVD) or liquid phase epitaxy (LPE). Hard magnetic materials including α''-$Fe_{16}N_2$ may provide an alternative to permanent magnets that include a rare earth element, as $Fe_{16}N_2$ has high saturation magnetization, high magnetic anisotropy constant, and high magnetic energy product.

In some examples, the disclosure describes a method including heating an iron source to form a vapor comprising iron-containing compound; depositing iron from the vapor comprising the iron-containing compound and nitrogen from a vapor comprising a nitrogen-containing compound on a substrate to form a layer comprising iron and nitrogen; and annealing the layer comprising iron and nitrogen to form at least some crystals comprising α''-$Fe_{16}N_2$.

In some examples, the disclosure describes a method including submerging a substrate in a coating solution comprising a nitrogen-containing solvent and an iron source. The coating solution may be saturated with the iron source at a first temperature above a liquidus temperature of an iron-nitrogen mixture to be deposited from the coating solution. The method further may include submerging a substrate in the coating solution and cooling the coating solution to a second temperature to form a supersaturated coating solution. The second temperature may be below the liquidus temperature of the iron-nitrogen mixture. The method additionally may include keeping the substrate in the supersaturated coating solution to allow a coating comprising iron and nitrogen to form on the substrate, and annealing the coating comprising iron and nitrogen to form at least some crystals comprising α''-$Fe_{16}N_2$.

In some examples, the disclosure describes an article comprising a substrate and a layer comprising α''-$Fe_{16}N_2$ on the substrate, wherein the layer was formed using at least one of CVD or LPE.

In some examples, the disclosure describes a system for performing at least one of CVD or LPE to form an article comprising a substrate and a layer comprising α''-$Fe_{16}N_2$ on the substrate.

In some examples the disclosure describes a workpiece comprising at lest one phase domain including α''-$Fe_{16}N_2$, wherein the at least one phase domain was formed using at least one of CVD or LPE.

In some examples, the disclosure describes an article comprising a plurality of workpieces. At least one workpiece of the plurality of workpieces includes at least one phase domain including α''-$Fe_{16}N_2$, and the at least one phase domain was formed using at least one of CVD or LPE.

The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

The summary, as well as the following detailed description, is further understood when read in conjunction with the appended drawings. For the purpose of illustrating the disclosure, there are shown in the drawings examples; however, the disclosure is not limited to the specific techniques, compositions, and devices disclosed. In addition, the drawings are not necessarily drawn to scale.

FIG. **1** is a conceptual and schematic diagram illustrating an example chemical vapor deposition system for forming a hard magnetic material including α''-$Fe_{16}N_2$.

FIG. **2** is an iron nitride phase diagram.

FIG. **3** is a conceptual diagram that shows an α''-$Fe_{16}N_2$ unit cell.

FIG. **4** is a conceptual diagram illustrating a material having iron or iron nitride (e.g., Fe_8N) domains and α''-$Fe_{16}N_2$ domains.

FIG. **5** is a conceptual and schematic diagram illustrating an example chemical vapor deposition system for forming a hard magnetic material including α''-$Fe_{16}N_2$.

FIG. **6** is a conceptual and schematic diagram illustrating an example system for forming a coating including α''-$Fe_{16}N_2$ on a substrate using LPE.

FIG. **7** is an iron-nitrogen solid-liquid phase diagram.

DETAILED DESCRIPTION

The present disclosure may be understood more readily by reference to the following detailed description taken in connection with the accompanying figures and examples, which form a part of this disclosure. It is to be understood that this disclosure is not limited to the specific devices, methods, applications, conditions or parameters described and/or shown herein, and that the terminology used herein is for the purpose of describing particular examples and is not intended to be limiting of the claims. When a range of values is expressed, another example includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another example. All ranges are inclusive and combinable. Further, a reference to values stated in a range includes each and every value within that range. As used herein, use of the term "comprising" should also support other embodiments utilizing the terms "consisting of" and "consisting essentially of."

It is to be appreciated that certain features of the disclosure which are, for clarity, described herein in the context of separate examples, may also be provided in combination in a single example. Conversely, various features of the disclosure that are, for brevity, described in the context of a single example, may also be provided separately or in any subcombination.

The disclosure describes hard magnetic materials including α''-$Fe_{16}N_2$ and techniques for forming hard magnetic materials including α''-$Fe_{16}N_2$ using chemical vapor deposition (CVD) or liquid phase epitaxy (LPE). Hard magnetic materials including α''-$Fe_{16}N_2$ may provide an alternative to permanent magnets that include a rare earth element, as $Fe_{16}N_2$ has high saturation magnetization, high magnetic anisotropy constant, and high magnetic energy product.

In some examples, the hard magnetic materials including α''-$Fe_{16}N_2$ may be in the form of a workpiece comprising at least one phase domain comprising α''-$Fe_{16}N_2$. The workpiece may include, for example, a pellet, a rod, a thin film, a nanoparticle, a powder, or a nanoscale powder. In some examples, the hard magnetic materials including α''-$Fe_{16}N_2$ may be in the form of an article including a plurality of workpieces. At least one workpiece of the plurality of workpieces may include at least one phase domain comprising α''-$Fe_{16}N_2$. The article may include, for example, an electric motor, a generator, a sensor, an actuator, a component of an automotive vehicle, or a component of a wind turbine.

The techniques for forming hard magnetic materials including α''-$Fe_{16}N_2$ may include CVD or LPE. Either of these techniques may be used to deposit a thin film including at least one layer including α''-$Fe_{16}N_2$ on a substrate. In some examples, the substrate may include a semiconductor, such as silicon, GaAs, InGaAs, or the like. In other examples, the substrate may include another material, such as a glass, a high temperature polymer, SiC, MgO, SiO_2 (e.g., a layer of SiO_2 on a Si or other semiconductor substrate), SiN, SiAlC, TiN, or the like.

Chemical vapor deposition may allow incorporation of hard magnetic materials including α''-$Fe_{16}N_2$ into semiconductor devices and incorporation of forming of α''-$Fe_{16}N_2$ into semiconductor processes. For example, hard magnetic materials including α''-$Fe_{16}N_2$ may be incorporated into magnetic random access memory (MRAM), magnetic logic devices, magnetic storage devices, magnetic microelectromechanical systems (MEMS), micro motors, micro actuators, nano motors, nano actuators, or the like.

FIG. **1** is a conceptual and schematic diagram illustrating an example chemical vapor deposition system **10** for forming a hard magnetic material including α''-$Fe_{16}N_2$. System **10** includes a chemical vapor deposition (CVD) chamber **12**, which may enclose a susceptor **14**. A substrate **16** is held by susceptor **14**, and a coating **18** is formed on at least a portion of substrate **16**. CVD chamber **12** may include, for example, quartz or another refractory material. In some examples, CVD chamber **12** may be formed of a material that is substantially transparent to radio frequency (RF) magnetic energy.

In some examples, CVD chamber **12** is at least partially surrounded by RF induction coils **20**. RF induction coils **20** may be electrically connected to an RF source (not shown in FIG. **1**), which causes an alternating electrical current at RF to flow through RF induction coils **20**. In some examples, the RF magnetic field generated by RF induction coils **20** may be absorbed by susceptor **14**, which converts the RF energy to heat. This heats substrate **16**. Hence, in some examples, susceptor **14** may include graphite or another material that absorbs RF energy of the frequency generated by RF induction coils **20**.

In some examples, susceptor **14** may be shaped or oriented to position substrate **16** at an incline with respect to inlet **22**. Positioning substrate **16** at an incline with respect to inlet **22** may reduce or substantially eliminate downstream depletion, which is a phenomena in which downstream portions of substrate **16** are coated with a thinner coating than upstream portions of substrate **16** due to depletion of reactants from the coating gas as the coating gas flows along a substantially horizontal substrate **16**.

In some examples, rather than including a susceptor **14** heated by RF induction coils **20**, CVD chamber **12** may be heated such that an entire volume of CVD chamber **12** is heated. For example, CVD chamber **12** may be disposed in a furnace, or CVD chamber **12** may be formed of a material that absorbs RF energy and heats the volume of CVD chamber **12**.

Substrate **16** may include any material on which coating **18** may be formed. In some examples, substrate **16** may include a semiconductor, such as silicon, GaAs, InGaAs, or the like. In other examples, the substrate may include another material, such as a glass, a high temperature polymer, SiC, MgO, SiO_2 (e.g., a layer of SiO_2 on a Si or other semiconductor substrate), SiN, SialC, TiN, or the like.

In some examples, substrate **16** may include a crystalline material with a different lattice structure, different lattice parameters, or both, than α''-$Fe_{16}N_2$. In some examples, substrate **16** additionally or alternatively may have a different coefficient of thermal expansion (CTE) than α''-$Fe_{16}N_2$. In examples in which substrate **16** includes at least one of a different lattice structure, different lattice parameters, or a different CTE than α''-$Fe_{16}N_2$, substrate **16** may exert a strain on layer **18** during an annealing technique, which may facilitate formation of α''-$Fe_{16}N_2$ in coating **18**.

CVD chamber **12** may include an inlet **22** and an outlet **24**. Inlet **22** may be fluidically connected to one or more sources of coating gases. For example, in system **10**, inlet **22** is fluidically connected to a carrier gas source **26**, a first source **30** of a coating constituent, and a second source **34** of coating constituent.

In some examples, carrier gas source **26** may include a gas that carries the coating gas to the interior of CVD chamber **12**. In some examples, carrier gas source **26** may include a

source of substantially inert gas (e.g., a gas that is substantially non-reactive with other elements and compounds present in system **10** during operation of system **10**). A substantially inert gas may include, for example, a noble gas, such as argon.

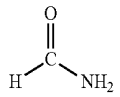
In some examples, carrier gas source **26** additionally or alternatively may include a gas that may react with one or more elements and compounds present in system **10**. For examples, carrier gas source **26** may include a source of hydrogen gas (H_2). In some examples, hydrogen gas may react with an iron precursor to liberate iron. In some instances, carrier gas source **26** may include a mixture of a substantially inert gas and a gas that reacts with one or more elements and compounds present in system **10**. For example, carrier gas source **26** may include a mixture of hydrogen gas and argon.

Carrier gas source **26** may be fluidically connected to CVD chamber **12** via conduit or piping, and at least one valve **28**. Valve **28** may be used to control flow of carrier gas from carrier gas source **26** to CVD chamber **12**.

System **10** also includes first source **30**. First source **30** may include a source of a vapor including a nitrogen-containing compound. In some examples, first source **30** may include a gaseous source of a nitrogen precursor, such as gaseous ammonia (NH_3). In other examples, first source **30** may include a liquid or solid source of a nitrogen precursor, such as ammonium nitrate (NH_4NO_3; solid), an amide (liquid or solid), or hydrazine (liquid).

Amides include a C—N—H bond and hydrazine includes an N—N bond. Ammonium nitrate, amides and hydrazine may serve as a nitrogen donor for forming the powder including iron nitride. Example amides include carbamide ($(NH_2)_2CO$; also referred to as urea), methanamide (Formula 1), benzamide (Formula 2), and acetamide (Formula 3), although any amide may be used.

Formula 1



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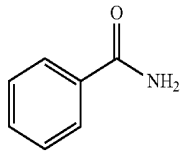

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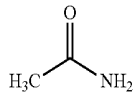

In some examples, amides may be derived from carboxylic acids by replacing the hydroxyl group of a carboxylic acid with an amine group. Amides of this type may be referred to as acid amides.

In examples in which the nitrogen-containing compound in first source **30** is a solid or liquid, first source **30** may include a heat source to vaporize the nitrogen-containing compound and form a vapor including a nitrogen-containing compound.

First source **30** may be fluidically connected to CVD chamber **12** via conduit or piping, and at least one valve **32**. Valve **32** may be used to control flow of nitrogen-containing vapor from first source **30** to CVD chamber **12**.

System **10** also includes second source **34**. Second source **34** may include a source of iron or an iron precursor (or donor). In the example shown in FIG. **1**, second source **34** contains a liquid iron donor **36**, such as $FeCl_3$ or $Fe(CO)_5$. Second source **34** is fluidically coupled to a gas source **38** via valve **40**, which controls flow of gas source **38** into second source **34**. In some examples, gas source **38** may be a source of hydrogen (H_2) gas or another reducing gas.

Gas from gas source **38** flows into second source **34** and vaporizes at least some of liquid iron donor **36**. Gas from gas source **38** then carries the vapor including the iron-containing compound into CVD chamber **12** through inlet **22**.

Valves **28**, **32**, and **40** may be used to control the total flow rate of gases and vapors into CVD chamber **12**, and the relative proportion of carrier gas, the vapor including the nitrogen-containing compound, and the vapor including the iron-containing compound in the gases and vapors flowing into CVD chamber **12**. In some examples, valves **28**, **32**, and **40** may be controlled to produce an atomic ratio of iron to nitrogen in the gases and vapors flowing into CVD chamber **12** to be between about 11.5:1 (iron:nitrogen) and about 5.65:1 (iron:nitrogen). For example, the atomic ratio between iron and nitrogen atoms in the gases and vapors flowing into CVD chamber **12** may be about 9:1 (iron:nitrogen), about 8:1 (iron:nitrogen), or about 6.65:1 (iron:nitrogen).

In some examples, the flow rate of the carrier gas may be between about 5 standard cm^3/minute (sccm) and about 5,000 sccm, the flow rate of the vapor including the nitrogen-containing compound may be between about 10 sccm and about 1,000 sccm, and the flow rate of the vapor including the iron-containing compound may be between about 100 sccm and about 5,000 sccm. Flow rates such as these may result in a growth rate of coating **18** of between about 100 micrometers per hour (μm/h) and about 1,000 μm/h.

In some examples, substrate **16** may be heated by susceptor **14** and RF induction coils **20** above a decomposition temperature of the iron-containing compound, the decomposition temperature of the nitrogen-containing compound, or both. For example, substrate **16** may be heated to a temperature between about 200° C. and about 1,000° C. by susceptor **14** and RF induction coils **20**.

In some examples in which substantially only susceptor **14** and substrate **16** is heated, the iron-containing compound and the nitrogen-containing compound may decompose to release iron and nitrogen, or may react with each other to form an iron nitride compound. Because substrate **16** is heated, this reaction or reactions may occur at the surface of substrate **16**, resulting in coating **18** being formed and including iron and nitrogen.

In examples in which substantially the entire volume of CVD chamber **12** is heated (e.g., by a furnace), the decomposition reactions or reaction between the iron-containing compound and the nitrogen-containing compound may occur above substrate within the volume of CVD chamber **12**. The liberated iron and nitrogen atoms or iron nitride compound then may deposit on the surface of substrate **16** in coating **18**.

In some examples, a reaction between the iron-containing compound and the nitrogen containing compound may include:

$$16FeCl_3+2NH_3+21H_2 \rightarrow 2Fe_8N+48HCl$$

In some examples, portions of substrate **16** may be masked, leaving only portions of substrate **16** exposed for coating **18** to be formed. In other examples, portions of

coating **18** may be etched after deposition of coating **18** to remove the portions of coating **18**, leaving only portions of substrate **16** coated with coating **18**. In this way, coating **18** may be controllably formed on only selected portions of substrate **16**.

As described above, the ratio of iron to nitrogen in the gases and vapors entering CVD chamber **12** may be between about 11.5:1 (iron:nitrogen) and about 5.65:1 (iron:nitrogen), such as about 8:1 (iron:nitrogen). Coating **18** may include approximately the same ratio of iron to nitrogen in the gases and vapors entering CVD chamber **12**. Thus, coating **18** may include an iron to nitrogen ratio of between about 11.5:1 (iron:nitrogen) and about 5.65:1 (iron:nitrogen), such as about 9:1 (iron:nitrogen), about 8:1 (iron:nitrogen), or about 6.65:1 (iron:nitrogen).

In some examples, coating **18**, as deposited, may include at least one type of iron nitride, such as, for example, FeN, Fe_2N (e.g., ξ-Fe_2N), Fe_3N (e.g., ε-Fe_3N), Fe_4N (e.g., γ'-Fe_4N, γ-Fe_4N, or both), Fe_2N_6, Fe_8N, α''-$Fe_{16}N_2$, or FeN_x (where x is between about 0.05 and about 0.5), in addition to iron and/or nitrogen. In some examples, coating **18** may have a purity (e.g., collective iron and nitrogen content) of at least 92 atomic percent (at. %).

Coating **18** may include any selected thickness, and the thickness may at least partially depend on the CVD parameters, including the time for which the CVD technique is carried out.

In some examples, coating **18** additionally may include at least one dopant, such as a ferromagnetic or nonmagnetic dopant and/or a phase stabilizer. In some examples, at least one ferromagnetic or nonmagnetic dopant may be referred to as a ferromagnetic or nonmagnetic impurity and/or the phase stabilizer may be referred to as a phase stabilization impurity. A ferromagnetic or nonmagnetic dopant may be used to increase at least one of the magnetic moment, magnetic coercivity, or thermal stability of the hard magnetic material formed from coating **18**. Examples of ferromagnetic or nonmagnetic dopants include Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Pt, Au, Sm, C, Pb, W, Ga, Y, Mg, Hf, and Ta. For example, including Mn dopant atoms at levels between about 5 at. % and about 15 at. % in an iron nitride material including at least one $Fe_{16}N_2$ phase domain may improve thermal stability of the $Fe_{16}N_2$ phase domains and magnetic coercivity of the material compared to an iron nitride material not including Mn dopant atoms. In some examples, more than one (e.g., at least two) ferromagnetic or nonmagnetic dopants may be includes in the mixture including iron and nitrogen. In some examples, the ferromagnetic or nonmagnetic dopants may function as domain wall pinning sites, which may improve coercivity of the magnetic material formed from coating **18**. Table 1 includes example concentrations of ferromagnetic or nonmagnetic dopants within coating **18**.

TABLE 1

Dopant	Concentration (at. %)
Sc	0.1-33
Ti	0.1-28
V	0.1-25
Nb	0.1-27
Cr	0.1-10
Mo	0.1-3
Mn	0.1-28
Ru	2-28
Co	0.1-50
Rh	11-48
Ni	2-71
Pd	0.1-55
Pt	0.1-15
Cu	0.1-30
Ag	1-10
Au	1-10
Zn	0.1-30
Cd	0.1-35
Zr	0.1-33
Pb	0.1-60
Mg	0.1-60
W	0.1-20
Ta	0.1-20
Ga	0.1-10
Sm	0.1-11

Alternatively or additionally, coating **18** may include at least one phase stabilizer. The at least one phase stabilizer may be an element selected to improve at least one of $Fe_{16}N_2$ volume ratio, thermal stability, coercivity, and erosion resistance. When present in coating **18**, the at least one phase stabilizer may be present in the mixture including iron and nitrogen at a concentration between about 0.1 at. % and about 15 at. %. In some examples in which at least two phase stabilizers at present in the mixture, the total concentration of the at least two phase stabilizers may be between about 0.1 at. % and about 15 at. %. The at least one phase stabilizer may include, for example, B, Al, C, Si, P, O, Co, Cr, Mn, and/or S. For example, including Mn dopant atoms at levels between about 5 at. % and about 15 at. % in an iron nitride material including at least one $Fe_{16}N_2$ phase domain may improve thermal stability of the $Fe_{16}N_2$ phase domains and magnetic coercivity of the iron nitride material compared to an iron nitride material not including Mn dopant atoms.

Once coating **18** has been formed to a predetermined thickness, substrate **16** and coating **18** may be removed from CVD chamber **12** and subjected to an annealing technique. The annealing technique may facilitate formation of α''-$Fe_{16}N_2$ hard magnetic phase in coating **18**.

The annealing technique may be carried out at a temperature that produces strain in coating **18** due to differences in the coefficients of thermal expansion for substrate **16** and coating **18** to access the α''-$Fe_{16}N_2$ phase. Additionally, the annealing technique allows diffusion of N+ ions within iron crystals in coating **18** to form iron nitride, including α''-$Fe_{16}N_2$ phase domains and Fe_8N phase domains. FIG. **2** is an iron nitride phase diagram, reproduced from E. H. Du Marchi Van Voorthuysen et al. *Low-Temperature Extension of the Lehrer Diagram and the Iron-Nitrogen Phase Diagram,* 33A Metallurgical and Materials Transactions A 2593, 2597 (August 2002), the entire content of which is incorporated herein by reference. As shown in FIG. **2**, annealing at relatively low temperatures allows transformation of partial Fe_8N disordered phase into α''-$Fe_{16}N_2$ ordered phase.

In some examples, the annealing technique may be carried out at a temperature below about 250° C., such as between about 120° C. and about 220° C., between about 120° C. and about 200° C., between about 150° C. and about 200° C., or at about 150° C. The annealing technique may be performed in a nitrogen (N_2) or argon (Ar) atmosphere, or in a vacuum or near-vacuum.

The temperature and duration of the annealing step may be selected based on, for example, a size of the sample and a diffusion coefficient of nitrogen atoms in iron at the

annealing temperature. Based on these factors, the temperature and duration may be selected to provide sufficient time for nitrogen atoms to diffuse to locations within coating **18** to form $Fe_{16}N_2$ domains.

Additionally, the temperature and duration of the annealing technique may be selected based on a desired volume fraction of α"-$Fe_{16}N_2$ phase domains in coating **18**. For example, at a selected temperature, a longer annealing technique may result in a higher volume fraction of α"-$Fe_{16}N_2$. Similarly, for a given annealing technique duration, a higher temperature may result in a higher volume fraction of α"-$Fe_{16}N_2$. However, for durations above a threshold value, the additional volume fraction of α"-$Fe_{16}N_2$ may be limited or eliminated, as the volume fraction of α"-$Fe_{16}N_2$ reaches a relatively stable value. For example, at a temperature of about 150° C., after about 20 hours, the volume fraction of α"-$Fe_{16}N_2$ reaches a stable value. The duration of the annealing technique may be at least about 5 hours, such as at least about 20 hours, or between about 5 hours and about 100 hours, or between about 5 hours and about 80 hours, or between about 20 hours and about 80 hours, or about 40 hours.

Fe_8N and α"-$Fe_{16}N_2$ have similar body-centered tetragonal (bct) crystalline structure. However, in α"-$Fe_{16}N_2$, nitrogen atoms are ordered within the iron lattice, while in Fe_8N, nitrogen atoms are randomly distributed within the iron lattice. FIG. **3** is a conceptual diagram that shows an α"-$Fe_{16}N_2$ unit cell. As shown in FIG. **3**, in the α"-$Fe_{16}N_2$ phase, the nitrogen atoms are aligned along the (002) (iron) crystal planes. Also shown in FIG. **3**, the iron nitride unit cell is distorted such that the length of the unit cell along the <001> axis is approximately 6.28 angstroms (Å) while the length of the unit cell along the <010> and <100> axes is approximately 5.72 Å. The α"-$Fe_{16}N_2$ unit cell may be referred to as a bct unit cell when in the strained state. When the α"-$Fe_{16}N_2$ unit cell is in the strained state, the <001> axis may be referred to as the c-axis of the unit cell.

The annealing technique facilitates formation of the bct crystalline structure at least in part due to the strain exerted on the iron crystal lattice as a result of differential expansion of the substrate and the iron nitride workpiece during the post-annealing step. For example, the coefficient of thermal expansion for iron is 11.8 μm/m·K, while for silicon it is 2.6 μm/m·K. This difference in thermal expansion coefficients results in a compression stress substantially parallel the major plane of coating **18** and a corresponding stretching force being generated along the <001> crystalline direction on a coating **18** with an (110) face. In some examples, the strain on coating **18** may be between about 0.3% and about 7%, which may result in a substantially similar strain on individual crystals of the iron nitride, such that the unit cell is elongated along the <001> axis between about 0.3% and about 7%. This may facilitate incorporation of nitrogen atoms at the preferred positions of the α"-$Fe_{16}N_2$ crystal.

In some examples, rather than transforming all of coating **18** to α"-$Fe_{16}N_2$ phase, the annealing technique may result in formation of α"-$Fe_{16}N_2$ phase domains within domains of Fe, Fe_8N, and/or iron nitride compositions. FIG. **4** is a conceptual diagram illustrating a material having iron or iron nitride (e.g., Fe_8N) domains **42** and α"-$Fe_{16}N_2$ domains **44**. Because coating **18** may be structured on a nanometer scale (e.g., the sizes of iron or iron nitride domains **42** and α"-$Fe_{16}N_2$ domains **44** are on the order of nanometers), magnetic coupling between the magnetically hard α"-$Fe_{16}N_2$ domains **44** and the magnetically soft iron or iron nitride domains **42** may occur substantially throughout coating **18**. Because the α"-$Fe_{16}N_2$ and iron or iron nitride crystals have substantially similar crystalline structure, the material can be naturally crystallographically coherent, meaning having an aligned easy axis, which produces anisotropy. This may facilitate exchange-spring coupling through phase boundaries between α"-$Fe_{16}N_2$ domains **44** and iron or iron nitride domains **42**.

Exchange-spring coupling may effectively improve the magnetic energy product of magnetic materials and provide magnetic properties for the bulk material similar to those of a bulk material formed of α"-$Fe_{16}N_2$. To achieve exchange-spring coupling throughout the volume of the magnetic material, the α"-$Fe_{16}N_2$ domains may be distributed throughout coating **18**, e.g., at a nanometer or micrometer scale. For example, the magnetically hard $Fe_{16}N_2$ phase may constitute between about 5 vol. % and about 40 vol. % of the total volume of coating **18**, or between about 5 vol. % and about 20 vol. % of the total volume of coating **18**, or between about 10 vol. % and about 20 vol. % of the total volume of coating **18**, or between about 10 vol. % and about 15 vol. % of the total volume of coating **18**, or about 10 vol. % of the total volume of coating **18**, with the remainder of the volume of coating **18** being magnetically soft materials. The magnetically soft materials may include, for example, Fe, FeCo, Fe_8N, or combinations thereof.

In some examples, such as when the magnetically soft material includes Fe or FesN, the crystallographic texture of the $Fe_{16}N_2$ and the Fe or Fe_8N domains may be coherent. In other words, there may be a lattice match between the domains. This may facilitate efficient exchange-spring coupling between the magnetically hard $Fe_{16}N_2$ domains **77** and the magnetically soft iron or iron nitride domains **42**, particularly across phase boundaries.

By using CVD to form coating **18** on substrate **16**, hard magnetic material including α"-$Fe_{16}N_2$ may be incorporated into other products formed using CVD and existing manufacturing techniques that utilize CVD. Using existing CVD manufacturing operations, including masking, hard magnetic material including α"-$Fe_{16}N_2$ may be deposited on predetermined portions or regions of substrate **16**. For example, hard magnetic materials including α"-$Fe_{16}N_2$ may be incorporated into CMOS (complementary metal-oxide-semiconductor) integrated circuit devices, and the CVD technique for forming hard magnetic materials including α"-$Fe_{16}N_2$ may be incorporated into existing CMOS processing techniques. For example, hard magnetic materials including α"-$Fe_{16}N_2$ may be incorporated into magnetic random access memory (MRAM), magnetic logic devices, magnetic storage devices, magnetic microelectromechanical systems (MEMS), micro motors, micro actuators, nano motors, nano actuators, or the like. In other examples, hard magnetic materials including α"-$Fe_{16}N_2$ formed using CVD may be incorporated into other devices utilizing hard magnetic materials, such as electric motors, electric generators, magnetic recording media, and magnetic resonance imaging (MRI) magnets, among other applications.

CVD may allow growth of coating **18** faster than some other techniques, such as molecular beam epitaxy (MBE), while, in some examples, forming superior coatings compared to some other techniques, such as sputtering.

Although FIG. **1** illustrates an example system **10** for CVD using a liquid iron-containing material, in other examples, CVD may be performed using a solid iron-containing material. FIG. **5** is a conceptual and schematic diagram illustrating an example chemical vapor deposition system **50** for forming a hard magnetic material including α"-$Fe_{16}N_2$. In some examples, system **50** of FIG. **5** may be

similar to or substantially the same as system **10** described with reference to FIG. **1**, aside from the differences described herein.

System **50** includes a CVD chamber **52**. CVD chamber **52** encloses a susceptor **54**, which may be similar or substantially the same as susceptor **14** of FIG. **1**. In the example illustrated in FIG. **5**, susceptor **54** is not shaped or oriented to position substrate **16** at an incline with respect to inlets **56** and **58**. In other examples, susceptor **54** may be shaped or oriented to position substrate **16** at an incline with respect to inlets **56** and **58**. CVD chamber **52** may include, for example, quartz or another refractory material. In some examples, CVD chamber **52** may be formed of a material that is substantially transparent to radio frequency (RF) magnetic energy.

CVD chamber **52** is at least partially surrounded by RF induction coils **20**. RF induction coils **20** may be similar to or substantially the same as RF induction coils illustrated in FIG. **1**. CVD chamber **52** encloses substrate **16**, on which coating **18** is formed. Substrate **16** is disposed on susceptor **54**.

In some examples, rather than including a susceptor **54** heated by RF induction coils **20**, CVD chamber **52** may be heated such that an entire volume of CVD chamber **52** is heated. For example, CVD chamber **52** may be disposed in a furnace, or CVD chamber **52** may be formed of a material that absorbs RF energy and heats the volume of CVD chamber **52**.

CVD chamber **52** may include inlet **56** and **58** and an outlet **24**. Inlets **56** and **58** may be fluidically connected to one or more sources of coating gases. For example, in system **50**, inlet **56** is fluidically connected to a chamber **60** enclosing a solid iron-containing material **62** and inlet **58** is fluidically coupled to first source **30** via a valve **32**. First source **30** and valve **32** may be similar to or substantially the same as described above with respect to FIG. **1**. For example, first source **30** may include a source of a vapor including a nitrogen-containing compound.

Chamber **60** encloses a solid iron-containing material **62**. In some examples, iron-containing material **62** may include an iron-containing powder, billet, or thin film deposited on a substrate. In some examples, the particles in iron-containing powder may define an average characteristic dimension of on the order of nanometers or micrometers. In some examples, the iron containing film may define a thickness between about 500 nanometers (nm) and about 1 millimeter (mm). In some examples, iron-containing material **62** includes substantially pure iron (e.g., iron with a purity of greater than 90 at. %). In other examples, iron-containing material **62** may include iron oxide (e.g., Fe_2O_3 or Fe_3O_4).

Chamber **60** may include a first inlet **64** and a second inlet **66**. First inlet **64** may fludically connected to a first gas source **68** by a valve **70**. First gas source **68** may include a source of an acid or chloride, such as HCl. The acid or chloride may react with iron-containing material **62** to form an iron-containing vapor. For example, HCl may react with iron-containing material **62** to form iron chloride ($FeCl_3$), which may be heated to form a vapor.

Second inlet **66** may be fluidically coupled to a carrier gas source **72** by a valve **74**. In some examples, carrier gas source **72** may include a source of substantially inert gas (e.g., a gas that is substantially non-reactive with other elements and compounds present in system **50** during operation of system **50**). A substantially inert gas may include, for example, a noble gas, such as argon.

Valves **32**, **70**, and **74** may be used to control the total flow rate of gases and vapors into CVD chamber **52**, and the relative proportion of carrier gas, nitrogen-containing vapor, and iron-containing vapor in the gases and vapors flowing into CVD chamber **52**. In some examples, valves **32**, **70**, and **74** may be controlled to produce an atomic ratio of iron to nitrogen in the gases and vapors flowing into CVD chamber **52** to be between about 11.5:1 (iron:nitrogen) and about 5.65:1 (iron:nitrogen). For example, the atomic ratio between iron and nitrogen atoms in the of the gases and vapors flowing into CVD chamber **52** may be about 9:1 (iron:nitrogen), about 8:1 (iron:nitrogen), or about 6.65:1 (iron:nitrogen).

In some examples, the flow rate of the carrier gas may be between about 100 sccm and about 5,000 sccm, the flow rate of the nitrogen-containing vapor may be between about 10 sccm and about 1,000 sccm, and the flow rate of the acid or chloride may be between about 10 sccm and about 1,000 sccm. Flow rates such as these may result in a growth rate of coating of between about 100 μm/h and about 1,000 μm/h.

In some examples, the HCl may react with Fe in chamber **60** according to the following reaction:

$$Fe+HCl \rightarrow FeCl_3+H_2$$

The $FeCl_3$ and H_2 may flow into CVD chamber **52** through first inlet **56**, where the vapors may mix with the nitrogen-containing vapor, such as NH_3. In some examples, the nitrogen-containing vapor and the iron containing vapor may react according to the following reaction to deposit coating **18** including an approximately 8:1 ratio of iron to nitrogen:

$$16FeCl_3+2NH_3+21H_2 \rightarrow 2Fe_8N+48HCl$$

As described above with respect to FIG. **1**, once coating **18** has been formed to a predetermined thickness, coating **18** may be annealed to transform at least some of the iron nitride mixture in coating **18** to α''-$Fe_{16}N_2$. The annealing technique may be similar to or substantially the same as that described above with respect to FIG. **1**.

In other examples, a coating (e.g., coating **18**) may be formed on a substrate (e.g., substrate **16**) using liquid phase epitaxy (LPE). In LPE, a solution including the coating materials may be cooled to form a supersaturated solution. The coating materials in the solution deposit a coating on a substrate immersed in the solution. In some examples, the degree of supersaturation may be low, such that the LPE technique is a near-equilibrium process. This may result in coatings with high crystalline quality (e.g., near-perfect crystalline structure). Additionally, because the concentration of the coating materials in the solution are much greater than the concentration of coating materials in vapor phase techniques, the growth rate of the coating may be greater than the growth rate for coatings grown using vapor phase techniques.

FIG. **6** is a conceptual and schematic diagram illustrating an example system **80** for forming a coating including α''-$Fe_{16}N_2$ on a substrate **82** using LPE. System **80** includes a crucible **82** in which a coating solution **86** is contained. System **80** also includes RF induction coils **84**, which at least partially surrounded crucible **82**. RF induction coils **84** may be electrically connected to an RF source (not shown in FIG. **6**), which causes an alternating electrical current at RF to flow through RF induction coils **84**. In some examples, the RF magnetic field generated by RF induction coils **84** may be absorbed by coating solution **86** or by crucible **82**, such that coating solution **86** is heated.

Coating solution **86** may include a solution of iron in a solvent. In some examples, the solvent may include a nitrogen-containing compound, such as ammonium nitrate,

urea, an amide or hydrazine. In some examples, the solvent may be oversaturated with nitrogen at the deposition temperature and pressure. Example amides include carbamide ($(NH_2)_2CO$; also referred to as urea), methanamide (Formula 1 above), benzamide (Formula 2 above), acetamide (Formula 3 above), and acid amides, although any amide may be used. The amide may be selected to be a liquid at the temperatures experienced by coating solution **86** during the LPE technique.

Coating solution **86** also includes an iron source. In some examples, the iron source may include an iron-containing compound. In some examples, the iron source includes a liquid iron donor, such as $FeCl_3$ or $Fe(CO)_5$. In other examples, the iron source may include an iron-containing powder. In some examples, the iron-containing powder may include substantially pure iron (e.g., iron with a purity of greater than 90 at. %). In some examples, the iron-containing powder may include iron oxide (e.g., Fe_2O_3 or Fe_3O_4).

During the LPE process, the coating solution **86** may be heated to a temperature above the liquidus temperature of the liquid-solid iron-nitrogen phase diagram shown in FIG. **7**. For example, the solvent may be heated to the temperature indicated by point A in the liquid-solid iron-nitrogen phase diagram. In some examples, the solvent may not include the iron source when heated to the temperature indicated by point A.

The iron source or iron-containing material then may be dissolved in the solvent to form a coating solution **86** that is saturated with the iron-containing material. This solution saturated solution is indicated by point B on the liquid-solid iron-nitrogen phase diagram. Substrate **16** then may be immersed in coating solution **86**.

Coating solution **86** and substrate **16** then may be cooled to a temperature, indicated by point C, that is below the liquidus. This causes coating solution **86** to be supersaturated with the iron-containing material, which drives the LPE coating technique. In some examples, the temperature indicated by point C, at which the LPE coating technique is performed, may be between about 600° C. and about 800° C. (although point C indicates a higher temperature). Point C is in the two-phase region, which provides a driving force for precipitation of iron nitride on the surface of substrate **16**, until point D on the liquidus line is reached where precipitation ends. In some examples, the concentration of iron and nitrogen in coating solution **86** and the temperature at which the LPE coating technique is performed may be controlled to provide an atomic ratio of iron to nitrogen between about 11.5:1 (iron:nitrogen) and about 5.65:1 (iron:nitrogen). For example, the atomic ratio between iron and nitrogen atoms may be about 9:1 (iron:nitrogen), about 8:1 (iron:nitrogen), or about 6.65:1 (iron:nitrogen).

Once the coating including iron and nitrogen is formed by LPE, substrate **16** may be removed from crucible **82**, and the coating may be annealed under conditions similar to or substantially the same as those described with respect to FIG. **1**. The annealing may facilitate formation of α''-$Fe_{16}N_2$ in the coating.

Because α''-$Fe_{16}N_2$ has high saturation magnetization and magnetic anisotropy constant. The high saturation magnetization and magnetic anisotropy constants result in a magnetic energy product that may be higher than rare earth magnets. For example, experimental evidence gathered from thin film α''-$Fe_{16}N_2$ permanent magnets suggests that bulk $Fe_{16}N_2$ permanent magnets may have desirable magnetic properties, including a magnetic energy product of as high as about 134 MegaGauss * Oerstads (MGOe), which is about two times the magnetic energy product of NdFeB (which has a magnetic energy product of about 60 MGOe). Additionally, iron and nitrogen are abundant elements, and thus are relatively inexpensive and easy to procure. The high magnetic energy product of α''-$Fe_{16}N_2$ magnets may be used in electric motors, electric generators, magnetic recording media, and magnetic resonance imaging (MRI) magnets, among other applications.

When ranges are used herein for physical properties, such as molecular weight, or chemical properties, such as chemical formulae, all combinations and subcombinations of ranges for specific examples therein are intended to be included.

Various examples have been described. Those skilled in the art will appreciate that numerous changes and modifications can be made to the examples described in this disclosure and that such changes and modifications can be made without departing from the spirit of the disclosure. These and other examples are within the scope of the following claims.

This patent application is related to International Patent Application No. PCT/US2012/051382, filed Aug. 17, 2012; International Patent Application No. PCT/US2014/015104, filed Feb. 6, 2014; and International Patent Application No. PCT/US2014/043902, filed Jun. 24, 2014. The entire contents of these international patent applications are incorporated herein by reference.

Clause 1: A method comprising: heating an iron source to form a vapor comprising an iron-containing compound; depositing iron from the vapor comprising the iron-containing compound and nitrogen from a vapor comprising a nitrogen-containing compound on a substrate to form a layer comprising iron and nitrogen; and annealing the layer comprising iron and nitrogen to form at least some crystals comprising α''-$Fe_{16}N_2$.

Clause 2: The method of clause 1, wherein the iron source comprises solid iron.

Clause 3: The method of clause 1, wherein the solid iron comprises at least one of iron powder or an iron thin film.

Clause 4: The method of clause 1, wherein iron source comprises a solid iron precursor.

Clause 5: The method of clause 4, wherein the solid iron precursor comprises at least one of Fe_2O_3 powder or Fe_2O_4 powder.

Clause 6: The method of clause 1, wherein the iron source comprises a liquid iron precursor.

Clause 7: The method of clause 6, wherein the liquid iron precursor comprises at least one of $FeCl_3$ or $Fe(CO)_5$.

Clause 8: The method of any one of clauses 1 to 7, wherein the vapor comprising the nitrogen-containing compound is formed by heating urea to form a urea vapor.

Clause 9: The method of any one of clauses 1 to 7, wherein the vapor comprising the nitrogen-containing compound is formed by heating at least one of an amide or hydrazine to form the vapor comprising nitrogen.

Clause 10: The method of any one of clauses 1 to 7, wherein the vapor comprising the nitrogen-containing compound comprises NH_3 vapor.

Clause 11: The method of any one of clauses 1 to 7, wherein the vapor comprising the nitrogen-containing compound comprises atomic nitrogen formed from diatomic nitrogen using a plasma.

Clause 12: The method of any one of clauses 1 to 11, further comprising heating the vapor comprising the iron-containing compound and the vapor comprising the nitrogen-containing compound to decompose the vapor comprising the iron-containing compound and the vapor comprising

the nitrogen-containing compound to form atomic nitrogen and atomic iron, which deposit on the substrate.

Clause 13: The method of any one of clauses 1 to 11, further comprising heating the substrate above a decomposition temperature of at least one of the vapor comprising the iron-containing compound and the vapor comprising the nitrogen-containing compound.

Clause 14: The method of any one of clauses 1 to 13, wherein annealing the layer comprising iron and nitrogen to form at least some crystals comprising α"-$Fe_{16}N_2$ comprises heating the layer at a temperature between about 100° C. and about 220° C. for between about 5 hours and 80 hours.

Clause 15: The method of any one of clauses 1 to 14, wherein the substrate comprises at least one of silicon, GaAs, SiC, InGaAs, MgO, SiO_2, a high temperature polymer, or glass.

Clause 16: A method comprising: submerging a substrate in a coating solution comprising a nitrogen-containing solvent and an iron source, wherein the coating solution is saturated with the iron source at a first temperature above a liquidus temperature of an iron-nitrogen mixture to be deposited from the coating solution; cooling the coating solution to a second temperature to form a supersaturated coating solution, wherein the second temperature is below the liquidus temperature of the iron-nitrogen mixture; keeping the substrate in the supersaturated coating solution to allow a coating comprising iron and nitrogen to form on the substrate; and annealing the coating comprising iron and nitrogen to form at least some crystals comprising α"-$Fe_{16}N_2$.

Clause 17: The method of clause 16, wherein the solvent comprises at least one of ammonium nitrate, an amide, or hydrazine.

Clause 18: The method of clause 16 or 17, wherein the iron source comprises at least one of substantially pure iron, $FeCl_3$, $Fe(CO)_5$, or an iron oxide.

Clause 19: The method of any one of clauses 16 to 18, wherein the second temperature is between about 600° C. and about 800° C.

Clause 20: The method of any one of clauses 16 to 19, wherein the coating comprising iron and nitrogen comprises an atomic ratio of iron to nitrogen between about 11.5:1 (iron:nitrogen) and about 5.65:1 (iron:nitrogen).

Clause 21: The method of any one of clauses 16 to 19, wherein the coating comprising iron and nitrogen comprises an atomic ratio of iron to nitrogen about 8:1 (iron:nitrogen).

Clause 22: The method of any one of clauses 16 to 21, wherein annealing the layer comprising iron and nitrogen to form at least some crystals comprising α"-Fe15N2 comprises heating the layer at a temperature between about 100° C. and about 220° C. for between about 5 hours and 80 hours.

Clause 23: The method of any one of clauses 16 to 22, wherein the substrate comprises at least one of silicon, GaAs, SiC, InGaAs, MgO, SiO2, a high temperature polymer, or glass.

Clause 24: An article formed by the method of any one of clauses 1 to 23.

Clause 25: A system for performing the method of any one of clauses 1 to 23.

The disclosure of each patent, patent application, and publication cited or described in this document are hereby incorporated herein by reference, in its entirety.

What is claimed is:

1. A method comprising:

heating an iron source to form a vapor comprising an iron-containing compound;

depositing iron from the vapor comprising the iron-containing compound and nitrogen from a vapor comprising a nitrogen-containing compound on a substrate to form a layer comprising iron and nitrogen; and

annealing the layer comprising iron and nitrogen to form hard magnetic material comprising at least some crystals comprising α"-$Fe_{16}N_2$.

2. The method of claim **1**, wherein the iron source comprises solid iron.

3. The method of claim **1**, wherein the iron source comprises at least one of iron powder or an iron film.

4. The method of claim **1**, wherein iron source comprises at least one of Fe_2O_3 powder or Fe_2O_4 powder.

5. The method of claim **1**, wherein the iron source comprises a liquid iron precursor.

6. The method of claim **5**, wherein the liquid iron precursor comprises at least one of $FeCl_3$ or $Fe(CO)_5$.

7. The method of claim **1**, wherein the vapor comprising the nitrogen-containing compound is formed by heating urea to form a urea vapor.

8. The method of claim **1**, wherein the vapor comprising the nitrogen-containing compound is formed by heating at least one of an amide or hydrazine to form the vapor comprising nitrogen.

9. The method of claim **1**, wherein the vapor comprising the nitrogen-containing compound comprises NH_3 vapor.

10. The method of claim **1**, wherein the vapor comprising the nitrogen-containing compound comprises atomic nitrogen formed from diatomic nitrogen using a plasma.

11. The method of claim **1**, further comprising heating the vapor comprising the iron-containing compound and the vapor comprising the nitrogen-containing compound to decompose the vapor comprising the iron-containing compound and the vapor comprising the nitrogen-containing compound to form atomic nitrogen and atomic iron, which deposit on the substrate.

12. The method of claim **1**, further comprising heating the substrate above a decomposition temperature of at least one of the vapor comprising the iron-containing compound and the vapor comprising the nitrogen-containing compound.

13. The method of claim **1**, wherein annealing the layer comprising iron and nitrogen to form at least some crystals comprising α"-$Fe_{16}N_2$ comprises heating the layer at a temperature between about 100° C. and about 220° C. for between about 5 hours and 80 hours.

14. The method of claim **1**, wherein the substrate comprises at least one of silicon, GaAs, SiC, InGaAs, MgO, SiO_2, SiN, SiAlC, TiN, a polymer, or glass.

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