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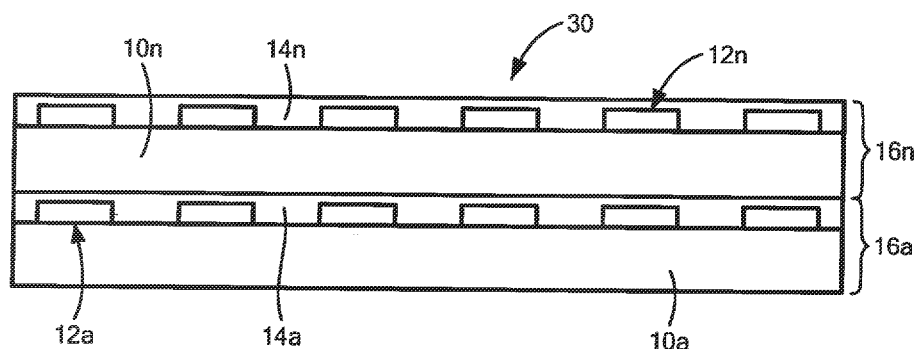


FIG. 4

(57) Abstract: Embodiments of the present disclosure relate to depositing a superconductor directly onto a magnet structure. Superconductor deposition systems operable to handle full-sized, magnet-scale objects can be used for the depositing methods. In an embodiment, a strong base material structure (e.g., a plate) with the profile of a magnet is selected, and the method includes depositing a buffer, superconductor, and protection onto the base structure. Photolithography or laser etching methods can be used to selectively remove superconductor to form "windings" on the plate. Multiple plates can then be assembled similar to the assembly of a traditional Bitter plate magnet. Cooling channels can be integrated into the base structure, before or after superconductor deposition.



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- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
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TECHNIQUES FOR DIRECT DEPOSITION OF SUPERCONDUCTOR MATERIAL AND RELATED SYSTEMS AND METHODS

BACKGROUND

[0001] Superconductors are materials that have no electrical resistance to current (are “superconducting”) below some critical temperature. For many superconductors, the critical temperature is below 30 K, such that operation of these materials in a superconducting state requires significant cooling, such as with liquid helium or supercritical helium. High temperature superconductors (“HTS”) are a class of superconductors that have a comparatively high critical temperature, such as between 50 K - 100 K. Some HTS materials, such as rare-earth barium copper oxide (“REBCO”), can be produced as long strands, leading to the possibility of using these materials to wind large bore magnets for use in fusion devices, among other applications.

SUMMARY

[0002] This Summary is provided to introduce a selection of concepts in simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key or essential features or combinations of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

[0003] Embodiments of the present disclosure relate to superconducting magnets and methods for simplifying construction of superconducting magnets.

[0004] In accordance with one aspect of the concepts described herein, a method for constructing a superconducting magnet comprises directly depositing a superconductor material onto a frame (also sometimes referred to herein as a support structure, substrate, or plate) which has been provided having a shape substantially corresponding to a final desired magnet shape. That is, a frame is formed or otherwise provided having a final desired magnet shape prior to a superconductor material deposition process. A superconductor material is then directly deposited onto the magnet-shaped frame to provide a superconducting magnet.

[0005] With this particular arrangement, a technique for construction of a superconducting magnet which is relatively simple compared with prior art construction techniques is provided. Depositing superconductor material onto a frame having a shape substantially corresponding to a final desired magnet shape simplifies construction of a superconducting magnet. In embodiments, the superconductor material may be selectively provided on desired portions of the magnet-shaped frame using additive or subtractive techniques.

[0006] In further examples, the frame can be formed, shaped or otherwise provided as a macroscopic magnet structure. In such examples, a superconductor deposition system operable to handle macroscopic magnet-scale objects can be used to implement said methods. Subsequently, the method includes depositing a first buffer layer, a second superconductor layer, and a third protection layer onto the base material structure.

[0007] In further embodiments, depositing superconductor material onto a frame having a shape substantially corresponding to a final desired magnet shape can include patterning the superconductor material onto a magnet-shaped frame (e.g., using the process of photolithography and optical masks to print patterns on the frame that guide the deposition or removal of superconducting material from the magnet-shaped frame at specific steps in the superconducting magnet fabrication process). At each layer of the superconducting magnet, material (e.g., superconducting or other material) may be deposited or removed in those areas not covered by the mask and then a new mask may be used on the next layer. The magnet-shaped frame may be repeatedly processed in this fashion to create multiple layers of circuitry. Laser etching techniques may also be used to selectively remove deposited superconductor material. Either technique may be used to form windings on the magnet-shaped frame.

[0008] In examples, a magnet can be formed by multiple layers of the structure having the superconductor material deposited thereon. Such a system can be adaptable to a variety of insulation techniques (or lack thereof) and geometries. Cooling channels can be integrated into the structure, before or after superconductor deposition.

[0009] In additional embodiments, photolithography-like techniques could be used to print multiple layers of superconductor on a substrate with patterns specifically

designed to form electrical current paths. Additional methods can include 3D-printing a matched pair of substrate layers with superconductor patterns such that they form current paths when each layer is pressed together.

[0010] Advantageously, the disclosed methods simplify the construction and assembly of magnets as compared to traditional tape-to-cable methods.

[0011] According to some aspects, a superconducting magnet is provided comprising a plurality of high temperature superconductor (HTS) winding layers including a first HTS winding layer arranged over a second HTS winding layer, each of the plurality of HTS winding layers comprising a substrate, an HTS winding consisting essentially of an HTS material deposited on the substrate, and a protective layer arranged over the HTS winding and the substrate, wherein the protective layer of the second HTS winding layer is in contact with the substrate of the first HTS winding layer.

[0012] According to some embodiments, the HTS material is a rare earth barium copper oxide superconductor.

[0013] According to some embodiments, each of the plurality of HTS winding layers further comprises an insulating layer arranged between the HTS winding and the protective layer.

[0014] According to some embodiments, the protective layer of the first HTS winding layer is in contact with the HTS winding of the first HTS winding layer and is in contact with the substrate of the first HTS winding layer.

[0015] According to some embodiments, the superconducting magnet further comprises one or more cooling channels arranged within substrates of the plurality of HTS winding layers.

[0016] According to some embodiments, the substrate comprises a metal alloy and/or a fiber composite.

[0017] According to some embodiments, at least some of the substrates of the plurality of HTS winding layers have cross-sectional shape that is a closed shape with an opening.

[0018] According to some embodiments, the cross-sectional shape that is a closed shape with an opening is an annulus or a D-shape.

- [0019] According to some embodiments, the protective layer comprises silver.
- [0020] According to some embodiments, the protective layer comprises copper.
- [0021] According to some embodiments, the protective layer comprises brass.
- [0022] According to some aspects, a method of making a superconducting magnet is provided, the method comprising applying a mask to a surface of a substrate to define a plurality of turns of a winding, wherein the surface of the substrate has a closed shape with an opening, depositing a layer of high temperature superconductor (HTS) onto one or more portions of the surface defined by the mask.
- [0023] According to some embodiments, the substrate is electrically conductive.
- [0024] According to some embodiments, the method further comprises depositing a protective layer over the layer of HTS.
- [0025] According to some embodiments, the protective layer is electrically conductive.
- [0026] According to some embodiments, the method further comprises depositing an electrical insulator onto the layer of HTS.
- [0027] According to some embodiments, the method further comprises depositing a buffer layer onto the surface of the substrate prior to depositing the layer of HTS onto the portions of the surface.
- [0028] According to some embodiments, the method further comprises fabricating the substrate via additive fabrication.
- [0029] According to some embodiments, the substrate comprises one or more cooling channels.
- [0030] According to some embodiments, depositing the layer of HTS onto the portions of the surface comprises depositing the layer using physical vapor deposition, pulsed laser deposition and/or reactive co-evaporation deposition.
- [0031] According to some aspects, a method of making a superconducting magnet is provided, the method comprising depositing a layer of high temperature superconductor (HTS) onto a surface of a substrate, wherein the surface of the substrate

has a closed shape with an opening, laser etching the layer of HTS to define one or more turns of a winding.

[0032] According to some embodiments, the substrate is electrically conductive.

[0033] According to some embodiments, the method further comprises depositing a protective layer over the layer of HTS.

[0034] According to some embodiments, the protective layer is electrically conductive.

[0035] According to some embodiments, the method further comprises depositing an electrical insulator onto the layer of HTS.

[0036] According to some embodiments, the method further comprises depositing a buffer layer onto the surface of the substrate prior to depositing the layer of HTS.

[0037] According to some embodiments, the method further comprises fabricating the substrate via additive fabrication.

[0038] According to some embodiments, the substrate comprises one or more cooling channels.

[0039] According to some embodiments, depositing the layer of HTS onto the surface comprises depositing the layer using physical vapor deposition, pulsed laser deposition and/or reactive co-evaporation deposition.

[0040] According to some aspects, a method of making a superconducting magnet is provided, the method comprising preparing a surface of a substrate for deposition of a superconductor, the substrate having a closed shape corresponding to a final magnet shape, masking the surface so as to define a superconductor pattern, and depositing a superconductor layer onto the surface, the superconductor layer comprising a superconductor.

[0041] According to some embodiments, the substrate comprises a high-strength, high-stiffness, and macroscopic scale material.

[0042] According to some embodiments, the material comprises one or more of a thin-rolled metal alloy, an additive manufactured metal, and a fiber composite.

[0043] According to some embodiments, the final magnet shape is selected based at least on an anticipated electromagnetic load of the substrate.

[0044] According to some embodiments, preparing the substrate's surface comprises depositing a buffer layer on the substrate's surface.

[0045] According to some embodiments, the method further comprises depositing a protective layer on the superconductor layer.

[0046] According to some embodiments, the method further comprises depositing one or more additional layers comprising sets of another substrate on which other superconductor and protective layers are deposited.

[0047] According to some embodiments, the method further comprises forming cooling channels in the substrate.

[0048] According to some embodiments, the method further comprises depositing an electric insulator between the sets of superconductor and protective layers.

[0049] According to some embodiments, the method further comprises encapsulating the superconductor with an electric insulator.

[0050] According to some embodiments, the method further comprises depositing a semiconductor layer between the sets of superconductor and protective layers.

[0051] According to some embodiments, the method further comprises encapsulating the superconductor with a semiconductor.

[0052] According to some aspects, method of making a superconducting magnet is provided, the method comprising preparing a surface of a substrate for deposition of a superconductor, the substrate having a closed shape corresponding to a final magnet shape, depositing a superconductor layer onto the surface, the superconductor layer comprising a superconductor, and laser etching the superconductor layer to define a superconductor pattern.

[0053] According to some embodiments, the substrate comprises one or more of a thin-rolled metal alloy, an additive manufactured metal, and a fiber composite.

[0054] According to some embodiments, the final magnet shape is selected based at least on an anticipated electromagnetic load of the substrate.

[0055] According to some embodiments, preparing the substrate's surface comprises depositing a buffer layer on the substrate's surface.

[0056] According to some embodiments, the method further comprises depositing a protective layer on the superconductor layer.

[0057] According to some embodiments, the method further comprises forming cooling channels in the substrate.

[0058] According to some aspects, method of making a superconducting magnet is provided, the method comprising preparing a surface of a substrate for deposition of a superconductor, the substrate having a closed shape corresponding to a final magnet shape, selectively depositing a superconductor layer onto the surface to define a superconductor pattern, and wherein the superconductor layer comprises a superconductor.

[0059] According to some embodiments, the final magnet shape is selected based at least on an anticipated electromagnetic load of the substrate.

[0060] The foregoing apparatus and method embodiments may be implemented with any suitable combination of aspects, features, and acts described above or in further detail below. These and other aspects, embodiments, and features of the present teachings can be more fully understood from the following description in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

[0061] The foregoing and other objects, features and advantages will be apparent from the following more particular description of the embodiments, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the embodiments.

[0062] FIG. 1 is a cross-sectional view of a frame having a shape corresponding to a final shape of a superconducting magnet, according to some embodiments;

[0063] FIG. 2 is a cross-sectional view of the frame of FIG. 1 having a superconductor layer disposed on a surface thereof, according to some embodiments;

[0064] FIG. 3 is a cross-sectional view of the frame of FIGs. 1 and 2 having a protective layer disposed onto the superconductor layer of FIG. 2, according to some embodiments;

[0065] FIG. 4 is a cross-sectional view of a layered superconducting structure which may be formed, for example, from the structures illustrated in FIGs. 1-3, according to some embodiments;

[0066] FIG. 5 is a cross-sectional view of a layered superconducting structure, which may be the same as or similar to the layered superconducting structure of FIG. 4, having cooling channels integrated into substrate layers thereof, according to some embodiments;

[0067] FIG. 6 is a cross-sectional view of a layered superconducting structure, which may be the same as or similar to the layered superconducting structure of FIG. 4, having an electric insulator inserted between layers thereof, according to some embodiments;

[0068] FIG. 7 is a cross-sectional view of a layered superconducting structure having electric insulators encapsulating superconductor elements, according to some embodiments;

[0069] FIG. 8 is a cross-sectional view of a layered superconducting structure having a semiconductor layer inserted between layers of the superconducting structure, according to some embodiments;

[0070] FIG. 9 is a cross-sectional view of a layered superconducting structure which illustrates semiconductor materials encapsulating superconductor elements of the superconducting structure, according to some embodiments;

[0071] FIG. 10 is a block diagram of a depositing system configured to deposit a superconductor onto a substrate having a closed shape corresponding to a final magnet shape, according to some embodiments;

[0072] FIG. 10A is a cross-sectional view of a series of layered superconducting structures illustrating superconducting circuit layers deposited onto the substrate of FIG. 10, according to some embodiments;

[0073] FIG. 10B is a block diagram of a portion of a fusion system comprising a plurality of magnets having the closed shape of FIG. 10, according to some embodiments;

[0074] FIG. 11 is a block diagram of a magnetic resonance imaging (MRI) system comprising a superconducting magnet provided in accordance with the concepts described herein, according to some embodiments;

[0075] FIG. 11A is a block diagram of a deposition system configured to deposit a superconductor onto a substrate having a closed shape corresponding to a final magnet shape for the MRI system of FIG. 11, according to some embodiments;

[0076] FIG. 11B is a cross-sectional view of a series of layered superconducting structures having superconducting layers deposited onto the substrate of FIG. 11A in accordance with the concepts described herein, according to some embodiments;

[0077] FIGs. 12A-12B illustrate cross-sectional views of windings of a superconducting magnet formed from, respectively, a stack of superconducting tape and a monolithic volume of superconducting material, according to some embodiments.

DETAILED DESCRIPTION

[0078] High-field magnets are often constructed from superconductors due to the capability of superconductors to carry a high current without resistance. Superconducting magnets may be built from individual wires or tapes of superconductors.

Superconducting tapes are made with a strong base (typically a steel alloy) on which a buffer layer is deposited. The buffer layer provides a uniform surface on which superconductor crystals are grown. Protective layers of silver and copper may then be plated over the superconductor. These tapes can either be wound directly into plates (e.g., so-called “pancake assemblies”) which are then assembled into magnets or assembled into cables that are then wound to form a magnet assembly. The magnet assemblies may also require additional structure structures to support large current loads which occur due to forces generated by the magnet as well as cooling channels to keep the superconductor at an operational temperature.

[0079] A high-field superconducting magnet often comprises multiple electrically insulated cable turns grouped in a multi-layer arrangement. For instance, the so-called Cable in Conduit Conductor (CICC) braided cable approach includes small diameter filaments embedded and twisted together with conductive wires in addition to coolant conduits, which flow next to, or near to, the conductive wires. The large surface area on the wires provides good heat transfer with the coolant, which is necessary to operate the

superconducting cables at the low temperatures (e.g., below 10 Kelvin) for the conductors to become superconducting.

[0080] Superconducting cables containing high temperature superconductors (HTS), on the other hand, are typically not formed from wires but rather from structures often referred to as “tapes.” An HTS tape is a structure having a wide aspect ratio (e.g., long, thin and flat) that contains HTS material in addition to other materials such as conventional conductors and/or buffer layers. While HTS tapes have several advantages including the ability to potentially produce a large superconducting volume within a cable, there are also challenges in their fabrication. In particular, the HTS material in a tape is typically polycrystalline due to its length and the techniques by which the tape is produced. In a polycrystalline material, the interfaces between crystallites, known as “grain boundaries,” may, however, interfere with the electrical properties of the material. As a result, it is important that HTS tapes are fabricated with a high degree of grain alignment, which can present a manufacturing challenge, particular if tapes with a width of tens of centimeters, or even a meter, are desired.

[0081] In addition, while one of the advantages of HTS tapes is their ability to be fabricated as flat tapes and then folded or otherwise arranged into a coil, this also leads to two further requirements. First, that a suitable structure is arranged around the HTS cable to mechanically support it, and second, that any gaps between the HTS tape and the structure are filled in a suitable manner to ensure the desired electrical properties of the coil.

[0082] The inventors have recognized and appreciated techniques for depositing superconducting material that may be suitable for fabrication of high field magnets. In contrast to the above-described conventional approaches in which a cable or tape is formed and arranged as a coil, the techniques described herein deposit superconducting material directly as windings on a substrate in the final shape of the coil. Thus, while the techniques described herein may lack the flexibility of the conventional approaches for producing cables or tapes, then arranging them in a desired configuration, the direct deposition approach may be suitable for producing large volumes of superconducting material within windings.

[0083] According to some embodiments, the techniques described herein may produce a superconducting magnet in which the windings of the magnet comprise a monolithic region of material. For instance, in a magnet comprising HTS tapes, typically a number of tapes are stacked on top of one another to produce a winding of the magnet, and each HTS tape includes several layers in addition to the HTS material, such as a substrate, buffer layers, overlayers and/or stabilizing layers. As such, the actual thickness of HTS material in a stack of HTS tapes may be a small fraction of the thickness of the stack. In contrast, by depositing superconducting material via the techniques described herein, the windings of a superconducting material may consist only of HTS material (or may consist essentially of HTS material).

[0084] One result of the techniques described herein may be that a larger region of superconducting material may be produced within a superconducting magnet compared with an approach based on wires or tapes. To illustrate this point, FIG. 12A illustrates a cross-sectional view of a stack of HTS tapes arranged to produce windings of a superconducting magnet (e.g., the depicted cross-section may be that of a single turn within a winding). While in the example of FIG. 12A there are only six tapes in the stack, in practice a stack may contain many more than six stacks. Each HTS tape includes a region of HTS superconductor 1211 in addition to layers 1212 (e.g., substrate, buffer layers, an overlayer, etc.) and a stabilizer layer 1215 (e.g., copper). The dimensions of the tape may be different to that shown in FIG. 12A – for instance, the thickness of the HTS superconductor 1211 may represent 1% or less of the total thickness of each tape. As such, the total volume of HTS superconductor 1211 within the stack of HTS tapes shown in FIG. 12A may be a small fraction of the total volume of material.

[0085] In contrast, FIG. 12B illustrates a cross-sectional view of a monolithic volume of superconducting material arranged to produce windings of a superconducting magnet. Since the techniques described herein may allow for formation of superconducting material as a single volume, windings of superconducting material in a magnet produced in accordance with these techniques may consist only of, or may essentially consist of, superconducting material.

[0086] According to some embodiments, the techniques described herein may produce a superconducting magnet by depositing superconducting material onto a substrate that has a cross-section that is a closed shape, such as a D-shape, circular shape, or any other shape that defines a space or structure that is completely enclosed by lines, or unbroken contours. In some embodiments, the closed shape may have one or more openings. For instance, a closed circular shape may have a circular opening so that the cross-sectional shape is a toroidal shape such as an annulus. In some embodiments, a surface of the substrate onto which the superconducting material is deposited may have the aforementioned cross-sectional shape. For example, the surface of a substrate may have an annular shape, and superconducting material may be deposited in a spiral shapes around the annulus to form multiple turns of a winding of the magnet.

[0087] Referring now to FIG. 1, a substrate 10 (also sometimes referred to herein as a frame, support structure, or plate) is prepared such that a superconductor material can be deposited onto one or more surfaces of the substrate so as to form a superconductor layer such as superconductor 12 (FIG. 2). The substrate 10 combined with the superconductor layer can form a superconducting structure, such as a superconducting magnet.

[0088] In embodiments, the substrate 10 can be formed from one or more of a high-strength and/or high-stiffness thin (e.g., thin-rolled) metal alloy, an additively manufactured metal, or a fiber composite. As used herein, a high-strength substrate refers to any substrate having a yield strength greater than or equal to one GPa (>1 GPa yield strength). Such a yield strength is generally needed because the field strength of the magnet sets the forces and the size of the structure then sets the stresses. So, if one wants a compact, high-field magnet, it must be made of high strength materials. As used herein, a high-stiffness substrate refers to any substrate having a modulus of greater than or equal to 200 GPa (>200 GPa modulus). Such a yield strength is generally needed because the superconductor has a low strain limit. So a stiff structure has less strain for a given stress. As used herein, a thin substrate refers to any substrate having a thickness in the range of 10 μm to 10 mm. After reading the disclosure provided herein, one of ordinary skill in the art will appreciate how to select a substrate thickness to suit the needs of a particular application. In general, a thickness may be selected to meet the stress and/or strain requirements of a particular application. In embodiments, it may be

preferred that a thickness which is greater than that required to meet the stress and/or strain requirements of a particular application not be used such that a resulting structure does not include excess material (for size or weight, depending on application)..

[0089] In embodiments, the substrate (or frame) 10 is formed into a shape (or otherwise provided having a shape) that corresponds to a final magnet shape. Ideally, substrate 10 is provided in the form of a final magnet shape. This may be accomplished using a variety of techniques including, but not limited to additive manufacturing techniques such as direct metal laser sintering (DMLS). The substrate may also be made from a sub-section of the final shape that is then assembled into the final shape. The substrate could generally be a larger piece that is then reduced down in size by many different techniques as long as the technique selected to fabricate or otherwise provide the frame: (1) does not heat the superconductor to a point where characteristics of the superconductor are adversely changed (e.g., it is desirable to not excessively heat the superconductor); and (2) does not strain the superconductor to a point where characteristics of the superconductor are adversely changed or otherwise affected (e.g., does not excessively strain the superconductor). Heating and/or applying a strain to a point where characteristics of the superconductor are changed or otherwise affected may degrade the performance of the superconductor.

[0090] The final magnet shape of the substrate 10 can be a closed shape such as a D-shape, toroidal shape, circular shape, or any other shape that defines a space or structure that is completely enclosed by lines, or unbroken contours (see, e.g., FIG. 10 and 11A). In other examples, the substrate 10 can have an open shape such as a C-shape or any other shape that is not completely enclosed by lines and has broken contours. In further examples, the magnet shape (i.e., geometry) of the substrate 10 can be selected based on an anticipated load of the superconducting magnet. One of ordinary skill in the art will appreciate how to select a magnet shape to suit the needs of a particular application.

[0091] As used herein, a “final magnet shape” refers to the shape of the magnet once fabricated has completed and the magnet may be operated to produce a magnetic field. In some embodiments described herein, a substrate may be referred to as being provided with a shape that corresponds to the final magnet shape. It may be appreciated

that in such cases minor modifications to the substrate may be made without causing the shape of the substrate to no longer correspond to the final magnet shape. For instance, a small amount of material may be removed from a D-shaped substrate subsequent to deposition of superconducting material onto the substrate and fabrication of the magnet. In this case, the D-shape of the substrate may still correspond to that of the magnet, which is still substantially D-shaped, the removal of a small amount of material notwithstanding. As such, the term “final magnet shape” should not be viewed as strictly limiting the shape of the substrate to being identical to the shape of the magnet.

[0092] In embodiments, the substrate 10 may be prepared by depositing a buffer layer 11 on the substrate 10. The buffer layer 11 may be provided from one or more classes of substrates, including but not limited to, rolling assisted, biaxially textured substrates (RABiTS) and ion beam assisted deposition (IBAD) substrates, or combinations thereof. RABiT substrates may comprise a variety of materials including, but not limited to Y_2O_3 , YSZ, CeO_2 , or combinations thereof. IBAD substrates may be provided from a variety of materials including, but not limited to Al_2O_3 , Y_2O_3 , MgO, LMO, or combinations thereof. It should be noted that a given buffer may be made up of multiple layers. The buffer layer 11 can be configured to provide a surface texture appropriate for the superconductor to grow well-aligned crystals.

[0093] The buffer layer 11 can be deposited on those surfaces of the substrate required to form a magnet having characteristics suitable for the needs of the particular application. It should be note that in embodiments, edges of the substrate are sharp to have well-defined layers. It should be appreciated that the edge shape may be either dependent upon or as a result of the method used to form the magnet shape. In embodiments, the deposition process controls how close to the edge the buffer or superconductor get. In embodiments, the deposition process covers the whole surface in which case there may be a need for a subtractive step to define where the superconductor results.

[0094] Referring now to FIG. 2, a superconducting layer 12 can be deposited onto the surface of the substrate 10 to form a superconducting structure. The superconducting layer 12 may be provided from one or more of the following materials or a combination of such materials including but not limited to: a rare earth barium copper oxide

(REBCO) superconductor (such as may be provided by a number of different yttrium barium copper oxide (YBCO) compounds). In general, any superconductor for which there is a reliable industrial deposition process may be deposited onto the surface of the substrate (i.e., any superconductor capable of being deposited on the frame may be used).

[0095] In embodiments, depositing or otherwise providing superconductor material can include the use of additive or subtractive techniques. For example, a patterning technique may be used to provide the superconductor material onto the substrate 10 (e.g., using the process of photolithography and optical masks to print patterns on the frame that guide the deposition or removal of superconducting material from the substrate at specific steps or points in time during the superconducting magnet fabrication process). At each layer of the superconducting magnet (see, e.g., FIG. 4), material (e.g., superconducting or other material) may be deposited or removed in those areas not covered by the mask and then a new mask may be used on a next layer. The magnet-shaped frame may be repeatedly processed in this fashion to create multiple layers of circuitry. Laser etching techniques may also be used to selectively remove deposited superconductor material. Either technique may be used to form windings on the structure (i.e., the magnet-shaped frame). In further embodiments, laser ablation techniques can be used to remove superconducting material from the layer 12 to form the pre-defined patterns. A skilled artisan understands that any other technique, now known or later discovered, can be used to form the pre-defined patterns. In some embodiments, depositing the superconductor material may comprise any one or more of physical vapor deposition, pulsed laser deposition and/or reactive co-evaporation deposition.

[0096] In embodiments, the superconductor material may be deposited or otherwise provided in a pattern that defines a plurality of turns of a winding, such as a spiral shape. It should, of course, be appreciated that a varying number of turns in the spirals may be used. After reading the disclosure provided herein, one of ordinary skill in the art will appreciate how to select the number of turns to use in any particular application to suit the needs of the application. Furthermore, the particular pattern (e.g., the particular spiral pattern) to use for any particular application can be selected by taking into account a variety of factors. For example, a particular magnet design may require a certain amount of current flowing in a certain number of turns. In some cases, the required current may be achieved by producing all of the current in a single turn of a

winding. In these cases, the magnet design may have a low inductance with a high current. Alternatively, the same required current may be produced over many turns, in which case the magnet design may have a high inductance with a low current.

[0097] Referring now to FIG. 3, a protective layer 14 is deposited or otherwise disposed over the superconducting layer 12. The protective layer 14 is configured to protect the superconducting layer 12. In embodiments, the protective layer 14 may be formed or otherwise provided as a diffusion barrier configured to prevent corruption of layers disposed on opposing surfaces of the diffusion barrier. In embodiments, the protective layer 14 can comprise stabilizing conductors (also referred to as a stabilizer) configured to provide one or more paths through which current may flow if current is not solely flowing through the superconductor (e.g., if the superconductor is in a normal, non-superconducting, state). In embodiments, the stabilizer may comprise an electrically conductive material (e.g., a metal such as copper), which gives the current a path to flow around if current is not solely flowing through the superconductor (e.g., if the superconductor is in a normal, non-superconducting, state). In embodiments, stabilizing conductors thus stabilize the tape thereby reducing the chance of damage to the superconductor during a quench (an event in which heating or other effects during operation lead to the superconductor losing its superconducting properties).

[0098] In embodiments, the protective layer 14 may comprise silver, copper, brass, or combinations of these and/or other materials. In embodiments, silver is a typical diffusion barrier. In embodiments, copper is a common stabilizer. In embodiments, brass is sometimes also used. In embodiments, the protective layer 14 can comprise any combination of the aforementioned materials.

[0099] Referring to the example of FIG. 4, a superconducting structure 30 may comprise a plurality of superconducting structure layers 16a-n, generally denoted 16. Each of the layers 16 may comprise a respective one of substrate layers 10a-n on which a superconducting layer 12a-n is disposed. Protective layers 14a-n are disposed on each of the superconducting layers 12a-n. The number of layers n to include in superconducting structure 30 is selected in accordance with a variety of factors including but not limited to the amount of current needed for a given designed magnet performance. That is, the number of layers to use in a particular application must be a large enough number of

superconducting layers to carry the current needed for a given designed magnet performance. In general, the greater the number of superconducting layers 16, the greater the superconducting capability for the superconducting structure 30. Superconducting capability may for instance be on the order of $\sim 1000 \text{ A/mm}^2$. The number of layers may depend on the intended application of the superconducting structure and available manufacturing capabilities.

[00100] FIGs. 5-9, discussed below, depict additional example alternatives to the embodiments illustrated in FIGs. 1-4 and which include additional materials not present in the embodiments of FIGs. 1-4. Notwithstanding the presence of these additional materials, the techniques described above in relation to FIGs. 1-4 may also be applied to the embodiments of FIGs. 5-9 with respect to the elements that are present in each embodiment. For instance, FIG. 5 includes cooling channels within the substrate layers, but it will be appreciated that the superconductor layers and protective layers in the example of FIG. 5 may be arranged and fabricated in the same manner as discussed above. Similarly, while the substrates of FIG. 5 include cooling channels, it will be appreciated that the substrates of FIG. 5 may otherwise be arranged and fabricated as discussed above in relation to the substrates of FIGs. 1-4.

[00101] Referring to FIG. 5, each of substrate layers 10a-n can comprise one or more cooling channels 18. Cooling channels 18 are provided having a size and shape which helps cool the superconducting structure 30 during high temperature operations (e.g., during operations in the temperature range typically of about 4 K to about 77 K. It should be appreciated that operating temperature ranges will vary (i.e., be different) for different applications. Accordingly, the cooling channels 18 are configured to (i.e., provided having structural and/or thermal characteristics selected to) keep the superconducting structure 30 at an operational temperature. As such, the cooling channels 18 in each layer are configured to pass a cooling fluid through the substrate layers 10a-n to dissipate heat from the structure 30. In embodiments, some or all of the cooling channels 18 in each of the layers 10a-n are in fluid communication (i.e., there is fluid communication among at least some cooling channels in all layer 10a-n). In embodiments, some or all of the cooling channels 18 in each respective layer are in fluid communication (i.e., there is fluid communication among at least some cooling channels within a single layer, but not among different layers). In embodiments, some or all of the

cooling channels 18 in each respective layer are separate from other cooling channels (i.e., at least some cooling channels within a single layer are not in fluid communication with any other cooling channel 18). This different cooling channels 18 may be provided having different fluids flowing, or otherwise provided, therein.

[00102] The cooling channels 18a-n can be provided using any one of a variety of different techniques including, but not limited to any additive or subtractive technique(s). In particular, cooling channels may be made through additive manufacturing processes, by fabricating a substrate that comprises voids for the channels. Substrates also may be made with subtractive processes to form the channel, such as by removing material from the substrate after it is fabricated. In some cases, forming the cooling channels may comprise inserting tubes onto and/or into the substrate structure. The number of cooling channels used is determined by the cooling power of each channel and the cooling power required for the magnet. Increasing the number of cooling channels reduces the amount of structural space to handle the forces. Thus, a trade-off exists between the number, size (e.g., diameter, area or volume) and shape of the cooling channels and structural integrity of the substrate.

[00103] In embodiments, the cooling channels 18 can be formed or otherwise provided as annular channels (channels with an annular cross-section) within the substrate layers 10a-n. In general, annular structures are more common than open channels (channels with a circular cross-section) although in some embodiments, either open or annular channels may be used. Superconducting magnets are typically housed in a vacuum to reduce the heat transfer to surrounding structures. Thus, the use of open channels could cause evaporation, degrading the vacuum. Another possibility is a magnet in a “bath” of the cryogen. Here, the annular structures serve to constrain the flow. Cross-sectional shape is designed to handle the pressure of the coolant, have sufficient area to get high enough mass flow rate, and/or high enough surface area to get appropriate heat transfer.

[00104] Referring now to FIG. 6, a layer of an electric insulator 20 can be disposed between superconducting structure layers 16a-16n. The insulating layer 20 functions to provide well-defined current paths, and thus high-precision magnet performance. It also serves to reduce (essentially to zero) the leakage current between superconducting

windings, which allows for quick charging and discharging. This is in contrast to no-insulation magnets. The electric insulator 20 can be comprised of one or more of the following materials either individually or in combination including but not limited to: glass epoxy resin composites, polyimide tapes, various oxides (alumina). The composites, tapes and oxides may be applied using any suitable technique or techniques.

[00105] In other embodiments and referring now to FIG. 7, electric insulators 22a-n can encapsulate superconducting layers 12a-n. For example, each of the superconducting layers 12a-n can comprise patterns of superconducting elements disposed on each of the substrate layers 10a-n. In such examples, the electric insulators 22a-n encapsulate the superconducting elements. In embodiments, the insulator may completely surround each superconducting layer from the other superconducting layers, and may for instance be arranged under the buffer layers and/or be arranged within a cut through the substrates.

[00106] Referring to now to FIG. 8, in some embodiments a semiconductor layer 24 can be disposed between superconducting structure layers 16a-16n. The semiconductor 24 is configured to provide a high resistance to current flow at low voltages and low resistance to current at high voltages. semiconductor 24 could serve as a “switch” to allow current to flow out of the superconductor in the case of a fault, but restricts the current to flow in the superconductor under standard operation. The semiconductor 24 can be comprised of one or more of the following materials either individually or in combination including but not limited to: Si, Ge, Ga, In based semiconductors with appropriate donors (including but not limited to: P, As, Sb, S, Se, Te, or combinations thereof) or acceptors (including but not limited to: B, Al, Ga, Zn, Cd, or combinations thereof).

[00107] In other embodiments and referring now to FIG. 9, semiconductor elements 26a-n can encapsulate superconducting layers 12a-n. For example, each of the superconducting layers 12a-n can comprise patterns of superconducting elements disposed on each of the substrate layers 10a-n. In such examples, the semiconductor elements 26a-n encapsulate the superconducting elements using conventional techniques known to those of ordinary skill in the art.

[00108] Referring now to FIG. 10, a superconductor deposition system 50 is operable to deposit a superconductor onto a surface of a substrate 10. Example superconductor deposition systems include but are not limited to: a 350 mm wide web, 300 mm wide Plasma Enhanced Chemical Vapor Deposition (PECVD) system of SiO_x on a polymer substrate as described by “Roll to Roll PECVD system for transparent High Barrier Coating,” H Tamagaki et al., (2013); a 0.6 to 3 m roll-to-roll system such as described by “Roll-to-roll Manufacturing of Thin Film Electronic,” J. Sheats, Proc. SPIE 4688, p. 240; a 150 mm wide flexible solar cell such as described by “Electrodeposition of In-Se and Ga-Se Thin Films for Preparation of CIGS Solar Cells,” S. Aksu et al., Electrochem. Solid-State Lett. 2009 12(5): D33-D35; Slot die coaters 300 mm wide as described by “Roll-to-Roll Fabrication of Large Area Functional Organic Materials,” R. Sondergaard et al., J. Polym. Sci. B Polym. Phys., 51: 16-34; REBCO manufactured in 40 mm wide webs in machines capable of 100 mm wide as described by “Advances in second generation high temperature superconducting wire manufacturing and R&D at American Superconductor Corporation,” M. Rupich et al., Superconducting Science and Technology, Vol. 23, No. 1 (2009); REBCO manufactured in 120 mm and 260 mm widths as described by “HTS Development and Industrialization at SuNAM,” S. Moon, First Workshop on Accelerator Magnets in HTS (2014).

[00109] In the example of FIG. 10, the substrate 10 defines a macroscopic, full-sized D-shaped magnet structure (e.g., a macroscopic, full-sized D-shaped magnet structure for the fusion system 100 illustrated in FIG. 10B – e.g., having diameters in the range of about 1 m to about 4 m for use in a tokamak reactor and having diameters in the range of about 1 cm for NMR type applications.).

[00110] The superconductor deposition system 50 can be configured to evenly distribute a superconductor along a width of the substrate. In an example embodiment, the system 50 can be disposed on a rail assembly (not shown). The rail system enables the deposition system 50 to move along the surface of the substrate 10 such that the deposition system 50 can deposit the superconductor. In some embodiments, the deposition system 50 may deposit the superconductor during motion, or may move, stop, and deposit the superconductor before moving again. In some embodiments, the substrate 10 can be disposed on a platform which causes the substrate to move with respect to the deposition system 50 such that the superconductor is evenly deposited on

the substrate's surface. For example, the platform may be tilted, thereby tilting the surface of the substrate such that it is further away on the smaller radius, thus having a lower flux to compensate for the slower rate passing over that area.

[00111] Referring to now to FIG. 10A, a magnet 105 having a D-shaped magnet structure such as the shape defined by the substrate 10 of FIG. 10 can comprise a plurality of superconducting layers 16a-n. Each of the layers 16a-n can comprise substrate layers 10a-n that have a macroscopic, full-sized D-shaped magnet structure for use with, e.g., a fusion system (e.g., the fusion system 100 of FIG. 10B). The superconductor deposition system 50 of FIG. 10 deposits superconducting layers 12a-n onto each of the substrate layers 10a-n as discussed above. Additionally, the deposition system 50 can deposit protective layers 14a-n onto each of the superconducting layers 12a-n.

[00112] Referring now to 10B, a fusion system 100 is configured to produce fusion power. The system 100 comprises a plasma tube 102 and a plurality of superconducting magnets 105a-n. These magnets 105a-n may be the same as or similar to the magnetic 105 described in FIG 10A. For example, each of the magnets 105a-n includes a series of stacked plates (i.e., stacked superconducting structures 16a-n). As current flows through the superconducting layers (e.g., superconducting layers 12a-n of FIG. 10A) of the staked plates, a magnetic field is generated.

[00113] For instance, during energy generation, high temperature plasma (which fuels the fusion reaction) circulates within plasma tube 102. Because the plasma is at such high temperatures, if it were to contact the walls of plasma tube 102 it could destroy plasma tube 102. Thus, system 100 generates magnetic fields, using the magnets 105a-n, that compress and suspend the plasma into a stream within plasma tube 102 that does not contact the walls of plasma tube 102.

[00114] Referring now to FIG. 11, an MRI system 110 is configured to use a strong magnetic field and radio waves to create detailed images of organs and tissues within a person's body. The MRI system 110 comprises a patient table 130 on which the patient is delivered into a tube defined by the MRI system 110 for scanning. A scanner 125 uses magnets 106, radio frequency (RF) coils 115, and gradient coils 120 to create the images.

[00115] The magnets 106 can be superconducting magnets that can create a magnetic field of up to about 2.0 tesla. Maintaining such a large magnetic field requires a good deal of energy, which can be accomplished by using superconductive structures such as superconductive structures 16a-n of FIG. 11B.

[00116] Referring now to FIG. 11A, a superconductor deposition system 50 is configured to create a magnet 106. The superconductor deposition can include those types of deposition systems described above in reference to FIG. 10. The deposition system 50 is operable to deposit a superconductor onto a substrate 11. The substrate 11 can be a macroscopic, full-sized O-shaped (annular) magnet structure (e.g., an O-shaped magnet structure for use with the MRI system 110 of FIG. 11). The superconductor deposition system 50 can be configured to evenly distribute a superconductor along a width of the substrate. In an example embodiment, the system 50 can be disposed on a rail assembly (not shown). The rail system enables the deposition system 50 to move along the surface of the substrate 10 such that the deposition system 50 can deposit the superconductor. In other examples, the substrate 11 can be disposed on a platform which causes the substrate to move with respect to the deposition system 50 such that the superconductor is evenly deposited on the substrate's surface.

[00117] Referring now to FIG. 11B, a magnet 106 having an O-shaped magnet structure such as the shape defined by the substrate 11 of FIG. 11A can comprise a plurality of superconducting layers 16a-n. Each of the layers 16a-n can comprise substrate layers 11a-n that have the macroscopic, full-sized O-shaped magnet structure for use with, e.g., the MRI system 110 of FIG. 11. The superconductor deposition system 50 of FIG. 11A deposits superconducting layers 12a-n onto each of the substrate layers 11a-n as discussed above. Additionally, the deposition system 50 can deposit protective layers 14a-n onto each of the superconducting layers 11a-n.

[00118] This disclosure relates to systems for manufacturing or otherwise providing superconducting magnets for use in a wide variety of applications. It should be appreciated that while reference may be made herein to specific applications, such references are made solely to promote clarity in explaining the broad concepts described herein. It should be appreciated that the concepts, systems, circuits and techniques described herein find use in a wide variety of different applications.

[00119] For example, after reading the description provided herein, one of ordinary skill in the art will readily appreciate that the concepts, systems, circuits and techniques described herein are generally applicable for use in a wide range of applications (e.g., a wide range of industrial uses) which may make use of high-field magnets and that the described manufacturing processes may facilitate commercialization of high-field magnets for use in a wide variety of different applications. Such applications include but are not limited to: applications in the medical and life sciences field (e.g., magnetic resonance imaging and spectroscopy); applications in the chemistry, biochemistry and biology fields (e.g., nuclear magnetic resonance (NMR), NMR spectroscopy, electron paramagnetic resonance (EPR), and Fourier-transform ion cyclotron resonance (FT-ICR)); applications in particle accelerators and detectors (e.g., for use in health care applications such as in instruments for radiotherapy); application in devices for generation and control of hot hydrogen plasmas; applications in the area of transportation; applications in the area of power generation and conversion; applications in heavy industry; applications in weapons and defense; applications in the area of high-energy particle physics; and applications in the area of fusion power plants (e.g., compact fusion power plants).

[00120] Thus, although reference is sometimes made herein to the use of high-field magnet assemblies including the subject control circuits in connection with a specific application (e.g., fusion or MRI) such references are not intended to be, and should not be construed as, limiting. Rather, it should be appreciated that manufacturing processes for high-field magnet assemblies provided in accordance with the concepts described herein find use in a wide variety of applications.

[00121] After reading the description of the concepts, systems, and techniques provided herein, one of ordinary skill in the art will recognize that the concepts, systems, and techniques described herein may be embodied in other specific forms without departing from the spirit or essential characteristics of the described. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting of the concepts described herein. Scope of the concepts is thus indicated by the appended claims, rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

[00122] Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

[00123] The terms “approximately” and “about” may be used to mean within $\pm 20\%$ of a target value in some embodiments, within $\pm 10\%$ of a target value in some embodiments, within $\pm 5\%$ of a target value in some embodiments, and yet within $\pm 2\%$ of a target value in some embodiments. The terms “approximately” and “about” may include the target value. The term “substantially equal” may be used to refer to values that are within $\pm 20\%$ of one another in some embodiments, within $\pm 10\%$ of one another in some embodiments, within $\pm 5\%$ of one another in some embodiments, and yet within $\pm 2\%$ of one another in some embodiments.

[00124] The term “substantially” may be used to refer to values that are within $\pm 20\%$ of a comparative measure in some embodiments, within $\pm 10\%$ in some embodiments, within $\pm 5\%$ in some embodiments, and yet within $\pm 2\%$ in some embodiments. For example, a first direction that is “substantially” perpendicular to a second direction may refer to a first direction that is within $\pm 20\%$ of making a 90° angle with the second direction in some embodiments, within $\pm 10\%$ of making a 90° angle with the second direction in some embodiments, within $\pm 5\%$ of making a 90° angle with the second direction in some embodiments, and yet within $\pm 2\%$ of making a 90° angle with the second direction in some embodiments.

[00125] The terms “consist essentially of” or “consisting essentially of” a material may be used to refer to an element that contains at least 80% of the material in some embodiments, at least 90% of the material in some embodiments, at least 95% of the material in some embodiments, at least 97% of the material in some embodiments, at least 98% of the material in some embodiments, at least at least 99% of the material in some embodiments, or 100% of the material in some embodiments. For example, where a winding is referred to as consisting essentially of an HTS superconductor, the winding may contain only the HTS superconductor, or may in some embodiments be made up of

at least 80% of the HTS superconductor, in some embodiments be made up of at least 90% of the HTS superconductor, in some embodiments be made up of at least 95% of the HTS superconductor, in some embodiments be made up of at least 97% of the HTS superconductor, in some embodiments be made up of at least 98% of the HTS superconductor, or in some embodiments be made up of at least 99% of the HTS superconductor. The percentages referred to in this paragraph may refer to composition by weight or by volume.

[00126] Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having,” “containing,” “involving,” and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

CLAIMS

1. A superconducting magnet comprising:
a plurality of high temperature superconductor (HTS) winding layers including a first HTS winding layer arranged over a second HTS winding layer, each of the plurality of HTS winding layers comprising:
a substrate;
an HTS winding consisting essentially of an HTS material deposited on the substrate; and
a protective layer arranged over the HTS winding and the substrate,
wherein the protective layer of the second HTS winding layer is in contact with the substrate of the first HTS winding layer.
2. The superconducting magnet of claim 1, wherein the HTS material is a rare earth barium copper oxide superconductor.
3. The superconducting magnet of claim 1, wherein each of the plurality of HTS winding layers further comprises an insulating layer arranged between the HTS winding and the protective layer.
4. The superconducting magnet of claim 1, wherein the protective layer of the first HTS winding layer is in contact with the HTS winding of the first HTS winding layer and is in contact with the substrate of the first HTS winding layer.
5. The superconducting magnet of claim 1, further comprising one or more cooling channels arranged within substrates of the plurality of HTS winding layers.
6. The superconducting magnet of claim 1, wherein the substrate comprises a metal alloy and/or a fiber composite.

7. The superconducting magnet of claim 1, wherein at least some of the substrates of the plurality of HTS winding layers have cross-sectional shape that is a closed shape with an opening.
8. The superconducting magnet of claim 7, wherein the cross-sectional shape that is a closed shape with an opening is an annulus or a D-shape.
9. The superconducting magnet of claim 1, wherein the protective layer comprises silver.
10. The superconducting magnet of claim 1, wherein the protective layer comprises copper.
11. The superconducting magnet of claim 1, wherein the protective layer comprises brass.
12. A method of making a superconducting magnet, the method comprising:
applying a mask to a surface of a substrate to define a plurality of turns of a winding, wherein the surface of the substrate has a closed shape with an opening;
depositing a layer of high temperature superconductor (HTS) onto one or more portions of the surface defined by the mask.
13. The method of claim 12, wherein the substrate is electrically conductive.
14. The method of claim 12, further comprising depositing a protective layer over the layer of HTS.
15. The method of claim 14, wherein the protective layer is electrically conductive.
16. The method of claim 12, further comprising depositing an electrical insulator onto the layer of HTS.

17. The method of claim 12, further comprising depositing a buffer layer onto the surface of the substrate prior to depositing the layer of HTS onto the portions of the surface.
18. The method of claim 12, further comprising fabricating the substrate via additive fabrication.
19. The method of claim 18, wherein the substrate comprises one or more cooling channels.
20. The method of claim 12, wherein depositing the layer of HTS onto the portions of the surface comprises depositing the layer using physical vapor deposition, pulsed laser deposition and/or reactive co-evaporation deposition.
21. A method of making a superconducting magnet, the method comprising:
depositing a layer of high temperature superconductor (HTS) onto a surface of a substrate, wherein the surface of the substrate has a closed shape with an opening;
laser etching the layer of HTS to define one or more turns of a winding.
22. The method of claim 21, wherein the substrate is electrically conductive.
23. The method of claim 21, further comprising depositing a protective layer over the layer of HTS.
24. The method of claim 23, wherein the protective layer is electrically conductive.
25. The method of claim 21, further comprising depositing an electrical insulator onto the layer of HTS.
26. The method of claim 21, further comprising depositing a buffer layer onto the surface of the substrate prior to depositing the layer of HTS.

27. The method of claim 21, further comprising fabricating the substrate via additive fabrication.
28. The method of claim 27, wherein the substrate comprises one or more cooling channels.
29. The method of claim 21, wherein depositing the layer of HTS onto the surface comprises depositing the layer using physical vapor deposition, pulsed laser deposition and/or reactive co-evaporation deposition.
30. A method of making a superconducting magnet, the method comprising:
preparing a surface of a substrate for deposition of a superconductor, the substrate having a closed shape corresponding to a final magnet shape;
masking the surface so as to define a superconductor pattern; and
depositing a superconductor layer onto the surface, the superconductor layer comprising a superconductor.
31. The method of claim 30, wherein the substrate comprises a high-strength, high-stiffness, and macroscopic scale material.
32. The method of claim 31, wherein the material comprises one or more of a thin-rolled metal alloy, an additive manufactured metal, and a fiber composite.
33. The method of claim 30, wherein the final magnet shape is selected based at least on an anticipated electromagnetic load of the substrate.
34. The method of claim 30, wherein preparing the substrate's surface comprises depositing a buffer layer on the substrate's surface.
35. The method of claim 30, further comprising depositing a protective layer on the superconductor layer.

36. The method of claim 35, further comprising depositing one or more additional layers comprising sets of another substrate on which other superconductor and protective layers are deposited.
37. The method of claim 30, further comprising forming cooling channels in the substrate.
38. The method of claim 36, further comprising depositing an electric insulator between the sets of superconductor and protective layers.
39. The method of claim 30, further comprising encapsulating the superconductor with an electric insulator.
40. The method of claim 36, further comprising depositing a semiconductor layer between the sets of superconductor and protective layers.
41. The method of claim 30, further comprising encapsulating the superconductor with a semiconductor.
42. A method of making a superconducting magnet, the method comprising:
preparing a surface of a substrate for deposition of a superconductor, the substrate having a closed shape corresponding to a final magnet shape;
depositing a superconductor layer onto the surface, the superconductor layer comprising a superconductor; and
laser etching the superconductor layer to define a superconductor pattern.
43. The method of claim 42, wherein the substrate comprises one or more of a thin-rolled metal alloy, an additive manufactured metal, and a fiber composite.
44. The method of claim 42, wherein the final magnet shape is selected based at least on an anticipated electromagnetic load of the substrate.

45. The method of claim 42, wherein preparing the substrate's surface comprises depositing a buffer layer on the substrate's surface.
46. The method of claim 42, further comprising depositing a protective layer on the superconductor layer.
47. The method of claim 42, further comprising forming cooling channels in the substrate.
48. A method of making a superconducting magnet, the method comprising:
preparing a surface of a substrate for deposition of a superconductor, the substrate having a closed shape corresponding to a final magnet shape;
selectively depositing a superconductor layer onto the surface to define a superconductor pattern; and
wherein the superconductor layer comprises a superconductor.
49. The method of claim 48, wherein the final magnet shape is selected based at least on an anticipated electromagnetic load of the substrate.

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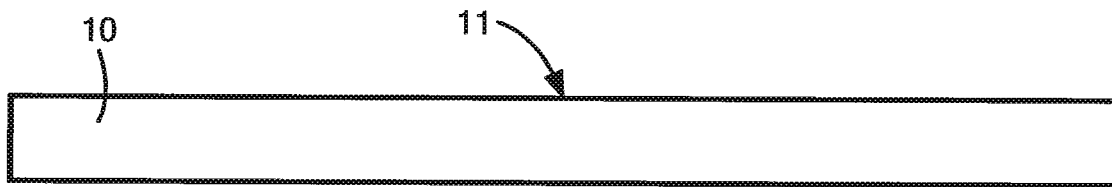


FIG. 1

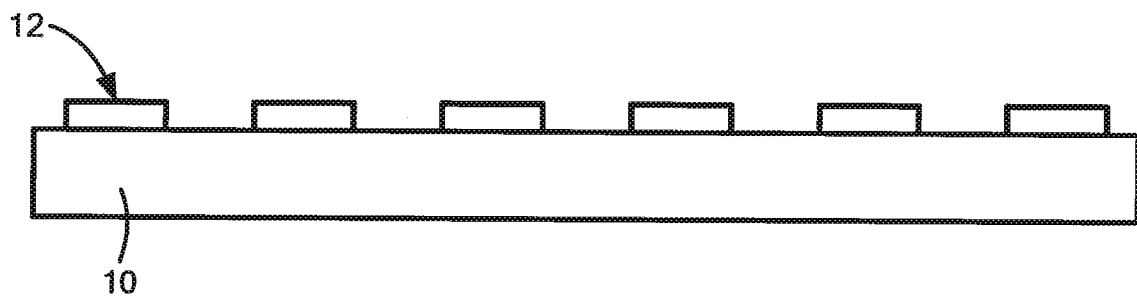


FIG. 2

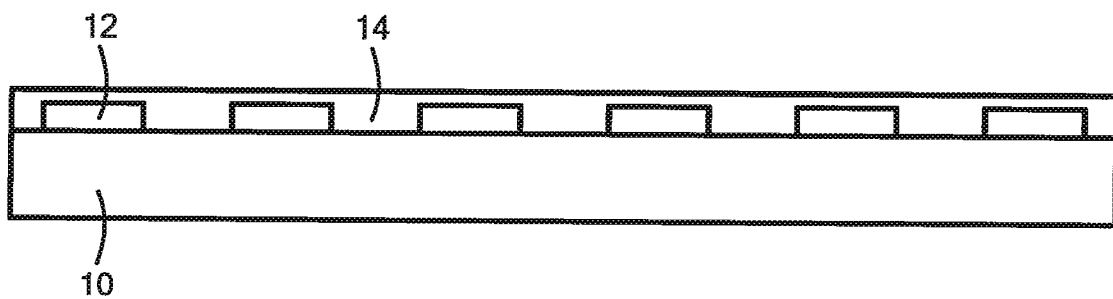


FIG. 3

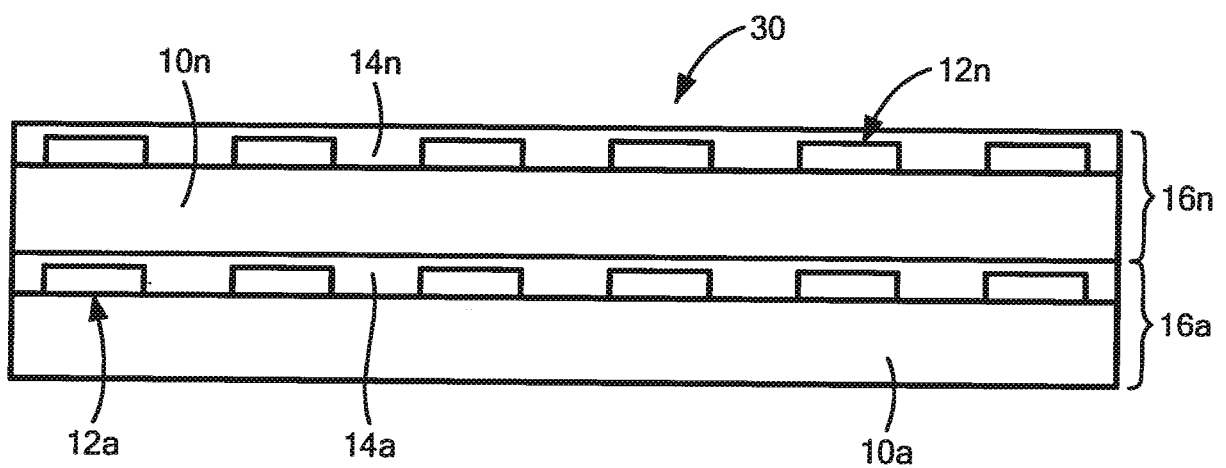


FIG. 4

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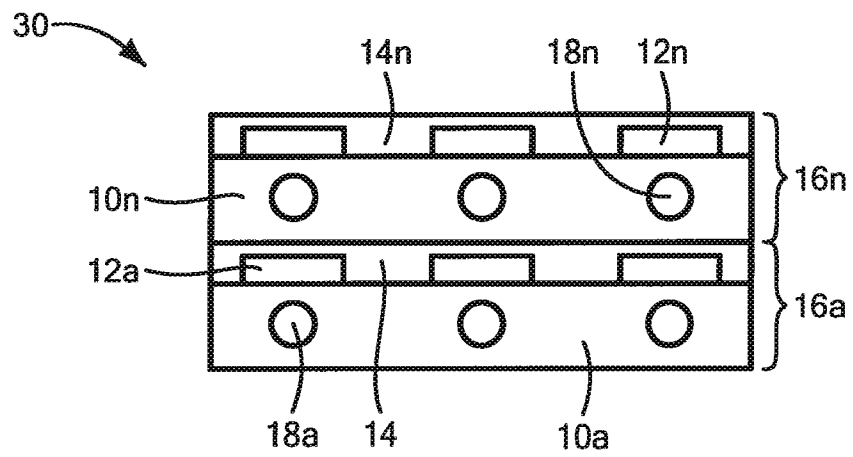


FIG. 5

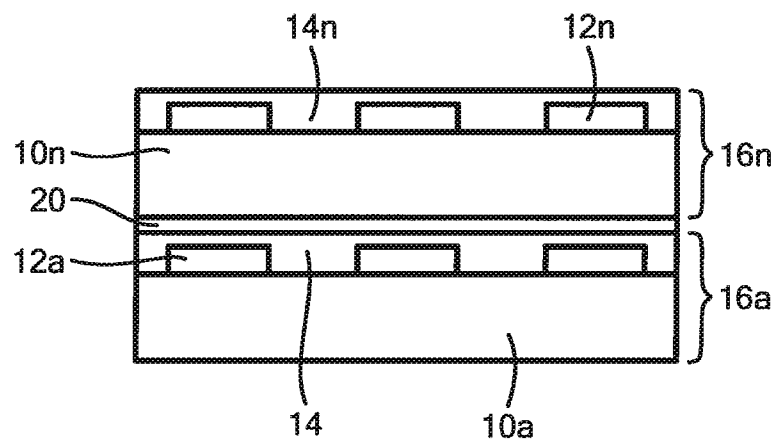


FIG. 6

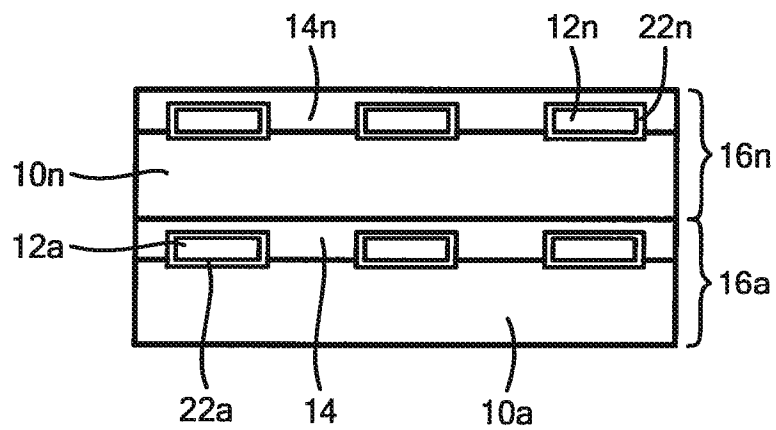
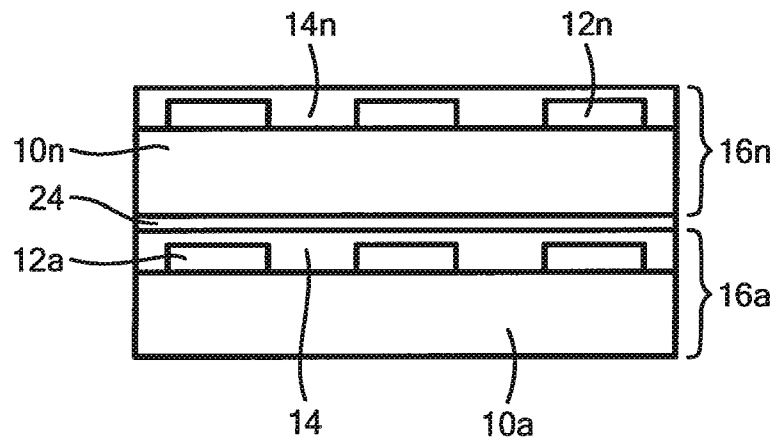
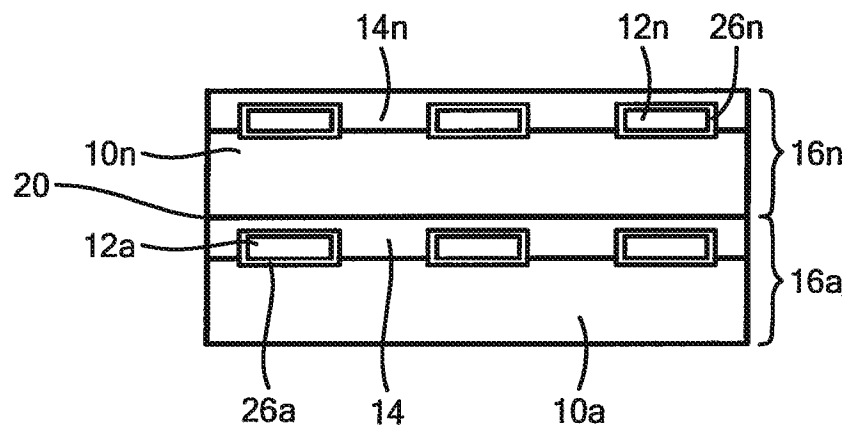


FIG. 7

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**FIG. 8****FIG. 9**

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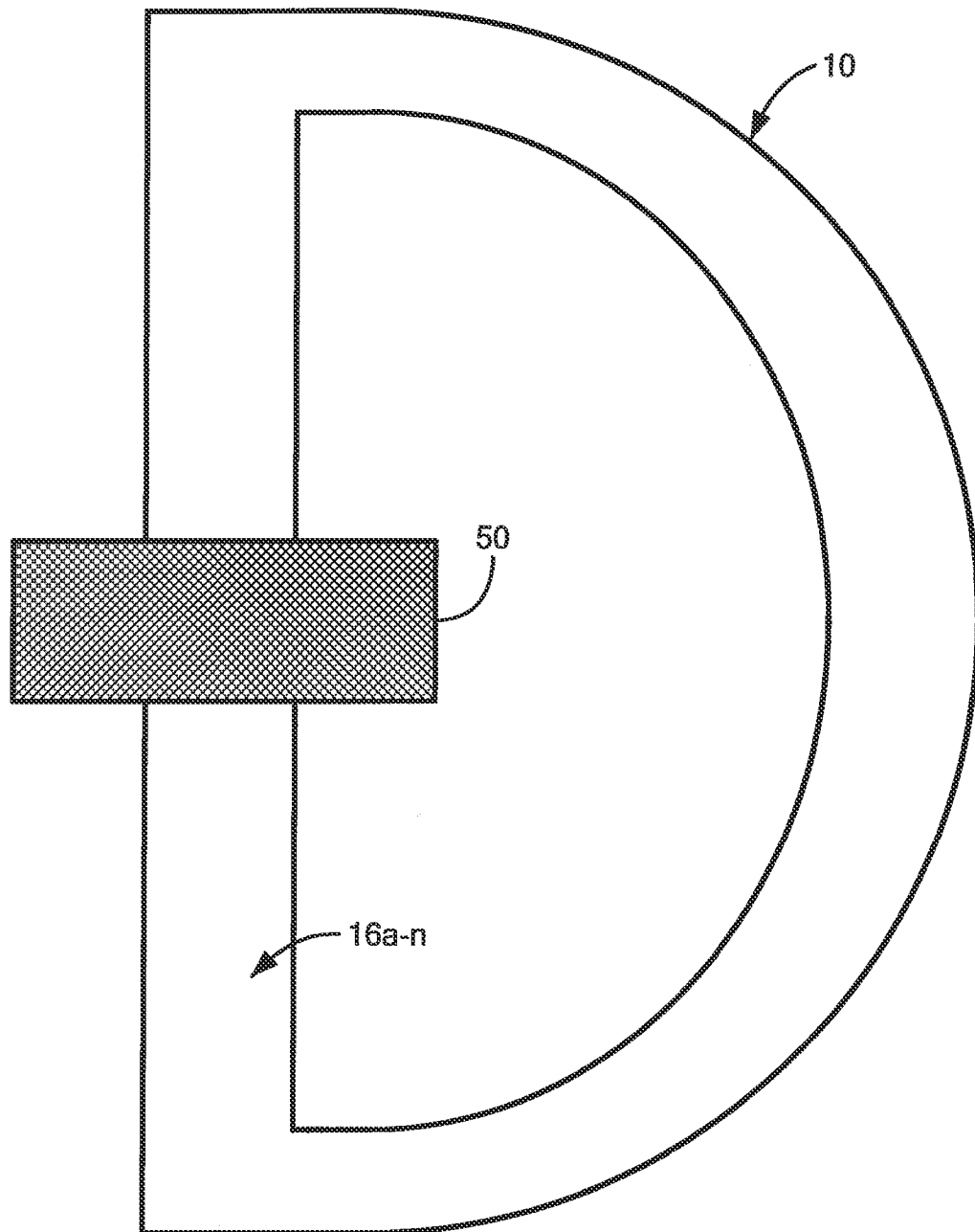


FIG. 10

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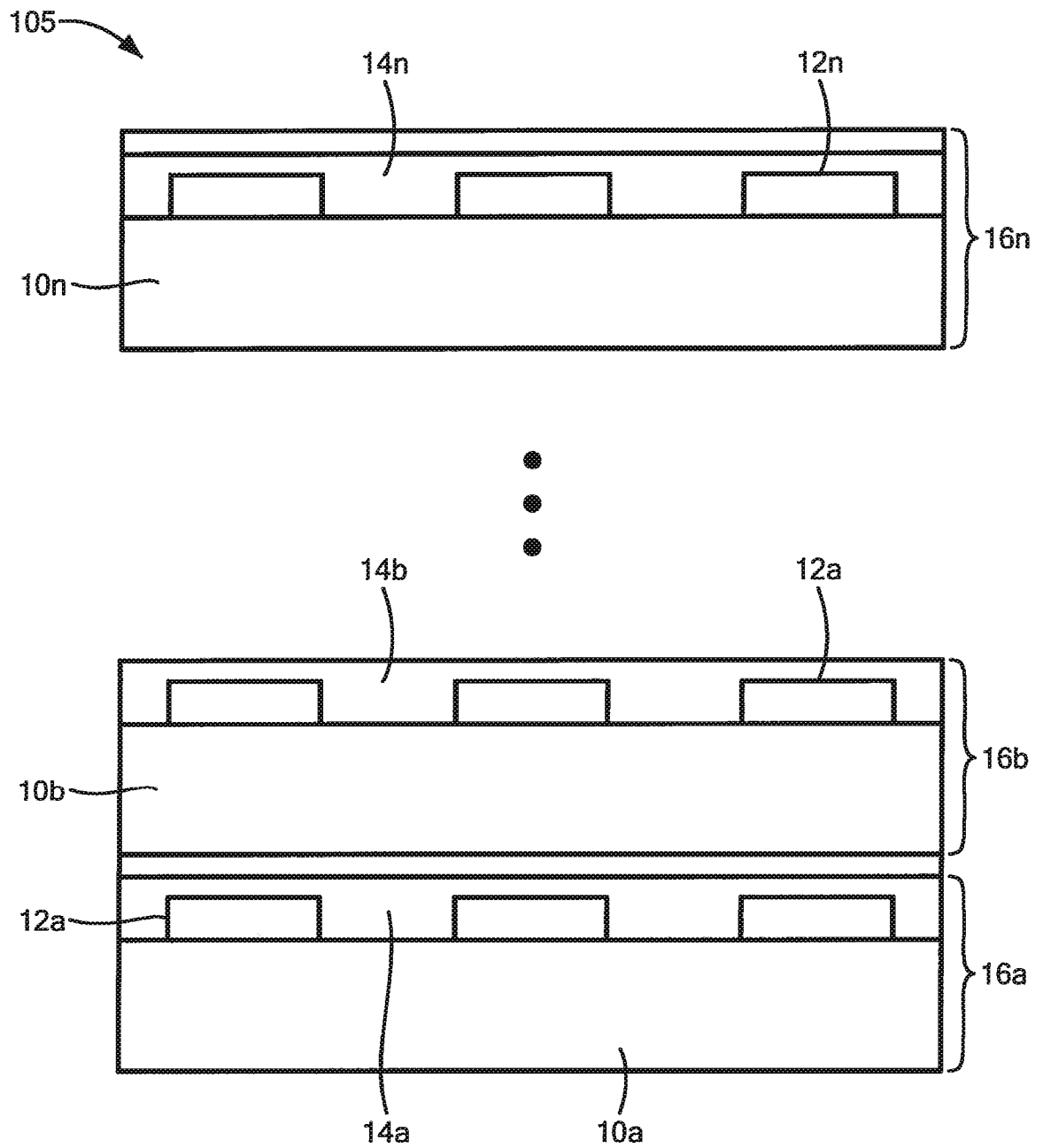


FIG. 10A

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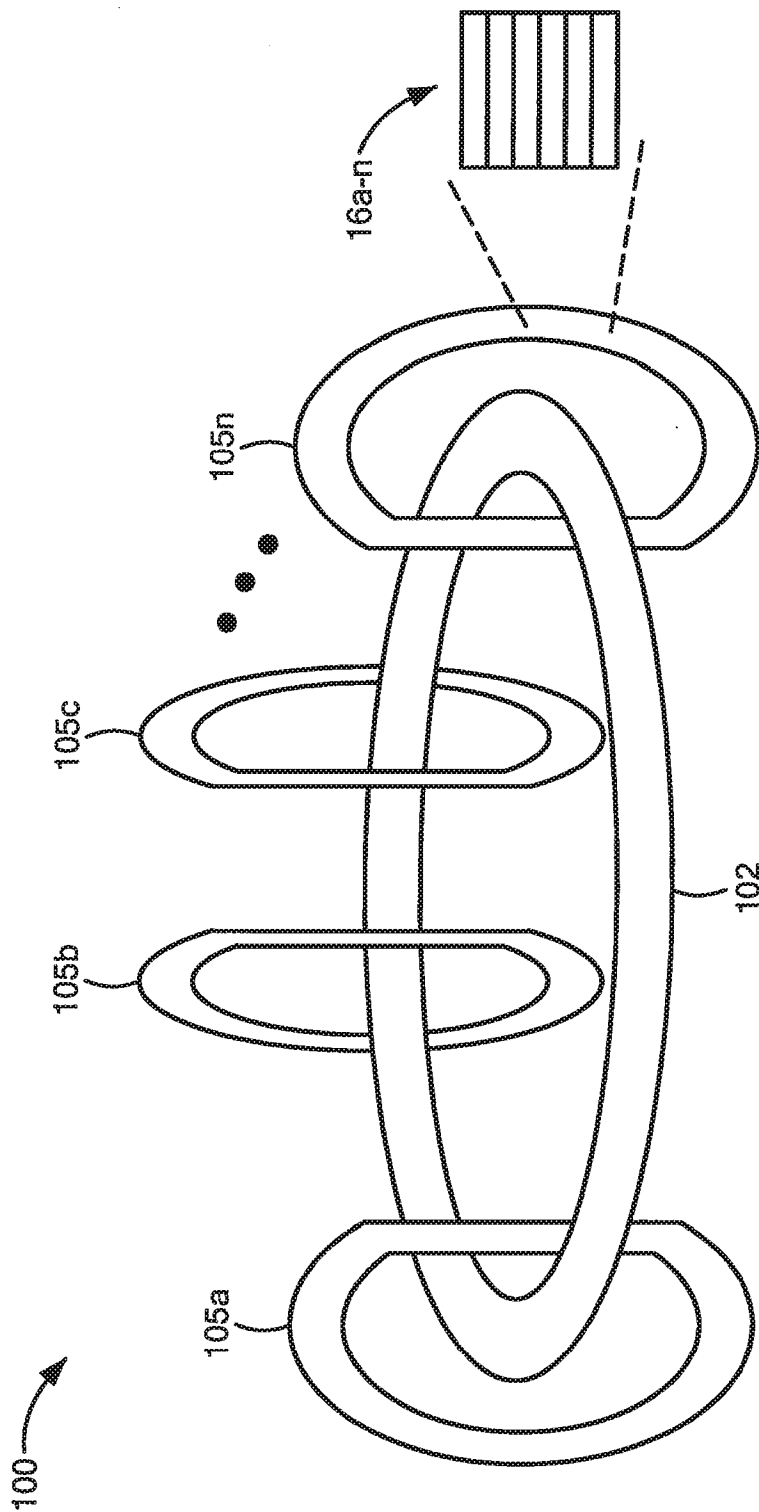


FIG. 10B

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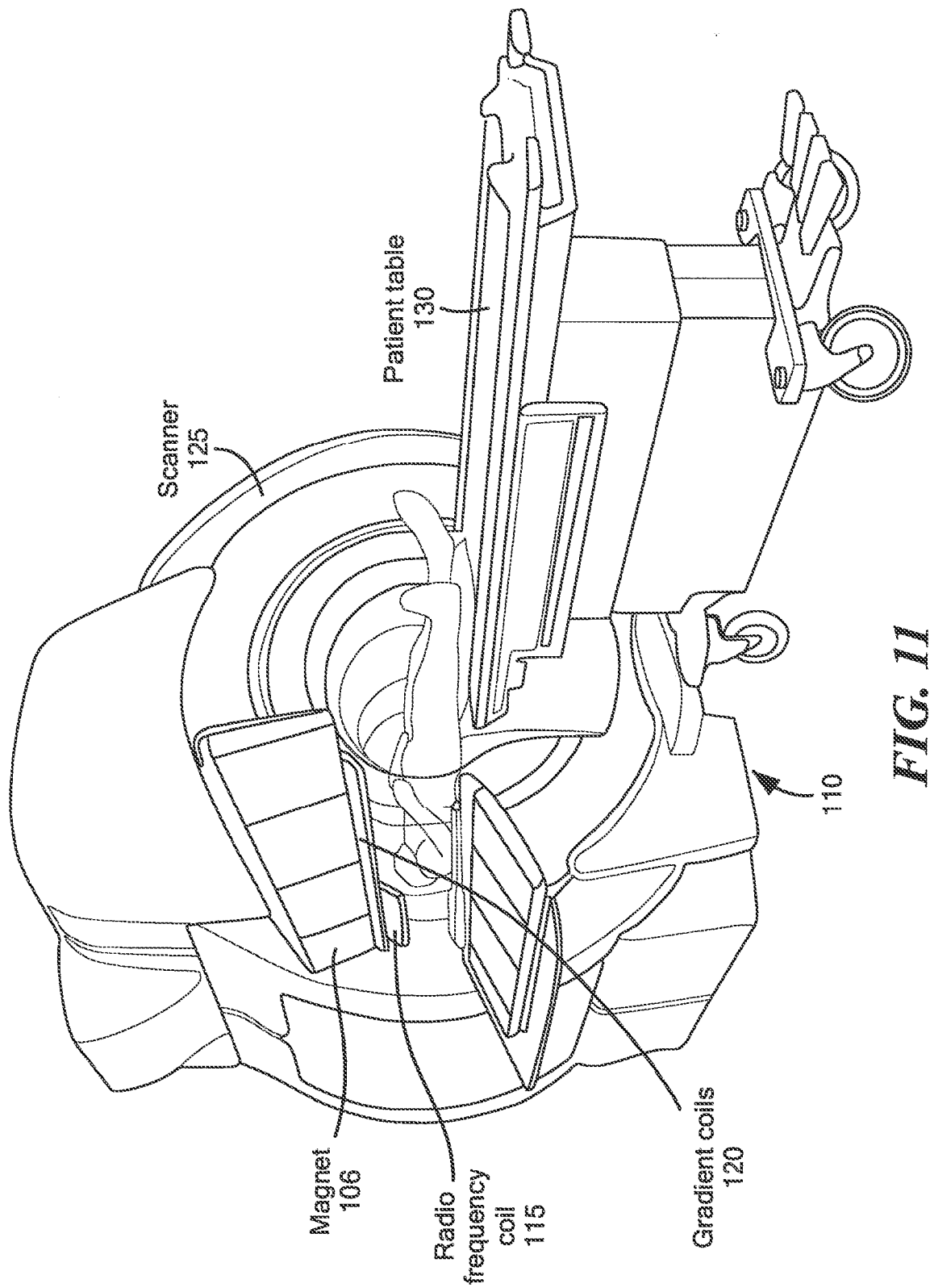
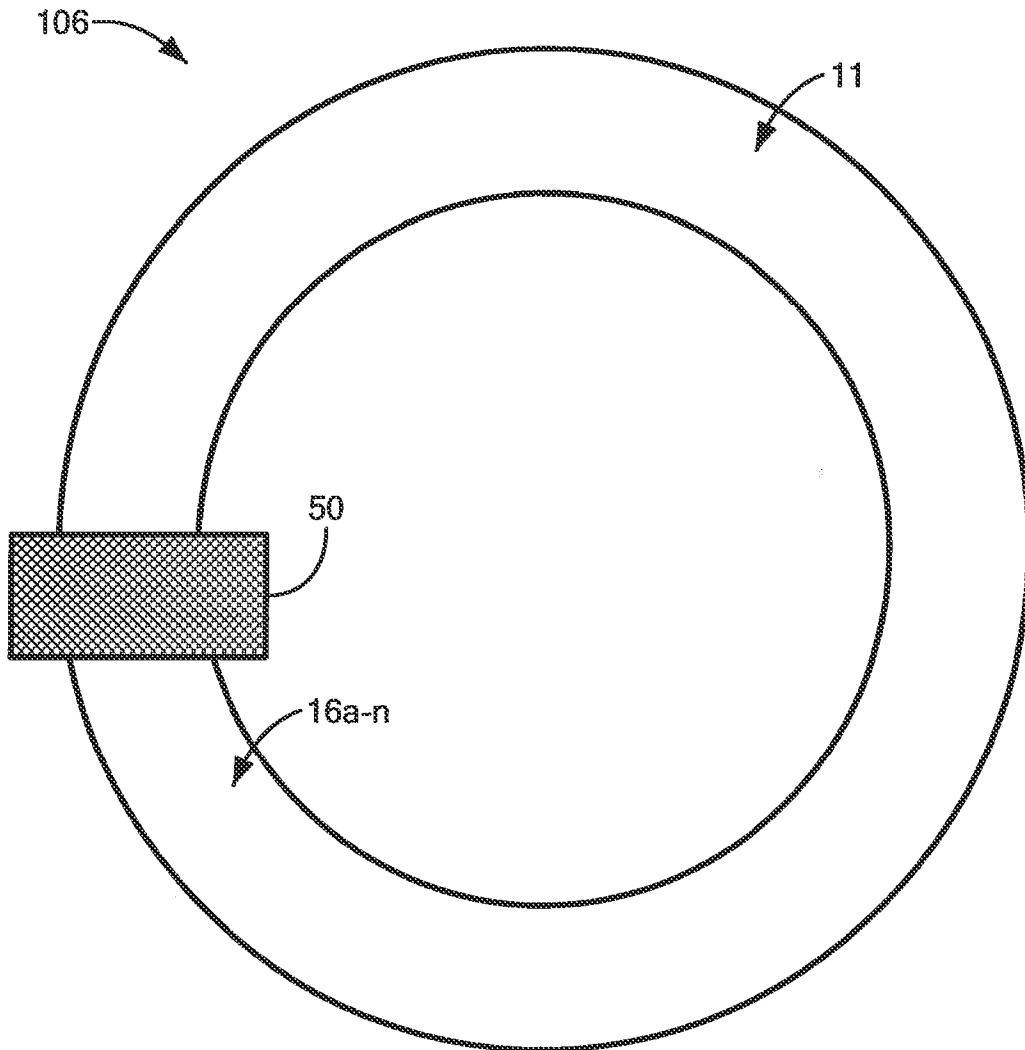


FIG. 11

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**FIG. 11A**

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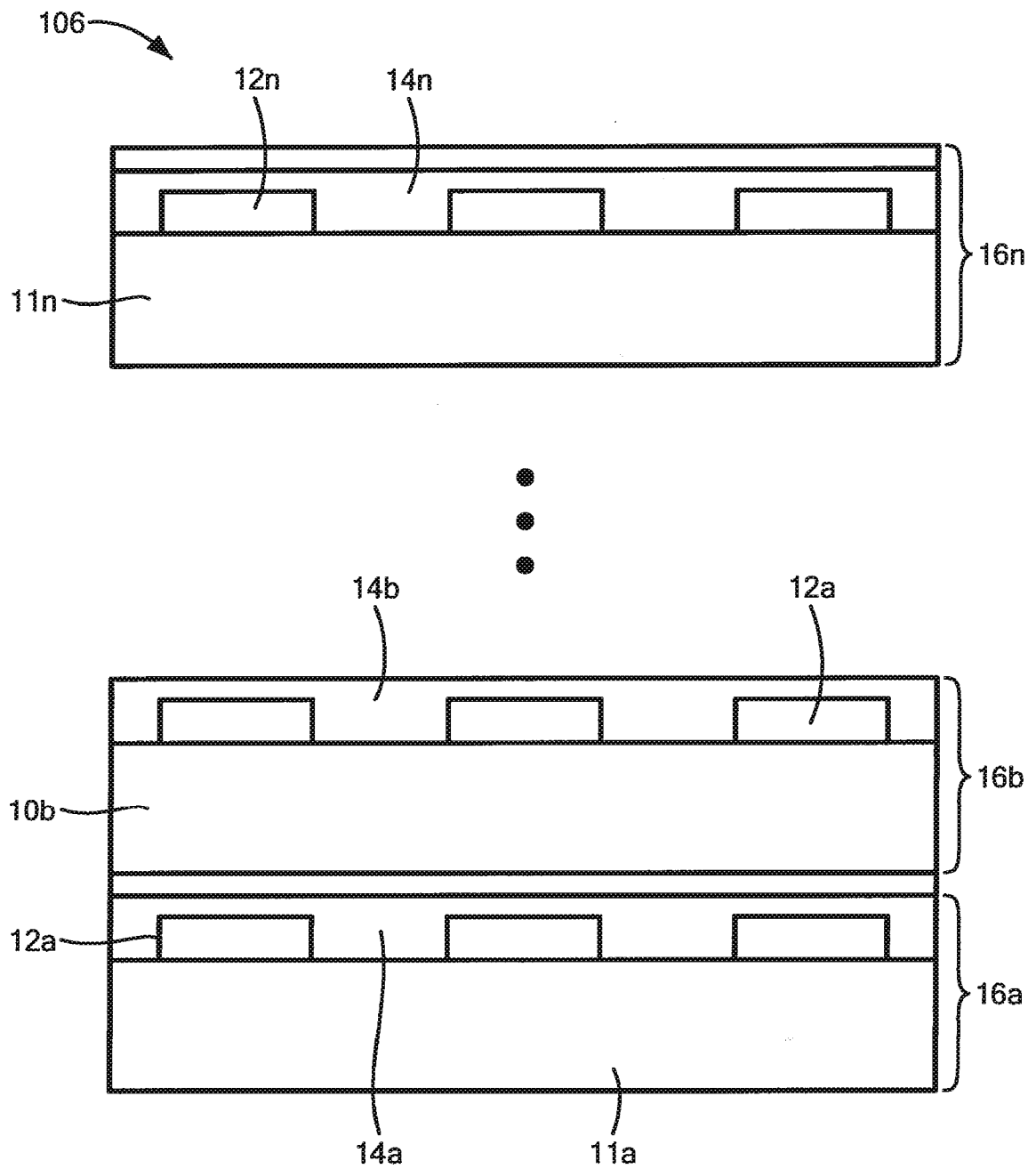


FIG. 11B

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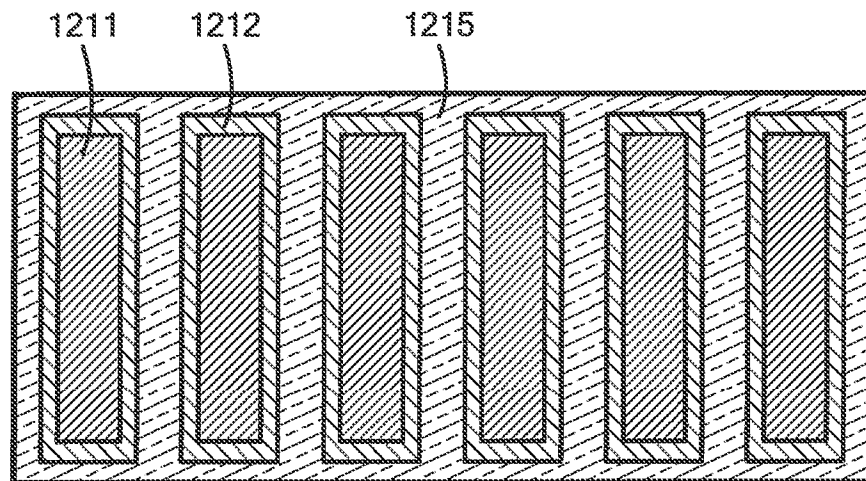


FIG. 12A

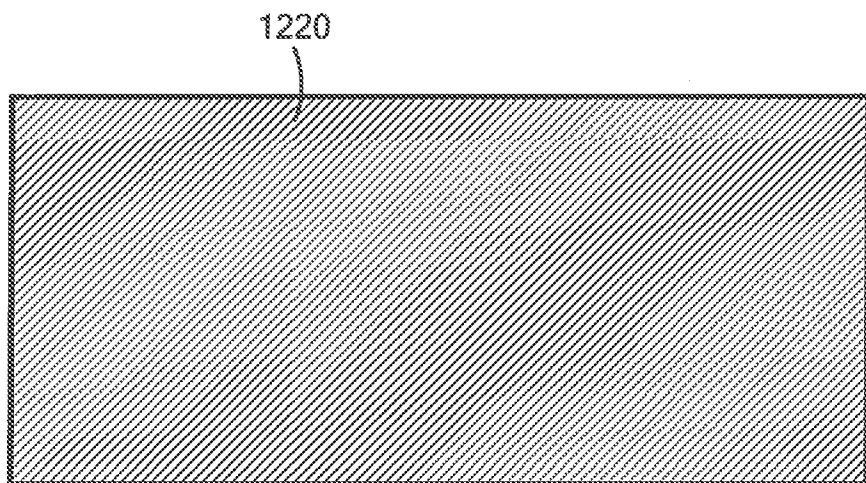


FIG. 12B