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Superconducting wire material, superconducting coil, superconducting magnet, superconducting motor, superconducting generator, superconducting aircraft, and superconducting device

Abstract

A superconducting wire according to an embodiment includes: a substrate; a first region provided on the substrate and containing a first rare earth element, Ba, Cu, and O; a second region provided on the substrate and containing a second rare earth element, Ba, Cu, and O; and a third region provided on the substrate, provided between the first region and the second region, and containing a third rare earth element, Pr, Ba, Cu, and O. A surface density of particles having an aspect ratio of 3 or more present on a surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on surfaces of the first region and the second region.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION
(1) This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2023-046067, filed on Mar. 22, 2023, the entire contents of which are incorporated herein by reference.
FIELD
(2) Embodiments described herein relate generally to a superconducting wire, a superconducting coil, a superconducting magnet, a superconducting motor, a superconducting generator, a superconducting aircraft, and a superconducting device.
BACKGROUND
(3) For example, in a case where a superconducting coil using a superconducting wire is applied to a motor, in order to change a magnetic field generated in the superconducting coil, an alternating current in which a direction of a current is reversed flows through the superconducting wire constituting the superconducting coil. The use of the superconducting wire through which the alternating current flows is referred to as a superconducting alternating current application.
(4) In the superconducting alternating current application, an energy loss occurs due to an inductance component of the superconducting wire. The energy loss due to the inductance component of the superconducting wire is also referred to as an alternating current loss. In the superconducting alternating current application, it is desirable to reduce the alternating current loss of the superconducting wire.
(5) In the following description, an application in which the current is changed without being inverted and the inductance component becomes a problem is also referred to as an alternating current application.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a schematic top view of a superconducting wire according to a first embodiment;
(2) FIG. **2** is a schematic cross-sectional view of the superconducting wire according to the first embodiment;
(3) FIGS. **3**A and **3**B are schematic views of the superconducting wire according to the first embodiment;
(4) FIG. **4** is an explanatory view of a method for manufacturing the superconducting wire according to the first embodiment;
(5) FIG. **5** is an explanatory view of the method for manufacturing the superconducting wire according to the first embodiment;
(6) FIGS. **6**A and **6**B are explanatory views of the method for manufacturing the superconducting wire according to the first embodiment;
(7) FIG. **7** is an explanatory view of the method for manufacturing the superconducting wire according to the first embodiment;
(8) FIGS. **8**A and **8**B are schematic cross-sectional views of a superconducting motor according to a second embodiment;
(9) FIG. **9** is a schematic top view of a superconducting aircraft according to a third embodiment; and
(10) FIG. **10** is a block diagram of a superconducting device according to a fourth embodiment.
DETAILED DESCRIPTION
(11) A superconducting wire according to an embodiment includes: a substrate; a first region provided on the substrate, the first region containing barium (Ba), copper (Cu), oxygen (O), and at least one first rare earth element selected from the group consisting of yttrium (Y), lanthanum (La),

neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the first region extending in a first direction along a surface of the substrate; a second region provided on the substrate, the second region containing barium (Ba), copper (Cu), oxygen (O), at least one second rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the second region extending in the first direction; and a third region provided on the substrate, the third region being provided so as to be in contact with the first region and the second region between the first region and the second region, the third region containing praseodymium (Pr), barium (Ba), copper (Cu), oxygen (O), and at least one third rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the third region extending in the first direction. A surface density of particles having an aspect ratio of 3 or more present on a surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the first region, and the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the second region.

(12) Qualitative analysis and quantitative analysis of the chemical composition of members constituting the superconducting wire in the present specification can be performed by, for example, secondary ion mass spectroscopy (SIMS) or an electron probe micro analyzer (EPMA). In addition, for example, a transmission electron microscope (TEM) or a scanning electron microscope (SEM) can be used for measuring the width of the member constituting the superconducting wire, the thickness of the member, the distance between the members, and the like, and identifying the continuity of the crystal structure. In addition, for example, X-ray diffraction (XRD) can be used for identifying a constituent material of the member constituting the superconducting wire and identifying orientation of crystal axes.

(13) The “aspect ratio of particles” contained in the superconducting wire in the present specification is defined as follows. When particles determined from a two-dimensional image obtained by imaging the superconducting wire are fitted with an ellipse, a length of a long axis is defined as a long diameter, and a length of a short axis is defined as a short diameter. A ratio of the long diameter to the short diameter (long diameter/short diameter) is defined as the aspect ratio of the particles. For example, a shape of the particle is determined by performing image processing on an SEM image of the superconducting wire, and the “aspect ratio of the particle” can be obtained from the determined shape of the particle.

(14) The SEM image of the superconducting wire is analyzed using, for example, image processing software ImageJ. Particles having a high aspect ratio in the SEM image are extracted as bright regions. The extraction is performed by binarization of the SEM image. A threshold of the binarization is set such that the original SEM image is compared with the SEM image after the binarization, and particles having a high aspect ratio are appropriately extracted. When adjacent particles are in contact with each other, the particles may be connected after the binarization. In such a case, the particles are divided by, for example, segmentation. In addition, processing necessary for extraction of the particles is appropriately performed, and particles having a high aspect ratio are appropriately extracted from the original SEM image.

(15) Hereinafter, the superconducting wire according to the embodiment will be described with reference to the drawings.

First Embodiment

(16) A superconducting wire according to a first embodiment includes: a substrate; a first region provided on the substrate, the first region containing barium (Ba), copper (Cu), oxygen (O), and at least one first rare earth element selected from the group consisting of yttrium (Y), lanthanum (La),

neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the first region extending in a first direction parallel to a surface of the substrate; a second region provided on the substrate, the second region containing barium (Ba), copper (Cu), oxygen (O), and at least one second rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the second region extending in a first direction along a surface of the substrate; and a third region provided on the substrate, the third region being provided so as to be in contact with the first region and the second region between the first region and the second region, the third region containing praseodymium (Pr), barium (Ba), copper (Cu), oxygen (O), and at least one third rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the third region extending in the first direction. In addition, a surface density of particles having an aspect ratio of 3 or more present on a surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the first region, and the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the second region.
(17) FIG. **1** is a schematic top view of the superconducting wire according to the first embodiment. FIG. **2** is a schematic cross-sectional view of the superconducting wire according to the first embodiment. FIG. **1** is a top view of a state in which a protective layer in FIG. **2** is removed. FIG. **2** is a cross-sectional view taken along the line AA′ of FIG. **1**.
(18) The superconducting wire of the first embodiment is a superconducting wire **100**.
(19) As illustrated in FIG. **2**, the superconducting wire **100** includes a substrate **10**, an intermediate layer **20**, an oxide superconducting layer **30**, and a protective layer **40**. The substrate **10** increases the mechanical strength of the oxide superconducting layer **30**. The intermediate layer **20** is a so-called orientation intermediate layer. The intermediate layer **20** is provided to orient the oxide superconducting layer **30** when the oxide superconducting layer **30** is formed. The protective layer **40** protects the oxide superconducting layer **30**.
(20) A length of the superconducting wire **100** in a first direction parallel to a surface of the substrate **10** is, for example, equal to or more than 0.1 m and equal to or less than 500 m.
(21) The substrate **10** is, for example, a metal such as a nickel-tungsten alloy. In addition, the intermediate layer is, for example, yttrium oxide (Y.sub.2O.sub.3), yttria stabilized zirconia (YSZ), and cerium oxide (CeO.sub.2) from the side of the substrate **10**. A layer configuration of the substrate **10** and the intermediate layer **20** is, for example, nickel-tungsten alloy/yttrium oxide/yttria stabilized zirconia/cerium oxide. In this case, the oxide superconducting layer **30** is formed on cerium oxide.
(22) The substrate **10** may be, for example, a single crystal layer lattice-matched with the oxide superconducting layer **30**. The single crystal layer is, for example, lanthanum aluminate (LaAlO.sub.3, hereinafter also referred to as LAO). When lanthanum aluminate is applied to the substrate **10**, the intermediate layer **20** can be omitted.
(23) For example, silver (Ag) or copper (Cu) is a metal of a base material of the protective layer **40**. The protective layer **40** is, for example, an alloy. It is also possible to use an oxide layer as the protective layer **40**.
(24) The oxide superconducting layer **30** is provided between the substrate **10** and the protective layer **40**. The oxide superconducting layer **30** is provided between the intermediate layer **20** and the protective layer **40**. The oxide superconducting layer **30** is provided on the intermediate layer **20** in contact with the intermediate layer **20**.
(25) The oxide superconducting layer **30** includes a first superconducting region **31***a*, a second

superconducting region **31***b*, a third superconducting region **31***c*, a fourth superconducting region **31***d*, a first non-superconducting region **32***a*, a second non-superconducting region **32***b*, and a third non-superconducting region **32***c*.

(26) The first superconducting region **31***a* is an example of the first region. The second superconducting region **31***b* is an example of the second region. The first non-superconducting region **32***a* is an example of the third region.

(27) The first superconducting region **31***a*, the second superconducting region **31***b*, the third superconducting region **31***c*, the fourth superconducting region **31***d*, the first non-superconducting region **32***a*, the second non-superconducting region **32***b*, and the third non-superconducting region **32***c* extend in the first direction along the surface of the substrate **10**. The first direction is, for example, a longitudinal direction of the substrate **10**.

(28) The first non-superconducting region **32***a* is provided between the first superconducting region **31***a* and the second superconducting region **31***b*. The first non-superconducting region **32***a* is in contact with the first superconducting region **31***a* and the second superconducting region **31***b*.

(29) The second non-superconducting region **32***b* is provided between the second superconducting region **31***b* and the third superconducting region **31***c*. The second non-superconducting region **32***b* is in contact with the second superconducting region **31***b* and the third superconducting region **31***c*.

(30) The third non-superconducting region **32***c* is provided between the third superconducting region **31***c* and the fourth superconducting region **31***d*. The third non-superconducting region **32***c* is in contact with the third superconducting region **31***c* and the fourth superconducting region **31***d*.

(31) Hereinafter, for ease of description, the first superconducting region **31***a*, the second superconducting region **31***b*, the third superconducting region **31***c*, and the fourth superconducting region **31***d* may be collectively referred to simply as a superconducting region **31**. In addition, the first non-superconducting region **32***a*, the second non-superconducting region **32***b*, and the third non-superconducting region **32***c* may be collectively referred to simply as a non-superconducting region **32**.

(32) A second direction is perpendicular to the first direction and is a direction along the surface of the substrate **10**. The second direction is a direction from the non-superconducting region **32** toward the superconducting region **31**. The second direction is, for example, a lateral direction or transverse direction of the substrate **10**. A direction perpendicular to the first direction and the second direction is a third direction. The third direction is a thickness direction of the substrate **10** and is substantially perpendicular to the surface of the substrate **10**.

(33) The oxide superconducting layer **30** includes the non-superconducting region **32** and the superconducting region **31**. The oxide superconducting layer **30** is divided into a plurality of superconducting regions **31** with the non-superconducting region **32** interposed therebetween. In the case of FIGS. **1** and **2**, the oxide superconducting layer is divided into four superconducting regions **31**. The oxide superconducting layer **30** may be divided into, for example, two or three. In addition, the oxide superconducting layer **30** may be divided into, for example, five or more regions.

(34) The superconducting region **31** has superconducting characteristics. The non-superconducting region **32** does not have superconducting characteristics. The non-superconducting region **32** electrically separates the superconducting region **31**. The non-superconducting region **32** functions as an insulator when a current flows through the superconducting wire **100**.

(35) A length (L in FIG. **1**) of the oxide superconducting layer **30** in the first direction is, for example, equal to or more than 0.1 m and 1 km or less. A length of the superconducting region **31** in the first direction is, for example, equal to or more than 0.1 m and 1 km or less. A length of the non-superconducting region **32** in the first direction is, for example, equal to or more than 0.1 m and 1 km or less.

(36) A width W**1** of the superconducting region **31** in the second direction is, for example, equal to or more than 5 μm and equal to or less than 10 mm. A width W**2** of the non-superconducting region

32 in the second direction is, for example, equal to or more than 1 μm and equal to or less than 2 mm. For convenience, in FIG. **1**, the widths of the superconducting regions **31***a*, **31***b*, **31***c*, and **31***d* are all equally expressed as W**1**, but actually, the widths may be different from each other. Here, a median value of the widths of the superconducting regions **31***a*, **31***b*, **31***c*, and **31***d* is expressed as W**1**. Similarly, in the non-superconducting regions **32***a*, **32***b*, and **32***c*, the widths of the non-superconducting regions **32***a*, **32***b*, and **32***c* may be different from each other, and the median value of the widths of the non-superconducting regions **32***a*, **32***b*, and **32***c* is expressed as W**2**.
(37) A width (Wx in FIG. **1**) of the oxide superconducting layer **30** in the second direction is, for example, equal to or more than 1 mm and equal to or less than 20 mm. A width (W**2** in FIG. **1**) of the non-superconducting region **32** in the second direction is, for example, equal to or less than the width (W**1** in FIG. **1**) of the superconducting region **31** in the second direction. The width (W**2** in FIG. **1**) of the non-superconducting region **32** in the second direction is, for example, smaller than the width (W**1** in FIG. **1**) of the superconducting region **31** in the second direction.
(38) A boundary between the superconducting region **31** and the non-superconducting region **32** can be determined, for example, by performing mapping and point analysis on the surface of the oxide superconducting layer **30** by EPMA, and defining a region in which the concentration of praseodymium (Pr) in the rare earth element RE is less than 1% as the superconducting region **31** and a region in which the concentration of praseodymium (Pr) in the rare earth element RE is equal to or more than 1% as the non-superconducting region **32**.
(39) A thickness of the oxide superconducting layer **30** in the third direction is, for example, equal to or more than 100 nm and equal to or less than 10 μm.
(40) The oxide superconducting layer **30** is an oxide containing a rare earth element. The oxide containing the rare earth element contained in the oxide superconducting layer **30** has a perovskite structure. The crystal of the oxide containing the rare earth element contained in the oxide superconducting layer **30** is, for example, an orthorhombic crystal.
(41) The oxide containing the rare earth element contained in the oxide superconducting layer **30** has, for example, a chemical composition of REBa.sub.ACu.sub.BO.sub.7-c (1.8≤A≤2.2, 2.7≤B≤3.3, −0.2≤C≤1). The oxide containing the rare earth element contained in the oxide superconducting layer **30** includes, for example, an oxide having a chemical composition of REBa.sub.2Cu.sub.3O.sub.7-y (−0.2≤y≤1). RE is a rare earth site.
(42) The superconducting region **31** contains barium (Ba), copper (Cu), oxygen (O), and at least one rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).
(43) The concentration of praseodymium (Pr) in the rare earth element RE in the superconducting region **31** is, for example, less than 1 atom %. The concentration of praseodymium (Pr) in the superconducting region **31** is smaller than the concentration of praseodymium (Pr) in the non-superconducting region **32**.
(44) The oxide containing the rare earth element contained in the superconducting region **31** has, for example, a chemical composition of REBa.sub.DCu.sub.EO.sub.7-F (1.8≤D≤2.2, 2.7≤E≤3.3, −0.2≤F≤1). The superconducting region **31** contains, for example, an oxide having a chemical composition of REBa.sub.2Cu.sub.3O.sub.7-y (−0.2≤y≤1).
(45) The superconducting region **31** has, for example, a perovskite structure. The superconducting region **31** is, for example, a single crystal having a perovskite structure.
(46) The superconducting region **31** is, for example, c-axis oriented. A c axis of a crystal of a compound REBa.sub.DCu.sub.EO.sub.7-F (1.8≤D≤2.2, 2.7≤E≤3.3, −0.2≤F≤1) contained in the superconducting region **31** is aligned, for example, in the thickness direction of the oxide superconducting layer **30**, that is, in a direction substantially perpendicular to the surface of the substrate **10**, that is, the third direction.
(47) The non-superconducting region **32** contains praseodymium (Pr), barium (Ba), copper (Cu),

and oxygen (O), and at least one rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).
(48) Since the non-superconducting region **32** contains praseodymium (Pr), superconducting characteristics are not exhibited. The concentration of praseodymium (Pr) in the rare earth element RE in the non-superconducting region **32** is, for example, equal to or more than 10 atom % and equal to or less than 50 atom %. The concentration of praseodymium (Pr) in the rare earth element RE in the non-superconducting region **32** is more preferably equal to or more than 15 atom % and equal to or less than 45 atom %, and further preferably equal to or more than 20 atom % and equal to or less than 40 atom %.
(49) The oxide containing the rare earth element contained in the non-superconducting region **32** has, for example, a chemical composition of REBa.sub.GCU.sub.HO.sub.7-I (1.8≤G≤2.2, 2.7≤H≤3.3, −0.2≤I≤1). The non-superconducting region **32** includes, for example, an oxide having a chemical composition of REBa.sub.2Cu.sub.3O.sub.7-y (−0.2≤y≤1).
(50) The non-superconducting region **32** has, for example, a perovskite structure.
(51) At least one rare earth element selected from the group contained in each of the first superconducting region **31***a*, the second superconducting region **31***b*, the third superconducting region **31***c*, the fourth superconducting region **31***d*, the first non-superconducting region **32***a*, the second non-superconducting region **32***b*, and the third non-superconducting region **32***c* is, for example, the same.
(52) For example, at least one first rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) is contained in the first superconducting region **31***a*, at least one second rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) is contained in the second superconducting region **31***b*, and at least one third rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) is contained in the first non-superconducting region **32***a*.
(53) For example, the first rare earth element, the second rare earth element, and the third rare earth element are the same elements. For example, the first rare earth element, the second rare earth element, and the third rare earth element are all yttrium (Y).
(54) At least one rare earth element selected from the above group contained in each of the first superconducting region **31***a*, the second superconducting region **31***b*, the third superconducting region **31***c*, the fourth superconducting region **31***d*, the first non-superconducting region **32***a*, the second non-superconducting region **32***b*, and the third non-superconducting region **32***c* may be different.
(55) For example, the first rare earth element, the second rare earth element, and the third rare earth element are different elements. For example, the first rare earth element is yttrium (Y), the second rare earth element is samarium (Sm), and the third rare earth element is dysprosium (Dy).
(56) For example, any or all of the first rare earth element, the second rare earth element, and the third rare earth element may be two or more kinds of rare earth elements. For example, any or all of the first rare earth element, the second rare earth element, and the third rare earth element may be three or more kinds of rare earth elements.
(57) FIGS. **3**A and **3**B are schematic views of the superconducting wire according to the first embodiment.
(58) FIG. **3**A is a schematic view of the surface of the superconducting region **31**. FIG. **3**B is a schematic view of the surface of the non-superconducting region **32**. FIGS. **3**A and **3**B are top

views of a state in which the protective layer **40** on the oxide superconducting layer **30** is removed.
(59) As illustrated in FIGS. **3**A and **3**B, a surface density of high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32** is larger than a surface density of high-aspect-ratio particles **36** present on the surface of the superconducting region **31**. The high-aspect-ratio particles **36** have an aspect ratio of 3 or more.
(60) The high-aspect-ratio particles **36** are, for example, rod-shaped or needle-shaped particles. A long-axis direction of the high-aspect-ratio particles **36** is considered to be a c-axis direction of an oxide containing a rare earth element having an orthorhombic perovskite structure. Therefore, the high-aspect-ratio particles **36** are not c-axis oriented with respect to the surface of the substrate **10**.
(61) The larger the surface density of the high-aspect-ratio particles **36** is, the lower the degree of c-axis orientation is. Therefore, at least on the surface of the oxide superconducting layer **30**, the degree of c-axis orientation of the non-superconducting region **32** is lower than the degree of c-axis orientation of the superconducting region **31**.
(62) For example, the surface density of the high-aspect-ratio particles **36** present on the surface of the first non-superconducting region **32***a* is larger than the surface density of the high-aspect-ratio particles **36** present on the surface of the first superconducting region **31***a*. In addition, for example, the surface density of the high-aspect-ratio particles **36** present on the surface of the first non-superconducting region **32***a* is larger than the surface density of the high-aspect-ratio particles **36** present on the surface of the second superconducting region **31***b.*
(63) For example, the surface density of the high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32** is 2 times or more and 1000 times or less the surface density of the high-aspect-ratio particles **36** present on the surface of the superconducting region **31**. For example, the surface density of the high-aspect-ratio particles **36** present on the surface of the first non-superconducting region **32***a* is 2 times or more and 100 times or less the surface density of the high-aspect-ratio particles **36** present on the surface of the first superconducting region **31***a*. In addition, for example, the surface density of the high-aspect-ratio particles **36** present on the surface of the first non-superconducting region **32***a* is 2 times or more and 1000 times or less the surface density of the high-aspect-ratio particles **36** present on the surface of the second superconducting region **31***b.*
(64) The surface density of the high-aspect-ratio particles **36** is the number of the high-aspect-ratio particles **36** present per unit area. The unit area in calculating the surface density of the high-aspect-ratio particles **36** is, for example, 1 μm.sup.2.
(65) When the surface density of the high-aspect-ratio particles **36** present on the surface of the superconducting region **31** or the non-superconducting region **32** is obtained, for example, the surface density is obtained by counting the number of the high-aspect-ratio particles **36** in a plurality of 10 μm square regions, and an average value thereof is used.
(66) The surface density of the high-aspect-ratio particles **36** in the superconducting region **31** is, for example, less than 0.1 particles/μm.sup.2. The surface density of the high-aspect-ratio particles **36** in the non-superconducting region **32** is, for example, equal to or more than 0.1 particles/μm.sup.2 and equal to or less than 1 particle/μm.sup.2.
(67) For example, the surface density of the high-aspect-ratio particles **36** present inside the non-superconducting region **32** is smaller than the surface density of the high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32**. For example, the inside of the non-superconducting region **32** is a cross section along the surface of the non-superconducting region **32** at a position closer to the substrate **10** than the surface of the non-superconducting region **32**. For example, the inside of the non-superconducting region **32** is a cross section at a position closer to the substrate **10** than a position of half the thickness of the non-superconducting region **32** in the third direction. The surface density of the high-aspect-ratio particles **36** present inside the non-superconducting region **32** can be measured, for example, by removing the surface of the non-superconducting region **32** by polishing or the like. The surface of the non-superconducting region

32 is, for example, the vicinity of an interface between the non-superconducting region **32** and the protective layer **40**. The surface density of the high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32** can be measured, for example, by removing the protective layer **40** by peeling or the like.
(68) The oxide superconducting layer **30** may contain impurity elements that are elements other than yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), praseodymium (Pr), barium (Ba), copper (Cu), oxygen (O), aluminum (Al), and carbon (C), for example. The impurity elements may be two or more kinds of impurity elements.
(69) For example, an atomic concentration of the impurity element contained in the non-superconducting region **32** is higher than an atomic concentration of the impurity element contained in the superconducting region **31**.
(70) Hereinafter, an example of a method for manufacturing the superconducting wire **100** according to the first embodiment will be described.
(71) In the example of the method for manufacturing the superconducting wire **100** according to the first embodiment, the intermediate layer **20** is formed on the substrate **10**, the oxide superconducting layer **30** is formed on the intermediate layer **20**, and the protective layer **40** is formed on the oxide superconducting layer **30**. The oxide superconducting layer **30** is formed by a Trifluoro Acetates Metal Organic Deposition method (TFA-MOD method).
(72) FIG. **4** is an explanatory view of the method for manufacturing the superconducting wire according to the first embodiment. FIG. **4** is a flowchart illustrating an example of preparation of a coating solution in the manufacturing method according to the first embodiment.
(73) First, preparation of a first coating solution and a second coating solution will be described.
(74) As illustrated in FIG. **4**, metal acetates of yttrium (Y), barium (Ba), and copper (Cu) are prepared (a**1**). In addition, trifluoroacetic acid is prepared (a**2**). Next, the prepared metal acetate is dissolved in water to prepare an aqueous solution (b). The obtained aqueous solution is mixed with the prepared trifluoroacetic acid (c). The obtained solution is reacted and refined (d) to obtain a first gel containing impurities (e). After that, the obtained first gel is dissolved in methanol (f) to prepare a solution containing impurities (g). The obtained solution is reacted and refined to remove the impurities (h), thereby obtaining a second gel containing a solvent (i). In addition, the obtained second gel is dissolved in methanol (j) to prepare a coating solution (k). The method for reducing impurities by the gel including the solvent illustrated in FIG. **4** is called a Solvent-Into-Gel method (SIG method).
(75) A coating solution containing yttrium (Y), barium (Ba), and copper (Cu) becomes the first coating solution. Hereinafter, the first coating solution is referred to as a superconducting region forming coating solution.
(76) Next, preparation of the second coating solution will be described.
(77) As illustrated in FIG. **4**, metal acetates of praseodymium (Pr), yttrium (Y), barium (Ba), and copper (Cu) are prepared (a**1**). In addition, trifluoroacetic acid is prepared (a**2**). Next, the prepared metal acetate is dissolved in water to prepare an aqueous solution (b). The obtained aqueous solution is mixed with the prepared trifluoroacetic acid (c). The obtained solution is reacted and refined (d) to obtain a first gel containing impurities (e). After that, the obtained first gel is dissolved in methanol (f) to prepare a solution containing impurities (g). The obtained solution is reacted and refined to remove the impurities (h), thereby obtaining a second gel containing a solvent (i). In addition, the obtained second gel is dissolved in methanol (j) to prepare a coating solution (k).
(78) The coating solution containing praseodymium (Pr), yttrium (Y), barium (Ba), and copper (Cu) becomes the second coating solution. Hereinafter, the second coating solution is referred to as a non-superconducting region forming coating solution.
(79) FIG. **5** is an explanatory view of the method for manufacturing the superconducting wire

according to the first embodiment. FIG. **5** is a flowchart illustrating an example of a method for forming a superconducting film from a coating solution.
(80) As illustrated in FIG. **5**, first, a previously prepared coating solution is prepared (a). The coating solution is applied onto the substrate by, for example, an inkjet method to form a film (b), thereby obtaining a gel film (c). After that, the obtained gel film is subjected to calcination as a primary heat treatment to decompose an organic substance (d), thereby obtaining a calcined film (e). In addition, the calcined film is subjected to final firing as a secondary heat treatment (f), and then, for example, pure oxygen annealing is performed (g) to obtain a superconducting film (h).
(81) FIGS. **6**A and **6**B are explanatory views of the method for manufacturing the superconducting wire according to the first embodiment. FIGS. **6**A and **6**B are explanatory views of formation of a gel film on a substrate by an inkjet method according to the first embodiment. FIG. **6**A is a view of the substrate **10** as viewed from above, and FIG. **6**B is a view of the substrate **10** as viewed from a lateral direction.
(82) As illustrated in FIGS. **6**A and **6**B, a superconducting region forming coating solution **35***a* and a non-superconducting region forming coating solution **35***b* are injected from nozzles **34** toward the substrate **10**. As illustrated in FIG. **6**A, the superconducting region forming coating solution **35***a* and the non-superconducting region forming coating solution **35***b* are injected onto the substrate **10** such that the non-superconducting region forming coating solution **35***b* is sandwiched between the superconducting region forming coating solutions **35***a*, and the superconducting region forming coating solution **35***a* and the non-superconducting region forming coating solution **35***b* are in contact with each other.
(83) The substrate **10** moves in a first direction with respect to the nozzle **34**. The superconducting region forming coating solution **35***a* and the non-superconducting region forming coating solution **35***b* injected onto the substrate **10** extend in the first direction.
(84) An average diameter of droplets when the non-superconducting region forming coating solution **35***b* ejected onto the substrate **10** reaches the substrate **10** is, for example, equal to or less than 5 μm.
(85) Instead of the inkjet method, for example, a die coating method can also be used.
(86) FIG. **7** is an explanatory view of the method for manufacturing the superconducting wire according to the first embodiment. FIG. **7** is an explanatory diagram of a relation between a firing condition for calcination or final firing when the superconducting wire **100** is manufactured and a surface density of the high-aspect-ratio particles **36**.
(87) As illustrated in FIG. **7**, the relation between the firing condition and the surface density of the high-aspect-ratio particles **36** is different between the superconducting region **31** and the non-superconducting region **32**. The firing condition is, for example, a firing temperature, a firing time, or an oxygen partial pressure.
(88) For example, under a condition X, by setting the oxygen partial pressure during the final firing to an intermediate value between a value optimum for the superconducting region and a value optimum for the non-superconducting region, the surface density of the high-aspect-ratio particles **36** decreases in both the superconducting region **31** and the non-superconducting region **32**. In other words, under the condition X, a high degree of c-axis orientation is obtained in both the superconducting region **31** and the non-superconducting region **32**.
(89) On the other hand, under a condition Y where the oxygen partial pressure during the final firing is shifted from the optimum value for the superconducting region to a slightly higher side, the oxygen partial pressure is only slightly shifted from the optimum value with respect to the superconducting region, while the shift from the optimum value with respect to the non-superconducting region is larger than that in the superconducting region. For this reason, the surface density of the high-aspect-ratio particles **36** in the superconducting region **31** is small, but the surface density of the high-aspect-ratio particles **36** in the non-superconducting region **32** is large. In other words, under the condition Y, the degree of c-axis orientation of the superconducting

region **31** is high, but the degree of c-axis orientation of the non-superconducting region **32** is low.
(90) For example, in the method for manufacturing the superconducting wire **100** according to the first embodiment, by selecting the condition corresponding to the condition Y as the firing condition, the surface density of the high-aspect-ratio particles **36** in the non-superconducting region **32** can be made larger than the surface density of the high-aspect-ratio particles **36** in the superconducting region **31**. Furthermore, for example, by setting the oxygen partial pressure during the final firing to the condition X at the beginning and changing the oxygen partial pressure to the condition Y in the middle, it is possible to perform control to change the surface density of the high-aspect-ratio particles of the non-superconducting region **32** crystal-grown from the substrate side, decrease the surface density of the high-aspect-ratio particles inside the non-superconducting region **32**, and increase the surface density of the high-aspect-ratio particles on the surface of the non-superconducting region **32**.
(91) The superconducting wire **100** of the first embodiment including the oxide superconducting layer **30** is manufactured by the above manufacturing method.
(92) In the superconducting wire **100** of the first embodiment, the oxide superconducting layer **30** is divided into a plurality of superconducting regions **31** by the non-superconducting regions **32**. In other words, the oxide superconducting layer **30** is thinned in the plurality of superconducting regions **31**.
(93) Therefore, according to the superconducting wire **100**, an energy loss due to an inductance component can be reduced when AC application is performed. As a result, according to the superconducting wire **100**, the AC loss can be reduced.
(94) As a method for dividing the oxide superconducting layer of the superconducting wire, there is a method for performing ablation processing from above by a laser scribing method. In this method, there is a possibility that superconducting characteristics are deteriorated due to thermal damage of the laser scribing method, and mechanical strength of the oxide superconducting layer is reduced because gaps are formed between the divided oxide superconducting layers.
(95) In the superconducting wire **100** of the first embodiment, the oxide superconducting layer **30** is divided into a plurality of superconducting regions **31** by the non-superconducting regions **32**. The non-superconducting region **32** can be formed by injection or application of a coating solution. Therefore, the superconducting characteristics of the superconducting region **31** are hardly deteriorated. In addition, the non-superconducting region **32** exists between the divided superconducting regions **31**. Therefore, the mechanical strength of the oxide superconducting layer **30** is improved.
(96) In the superconducting wire **100** of the first embodiment, the surface density of the high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32** is larger than the surface density of the high-aspect-ratio particles **36** present on the surface of the superconducting region **31**. It is considered that the surface of the non-superconducting region **32** functions as a gettering site of impurities as the high-aspect-ratio particles **36** exist at a high density on the surface of the non-superconducting region **32**. That is, the surface of the non-superconducting region **32** can function as a region that captures impurities unintentionally introduced during manufacturing of the superconducting wire **100**.
(97) For example, when the unintentionally introduced impurities enter the superconducting region **31**, there is a risk of deteriorating the superconducting characteristics of the superconducting region **31**. In the superconducting wire **100** of the first embodiment, the surface of the non-superconducting region **32** functions as the gettering site of the impurities, so that the impurities can be suppressed from entering the superconducting region **31**. Therefore, the superconducting wire **100** having excellent superconducting characteristics can be realized.
(98) The surface density of the high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32** is preferably 2 times or more, more preferably 5 times or more, and further preferably 10 times or more the surface density of the high-aspect-ratio particles **36** present

on the surface of the superconducting region **31**. By exceeding the above lower limit value, capturing of the impurities on the surface of the non-superconducting region **32** is further promoted. Therefore, the superconducting wire **100** having further excellent superconducting characteristics can be realized.

(99) From the viewpoint of promoting capturing of the impurities on the surface of the non-superconducting region **32**, the surface density of the high-aspect-ratio particles **36** present inside the non-superconducting region **32** is preferably higher than the surface density of the high-aspect-ratio particles **36** present inside the superconducting region **31**. For example, the inside of the superconducting region **31** is a cross section along the surface of the superconducting region **31** at a position closer to the substrate **10** than the surface of the superconducting region **31**. The inside of the superconducting region **31** is, for example, a cross section closer to the substrate **10** than a position of half the thickness of the superconducting region **31** in the third direction. The surface density of the high-aspect-ratio particles **36** present inside the superconducting region **31** can be measured, for example, by removing the surface of the superconducting region **31** by polishing or the like. The surface of the superconducting region **31** is, for example, the vicinity of an interface with the protective layer **40** of the superconducting region **31**. The surface density of the high-aspect-ratio particles **36** present on the surface of the superconducting region **31** can be measured, for example, by removing the protective layer **40** by peeling or the like.

(100) On the other hand, from the viewpoint of improving the mechanical strength of the oxide superconducting layer **30**, the surface density of the high-aspect-ratio particles **36** present inside the non-superconducting region **32** is preferably smaller than the surface density of the high-aspect-ratio particles **36** present on the surface of the non-superconducting region **32**. The degree of c-axis orientation inside the non-superconducting region **32** is improved, and the continuity of the perovskite structure at the interface between the superconducting region **31** and the non-superconducting region **32** is improved. Therefore, the mechanical strength of the interface between the superconducting region **31** and the non-superconducting region **32** is improved.

(101) In the superconducting wire **100** of the first embodiment, the lengths of the superconducting region **31** and the non-superconducting region **32** in the first direction are preferably equal to or more than 0.1 m from the viewpoint of causing the superconducting wire **100** to function as a wire material.

(102) In the superconducting wire **100** of the first embodiment, from the viewpoint of reducing the AC loss, the width (W**2** in FIG. **1**) of the non-superconducting region **32** in the second direction is preferably smaller than the width (W**1** in FIG. **1**) of the superconducting region **31** in the second direction.

(103) In the superconducting wire **100** of the first embodiment, from the viewpoint of not impairing the superconducting characteristics, the width (W**1** in FIG. **1**) of the superconducting region **31** in the second direction is, for example, preferably equal to or more than 5 μm and more preferably equal to or more than 10 μm.

(104) In the superconducting wire **100** of the first embodiment, from the viewpoint of reducing the AC loss, the width (W**1** in FIG. **1**) of the superconducting region **31** in the second direction is, for example, preferably equal to or less than 1 mm, more preferably equal to or less than 50 μm, and further preferably equal to or less than 10 μm.

(105) In the superconducting wire **100** of the first embodiment, from the viewpoint of ensuring the insulating property, the width (W**2** in FIG. **1**) of the non-superconducting region **32** in the second direction is, for example, preferably equal to or more than 5 μm and more preferably equal to or more than 10 μm.

(106) In the superconducting wire **100** of the first embodiment, from the viewpoint of reducing the AC loss, the width (W**2** in FIG. **1**) of the non-superconducting region **32** in the second direction is, for example, preferably equal to or less than 1 mm, more preferably equal to or less than 50 μm, and further preferably equal to or less than 10 μm.

(107) In the superconducting wire **100** of the first embodiment, the concentration of praseodymium (Pr) contained in the non-superconducting region **32** is preferably equal to or more than 10 atom % and more preferably equal to or more than 20 atom %, from the viewpoint of not causing the non-superconducting region **32** to exhibit superconducting characteristics.
(108) In the superconducting wire **100** of the first embodiment, the concentration of praseodymium (Pr) contained in the superconducting region **31** is preferably less than 1 atom % and more preferably less than 0.1 atom %, from the viewpoint of not inhibiting the superconducting characteristics of the superconducting region **31**.
(109) As described above, according to the first embodiment, it is possible to provide a superconducting wire capable of reducing the AC loss. In addition, by providing the gettering site of the impurities, a superconducting wire having excellent superconducting characteristics can be provided.
Second Embodiment
(110) A superconducting motor of a second embodiment includes a superconducting coil including a superconducting wire of the first embodiment and a superconducting magnet including the superconducting coil. Hereinafter, description of contents overlapping with those of the first embodiment may be partially omitted.
(111) FIGS. **8**A and **8**B are schematic cross-sectional views of the superconducting motor according to the second embodiment. FIG. **8**B illustrates a cross-section taken along the line BB′ of FIG. **8**A.
(112) A superconducting motor **200** of the second embodiment is an all-superconducting motor using a superconducting coil for both a rotor and a stator.
(113) The superconducting motor **200** includes a case **50**, a stator **52**, a rotor **54**, and a shaft **56**. The stator **52** includes a stator coil **52***a*, and the rotor **54** includes a rotor coil **54***a*.
(114) A superconducting wire **100** of the first embodiment is used for the stator coil **52***a*. In addition, the superconducting wire **100** of the first embodiment is used for the rotor coil **54***a*. The stator coil **52***a* and the rotor coil **54***a* are examples of the superconducting coil.
(115) An AC current flows through the stator coil **52***a* of the stator **52**, and an AC magnetic field is generated. The stator **52** is an example of the superconducting magnet.
(116) According to the second embodiment, it is possible to realize a superconducting coil, a superconducting magnet, and a superconducting motor in which an AC loss is reduced by using the superconducting wire **100** of the first embodiment. In addition, by using the superconducting wire **100** having excellent superconducting characteristics, a superconducting coil, a superconducting magnet, and a superconducting motor having excellent characteristics can be realized.
Third Embodiment
(117) A superconducting aircraft of a third embodiment includes a superconducting motor of the second embodiment. Hereinafter, description of contents overlapping with those of the first and second embodiments may be partially omitted.
(118) FIG. **9** is a schematic top view of the superconducting aircraft of the third embodiment. A superconducting aircraft **300** of the third embodiment uses a superconducting motor **200** as a power source.
(119) The superconducting aircraft **300** includes a fuselage **60**, a main wing **62**, a gas turbine **64**, a superconducting generator **66**, and a plurality of superconducting motors **200**.
(120) The plurality of superconducting motors **200** are provided on the main wing **62**. The superconducting motor **200** includes a superconducting coil using a superconducting wire **100** of the first embodiment.
(121) A propulsion fan (not illustrated) is rotated by each of the plurality of superconducting motors **200**, and a propulsive force of the superconducting aircraft **300** is generated.
(122) The gas turbine **64** and the superconducting generator **66** are provided in the fuselage **60**. The superconducting generator **66** includes a superconducting coil using the superconducting wire **100**

of the first embodiment.
(123) The gas turbine **64** is driven by using liquid hydrogen as fuel, for example. The superconducting generator **66** is directly connected to the gas turbine **64**, and generates electric power by driving the gas turbine **64**. The plurality of superconducting motors **200** are driven by the electric power generated by the superconducting generator **66**.
(124) According to the third embodiment, it is possible to realize a superconducting generator and a superconducting aircraft in which an AC loss is reduced by using the superconducting wire **100** of the first embodiment. In addition, by using the superconducting wire **100** having excellent superconducting characteristics, a superconducting generator and a superconducting aircraft having excellent characteristics can be realized.
Fourth Embodiment
(125) A superconducting device of the fourth embodiment is a superconducting device including a superconducting coil using a superconducting wire of the first embodiment. Hereinafter, description of contents overlapping with those of the first embodiment will be partially omitted.
(126) FIG. **10** is a block diagram of the superconducting device according to the fourth embodiment. The superconducting device of the fourth embodiment is a heavy particle radiotherapy device **400**. The heavy particle radiotherapy device **400** is an example of the superconducting device.
(127) The heavy particle radiotherapy device **400** includes an incidence system **70**, a synchrotron accelerator **72**, a beam transport system **74**, an irradiation system **76**, and a control system **78**.
(128) The incidence system **70** has, for example, a function of generating carbon ions to be used for treatment and performing preliminary acceleration for incidence into the synchrotron accelerator **72**. The incidence system **70** includes, for example, an ion generation source and a linear accelerator.
(129) The synchrotron accelerator **72** has a function of accelerating a carbon ion beam incident from the incidence system **70** to energy suitable for treatment. A superconducting coil using a superconducting wire **100** of the first embodiment is applied to the synchrotron accelerator **72**.
(130) The beam transport system **74** has a function of transporting the carbon ion beam incident from the synchrotron accelerator **72** to the irradiation system **76**. The beam transport system **74** includes, for example, a bending electromagnet.
(131) The irradiation system **76** has a function of irradiating a patient to be irradiated with the carbon ion beam incident from the beam transport system **74**. The irradiation system **76** has, for example, a rotary gantry that enables irradiation with the carbon ion beam from an arbitrary direction. The superconducting coil using the superconducting wire **100** of the first embodiment is applied to the rotary gantry.
(132) The control system **78** controls the incidence system **70**, the synchrotron accelerator **72**, the beam transport system **74**, and the irradiation system **76**. The control system **78** is, for example, a computer.
(133) In the heavy particle radiotherapy device **400** according to the fourth embodiment, the superconducting coil using the superconducting wire **100** according to the first embodiment is used for the synchrotron accelerator **72** and the rotary gantry. Therefore, according to the fourth embodiment, a heavy particle radiotherapy device having excellent characteristics is realized.
(134) In the fourth embodiment, the case of the heavy particle radiotherapy device **400** has been described as an example of the superconducting device. However, the superconducting device may be, for example, a nuclear magnetic resonance apparatus (NMR), a magnetic resonance imaging apparatus (MRI), a magnetic field application type single crystal pulling device, or a superconducting magnetic-levitation railway vehicle.
(135) Hereinafter, examples will be described.
EXAMPLES
Example 1

(136) A superconducting wire similar to the superconducting wire **100** of the first embodiment was manufactured according to the flowcharts illustrated in FIGS. **4** and **5**. Yttrium (Y) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region. The coating solution was applied onto the substrate by using an inkjet method.

(137) As firing conditions of the gel film and the calcined film, conditions were selected in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 850 ppm.

Example 2

(138) A superconducting wire was manufactured by a method similar to that in Example 1, except that conditions in which the surface density of the high-aspect-ratio particles in the non-superconducting region is smaller than that in Example 1 were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 800 ppm.

Example 3

(139) A superconducting wire was manufactured by a method similar to that in Example 1, except that conditions in which the surface density of the high-aspect-ratio particles in the non-superconducting region is smaller than that in Example 2 were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 750 ppm.

Example 4

(140) A superconducting wire was manufactured by a method similar to that in Example 1, except that gadolinium (Gd) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 80 ppm.

Example 5

(141) A superconducting wire was manufactured by a method similar to that in Example 1, except that europium (Eu) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 35 ppm.

Example 6

(142) A superconducting wire was manufactured by a method similar to that in Example 1, except that lanthanum (La) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 0.2 ppm.

Example 7

(143) A superconducting wire was manufactured by a method similar to that in Example 1, except that neodymium (Nd) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density

of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 3.5 ppm.

Example 8

(144) A superconducting wire was manufactured by a method similar to that in Example 1, except that samarium (Sm) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 20 ppm.

Example 9

(145) A superconducting wire was manufactured by a method similar to that in Example 1, except that dysprosium (Dy) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 300 ppm.

Example 10

(146) A superconducting wire was manufactured by a method similar to that in Example 1, except that holmium (Ho) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 510 ppm.

Example 11

(147) A superconducting wire was manufactured by a method similar to that in Example 1, except that erbium (Er) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 920 ppm.

Example 12

(148) A superconducting wire was manufactured by a method similar to that in Example 1, except that thulium (Tm) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 1600 ppm.

Example 13

(149) A superconducting wire was manufactured by a method similar to that in Example 1, except that ytterbium (Yb) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing

conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 2000 ppm.

Example 14

(150) A superconducting wire was manufactured by a method similar to that in Example 1, except that lutetium (Lu) was selected as the rare earth element in the superconducting region and the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 2400 ppm.

Example 15

(151) A superconducting wire was manufactured by a method similar to that in Example 1, except that yttrium (Y) was selected as the rare earth element in the superconducting region and gadolinium (Gd) was selected as the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 760 ppm.

Example 16

(152) A superconducting wire was manufactured by a method similar to that in Example 1, except that yttrium (Y) was selected as the rare earth element in the superconducting region and europium (Eu) was selected as the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 755 ppm.

Example 17

(153) A superconducting wire was manufactured by a method similar to that in Example 1, except that gadolinium (Gd) was selected as the rare earth element in the superconducting region and europium (Eu) was selected as the rare earth element in the non-superconducting region, and conditions in which the surface density of the high-aspect-ratio particles in the superconducting region decreases and the surface density of the high-aspect-ratio particles in the non-superconducting region increases were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 80 ppm.

Comparative Example

(154) A superconducting wire was manufactured by a method similar to that in Example 1, except that conditions in which the surface density of the high-aspect-ratio particles in the superconducting region and the surface density of the high-aspect-ratio particles in the non-superconducting region decrease similarly were selected as firing conditions of the gel film and the calcined film. The firing conditions are specifically a final firing temperature of 790° C. and an oxygen partial pressure of 700 ppm.

(155) Table 1 shows evaluation results of the superconducting wires of Examples 1 to 17 and Comparative Example. Note that elements other than yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), praseodymium (Pr), barium (Ba), copper (Cu), oxygen (O), aluminum (Al), and carbon (C) were counted as impurities. As a result of the EPMA measurement, in Examples 1 to 17, the surface density of the particles having an aspect ratio of 3 or

more present on the surface of the non-superconducting region is larger than the surface density of the particles having an aspect ratio of 3 or more present on the surface of the superconducting region. In addition, it was found that chlorine (Cl) was segregated in the non-superconducting region. From Table 1, it can be seen that, in Examples 1 to 17, a critical current density increases as compared with Comparative Example, and superconducting characteristics are improved.

(156) TABLE-US-00001 TABLE 1 Surface Concentration density Ratio of of of surface praseodymium Surface high-aspect- density of (Pr) in density ratio high-aspect- rare earth Rare earth of particles ratio elements Rare earth element of high-aspect-ratio in non- particles (non-contained in element of non- particles in super- superconducting super- super- super-superconducting conducting region/ conducting conducting conducting region region superconducting region region region (particles/μm.sup.2) (particles/μm.sup.2) region) (atom %) Example 1 Y Y 0.05 0.68 12.8 less than 0.1 Example 2 Y Y 0.05 0.24 4.5 0.1 Example 3 Y Y 0.05 0.10 1.9 0.9 Example 4 Gd Gd 0.05 0.60 11.3 less than 0.1 Example 5 Eu Eu 0.05 0.65 12.4 less than 0.1 Example 6 La La 0.05 0.74 14.6 less than 0.1 Example 7 Nd Nd 0.05 0.75 13.6 less than 0.1 Example 8 Sm Sm 0.05 0.71 13.9 less than 0.1 Example 9 Dy Dy 0.06 0.69 12.0 less than 0.1 Example 10 Ho Ho 0.05 0.68 13.1 less than 0.1 Example 11 Er Er 0.06 0.75 12.8 less than 0.1 Example 12 Tm Tm 0.05 0.71 14.5 less than 0.1 Example 13 Yb Yb 0.05 0.73 14.0 less than 0.1 Example 14 Lu Lu 0.05 0.72 14.3 less than 0.1 Example 15 Y Gd 0.06 0.68 11.8 less than 0.1 Example 16 Y Eu 0.05 0.63 11.5 less than 0.1 Example 17 Gd Eu 0.06 0.64 10.9 less than 0.1 Comparative Y Y 0.05 0.05 1 2 Example 1 Concentration of Ratio of praseodymium impurity Critical (Pr) in Impurity Impurity element current rare earth element element concentrations density elements concentration concentration (non-super- (Jc) contained of of non- conducting (relative in non- super- super- region/ value superconducting conducting conducting super- based on region Impurity region region conducting Comparative (atom %) element (atom %) (atom %) region) Example) Example 1 20 Cl 0.01 0.40 40 2.2 Example 2 16 Cl 0.04 0.32 8 1.5 Example 3 12 Cl 0.10 0.28 2.8 1.2 Example 4 20 Cl 0.01 0.38 38 2.0 Example 5 20 Cl 0.01 0.40 39 2.1 Example 6 20 Cl 0.01 0.44 48 2.3 Example 7 20 Cl 0.01 0.45 45 2.3 Example 8 20 Cl 0.01 0.43 45 2.3 Example 9 20 Cl 0.01 0.39 38 2.1 Example 10 20 Cl 0.01 0.39 40 2.1 Example 11 20 Cl 0.01 0.44 42 2.2 Example 12 20 Cl 0.01 0.40 45 2.3 Example 13 20 Cl 0.01 0.43 46 2.3 Example 14 20 Cl 0.01 0.43 47 2.3 Example 15 20 Cl 0.01 0.38 35 2.0 Example 16 20 Cl 0.01 0.37 35 2.0 Example 17 20 Cl 0.01 0.36 32 1.9 Comparative 9 Cl 0.21 0.20 0.95 1 Example 1

(157) While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, a superconducting wire, a superconducting coil, a superconducting magnet, a superconducting motor, a superconducting generator, a superconducting aircraft, and a superconducting device described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the devices and methods described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the inventions.

(158) Hereinafter, some technical aspects of the present invention will be described in claim like clauses.

Clause 1

(159) A superconducting wire including: a substrate; a first region provided on the substrate, the first region containing barium (Ba), copper (Cu), oxygen (O), and at least one first rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the first region extending in a first direction along a surface of the substrate; a second region provided on the substrate, the second region containing barium (Ba), copper (Cu), oxygen (O), and at least one second rare earth element

selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the second region extending in the first direction; and a third region provided on the substrate, the third region provided between the first region and the second region, the third region being in contact with the first region and the second region, the third region containing praseodymium (Pr), barium (Ba), copper (Cu), oxygen (O), and at least one third rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the third region extending in the first direction, wherein a surface density of particles having an aspect ratio of 3 or more present on a surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the first region, and the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the second region.

Clause 2

(160) The superconducting wire according to Clause 1, wherein a concentration of praseodymium (Pr) contained in the first region and the second region is smaller than a concentration of praseodymium (Pr) contained in the third region.

Clause 3

(161) The superconducting wire according to Clause 1 or 2, wherein a concentration of praseodymium (Pr) in the rare earth elements contained in the first region and the second region is less than 1 atom %, and a concentration of praseodymium (Pr) in the rare earth elements contained in the third region is equal to or more than 10 atom %.

Clause 4

(162) The superconducting wire according to any one of Clauses 1 to 3, wherein the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is twice or more the surface density of the particles having an aspect ratio of 3 or more present on the surface of the first region, and the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is twice or more the surface density of the particles having an aspect ratio of 3 or more present on the surface of the second region.

Clause 5

(163) The superconducting wire according to any one of Clauses 1 to 4, wherein a width of the first region in a second direction perpendicular to the first direction and along the surface of the substrate is equal to or more than 5 μm and equal to or less than 10 mm, a width of the second region in the second direction is equal to or more than 5 μm and equal to or less than 10 mm, and a width of the third region in the second direction is equal to or more than 1 μm and equal to or less than 2 mm.

Clause 6

(164) The superconducting wire according to any one of Clauses 1 to 5, wherein a width of the third region in a second direction perpendicular to the first direction and along the surface of the substrate is equal to or less than a width of the first region in the second direction and a width of the second region in the second direction.

Clause 7

(165) The superconducting wire according to any one of Clauses 1 to 6, wherein a surface density of particles having an aspect ratio of 3 or more present on a cross section along the surface of the third region at a position closer to the substrate than the surface of the third region is smaller than the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region.

Clause 8

(166) The superconducting wire according to any one of Clauses 1 to 7, wherein an atomic

concentration of an impurity element contained in the third region is higher than an atomic concentration of an impurity element contained in the first region, and the atomic concentration of the impurity element contained in the third region is higher than an atomic concentration of an impurity element contained in the second region.
Clause 9
(167) A superconducting coil including the superconducting wire according to any one of Clauses 1 to 8.
Clause 10
(168) A superconducting magnet including the superconducting coil according to Clause 9.
Clause 11
(169) A superconducting motor including the superconducting coil according to Clause 9.
Clause 12
(170) A superconducting generator including the superconducting coil according to Clause 9.
Clause 13
(171) A superconducting aircraft including the superconducting motor according to Clause 11.
Clause 14
(172) A superconducting device including the superconducting wire according to any one of Clauses 1 to 8.

Claims

1. A superconducting wire comprising: a substrate; a first region provided on the substrate, the first region containing barium (Ba), copper (Cu), oxygen (O), and at least one first rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the first region extending in a first direction along a surface of the substrate; a second region provided on the substrate, the second region containing barium (Ba), copper (Cu), oxygen (O), and at least one second rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the second region extending in the first direction; and a third region provided on the substrate, the third region provided between the first region and the second region, the third region being in contact with the first region and the second region, the third region containing praseodymium (Pr), barium (Ba), copper (Cu), oxygen (O), and at least one third rare earth element selected from the group consisting of yttrium (Y), lanthanum (La), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), and the third region extending in the first direction, wherein a surface density of particles having an aspect ratio of 3 or more present on a surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the first region, and the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is larger than a surface density of particles having an aspect ratio of 3 or more present on a surface of the second region.
2. The superconducting wire according to claim 1, wherein a concentration of praseodymium (Pr) contained in the first region and the second region is smaller than a concentration of praseodymium (Pr) contained in the third region.
3. The superconducting wire according to claim 1, wherein a concentration of praseodymium (Pr) in the rare earth elements contained in the first region and the second region is less than 1 atom %, and a concentration of praseodymium (Pr) in the rare earth elements contained in the third region is equal to or more than 10 atom %.
4. The superconducting wire according to claim 1, wherein the surface density of the particles

having an aspect ratio of 3 or more present on the surface of the third region is twice or more the surface density of the particles having an aspect ratio of 3 or more present on the surface of the first region, and the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region is twice or more the surface density of the particles having an aspect ratio of 3 or more present on the surface of the second region.

5. The superconducting wire according to claim 1, wherein a width of the first region in a second direction perpendicular to the first direction and along the surface of the substrate is equal to or more than 5 μm and equal to or less than 10 mm, a width of the second region in the second direction is equal to or more than 5 μm and equal to or less than 10 mm, and a width of the third region in the second direction is equal to or more than 1 μm and equal to or less than 2 mm.

6. The superconducting wire according to claim 1, wherein a width of the third region in a second direction perpendicular to the first direction and along the surface of the substrate is equal to or less than a width of the first region in the second direction and a width of the second region in the second direction.

7. The superconducting wire according to claim 1, wherein a surface density of particles having an aspect ratio of 3 or more present on a cross section along the surface of the third region at a position closer to the substrate than the surface of the third region is smaller than the surface density of the particles having an aspect ratio of 3 or more present on the surface of the third region.

8. The superconducting wire according to claim 1, wherein an atomic concentration of an impurity element contained in the third region is higher than an atomic concentration of an impurity element contained in the first region, and the atomic concentration of the impurity element contained in the third region is higher than an atomic concentration of an impurity element contained in the second region.

9. A superconducting coil comprising the superconducting wire according to claim 1.

10. A superconducting magnet comprising the superconducting coil according to claim 9.

11. A superconducting motor comprising the superconducting coil according to claim 9.

12. A superconducting generator comprising the superconducting coil according to claim 9.

13. A superconducting aircraft comprising the superconducting motor according to claim 11.

14. A superconducting device comprising the superconducting wire according to claim 1.