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Magnetic Structure and Method for Forming Same

Technical Field

The present invention relates to magnetic structures and more particularly nanocomposite magnetic structures and methods of fabricating such structures.

5 Background of the Invention

Hard magnetic materials are characterised by high coercive force and low saturation magnetization. Soft magnetic materials, on the other hand, are characterised by low coercive force and high saturation magnetization. When magnetically hard and soft phases are uniformly mixed on a nanoscale, exchange
10 coupling occurs between the hard and soft magnetic phases and the mutually exchange-coupled phases take on the characteristics of high coercive force from the hard magnetic phase and high saturation polarization from the soft magnetic phase [1]. Such exchange-coupled systems have a larger energy product than conventional single-phase materials and thus hold great promise for advanced
15 permanent magnetic applications.

A number of conventional techniques, for example, melt-spinning [2, 3], mechanical milling [4, 5], and sputtering [6, 7], have been explored for the preparation of exchange-coupled magnets. However, the requirement for nanoscale control of both the hard and soft magnetic phases to ensure efficient
20 exchange coupling poses significant challenges in the preparation of such exchange-coupled systems.

Zeng, et al. disclose in "*Exchange-coupled nanocomposite magnets by nanoparticle self-assembly*", Nature, 420, 395-398 (2002) [8] a wet chemical based nanoparticle self-assembly method to overcoming the problem of nanoscale
25 control in exchange-coupled magnet production. The self-assembly approach disclosed by Zeng, et al. involves synthesizing two types of nanoparticles from wet chemical solutions and incorporating these as nanometre-scale building blocks



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into binary assemblies. Subsequent annealing converts the assembly of hard and soft nanoparticles into exchange-coupled nanocomposites. Although promising results arising from successful nanoscale mixing of soft and hard magnetic phases are obtainable using the described method, the self-assembly approach is limited to small scale applications. Nanoscale control of the hard and soft magnetic phases is difficult and uniform mixing of the hard and soft magnetic phases is hard to attain in large-scale productions.

Thus, there exists a need for a method of forming a nanocomposite magnetic structure that provides control over the hard and soft magnetic nanophases during production. There also exists a need for a method of forming a nanocomposite magnetic structure that achieves uniform mixing of the hard and soft magnetic nanophases. There further exists a need for a method of forming a nanocomposite magnetic structure that is implementable on a large scale.

Summary of the Invention

Accordingly, the present invention provides, in a first aspect, a method for forming a magnetic structure, the method comprising: providing a template having a plurality of pores; depositing a metallic material into the pores of the template, thereby forming a plurality of nanoscale elements; removing the template from the nanoscale elements; performing an annealing process on the nanoscale elements to convert the nanoscale elements into a plurality of hard magnetic nanoscale elements; and depositing a soft magnetic material between the hard magnetic nanoscale elements, thereby forming a soft magnetic nanophase interspacing the hard magnetic nanoscale elements.

As used throughout this specification, the "nano-" prefix means relating to or occurring on a scale of nanometres (nm). For example, an element having a maximum diameter of approximately less than 100 nm would be regarded as a nanoscale element.

Also, as used throughout this specification, the term “hard” makes reference to a magnetic material having a large coercivity, for example, a magnetic material having a coercivity greater than 10,000 Oersteds (Oe), and the term “soft” makes reference to a magnetic material having very small coercivity, for example, a magnetic material having a coercivity of less than 1 Oe.

The method according to the first aspect provides good control over hard and soft magnetic nanophases during production. Consequently, the present invention is implementable on a large scale.

In a preferred embodiment, the pores are arranged in an array within the template. This facilitates uniform mixing of the hard and soft magnetic nanophases. Each of the pores may have a diameter of between about 5 nm to about 50 nm.

The nanoscale elements may have a height of between about 5 nm to about 50 nm. The nanoscale elements may be substantially rod-shaped.

The nanoscale elements are preferably annealed in air. In one embodiment, a layer of metallic oxide is formed on exposed surfaces of the nanoscale elements during the annealing process. The nanoscale elements may be annealed at a temperature of between about 500 degree Celsius (°C) to about 800 °C.

In a preferred embodiment, a substrate is formed on a surface of the template prior to depositing the metallic material into the pores of the template. The substrate preferably comprises a conductive metallic seed layer. The substrate may have a thickness of between about 50 nm to about 200 nm. The substrate is preferably formed on the template by sputter deposition.

The metallic material may comprise one of a cobalt iron (CoFe) alloy, a cobalt platinum (CoPt) alloy and an iron platinum (FePt) alloy. Preferably, the

metallic material is deposited into the pores of the template via an electrodeposition process.

The template may be removed via a wet etching process. The template preferably comprises anodized alumina oxide (AAO).

5 The soft magnetic material may comprise one of a cobalt iron (CoFe) alloy, a nickel iron (NiFe), cobalt (Co), nickel (Ni) and iron (Fe). Preferably, the soft magnetic material is deposited between the nanoscale elements via an electrodeposition process. The soft magnetic nanophase preferably comprises a plurality of nanorods interspacing the nanoscale elements.

10 In a second aspect, the invention further provides a magnetic structure, comprising: a regular array of hard magnetic nanoscale elements; and a soft magnetic nanophase interspacing the array of hard magnetic nanoscale elements.

As will be understood by those of skill in the art, the use of the term "regular" throughout this specification is not intended to mean that the hard
15 magnetic nanoscale elements in the array must be positioned in strict conformity with perfect regularity in a geometric sense. Rather, it should be understood that deviations from perfect regularity, for example, a separation of about 10 per cent (%) less than an ideal separation between the hard magnetic nanoscale elements in the array, are also encompassed by the term "regular".

20 Advantageously, because the hard magnetic nanoscale elements are uniformly distributed and embedded within the soft magnetic nanophase, uniform mixing of hard and soft magnetic nanophases is achieved. Consequently, the magnetic structure is capable of functioning as an exchange-coupled nanocomposite. Additionally, because good control over the hard and soft
25 magnetic nanophases can be achieved during production, the present invention is implementable on a large scale.

The hard magnetic nanoscale elements in the array may have a diameter of between about 5 nm to about 50 nm, and a height of between about 5 nm to about 50 nm. The hard magnetic nanoscale elements in the array may be substantially rod-shaped. A layer of metallic oxide may be formed on surfaces of the hard magnetic nanoscale elements in the array.

In a preferred embodiment, the magnetic structure further comprises a substrate on which the array of hard magnetic nanoscale elements and the soft magnetic nanophase are formed. The substrate preferably comprises a conductive metallic seed layer. The substrate may have a thickness of between about 50 nm to about 200 nm.

The hard magnetic nanoscale elements in the array may comprise one of a cobalt iron (CoFe) alloy, a cobalt platinum (CoPt) alloy and an iron platinum (FePt) alloy. The soft magnetic nanophase may comprise one of a cobalt iron (CoFe) alloy, a nickel iron (NiFe), cobalt (Co), nickel (Ni) and iron (Fe). Preferably, the soft magnetic nanophase comprises a plurality of nanorods interspacing the array of hard magnetic nanoscale elements.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

Brief Description of the Drawings

The following detailed description of preferred embodiments of the invention will be better understood when read in conjunction with the appended drawings. The present invention is illustrated by way of example and is not limited by the accompanying figures, in which like references indicate similar elements.

FIGS. 1A-1F are enlarged cross-sectional views illustrating a method for forming a magnetic structure in accordance with one embodiment of the present invention; and

FIGS. 2A-2F are enlarged cross-sectional views illustrating a method for forming a magnetic structure in accordance with another embodiment of the present invention.

Detailed Description of the Invention

5 The detailed description set forth below in connection with the appended drawings is intended as a description of the presently preferred embodiments of the invention, and is not intended to represent the only form in which the present invention may be practiced. It is to be understood that the same or equivalent functions may be accomplished by different embodiments that are intended to be
10 encompassed within the scope of the invention.

FIGS. 1A-1F illustrate a method for forming a magnetic structure in accordance with one embodiment of the present invention.

Referring now to FIG. 1A, a template 10 having a plurality of pores 12 is provided as shown. The pores 12 extend between top and bottom surfaces 14
15 and 16 of the template 10 and are arranged in an array within the template 10. The template 10 is made of AAO and has a thickness $T_{\text{template1}}$ of between about 50 nm to about 50 000 nm. Each of the pores 12 has a diameter D_{pore1} of between about 5 nm to about 50 nm and may be formed in the template 10 by electrochemical anodization for example.

20 Referring now to FIG. 1B, a substrate 18 is formed on the bottom surface 16 of the template 10 as shown. The substrate 18 acts as a conductive metallic seed layer on which an array of hard magnetic nanoscale elements and a soft magnetic nanophase interspacing the hard magnetic nanoscale elements in the array are formed in subsequent processing steps described below. The substrate 18 has a
25 thickness $T_{\text{substrate1}}$ of between about 50 nm to about 200 nm and is formed by sputter depositing a layer of electrically conductive material such as, for example, gold (Au) or copper (Cu) onto the bottom surface 16 of the template 10. Because

particles of the electrically conductive material are of a larger dimension than the diameters D_{pore1} of the pores 12, the electrically conductive material is merely deposited on the bottom surface 16 of the template 10 and does not enter the pores 12.

5 Referring now to FIG. 1C, a metallic material 20 — a CoFe alloy in the present embodiment — is deposited into the pores 12 of the template 10 as shown. A plurality of substantially rod-shaped nanoscale elements 22, distributed in an array within the matrix of the template 10, is thus formed in the pores 12 of the template 10. The metallic material 20 is deposited into the pores 12 of the
10 template 10 via an electrodeposition process such as, for example, electroplating. Such electrodeposition processes are known to those of skill in the art. The nanoscale elements 22 have a height H_{element1} of between about 5 nm to about 50 nm and a diameter D_{element1} of between about 5 nm to about 50 nm, the diameter D_{element1} of the nanoscale elements 22 corresponding to the diameter D_{pore1} of the
15 pores 12.

Referring now to FIG. 1D, the template 10 is removed from the nanoscale elements 22, leaving behind a plurality of free-standing nanoscale elements 22. The template 10 may be removed via a wet etching process using, for example, a sodium hydroxide (NaOH) solution.

20 Referring now to FIGS. 1D and 1E, an annealing process is performed on the nanoscale elements 22 to convert the nanoscale elements 22 into a plurality of hard magnetic nanoscale elements 24. In the present embodiment, the nanoscale elements 22 are annealed in air at a temperature of between about 500 °C to about 800 °C. This oxidises the nanoscale elements 22 of CoFe into hard
25 magnetic nanoscale elements 24 of cobalt iron oxide (CoFeO).

Referring now to FIG. 1F, a soft magnetic material 26 is deposited between the hard magnetic nanoscale elements 24, thereby forming a soft magnetic nanophase 26 interspacing the hard magnetic nanoscale elements 24. A

nanocomposite magnetic structure 28 having a regular array of hard magnetic nanoscale elements 24 and a soft magnetic nanophase 26, in the form of a plurality of nanorods, interspersing the array of hard magnetic nanoscale elements 24 is thus formed.

5 The soft magnetic material 26 may be one of a CoFe alloy, a NiFe alloy, Co, Ni and Fe and is deposited between the nanoscale elements 24 via an electrodeposition process such as, for example, electroplating. Since the hard magnetic nanoscale elements 24 are non-metallic and therefore non-conductive, the soft magnetic material 26 is first deposited on the metallic substrate 18
10 between the nanoscale elements 24 and builds up from there; the soft magnetic material 26 is not deposited on the top surfaces of the hard magnetic nanoscale elements 24.

As can be seen from FIG. 1F, the hard magnetic nanoscale elements 24 are uniformly distributed and embedded within the soft magnetic nanophase 26
15 and uniform mixing of hard and soft magnetic nanophases is achieved. The nanocomposite magnetic structure 28 is thus capable of functioning as an exchange-coupled nanocomposite.

FIGS. 2A-2F illustrate a method for forming a magnetic structure in accordance with another embodiment of the present invention.

20 Referring now to FIG. 2A, a template 50 having a plurality of pores 52 is provided as shown. The pores 52 extend between top and bottom surfaces 54 and 56 of the template 50 and are arranged in an array within the template 50. The template 50 is made of AAO and has a thickness $T_{\text{template2}}$ of between about 50 nm to about 50 000 nm. Each of the pores 52 has a diameter D_{pore2} of between
25 about 5 nm to about 50 nm and may be formed in the template 50 by electrochemical anodization for example.

Referring now to FIG. 2B, a substrate 58 is formed on the bottom surface 56 of the template 50 as shown. The substrate 58 acts as a conductive metallic seed layer on which an array of hard magnetic nanoscale elements and a soft magnetic nanophase interspersing the hard magnetic nanoscale elements in the array are formed in subsequent processing steps described below. The substrate 58 has a thickness $T_{\text{substrate2}}$ of between about 50 nm to about 200 nm and is formed by sputter depositing a layer of electrically conductive material such as, for example, Au or Cu onto the bottom surface 56 of the template 50. Because particles of the electrically conductive material are of a larger dimension than the diameters D_{pore2} of the pores 52, the electrically conductive material is merely deposited on the bottom surface 56 of the template 50 and does not enter the pores 52.

Referring now to FIG. 2C, a metallic material 60 — a CoPt alloy or a FePt alloy — is deposited into the pores 52 of the template 50 as shown. A plurality of substantially rod-shaped nanoscale elements 62, distributed in an array within the matrix of the template 50, is thus formed in the pores 52 of the template 50. The metallic material 60 is deposited into the pores 52 of the template 50 via an electrodeposition process such as, for example, electroplating. Such electrodeposition processes are known to those of skill in the art. The nanoscale elements 62 have a height H_{element2} of between about 5 nm to about 50 nm and a diameter D_{element2} of between about 5 nm to about 50 nm, the diameter D_{element2} of the nanoscale elements 62 corresponding to the diameter D_{pore2} of the pores 52.

Referring now to FIG. 2D, the template 50 is removed from the nanoscale elements 62, leaving behind a plurality of free-standing nanoscale elements 62. The template 50 may be removed via a wet etching process using, for example, a NaOH solution.

Referring now to FIG. 2E, an annealing process is performed on the nanoscale elements 62 to convert the nanoscale elements 62 into a plurality of hard magnetic nanoscale elements 63. In the present embodiment, the nanoscale elements 62 are annealed in air at a temperature of between about 500 °C to

about 800 °C. A layer of metallic oxide 64 is formed on exposed surfaces of the nanoscale elements 62 during the annealing process due to partial oxidation of the metallic material 60. The layer of metallic oxide 64 has a thickness T_{oxide} of between about 5 nm to about 20 nm.

5 Referring now to FIG. 2F, a soft magnetic material 66 is deposited between the hard magnetic nanoscale elements 63, thereby forming a soft magnetic nanophase 66 interspacing the hard magnetic nanoscale elements 63. A nanocomposite magnetic structure 68 having a regular array of hard magnetic nanoscale elements 63 and a soft magnetic nanophase 66, in the form of a
10 plurality of nanorods, interspacing the array of hard magnetic nanoscale elements 63 is thus formed.

The soft magnetic material 66 may be one of a CoFe alloy, a NiFe alloy, Co, Ni and Fe and is deposited between the hard magnetic nanoscale elements 63 via an electrodeposition process such as, for example, electroplating. Since the
15 metallic oxide layer 64 is non-metallic and therefore non-conductive, the soft magnetic material 66 is first deposited between the hard magnetic nanoscale elements 63 and builds up from there; the soft magnetic material 66 is not deposited on the top surfaces of the hard magnetic nanoscale elements 63.

As can be seen from FIG. 2F, the hard magnetic nanoscale elements 63
20 are uniformly distributed and embedded within the soft magnetic material 66 and uniform mixing of hard and soft magnetic nanophases is achieved. The nanocomposite magnetic structure 68 is thus capable of functioning as an exchange-coupled nanocomposite.

As is evident from the foregoing discussion, the present invention provides
25 an exchange-coupled nanocomposite magnetic structure having uniformly mixed hard and soft magnetic nanophases and methods for producing such a structure. Because good control over the hard and soft magnetic nanophases is achieved during production, the present invention is implementable on a large scale.

The description of the preferred embodiments of the present invention have been presented for purposes of illustration and description, but are not intended to be exhaustive or to limit the invention to the forms disclosed. It will be appreciated by those skilled in the art that changes could be made to the embodiments described above without departing from the broad inventive concept thereof. It is understood, therefore, that this invention is not limited to the particular embodiments disclosed, but covers modifications within the scope of the present invention as defined by the appended claims.

Further, unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise", "comprising" and the like are to be construed in an inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to".

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Claims

1. A method for forming a magnetic structure, the method comprising:
providing a template having a plurality of pores;
5 depositing a metallic material into the pores of the template, thereby forming a plurality of nanoscale elements;
removing the template from the nanoscale elements;
performing an annealing process on the nanoscale elements to convert the nanoscale elements into a plurality of hard magnetic nanoscale elements; and
10 depositing a soft magnetic material between the hard magnetic nanoscale elements, thereby forming a soft magnetic nanophase interspacing the hard magnetic nanoscale elements.
2. The method for forming a magnetic structure according to claim 1, wherein
15 the pores are arranged in an array within the template.
3. The method for forming a magnetic structure according to claim 1 or 2, wherein each of the pores has a diameter of between about 5 nanometres (nm) to about 50 nm.
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4. The method for forming a magnetic structure according to any one of the preceding claims, wherein the nanoscale elements have a height of between about 50 nm to about 50 000 nm.
- 25 5. The method for forming a magnetic structure according to any one of the preceding claims, wherein the nanoscale elements are substantially rod-shaped.
6. The method for forming a magnetic structure according to any one of the preceding claims, wherein a layer of metallic oxide is formed on exposed surfaces
30 of the nanoscale elements during the annealing process.

7. The method for forming a magnetic structure according to any one of the preceding claims, wherein the nanoscale elements are annealed in air.

5 8. The method for forming a magnetic structure according to any one of the preceding claims, wherein the nanoscale elements are annealed at a temperature of between about 500 degree Celsius (°C) to about 800 °C.

9. The method for forming a magnetic structure according to any one of the
10 preceding claims, further comprising forming a substrate on a surface of the template prior to depositing the metallic material into the pores of the template.

10. The method for forming a magnetic structure according to claim 9, wherein the substrate comprises a conductive metallic seed layer.

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11. The method for forming a magnetic structure according to claim 9 or 10, wherein the substrate has a thickness of between about 50 nm to about 200 nm.

12. The method for forming a magnetic structure according to any one of claims
20 9 to 11, wherein the substrate is formed on the template by sputter deposition.

13. The method for forming a magnetic structure according to any one of the preceding claims, wherein the metallic material comprises one of a cobalt iron (CoFe) alloy, a cobalt platinum (CoPt) alloy and an iron platinum (FePt) alloy.

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14. The method for forming a magnetic structure according to any one of the preceding claims, wherein the metallic material is deposited into the pores of the template via an electrodeposition process.

15. The method for forming a magnetic structure according to any one of the preceding claims, wherein the template is removed via a wet etching process.

16. The method for forming a magnetic structure according to any one of the preceding claims, wherein the template comprises anodized alumina oxide (AAO).

17. The method for forming a magnetic structure according to any one of the preceding claims, wherein the soft magnetic material comprises one of a cobalt iron (CoFe) alloy, a nickel iron (NiFe), cobalt (Co), nickel (Ni) and iron (Fe).

18. The method for forming a magnetic structure according to any one of the preceding claims, wherein the soft magnetic material is deposited between the nanoscale elements via an electrodeposition process.

19. The method for forming a magnetic structure according to any one of the preceding claims, wherein the soft magnetic nanophase comprises a plurality of nanorods interspacing the nanoscale elements.

20. A magnetic structure, comprising:
a regular array of hard magnetic nanoscale elements; and
a soft magnetic nanophase interspacing the array of hard magnetic nanoscale elements.

21. The magnetic structure according to claim 20, wherein the hard magnetic nanoscale elements in the array have a diameter of between about 5 nm to about 50 nm.

22. The magnetic structure according to claim 20 or 21, wherein the hard magnetic nanoscale elements in the array have a height of between about 50 nm to about 50 000 nm.

23. The magnetic structure according to any one of claims 20 to 22, wherein the hard magnetic nanoscale elements in the array are substantially rod-shaped.

5 24. The magnetic structure according to any one of claims 20 to 23, further comprising a layer of metallic oxide formed on surfaces of the hard magnetic nanoscale elements in the array.

25. The magnetic structure according to any one of claims 20 to 24, further
10 comprising a substrate on which the array of hard magnetic nanoscale elements and the soft magnetic nanophase are formed.

26. The magnetic structure according to according to claim 25, wherein the substrate comprises a conductive metallic seed layer.

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27. The magnetic structure according to claim 25 or 26, wherein the substrate has a thickness of between about 50 nm to about 200 nm.

28. The magnetic structure according to any one of claims 20 to 27, wherein
20 the hard magnetic nanoscale elements in the array comprise one of a cobalt iron (CoFe) alloy, a cobalt platinum (CoPt) alloy and an iron platinum (FePt) alloy.

29. The magnetic structure according to any one of claims 20 to 28, wherein the soft magnetic nanophase comprises one of a cobalt iron (CoFe) alloy, a nickel
25 iron (NiFe), cobalt (Co), nickel (Ni) and iron (Fe).

30. The magnetic structure according to any one of claims 20 to 29, wherein the soft magnetic nanophase comprises a plurality of nanorods interspacing the array of hard magnetic nanoscale elements.

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