

MAGNETORESISTIVE SENSOR BASED ON OSCILLATIONS
IN THE MAGNETORESISTANCE

This invention relates in general to magnetoresistive sensors and in particular to sensors which exhibit high values of saturation magnetoresistance.

The prior art discloses a magnetic transducer referred to as a magnetoresistive (MR) sensor or head which has been shown to be capable of reading data from a magnetic surface at great linear densities. An MR sensor detects magnetic field signals through the resistance changes of a read element made from a magnetic material as a function of the amount and direction of magnetic flux being sensed by the element. These prior art MR sensors operate on the basis of the anisotropic magnetoresistive (AMR) effect in which a component of the resistance varies as $\cos^2$ of the angle between the magnetization and the direction of current flow. These MR sensors have operated on the basis of the AMR effect even though this effect produced only a very small percentage change in the resistance.

More recently, reports have been published of techniques for obtaining enhanced MR effects. One of these publications, "Enhanced Magnetoresistance in Layered Magnetic Structures with Antiferromagnetic Interlayer Exchange", G. Binasch, et al, Physical Review B. V39, p. 4828 (1989) describes a layered magnetic structure which yields enhanced MR effects caused by antiparallel alignment of the magnetization. However the saturation fields required to obtain these changes in resistance were too high and the effect too nonlinear and therefore unsuitable for producing a practical MR sensor.

Another of these publications, "Layered Magnetic Structures: Exchange Coupling of Ferromagnetic Layers Across Interlayers", P. Grunberg et al., MRS Intl. Mtg. Adv. Mats., V. 10, p. 255 (1989), and studies dating back to the 1960's have shown ferromagnetic coupling in

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such systems decaying monotonically with increasing separation of the magnetic layers for a wide range of systems.

A further publication, "Oscillations in Exchange Coupling and Magnetoresistance in Metallic Superlattice Structures: Co/Ru, Co/Cr, and Fe/Cr", S.S.P. Parkin et al., Physical Review Lett. Vol. 64, p.2304 (1990) discloses antiferromagnetic interlayer exchange coupling and enhanced saturation magnetoresistance in two metallic superlattice systems, Co/Cr and Co/Ru. In these systems and in Fe/Cr superlattices both the magnitude of the interlayer magnetic exchange coupling and the saturation magnetoresistance oscillate with the Cr or Ru spacer layer thickness. The superlattice structures described comprise a Silicon substrate on which is deposited alternating layers of either Co and Cr, Co and Ru, or Fe and Cr. For $t_{\text{Ru}} = 3\text{\AA}$, the value for saturation magnetoresistance attained was 6.5% with a saturation field of greater than 70 KOe.

The present invention employs the basic principle of magnetoresistance oscillations as described in the S. Parkin paper but provides new structures and/or material combinations which exhibit unexpected advantages over those structures described in the paper.

Accordingly, the invention provides, in one aspect, a magnetoresistive sensor comprising a substrate and a multilayered structure formed on the substrate comprising alternating layers of a ferromagnetic material and a non-magnetic metallic material, the ferromagnetic material and the non-magnetic material forming bilayers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of thickness of the layers of non-magnetic material and characterised in that the non-magnetic metallic material is Cu.

The use of copper as the non-magnetic metallic layer provides significant advantages over the previously disclosed structures. By choosing the thickness of the copper layer to that corresponding to a

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peak in the magnetoresistance, extraordinarily large saturation magnetoresistance can be achieved, reaching values greater than 50% which is larger than any previously observed in multilayer structures. At the same time, the magnitude of saturation field required to produce these changes in resistance is sufficiently low for use as a practicable MR sensor.

In a second aspect of the invention, there is provided a magnetoresistive sensor comprising a substrate and a multilayered structure formed on the substrate comprising alternating layers of a first and a second ferromagnetic material and a non-magnetic metallic material, the first and second ferromagnetic materials and the non-magnetic material forming quadlayers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of thickness of the layers of the non-magnetic material.

In a further aspect of the invention, there is provided a magnetoresistive sensor comprising: a substrate and a multilayered structure formed on said substrate comprising alternating layers of a ferromagnetic material and a non-magnetic metallic material, the ferromagnetic material and the non-magnetic material forming bilayers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of thickness of the layers of non-magnetic material and characterised in that the non-magnetic metallic material is chosen from the group consisting of Ir, Re and Rh.

Preferred embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 is a graph showing saturation magnetoresistance as a function of the thickness of the non-magnetic spacer layer in structure comprising ferromagnetic layers separated by a non-magnetic spacer layer according to the prior art;



Fig. 2 is a graph showing the saturation magnetoresistance versus non-magnetic layer thickness for a family of related multilayer structures according to the present invention.

Fig. 3 is an end view of a specific embodiment of a magnetoresistive sensor comprising a bilayer structure according to the present invention.

Fig. 4 is a graph showing saturation magnetoresistance versus non-magnetic layer thickness for a specific embodiment of a bilayer structure according to the present invention.

Fig. 5 is an end view of a specific embodiment of a magnetoresistive sensor comprising a quadlayer structure according to the present invention.

Fig. 6 is a graph showing saturation magnetoresistance versus non-magnetic layer thickness for a specific embodiment of a quadlayer structure according to the present invention.

Fig. 7 is an end view of an alternate embodiment of a magnetoresistive sensor comprising a bilayer structure according to the present invention.

Fig. 8 is a graph showing magnetoresistance versus in-plane magnetic field for four similar structures of the type shown in Fig. 7.

Fig. 9 is a graph showing the saturation magnetoresistance versus non-magnetic layer thickness for the family of structures shown in Fig. 2, but taken at a temperature of 4.2 K.

Fig. 10 is an end view of an alternate embodiment of a magnetoresistive sensor comprising a quadlayer structure according to the present invention.

Fig. 11 is a graph showing saturation field versus non-magnetic layer thickness for a structure of the type shown in Fig. 10.

Fig. 12 is a series of graphs (a)-(f) showing the magnetoresistance versus in-plane magnetic field for six representative structures of the type shown in Fig. 7.

Fig. 13 is a graph showing the magnetoresistance versus non-magnetic layer thickness for a structure of the type shown in Fig. 7.

Fig. 14 is a graph showing the magnetoresistance versus magnetic field for a structure of the type shown in Fig. 7 which shows high magnetoresistance at low field.

Fig. 15 is a graph showing magnetoresistance versus in plane magnetic field for three structures of the type shown in Fig. 7, but with varying thickness of the ferromagnetic layer.

As shown in Fig. 1, the prior art teaches that the saturation magnetoresistance for these layered structures decreases monotonically with non-magnetic layer thickness. In addition, the prior art also discloses certain superlattice structures in which the magnitude of the saturation magnetoresistance oscillates with non-magnetic layer thickness.

By the use of the materials that exhibit this oscillatory characteristic it is possible to build an MR sensor which produces large changes in magnetoresistance by selecting the thickness of the non-magnetic metallic layer to coincide with that for one of the peaks as shown in Fig. 2, for example.

Specific examples of those material systems which exhibit improved characteristics over prior art structures will now be given. A specific

embodiment of a magnetoresistive (MR) sensor is shown in Fig. 3. The MR sensor 10 comprises a multilayered metallic structure formed on a suitable substrate 11 having alternating layers of ferromagnetic material 12 and non-magnetic metallic material (in the form of copper) 14. A chosen number N of the material combination of layers 12 and 14 is formed and the assembly is provided with a capping layer 16 which serves as a protective layer to the sensor 10.

A specific embodiment of the invention shown in Fig. 3 comprises a bilayer structure of the following materials:

$$\text{Si}/48\text{\AA}\text{Cu}/[9\text{\AA}\text{Co}/\text{Cu}(t_{\text{Cu}})]/_{\text{N}}50\text{\AA}\text{Cu}$$

This structure was prepared in some samples having 20 bilayers, and others having 16 bilayers and the magnetoresistance of these structures is shown in Fig. 4. The magnetoresistance is somewhat less for the structures having 16 bilayers, but the oscillation is in the same pattern for both the 16 and 20 bilayers structures with peaks around 10, 20 and a little over 30 angstroms of copper. Shunting through the buffer layer and the capping layer reduces the magnitude of the magnetoresistance, but the magnitude of the magnetoresistance can be maximized by choosing the buffer layer and capping layer materials to be of high resistivity and by choosing a large number N of the material layer combinations (40-60, for example).

The specific embodiment of the invention shown in Fig. 5 comprises a quadlayer structure deposited on substrate 11 which includes a first layer of ferromagnetic material 12, a first layer of non-magnetic metallic material 14, a second layer of ferromagnetic material 13, and a second layer of non-magnetic metallic material 15. A chosen number N of the materials combinations of layers 12, 13, 14 and 15 is formed and the assembly is provided with a capping layer 16.

A specific embodiment of a quadlayer structure according to the invention comprises the following structure:

$$\text{Si}/[\text{Co } 10\text{\AA}/\text{Cu}(t_{\text{Cu}})/\text{Ni } 11.5\text{\AA}/\text{Cu}(t_{\text{Cu}})]/_{\text{N}}/$$

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Note that this structure shows, in the graph of Fig. 6, a definite oscillation versus thickness with peaks just below 10 and 20 angstroms.

It has also been discovered that the giant magnetoresistance effects observed in the layered structures described above can be substantially enhanced by deposition upon certain buffer layers.

Fig. 7 shows a bilayer structure similar to that shown in Fig. 3 with the exception that a buffer layer 18 is provided on substrate 11 prior to forming the first ferromagnetic layer 12. Following deposition of the capping layer 16, electrical leads 20 and 22 are provided to form a circuit pattern between the MR sensor structure, current source 24 and sensing means 26.

Fig. 8 shows four graphs of bilayer structures which have identical numbers of Co and Cu layers but which have various combination of Fe and Cu for the barrier layer 18 and the capping layer 16. These graphs show a variation in the saturation magnetoresistance by more than a factor of three. These differences are due to reduced current shunting through the buffer layer and by changes in the growth morphology of the thin films of the structure.

The buffer layer material must be chosen for optimum magnetoresistance. The first consideration is that it must not react with the substrate material, and the second requirement is flatness since this appears to be important, particularly for thin non-magnetic spacer layers (ie, in the vicinity of the first peak). In addition, the buffer layer should be as thin as possible to minimize shunting effects while at the same time insuring that the buffer layer is a continuous layer. The buffer layer may comprise Fe, Ru, Cu, Rh, Ir, Re, or Cr, for example, and suitable thicknesses for Fe comprise a range of about 15 to 50 angstroms.

The graph of Fig. 2 is a specific example of a structure having a buffer layer and has the following structure:

$\text{Si/Fe } 45\text{\AA}/[\text{Co } 10\text{\AA}/\text{Cu}(t_{\text{cu}})]_n$

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The data plotted in Fig. 2 was taken at room temperature, 300°K, and data from the same structure, but operated at Helium temperature (4.2K), is shown in Fig. 9. These two graphs are similar and demonstrate that the peaks in magnetoresistance are independent of temperature. It can be seen from Fig. 2 that there is a first peak in magnetoresistance in this specific embodiment between 9 and 10Å, a second peak around 19 or 20Å and a third peak just above 30Å.

Fig. 10 shows an MR sensor comprising a quadlayer structure similar to that shown in Fig. 5 with the exception that a buffer layer 18 is provided on substrate 11 prior to forming the first ferromagnetic layer 12. A specific embodiment of a quadlayer structure having a buffer layer comprises the following structure:

Si/Ru 100Å/[Co 16Å/Ru(t_s)/Ni45Å/Ru(t_s)]₁₀/Ru50Å

The saturation field vs thickness of the buffer layer 18 for this structure is shown in Fig. 11. Note that there are peaks in the saturation field below 10Å, below 20Å and near 30Å. This graph demonstrates that the saturation field and the saturation magnetoresistance are closely related and that their magnitude oscillates as a function of thickness of the Ru buffer layer with a period of approximately 8-10Å. The peaks in the saturation field fall off more quickly with non-magnetic spacer layer thickness than do the peaks in magnetoresistance. Whereas the peaks in saturation field vary as $1/(t_s)^P$, where P is approximately 1.7 to 2, the peaks in magnetoresistance vary as approximately $1/t_s$.

Fig. 12 shows magnetoresistance vs field curves for six identical Co/Cu bilayer structures with varying copper spacer layer thickness.

This structure comprises:

Si/Fe 40Å/[Co 10Å/Cu(t_{cu})]₁₆. Clearly the magnitude of the magnetoresistance is very small for Cu layer thickness of 5.3Å, but becomes large for a thickness of 9.3Å. With increasing Cu layer thickness the magnitude of the magnetoresistance oscillates from small to large values as shown in Fig. 12.

It can also be seen that the field required to produce the magnetoresistance response also varies with thickness of the Cu layer. For example, the first peak at 9.3Å Cu has a magnetoresistance of about 55%. However, the field required is ~3 KOe. The second peak at 19.1Å Cu has a lower magnetoresistance of about 45%, and also a lower field of about ~0.5 KOe. By the use of this data, a choice can be made in Cu layer thickness to operate at the first peak for maximum magnetoresistance, or at the second peak for large magnetoresistance but at a lower field.

Fig. 13 shows data for a specific embodiment of an MR sensor having the following structure:

Si/Ru 50Å/[Co 10Å/Cu(t_{Cu})]_n/Ru 15Å

This data shows oscillations in the magnetoresistance, and these oscillations are substantially damped at a copper layer thickness of about 60Å. At larger copper layer thickness, the magnetoresistance varies as the inverse copper layer thickness. This data also shows large values of magnetoresistance for extremely large copper layer thickness of up to more than 400 angstroms.

An example of a structure that produces somewhat lower magnetoresistance of 28% at still lower fields is shown in Fig. 14.

This structure comprises:

Si/50Å Ru/[10Å Co/17.4Å Cu]₂₀/15Å Ru

Cu will generally work with most ferromagnetic materials such as Co/Cu, NiFe/Cu, NiCo/Cu, Co/Cu/Ni/Cu, Co/Cu/Fe/Cu, Co/Cu/NiFe/Cu and Co/Cu/NiCo/Cu, for example. Ir, Re, and Rh also generally work with most ferromagnetic materials. In general, the material combinations employed in the structures of the present invention should be chosen so that they do not form compounds with one another.

The thickness of the ferromagnetic layer also has an influence on the magnetoresistance and it can be shown that the thickness of the ferromagnetic layer should be as thin as possible. However, Fig. 15

shows transverse magnetoresistance versus in-plane field for three bilayer structures of the form: $\text{Si/Fe}_{40\text{\AA}}[\text{Co}(t_{\text{Co}})/\text{Cu } 9.3\text{\AA}]_{16}/\text{Cu } 19\text{\AA}$. These curves show a large variations in both magnetoresistance and field with ferromagnetic layer thickness. As the cobalt layer thickness is increased above $\sim 10\text{\AA}$, the magnitude of the saturation magnetoresistance decreases approximately as the inverse cobalt layer thickness.

We have thus described an MR sensor which in one series of embodiments utilizes combinations of bilayers of ferromagnetic material layers and copper layers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of the thickness of the non-magnetic material layer. Such structures including the copper layers exhibit improved characteristics over previously described structures. By choosing the thickness of the copper layer to that corresponding to a peak in the magnetoresistance, a very large magnetoresistance, in excess of 60%, can be achieved. Furthermore, the saturation fields required to obtain these high values of saturation magnetoresistance are sufficiently low that the structure is useful as an MR sensor for use in reading data recorded on magnetic disks.

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CLAIMS

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1. A magnetoresistive sensor comprising:

a substrate (11); and

a multilayered structure formed on the substrate comprising alternating layers of a ferromagnetic material and a non-magnetic metallic material (14), the ferromagnetic material and the non-magnetic material forming bilayers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of thickness of the layers of non-magnetic material; characterised in that the non-magnetic metallic material is Cu.

2. A magnetoresistive sensor comprising:

a substrate (11); and

a multilayered structure formed on said substrate comprising alternating layers of a ferromagnetic material and a non-magnetic metallic material, the ferromagnetic material and the non-magnetic material forming bilayers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of thickness of the layers of non-magnetic material; characterised in that the non-magnetic metallic material is chosen from the group consisting of Ir, Re and Rh.

3. A magnetoresistive sensor comprising a substrate (11) and a multilayered structure formed on the substrate comprising alternating layers of a first (12) and a second (13) ferromagnetic material and a non-magnetic metallic material (14), the first and second ferromagnetic materials and the non-magnetic material forming quadlayers which exhibit the property that the magnetoresistance of the multilayered structure oscillates as a function of thickness of the layers of the non-magnetic material.



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4. A magnetoresistive sensor as claimed in any preceding claim, wherein the variation in magnetoresistance versus thickness of the layer of non-magnetic material comprises at least a first and a second peak.

5. A magnetoresistive sensor as claimed in claim 4, wherein the thickness of the layer of non-magnetic material is chosen so that the magnetoresistive sensor operates at said first magnetoresistance peak.

6. A magnetoresistive sensor as claimed in claim 4, wherein the thickness of the layer of non-magnetic material is chosen so that the magnetoresistive sensor operates at the second magnetoresistance peak.

7. A magnetoresistive sensor as claimed in any of claims 4 to 6, as dependent on claim 1, wherein the layer of ferromagnetic material is formed of a material taken from the group consisting of cobalt, NiFe and NiCo.

8. A magnetoresistive sensor as claimed in any of claims 4 to 6, as dependent on claim 3, wherein the layer of non-magnetic material is formed of a material taken from the group consisting of Cu, Cr, Ru, Ir, Re and Rh.

9. A magnetoresistive sensor as claimed in claim 8, wherein the layer of non-magnetic material is copper.

10. A magnetoresistive sensor as claimed in claim 9, wherein the first and the second layers of ferromagnetic material are formed of materials taken from the group consisting of Co and Ni, Co and Fe, Co and NiFe, and Co and NiCo.

11. A magnetoresistive sensor as claimed in claim 8, wherein the layer of non-magnetic material is formed of a material taken from the group consisting of Ru, Ir, Re, and Rh.

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12. A magnetoresistive sensor as claimed in claim 11, wherein the first and the second layers of ferromagnetic material are formed of materials taken from the group consisting of Fe and Co, Co and Ni, Co and NiCo, Co and NiFe, and Ni and Fe.

13. A magnetoresistive sensor as claimed in any preceding claim, additionally comprising a buffer layer between the substrate and the first layer of ferromagnetic material.

14. A magnetoresistive sensor as claimed in claim 13, wherein the buffer layer is formed of a material taken from the group consisting of Fe, Cu, Cr, Ru, Rh, Ir and Re.

15. A magnetoresistive sensing system comprising:

a magnetoresistive sensor (10) as claimed in any preceding claim;

means (24) for producing a current flow through said magnetoresistive sensor; and

means (26) for sensing the variations in the resistivity of said magnetoresistive sensor as a function of the magnetic field being sensed.

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