



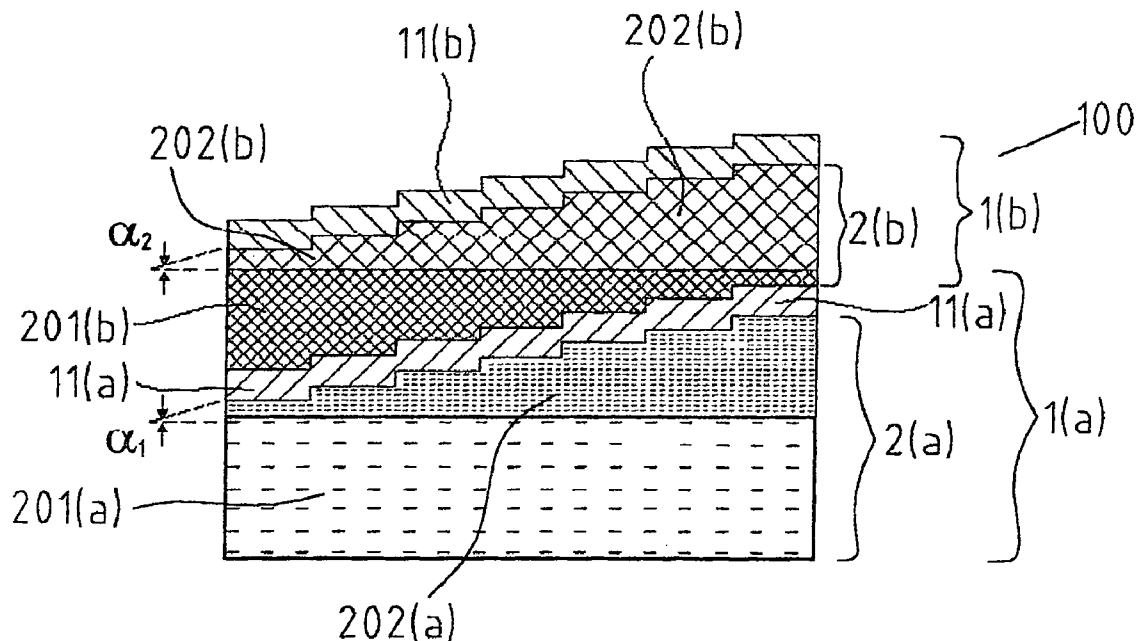
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(19) **United States**(12) **Patent Application Publication****Shvets et al.**(10) **Pub. No.: US 2006/0202292 A1**(43) **Pub. Date: Sep. 14, 2006**(54) **MAGNETORESISTIVE MEDIUM
INCLUDING A VICINALLY TREATED
SUBSTRATE**(52) **U.S. Cl. 257/422**(75) **Inventors: Igor Shvets, Dublin (IE); Sunil Kumar
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Trinity of Queen Elizabeth, Dublin (IE)**(21) **Appl. No.: 11/078,416**(22) **Filed: Mar. 14, 2005****Related U.S. Application Data**(63) **Continuation of application No. PCT/IE04/00034,
filed on Mar. 12, 2005.****Publication Classification**(51) **Int. Cl.
H01L 21/00 (2006.01)**(57) **ABSTRACT**

A magnetoresistive medium (1) comprises a substrate (2) which has been treated to provide a miscut vicinal surface (3) in the form of terraces (4(a), 4(b)) and steps (5) of atomic and nanometer scale. A further upper film (11) provides upper nanowires (10(a), 10(b)). A thin protective layer (15) covers the upper nanowires (10(a), 10(b)) which form two separate subsets of upper nanowires with different exchange interaction with the substrate and thus a different response to an external magnetic field. The substrate (2) is so chosen that the width of the terraces 4(a) and 4(b) are significantly non-uniform. This leads to a different response depending on which terrace (4(a) or 4(b)) the upper film 11 overlies. It can utilise, for example, step-induced magnetic anisotropy between the upper nanowires (10(a), 10(b)) and the substrate (2). In use, when an external magnetic field (H) is applied the response of the main nanowires (10(a), 10(b)) changes as the exchange coupling with the substrate (2) varies and the magnetisation on the main nanowires (10(a), 10(b)) change. This is shown by the arrows while prior to the application of the external magnetic field, they might, for example, be aligned. Many different constructions of magnetoresistive media are described.



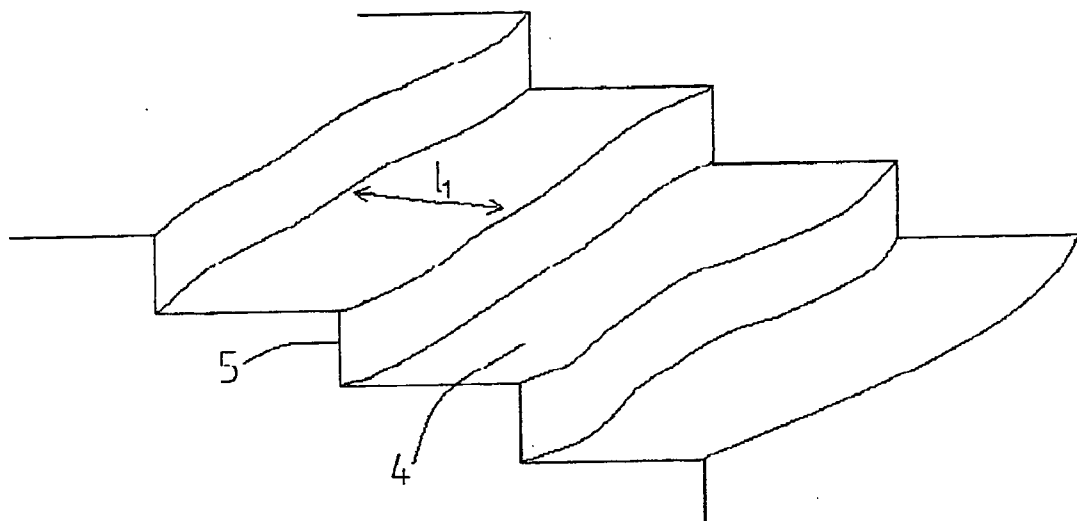


Fig. 1

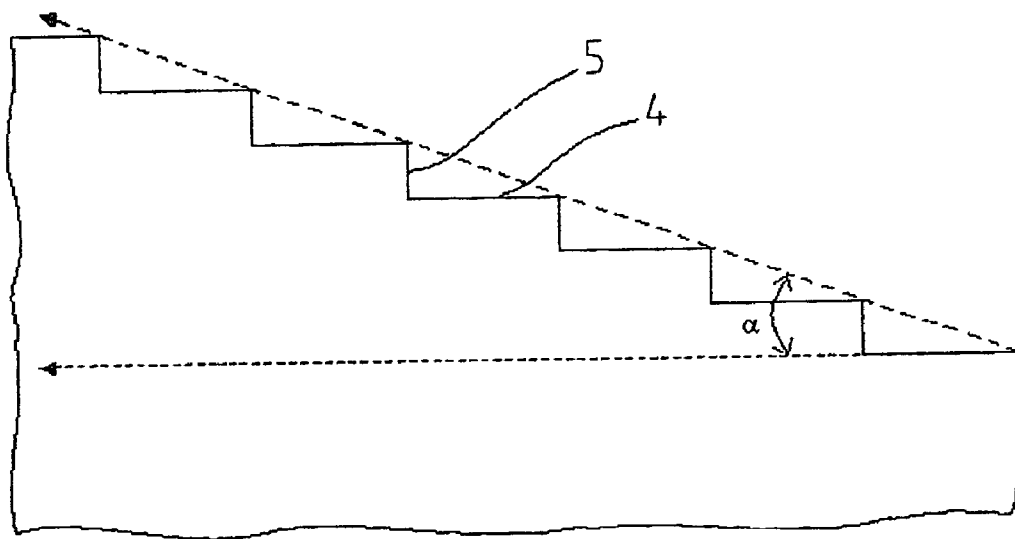


Fig. 2

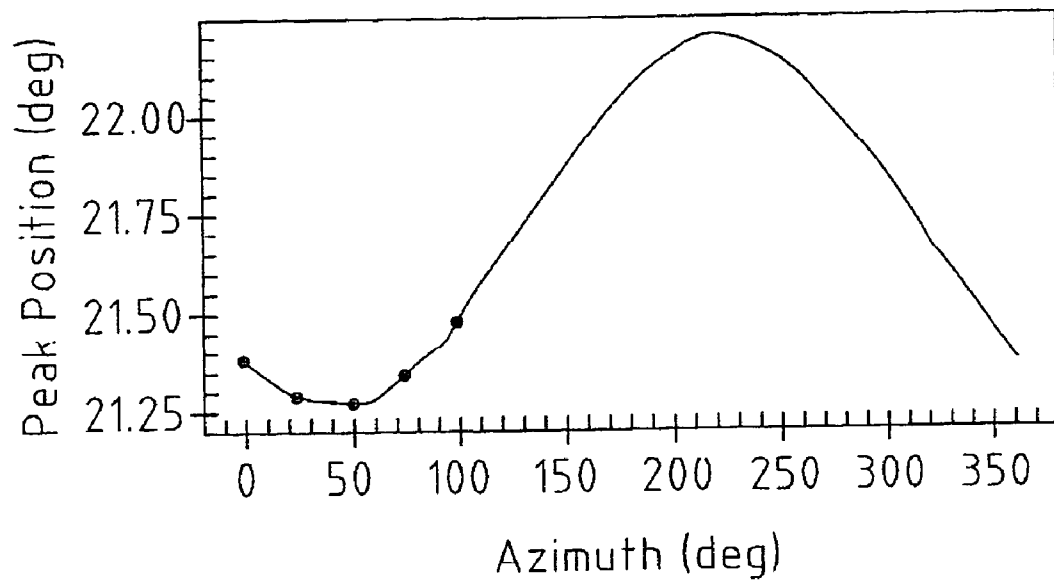


Fig. 3

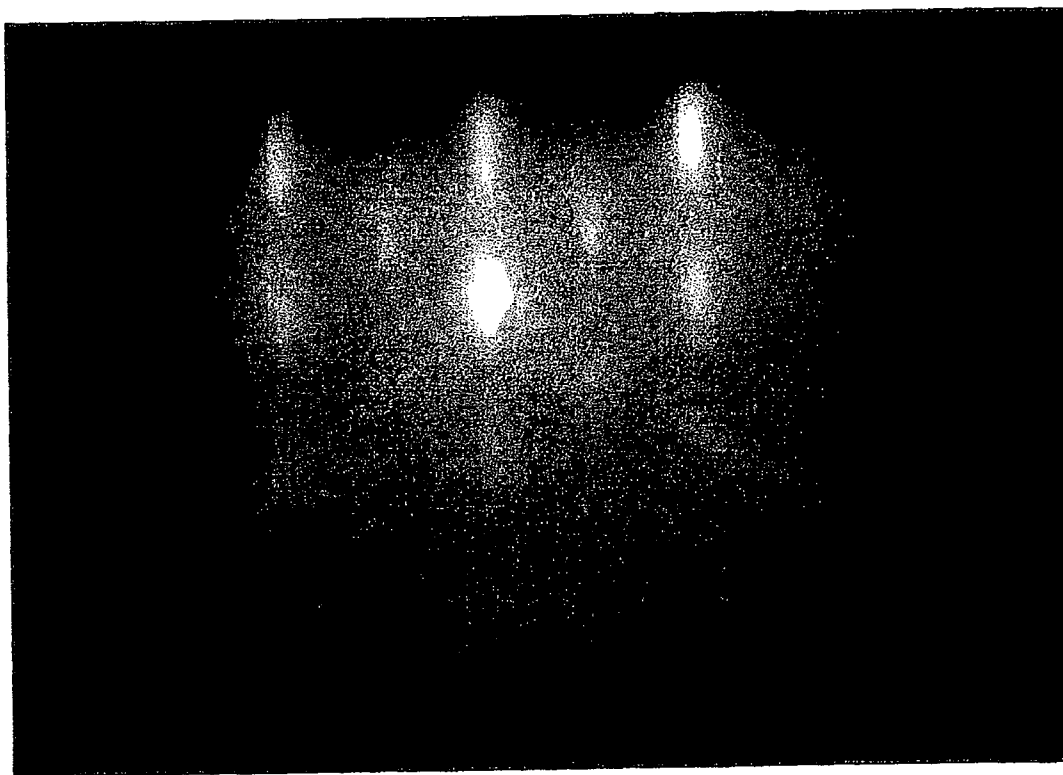


Fig. 4

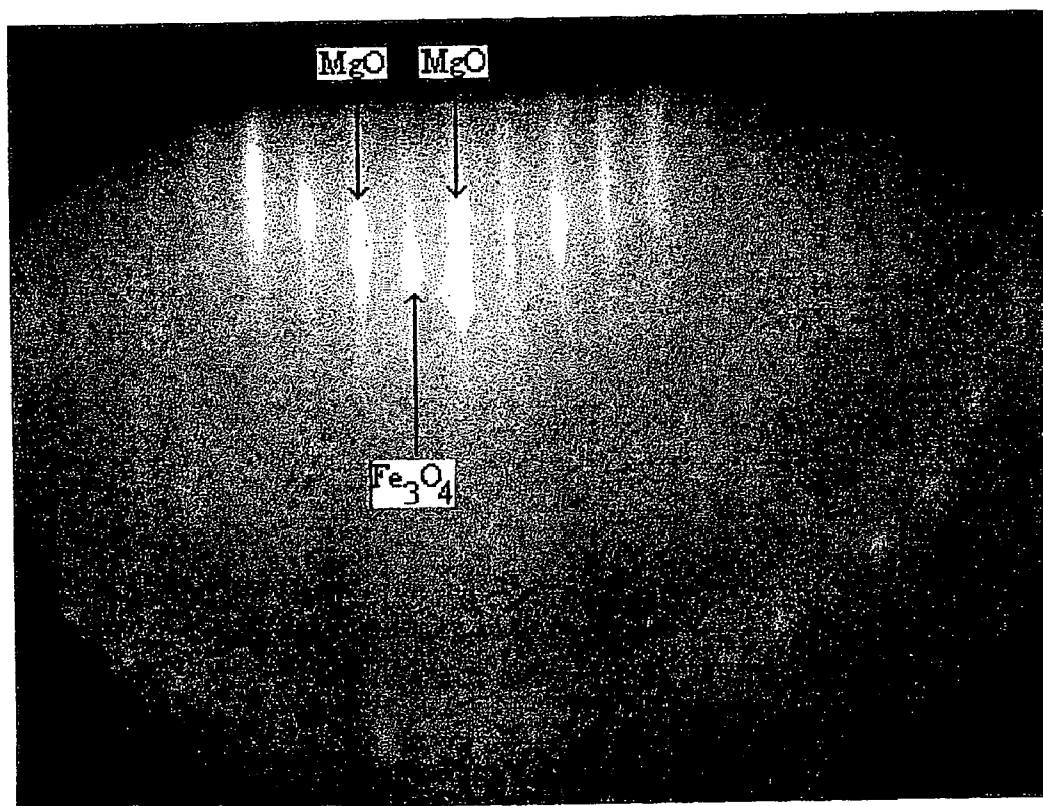


Fig. 5

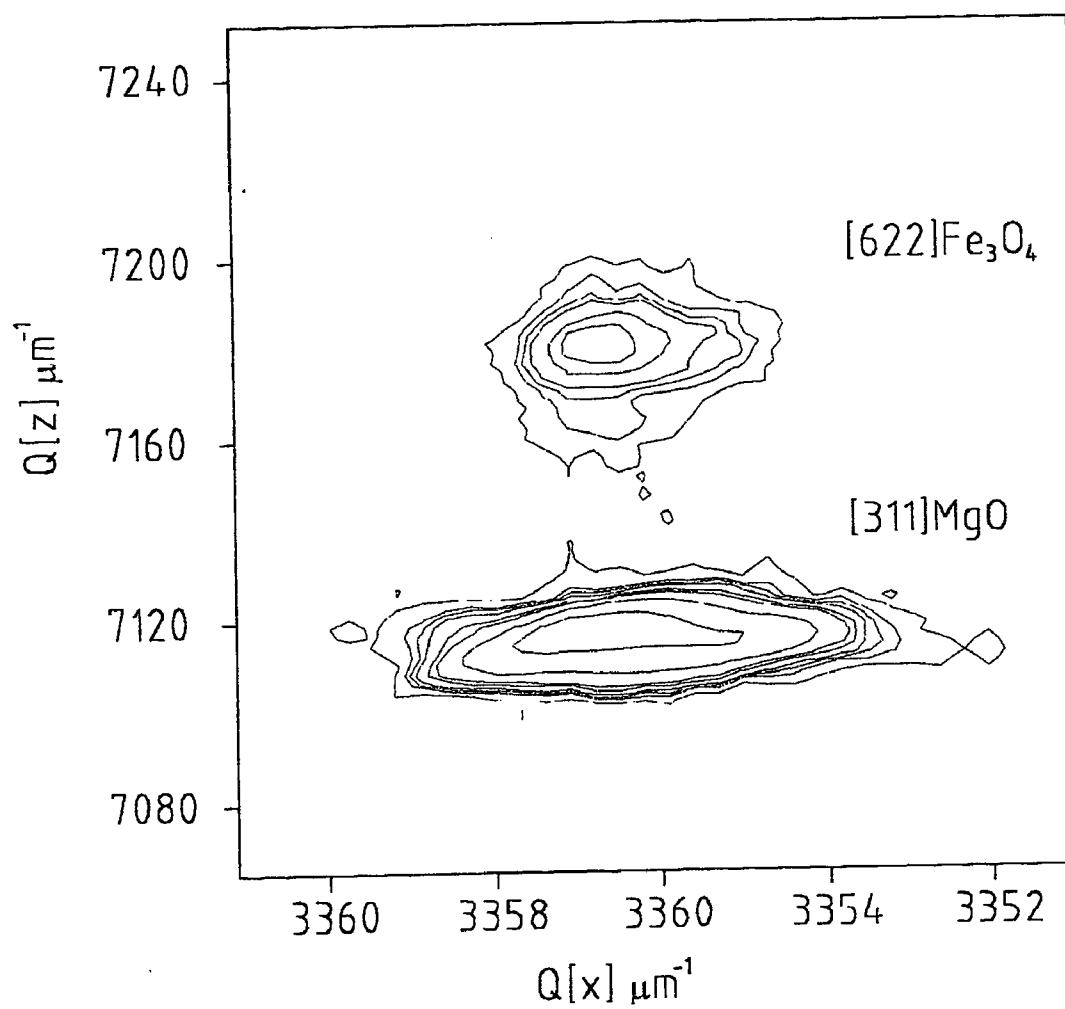


Fig. 6

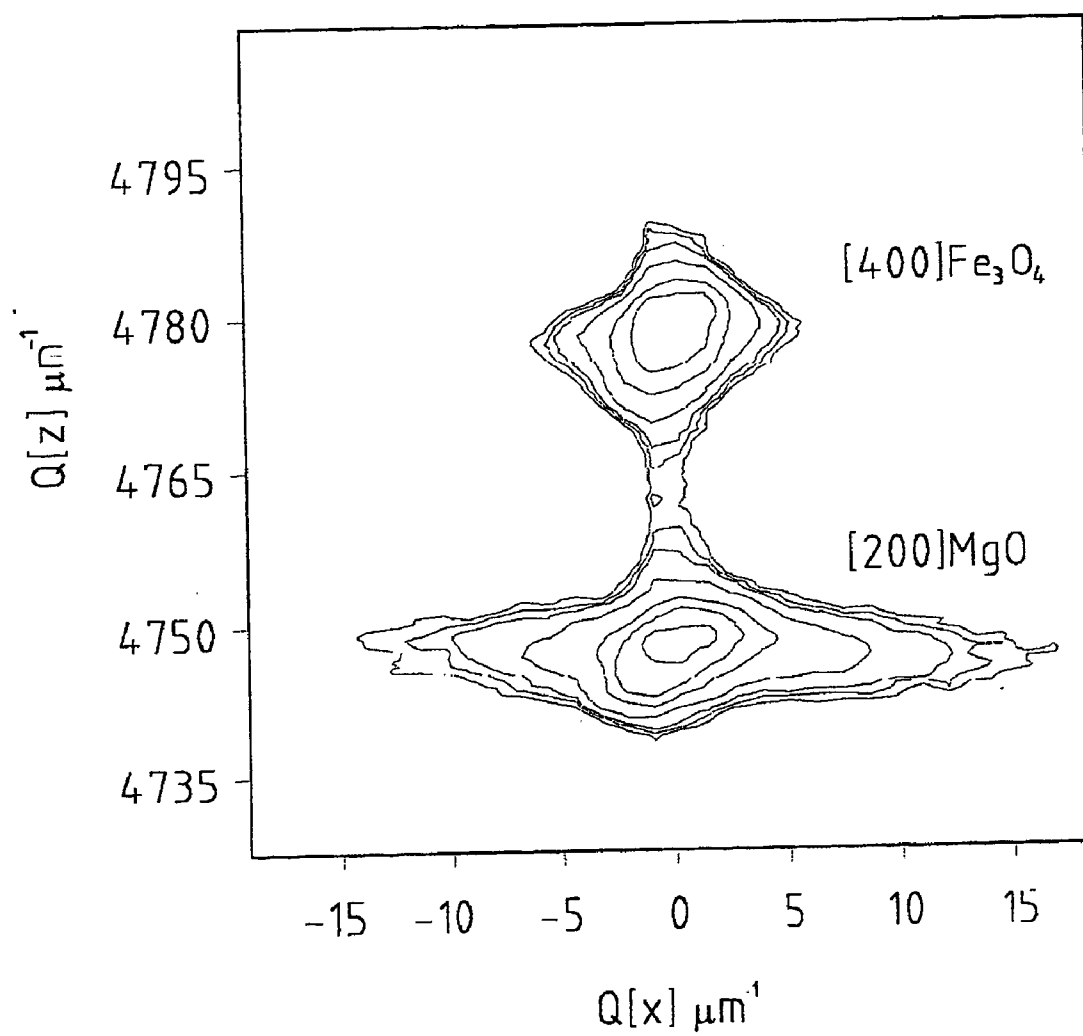
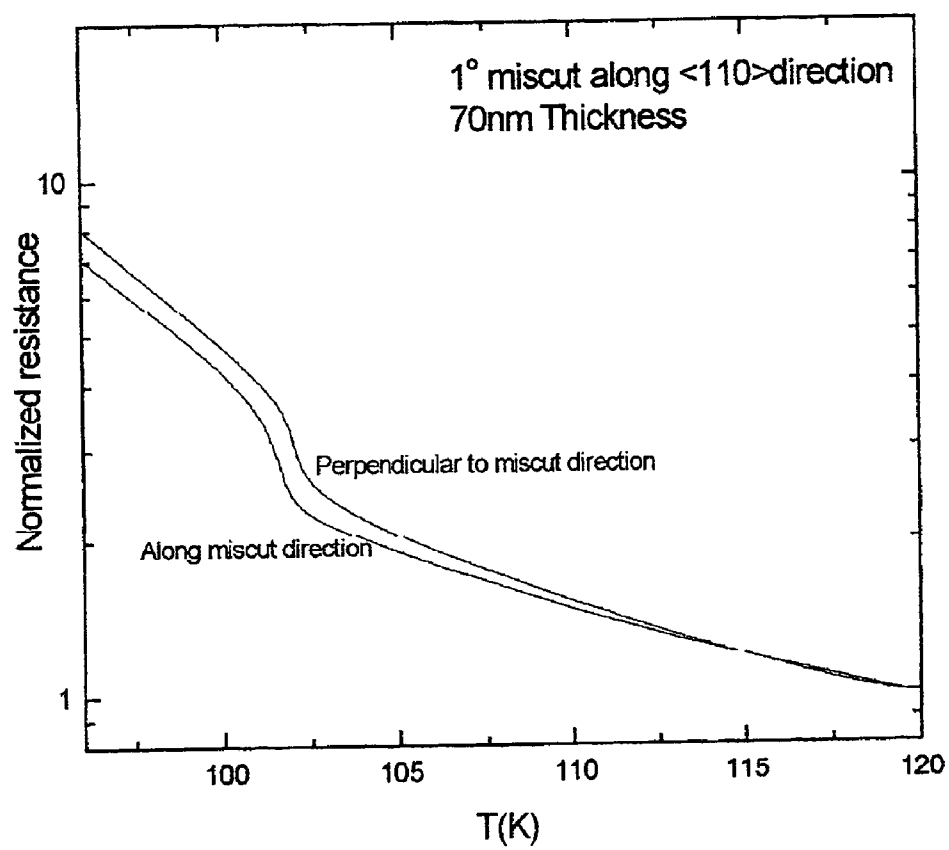
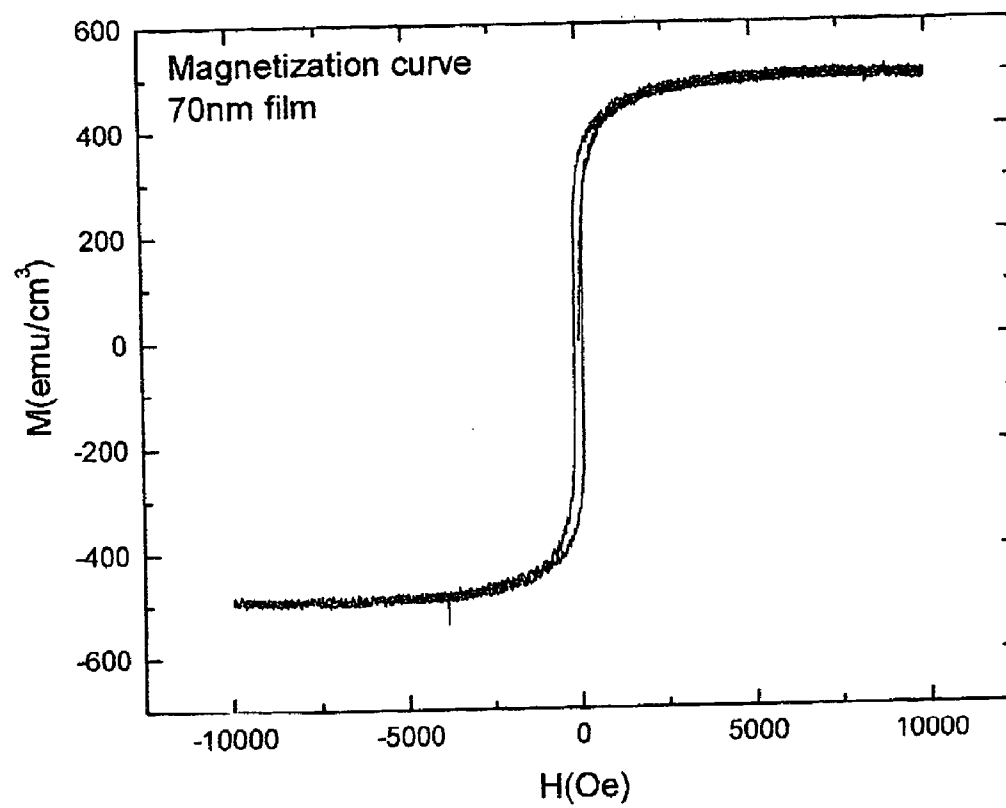
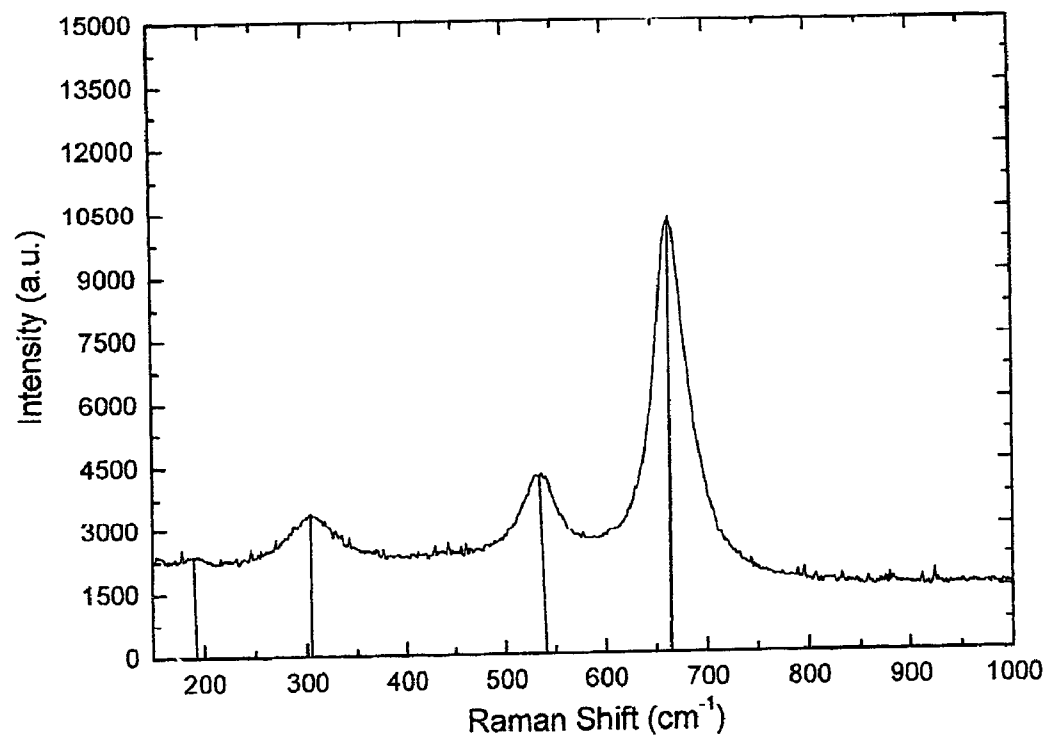
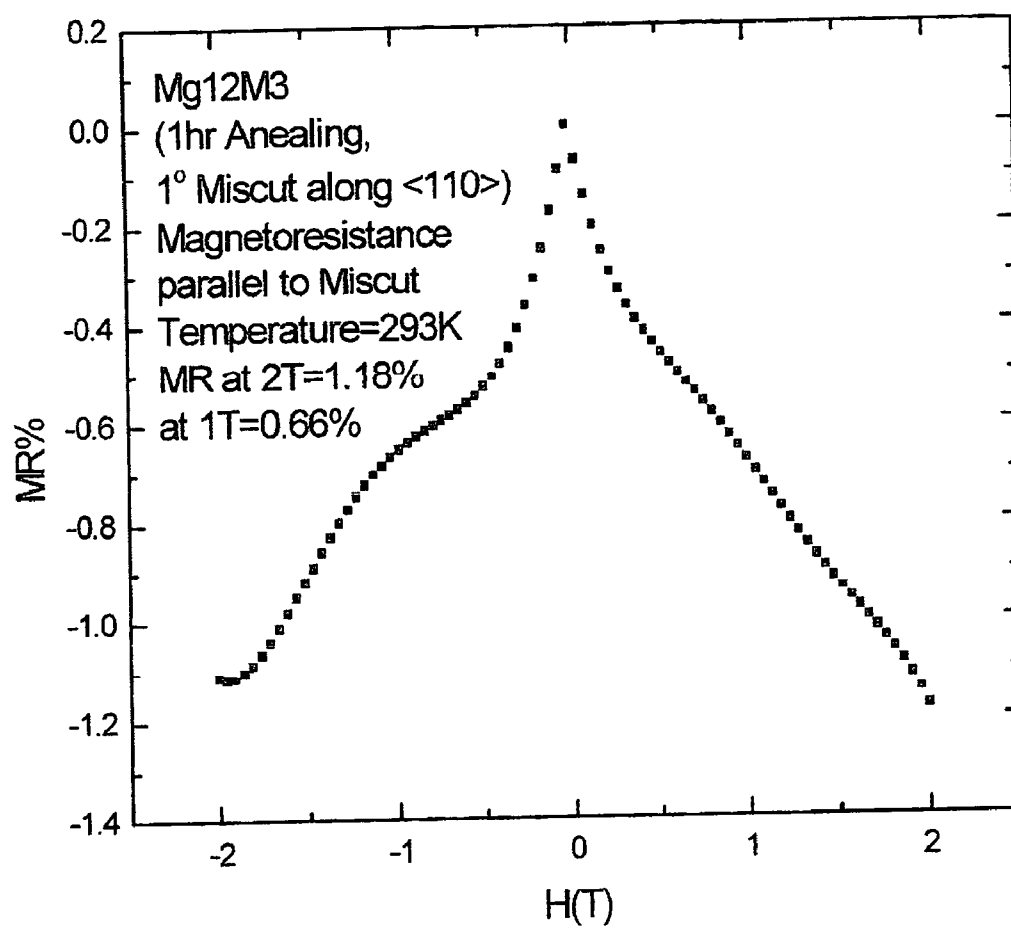


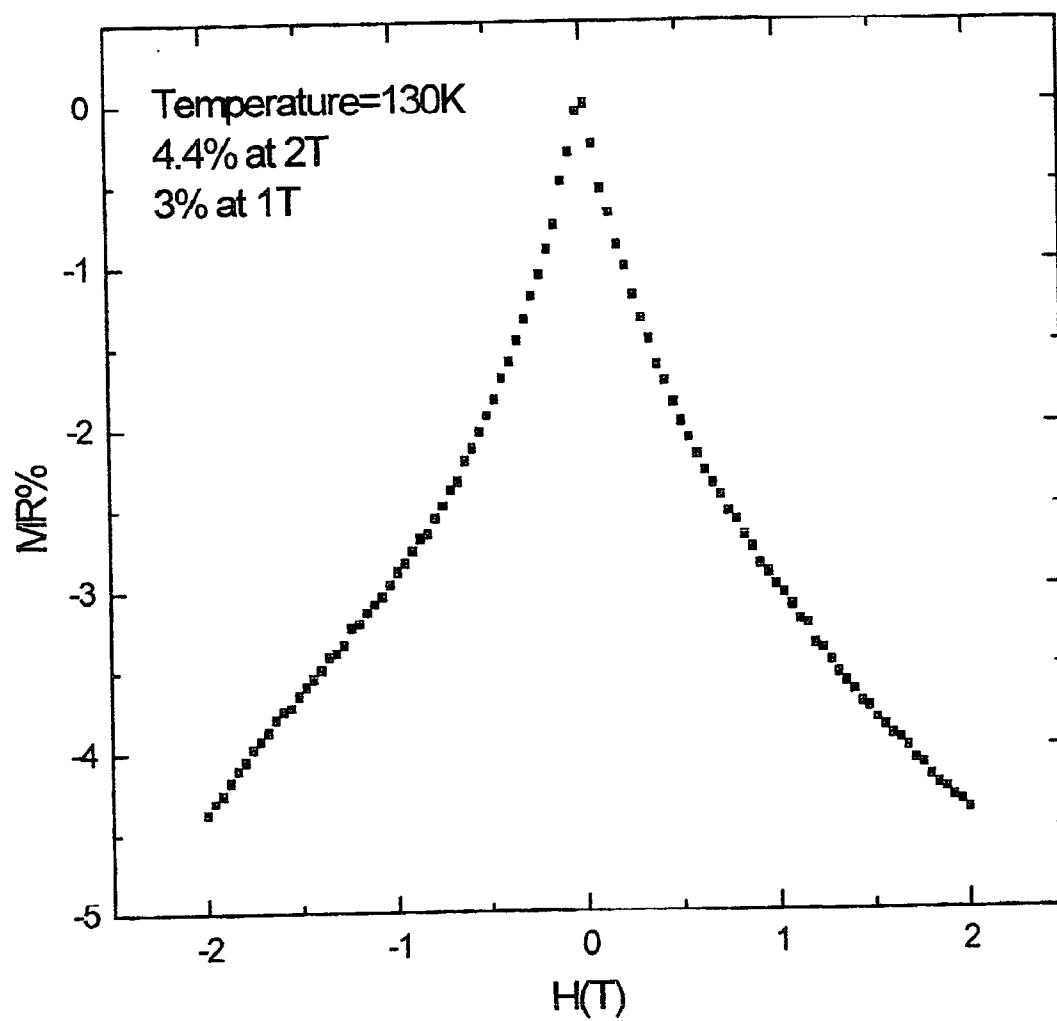
Fig. 7

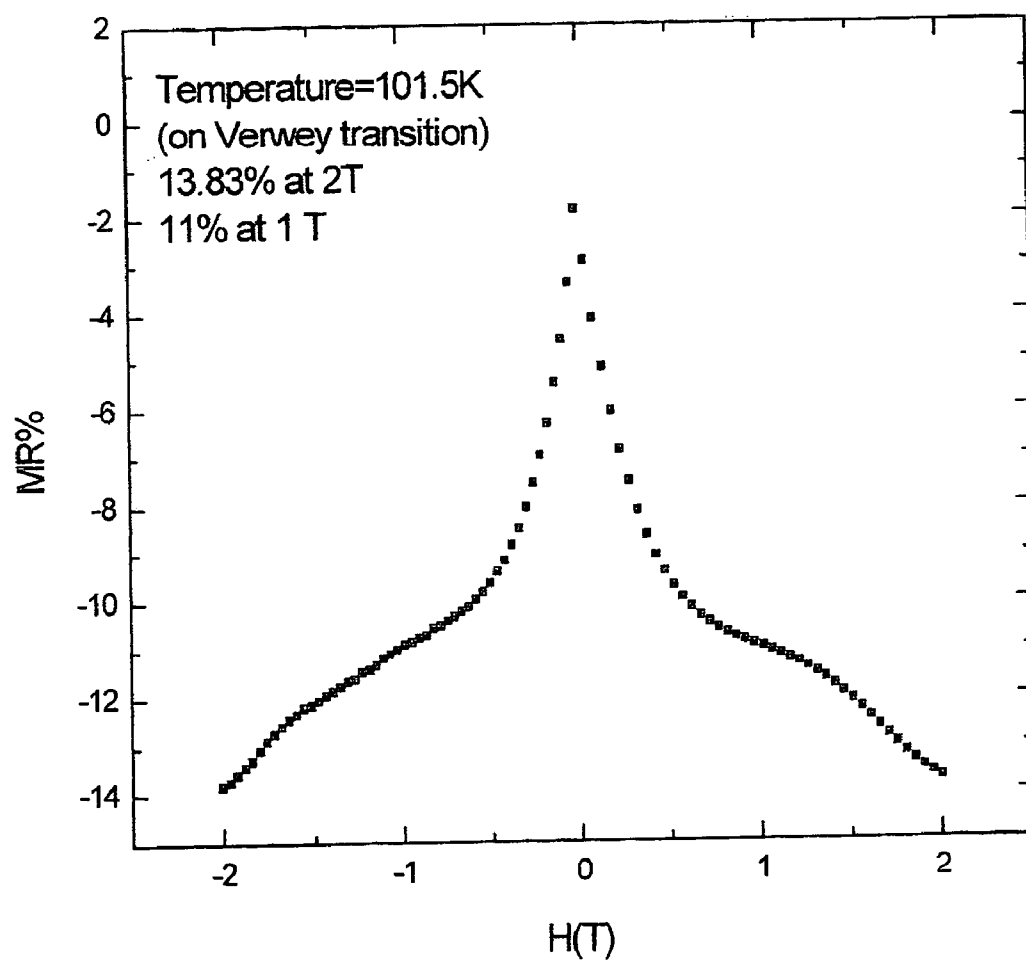
Fig. 8

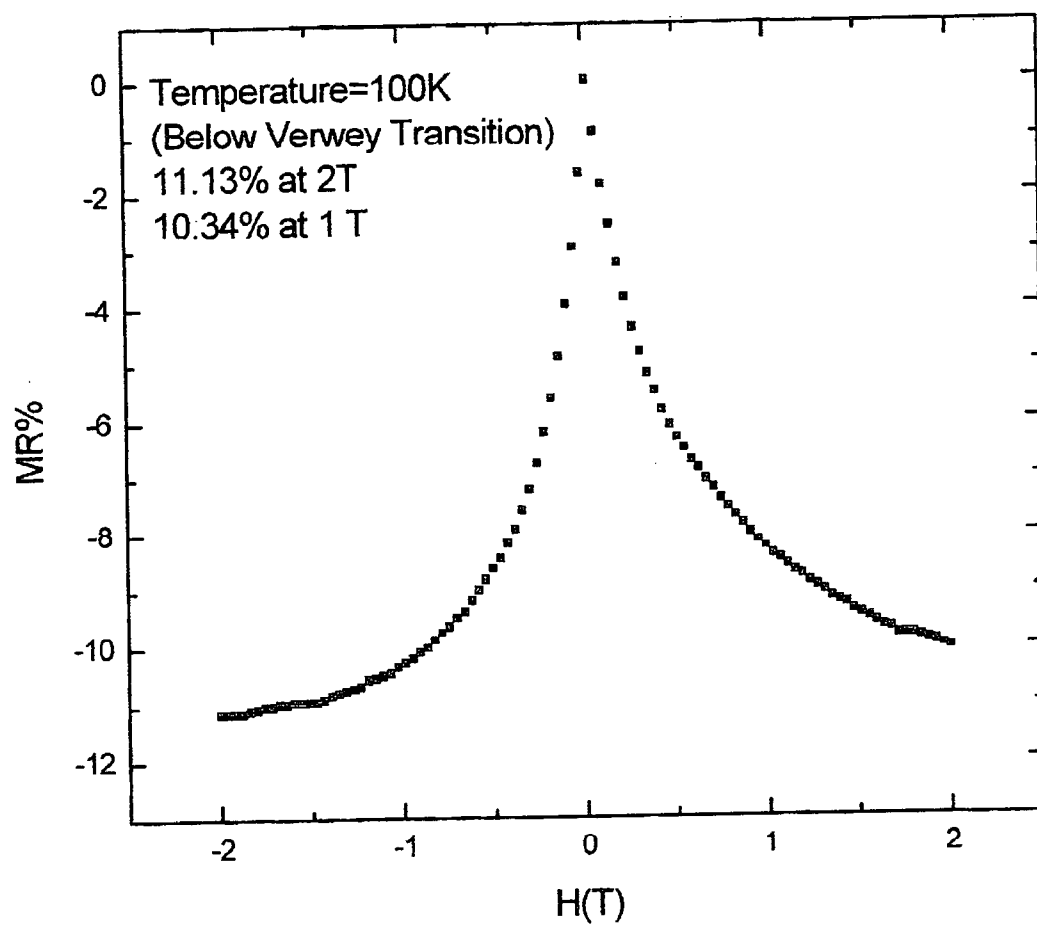
Fig. 9

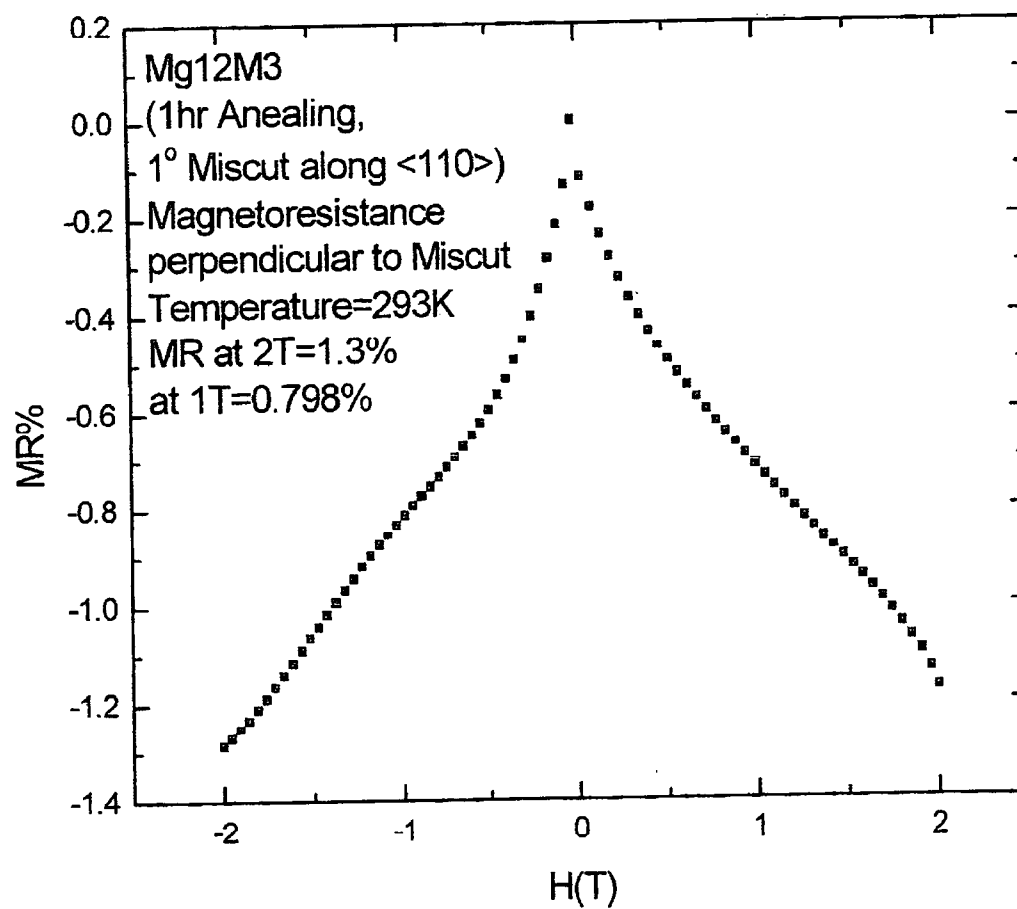
Fig. 10

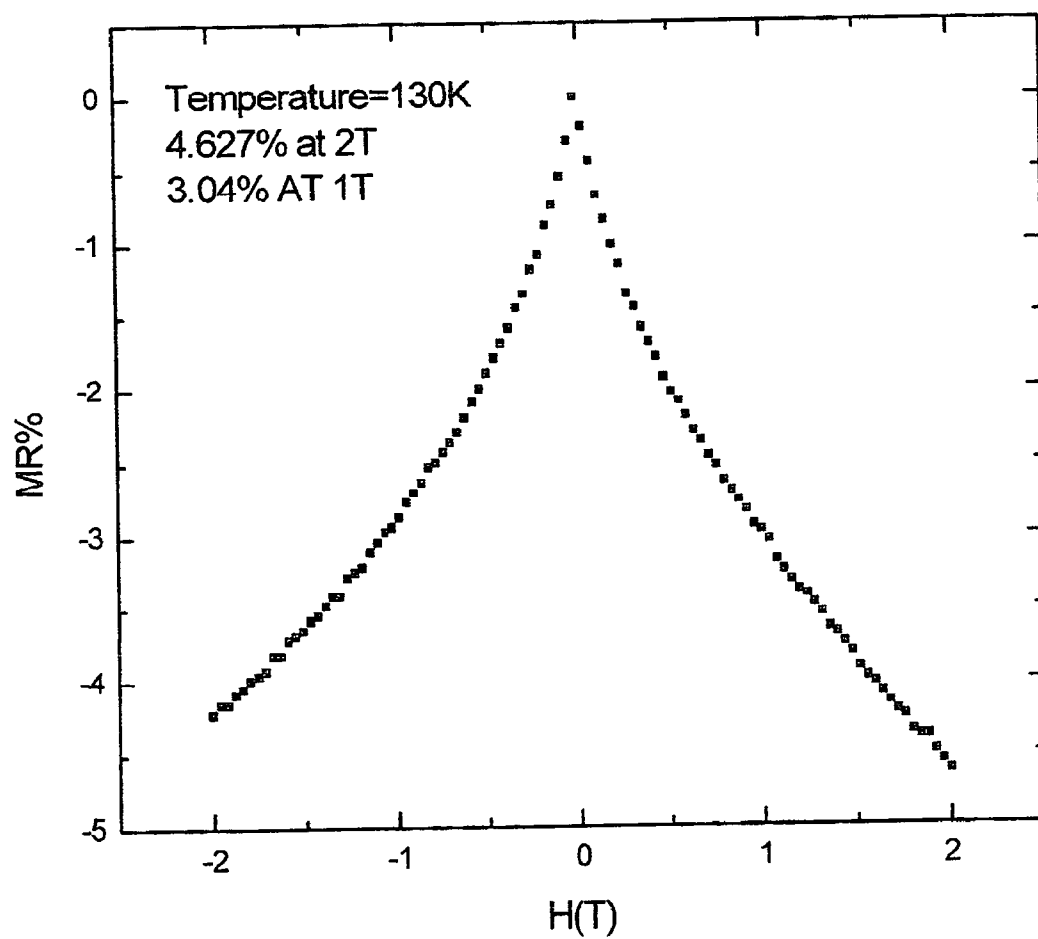
Fig. 11(a)

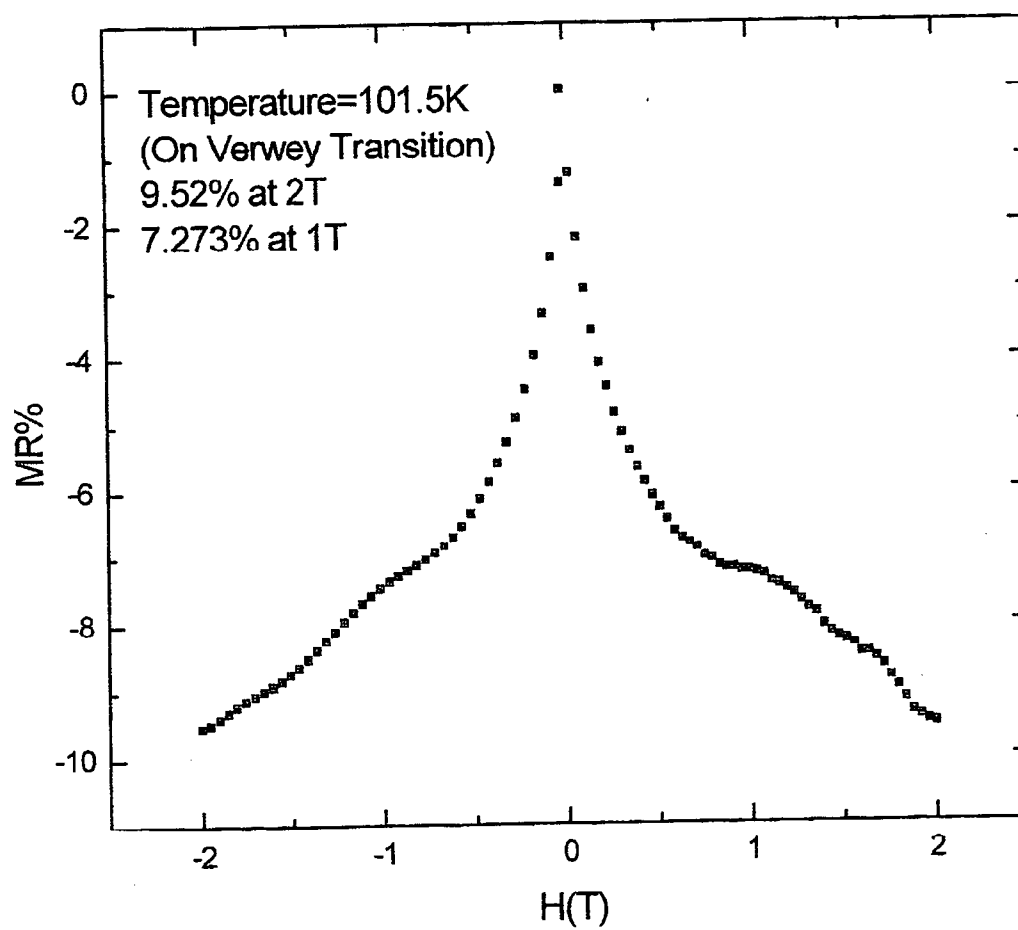
Fig. 11(b)

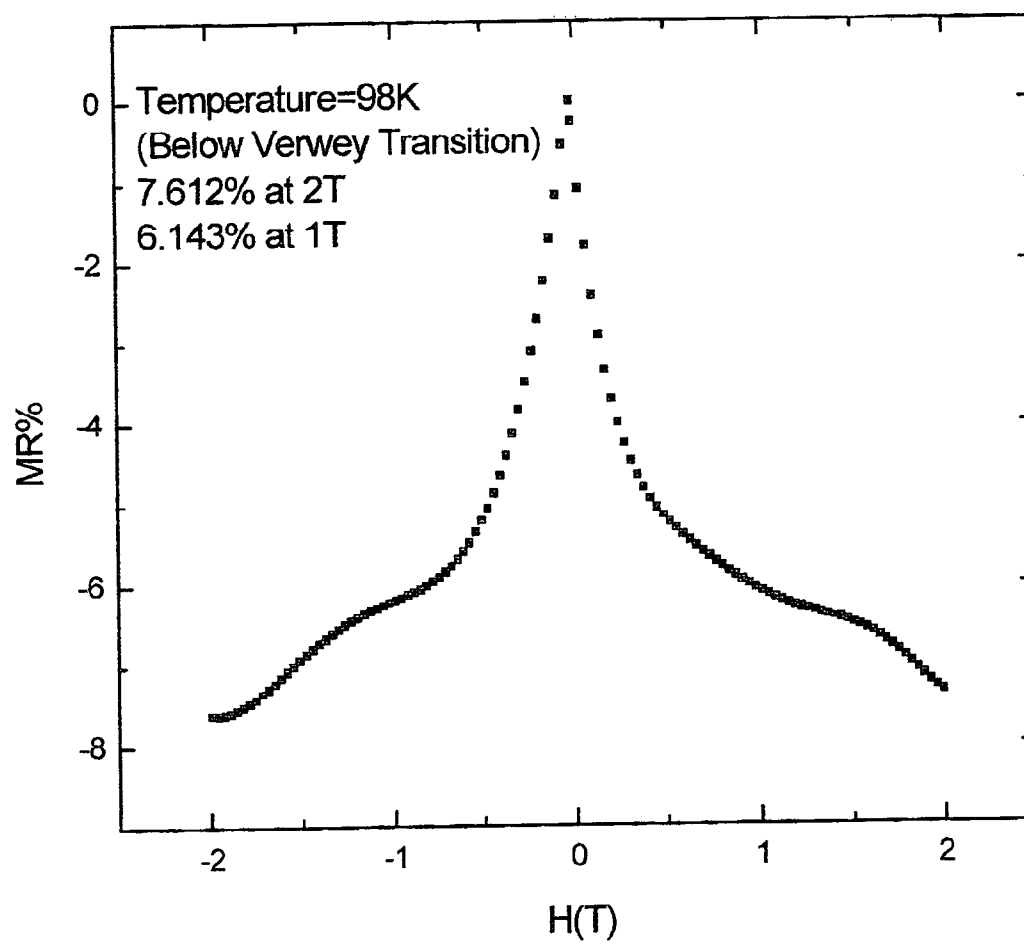
Fig. 11(c)

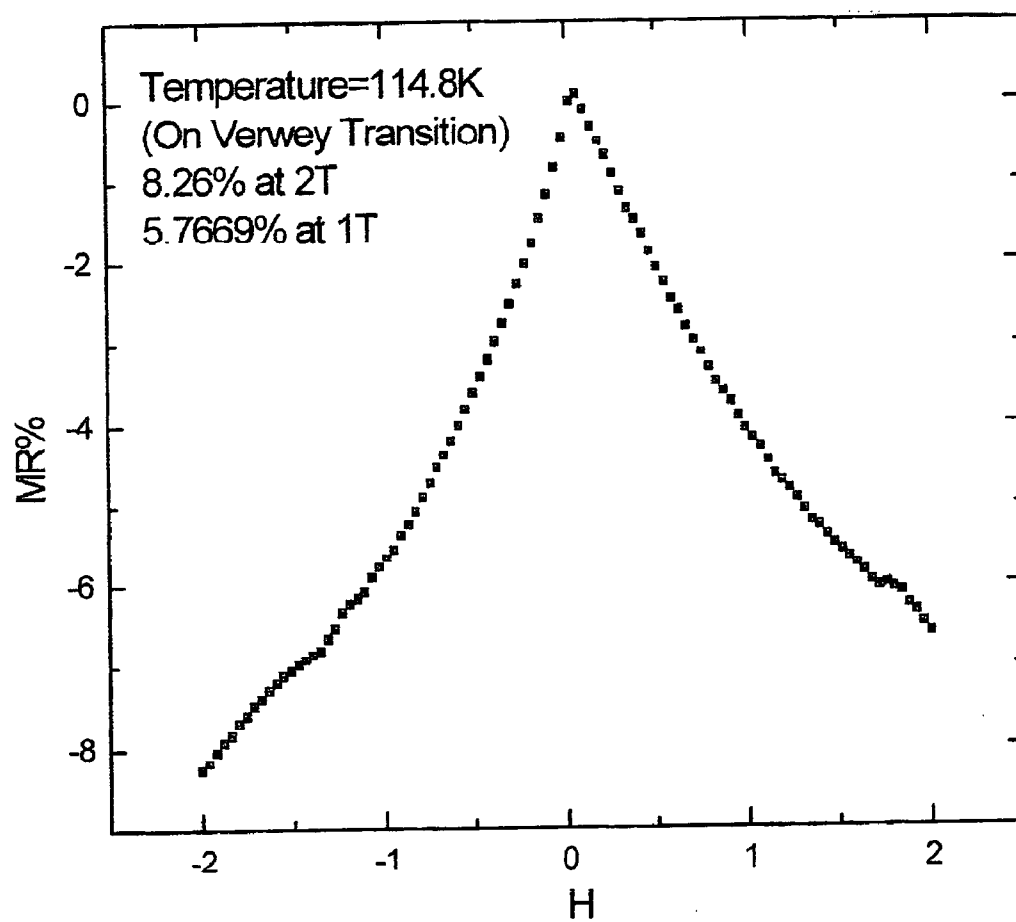
Fig. 11(d)

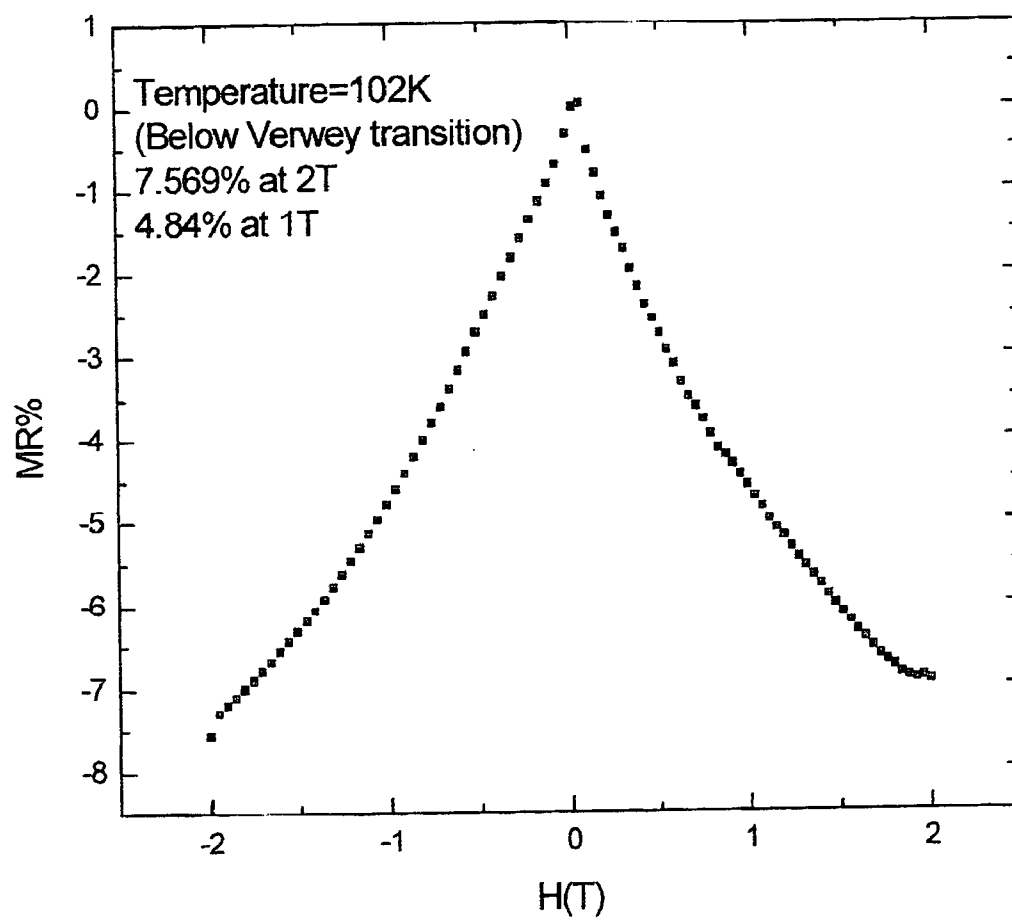
Fig. 12(a)

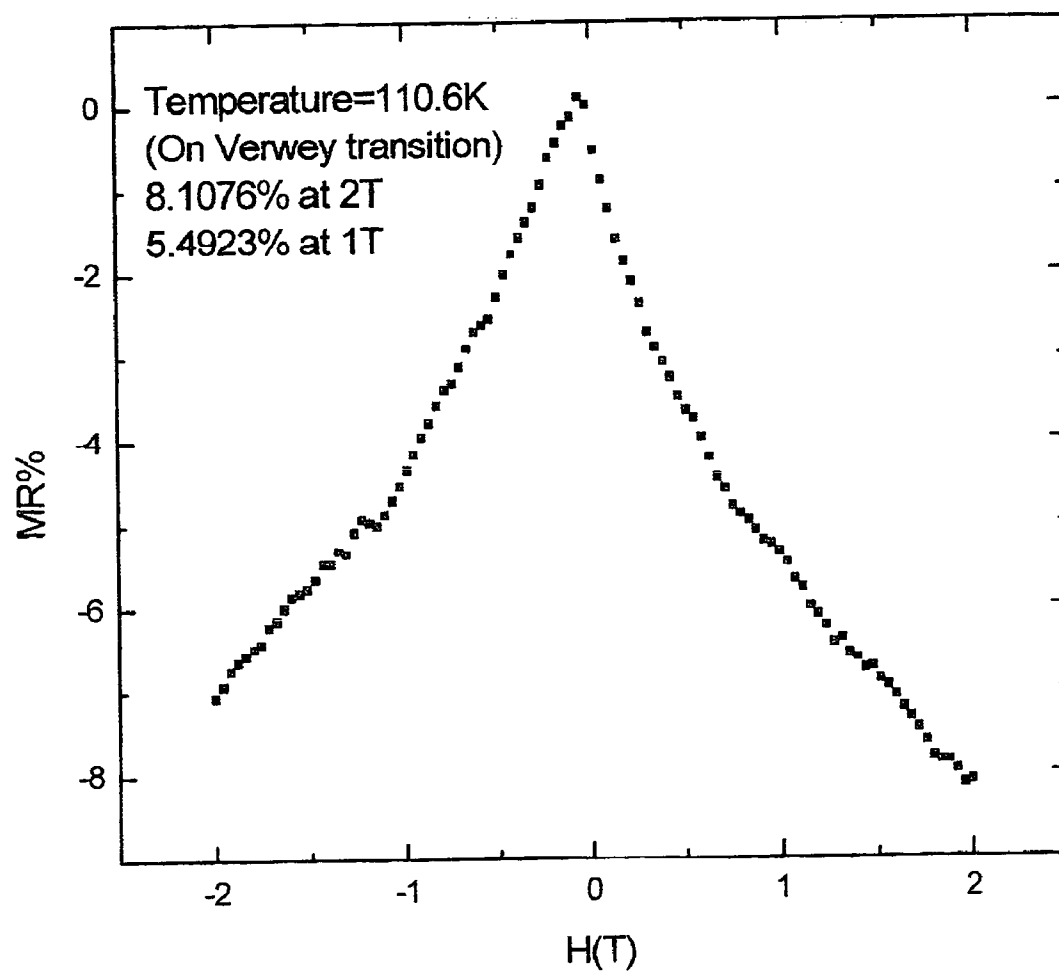
Fig. 12(b)

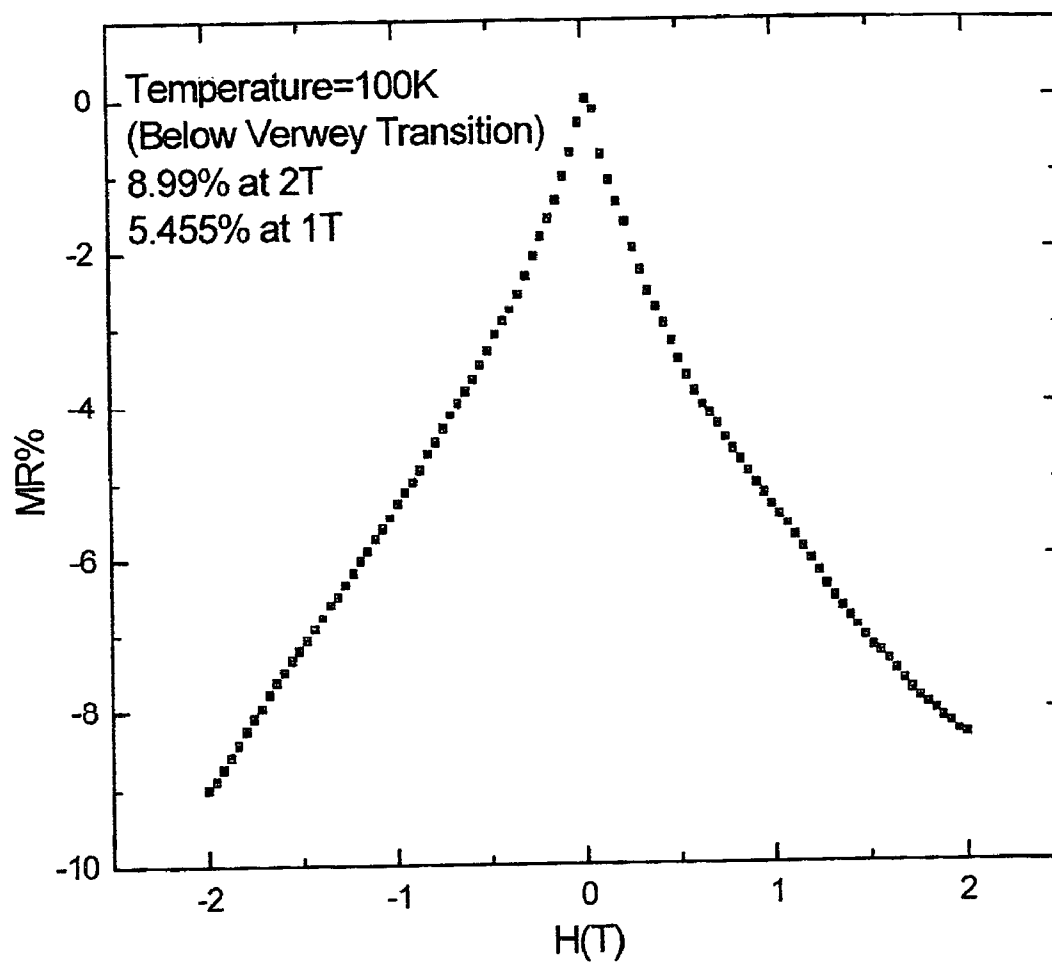
Fig. 12(c)

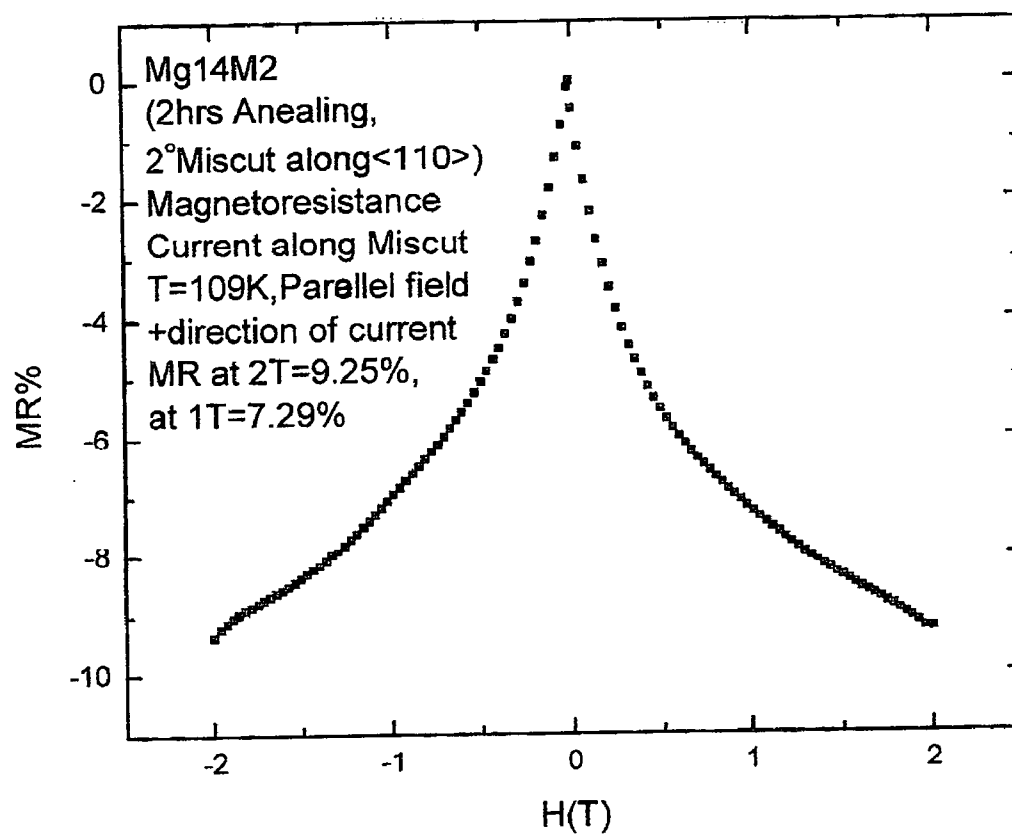
Fig. 12(d)

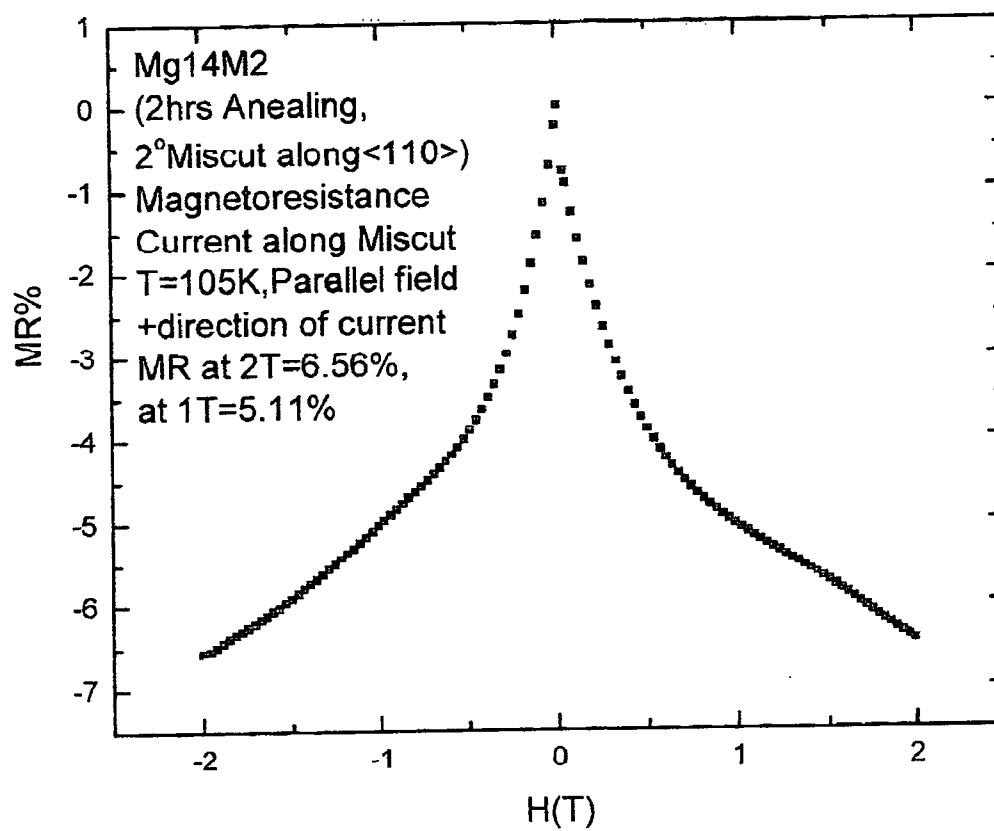
Fig. 13(a)

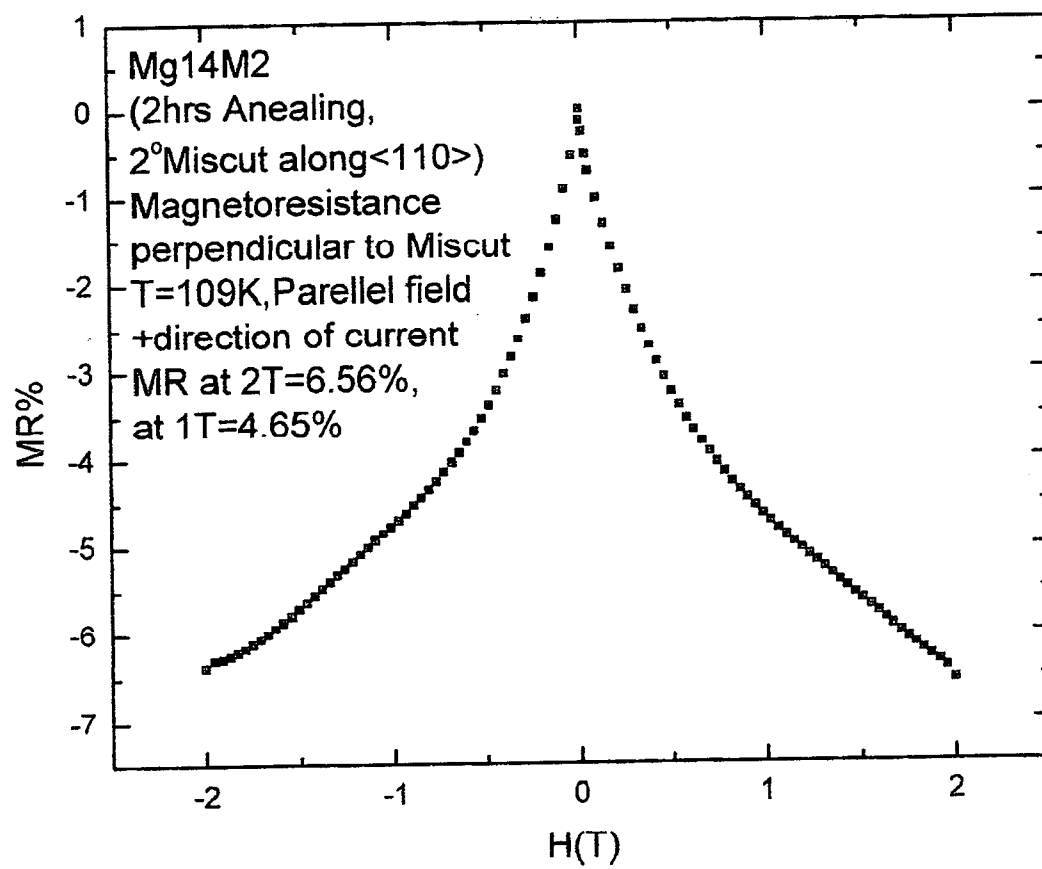
Fig. 13(b)

Fig. 14(a)

Fig. 14(b)

Fig. 15(a)

Fig. 15(b)

Fig. 16(a)

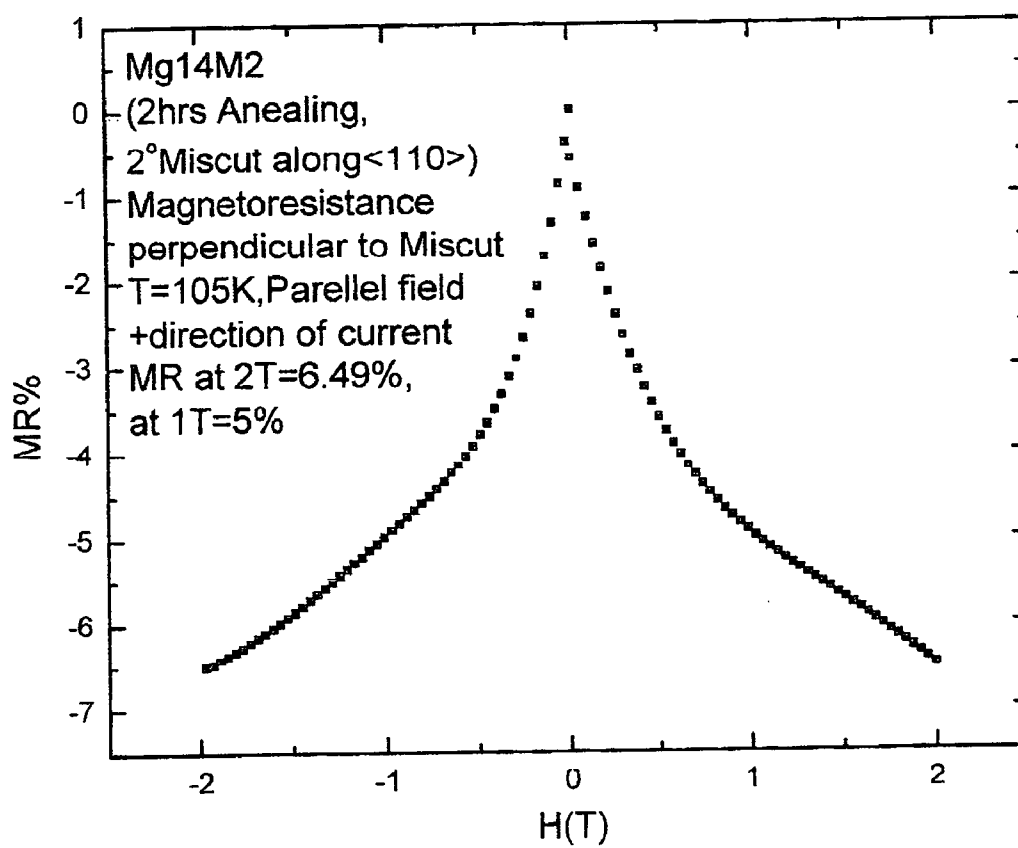


Fig. 16(b)

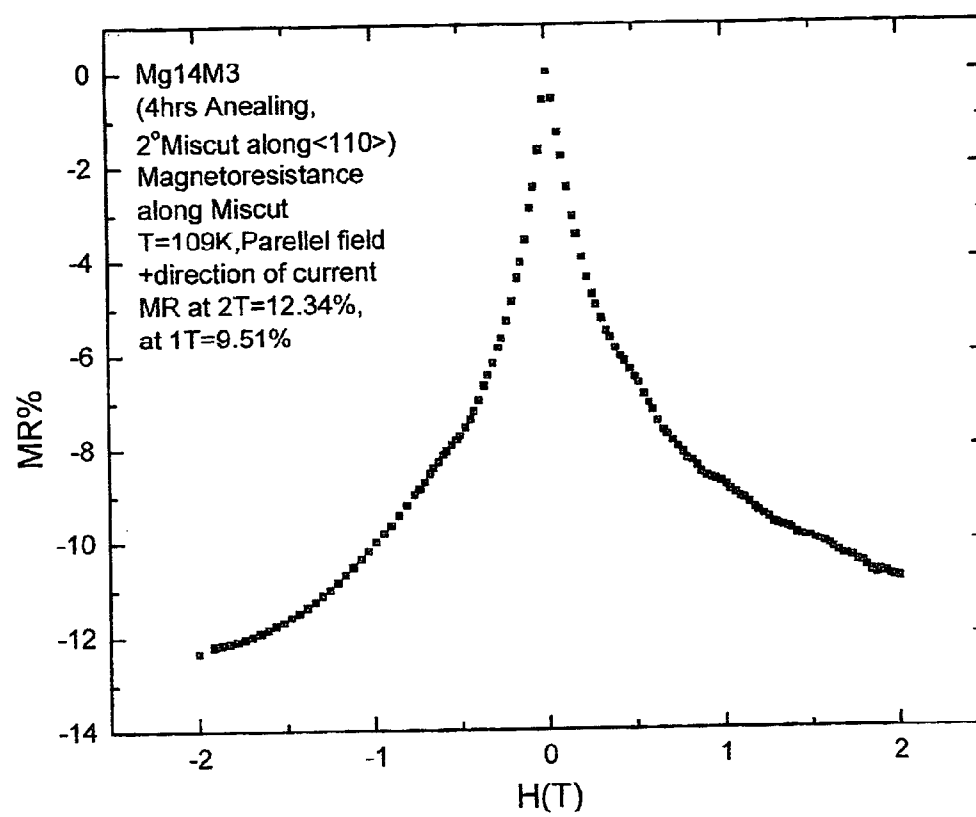


Fig. 17(a)

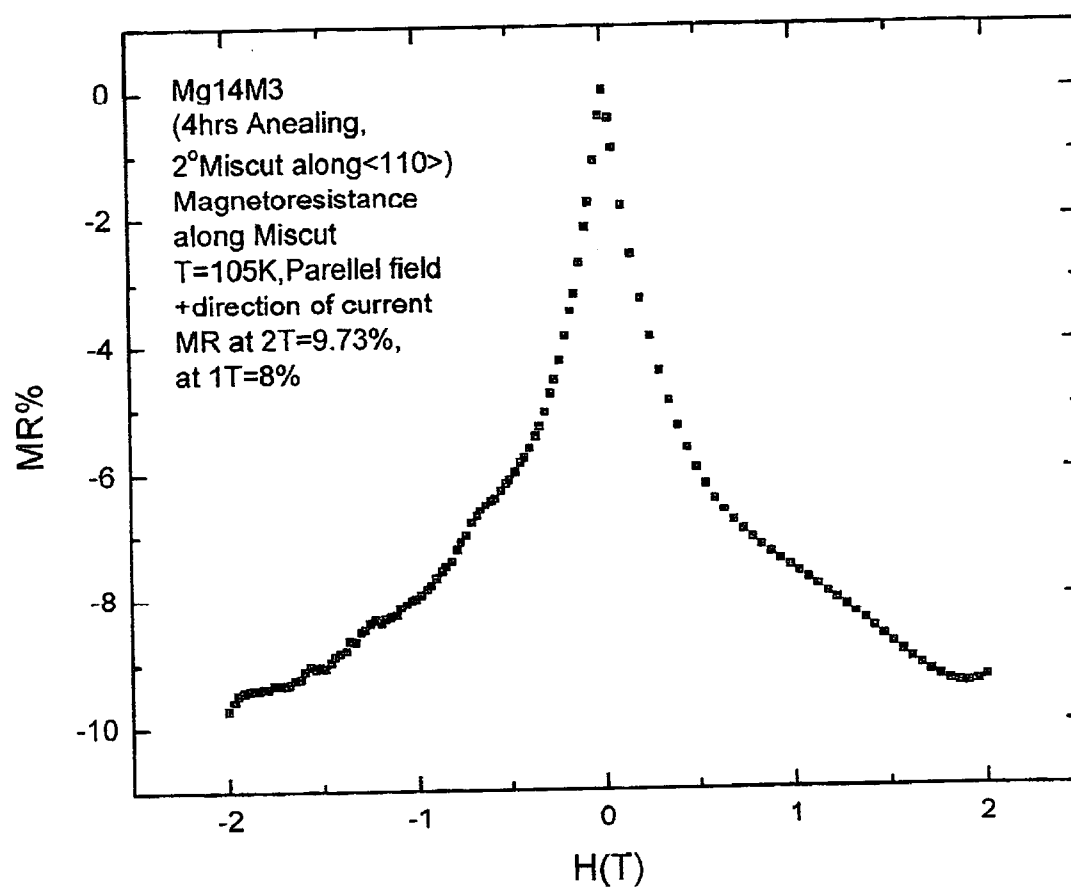
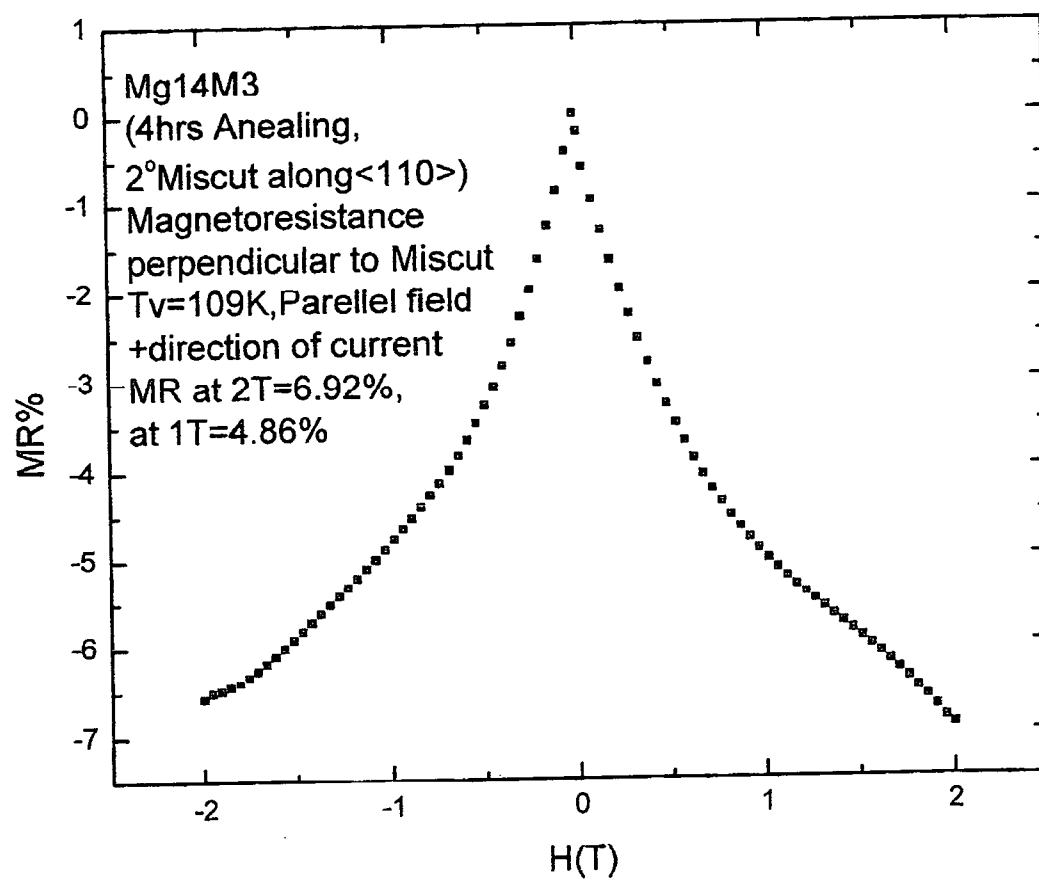
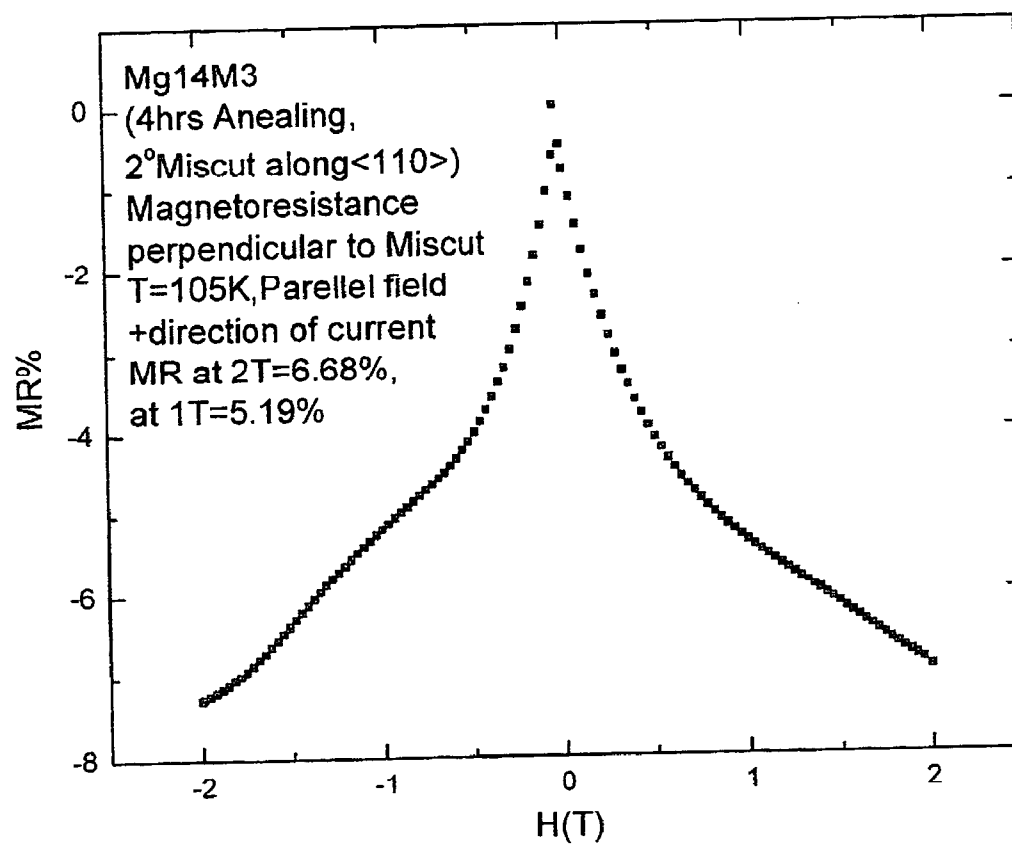


Fig. 17(b)

Fig. 18(a)

Fig. 18(b)

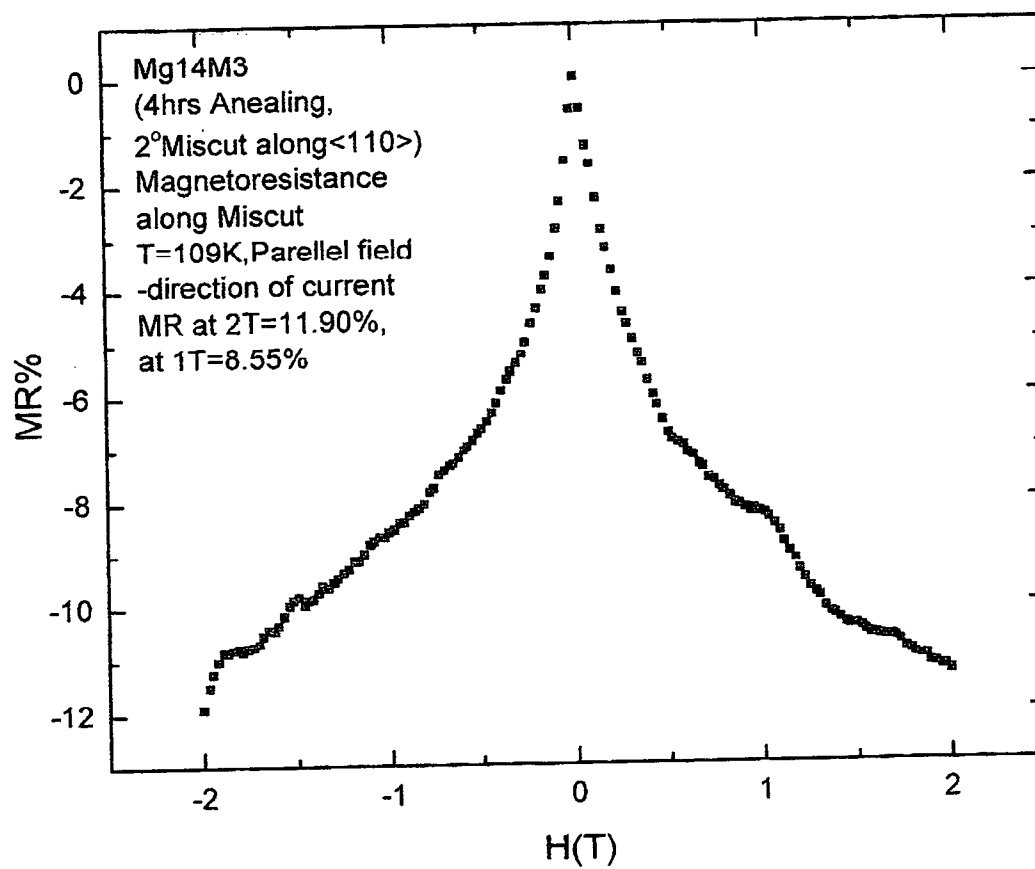
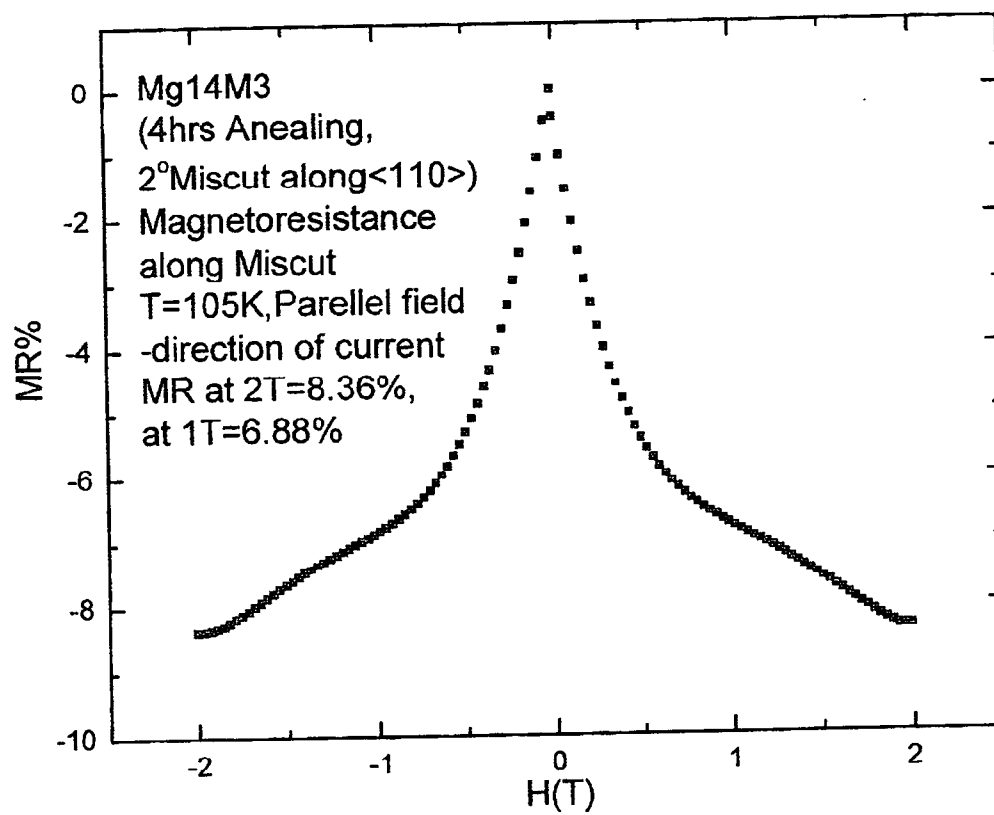


Fig. 19(a)

Fig. 19(b)

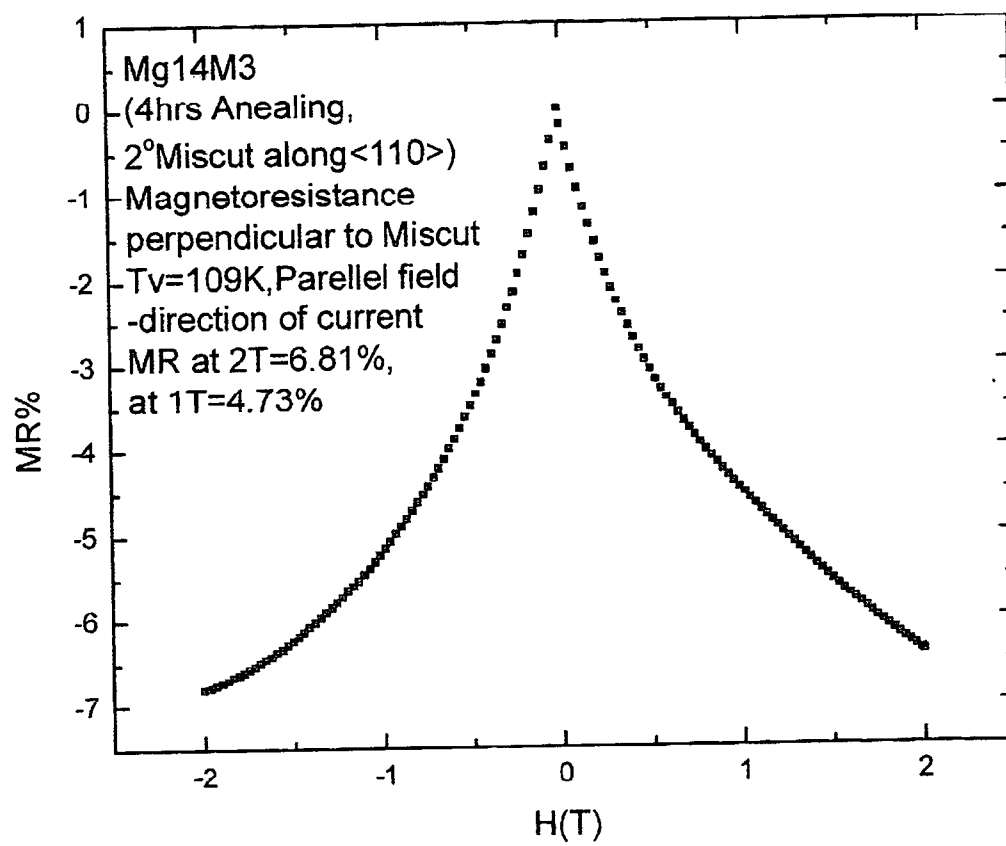
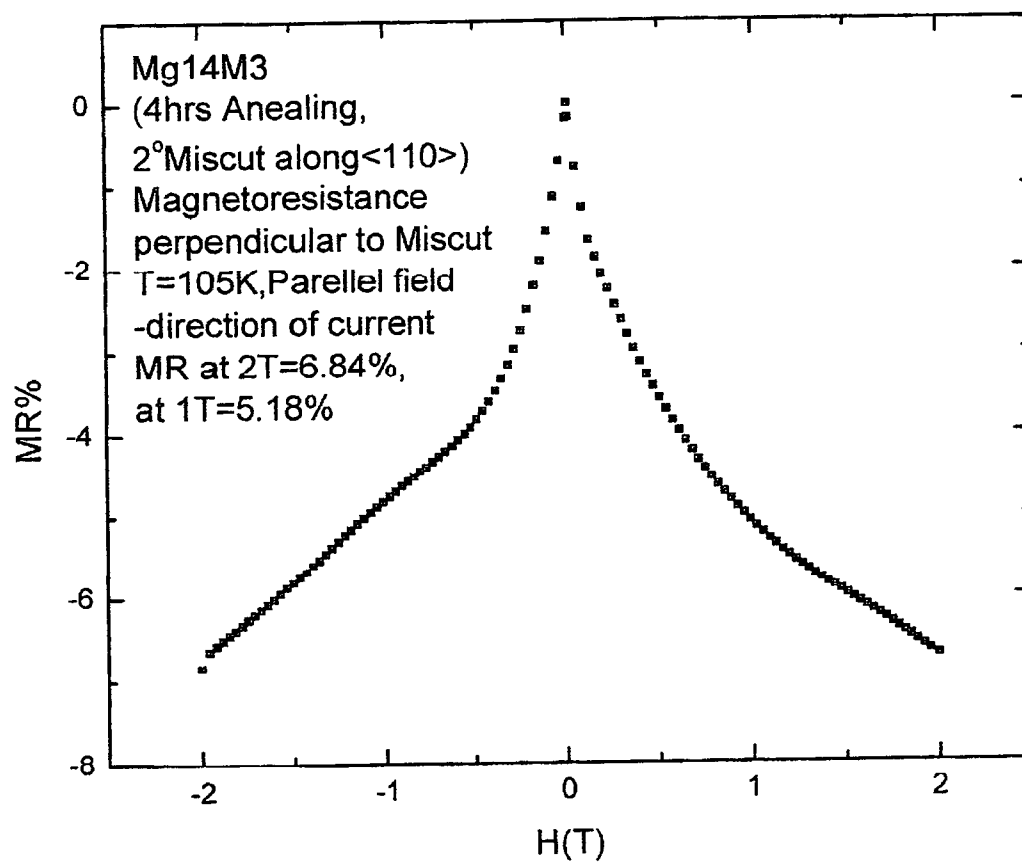


Fig. 20(a)

Fig. 20(b)

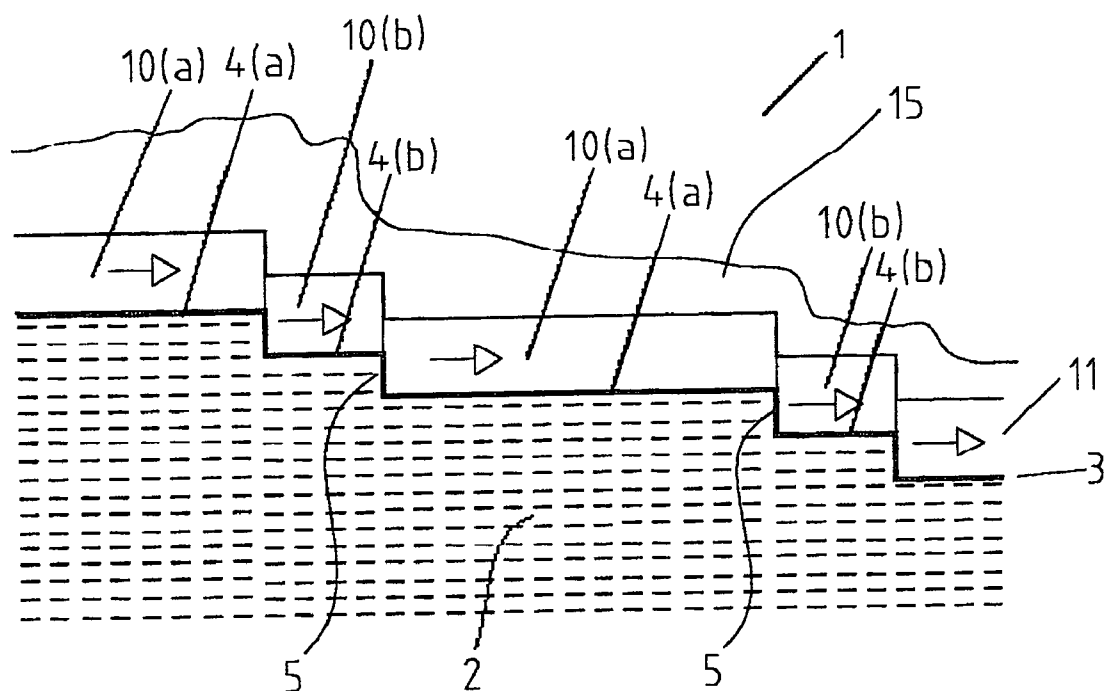


Fig. 21

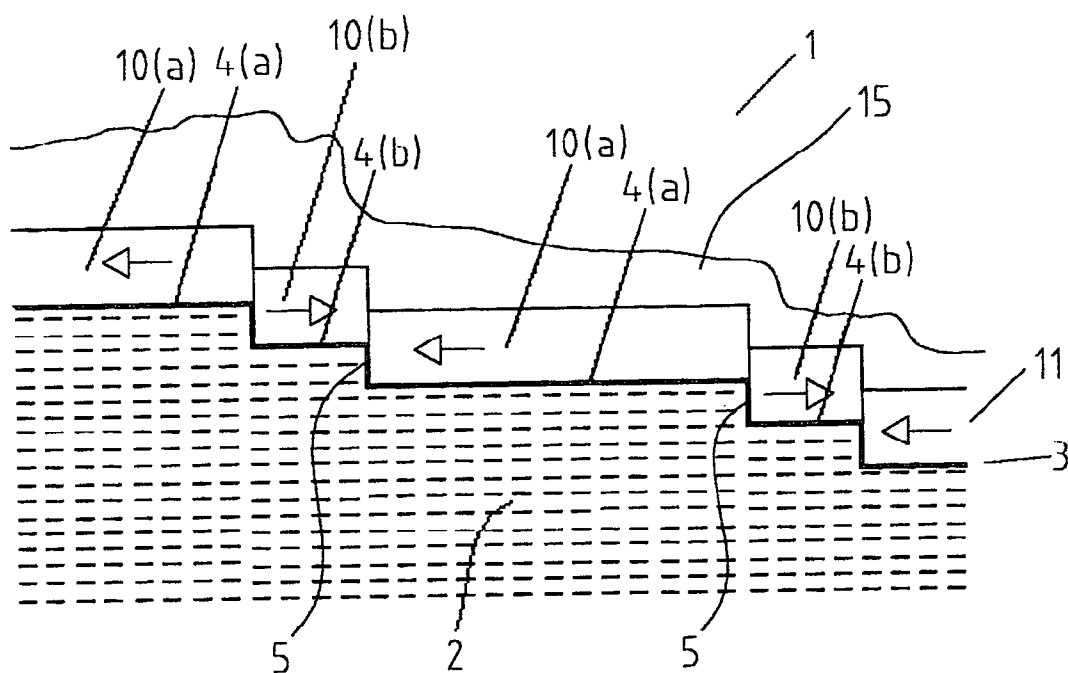


Fig. 22

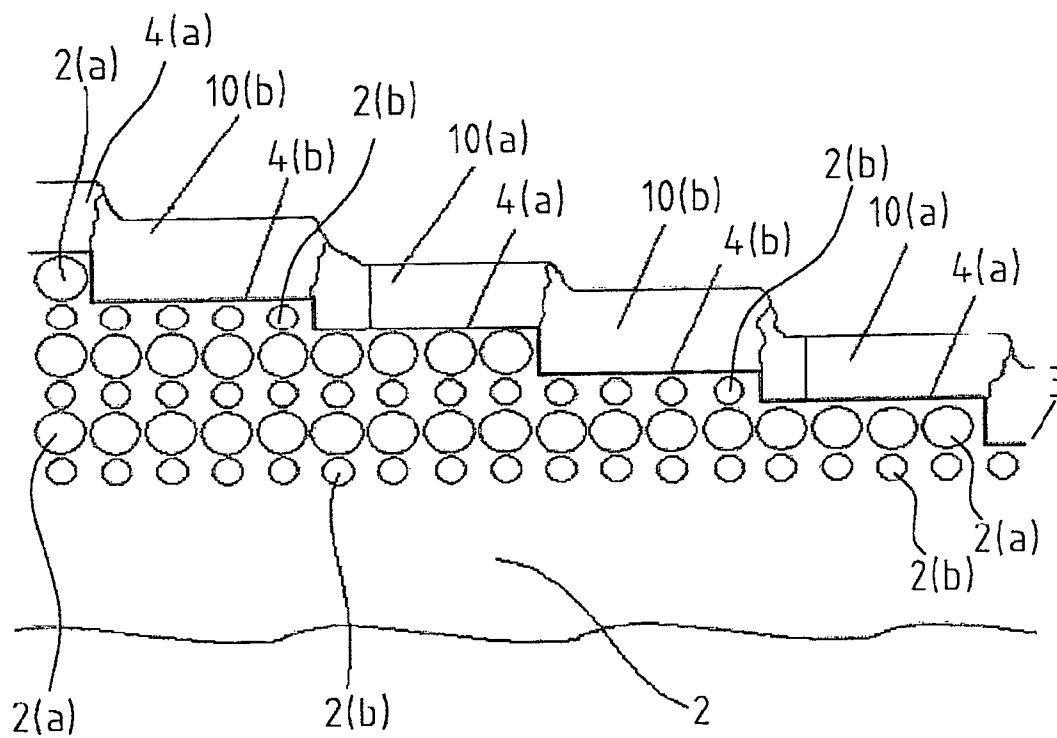


Fig. 23

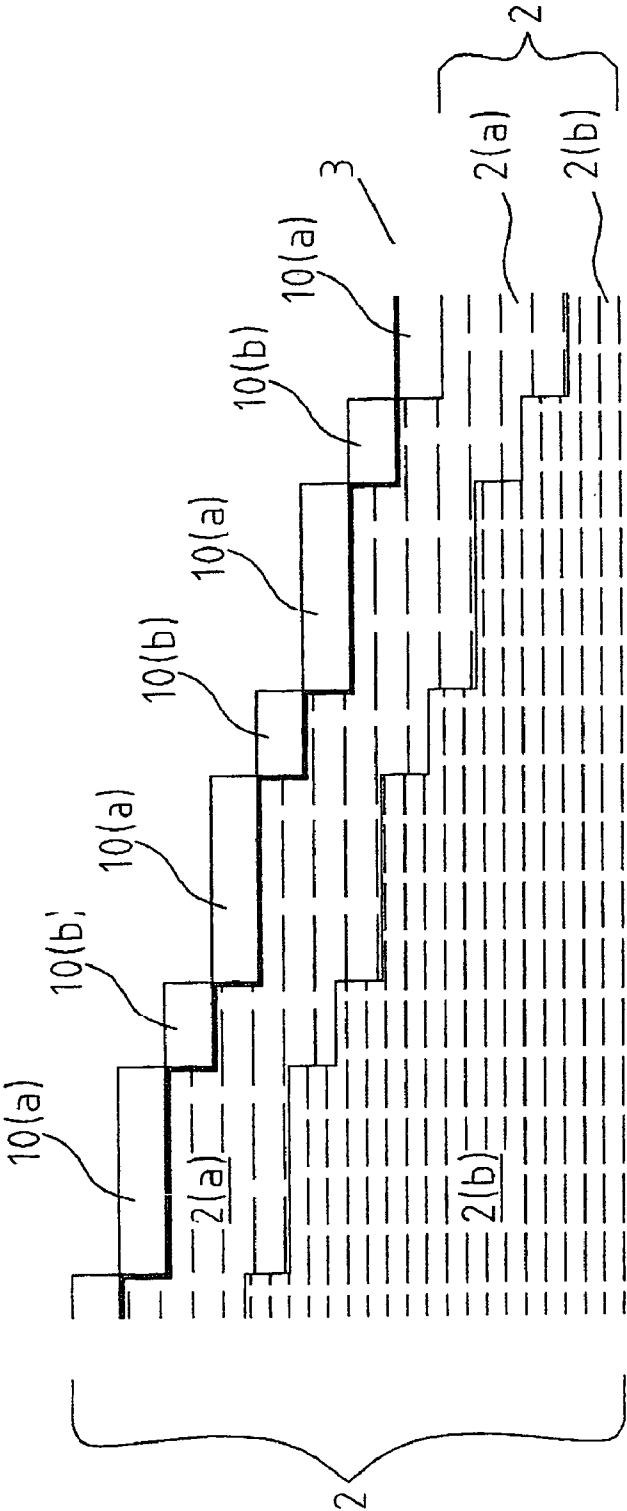


Fig. 24

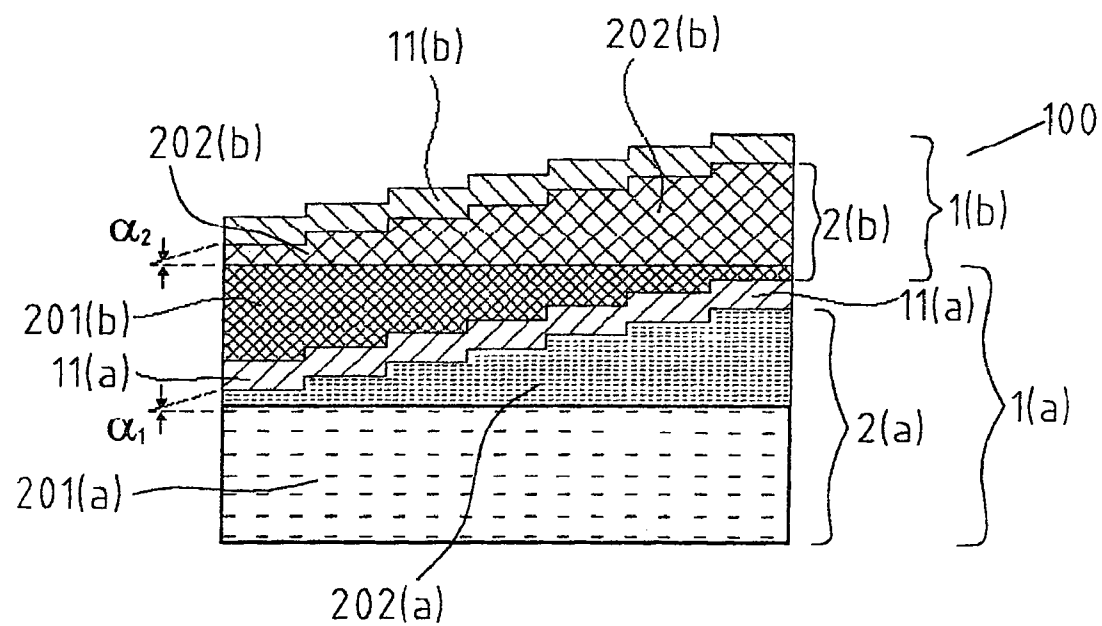


Fig. 25

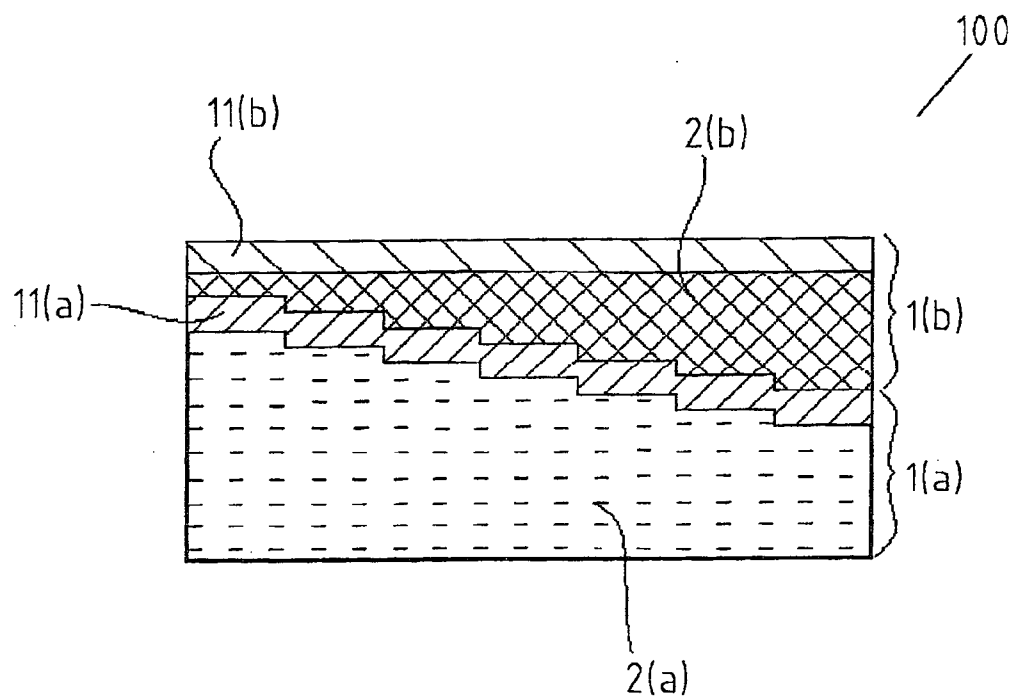


Fig. 26

MAGNETORESISTIVE MEDIUM INCLUDING A VICINALLY TREATED SUBSTRATE

[0001] The present invention relates to a magnetoresistive medium comprising a crystalline substrate and a thin film thereon.

[0002] Magnetoresistive media are media whose resistance to an electric current is sensitive to an external magnetic field. Such media are widely used in information and communication technologies e.g. in disk drive read heads, magnetic tape read heads, random access memory devices and in numerous other applications. Magnetoresistive media are also commonly used as sensors for a magnetic field in applications that are not directly related to the domain of information and communication technologies, e.g. in the automotive and aviation industries, security devices, goods labelling, position encoders, medical devices and numerous other applications. The best known magnetoresistive material is permalloy.

[0003] U.S. Pat. No. 4,949,039 (Gruenberg) describes a magnetic field sensor. The sensor comprises of a stack of ferromagnetic layers separated in such a way that the magnetisation of the layers can be rotated with respect to each other. Typically magnetisation of the layers is switched from mutually parallel to mutually anti-parallel. As the direction of the layers' magnetisation is reversed, the resistance of the stack changes. At present this sensor known as the spin valve, is commonly used in read heads of computer disk drives. U.S. Pat. No. 5,159,513 (Dieny et al) and U.S. Pat. No. 5,206,590 (Dieny et al) describe improvements to the magnetoresistive sensor based on the spin valve effect utilising two ferromagnetic layers. U.S. Pat. No. 5,422,571 (Gurney et al) also describes an improvement of the spin valve sensor. U.S. Pat. No. 5,578,385 (Saito et al) describes yet another improvement to the spin-valve sensor based on a stack of magnetic and nonmagnetic layers.

[0004] Virtually any spin valve sensor utilises coupling of one of the ferromagnetic layers to an antiferromagnetic layer. Such coupling, known as exchange pinning or exchange bias, has been well known for decades. It has been utilised in magnetoresistive sensors preceding the spin valve. For example, U.S. Pat. No. 4,755,897 (Howard) describes such a magnetoresistive sensor. This patent teaches the issues related to biasing a ferromagnetic layer by means of exchange interaction coupling with an antiferromagnetic layer.

[0005] There are inventions focusing on the utilisation of exchange bias in spin valve sensors. For example, U.S. Pat. No. 5,958,611 (Ohta et al) describes the magnetoresistance effect element based on a multilayered film. In this invention one of the ferromagnetic layers is pinned by the exchange interaction to a layer of antiferromagnetic oxide. It is interesting to note that according to the inventors, the roughness of the antiferromagnetic layer must be small in order to achieve good magnetoresistance sensitivity.

[0006] U.S. Pat. No. 5,923,504 (Araki et al.) is another invention describing exchange pinning in a spin-valve-like magnetoresistance device. In this invention one of two ferromagnetic layers is pinned by exchange to an antiferromagnetic layer of FeO_x . In some embodiments of this invention there is an oxygen-blocking layer between the pinning layer and the pinned ferromagnetic layer.

[0007] There are also inventions in which magnetisation in one of the two layers is fixed without the use of the antiferromagnetic layer. For example, U.S. Pat. No. 5,867,025 (Allenspach et. al.) describes a magnetic spin valve utilising a terraced substrate. The approach in this U.S. Pat. No. 5,867,025 capitalises on the finding by the inventors that when a Co film is deposited on a Cu terraced substrate there is a critical film thickness above which the direction of magnetisation of the film is pinned. This is known as step-induced anisotropy. Therefore, the magnetic spin valve proposed in this U.S. Pat. No. 5,867,025 comprises of two ferromagnetic layers separated by a nonmagnetic metal film like in a conventional spin valve with the difference that one of the two ferromagnetic layers is thinner than the critical thickness and the other one is thicker than it. In this arrangement, magnetisation in the first of the two layers can freely rotate and in the second layer it is pinned.

[0008] It is commonly held that surface roughness in a spin valve magnetoresistive medium should be small (Conference of the Materials Research Society (Dec. 1-5, 2003, Boston, Mass., USA, talk FF 5.3 by D. Zhou et. al).

[0009] Another recent class of devices sensitive to the external magnetic field are called magnetic tunnel junctions. U.S. Pat. No. 5,629,922 (Mooodera et al) and subsequently U.S. Pat. No. 5,835,314 (Mooodera et al) describe such electron tunnel junction devices. The devices include two ferromagnetic electrodes separated by a dielectric layer to form a tri-layer tunnel junction. Magnetisations of one of the ferromagnetic electrodes can be reversed with respect to the other. As the electric current passes between the two magnetic electrodes, the current value is sensitive to the relative orientation of the magnetisation directions in them. Therefore, the direction of magnetisation of one of the layers with respect to the other one can be identified. U.S. Pat. No. 5,835,314 further suggests that the greatest magnetoresistance effect is obtained when the tunnelling resistance is comparable to the electrode resistance. U.S. Pat. Nos. 5,734,605 and 5,978,257 (Zhu et al.) describe a tunnel junction element similar to the one described in U.S. Pat. No. 5,629,922 and further teaches how it could be utilised in a memory cell. U.S. Pat. No. 6,335,081 (Araki et al) describes an improved tunnel magnetoresistance effect element based on a multilayered film with a tunnel barrier having reduced the roughness of the layers. In most magnetic tunnel junction devices magnetisation of one of the two ferromagnetic layers is pinned by exchange to an antiferromagnetic layer. There are inventions that deal with improvements of the pinning characteristics. For example, U.S. Pat. No. 5,764,567 (Parkin) describes a magnetic tunnel junction device consisting of two ferromagnetic layers separated by a dielectric barrier layer. Magnetisation in one of the ferromagnetic layers is pinned to the antiferromagnetic layer. This invention teaches that an extra non-ferromagnetic layer should be added between the dielectric barrier layer and the second ferromagnetic layer in order to reduce the coupling between the fixed and free ferromagnetic layers.

[0010] U.S. Pat. No. 6,365,286 (Inomata et al) describes a magnetic element and magnetic memory device utilising spin dependent tunnelling between a ferromagnetic metal and a ferromagnetic-dielectric mixed layer. The tunnelling occurs through a dielectric layer of Al_2O_3 . The tunnel current depends on the orientation of magnetisations in the two layers: the ferromagnetic metal layer and the ferromag-

netic-dielectric mixed layer. This patent also describes structures comprising of three ferromagnetic layers: ferromagnetic metal layer, ferromagnetic-dielectric layer and again ferromagnetic metal layer all separated from each other by dielectric layers.

[0011] Yet another group of magnetoresistive media includes media in which the magnetoresistive effect is enhanced by utilising the array of particles or grains of different materials. The inventions that fall within this group are usually concerned with ways of forming such particulate media. For example, U.S. Pat. No. 6,015,632 (Chambliss et al) describes a self-assembled lateral multilayer for a magnetoresistive sensor. This invention utilises the finding that in the case of growth on Mo(110) substrate by simultaneous co-deposition of a ferromagnetic metal such as Co or Fe and nonferromagnetic metal (Ag) stripes of different materials are formed by self assembly. Although the patent contains no magnetic measurements, the inventors expect that neighbouring stripes of ferromagnetic metal should be aligned antiferromagnetically in the absence of the external magnetic field. The patent disclosure is limited to analysis of STM topography data. It remains to be seen what magnetoresistance effect if any could be achieved in such a lateral multilayer. The invention is further limited to co-deposition of immiscible materials. U.S. Pat. No. 5,858,455 describes the method of forming of such a multilayer by simultaneous co-deposition.

[0012] Another representative invention related to the same group of magnetoresistive devices and materials is described in U.S. Pat. No. 5,818,323 (Maeda et al.). According to the invention, the device is comprised of Ag/Co composite. The composite is a nonmagnetic conducting matrix of Ag that includes ferromagnetic anisotropic grains. The grains and the matrix are made of immiscible metals. The magnetoresistance material is produced by simultaneous co-deposition of the two metals. Further stripes are formed in the composite film by means of photolithography. The purpose of forming the stripes is to reduce the coercivity field and enhance magnetoresistance of the film. The invention further describes a multilayer of Cu and another Co/Cu composite. In the Co/Cu composite the Co grains are embedded into the Cu matrix and again the grains are anisotropic. Another U.S. Pat. No. 5,738,929 (Maeda et al.) describes a magnetoresistance effect element. The element comprises of ferromagnetic areas formed by photolithography covered by a non-magnetic metal overlayer. Again the magnetic areas and the nonmagnetic overlayer are made of non-soluble materials, e.g. Co and Cu. In a further U.S. Pat. No. 5,656,381 (Maeda et al.), the inventors utilise a similar composite film of immiscible materials. The film forms the magnetoresistive element. To reduce the operating magnetic field of the element, there are at least three areas of soft magnetic films magnetically coupled to the composite film. The areas are typically formed by means of photolithography. In U.S. Pat. No. 5,736,921 (Maeda et al), the magnetoresistive element is based on a similar composite material of immiscible nonmagnetic and magnetic materials. The inventors further suggest that forming a gradient of concentration of magnetic particles in the nonmagnetic matrix creates a positive effect on the magnetoresistance properties of the element. U.S. Pat. No. 5,585,196 (Koichiro et al.) is another example of a magnetoresistance effect element that utilises the particles of magnetic metals (Fe, Co or Ni) dispersed in a matrix of noble metal. The magnetic and

nonmagnetic metals are again immiscible and again the composite is produced by co-deposition of the two metals.

[0013] U.S. Pat. No. 6,168,845 (Fontana et al) describes another class of patterned magnetic media and method of making the same. The media is comprised of magnetic and nonmagnetic zones. These are obtained by selective oxidation process. Selective oxidation is achieved by subjecting a magnetic layer to oxygen plasma through voids in a patterned mask made by embossing and the reactive ion etching process. The media are not used as a sensor of magnetic field but rather as an information carrier for storage disks of high density. One of the advantages is that the media has minimal topography.

[0014] U.S. Pat. No. 6,387,530 (Chunling Liu et al) also describes a patterned magnetic media for high-density information storage. The media is formed by thermally induced phase transition in an initially amorphous layer of e.g. Ni—P. By heating the layer using a heat/light source the particles of at least a partially crystalline ferromagnetic material are formed in it. It is proposed that the multiplicity of light sources can be used to create an array of particles simultaneously.

[0015] Usually substrates for most magnetoresistive devices preferably need to be flat. However, there are inventions in which the magnetoresistive media are grown on non-flat and vicinal substrates. For example, U.S. Pat. No. 6,330,135 (Manako et al.) describes a magnetoresistance effect element based on a ferromagnetic oxide thin film grown on a stepped layer oxide. This invention utilises the fact that the crystal structure of some magnetic oxides (e.g. SrFeO_3) is such that antiphase boundaries are formed at the step edges of the substrate. The antiphase boundary is a crystal defect associated with the break in the translation symmetry of the material. The invention suggests that the antiphase boundaries result in additional magnetoresistance of the film.

[0016] U.S. Pat. No. 5,589,278 (Kamijo) describes magnetoresistive thin film and device. The patent teaches how to grow ferromagnetic film so that it forms pillars or staircase facets. It is suggested that such film has greater magnetoresistance. The patent further teaches how to control the width of the staircase facets and make them more homogeneous.

[0017] It should be appreciated that the key motivation for the development of materials and elements with improved magnetoresistance response is to further utilise them for numerous applications, e.g. in magnetic read heads, non-volatile memory elements, random access memory elements, encoders, security devices, etc. Some of these applications are described in the patents listed above. There are also numerous patents focusing on the development of specific devices utilising magnetoresistive materials. For example, a memory cell utilising a magnetoresistance element is described in U.S. Pat. No. 6,480,411 (Koganei).

[0018] In principle, the structures of magnetic layers described above are not limited to utilisation as passive magnetoresistive elements sensing the value of the external magnetic field. Some of these can also be used in various switching devices controlled by means of the current driven in the device or current injected in the structure. For example, U.S. Pat. No. 4,823,177 (Prinz et al.) describes a method and device for magnetising thin films by injecting

spin polarised current. According to the invention, the device has two electrodes deposited at two different locations on a material. One of the electrodes is ferromagnetic. When a spin polarised current is passed in between the electrodes, the magnetisation of the material changes.

[0019] An object of the present invention is to develop a magnetoresistive medium for applications in information and communications technologies and also for a range of sensor applications.

[0020] Another object of the present invention is to provide materials other than those sensitive to magnetic field in general or magnetoresistance in particular. More specifically these materials could be called directional nanowires. These can be thought of as an array of sub-micron size rods with strongly anisotropic shapes: they are elongated in one direction but in two other orthogonal directions the dimensions of the material are limited to typically between 0.2 nm and 50 nm only. Thus, the term "nanowires" is used for rods with small dimensions along two essentially orthogonal directions in the nanometer range combined with elongation along the third essentially orthogonal direction. Unlike conventional nanowires, these nanowires do not have to entirely consist of metal atoms. The nanowire could consist of atoms of any sort, e.g. atoms of semiconductor elements and oxygen atoms forming oxide, or metal atoms and atoms of the sulphur element group or indeed any combination of atoms. The term nanowire, therefore, refers to the shape rather than the electric conductance. However, it should be appreciated that if nanowires consist of e.g. metal atoms then their assembly will have strongly anisotropic electric conductance provided most of the nanowires are aligned along the same direction. Nanowires may have strongly anisotropic optical characteristics: e.g. for the polarisation of electric field along—and perpendicular to the direction of the elongation of the nanowires, optical and optoelectronic characteristics may be different. Magnetic susceptibility along—and perpendicular to the elongated direction may also differ. These materials are very new and their range of applications is yet to be fully explored.

[0021] The present invention is further directed to a method of fabrication of arrays of nanowires.

[0022] An objective of the invention is to develop a magnetoresistive medium, i.e. the material the resistance of which changes in response to changes in the value of an external magnetic field.

[0023] Yet another objective is to provide a method of fabrication of magnetoresistive media according to the invention.

[0024] Another objective is to develop a method for forming arrays of nanowires for a range of different applications including magnetic, electronic, optical and optoelectronic.

SUMMARY OF THE INVENTION

[0025] The invention provides a magnetoresistive medium having a crystalline substrate and an upper film on the substrate. In general, the substrate is a single crystal, while the film can be a single or polycrystal. There are stepped terraces of atomic and nanometer scale formed on the substrate by vicinally treating the substrate prior to application of the thin upper film. Many ways of treatment can be

used to obtain the necessary stepped terraces. At least some of the crystalline surface terminations formed on the terraces are non-equivalent to the crystalline surface terminations of other terraces such that at least two separate sets of upper nanowires, having a different response to an external magnetic field, are formed in the upper film. Terraces may be formed of a different width so as to cause one or more of lattice mismatch, step induced anisotropy, antiphase boundaries and misfit dislocations between the substrate and the upper thin film. The same effect may be achieved by having a crystal substrate which has a crystalline lattice which comprises a stack of at least two non-equivalent alternating crystallographic layers which will therefore interact differently with the upper film on the substrate and thus provide the separate sets of nanowires. One way of ensuring that there are different surface terminations is to provide terraces of different widths. By having different widths, it is possible to cause antiphase boundaries between the film and the substrate in one set of terraces, and to substantially suppress it in another set. Similarly, this could be arranged to cause misfit dislocations or to cause step induced anisotropy.

[0026] The invention also provides a substrate which is a composite substrate comprising one of a vicinally treated antiferromagnetic and a vicinally treated ferromagnetic upper substrate and a vicinally treated non-magnetic lower substrate. Needless to say, these can be reversed so that you have a non-magnetic upper substrate and then either a vicinally treated antiferromagnetic or ferromagnetic film on the lower substrate. There is also provided a substrate which is one of an antiferromagnetic material, ferromagnetic material and a semiconductor material, each material with a relatively high resistance to electric current, whereby the resistance of the substrate is sufficiently greater than that of the film to prevent, in use, the substrate shunting the current in the film.

[0027] The substrate can be one of:

[0028] NiO

[0029] FeO

[0030] CoO

[0031] Si

[0032] Ge

[0033] GaAs

and

[0034] a ferromagnetic material of high coercivity.

[0035] The substrate may be pre-annealed in an externally applied magnetic field or may indeed be a composite substrate comprising a base of non-magnetic material carrying a layer of one of antiferromagnetic and ferromagnetic material deposited thereon. This latter material will then have the vicinal surface formed on it. A buffer layer may be interspersed between them.

[0036] It will be appreciated that a final stabilising and protective layer may also be used which can be one of:

[0037] Al₂O₃

[0038] MgO

[0039] SrTiO₃

[0040] ZnO

[0041] SiO₂

[0042] TiO

[0043] ZrO and

[0044] HfO

[0045] Similarly, the substrate can form a surface with bunched atomic terraces. There may also be provided additional magnetic biasing layers in the medium in order to achieve smoother response of the resistance change on the value of the external magnetic field changing.

[0046] The magnetoresistive medium may be used to form a composite medium, namely, a stack of these media, one on top of the other. They can be oriented in various ways, the miscut angles of the vicinal substrates different, with the miscut angles offset with respect to each other, and so on.

DETAILED DESCRIPTION OF THE INVENTION

[0047] The invention will be more clearly understood from the following description of some embodiments thereof, given by way of example only, with reference to the accompanying drawings, in which:

[0048] **FIG. 1** is a perspective view of a typical vicinal surface of a substrate;

[0049] **FIG. 2** is a cross section perpendicular to the terrace steps of the vicinal substrate;

[0050] **FIG. 3** illustrates HRXRD characterization of the miscut for (100) surface of MgO single crystal;

[0051] **FIG. 4** shows RHEED pattern for the MgO(100) substrate measured in <110>azimuth;

[0052] **FIG. 5** shows RHEED pattern for the epitaxial Fe₃O₄ (100) film grown on MgO(100) substrate in <110> azimuth;

[0053] **FIG. 6** is a reciprocal space map of 70 nm thick Fe₃O₄ film on MgO (100) substrate measured in grazing exit geometry for the asymmetric (311)/(622) diffraction planes;

[0054] **FIG. 7** is a reciprocal space map of 70 nm thick Fe₃O₄ film on MgO (100) substrate measured for the symmetric (200)/(400) diffraction planes;

[0055] **FIG. 8** shows the dependency of normalized resistance R(T)/R(120K) as a function of temperature for the magnetite film;

[0056] **FIG. 9** shows the dependency of the magnetization on the in-plane magnetic field measured at room temperature;

[0057] **FIG. 10** is a representative Raman spectrum of magnetite film Fe₃O₄/MgO(100);

[0058] **FIGS. 11a,b,c,d** illustrate magnetoresistance of Fe₃O₄ film grown on MgO(100) measured for current along the miscut direction for sample temperatures of 293, 130, 101.5 and 100 K respectively. The magnetic field is parallel to the current direction. The miscut angle is 1 degree and the miscut direction is along <110>;

[0059] **FIGS. 12a,b,c,d** show the magnetoresistance measured for current directed perpendicular to the miscut direc-

tion (i.e. parallel to the terrace steps) for the same film of **FIG. 11** for sample temperatures of 293, 130, 101.5 and 98 K respectively substantially equivalent to the temperatures in **FIGS. 11a,b,c,d**. The magnetic field is parallel to the current direction. The miscut angle is 1 degree and the miscut direction is along <110>;

[0060] **FIGS. 13a** and **b** illustrate the magnetoresistance of Fe₃O₄ film grown on MgO(100) measured for current along the miscut direction. The miscut angle is 0.4618 degrees and the miscut direction is along <110>. The magnetic field is parallel to the current direction. **FIGS. 13a** and **13b** correspond to the sample temperatures of 114.8 and 102 K respectively;

[0061] **FIGS. 14a** and **b** show magnetoresistance measured for current directed perpendicular to the miscut direction for the same film as of **FIG. 13** for sample temperatures of 110.6 and 100 K respectively. The magnetic field is parallel to the current direction;

[0062] **FIGS. 15a** and **b** illustrate magnetoresistance of Fe₃O₄ film grown on MgO(100) (sample Mg14M2) measured for current along the miscut direction for sample temperatures of 109 and 105 K respectively. The magnetic field is parallel to the current direction;

[0063] **FIGS. 16a** and **b** illustrate magnetoresistance measured for current directed perpendicular to the miscut direction for the same film as in **FIG. 15** for sample temperatures of 109 and 105 K respectively. The magnetic field is parallel to the current direction;

[0064] **FIGS. 17a** and **b** illustrate magnetoresistance of Fe₃O₄ film grown on MgO(100) (sample Mg14M3) measured for current along the miscut direction for sample temperatures of 109 and 105 K respectively. The magnetic field is parallel to the current direction;

[0065] **FIGS. 18a** and **b** illustrate magnetoresistance measured for current directed perpendicular to the miscut direction for the same film as of **FIG. 17** for sample temperatures of 109 and 105 K respectively. The magnetic field is parallel to the current direction;

[0066] **FIGS. 19a** and **b** illustrate magnetoresistance of Fe₃O₄ film grown on MgO(100) (sample Mg14M3) measured for current along the miscut direction for sample temperatures of 109 and 105 K respectively. The current polarity is reversed with respect to the one in **FIG. 17**;

[0067] **FIGS. 20a** and **b** illustrate magnetoresistance measured for current directed perpendicular to the miscut direction for the same film as of **FIG. 19** for sample temperatures of 109 and 105 K respectively. The current polarity is reversed with respect to the one in **FIG. 18**;

[0068] **FIG. 21** is a cross-section through portion of a magnetoresistive medium according to the invention;

[0069] **FIG. 22** is a view similar to **FIG. 21** with an external magnetic field applied;

[0070] **FIG. 23** is a view similar to **FIG. 21** of an alternative construction of magnetoresistive medium;

[0071] **FIG. 24** is a cross sectional view of another magnetoresistive medium according to the invention;

[0072] **FIG. 25** is a typical sectional view of a composite magnetoresistive medium comprising a stack of two of the media of the invention, and

[0073] FIG. 26 is a cross sectional view through another composite magnetoresistive medium according to the invention.

[0074] In this specification, the term “vicinal” is used not simply in its common meaning of “neighbouring” or “adjacent” but also as a reference to the characteristics of the terraces formed by subsequent treatment of a miscut substrate. Thus, the phrase “the extent to which the substrate is vicinal” implies, as will be appreciated by those skilled in the art, how formed; what size; how mutually arranged; and so on. There is no one term which can describe how the vicinal surface is treated to achieve the desired terraces, so much depends on the substrate material. This is explained in detail in the specification. Again, as explained throughout the specification, the treatment is not uniform and indeed it is not always a treatment as such, but a selection process.

[0075] It appears that much attention has been paid to electron transport in films grown on vicinal substrates. There are several studies that address the issue of electron transport and even magneto-transport in low-dimensional vicinal systems. Usually they deal with the fundamental questions of physics and quantum mechanics as opposed to tackling the practical issues of increasing magnetoresistance in films. These studies often relate to semiconductor systems performed under the presence of very high magnetic fields of up to 30 Tesla and very low temperature. A study by RTF van Schaijk et al. published in Physics B 256-258 (1998) 243-247 is a good example of such an investigation. It deals with Shubnikov-de Haas oscillations. However, their use for the purpose of the present invention is not described in the literature.

[0076] Accordingly, “the extent to which the surface is vicinal” means the materials are chosen, various miscut angles are used, various treatments of the cut surface are performed and an optimum cut angle and treatment is determined to provide the necessary interaction between the film and the substrate to achieve the objects of the invention. Because the materials will change and the treatments will vary, all one can state is that the optimum cut angle and treatment is used to provide this vicinal surface, as again described in the specification. A convenient term for this could be “vicinal treatment” or “vicinally treated” to cover choosing for the combination of film and substrate, the correct miscut angle and miscut direction and the subsequent treatment of the substrate to provide the necessary upper nanowires in accordance with the invention.

[0077] In this specification, the term “film” and “layer” are used interchangeably. There is a difficulty in nomenclature when one refers to “vicinal surfaces”, “atomic terraces” and “terrace steps”. “The vicinal surface consists of “atomic terraces. Therefore, each atomic terrace is a relatively flat area of the vicinal surface. As it will be explained below, in practice atomic terraces are not perfectly flat and contain atomic corrugations, defects, adsorbates and atomic-scale surface reconstructions, however, at this point this is not essential. The separation between the neighbouring atomic terraces in the vertical direction, i.e. in the direction perpendicular to the atomic terraces is called terrace step. The dimension of the terrace step is typically comparable to the separation between the layers of atoms forming crystal lattice (typically 2 Å the same as 0.2 nm the same as 2×10^{-10} m), i.e. it is comparable to the interatomic distance although

it can also be a small integer multiple of this in the case of bunched steps or multiple steps. For example, it could be double or triple or quadruple of the separation between the layers of atoms in the crystal structure. On the other hand, the width of the atomic terraces is typically considerably greater than the interatomic distance, e.g. it would be at least 1 nm or more typically 10 to 50 nm or even greater than 100 nm. This is shown schematically in FIGS. 1 and 2, discussed in more detail below. However, in order to make the figures more readable, the widths of all the atomic terraces are typically shown reduced. The term “width” is used in the technology to describe the dimension which, in common usage for terraces such as those in buildings, would be used to describe the depth of the terrace, the term “width” being used more commonly to define the lateral extent of the terrace. For example, in FIGS. 1 and 2 the width of the atomic terraces are shown only some three times greater than the terrace steps which would make them only 0.6 nm wide, that is to say they are exceptionally narrow terraces in practical terms. They are of atomic and nanometer scale, the step height being of atomic and the width of nanometer scale. In a flat vicinal surface, the direction of the rising steps typically persists unchanged over a relatively large area. For example, the step to the left between atomic terraces is always a rising or always a falling step throughout many atomic terraces. It should be appreciated that the order of subsequently rising or subsequently falling steps is not perfectly preserved between all the atomic terraces. For example, in a typical vicinal surface rising steps may be followed by one or two falling steps and then by another rising steps and then perhaps by another falling step, etc. It should also be appreciated that macroscopically a vicinal surface is typically not parallel to the individual atomic terraces.

[0078] It should be noted that, strictly speaking, while in the present specification the reference is to a magnetoresistive medium, all that is illustrated is portion of the magnetoresistive medium.

[0079] In this specification, the term “ferromagnetic”, as is often the case is used, to encompass both ferromagnetic and ferrimagnetic materials. As those skilled in the art will know, the difference in the materials is that the ferrimagnetic material has more than one magnetic sub-lattice. Both materials have net spontaneous magnetic moments below their Curie temperatures. Sometimes the Curie temperature of a ferrimagnetic material is called Neel temperature and the ferrimagnetic materials are sometimes called ferrites. A well-known example of a ferrimagnetic material is Fe_3O_4 .

[0080] The term “crystalline” is used somewhat loosely in relation to the magnetoresistive medium according to the invention. In general, in relation to the substrate, the word “crystalline” means a single crystal, that is to say, a crystal with axes that have the same direction at different parts of the crystal. In relation to some of the films used, the word “crystalline”, as well as a single crystalline, i.e. an epitaxial film, can also mean “polycrystal”, that is to say, crystal with axes which may change direction at different parts of the film.

[0081] FIGS. 1 and 2 show schematically an example of a vicinal surface, indicated generally by the reference numeral 3. The vicinal surface 3 consists of terraces with low Miller indexes called in this specification, atomic ter-

aces 4. The atomic terraces 4 are separated by terrace steps 5 in the vertical direction, i.e. in the direction perpendicular to each atomic terrace. Vicinal surfaces can be formed for numerous crystalline materials. Atomic terraces can be formed to have various Miller indexes, e.g. (100), (110), (111) are common indexes for atomic terraces. Terraces with certain indexes can be formed readily, terraces with other indexes cannot. This depends on the surface energy of different atomic terraces, which in turn depends on the crystal structure of the material. Atomic terraces can readily be visualized by a Scanning Tunnelling Microscope (STM) on electrically conducting materials and by an Atomic Force Microscope (AFM) on conducting and insulating ones. Many researchers including some of the inventors have studied atomic terraces extensively, e.g. [S. Murphy, D. M. McMathuna, G. Mariotto, I. V. Shvets, *Physical Review B*, 66 (19) 195417 (2002), Morphology and strain induced defect structure of ultrathin epitaxial Fe films on Mo(110)]. The vicinal surface is characterized by the miscut direction, i.e. crystallographic direction of the terrace steps. For example, (001) surface in principle may have steps aligned along the $\langle 100 \rangle$ or $\langle 110 \rangle$ direction or along numerous other directions. Again, certain directions of terrace steps can be readily attained and others cannot. The result depends mainly on the crystallographic indexes of the atomic terraces and the type of material. It should be appreciated that for most surfaces the terrace steps are not perfectly straight. Nonetheless, for many surfaces the average representative direction of the terrace steps can be readily identified. Each terrace is characterized by the terrace width. In FIG. 1, the terrace width of one of the terraces is shown as I_1 . It is clear that the same terrace at different locations may have different widths, as the terrace steps in practice often do not form perfectly straight lines parallel to each other. Nonetheless, the average representative terrace width can often still be identified for the surface. This is related to the so-called average miscut angle. The miscut angle is identified in FIG. 2 by the letter a. FIG. 2 represents a cross-section of the surface perpendicular to the terrace steps. Generally, the greater the miscut angle, the smaller the average width of atomic terraces. The relative width I_1 of the terrace 4 is many times greater than the depth of the step 5 and not as shown in FIGS. 1 and 2, as explained above.

[0082] Methods of forming vicinal surfaces have been extensively described in the literature. Generally, the methods are based on cutting the surface at a desired angle with respect to the low index direction by diamond saw, spark erosion or another suitable technique and polishing the surface, e.g. by using diamond paste, or by means of electrochemical polishing. Then the surface is characterized by means of a High Resolution X-Ray Diffractometer (HRXRD). For the present invention, a HRXRD instrument from Bede Scientific Instruments Ltd (UK) was used. The miscut angle and the direction of the miscut, i.e. the direction on the surface perpendicular to the average terrace step is identified using the HRXRD. FIG. 3 shows an example of the HRXRD characterization of the MgO surface miscut. Because of the miscut, the angular position at which diffraction is found to vary as the specimen is rotated about its surface normal. The angular positions for different azimuthal positions are optimised. A sine curve can be fitted on the plot of peak positions against the azimuth. The miscut is the angle amplitude of the sine wave and the position of the maximum gives the direction of the miscut. The HRXRD

peak split software incorporates a utility for analysing such data. FIG. 3 shows a typical curve fitting for the miscut measurement. In this case the MgO(100) substrate has the miscut angle of 0.4563 degrees. The minimum tilt is at azimuth of 42.117 degrees and the maximum tilt is azimuth of 222.618 degrees. The miscut direction is then measured from the positions of the intensity minimum or maximum once crystallographic directions on the surface are identified from the asymmetric peaks. These procedures for identifying the miscut are standard and are known to specialists in the field.

[0083] To establish terraces on a miscut substrate, treatment leading to the atomic scale rearrangement is often required. There are numerous approaches resulting in such a rearrangement. According to one method, the surface may be annealed in vacuum or in ultra high vacuum. In between the annealing sessions it can be characterized by using in-situ scanning tunnelling microscopy, STM, i.e. the STM located inside the vacuum system. Another method includes ion etching of the surface kept at an elevated temperature by means of e.g. Ar ions in vacuum [J. Naumann, J. Osing, A. Quinn, I. V. Shvets, Morphology of sputtering damage on Cu(111) studied by scanning tunnelling microscopy, *Surface Science* 388 (1997) 212-219] which is included in this specification by way of reference. Alternatively, a chemical reaction can be set up on the surface such that the reaction speed is dependent on the Miller indexes of the atomic terraces. As a result, well-defined terraces can be formed. Other possible methods also include subjecting the surface to chemical or electrochemical reaction. There is no general hard rule of finding the conditions for the preparation of a vicinal surface with well-defined terraces. The conditions are generally optimised for any given material and desired Miller indexes of the atomic terraces.

[0084] Miscut and polished SrTiO₃(100) substrate is first washed in distilled water in another method. Then it is subjected for about 30 seconds exposure in a buffered hydro-fluoric acid at room temperature. The substrate is then rinsed in distilled water. This procedure results in well-defined atomic terraces. To make the edges of the terraces straight, the substrate may be further subjected to between 1 and 4 hours of anneal in oxygen atmosphere at 1 Bar pressure at a temperature of 10000° C.

[0085] A vicinal substrate of Si (111) can also be formed by means of anneal. Typical preparation includes annealing of a polished miscut substrate in an ultrahigh vacuum chamber at a temperature of 1050° C. for some 1 hour. Then the substrate is quickly annealed (flushed) at 1250° C. for 20 seconds also in an ultra high vacuum.

[0086] Vicinal substrates of another commonly used material: α -Al₂O₃ with a (0001) orientation can also be prepared by means of anneal. For this material the anneal needs to be carried out in air and the anneal temperature is 10000° C.

[0087] It is known that hysteresis loops of a miscut surface depend on the direction of the magnetic field with respect to the miscut direction. Measurements were performed by means of longitudinal magneto-optical Kerr effect. The sample was epitaxial film of Fe grown on the single crystal Mo(110) vicinal substrate. The miscut direction is $\langle 1-1-1 \rangle$ and the miscut angle is 4.6 degrees. We established that atomic terrace steps induce noticeable contribution to the magnetic anisotropy of Fe film for the film thickness of up to 10-12 Å.

[0088] In one representative experiment described below, the magnetoresistance of thin films of Fe_3O_4 (magnetite) deposited on MgO (100) vicinal substrates was measured. In this case the vicinal MgO (100) substrates had a miscut direction along $\langle 110 \rangle$ and varying miscut angles. The accuracy of the surface orientation was within ± 0.5 degrees. The film thickness was 70 nm.

[0089] Prior to insertion into the MBE chamber, substrates were chemically cleaned and mounted on a molybdenum sample holder. The film was deposited using Oxygen-Plasma-Assisted Molecular Beam Epitaxy (MBE) using the MBE system manufactured by DCA (Finland). The MBE system was equipped with facilities for sample heating, Reflection High Energy Electron Diffraction (RHEED), residual gas analyser (RGA), molecular beam sources for deposition of materials, deposition rate monitors as well as an Electron Cyclotron Resonance (ECR) oxygen plasma source. The base pressure in the system was lower than 5×10^{-10} Torr. The oxygen source used for the growth was the Radio Frequency (RF) OS Pray Plasma source from Oxford Scientific (UK). The RF power supplied to the source was 80 W during the deposition. The MgO substrate was annealed at 600°C . for up to 4 hours in a plasma oxygen environment at the pressure of 1×10^{-5} Torr prior to the deposition. In most cases the same level of RF power was applied to the plasma source during the substrate annealing. For some samples no RF power was supplied to the plasma source during the substrate annealing. Out of the samples referred to in this specification, sample Mg14M2 and Mg14M3 were annealed without any RF power and all the other samples were annealed at 80 W of RF power. FIG. 4 shows the RHEED pattern of the MgO single crystalline substrate along the $\langle 110 \rangle$ azimuth after the above-mentioned cleaning procedure. It shows vertical lattice rods and radial Kikuchi lines indicative of a well ordered and reasonably flat surface. The magnetite film was deposited by means of e-gun evaporation from an Fe pellet with a purity of 99.995% in a plasma oxygen environment with the pressure of 1×10^{-5} Torr and the substrate temperature of 250°C . The growth rate was 0.3 Å/sec. The growth mode and the crystalline quality of the films were monitored in-situ by reflection high-energy electron diffraction (RHEED). The film thickness was controlled by quartz-crystal thickness monitors, which were calibrated with the growth rate measured using RHEED intensity oscillations. After the deposition the film was kept at the same temperature for about 10 minutes in the MBE chamber. The magnetite film grown under these conditions is epitaxial. After the growth of 10 monolayers of iron oxide thin films, the RHEED pattern shows half order lattice rods, located in the middle of the lattice rods corresponding to MgO, indicating the formation of Fe_3O_4 (see FIG. 5). Magnetite diffraction pattern exhibits a weaker diffraction ring from the first diffraction zone, which is visible at the lower part of the image. The lattice constant of magnetite as determined from RHEED is 8.4 ± 0.1 Å. The appearance of half order streaks is accompanied by the oscillations in the intensity of the specular reflected beam, which confirms that the film grows in layer-by-layer mode.

[0090] The structural characterization was done using the high-resolution X-ray diffraction (HRXRD) measurements. With the HRXRD, when operated in a triple axis configuration one can detect lattice constant variations as low as 2×10^{-5} . This enables one to determine the status of the strain relaxation very precisely. The crystalline alignment of the

film with respect to the substrate can also be established. The in-plane ($a_{||}$) and out-of-plane ($a_{\perp}$) lattice parameters of the Fe_3O_4 thin films grown epitaxially on (100) MgO substrates were measured by performing symmetric (400), (800) and asymmetric (622) and (420) Bragg reflections.

[0091] We have established that for Fe_3O_4 films grown on MgO (100) substrates under the growth conditions described are fully strained to achieve one-to-one registry with the substrate for film thickness up to 100 nm and even greater. The representative results of the HRXRD measurements of a 70 nm thick film at room temperature are shown in FIGS. 6 and 7. In order to determine the in-plane lattice parameters, $a_{||}$, of the film, we have performed a reciprocal space map, RSM, around the (311) diffraction peak of the substrate located in the vicinity of (622) peak of the over layer. The RSM was obtained by measuring a number of (ω - 2θ) scan for different ω offset values. FIG. 7 shows the RSM of 70 nm thick Fe_3O_4 film grown on MgO (100) for the asymmetric (311)/(622) Bragg reflection performed for grazing exit geometry ($\omega=62.5685^\circ$, $2\theta=74.6582^\circ$). The reciprocal lattice vectors $Q(x)$ and $Q(z)$ represents the in-plane (110) and out-of-plane (100) directions respectively. From the position of the thin film peak in the RSM along $Q(x)$ and $Q(z)$ directions and independent ω - 2θ scan measured for grazing exit (GE) and grazing incidence (GI) geometries, we determined the in-plane lattice parameter of the film. The $a_{||}$ (0.8426 nm) estimated from the RSM, within the experimental accuracy, is exactly twice the substrate lattice constant. This indicates that the film has the same in-plane lattice constant that of substrate and is fully coherent (pseudomorphic) with the substrate.

[0092] FIG. 7 shows the RSM for the 70 nm thick Fe_3O_4 film on MgO performed along the (200)/(400) Bragg reflection to determine the out-of plane lattice parameter, $a_{\perp}$, of the film. The strong sharp peak corresponds to (200) peak of MgO and other weaker one at higher $Q(z)$ position corresponds to the (400) peak of Fe_3O_4 thin film. The full width at half maximum (FWHM) of the MgO (200) and Fe_3O_4 (400) determined from independent ω - 2θ scan are 0.0052° and 0.0136° respectively. The small FWHM for the thin film indicates that the films grown are of high crystalline quality. The value of $a_{\perp}$ for the Fe_3O_4 thin film determined from the film peak position along $Q(z)$ direction in the RSM and film-substrate peak separation (0.14605°) from independent ω - 2θ scan is 0.83717 nm. This value is consistent with the $a_{\perp}$ value determined from the asymmetric (311)/(622) GE and GI scans.

[0093] The results of the HRXRD characterization can be summarized as follows: the film is single crystalline with the tetragonally distorted unit cell. The strain is tensile in the film plane and the film is fully strained. The volume of unit cell is a good indication of the film stoichiometry and is consistent with the bulk magnetite suggesting that the film is stoichiometric.

[0094] FIG. 8 shows representative normalized resistance as a function of temperature for $\text{Fe}_3\text{O}_4/\text{MgO}(100)$ film. This was measured for the 70 nm thick film. The result is included in the specification to demonstrate that the film grown under conditions as described above, is indeed magnetite. The change in the slope of the $R(T)$ curve is Verwey transition, is an indication of a high quality Fe_3O_4 film. The Verwey temperature is 101.8 K. The Verwey temperature in thin

films of magnetite is known to be lower than in bulk. The very fact that a clear Verwey transition is visible in the $R(T)$ curve is an indication of a very good stoichiometry ratio in the film. It is interesting to note that the temperature dependences of the resistance along and perpendicular to the miscut direction differ.

[0095] FIG. 9 shows the magnetization as a function of the in-plane magnetic field for the same representative film as the one referred to in FIGS. 6-8. The measurements suggest that the value of the saturation magnetization M_s is also consistent with that of magnetite. The value measured is ~ 470 emu/cm³ (within 2% error) at room temperature.

[0096] The Raman optical spectrum for the film is shown in FIG. 10. Raman spectroscopy was used as an additional tool to ascertain the magnetite phase. The representative Raman spectra of thin films grown under conditions as described above, showed bands corresponding to Fe_3O_4 phase observed at 668, 537, 308 and 192 cm⁻¹, consistent with the spectrum of magnetite. Predictably, the observed values of Raman bands correspond to somewhat lower wave numbers than the ones observed for bulk single crystals of Fe_3O_4 and are representative of in-plane tensile strain. There was no signature of any other iron oxide phase present in the spectra.

[0097] This invention is not limited to magnetic oxides or to stoichiometric magnetite in particular. This specification describes a general phenomenon and how it can be exploited to form a magnetoresistive medium. Magnetite is just one example of magnetic material that utilizes the phenomenon.

[0098] The present invention can be summarised as follows. The magnetoresistance of a film can be controlled and enhanced by the miscut of the substrate on which the film is grown. Generally, other operations are also required and are encompassed within the term "vicinal treatment". Results of one representative experiment are shown in FIGS. 11a,b,c,d and 12a,b,c,d. The Fe_3O_4 film coded as Mg12M3 was grown, as described above. The film thickness was 70 nm. The substrate was annealed prior to film deposition for 0.5 hour in an ultra high vacuum at 600 C and then for 1 hour at the same temperature in an oxygen plasma environment at a pressure of 1×10^{-5} Torr. Magnetoresistance of magnetite film was measured in this experiment using a standard four-point technique using DC current of 10 μ A. In line with common practice we define magnetoresistance as $MR\% = 100 \times (R(T,H) - R(T,0)) / R(T,0)$, here $R(T,H)$ and $R(T,0)$ are the resistances with and without magnetic field H at a given temperature T respectively. Magnetoresistance, MR, is measured in percent. The magnetoresistance of the magnetite films was measured as a function of the miscut angle of the substrate. FIGS. 11a,b,c,d show the magnetoresistance measured with current along the miscut direction. The miscut angle is 1° and the miscut direction is along <110>. The magnetic field is parallel to the current direction. FIGS. 12a,b,c,d show the magnetoresistance of the same film measured with current directed perpendicular to the miscut direction and field parallel to the current. Above Verwey temperature there is no noticeable difference in the magnetoresistance between the two cases of current along the miscut direction and perpendicular to the miscut direction. The difference in magnetoresistance close to Verwey transition temperature (120 K) is significant: 4.31% at 2 Tesla field and 3.727% at 1 Tesla field. Below Verwey transition

the difference is 3.52% and 4.2% respectively. The maximum magneto resistance observed for the current parallel to the miscut direction is remarkably high: 13.83% for 2 Tesla field and 11% for 1 Tesla field. These values are summarized in Table 1 below.

TABLE 1

Sample: Mg12M3 (1° miscut along <110> direction)					
Direction of the current	Field value (Tesla)	T = 299 K	T = 130 K	T = 101 K	T = 100 K
Along miscut direction	2	1.18%	4.4%	13.83%	11.13%
	1	0.66%	3%	11%	10.34%
Perpendicular to miscut	2	1.3%	4.627%	9.52%	7.612%
	1	0.798%	3.04%	7.273%	6.143%

Difference in MR % along and perpendicular to miscut				
Field Value (Tesla)	T = 299 K	T = 130 K	T = 101 K	T = 100 K
2	0.12	0.227	4.31	3.518
1	0.138	0.04	3.727	4.197

[0099] Different values of the magnetoresistance can be found along different crystallographic directions in an epitaxial film. For example, on the (110) or (111) surface one may expect to find some difference between the magnetoresistance values measured along two orthogonal directions as they are crystallographically not equivalent. However, the results presented in FIGS. 11 and 12 do clearly suggest that the miscut is responsible for the difference. The reason is based on the fundamental symmetry consideration: on (100) surface of a cubic crystal two orthogonal directions are always equivalent. Clearly, one should also expect that for other surface terminations, e.g. (110), (111) etc. the magnetoresistance along and perpendicular to the miscut direction should differ. However, as two crystallographic orthogonal directions are equivalent on the (100) surface, the clarity of the result is more transparent on the (100) surface and that is why we refer to this surface.

[0100] It can be further demonstrated that the miscut angle is an important factor in defining the value of the magnetoresistance. FIGS. 13a, b and 14a, b show the results for magnetoresistance measurements for Fe_3O_4 film grown under conditions substantially identical to the ones corresponding to the results presented in FIGS. 11 and 12 with the only difference that the miscut angle was lower. The results presented here are for only two representative temperatures namely at and below Verwey temperature. At these temperatures only a significant affect of miscut angle on MR properties was observed. Like in FIGS. 11 & 12 the magnetic field is directed along the current direction. In this film coded by us as sample Mg6M1 the substrate miscut angle was 0.4618° and the miscut direction was the same, as in the sample M12M3: along <110>. One can see that the difference in magnetoresistance for the cases of current directed along and perpendicular to the miscut direction was much lower than in the case of the film grown on a substrate with 1° miscut. The magnetoresistance results for the sample Mg6M1 at various temperatures are summarized in Table. 2 below.

TABLE 2

Mg6M1 (0.4618° miscut along <110> direction)					
Direction of the current	Field Value (Tesla)	T = 299 K	T = 135 K	T = 114.8 K	T = 102 K
Along miscut direction	2	1.63%	4.8495%	8.26%	7.569%
	1	1.0123	3.177%	5.7669%	4.84%
Perpendicular to miscut	2	1.52%	5.4767%	8.1076%	8.99%
	1	0.91%	3.3567%	5.4923%	5.455%
Difference in MR % along and perpendicular to miscut					
Field Value (Tesla)	T = 299 K	T = 135 K	T = 114.8	T = 102 K	
2	0.11	0.6272	0.1524	1.421	
1	0.9213	0.1797	0.2746	0.615	

[0101] The specification emphasizes the importance of the difference between the magnetoresistance of films grown on vicinal and non-vicinal substrates. The difference is highly beneficial as magnetoresistance has increased considerably. It appears that the magnetoresistance values shown in FIG. 11c are higher than any value published for the magnetoresistance of this material heretofore.

[0102] FIGS. 15, 16, 17, 18 present results of magnetoresistance measurement for the samples Mg14M2 (FIGS. 15, 16) and Mg14M3 (FIGS. 17, 18). Both the samples are 45 nm thick films of epitaxial Fe₃O₄ grown under conditions substantially similar to the ones described above. The samples Mg14M2 and Mg14M3 were grown on MgO(100) substrates with the identical miscut angle of 2° and miscut direction of <110>. The most substantial difference between the two samples is that the substrate of Mg14M3 was annealed for a longer time prior to the film deposition. The substrate of Mg14M2 was annealed for 0.5 hour in UHV and then for 2 hour in an oxygen pressure of 1×10⁻⁵ Torr prior to the film deposition. The substrate of Mg14M3 was annealed for 4 hours at an oxygen pressure of 1×10⁻⁵ Torr. FIGS. 15a, b correspond to the sample Mg14M2 for the temperatures 109, 105 K respectively for the current along the miscut direction. FIGS. 16a, b correspond to the sample Mg14M2 for essentially the identical temperatures of 109 and 105 K respectively for the current perpendicular to the

miscut direction. In both, FIGS. 15 and 16 the magnetic field is parallel to the current direction. Magnetoresistance results for the sample Mg14M2 measured at different temperatures are summarized in Table 3 below.

TABLE 3

Mg14M2 (2° Miscut along <110> direction)					
Direction of the current	Field Value (Tesla)	T = 299 K	T = 130 K	T = 109 K	T = 105 K
Along miscut direction	2	1.29%	5.63%	9.25%	6.56%
	1	0.82%	3.61%	7.29%	5.11%
Perpendicular to miscut	2	1.33%	5.35%	6.56%	6.49%
	1	0.66%	3.56%	4.65%	5%
Difference in MR % along and perpendicular to miscut					
Field Value (Tesla)	T = 299 K	T = 130 K	T = 109 K	T = 105 K	
2	0.04	0.28	2.69	0.07	
1	0.16	0.05	2.64	0.11	

[0103] FIGS. 17a, b show the results of magnetoresistance measurements for the sample Mg14M3 for the current along the miscut direction at the temperatures of 109 and 105 K respectively. FIGS. 18a, b show the results of magnetoresistance measurements for the same sample Mg14M3 for the current direction perpendicular to the miscut direction at temperatures of 109, 105 K respectively that are substantially equivalent to the temperatures of FIGS. 17a, b. In both FIGS. 17 and 18 the magnetic field is directed along the direction of the current. One can see that the magnetoresistance difference along and perpendicular to the miscut direction is much greater for the sample that was annealed for 4 hours than for the one annealed for 2 hours. The longer anneal time leads to better-defined atomic terraces on the nanometer scale. These results demonstrate the fact that not only the miscut angle and miscut direction are important but also the morphology of terraces on the nanometer scale. The magnetoresistance results for sample Mg14M3 are summarized in Table 4 below.

TABLE 4

Mg14M3 (2° Miscut along <110> direction)-MR % dependence on direction of current									
Direction of the current	Field Value (Tesla)	T = 299 K		T = 130 K		T = 109 K		T = 105 K	
		+I	-I	+I	-I	+I	-I	+I	-I
Along miscut direction	2	1.33%		5.92%	5.84%	12.34%	11.90%	9.78%	8.36%
	1	0.85%		4%	3.9%	9.51%	8.55%	8%	6.88%
Perpendicular to Miscut	2	1.48%	1.52%	5.59%	5.56%	6.92%	6.81%	6.68%	6.84%
	1	0.7%	0.87%	3.68%	3.66%	4.86%	4.73%	5.19%	5.18%
Difference in MR % along and perpendicular to Miscut									
Field Value	T = 299 K	T = 130 K		T = 109 K		T = 105 K			
2T	0.15	0.33		5.42		3.1			
1T	0.15	0.32		4.65		2.81			

[0104] In Table 5 below, the difference in MR on the Mg14M2 and Mg14M3 are summarized which shows the significant effect of surface preparation conditions on magnetoresistive properties.

TABLE 5

Difference in MR % between Mg14M2 and MG14M3				
Field Value(Tesla) & Direction	T = 299 K	T = 130 K	T = 109 K	T = 105 K
2 (MC)	0.04	0.29	3.09	3.22
1 (MC)	0.03	0.39	2.22	2.89
2 (PMC)	0.15	0.24	0.36	0.19
1 (PMC)	0.04	0.12	0.21	0.19

[0105] FIGS. 19 and 20 show the results of another interesting observation: the magnetoresistance of a film grown on a miscut substrate is sensitive to the polarity of the current when the current is directed along the miscut direction. This phenomenon has been observed primarily on films grown on miscut substrates with well-defined atomic terraces, i.e. after a long anneal in oxygen plasma. FIGS. 19a, b show the magnetoresistance results on the Mg14M3 sample at temperatures of 109 and 105 K respectively whereby the current is along the miscut direction and reversed compared to the direction of FIGS. 17. Similarly, FIGS. 20a, b show the magnetoresistance results at the temperature of 109 and 105 K respectively for the same sample Mg14M3 whereby the current is perpendicular to the miscut direction and is reversed with respect to the current direction of FIG. 18. Like in FIGS. 11-18, the magnetic field direction in FIGS. 19 and 20 is also directed along the current direction. The results of these magnetoresistance measurements are summarized in Table 6 below and they demonstrate the conclusion: in films grown on miscut substrate the magnetoresistance can be asymmetric, i.e. by reversing the current polarity the value of magnetoresistance changes. This difference between the two opposite current polarities is sensitive to the current direction with respect to the miscut direction.

TABLE 6

Difference in MR % for positive and negative direction of current				
Field Value & direction	T = 299 K	T = 130 K	T = 109 K	T = 105 K
2 Tesla (MC)		0.8	0.44	1.42
1 Tesla (MC)		0.1	0.96	1.12
2 Tesla (PMC)	0.04	0.03	0.11	0.16
1 Tesla (PMC)	0.17	0.02	0.13	0.01

[0106] The results suggest that the dependency of the magnetoresistance of a film on the miscut of the substrate on which the film is grown is the general property that is not limited to just one substrate-film combination. We have confirmed that similar results are observed for other materials, e.g. thin epitaxial Fe films grown on MgO(100). The effect observed on this material was smaller than in Fe₃O₄/MgO(100) films but the conclusion is the same: the magnetoresistance of the film can be enhanced by growing it on a miscut substrate forming atomic terraces. The effect observed depends on the angle and direction of the miscut and also on the film thickness.

[0107] In order to explain why miscut substrates affects the magnetoresistance of the film grown on it and how the magnetoresistance can be maximized through the choice of the vicinal substrate, it is important to consider under what conditions one may achieve substantial magnetoresistance. Only magnetoresistance caused by a moderate magnetic field is considered in this document. For example, some materials may have a massive magnetoresistance in a large field of say 20 Tesla. In some materials such as MnSe, this magnetoresistance could be so large, that effectively the material undergoes through the metal-insulator transition caused by the magnetic field. This magnetoresistance was termed as colossal magnetoresistance. The present invention relates to magnetoresistance that can be caused by a relatively small field of say a few 10's of Oe and up to some 10 kOe (10 kOe=1 Tesla). These values are given here as a rough indication. When spin polarized electrons traverse between areas with nonparallel direction of spins, the spin scattering is different from the situation when electrons traverse between the areas with the parallel direction of spins. Therefore, if the external magnetic field allows switching between the two situations, substantial values of magnetoresistance will result. In terms of a thin film medium this teaching can be interpreted as follows. If one is capable of creating the situation in which the medium comprises numerous areas of substantially unparallel direction of magnetization and then with the imposition of the magnetic field all the areas become substantially magnetized along the same direction, this results in resistance change, i.e. magnetoresistance, provided the current flows in the medium between these areas or alternatively electrons come in contact with boundaries between different areas and suffer additional spin scattering.

[0108] The above explains, in a relatively theoretical way, how the vicinal treatment can be carried out to prepare a substrate to allow the correct miscut angle and subsequently to provide the necessary change in magnetoresistance.

[0109] Referring to FIG. 21, there is illustrated a magnetoresistive medium according to the invention, indicated generally by the reference numeral 1. This magnetoresistive medium 1 comprises a crystalline substrate 2 which has been vicinally treated to provide a miscut vicinal surface, indicated generally by the reference numeral 3, in the form of stepped terraces, namely, terraces 4(a) and 4(b) and steps 5, each of atomic or nanometer scale. The vicinal substrate 2 is chosen in such a way that the width of the atomic terraces 4, namely, the atomic terraces 4(a) and 4(b) is significantly non-uniform. The differences between the terraces 4(a) and 4(b) is only in the width, i.e. the atomic structure and the atomic termination of the terraces 4(a) and 4(b) are substantially identical. There are two sets of upper nanowires 10(a) and 10(b). The upper wires 10(a) are in contact with the terraces 4(a) and the upper nanowires 10(b) are in contact with the terraces 4(b). The upper nanowires 10(a) and 10(b) are formed from the one upper film 11. A protective layer 15 covers the upper film 11. The difference between the two sets of upper nanowires 10(a) and 10(b) is simply that they are overlying different terraces 4(a) and 4(b). The magnetic response of the areas(nanowires) 10(a) and 10(b) is different. This difference can be achieved in a number of ways. The first one utilizes step-induced magnetic anisotropy. The nature of this anisotropy is that each terraces step makes additional contribution to the magnetic anisotropy.

ropy energy The contribution of the terrace step-induced anisotropy energy is the same for the wide and narrow terraces.

[0110] Before describing the operation of the magnetoresistive medium **1**, it should be noted that the substrate **2** can be manufactured of an antiferromagnetic material and preferably one with a large resistance to electric current e.g. NiO, FeO, CoO etc. The upper nanowires **10(a)** and **10(b)** are magnetic. The magnetic nanowires can be either ferromagnetic or ferrimagnetic. They could consist, for example, of Fe, Ni, Co or permalloy. They could also be formed by a layer of magnetic oxide, e.g. Fe₃O₄ or a layer of another magnetic material such as Heusler alloy, Fe₃Si, rare earth doped manganites or many other materials.

[0111] The terrace steps **5** may be just one atomic layer high, but could also be more than one atomic layer high if the substrate has so-called bunched terrace steps. Bunched steps (or step bunching) are known to exist on some substrates when height separation between the terraces **4(a)** and **4(b)** is greater than one atomic layer. Bunched steps are formed when the energy associated with the terrace steps is too high and it is energetically favorable for the surface to reduce the number of the terraces while maintaining the overall miscut angle. Step pairing is a common type of step bunching forming terrace steps with an effective height equal to two regular separations between atomic planes. Mechanisms of step bunching are well understood. Reference is made to the state-of-the-art description of the topic published e.g. in K. Yagi, H. Minoda, M. Degawa, Step bunching, step wandering and faceting: self organization at Si surfaces, Surface Science Reports, 43 (2001) 45-126; or O. Pierre-Louis, Step bunching with general kinetics: stability analysis and macroscopic models, Surfaces Science 529 (2003) 114-134; B. S. Swartzentruber, Y-W. Mo, R. Kariotis, M. G. Lagally, M. B. Webb, Direct determination of Step and kink energies on vicinal Si(001) surface, Physical Review Letters, 65 (1990) 1913-1916. All are included herein by way of reference.

[0112] The protective layer **15** could be e.g. a layer of Al₂O₃, MgO, SrTiO₃ or a thin gold or platinum layer. It could also be a layer of a magnetic oxide with large resistance, e.g. NiO. The protective layer, as well as protecting the film **11** forming the upper nanowires **10(a)** and **10(b)** from the ambient conditions, may also act as a stabiliser, i.e. effectively dampening the surface diffusion so that the pattern of the areas forming the upper nanowires **10(a)** and **10(b)** of ferromagnetic material does not change over time.

[0113] To summarise, in accordance with the invention, the vicinal surface, after it has been vicinally treated, ensures that the upper nanowires form two subsets of upper nanowires which are positioned substantially differently with respect to the atomic steps of the substrate.

[0114] It should again be noted that the dimensions in **FIG. 21** are distorted for clarity of the drawing. The height of the terrace step **5** is typically much smaller than the width of the atomic terraces **4**. For example, as stated already, the height of the terrace step could be some 0.2 nm and width of the atomic terraces is some 3 to 500 nm although smaller or greater values are also possible. As explained above, the latter depends on the miscut angle. However, it is easier to analyse the drawings in which the width of the atomic terrace is shown disproportionately small.

[0115] It should also be kept in mind that the nanowires **10(a)** and **10(b)** do not have to be positioned in strict alternation, i.e. each nanowires **10(a)** does not have to be flanked by two nanowires **10(b)** and vice versa. However, preferably a significant extent of intermixing between the two groups of nanowires is desirable so as to provide the situation when a sizeable fraction of the nanowires **10(a)** has nanowires **10(b)** as their neighbours and vice versa.

[0116] The operation of the magnetoresistive medium **1** can be understood from **FIGS. 21 and 22**. When no external magnetic field is applied, the film is characterized by a particular arrangement of magnetizations different for the magnetic upper nanowires **10(a)** and **10(b)**. For simplicity these are all shown magnetized parallel to each other in **FIG. 21**. In reality, a more complex pattern of magnetizations may be established that could be considered as a domain pattern in the upper film **11**. The magnetization in the magnetic nanowires **10(b)** may not be parallel to the one in the nanowires **10(a)**. Moreover, the directions of magnetization in the nanowires **10(a)** or **10(b)** at different locations on the surface may differ. The details of the alignment of magnetizations in the upper nanowires **10(a)** and **10(b)** depend on the specific materials forming the layer or upper film **11**, thickness of the film **11** and also on the strain maintained by the film **11**, that in turn depends on the choice of the substrate material and film growth conditions. In this particular embodiment, however, as the effective anisotropy field is inversely proportional to the magnetic moment and the moment is in turn proportional to the width of the terrace, magnetizations in the nanowires **10(a)** and **10(b)** of the upper film **11** will respond differently to the magnetic field. Therefore, once again one forms the situation whereby the relative directions of magnetisation in the upper nanowires **10(a)** and **10(b)** can change with the change in the value of the external magnetic field. This results in the resistance change and therefore, in magnetoresistance.

[0117] Therefore, as an electric current passes through the magnetoresistive medium in the direction along the substrate miscut, in a zero external magnetic field (**FIG. 21**) electrons travel between the areas with parallel directions of magnetization and in **FIG. 22** they travel between areas with antiparallel directions of magnetization. Therefore, the amount of spin scattering changes and this results in magnetoresistance. Generally for materials with greater spin polarization at the Fermi level, the spin dependent electron scattering will be greater between the areas with non collinear spin direction.

[0118] If an electric current passes perpendicular to the miscut direction, additional spin scattering may still be created. When current passes perpendicular to the miscut direction, i.e. along the upper nanowires **10(a)** and **10(b)** there is scattering of the charge carriers along the boundaries between each two neighbouring nanowires. The scattering depends on the relative orientation of magnetisations in the neighbouring upper nanowires. With the application of a magnetic field the relative directions of magnetisation in the upper nanowires change with respect to each other thus changing the scattering of electrons and leading to magnetoresistance.

[0119] As stated, **FIG. 21** shows the case when in the absence of an external magnetic field the magnetization directions in the areas forming the upper nanowires **10(a)**

and **10(b)** are parallel and once the field is applied they switch to an antiparallel configuration. One can also consider the opposite case: antiparallel magnetizations in the absence of the field turn parallel or almost parallel once the field is applied. Needless to say, that any intermediate case can also be considered, e.g. the magnetizations of the areas in the upper film **11**, i.e. the nanowires **10(a)** and **10(b)** could be aligned at an angle with respect to each other of say 90° or another angle. The result depends entirely on the specific choice of the materials for the nanowires **10(a)**, **10(b)**, thickness of the layers or films forming these nanowires **10(a)**, and **10(b)**, as well as the width of the nanowires **10(a)** and **10(b)**, i.e. on the miscut angle and thus terrace width.

[0120] It should also be noted that the directions of magnetization in the areas forming the upper nanowires **10(a)** and **10(b)** do not have to rotate by the full 180° degrees once the external magnetic field is applied. They could rotate by a smaller angle still resulting in change of spin scattering and therefore in resistance change. Moreover, for certain applications it is desirable to have a gradual rotation of magnetization in response to change in external magnetic field as opposed to a sudden flip over of the magnetization. This is particularly important in sensors of magnetic field. To achieve more gradual deviation of magnetization in response to the magnetic field, an additional ferromagnetic biasing layer could be deposited e.g. on top of the upper film **11**. This layer could be composed of a hard ferromagnetic material and could function by creating a stray field sensed by upper nanowires **10(a)** and **10(b)** and acting as an offset field.

[0121] Alternatively, the difference in the magnetic response of the upper nanowires **10(a)** and **10(b)** could be based on the fact that the upper nanowires **10(a)** and **10(b)** contain different densities of structural defects. In this embodiment the materials forming the upper nanowires **10(a)** and **10(b)** and of the substrate are selected in such a way that there is lattice mismatch between them. The lattice mismatch results in the formation of misfit dislocations that release strain energy in the film. There is the critical width of the terrace, below which the formation of misfit dislocations is considerably suppressed. This issue has been studied for the Fe/Mo(110) system where the lattice mismatch between the film and the substrate is some 9% [S. Murphy, D. M. McMathuna, G. Mariotto, I. V. Shvets, *Physical Review B*, 66(19) 195417 (2002), Morphology and strain induced defect structure of ultrathin epitaxial Fe films on Mo(110)]. The study demonstrated that for narrow terraces of Fe/Mo(110), the formation of misfit dislocations is suppressed. Alternatively, a medium utilizing another type of film growth defect called, antiphase boundaries, could be employed. The density of antiphase boundaries at more narrow terraces should be lower as this should be proportional to the density of the film nucleation centers during the film growth, which should be smaller for the more narrow terraces.

[0122] As stated, it should be noted that the wide and narrow atomic terraces **4(a)** and **4(b)** do not have to be in strict alternation with each other, i.e. each wide terrace does not have to neighbour two narrow terraces and vice versa. Indeed, it is sufficient to get a mix of wide and narrow atomic terraces on the substrate **2**. For example the surface where two wide terraces are followed by one or two narrow ones is a good example of such a mix.

[0123] **FIG. 23** illustrates another construction of magnetoresistive medium, again identified, for simplicity, by the reference numeral **1**, with a different vicinal treatment. In this embodiment, the crystalline structure of the substrate **2** is such that it can be represented by an array of nonequivalent layers placed on top of each other, that is to say non-equivalent atomic planes. There are many examples of such crystal structures. For example, the structure of MgO can be represented by a stack of alternating anion-rich and cation-rich layers with the Miller index (111). In this embodiment the substrate **2** is prepared in such a way that the neighbouring atomic terraces **4(a)** and **4(b)** have their upper exposed surfaces formed by, these two nonequivalent layers of different atomic terminations, identified by the reference numerals **2(a)** and **2(b)**. It should be mentioned that in order to achieve such layers it may not be sufficient to cut the substrate at a desired miscut angle. The reason is that the surface may undergo significant reconstruction driven by a reduction in the surface energy. This kind of reconstruction is common in the case of polar surfaces. Such polar surfaces do fall in the category of surfaces of materials whose crystal structure can be represented as a stack of nonequivalent layers parallel to the surface. Alternatively, the surface may present atomic terraces with just one type of termination and "hide" the other one. This should be expected when the surface energy of one termination is considerably greater than that of the second one. For example, in the case of spinel $\text{Fe}_3\text{O}_4(100)$, one may expect to observe layers(terminations) with cations in octahedral and tetrahedral interstitial positions. In practice, unless special care is taken of the substrate preparation conditions, all the atomic terraces are generally equivalent and they represent the termination with cations in octahedral positions and terraces with cations in tetrahedral positions are not present [G. Mariotto, S. Murphy, I. V. Shvets, Charge ordering on the surface of Fe_3O_4 (001) *Physical Review B*, 66 245426 (2002)]. At the same time under special preparation conditions, both terraces with cations in octahedral and tetrahedral positions can be observed simultaneously. Again we refer to this publication which deals with the issues of atomic terminations, as general state-of-the-art knowledge and is included in its totality by way of reference. There are also examples of materials where the structure can be represented as stack of more than two kinds of atomic planes. For example, the structure of spinel can be represented as a stack of six different atomic planes with (111) Miller indexes. Again in practice unless, preparation conditions are optimised to reveal several terminations(atomic planes) at once, only one termination is usually seen.

[0124] The same comment applies as in relation to **FIGS. 21 and 22**. The two non-equivalent layers (terminations) do not have to be in strict alternation with each other. It can be sufficient to have a mix of terraces representing the two non-equivalent layers(terminations). For example, a mix with two terraces of type **2(a)** followed by one terrace of type **2(b)** etc. is a good example of such a mix.

[0125] Referring again to **FIG. 23**, the upper film **11** forming the upper nanowires **10(a)** and **10(b)** is deposited on top of the substrate **2** so prepared that different atomic terminations appear at neighbouring atomic terraces preferably in alternation. We have shown the crystal structure schematically as layers of large and small spheres representing atoms of two different kinds marked with numbers **2(a)** and **2(b)**. This would be a rather fair representation for the

structure of MgO with the (111) surface prepared to achieve the result as described above. This is a simple structural arrangement and more complex situations can exist: atoms of more than two kinds could be involved in the structure or atoms of more than one kind can be involved in each atomic plane. The magnetic properties of the upper nanowires **10(a)** and **10(b)** deposited respectively on the atomic terraces **4(a)** and **4(b)** are different as they are grown on different templates. Therefore, their response to the magnetic field is different.

[0126] If there are more than two types of atomic terminations (say, **2(a)**, **2(b)** and **2(c)**) then we identify more than two types of nanowires (in this case **10(a)**, **10(b)** and **10(c)**). We do not show this on the drawings as it can be readily understood.

[0127] To make the difference between the terraces more profound and amplify the difference between magnetic responses of the nanowires **10(a)** and **10(b)** the vicinal substrate could be subjected to a plasma or reactive gas or another treatment prior to the deposition of the material for the upper nanowires **10(a)** and **10(b)**, optimised in such a way that the reaction on atomic terraces of different kinds takes place differently, e.g. reaction takes places on the terraces **4(a)** but not on the **4(b)** terraces. This reaction could lead to a selective deposition of an adsorbate material or inducement of atomic disorder or inducement of surface reconstructions on either of the terraces **4(a)** and **4(b)**. In this situation, the nanowires **10(a)** and **10(b)** are grown on significantly different templates and the conditions can be selected in such a way that the magnetic response of the nanowires **10(a)** and **10(b)** is different. The difference in magnetic response could be based on any of the factors discussed in detail below. For example, the nanowires **10(a)** could be epitaxial and the nanowires **10(b)** not. Alternatively, both nanowires **10(a)** and **10(b)** could be epitaxial but could be of different crystallographic orientations. This is schematically shown in **FIG. 23** by different thickness of the upper nanowires **10(a)** and **10(b)**. Alternatively, the upper nanowires **10(a)** and **10(b)** could contain a different density of misfit dislocations and antiphase boundaries. Alternatively, if the substrate is magnetic, e.g. NiO or FeO, then the exchange coupling of the nanowires **10(a)** and **10(b)** to the substrate could differ markedly. The latter mechanism becomes easier to understand if one considers the small and large circles of the substrate **2** as magnetic and nonmagnetic ions respectively.

[0128] Another mechanism that may result in a different response to the magnetic field between the areas forming the upper nanowires **10(a)** and **10(b)** is step-induced anisotropy. Step-induced anisotropy results from breaking the rotational symmetry at the terraces **4**. Step-induced anisotropy is usually uniaxial for a surface with well-aligned steps **5**. The anisotropy energy depends on the electronic structure of the film that in turn depends on the type of substrate, strain, crystallographic orientation of the film surface and crystallographic orientation of the step edges. Therefore, the step induced-anisotropy will differ for the areas forming the upper nanowires **10(a)** and **10(b)**. The influence of step-induced anisotropy will diminish as the film thickness increases. Therefore, depending on the type of materials for the substrate **2**, and upper nanowires **10(a)** and **10(b)** and depending primarily on the thickness of the upper nanowires **10(a)** and **10(b)**, the step-induced anisotropy may or may not

play a significant role in determining the difference between the magnetic responses of the nanowires **10(a)** and **10(b)**. However, this does not fundamentally change the substance of the operation of the embodiment in **FIG. 21** as the prime goal: achieving the difference in magnetic response between the upper nanowires **10(a)** and **10(b)** is reached.

[0129] **FIG. 24** illustrates an alternative embodiment in which the substrate **2** does not entirely consist of antiferromagnetic material but is rather a nonmagnetic substrate **2(b)** with a layer of antiferromagnetic material **2(a)** deposited on it to form the vicinal surface **3**. Thus, the substrate (**2**) comprises a vicinally treated upper substrate **2(a)** on top of a vicinally treated lower substrate **2(b)**. This can broadly be termed another form of vicinal treatment. For ease of reference, the various parts of the magnetoresistive medium are, where possible, identified by the same reference numerals, even where they are of clearly different construction such as the substrate **2** of this **FIG. 24**. This could be for example a substrate of MgO, MgAl₂O₄, SrTiO₃, sapphire, Si, GaAs, Ge or another suitable material with a film of e.g. insulating antiferromagnetic material NiO deposited on it. As the two materials have similar crystal structures and comparable lattice constants, such structures can be grown by molecular beam epitaxy. The antiferromagnetic film could also be made of a conducting material, e.g. MnNi, MnPt, MnAu, MnIr, as opposed to an insulating one. This will partially shunt the current flowing through the film **11** forming the upper nanowires **10(a)** and **10(b)** but this could still be acceptable provided the resistance of the antiferromagnetic layer is not much smaller than the resistance of the layer or upper film **11**. Again to strengthen the exchange bias, the antiferromagnetic layer **2(a)** may need to be annealed in an external magnetic field. The anneal leads to alignment of antiferromagnetic vectors in the layer **2(a)** as will be appreciated by those skilled in the art of exchange bias.

[0130] It should be pointed that in some cases further layers may need to be added in the magnetoresistive medium **1**. For example a buffer layer may need to be added between the substrate **2(a)** and substrate **2(b)**. The purpose of buffer layer is to prevent diffusion of atoms of material of substrate **2(a)** into that of the substrate **2(b)** and vice versa. This will be readily appreciated by those skilled in the art of heteroepitaxy. For example, very thin buffer layers of S, Ge, Cr, Ag, Au are often used with the substrates of GaAs and Ge. Buffer layers of Cu and Cr are commonly used with Si substrates. Similarly a thin seed layer may need to be added e.g. to improve the growth or adhesion of the key functional layers. These additional layers are not included in the drawings as they are secondary and will complicate understanding the invention.

[0131] The material forming the layer **2(a)** could also be a ferromagnetic material preferably having high coercivity. The principle of operation of such a magnetoresistive medium is the same as the one of the medium shown in **FIGS. 21 and 22**. The exchange coupling of the ferromagnetic layer **2(a)** with the upper nanowires **10(a)** and **10(b)** is different. If the material of the layer **2(a)** has large coercivity, its direction of magnetization will not be affected by the field that is strong enough to change the directions of magnetization in the nanowires **10(a)** and/or **10(b)** as described above. One difference between the embodiments utilizing antiferromagnetic material of layer **2(a)** and the one with

ferromagnetic material is that the stray magnetic field from the ferromagnetic layer 2(a) will be superimposed on the external field sensed by the film 11 forming the upper nanowires 10(a) and 10(b) which will affect the values of the external magnetic field required to achieve magnetoresistive effect.

[0132] Referring again to FIG. 21, different materials may be used than those previously described. This leads to different embodiments of the invention. For example, the upper nanowires 10(a) and 10(b) may be strained to a different extent. This can be achieved if the adhesion of the magnetic nanowires 10(b) to the terrace 4(b) is different from the one of the magnetic nanowires 10(a) to the terrace 4(a), and at the same time the lattice constant of the substrate 2 is different from one of the upper nanowires 10(a) and 10(b). For example, if the material of the magnetic nanowires 10(a) and 10(b) has a lattice constant greater than that of the substrate 2, the upper nanowires 10(b) may maintain the one-to-one registry with the substrate and therefore remain strained. At the same time the nanowires 10(a) may develop misfit dislocations and relax their strain as their adhesion to the terrace 4(a) is reduced. Needless to say, the opposite case can also be considered when the upper nanowires 10(a) are strained and the upper nanowires 10(b) are relaxed. Magnetic anisotropy and coercivity of a material generally depends on the strain status. As a result of the different strain status, magnetic response of the upper nanowires 10(a) and 10(b) will differ.

[0133] Again referring to FIG. 21, an entirely different embodiment of the invention may be provided. In this embodiment the substrate 2 does not have to be magnetic. It could be MgO, MgAl_2O_4 , SrTiO_3 , sapphire, Si, GaAs, Ge or another suitable material. As in the previous embodiments, the upper nanowires 10(a) and 10(b) are composed of the same material, e.g. both are nanowires of iron or both are nanowires of the same iron oxide. The choice of the substrate 2 is such that the upper nanowires 10(a) and 10(b) grow with different amounts of strain in them. For example, let us consider the material for the nanowires 10(a) and 10(b) that has in-plane lattice constants c_1 , c_2 comparable to the ones of the substrate 2 a_1 , a_2 ; ($c_1 \approx a_1$; $c_2 \approx a_2$). Because of the close lattice match between the nanowires 10(b) and the terrace 4(b), the nanowires 10(b) grow epitaxially on the substrate and contain little strain. The nanowires 10(a) may grow on the terrace 4(a) so that there is massive strain in them caused by the large lattice mismatch. The fundamentals of the mechanism that lead to the destruction of such registry are based on the fact that reduction of strain energy is greater than the increase in energy of the interface. These phenomena are described e.g. in (S. Murphy, D. Mac Mathuna, G. Mariotto, I. V. Shvets, Morphology and strain-induced defect structure of ultrathin epitaxial Fe films on Mo(110), Physical Review B 66 195417 (2002)) although that publication does not deal with the subject matter of the present specification. It is included here as an explanation of the phenomena. In this case the nanowires 10(a) and 10(b) are forced to grow on templates having different lattice periodicities. Therefore, this choice of the materials for the substrate 2 and upper nanowires 10(a) and 10(b) leads to the result that nanowires 10(b) are epitaxial and the upper nanowires 10(a) are not. Therefore, the response to an external magnetic field of the upper nanowires 10(a) and 10(b) will differ (coercivity and anisotropy). As a result, when a magnetic field is applied to the medium, directions

of magnetization in the upper nanowires 10(a) and 10(b) with respect to each other change leading to magnetoresistance when current passes through the film 11 of the nanowires 10(a) and 10(b) as described above.

[0134] One can also construct a magnetoresistive medium where due to the lattice mismatch between the materials forming the substrate 2 and the upper nanowires 10(a) and 10(b), the upper nanowires 10(a) and 10(b) are both epitaxial but are characterized by different amounts of strain as they grow on, what are in effect, different templates. This will lead to the same result: their response to the external magnetic field will be different. Consequently, the relative orientations of magnetisations in the upper nanowires 10(a) and 10(b) with respect to each other can be altered by the external magnetic field thus leading to magnetoresistance when current passes through the film of the nanowires 10(a) and 10(b) as described above.

[0135] Alternatively, one can also provide a magnetoresistive medium in which the upper nanowires 10(a) are epitaxial and the upper nanowires 10(b) are not.

[0136] Alternatively there can be provided a magnetoresistive medium where the upper nanowires 10(a) and 10(b) are both epitaxial but have different crystallographic orientations: e.g. the surface of upper nanowires 10(b) has (100) orientation and one of the upper nanowires 10(a) has (110) orientation. In this case the upper nanowires 10(a) and 10(b) will also respond differently to external magnetic field as they have different surface anisotropy due to different surface terminations as well as different effective fields of the magnetocrystalline anisotropy.

[0137] The magnetoresistive medium can be readily easily provided and it's construction will be appreciated by those skilled in the art. The reader is presumed to know, in general terms, how full and fractional layers can be formed and be familiar with the terms "flux" and the use of evaporators. Once the magnetoresistive medium has been formed, then electrodes are deposited on top to apply the current/voltage to the medium and to measure resistivity of the magnetoresistive medium or voltage across it. The application of electrodes is not described in detail in this document, as this aspect of magnetoresistive medium is standard and well described in literature, neither are the electrodes or the rest of the magnetoresistive medium illustrated. The optional protective layer 15 can also be deposited and this, also, is not described in detail in the specification, as such layers are common for thin film devices used in many applications.

[0138] Referring again to FIG. 21, in another embodiment, the vicinal substrate 2 is formed of a nonmagnetic material. This could be e.g. single crystals of MgO , MgAl_2O_4 or SrTiO_3 with (100) or (110) surface terminations.

[0139] In yet another embodiment related to FIG. 21, the nanowires 10(a) and 10(b) have the same crystal structure. However, the crystallographic orientation of the nanowires 10(b) positioned above the substrate terraces 4(b) differs from that of nanowires 10(a) positioned above the terraces 4(a). The difference in magnetic response between the nanowires 10(a) and 10(b) comes from the magnetocrystalline anisotropy and anisotropy of the coercivity field as external magnetic field is applied differently with respect to the crystallographic axes of the nanowires 10(a) and 10(b).

[0140] Referring again to FIG. 21, in an alternative embodiment, instead of providing the protective layer, there

can be substituted a layer of surfactant. Surfactant is a layer that facilitates the diffusion of adatoms on the surface. To utilize the benefit of the surfactant, in a typical embodiment, the surfactant is deposited on a vicinal substrate first. Then the layer or film of material forming the upper film **11** is deposited to form the upper nanowires. Typically the surfactant layer is highly mobile and it “floats” on top of materials, i.e. as the material forming the upper nanowires **10(a)** and **10(b)** is deposited on the substrate **2**, its atoms move underneath the surfactant layer to come in direct contact with the substrate. That is why with reference to **FIG. 21**, the topmost layer, described as the protective layer **15** is now the layer of surfactant although it has been deposited on the substrate **2** first. Again, obviously if a surfactant is used, a protective layer could be added. Again, for brevity and simplicity, another figure is not provided. Any attempt to provide a multiplicity of figures, all superficially the same as **FIG. 21**, would cause endless confusion. Surfactants for many transition metal atoms are well known from literature. For example, CO molecule and atomic N and O as well as Au are surfactants for Fe. Pb is a known surfactant for Co.

[0141] The magnetic response of the areas(nanowires) **10(a)** and **10(b)** is different. This difference can be achieved in a number of ways. The first one utilizes step-induced magnetic anisotropy. The nature of this anisotropy is that each terraces step makes additional contribution to the magnetic anisotropy energy. The contribution of the terrace step-induced anisotropy energy is the same for the wide and narrow terraces. However, as the effective anisotropy field is inversely proportional to the magnetic moment and the moment is in turn proportional to the width of the terrace, magnetizations in the nanowires **10(a)** and **10(b)** of the upper film **11** will respond differently to the magnetic field. Therefore, once again one forms the situation whereby the relative directions of magnetisation in the upper nanowires **10(a)** and **10(b)** can change with the change in the value of the external magnetic field. This results in the resistance change and therefore, in magnetoresistance.

[0142] Referring to **FIG. 25**, there is illustrated in cross section a composite magnetoresistive medium, indicated generally by the reference numeral **100**, comprising a medium **1(a)** having a miscut angle α_1 and having deposited thereon a further medium **1(b)**, in turn, having a miscut angle α_2 . The medium **1(a)** comprises a substrate **2(a)** having a vicinal surface on which a film **11(a)** has been deposited. The magnetoresistive medium **1(a)** is similar to any of the magnetoresistive media previously described. On top of the magnetoresistive medium **1(a)** is deposited a further magnetoresistive medium **1(b)**. The substrate **2(a)** comprises what is effectively a rectangular portion **201(a)** on top of which is formed the portion of the substrate **2(a)** that provides the vicinally treated surface. This portion is identified by the reference numeral **202(a)**. The substrate **2(b)** of the magnetoresistive medium **1(b)** comprises two wedge-shaped portions **201(b)** and **202(b)**, the latter again forming a vicinal surface for a film **11(b)**.

[0143] The substrate **2(a)** can be formed as previously described or may be formed by growing the wedge **202(a)** on the flat essentially rectangular portion **201(a)** by carrying out growth of a film with a shadow mask in a normal incident condition and withdrawing the mask gradually over the substrate. Alternatively, this may be provided by moving

the substrate away from the mask to create the wedge shaped film **202(a)** forming part of the substrate **2(a)**. Then the remainder, for example, with the deposition of the film **11(a)**, can be carried out, as previously described. Then the first part **201(b)** of the substrate **2(b)** of the next magnetoresistive medium **1(b)** may be formed in the same way and then subsequently the remainder of the substrate **2(b)**, namely the portion **202(b)** may again be formed and finally the next film **11(b)** may be deposited. Obviously, the two vicinal surfaces so formed, that is to say, on the substrate **2(a)** and the substrate **2(b)**, may have different miscut angles α_1 , and α_2 , as shown.

[0144] The speed of mask withdrawal and growth rate provides an efficient method of controlling the variation in thickness of the film or the vicinal angle. The method is standard and well known in the art [V. I. Nikitenko, V. S. Gornakov, A. J. Shapiro, R. D. Shull, K. Liu, S. M. Zhou and C. L. Chien, Asymmetry in Elementary Events of Magnetisation Reversal in Ferromagnetic/Antiferromagnetic Bilayer, Phys. Rev. Lett. 84(4) 765(2000)].

[0145] It will be appreciated that that portion **201(b)** of the second substrate **2(b)** provides a protection for the first magnetoresistive medium **1(a)**. As illustrated in **FIG. 25**, the miscut angles α_1 and α_2 , whether different or the same, are oriented in the same way.

[0146] Referring to **FIG. 26**, there is illustrated an alternative construction of composite magnetoresistive medium, again identified by the same reference numerals as those used in **FIG. 25**. However, in this case, the media **1(a)** and **1(b)** are orthogonal to each other in the sense that the miscut angles are offset with respect to each other, in this embodiment, by approximately 90°.

[0147] It will be appreciated that various forms of composite magnetoresistive medium may be used. A large number of magnetoresistive media according to the present invention may be stacked one on top of the other. It will also be appreciated that the other combination of miscut angle ratios and miscut directions may also be possible.

[0148] Such composite magnetoresistive media, formed by the stacking of magnetoresistive media, one on top of each other, may be advantageous for using the magnetoresistive media in memory devices where increasingly the density of the memory cells is a prime requirement.

[0149] It will be appreciated that for certain applications, it may be advantageous to have the two miscut directions of substrates, which are adjacent to each other, offset through 90°. As the directions of the upper nanowires in the magnetoresistive media **1(a)** and **1(b)** are not collinear, the cross-talk between them(influence of the sensing current in one media on the other one) is reduced. Also, any desired pattern of sensitivity to the magnetic field can be developed as each of the media **1(a)** and **1(b)** is anisotropically sensitive to the magnetic field.

[0150] In accordance with the present invention, while it has been described that the substrate can be cut along the required miscut direction, one could equally well deposit a wedge-shaped film, as described with reference to **FIG. 25**, on a flat non-miscut substrate, as described. In the same way, one can alter the miscut angle of the miscut direction.

[0151] It is envisaged, for example, that when a substrate is manufactured in accordance with **FIG. 25**, namely, when

one portion of the substrate **201** is rectangular, as it were or block shaped or parallelepiped, the materials for the two portions forming the substrate may be the same or different. Further, it is not necessarily essential that, for example, the magnetoresistive medium **1(b)** should cover the whole of the magnetoresistive medium **1(a)** and vice versa.

[0152] Clearly, stacks of more than two magnetoresistive media can be formed in the same way. Another situation which can be considered here is the formation of a multi-layered superlattice structure based on magnetoresistive medium. This can be realized by producing in sequence a number of e.g. 10-100 repeat units of the magnetoresistive medium **1**, as shown in **FIG. 25**, for the case of two repeat units.

[0153] It will be appreciated that the magnetoresistive medium according to the present invention can be used for many devices which require the use of such magnetoresistive material. The invention is not limited to the use of this material in any particular device.

[0154] In the specification the terms “comprise, comprises, comprised and comprising” or any variation thereof and the terms “include, includes, included and including” or any variation thereof are considered to be totally interchangeable and they should all be afforded the widest possible interpretation and vice versa.

[0155] The invention is not limited to the embodiment hereinbefore described, but may be varied in both construction and detail within the scope of the appended claims.

1. A magnetoresistive medium comprising:

a crystalline substrate;

an upper film on the substrate; and

stepped terraces of atomic and nanometer scale on the substrate formed by vicinally treating the substrate prior to application of the thin upper film, at least some of the crystalline surface terminations formed on the terraces being non-equivalent to the crystalline surface terminations of other terraces such that at least two separate sets of upper nanowires, having a different response to an external magnetic field, are formed in the upper film.

2. A magnetoresistive medium as recited in claim 1, in which the substrate is a composite substrate comprising one of a vicinally treated antiferromagnetic and a vicinally treated ferromagnetic upper substrate and a vicinally treated non-magnetic lower substrate.

3. A magnetoresistive medium as recited in claim 1, in which the substrate is a composite substrate comprising a vicinally treated non-magnetic upper substrate and one of a vicinally treated anti-ferromagnetic and a vicinally treated ferromagnetic lower substrate.

4. A magnetoresistive medium as recited in claim 1, in which the substrate is one of an antiferromagnetic material, ferromagnetic material and a semiconductor material, each material with a relatively high resistance to electrical current whereby the resistance of the substrate is sufficiently greater than that of the film to prevent, in use, the substrate shunting the current in the film.

5. A magnetoresistive medium as recited in claim 1, in which the substrate is one of:

NiO,

FeO,

CoO

Si,

Ge,

GaAs,

and

a ferromagnetic material of high coercivity.

6. A magnetoresistive medium as recited in claim 1, in which the substrate is pre-annealed in an externally applied magnetic field.

7. A magnetoresistive medium as recited in claim 1, in which the substrate is a composite substrate comprising a base of non-magnetic material carrying a layer of one of anti-ferromagnetic and ferromagnetic material deposited thereon on which is formed the vicinal surface.

8. A magnetoresistive medium as recited in claim 1, in which the substrate comprises:

a base layer of non-magnetic material;

a buffer layer on the base layer; and

an upper layer of one of anti-ferromagnetic and ferromagnetic material deposited on the buffer layer in which upper layer is formed to create the vicinal surface.

9. A magnetoresistive medium as recited in claim 1, in which the substrate is formed from one of:

MgO,

Mg Al₂O₄,

Sr Ti O₃,

Al₂O₃,

Si,

GaAs,

InP,

Ge,

ZnO, and

GaN.

10. A magnetoresistive medium as recited in claim 1, in which a final stabilising and protective layer is deposited thereon.

11. A magnetoresistive medium as recited in claim 1, in which a final stabilising and protective layer of one of:

Al₂O₃,

MgO,

SrTiO₃,

ZnO,

SiO₂,

TiO,

ZrO, and

HfO

is deposited thereon.

12. A magnetoresistive medium as recited in claim 1, in which the substrate forms a surface with bunched atomic terraces.

13. A magnetoresistive medium as recited in claim 1, in which there are provided additional magnetic biasing layers in the medium in order to achieve smoother response of the resistance change on the value of the external magnetic field changing.

14. A magnetoresistive medium comprising a stack of a plurality of the media as recited in claim 1, one medium on top of another medium.

15. A magnetoresistive medium as recited in claim 1, comprising a stack of a plurality of media, one medium on top of the other and in which the miscut angles of the vicinal substrates are different.

16. A magnetoresistive medium as recited in claim 1, comprising a stack of a plurality of media, one medium on top of the other and in which the substrates are so arranged as to have miscut angles offset with respect to each other.

17. A magnetoresistive medium as recited in claim 1, comprising a stack of a plurality of media, one medium on top of the other and in which at least one pair of adjacent media have miscut angles offset by substantially 90°.

18. A magnetoresistive medium as recited in claim 1, in which at least some of the terraces formed are of a different width to that of other terraces so as to cause one or more of:

lattice mismatch;
step induced anisotropy;
antiphase boundaries; and
misfit dislocations;

in the upper nanowires positioned on one set of terraces and substantially suppress it on another set of terraces.

19. A magnetoresistive medium as recited in claim 18, in which the substrate is a composite substrate comprising one of a vicinally treated antiferromagnetic and a vicinally treated ferromagnetic upper substrate and a vicinally treated non-magnetic lower substrate.

20. A magnetoresistive medium as recited in claim 18, in which the substrate is a composite substrate comprising a vicinally treated non-magnetic upper substrate and one of a vicinally treated antiferromagnetic and a vicinally treated ferromagnetic lower substrate.

21-115. (canceled)

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