



US007579042B2

(12) **United States Patent**
Chang et al.

(10) **Patent No.:** **US 7,579,042 B2**
(45) **Date of Patent:** **Aug. 25, 2009**

(54) **METHODS FOR THE FABRICATION OF THERMALLY STABLE MAGNETIC TUNNEL JUNCTIONS**

(75) Inventors: **Y. Austin Chang**, Middleton, WI (US);
Jianhua J. Yang, Madison, WI (US);
Peter F. Ladwig, Hutchinson, MN (US)

(73) Assignee: **Wisconsin Alumni Research Foundation**, Madison, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 289 days.

(21) Appl. No.: **10/902,281**

(22) Filed: **Jul. 29, 2004**

(65) **Prior Publication Data**

US 2006/0021213 A1 Feb. 2, 2006

(51) **Int. Cl.**
C23C 16/00 (2006.01)
B05D 3/00 (2006.01)

(52) **U.S. Cl.** **427/248.1; 427/250; 427/295; 427/127**

(58) **Field of Classification Search** None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

- 5,640,343 A 6/1997 Gallagher et al.
- 5,729,410 A 3/1998 Fontana, Jr. et al.
- 6,261,646 B1 7/2001 Chen et al.
- 6,296,741 B1 10/2001 Pinarbasi

- 6,333,103 B1 * 12/2001 Ishii et al. 428/325
- 6,359,289 B1 3/2002 Parkin
- 6,452,204 B1 9/2002 Ishiwata et al.
- 6,655,006 B2 12/2003 Pinarbasi
- 6,693,774 B2 2/2004 Watanabe et al.
- 2003/0198754 A1 * 10/2003 Xi et al. 427/576
- 2004/0145850 A1 * 7/2004 Fukumoto et al. 361/143

OTHER PUBLICATIONS

- Waits, Robert K. "Monitoring residual and process gases in PVD processes: The importance of sensitivity" Micromagazine.com Jun. 1997 <http://www.micromagazine.com/archive/97/06/waits.html>.*
- Moller, W. et al. "Surface processes and diffusion mechanisms of ion nitriding of stainless steel and aluminum" Surface Coatings and Technology 136 (2001) 73-79.*
- Moodera, et al., "Optimum tunnel barrier in ferromagnetic-insulator-ferromagnetic tunneling structures." *Appl. Phys. Lett.* 70 (22), pp. 3050-3052, 1997. Published by American Institute of Physics.

(Continued)

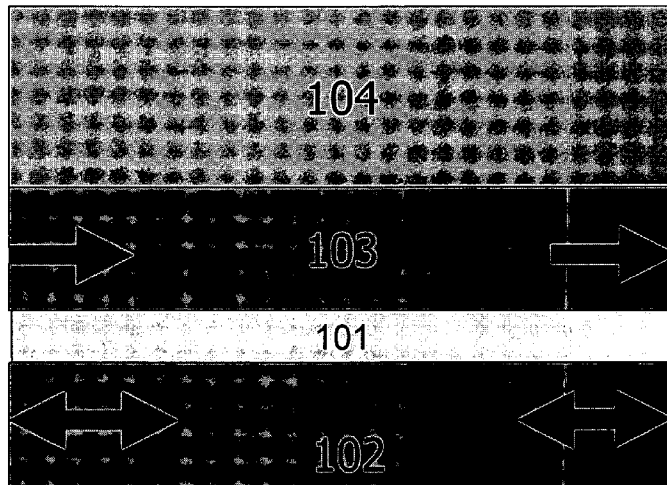
Primary Examiner—Frederick Parker
Assistant Examiner—Kelly M Stouffer
(74) *Attorney, Agent, or Firm*—Foley & Lardner LLP

(57) **ABSTRACT**

Magnetic tunnel junctions and method for making the magnetic tunnel junctions are provided. The magnetic tunnel junctions are characterized by a tunnel barrier oxide layer sandwiched between two ferromagnetic layers. The methods used to fabricate the magnetic tunnel junctions are capable of completely and selectively oxidizing a tunnel junction precursor material using an oxidizing gas containing a mixture of gases to provide a tunnel junction oxide without oxidizing the adjacent ferromagnetic materials. In some embodiments the gas mixture is a mixture of CO and CO₂ or a mixture of H₂ and H₂O.

28 Claims, 3 Drawing Sheets

100 →



OTHER PUBLICATIONS

- Zhu, et al., "Determination of the thickness of Al oxide films used as barriers in magnetic tunneling junctions." *Applied Physics Letters*, 78 (20), pp. 3103-3105, 2001. Published by the American Institute of Physics.
- Kottler, et al., "An in situ x-ray photoelectron spectroscopy study of AlO_x spin tunnel barrier formation." *Journal of Applied Physics*, 89 (6), pp. 3301-3306, 2001. Published by American Institute of Physics.
- Sugahara, et al. Tunneling magnetoresistance in fully epitaxial MnAs/AlAs/MnAs ferromagnetic tunnel junctions grown on vicinal GaAs(111)B substrates. *Applied Physics Letters*, 80 (11) pp. 1969-1971, 2002. Published by American Institute of Physics.
- Ladwig, et al. Fabrication of Thermodynamically Stable Oxide Layers for Use in Tunneling Magnetoresistive (TMR) Readers. A proposal submitted to Seagate Technology on Jul. 30, 2002.
- Ladwig, et al. Fabrication of Thermodynamically Stable Oxide Layers for Use in Tunneling Magnetoresistive (TMR) Readers. A proposal submitted to Seagate Technology on Sep. 30, 2002.
- Yang, "Fabrication of Thermodynamically Stable Oxide Layers for Use in Tunneling Magnetoresistive (TMR) Readers." Written report for Research Readiness Exam presented by Jianhua Yang to his research committee on Aug. 28, 2003.
- Boubeta, et al., "Epitaxy, magnetic and tunnel properties of transition metal/MgO(001) heterostructures." *Journal of Physics: Condensed Matter* 15, pp. R1123-R1167, 2003. Published by Institute of Physics Publishing.
- Mitani, et al. "Fe/MgO/FeCo(100) epitaxial magnetic tunnel junctions prepared by using in situ plasma oxidation." *Journal of Applied Physics*, 93 (10), pp. 8041-8043, 2003. Published by American Institute of Physics.
- Chang. "Fabrication of Thermodynamically Stable Oxide Layers for Use in Tunneling Magnetoresistive Readers." Power Point slides from oral presentation at Seagate Technology, Oct. 6, 2003.
- Shen, et al., "Observation of the barrier structure in magnetic tunnel junctions using high-resolution electron microscopy and electron holography." *Applied Physics Letters*, 83 (26), pp. 5482-5484, 2003. Published by American Institute of Physics.
- Yu, et al., "Electron transport properties in magnetic tunnel junctions with epitaxial NiFe (111) ferromagnetic bottom electrodes." *Applied Physics Letters*, 82 (26) pp. 4735-4737, 2003. Published by American Institute of Physics.
- Pages 148-167; 187-188; 247-258 and 264-271 of Peter Ladwig's thesis presented on Jul. 30, 2003 and cataloged Feb. 6, 2004.
- Oleynik, et al. "Metal-oxide interfaces in magnetic tunnel junctions." *Interface Science*, 12, pp. 105-116, 2004. Published by Kluwer Academic Publishers.
- Banach, et al. Delocalization and charge disproportionation in $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$, *Physical Review B*, 69, p. 054427-1, 2004. Published by The American Physical Society.
- Lacour, et al., "On the use of exchange biased top electrodes in magnetic tunnel junctions." *Journal of Magnetism and Magnetic Materials*, 270, pp. 403-406, 2004. Published by Elsevier.
- A research progress report on $\text{H}_2\text{O}/\text{H}_2$ gas mixture. Power Point slides presented in oral presentation to Seagate Technology on Feb. 6, 2004.
- Chang "Fabrication of Thermodynamically Stable Oxide Layers for Use in Tunneling Magnetoresistive Readers." Power Point slides from oral presentation at Seagate Technology, Oct. 6, 2003.
- "A research progress report on $\text{H}_2\text{O}/\text{H}_2$ gas mixture." Power Point slides presented in oral presentation to Seagate Technology on Feb. 6, 2004.

* cited by examiner

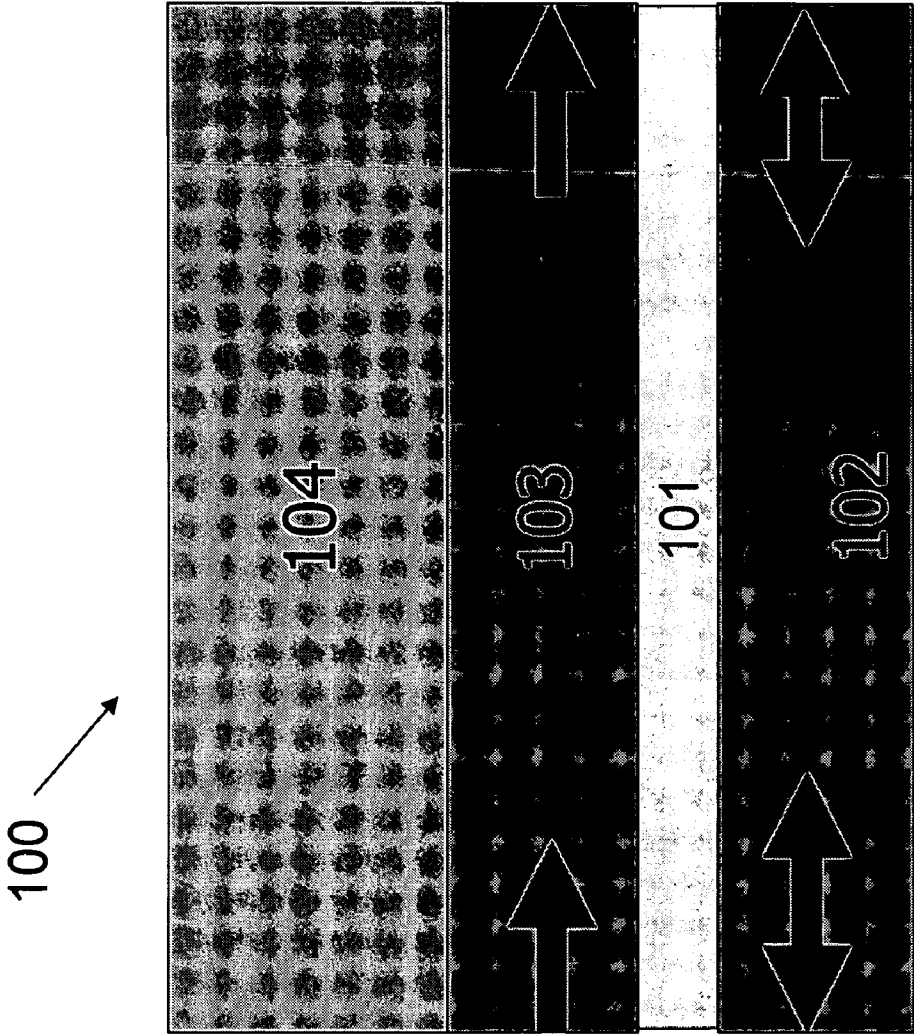


FIG. 1

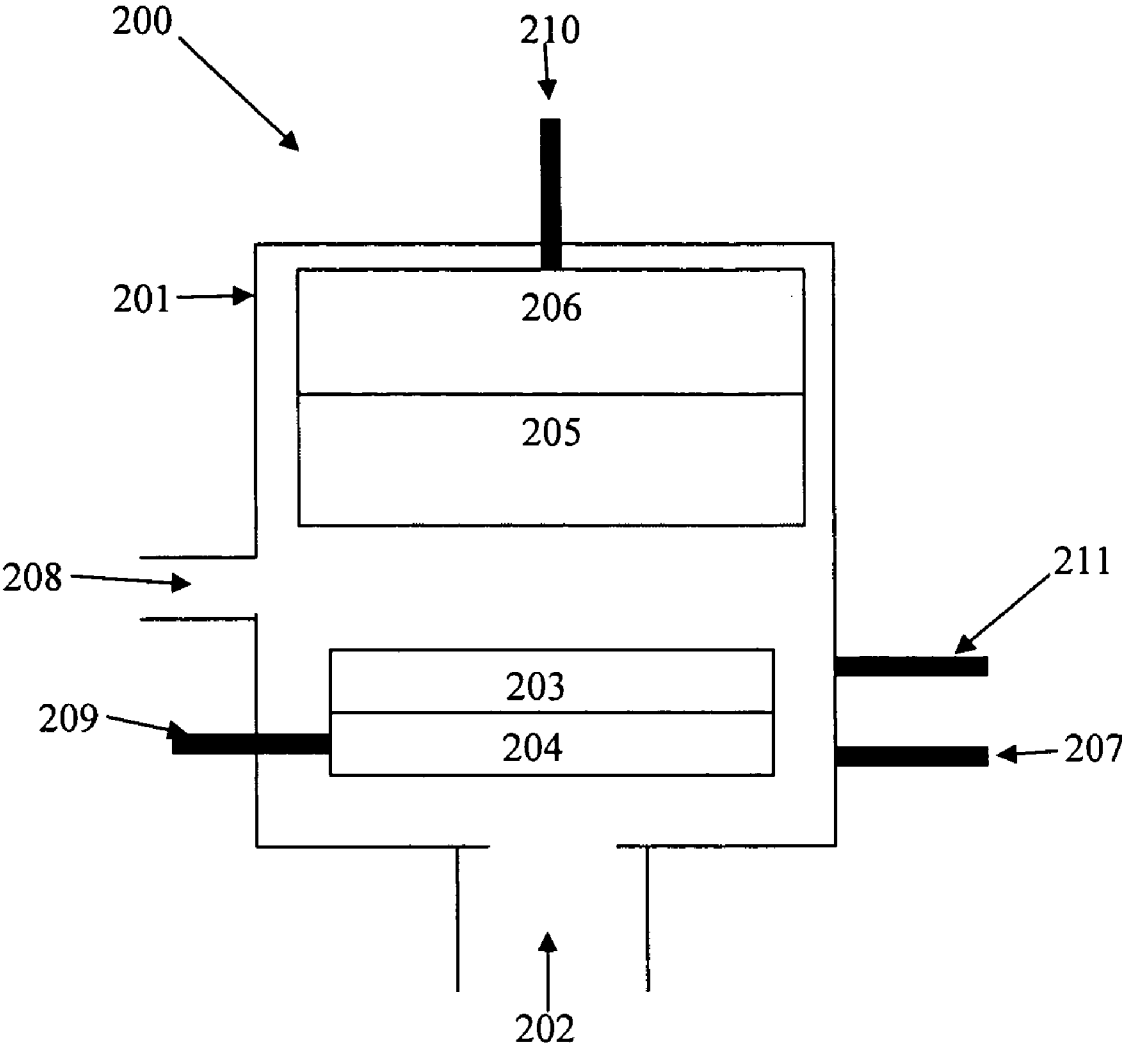


FIG. 2

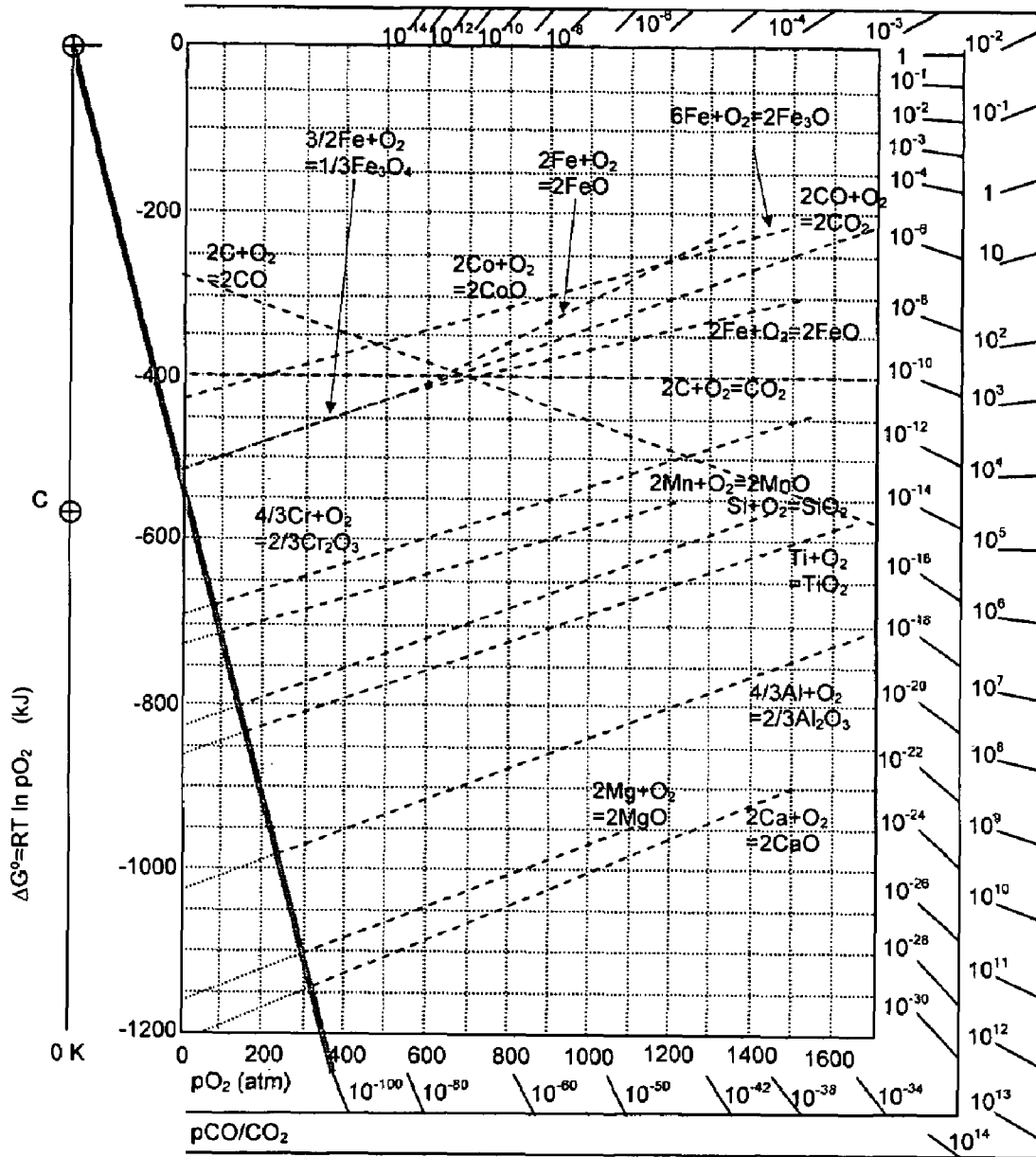


FIG. 3

1

METHODS FOR THE FABRICATION OF THERMALLY STABLE MAGNETIC TUNNEL JUNCTIONS

STATEMENT OF GOVERNMENT RIGHTS

Research funding was provided for this invention by the United States Department of Energy under grant No. DE-FG02-99ER45777. The United States government has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates generally to magnetic tunnel junctions and to methods for fabricating the same.

BACKGROUND

The demand for increasing areal density in the magnetic storage industry drives the search for new magnetoresistive readers with increased sensitivity. The tunneling magnetoresistive (TMR) read head is one device that has been investigated recently as a highly sensitive magnetoresistive reader. A TMR utilizes a magnetic tunnel junction (MTJ) composed of a tunnel barrier layer made from a non-magnetic insulating material sandwiched between two ferromagnetic layers. The insulating layer is thin enough to permit quantum-mechanical tunneling of charge carriers between the ferromagnetic layers. The tunneling is electron spin-dependent and, therefore, the tunneling current depends on the spin-dependent electronic properties of the ferromagnetic materials and the relative orientations of the magnetization directions of the ferromagnetic layers. For this reason, the two ferromagnetic layers are designed to have different responses to magnetic fields so that the orientation of their magnetic moments may be varied by an external magnetic field. One of the ferromagnetic layers in the MTJ, called the pinned layer, is composed of a material whose magnetic moment does not rotate in response to an applied magnetic field in the device's range of interest. In some MTJs the ferromagnetic layer is pinned by being exchange coupled to an antiferromagnetic layer. The other ferromagnetic layer is a free layer, that is, its magnetic moment is free to respond to an applied magnetic field in the device's range of interest.

Some MTJs include a tunnel barrier layer doped with magnetic particles. This doping provides an increase in magnetoresistance and an improved signal to noise ratio. For example, some MTJs have an aluminum oxide tunnel barrier layer doped with magnetic particles such as cobalt, iron or nickel particles.

The success of the tunneling in an MTJ will depend on the quality of the insulating tunnel barrier layer in the device. A high quality tunnel barrier layer is desirably made from a uniform, stoichiometric oxide composition sandwiched between two completely unoxidized ferromagnetic layers. Unfortunately the production of such high quality tunnel barrier layers has proven to present a significant challenge because it is difficult to completely oxidize the tunnel barrier layer in the MTJ without at least partially oxidizing the neighboring ferromagnetic layers and any magnetic particles used to dope the tunnel barrier layer. In one common fabrication scheme a pure metal is deposited on a ferromagnetic layer and subsequently oxidized in air or in an oxygen gas or plasma. Using this method, the oxidation progress must be precisely monitored in order to avoid over- or under-oxidizing the tunnel barrier layer. In addition, this approach may result in an oxygen concentration gradient across the tunnel barrier layer

2

and the underlying ferromagnetic layer. Such an oxygen concentration gradient may be difficult to eliminate once formed. Another method presently used to produce MTJs is reactive sputtering from a metal target in an oxygen gas atmosphere to deposit a metal oxide onto a ferromagnetic layer. Unfortunately this approach exposes the underlying ferromagnetic layer to an oxygen rich plasma, causing at least a portion of the ferromagnetic material to become oxidized. Sputtering from an oxide target is another technique used to deposit a metal oxide layer on a ferromagnetic layer. However, this approach typically provides low yield and poor reproducibility and is characterized by an inability to consistently form thin, uniform, pinhole-free layers of metal oxide.

In the production of a MTJ it is important to use an insulating tunnel barrier layer that is neither over-nor under-oxidized, as both conditions will affect the performance of the device. The effects of over- or under-oxidation of the tunnel barrier layer may be illustrated using a MTJ with an aluminum oxide tunnel barrier layer as an example. If the pure aluminum (Al) layer is under-oxidized, the unoxidized Al adjacent the neighboring ferromagnetic layer will significantly influence the behavior of tunneling in the device. Specifically, at the ferromagnetic/aluminum interface, the ferromagnetic material may induce spin polarization of the Al layer to an extent that is lower than the polarization of the ferromagnetic material. Thus, the tunneling current coming from the underlying ferromagnetic layer in contact with the Al metal will be only weakly polarized, thereby decreasing the junction magnetoresistance. In addition, the pure Al present in the tunnel barrier layer may react with the underlying ferromagnetic materials (e.g., Co and Fe) to form intermetallic compounds and degrade the performance of the junction. On the other hand, if the tunnel barrier layer is over-oxidized there is a possibility that the oxidation will continue into the underlying ferromagnetic surface. The formation of an oxide of the ferromagnetic material gives rise to spin scattering and an increase in the junction resistance, resulting in a decrease in the junction magnetoresistance.

Thus a need exists for a method of selectively and completely oxidizing the tunnel barrier layer in an MTJ without oxidizing the neighboring ferromagnetic layers to provide a thermodynamically stable MTJ.

SUMMARY OF THE INVENTION

Magnetic tunnel junctions and methods for making the magnetic tunnel junctions are provided. The magnetic tunnel junctions are characterized by a tunnel barrier oxide layer sandwiched between two ferromagnetic layers. The methods used to fabricate the magnetic tunnel junctions are capable of completely and selectively oxidizing a tunnel junction precursor material to provide a tunnel junction oxide without oxidizing the adjacent ferromagnetic materials.

The present methods include the steps of depositing a tunnel barrier precursor material onto an underlying ferromagnetic substrate and exposing the tunnel barrier precursor material to an oxidizing gas having a low oxygen partial pressure in order to provide for the controlled and selective oxidation of the tunnel barrier precursor material under conditions wherein the formation of the tunnel barrier oxide is thermodynamically stable and the formation of oxides of the ferromagnetic materials is not. In some instances the partial pressure of oxygen used to oxidize the precursor materials may be 10^{-50} Torr or even lower. Such low oxygen partial pressures are difficult to achieve using air or O_2 as an oxidizing gas. However, such low oxygen partial pressures may be readily achieved and carefully controlled in the present meth-

ods by controlling the ratio of partial pressures of a first gas and a second gas in an oxidizing gas composed of a mixture of the two gases. Examples of gas mixtures that may be used to achieve sufficiently low oxygen partial pressures include a mixture of carbon monoxide (CO) (i.e., the first gas) and carbon dioxide (CO₂) (i.e., the second gas) or a mixture of hydrogen gas (H₂) (i.e., the first gas) and water (H₂O) (i.e., the second gas). In order to speed up the kinetics of oxidation, the oxidation may be carried out at elevated temperatures and pressures.

The tunnel barrier precursor material may be a metal or a semiconductor. Aluminum is well suited as a metal tunnel barrier precursor because aluminum oxides (e.g. Al₂O₃) provide well-known tested tunnel barrier oxides in MTJs. Examples of suitable ferromagnetic layers for use in the MTJs include alloys of cobalt and iron and alloys of nickel and iron.

The MTJs provided herein are well suited for use in a variety of magnetic sensor and storage devices, including magnetoresistive read heads and nonvolatile random access memory.

Further objects, features and advantages of the invention will be apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 is a schematic cross-sectional diagram of a magnetic tunnel junction in accordance with the present invention.

FIG. 2 is a schematic cross-sectional diagram of an apparatus that may be used to fabricate a magnetic tunnel junction in accordance with the present invention.

FIG. 3 is an Ellingham diagram for various metal oxides.

DETAILED DESCRIPTION OF THE INVENTION

Methods for making an MTJ with a uniform oxide tunnel barrier layer sandwiched between two non-oxidized ferromagnetic layers are provided. The methods provided herein are based on the complete, selective, thermodynamically controlled oxidation of a metal or semiconductor layer deposited over a ferromagnetic layer. These methods take advantage of the ability to carefully control the O₂ partial pressure (pO₂) in an oxidizing gas by employing an oxidizing gas containing a mixture of a first gas and a second gas, wherein the ratio of the partial pressure of the first gas to the partial pressure of the second gas may be adjusted to provide a desired oxygen partial pressure in the oxidizing gas. For example, the oxidizing gas mixture may contain a mixture of CO and CO₂ or a mixture of H₂ and H₂O.

As shown in FIG. 1, an MTJ **100** produced in accordance with the present methods generally includes an oxide tunnel barrier layer **101** sandwiched between a free ferromagnetic layer **102** and a pinned ferromagnetic layer **103**. Typically, the pinned ferromagnetic layer is pinned by exchange coupling to an adjacent antiferromagnetic pinning layer **104**. The oxide tunnel barrier layer **101** of the MTJ optionally may be doped with magnetic particles (not shown).

The tunnel barrier layers **101** in the MTJs in accordance with the invention are composed of high quality oxide layers desirably characterized by a uniform concentration of oxygen throughout the tunnel barrier layer. The materials selected to provide the tunnel barrier oxides are desirably characterized as being good oxide formers, (e.g. metal oxides or semiconductor oxides having large negative enthalpies of formation). The selected materials are also desirably characterized by low

band gaps, and therefore low junction resistances, which lead to improved sensitivity of the MTJs into which they are incorporated. For the purposes of this disclosure the materials (i.e. metals or semiconductors) that are oxidized to provide tunnel barrier oxides are referred to as "tunnel oxide precursors." Suitable metals for use in the production of metal oxide tunnel barrier layers in accordance with the present methods include transition metals, rare earth metals (lanthanides), actinides, alkali metals and alkaline earth metals. Specific examples of metal and semiconductor materials that may be oxidized to produce the oxide tunnel barrier layers include, but are not limited to, aluminum (Al), yttrium (Y), tantalum (Ta), hafnium (Hf), zirconium (Zr), gallium (Ga), chromium (Cr), manganese (Mn), silicon (Si), titanium (Ti), magnesium (Mg), niobium (Nb) and calcium (Ca), and alloys thereof. Aluminum oxide (Al₂O₃) is perhaps the best known material for use as a tunnel barrier layer in MTJs and is particularly well-suited as a tunnel barrier layer in accordance with the present methods.

The tunnel barrier layers will generally be quite thin in order to provide low RA (i.e., resistance×area). Typically, the tunnel barrier layers will have a thickness of no more than about 10 nanometers (nm). This includes tunnel barrier layers having a thickness of no more than about 2 nm, further includes tunnel barrier layers having a thickness of no more than about 1 nm and still further includes tunnel barrier layers having a thickness of no more than about 5 angstroms (Å).

The ferromagnetic materials used to provide the free and pinned ferromagnetic layers and, optionally, dopant particles in the tunnel barrier layer in the MTJs may be selected to provide a thermodynamically stable interface between the ferromagnetic layers and tunnel barrier layer in order to minimize or eliminate reactions between the ferromagnetic material and the tunnel barrier oxides. As discussed in greater detail below, this generally means that the materials should be selected such that the free energy for the production of the oxides in the tunnel barrier layer is less than the free energy for production of oxides of the ferromagnetic materials. The pinned and free ferromagnetic layers may be made of the same or of different ferromagnetic materials. Suitable ferromagnetic materials for use as the ferromagnetic layers in the MTJs provided herein include iron (Fe), cobalt (Co), nickel (Ni), and their alloys. Specific examples of suitable metal alloys for use as ferromagnetic materials include, but are not limited to, Co—Fe alloys (e.g., Co_{0.9}Fe_{0.1}, or Cu_{0.5}Fe_{0.5}, and more generally Co_xFe_{1-x}) and Ni—Fe alloys (e.g. Ni_{0.8}Fe_{0.2} and more generally Ni_xFe_{1-x}). For the purposes of this disclosure, Co—Fe alloys will be denoted by "CoFe" and Ni—Fe alloys will be denoted by "NiFe." Like the tunnel barrier layers, the ferromagnetic layers are typically quite thin. For example, in some MTJs the thickness of the ferromagnetic layers may be no more than about 10 nanometers. This includes embodiments where the ferromagnetic layers each have a thickness of no more than about 2 nanometers and further includes embodiments with a ferromagnetic layers each have a thickness of about 1 nanometer.

The antiferromagnetic layer, which serves as a pinning layer in the MTJs provided herein, may be selected from a variety of known antiferromagnetic materials that have conventionally been used for this purpose. Such antiferromagnetic materials include, but are not limited to, Ni—Mn alloys, Fe—Mn alloys and Pt—Mn alloys. In addition to the antiferromagnetic layer, the pinned layer, the tunnel barrier layer and the free layer, the MTJs may optionally include other layers, such as a support substrate and/or various insulating or conducting layers.

5

The ferromagnetic materials and the metal or semiconductor materials may be deposited over their respective underlying layers or substrates using a variety of deposition techniques, many of which are well known. Such techniques include, but are not limited to, sputter deposition and evaporative deposition. FIG. 2 is a schematic diagram of an apparatus that may be used to deposit the various layers in the MTJ. The apparatus 200 includes an ultrahigh vacuum chamber 201 in fluid communication through a vacuum port 202 with one or more vacuum pumps (not shown). The vacuum chamber 201 houses a substrate 203 on which the various layers of the MTJ will be grown. The substrate 203 may be mounted over a heater 204 connected to a power source 209. A target material 205 (e.g., a tunnel barrier precursor target or a ferromagnetic target) is disposed over the substrate 203. The target material is in electrical contact with a thin film deposition source 206. As shown in FIG. 2, the deposition source 206 may be a DC magnetron sputtering source connected to a power input 210 and adapted to apply a negative potential to the target material 205. A plasma precursor gas, such as argon, is introduced into the chamber 201 through a plasma precursor gas inlet port 211 and a sputter plasma is ignited in the chamber. After a tunnel barrier precursor thin film has been deposited, an oxidizing gas is introduced into the chamber 201 through an oxidizing gas inlet port 207. The pressure in the chamber may be monitored using an appropriate pressure gauge mounted to a gauge mount 208. Other suitable methods and apparatus for depositing metal and ferromagnetic thin films are described in Kottler et al., *J. App. Phys.*, 89, 3301-3306 (2001) and Moordera et al., *Appl. Phys. Lett.*, 70, 3050-3052 (1997), the entire disclosures of which are incorporated herein by reference.

In one basic embodiment of the methods provided herein, a MTJ is made by depositing a layer of metal or semiconductor over an underlying ferromagnetic layer. The metal or semiconductor layer is then exposed to an oxidizing gas containing O₂ and at least two additional gases under oxidizing conditions that promote the formation of a tunnel barrier oxide but not the formation of oxides of the ferromagnetic elements. The at least two additional gases are characterized in that their ratio in the oxidizing gas mixture may be used to control the level of O₂ present in the oxidizing gas. Oxidizing gas mixtures containing CO and CO₂ or H₂ and H₂O are examples of suitable oxidizing gas mixtures. By controlling the ratio of pCO to pCO₂ or the ratio of pH₂ to pH₂O in the oxidizing gas, it is possible to selectively and completely oxidize the metal layer without oxidizing the adjacent ferromagnetic layers. After oxidation is complete, a second ferromagnetic layer is formed over the tunnel barrier oxide layer.

The conditions under which the metal or semiconductor material is oxidized to provide the tunnel barrier oxide layer should be selected such that the layer is selectively and completely oxidized while minimizing the oxidation of the adjacent ferromagnetic layer. In preferred embodiments, the conditions are selected to completely avoid any oxidation of the adjacent ferromagnetic material. Generally, this will involve the use of a very low O₂ partial pressure in the oxidizing gas. Specifically, the O₂ partial pressure is desirably low enough that oxidation of the metal or semiconductor layer is thermodynamically favored while oxidation of the ferromagnetic layer is not. As one of skill in the art would understand, the maximum desirable O₂ partial pressure in the oxidizing gas will depend both on the nature of the ferromagnetic material and the tunnel barrier material and on the oxidation temperature. However, in some instances the methods provided herein carry out the oxidation to form the tunnel barrier oxide at O₂ partial pressures of no more than about 1×10⁻²⁰ atmo-

6

spheres (atm). This includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 1×10⁻³⁰ atm, further includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 10⁻⁴⁰ atm, further includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 10⁻⁵⁰ atm, further includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 10⁻⁶⁰ atm, further includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 10⁻⁷⁰ atm, further includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 10⁻⁸⁰ atm, and still further includes embodiments where the oxidation takes place using O₂ partial pressures of no more than about 10⁻¹⁰⁰ atm.

These very low partial pressures of oxygen may not be practically achieved and controlled using air or pure O₂ as an oxidation gas. Instead, conventional approaches using such gases rely on kinetic control of the oxidation process under considerably higher O₂ partial pressures. These approaches have met with limited success, typically resulting in significant oxidation of adjacent ferromagnetic layers. In contrast, the inventors have discovered that such low O₂ partial pressures may be readily achieved and controlled using an oxidizing gas containing at least two gases in addition to O₂ wherein the level of O₂ in the mixture depends on the equilibrium between the at least two gases. In such systems, the ratio of the at least two other two gases present in the mixture may be used to adjust and control the level of O₂ present in the oxidizing gas. This relationship may be expressed using the equilibrium equation for the gases in the mixture. For example, an equilibrium reaction for a mixture containing O₂, a first gas ("A") and a second gas ("B"), may be expressed as: nA+mO₂=qB, where n, m and q represent the appropriate coefficients in the balanced equation. The equilibrium expression for the reaction is: K=pB^q/(pAⁿ×pO₂^m), where K is a constant at a given temperature. Thus, the relationship between pO₂ and the ratio pB:pA is: p^{O2}=(pB^q/(K×pAⁿ))^{1/m}. Thus, by way of illustration, an oxidizing gas containing a mixture of CO and CO₂ may be represented by the equilibrium reaction 2CO+O₂=2CO₂, where the partial pressure of O₂ in the mixture may be adjusted according to the equation: pO₂=pCO₂²/(K×pCO²). Alternatively, an oxidizing gas containing a mixture of H₂ and H₂O may be represented by the equilibrium reaction 2H₂+O₂=2H₂O, where the partial pressure of O₂ in the mixture may be adjusted according to the equation: pO₂=pH₂O²/(K×H₂²).

The oxidation of the metals or semiconductors to provide oxide tunnel barrier layers is desirably carried out at elevated oxidation temperatures, elevated oxidation pressures or a combination of elevated oxidation temperatures and pressures. Elevated temperatures may be used to speed up the oxidation kinetics. Although the oxidation of the tunnel barrier layer may be carried out at room temperature (e.g. about 20 to 25° C.), in many instances it may be desirable to use elevated oxidation temperatures in order to reduce the necessary oxidation time. For example, in some embodiments of the methods provided herein, oxidation may be carried out at a temperature of at least about 50° C. This includes embodiments where the oxidation is carried out at a temperature of at least about 100° C., also includes embodiments where the oxidation is carried out at a temperature of at least about 200° C., further includes embodiments where oxidation is carried out at a temperature of at least 300° C., even further includes embodiments where the oxidation is carried out at a temperature of at least 400° C., and still further includes embodiments where the oxidation is carried out at a temperature of at least

about 500° C. Generally, the oxidation temperature should be selected such that it is low enough to avoid the onset of reactions and interdiffusions between the elements in the tunnel barrier layer and the ferromagnetic material in the ferromagnetic layers. Thus, for example, if the ferromagnetic layers are made from a Co-containing material (e.g. CoFe), and Al is used as the metal in the tunnel barrier layer, the oxidation temperature is desirably no more than about 500° C. in order to avoid reactions and/or interdiffusion between Al atoms in the tunnel barrier layer and Co atoms in the ferromagnetic layer.

Elevated oxidation gas pressures may also be used to speed up the oxidation kinetics. For example, in some embodiments of the methods provided herein, the total pressure of the oxidizing gas (e.g. the total pressure of CO, CO₂ and O₂ or the total pressure of H₂, H₂O and O₂) to which the metal or semiconductor layer is exposed will be at least about 100 Torr. This includes embodiments where the total pressure of the oxidizing gas is at least about 200 Torr, further includes embodiments where the total pressure of the oxidizing gas is at least about 300 Torr, still further includes embodiments where the total pressure of the oxidizing gas is at least about 400 Torr and even further includes embodiments where the total pressure of the oxidizing gas is at least about 500 Torr. In order to minimize the time required for the complete oxidation of the tunnel barrier layer, it may be desirable to use a combination of elevated temperatures and pressures.

The time required for the complete oxidation of the tunnel barrier layer in the MTJ will depend, at least in part, on the oxidation temperature and pressure and on the nature and thickness of the metal or semiconductor layer. However, in some embodiments of the methods provided herein, a completely oxidized tunnel barrier layer may be produced from a metal or semiconductor layer in no more than about eight hours. This includes embodiments where the tunnel barrier layer is completely oxidized in less than about five hours, further includes embodiments where the tunnel barrier layer is completely oxidized in less than about three hours, still further includes embodiments where the tunnel barrier layer is completely oxidized in less than about an hour and even further includes embodiments where the tunnel barrier layer is oxidized in less than about thirty minutes.

The MTJs provided in accordance with the present methods are well-suited for use in a variety of devices, including magnetic sensor and storage devices. For example, the MTJs may be used as magnetic field sensors (e.g. magnetoresistive read heads) for sensing the magnetic field signals from a rotating magnetic disk in a magnetic disk drive of a computer, as described in U.S. Pat. No. 5,729,410, the entire disclosure of which is incorporated herein by reference. The MTJs are also well suited for use as a memory cell in a nonvolatile magnetic random access memory (MRAM) array, as described in U.S. Pat. No. 5,640,343, the entire disclosure of which is incorporated herein by reference. A typical MRAM made from the MTJs provided herein includes an array of individual magnetic memory cells, each comprising an MTJ and a diode electrically connected in series.

The following is a description of a method for calculating a desirable pO₂ for the production of an MTJ composed of an Al₂O₃ tunnel barrier layer disposed between two CoFe ferromagnetic layers. These calculations, and those that follow, are based on an exemplary MTJ having a Co_{0.9}Fe_{0.1} alloy as the ferromagnetic layer. These calculations are based on the Ellingham diagram shown in FIG. 3. The Ellingham diagram is a type of phase diagram that plots the oxidation potential of several metal-metal oxide systems vs. temperature. Note that the slopes of all of the metal reactions in the diagram of FIG.

3 are positive and are of roughly the same magnitude. The slope is related to the entropy change (ΔS) in the Gibbs free energy equation:

$$\Delta G = \Delta H - T\Delta S.$$

The metal-metal oxide reactions involve the incarceration of a high entropy gaseous species, O₂, in a lower entropy solid phase (note the negative sign in the equation which makes the slopes positive). Therefore, as temperature increases and the entropy contribution becomes larger, the oxidation reactions generally become less stable and require a higher O₂ partial pressure for stability.

The driving force for oxidation can be roughly calculated from the Ellingham diagram in the following manner. Lines of constant O₂ partial pressure are drawn diagonally from the origin to the desired position on the O₂ axis. For example, the grey line in FIG. 3 represents an O₂ partial pressure of 10⁻¹⁰⁰ atm. At this partial pressure (for the oxidation reactions of interest), the dotted lines indicate regions where the oxidation reaction is stable, while the dashed lines indicate regions where the reduction of the oxide to pure metal is stable. At any given temperature, the length of a vertical line drawn from the grey line to the desired reaction yields the driving force for the oxidation/reduction reactions. Therefore, at an O₂ partial pressure of 10⁻¹⁰⁰ atm and a temperature of 50° C. (based on the Ellingham diagram an O₂ partial pressure of 10⁻⁸⁰ atm could also be used at 50° C.), there is a significant driving force to oxidize Cr, Mn, Si, Al, Mg and Ca, while Co, Fe and Ni will not oxidize.

In practical applications, an O₂ partial pressure of 10⁻¹⁰⁰ atm is not attainable by introducing a known amount of O₂ into a high purity carrier gas such as argon (Ar). However, the O₂ partial pressure may be readily controlled by introducing an oxidizing gas having a known ratio of pCO:pCO₂.

Once a desirable O₂ partial pressure has been calculated or estimated, an appropriate pCO:pCO₂ ratio for the production of a MTJ, may be determined. Here again, we use an exemplary CoFe/Al₂O₃/CoFe MTJ as an illustration. As noted above, to avoid oxidizing Co at 298 K, the partial pressure of O₂ will have to be very low. For this illustration an O₂ partial pressure lower than 10⁻⁸⁰ atm is used. This is extremely difficult to obtain even with high purity process gases. However, by using an appropriate pCO:pCO₂ ratio, this partial pressure of O₂ is attainable. An appropriate pCO:pCO₂ ratio may be calculated based on the thermodynamics of the equilibrium reaction 2CO+O₂=2CO₂ (Reaction I), and the energies of formation (ΔG_f^o) from pure elements at 298 K of O₂, CO₂ and CO (i.e. ΔG_{f,CO₂}^o=0 (by definition); ΔG_{f,CO₂}^o=-3.946 E5 J/mol; and ΔG_{f,CO}^o=-1.379 E5 J/mol, where "E" indicates that the number that follows represents an exponent, i.e. "E5"="×10⁵"). The equilibrium equation for Reaction I is:

$$\Delta G_{rxn I}^{\circ} = 2 \Delta G_{f,CO_2}^{\circ} - \Delta G_{f,O_2}^{\circ} - 2 \Delta G_{f,CO}^{\circ}; \text{ also}$$

$\Delta G_{rxn I}^{\circ} = -RT \ln(K) = -5.134 \text{ E5 J/mol}$, where R is the gas constant, T is temperature and K is the equilibrium constant which equals:

$$K = \exp\left(\frac{-\Delta G_{rxn}^{\circ}}{R \cdot T}\right) = \left(\frac{p_{CO_2}^2}{p_{CO}^2 \cdot p_{O_2}}\right) = 8.937 \text{ E89},$$

wherein p represents a partial pressure. With this expression for K in terms of p, the required pCO:pCO₂ ratio needed to maintain any desired O₂ partial pressure may be determined.

Therefore, for a $p_{O_2}=10^{-80}$ atm, the $p_{CO}:p_{CO_2}$ needed to provide this partial pressure is:

$$\frac{p_{CO}}{p_{CO_2}} = (1/(p_{O_2} \cdot K))^{1/2} = 1.1 \text{ E-5 or higher.}$$

Thus, the calculations indicate that in order to avoid oxidation of Co using a PO_2 of 10^{-80} atm at 50°C ., the $p_{CO}:p_{CO_2}$ ratio needs to be greater than 1.1×10^{-5} . This is easily attainable using commercially available process gases.

It should be noted, however, that because the Ellingham diagram is based on pure elemental oxidation it provides only a guide for estimating the minimum desirable $p_{CO}:p_{CO_2}$ ratio in the oxidizing gas. For ferromagnetic layers composed of alloys, this estimate may be too low and the user may benefit from choosing a ratio that is several orders of magnitude higher. Fortunately, if a more accurate estimate is needed or desired, it may be calculated using known thermodynamic data, as described below.

A refined set of calculations for determining an appropriate minimum $p_{CO}:p_{CO_2}$ ratio for an MTJ (e.g. a CoFe/Al₂O₃/CoFe MTJ) follows. One main consideration regarding an alloy system, is that the activities of the individual atom types in the alloy are not unity. Therefore, if possible, every likely oxidation reaction should be calculated with respect to the elemental activity in the alloy. The proper $p_{CO}:p_{CO_2}$ ratio is then chosen to forbid the formation of the most stable ferromagnetic layer oxide while still providing significant driving force to oxidize the tunnel barrier layer. In accordance with the calculations outlined below (i.e., for Reactions II-VI) for the Co—Fe—Al system considered here, a $p_{CO}:p_{CO_2}$ ratio above 0.04 is needed to avoid oxidation of the ferromagnetic layer while it is practically impossible to avoid the oxidation of Al using a $p_{CO}:p_{CO_2}$ ratio at 25°C .

The minimum desirable $p_{CO}:p_{CO_2}$ ratio may be determined by calculating the minimum desirable $p_{CO}:p_{CO_2}$ ratio needed to forbid the formation of each possible ferromagnetic layer oxide. These calculations are outlined briefly for a CoFe ferromagnetic layer below.

Reaction II: $\text{Fe}+\text{CO}_2=\text{FeO}+\text{CO}$ @298 K

Energies of formation from pure elements at 298 K: $\Delta G^\circ_{f,Fe} = 0$ (by definition); $\Delta G^\circ_{f,FeO} = 2.456 \text{ E5 J/mol}$; $\Delta G^\circ_{f,CO_2} = -3.946 \text{ E5 J/mol}$; and $\Delta G^\circ_{f,CO} = -1.379 \text{ E5 J/mol}$. The equilibrium equation for Reaction II is:

$$\Delta G^\circ_{rxn II} = \Delta G^\circ_{f,CO} + \Delta G^\circ_{f,FeO} - \Delta G^\circ_{f,Fe} - \Delta G^\circ_{f,CO_2}; \text{ also}$$

$\Delta G^\circ_{rxn II} = -RT \ln(K) = 1.114 \text{ E4 J/mol}$, where R is the gas constant, T is temperature and K is the equilibrium constant which equals:

$$K = \exp\left(\frac{-\Delta G^\circ_{rxn II}}{R \cdot T}\right) = \left(\frac{p_{CO} \cdot a_{FeO}}{p_{CO_2} \cdot a_{Fe}}\right) = 1.118 \text{ E-2,}$$

where a represents activity. For gaseous species, activity is equal to partial pressure. Here, the iron is assumed to have a concentration of 10 at. % in Co. Thus,

$$\frac{p_{CO}}{p_{CO_2}} = \frac{a_{Fe}}{a_{FeO}} K = 1.2 \text{ E-3}$$

or higher to avoid oxidation of Fe.

Reaction III: $2\text{Fe}+3\text{CO}_2=\text{Fe}_2\text{O}_3+3\text{CO}$ @298 K

Energies of formation from pure elements at 298 K: $\Delta G^\circ_{f,Fe} = 0$ (by definition); $\Delta G^\circ_{f,Fe_2O_3} = -2.093 \text{ E6 J/mol}$; $\Delta G^\circ_{f,CO_2} = -3.946 \text{ E5 J/mol}$; and $\Delta G^\circ_{f,CO} = -1.379 \text{ E5 J/mol}$. The equilibrium equation for Reaction III is:

$$\Delta G^\circ_{rxn III} = 3\Delta G^\circ_{f,CO} + \Delta G^\circ_{f,Fe_2O_3} - 2\Delta G^\circ_{f,Fe} - 3\Delta G^\circ_{f,CO_2}; \text{ also}$$

$\Delta G^\circ_{rxn III} = -RT \ln(K) = 2.637 \text{ E4 J/mol}$, where R is the gas constant, T is temperature and K is the equilibrium constant which equals:

$$K = \exp\left(\frac{-\Delta G^\circ_{rxn III}}{R \cdot T}\right) = \left(\frac{p_{CO}^3 \cdot a_{Fe_2O_3}}{p_{CO_2}^3 \cdot a_{Fe}^2}\right) = 2.397 \text{ E-5,}$$

where a represents activity. Here, the iron is assumed to have a concentration of 10 at. % in Co. Thus,

$$\frac{p_{CO}}{p_{CO_2}} = \left(\frac{a_{Fe}^2}{a_{Fe_2O_3}} K\right)^{1/3} = 6.2 \text{ E-3}$$

or higher to avoid oxidation of Fe.

Reaction IV: $3\text{Fe}+4\text{CO}_2=\text{Fe}_3\text{O}_4+4\text{CO}$ @298 K

Energies of formation from pure elements at 298 K: $\Delta G^\circ_{f,Fe} = 0$ (by definition); $\Delta G^\circ_{f,Fe_3O_4} = -1.012 \text{ E6 J/mol}$; $\Delta G^\circ_{f,CO_2} = -3.946 \text{ E5 J/mol}$; and $\Delta G^\circ_{f,CO} = -1.379 \text{ E5 J/mol}$. The equilibrium equation for Reaction IV is:

$$\Delta G^\circ_{rxn IV} = 4\Delta G^\circ_{f,CO} + \Delta G^\circ_{f,Fe_3O_4} - 3\Delta G^\circ_{f,Fe} - 4\Delta G^\circ_{f,CO_2}; \text{ also}$$

$\Delta G^\circ_{rxn IV} = -RT \ln(K) = 1.503 \text{ E4 J/mol}$, where R is the gas constant, T is temperature and K is the equilibrium constant which equals:

$$K = \exp\left(\frac{-\Delta G^\circ_{rxn IV}}{R \cdot T}\right) = \left(\frac{p_{CO}^4 \cdot a_{Fe_3O_4}}{p_{CO_2}^4 \cdot a_{Fe}^3}\right) = 2.328 \text{ E-3,}$$

where a represents activity. Here, the iron is assumed to have a concentration of 10 at. % in Co. Thus,

$$\frac{p_{CO}}{p_{CO_2}} = \left(\frac{a_{Fe}^3}{a_{Fe_3O_4}} K\right)^{1/4} = 3.9 \text{ E-2}$$

or higher to avoid oxidation of Fe.

Reaction V: $\text{Co}+\text{CO}_2=\text{CoO}+\text{CO}$ @298 K

Energies of formation from pure elements at 298 K: $\Delta G^\circ_{f,Co} = 0$ (by definition); $\Delta G^\circ_{f,CoO} = -2.129 \text{ E5 J/mol}$; $\Delta G^\circ_{f,CO_2} = -3.946 \text{ E5 J/mol}$; and $\Delta G^\circ_{f,CO} = -1.379 \text{ E5 J/mol}$. The equilibrium equation for Reaction V is:

$$\Delta G^\circ_{rxn V} = \Delta G^\circ_{f,CO} + \Delta G^\circ_{f,CoO} - \Delta G^\circ_{f,Co} - \Delta G^\circ_{f,CO_2}; \text{ also}$$

$\Delta G^\circ_{rxn V} = -RT \ln(K) = 4.376 \text{ E4 J/mol}$, where R is the gas constant, T is temperature and K is the equilibrium constant which equals:

11

$$K = \exp\left(\frac{-\Delta G_{rxn}^{\circ}}{R \cdot T}\right) = \left(\frac{\rho_{CO} \cdot a_{CoO}}{\rho_{CO_2} \cdot a_{Co}}\right) = 2.153 E-8,$$

wherein a represents activity. Here, the Co is assumed to have a concentration of 90 at. % in Fe. Thus,

$$\frac{\rho_{CO}}{\rho_{CO_2}} = \frac{a_{Co}}{a_{CoO}} K = 1.9 E-8$$

or higher to avoid oxidation of Co.

Reaction VI: $3Co+4CO_2=Co_3O_4+4CO$ @298 K

Energies of formation from pure elements at 298 K: $\Delta G_{f,Co}^{\circ}=0$ (by definition); $\Delta G_{f,Co_3O_4}^{\circ}=-8.664 E5$ J/mol; $\Delta G_{f,CO_2}^{\circ}=-3.946 E5$ J/mol; and $\Delta G_{f,CO}^{\circ}=-1.379 E5$ J/mol. The equilibrium equation for Reaction VI is:

$$\Delta G_{rxn}^{\circ} = 4\Delta G_{f,Co}^{\circ} + \Delta G_{f,Co_3O_4}^{\circ} - 3\Delta G_{f,CO}^{\circ} - 4\Delta G_{f,CO_2}^{\circ};$$

also

$\Delta G_{rxn}^{\circ} = -RT \ln(K) = 1.604 E5$ J/mol, where R is the gas constant, T is temperature and K is the equilibrium constant which equals:

$$K = \exp\left(\frac{-\Delta G_{rxn}^{\circ}}{R \cdot T}\right) = \left(\frac{\rho_{CO}^4 \cdot a_{Co_3O_4}}{\rho_{CO_2}^4 \cdot a_{Co}^3}\right) = 7.841 E-29,$$

wherein a represents activity. Here, the Co is assumed to have a concentration of 90 at. % in Fe. Thus,

$$\frac{\rho_{CO}}{\rho_{CO_2}} = \left(\frac{a_{Co}^3}{a_{Co_3O_4}} K\right)^{1/4} = 8.695 E-8$$

or higher to avoid oxidation of Co.

It should be noted that these calculations and the Ellingham diagram (FIG. 2) do not provide information about reaction kinetics, only thermodynamic reaction stability. For example, Al and its alloys are generally considered to be oxidation resistant materials for structural applications even though the Ellingham diagram predicts a large driving force for oxidation under atmospheric conditions. The explanation for this apparent contradiction lies in the consideration of reaction kinetics. Al_2O_3 quickly forms on all exposed Al surfaces, but then abruptly stops. This happens because of the good lattice match between Al_2O_3 and Al; after the initial oxide forms, the only way for O_2 to reach the remaining Al is by diffusion, which is very slow at standard atmospheric conditions. Fortunately, for many TMR devices, the desired oxide layer thickness is on the order of 0.5 nm and the initial oxide formation may be enough to fully penetrate the layer. In addition, the reaction kinetics may be increased by oxidizing under elevated temperature and/or elevated pressure conditions, as illustrated in Example 1, below.

Exemplary embodiments of the present methods for the production of thermodynamically stable magnetic tunnel junctions are provided in the following examples. These examples are presented to illustrate the methods and assist

12

one of ordinary skill in using the same. These examples are not intended in any way to otherwise limit the scope of the invention.

EXAMPLES

Example 1

Production of a CoFe/Aluminum Oxide/CoFe Magnetic Tunnel Junction Using a CO/CO₂ Oxidizing Gas

This example illustrates a method for producing an MTJ composed of an aluminum oxide tunnel barrier layer sandwiched between two $Co_{0.9}Fe_{0.1}$ ferromagnetic layers. In this example, an Al layer and a CoFe layer were exposed separately to an oxidizing gas composed of a mixture of CO and CO_2 having a pCO:pCO₂ ratio of 0.1 in order to test for the oxidation. One advantage of this method is that the oxidation process was removed from the sputter deposition process. This allowed the total pressure of the CO/CO₂ oxidizing gas to become an independent parameter and eliminated the need to mix CO/CO₂ with Ar gas, as in a sputter plasma approach, and removed concerns about changes to the calculated reactivity due to a sputter plasma.

A CoFe ferromagnetic layer was deposited onto a Ti buffer layer having a thickness of approximately 100 nm using DC magnetron sputtering from a CoFe target in a high vacuum chamber. The Ti buffer layer was supported on a silicon substrate with a thin intervening silicon oxide layer. The ferromagnetic layer was then exposed to an oxidizing gas containing a CO/CO₂ mixture to verify that the ferromagnetic layer would not oxidize. In this experiment, the CoFe layer was deposited onto the underlying Ti substrate in a series of deposition steps. In each deposition step, a layer of CoFe was deposited using DC magnetron sputtering from a CoFe target. A CoFe layer having a thickness of approximately 9 nm was deposited initially. Next a second CoFe layer having a thickness of approximately 1 nm was deposited. The sputter plasma was then turned off and the deposited CoFe material was exposed to a gas containing a mixture of CO and CO_2 at a 1 minute flow of 0.25 mTorr. The pCO:pCO₂ ratio in the gas was about 0.1. The chamber was then evacuated and another 9 nm thick layer of CoFe was sputter deposited. For comparison, the procedure was repeated without exposing the CoFe material to the CO/CO₂ gas mixture between deposition cycles.

X-ray photoelectron spectroscopy (XPS) spectra were obtained for both CoFe samples. The spectra revealed no difference in the O signal observed in the middle layer of the CoFe samples in either sample, verifying that a CO/CO₂ ratio of 0.1 will not oxidize CoFe. Methods for obtaining XPS spectra from MTJ structures are described in Kottler et al., *J. Appl. Phys.*, 89, 3301-3306 (2001), the entire disclosure of which is incorporated herein by reference.

Another XPS experiment was used to verify that the CO/CO₂ oxidizing gas does not oxidize the CoFe. In this experiment, a first sample composed of a single 2 nm thick layer of CoFe was exposed to an oxidizing gas containing CO and CO_2 at a pCO:pCO₂ ratio of about 0.1. The ferromagnetic layer was exposed to the oxidizing gas at a pressure of 100 Torr for 20 minutes at 200° C. These elevated temperatures and pressures were used in order to speed up the reaction kinetics and decrease the time for oxidation. The CoFe layer was subsequently capped with a 4 nm layer of Al deposited onto its surface via magnetron sputter deposition from an Al target. The experiment was then repeated on a second CoFe

sample without exposing the CoFe layer to the oxidizing gas prior to Al deposition. Finally, the experiment was repeated on a third CoFe sample where the oxidizing gas contained O₂ rather than a CO/CO₂ mixture. This time the CoFe was exposed to the oxidizing gas at a pressure of 20 mTorr for 20 minutes at 200° C. XPS experiments were then performed without depth profiling due to concerns of profiling technique smearing out composition data from thin layers. Changes in the Co-2p₃ photoelectron peaks were used to determine the presence of oxygen in the resulting structures. The spectra showed no significant difference in the Co-2p₃ peak collected from the CoFe layer that was not subjected to an oxidizing gas and the CoFe layer that was subjected to 100 Torr of CO/CO₂ for 20 min at 200° C. However, the CoFe layer that was subjected to just 20 mTorr of O₂ for 20 min at 200° C. showed significant change as the Co-2p₃ peak broadened significantly due to partial oxidation.

After establishing that the CoFe layer does not oxidize upon exposure to the CO/CO₂ oxidizing gas, experiments were performed to demonstrate the effective oxidation of the Al under oxidizing conditions. In these experiments, a first sample composed of a 1 nm thick Al layer deposited on a 100 nm thick Ti buffer layer was exposed to an oxidizing gas containing CO and CO₂ at apCO:pCO₂ ratio of about 0.1. The Al layer was exposed to the oxidizing gas at a pressure of 100 Torr for 20 minutes at 200° C., then capped with 3 nm of Ti. A second sample composed of a 1 nm thick Al layer deposited on a Ti buffer layer was exposed to an oxidizing gas of O₂. This second Al layer was also exposed to the oxidizing gas at a pressure of 100 Torr for 20 minutes at 200° C., then capped with 3 nm of Ti.

The samples used for the above XPS experiments (and the FTIR experiments described below) were deposited with Ti buffer and cap layers rather than CoFe layers because thinner layers of Ti could be used to effectively protect the Al. (A pure Al sample capped with only 3 nm of Ti showed no traces of oxidation after exposure to air for several weeks.) This is important because the signal from the underlying Al layer must escape the capping layer in order to be detected by XPS and FTIR. A study on the early stages of Ti/Al reactions in thin-films is presented in Michaelsen et al., *Mat. Res. Soc. Symp. Proc.*, 398, 245 (1998). Their calorimetry results show that onset temperatures for Ti/Al reactions are above 225° C. for all examined thicknesses, and about 275° C. for thicknesses comparable to those used in this analysis. This information was taken into consideration when designing experiments involving samples with Ti/Al interfaces. An underlying Ti buffer layer was used as it is more reflective than the Si substrate.

XPS experiments were performed on the resulting structures without depth profiling due to concerns of profiling technique smearing out composition data from thin layers. Changes in the Al-2s photoelectron peaks were used to determine the presence of aluminum oxide in the resulting structures. The Al layers subjected to the CO/CO₂ oxidizing gas showed oxidation of the Al. In fact, the Al-2s peak shift results for this system were similar to the Al-2s peak shift results observed for the Al layer oxidized in O₂.

The presence of the aluminum oxide was also confirmed using Fourier transform infrared spectroscopy (FTIR). The detection of thin Al-oxide layers with FTIR spectroscopy carried out using the methods described by Zhu et al., *Appl. Phys. Lett.*, 78, 3103 (2001), the entire disclosure of which is incorporated herein by reference. Briefly, two significant modifications to standard FTIR were required to obtain the sensitivity required to detect thin Al-oxide layers. First, the experiments had to be performed with a synchrotron radiation

source in order to significantly increase the incident infrared radiation intensity. Second, a special grazing incidence setup (86°) was added to obtain more surface sensitivity. This experimental setup was duplicated with the addition of an 80° grazing incidence setup to the existing FTIR beamline at the University of Wisconsin Synchrotron Radiation Center.

The FTIR experiments detected the absorbance of infrared radiation. Al—O bonds are found to effectively absorb radiation at 960 cm⁻¹ wavenumber. The FTIR experiments were performed on the 1 nm thick Al layers capped with 3 nm of Ti. As before, a first sample composed of a 1 nm thick Al layer was exposed to an oxidizing gas containing CO and CO₂ at apCO:pCO₂ ratio of about 0.1. The Al layer was exposed to the oxidizing gas at a pressure of 100 Torr for 20 minutes at 200° C., then capped with 3 nm of Ti. A second sample composed of a 1 nm thick Al layer was exposed to an oxidizing gas of O₂. The Al layer was exposed to the oxidizing gas at a pressure of 100 Torr for 20 minutes at 200° C., then capped with 3 nm of Ti.

In the FTIR spectra, Ti—O peaks are located at wavenumbers in the upper 800's to the low 900's according to the FTIR study of Chertihin et al., *J. Phys. Chem.*, 99, 6356 (1995). To eliminate the potential for artifacts, a pure Al layer capped with Ti was chosen for background subtraction. Therefore, all of the observed peaks in the absorbance spectrum in this 800-1100 cm⁻¹ wavenumber regime were assumed to be due to Al oxidation reactions.

The results of FTIR experiments agreed with those obtained from the XPS experiments. Furthermore, the results were repeatable, as evidenced by a rescans of the O₂ oxidized sample weeks after the initial scan.

The location of the peak in the FTIR data gives some information about the oxide layer thickness. According to Zhu et al., the location of the oxide peak decreases in wavenumber with oxide thickness. The observed peak locations were all roughly 925 cm⁻¹, which corresponds to an oxide layer thickness of roughly 5 Å.

For MTJs having a thicker tunnel barrier layer, it may be advantageous to decrease the time for oxidation by increasing the oxidation temperature and pressure. For this reason, the experiment was repeated, however, this time the sample was oxidized at higher temperatures and pressures. As before, a sample composed of a 1 nm thick Al layer deposited on a Ti buffer layer was exposed to an oxidizing gas containing CO and CO₂ at apCO:pCO₂ ratio of about 0.1. However, this time the Al layer was exposed to the oxidizing gas at a pressure of 500 Torr for 7 hours at 270° C., then capped with 3 nm of Ti. An FTIR analysis of the sample was conducted as described above and the peak shift data indicated that almost no metallic Al remained in the tunnel barrier layer. An FTIR analysis of a CoFe layer treated in an oxidizing gas of CO and CO₂ under the same conditions revealed no oxidation.

In another experiment, a sample composed of a 0.5 nm thick Al layer deposited on a Ti buffer layer was exposed to an oxidizing gas containing CO and CO₂ at a pCO:pCO₂ ratio of about 0.1. This time the Al layer was exposed to the oxidizing gas at a pressure of 500 Torr for 40 minutes at 230° C., then capped with 3 nm of Ti. An XPS analysis of the sample was conducted as described above and the data indicated that the Al layer had been completely oxidized. An XPS analysis of a CoFe layer treated in an oxidizing gas of CO and CO₂ under the same conditions revealed no oxidation.

15

Example 2

Production of a CoFe/Aluminum Oxide/CoFe Magnetic Tunnel Junction Using an H₂O/H₂ Oxidizing Gas

This example illustrates a method for producing an MTJ composed of an aluminum oxide tunnel barrier layer sandwiched between two CoFe ferromagnetic layers. A pure Al layer was deposited onto a Ti buffer layer, as described in Example 1, using DC magnetron sputter deposition from an Al target. The resulting Al layer was subsequently oxidized in an H₂O/H₂ oxidizing gas.

In these experiments, a first sample composed of a 0.5 nm thick Al layer deposited on a Ti buffer layer was exposed to an oxidizing gas containing H₂O and H₂ at a p_{H₂O}:p_{H₂} ratio of about 2×10⁻⁴. The Al layer was exposed to the oxidizing gas at a pressure of 500 Torr for 20 minutes at 200° C., then capped with 3 nm of Ti. A second sample composed of a 0.5 nm thick Al layer deposited on a Ti buffer layer was exposed to an oxidizing gas of O₂. The Al layer was exposed to this oxidizing gas at a pressure of 0.02 Torr for 20 minutes at 25° C., then capped with 3 nm of Ti.

An XPS analysis of the sample was conducted as described above and the data indicated that the Al layer had been completely oxidized. An XPS analysis of a CoFe layer treated in an oxidizing gas of H₂O and H₂ under the same conditions revealed no oxidation. In contrast, an XPS analysis of the CoFe layer treated in an oxidizing gas of O₂ at a pressure of 0.02 Torr for 20 minutes at 25° C. showed significant oxidation.

Example 3

Production of a CoFe/Yttrium Oxide/CoFe Magnetic Tunnel Junction Using an H₂O/H₂ Oxidizing Gas

This example illustrates a method for producing an MTJ composed of a yttrium oxide tunnel barrier layer sandwiched between two CoFe ferromagnetic layers. A pure Y layer was deposited onto a Ti buffer layer using DC magnetron sputter deposition from a Y target. The resulting Y layer was subsequently oxidized in an H₂O/H₂ oxidizing gas.

In these experiments, a first sample composed of a 1 nm thick Y layer deposited on a Ti buffer layer was exposed to an oxidizing gas containing H₂O and H₂ at a p_{H₂O}:p_{H₂} ratio of about 2×10⁻⁴. The Y layer was exposed to the oxidizing gas at a pressure of 1 Torr for 20 minutes at room temperature, then capped with 3 nm of Ti.

An XPS analysis of the sample was conducted as described above and the data indicated that the Y layer had been completely oxidized. An XPS analysis of a CoFe layer treated in an oxidizing gas of H₂O and H₂ under the same conditions revealed no oxidation.

Example 4

Production of a CoFe/Tantalum Oxide/CoFe Magnetic Tunnel Junction Using an H₂O/H₂ Oxidizing Gas

This example illustrates a method for producing an MTJ composed of a tantalum oxide tunnel barrier layer sandwiched between two CoFe ferromagnetic layers. A pure Ta layer was deposited onto a CoFe layer using DC magnetron sputter deposition from a Ta target. The resulting Ta layer was subsequently oxidized in an H₂O/H₂ oxidizing gas.

16

In these experiments, a first sample composed of a 0.5 nm thick Ta layer deposited on a Ti buffer layer was exposed to an oxidizing gas containing H₂O and H₂ at a p_{H₂O}:p_{H₂} ratio of about 2×10⁻⁴. The Ta layer was exposed to the oxidizing gas at a pressure of 500 Torr for 60 minutes at 490° C., then capped with 3 nm of Ti.

An XPS analysis of the sample was conducted as described above and the data indicated that the Ta layer had been completely oxidized. An XPS analysis of a CoFe layer treated in an oxidizing gas of H₂O and H₂ under the same conditions revealed no oxidation.

The invention has been described with reference to specific and illustrative embodiments. However, it should be understood that many variations and modifications may be made while remaining within the scope of the following claims.

What is claimed is:

1. A method for making a magnetic tunnel junction comprising a layer of metal oxide or semiconductor oxide on a first ferromagnetic layer, the method comprising:

(a) selecting a temperature and an O₂ partial pressure at which the oxidation of the metal or semiconductor is thermodynamically favored while the oxidation of the first ferromagnetic layer is not; and

(b) exposing a layer of the metal or the semiconductor deposited on the first ferromagnetic layer to a gas comprising a mixture of CO₂ and CO or a mixture of H₂ and H₂O to oxidize the metal or semiconductor and provide a tunnel barrier oxide layer on the first ferromagnetic layer;

wherein (pCO/pCO₂) or (pH₂pH₂O)≧(1/(pO₂*K))^{1/2},

where pCO is the partial pressure of CO in the gas mixture; pCO₂ is the partial pressure of CO₂ in the gas mixture; pH₂ is the partial pressure of H₂ in the gas mixture; pH₂O is the partial pressure of H₂O in the gas mixture; pO₂ is the selected O₂ partial pressure; and K is an equilibrium constant calculated from exp(-ΔG^o_{rxn}/R*T), where R is the gas constant, T is the selected temperature, and -ΔG^o_{rxn} is the free energy of formation of CO₂ from CO and O₂ or the free energy of formation of H₂O from H₂ and O₂;

further wherein the selected O₂ partial pressure is no greater than 10⁻²⁰ torr, and the free energy for the production of an oxide in the metal or semiconductor is less than the free energy for the production of an oxide in the ferromagnetic layer at the selected temperature and O₂ partial pressure;

and further wherein the first ferromagnetic layer comprises a Co—Fe alloy or a Ni—Fe alloy.

2. The method of claim 1, further comprising depositing a second ferromagnetic layer over the tunnel barrier oxide layer.

3. The method of claim 1 wherein the first ferromagnetic layer comprises a Co—Fe alloy.

4. The method of claim 1 wherein the first ferromagnetic layer comprises a Ni—Fe alloy.

5. The method of claim 1 wherein a layer of a semiconductor is deposited onto the first ferromagnetic layer.

6. The method of claim 1 wherein a layer of a metal or metal alloy is deposited onto the first ferromagnetic layer.

7. The method of claim 6 wherein the metal is selected from the group consisting of aluminum, chromium, manganese, silicon, titanium, magnesium, calcium, hafnium, zirconium, gallium and niobium.

8. The method of claim 6 wherein the metal is aluminum.

9. The method of claim 6 wherein the metal is yttrium or tantalum.

17

10. The method of claim 3 wherein the oxidizing gas comprises a mixture of CO and CO₂ and the ratio of CO partial pressure to CO₂ partial pressure in the gas mixture is at least about 0.1.

11. The method of claim 1 wherein the total pressure of CO₂ and CO in the gas mixture is at least about 100 Torr and the gas temperature is at least about 200° C.

12. The method of claim 8 wherein the total pressure of CO₂ and CO in the gas mixture is about 100 to 500 Torr and the gas temperature is about 200° C. to 500° C.

13. The method of claim 3 wherein the oxidizing gas comprises a mixture of H₂ and H₂O and the ratio of H₂O partial pressure to H₂ partial pressure in the gas mixture is at least about 0.0002.

14. The method of claim 1 wherein the total pressure of H₂ and H₂O in the gas mixture is at least about 100 Torr and the gas temperature is at least about 200° C.

15. The method of claim 8 wherein the total pressure of H₂ and H₂O in the gas mixture is about 100 to 500 Torr and the gas temperature is about 200° C. to 500° C.

16. The method of claim 1 wherein the tunnel barrier oxide layer has a thickness of no more than about 10 nm.

17. The method of claim 1 wherein the tunnel barrier oxide layer has a thickness of no more than about 2 nm.

18. The method of claim 17 wherein the first ferromagnetic layer has a thickness of no more than about 10 nm.

19. The method of claim 1 further comprising depositing the first ferromagnetic layer on an antiferromagnetic layer.

20. The method of claim 1, wherein the first ferromagnetic layer is not oxidized during the step of exposing the layer of the metal or the semiconductor to a gas comprising a mixture of CO₂ and CO or a mixture of H₂ and H₂O.

21. The method of claim 1, wherein the first ferromagnetic layer comprises a Co—Fe alloy, and further wherein a layer of metal is deposited onto the first ferromagnetic layer and the metal is aluminum, yttrium, or tantalum.

22. The method of claim 1, wherein the first ferromagnetic layer comprises a Co—Fe alloy and the oxidizing gas comprises a mixture of H₂ and H₂O and the ratio of H₂O partial pressure to H₂ partial pressure in the gas mixture is at least about 0.0002, and further wherein a layer of metal is deposited onto the first ferromagnetic layer and the metal is aluminum, yttrium, or tantalum.

23. The method of claim 1, wherein the first ferromagnetic layer comprises a Co—Fe alloy and the oxidizing gas comprises a mixture of CO and CO₂ and the ratio of CO partial pressure to CO₂ partial pressure in the gas mixture is at least about 0.1, and further wherein a layer of metal is deposited onto the first ferromagnetic layer and the metal is aluminum.

24. The method of claim 1, wherein the selected O₂ partial pressure is no greater than 10⁻⁸⁰ torr.

25. A method for making a magnetic tunnel junction comprising a layer of metal oxide or semiconductor oxide on a first ferromagnetic layer, the method comprising:

(a) selecting a temperature and an O₂ partial pressure at which the oxidation of the metal or semiconductor is thermodynamically favored while the oxidation of the first ferromagnetic layer is not; and

(b) exposing a layer of the metal or the semiconductor deposited on the first ferromagnetic layer to a gas comprising a mixture of CO₂ and CO or a mixture of H₂ and H₂O to oxidize the metal or semiconductor and provide a tunnel barrier oxide layer on the first ferromagnetic layer;

wherein $(p\text{CO}/p\text{CO}_2)$ or $(p\text{H}_2/p\text{H}_2\text{O}) \leq (1/p\text{O}_2 * K)^{1/2}$, where pCO is the partial pressure of CO in the gas mixture; pCO₂ is the partial pressure of CO₂ in the gas mixture;

18

pH₂ is the partial pressure of H₂ in the gas mixture; pH₂O is the partial pressure of H₂O in the gas mixture; pO₂ is the selected O₂ partial pressure; and K is an equilibrium constant calculated from $\exp(-\Delta G^\circ_{rxn}/R*T)$, where R is the gas constant, T is the selected temperature, and $-\Delta G^\circ_{rxn}$ is the free energy of formation of CO₂ from CO and O₂ or the free energy of formation of H₂O from H₂ and O₂;

further wherein the selected O₂ partial pressure is no greater than 10⁻²⁰ torr, and the free energy for the production of an oxide in the metal or semiconductor is less than the free energy for the production of an oxide in the ferromagnetic layer at the selected temperature and O₂ partial pressure;

and further wherein the first ferromagnetic layer is selected from the group consisting of Co, Fe, Ni, a Co—Fe alloy, and a Ni—Fe alloy, a layer of metal is deposited onto the first ferromagnetic layer, and the metal is selected from the group consisting of Cr, Mn, Si, Al, Mg, Ca, Y, and Ta.

26. A method for making a magnetic tunnel junction comprising a layer of metal oxide or semiconductor oxide on a first ferromagnetic layer, the method comprising:

(a) selecting a temperature and an O₂ partial pressure at which the oxidation of the metal or semiconductor is thermodynamically favored while the oxidation of the first ferromagnetic layer is not; and

(b) exposing a layer of the metal or the semiconductor deposited on the first ferromagnetic layer to a gas comprising a mixture of CO₂ and CO or a mixture of H₂ and H₂O to oxidize the metal or semiconductor and provide a tunnel barrier oxide layer on the first ferromagnetic layer;

wherein $(p\text{CO}/p\text{CO}_2)$ or $(p\text{H}_2/p\text{H}_2\text{O}) \leq (1/(p\text{O}_2 * K))^{1/2}$, where pCO is the partial pressure of CO in the gas mixture; pCO₂ is the partial pressure of CO₂ in the gas mixture; pH₂ is the partial pressure of H₂ in the gas mixture; pH₂O is the partial pressure of H₂O in the gas mixture; pO₂ is the selected O₂ partial pressure; and K is an equilibrium constant calculated from $\exp(-\Delta G^\circ_{rxn}/R*T)$, where R is the gas constant, T is the selected temperature, and $-\Delta G^\circ_{rxn}$ is the free energy of formation of CO₂ from CO and O₂ or the free energy of formation of H₂O from H₂ and O₂;

further wherein the selected O₂ partial pressure is no greater than 10⁻²⁰ torr, and the free energy for the production of an oxide in the metal or semiconductor is less than the free energy for the production of an oxide in the ferromagnetic layer at the selected temperature and O₂ partial pressure;

and further wherein a layer of a metal or metal alloy is deposited onto the first ferromagnetic layer and the metal is selected from the group consisting of aluminum, chromium, manganese, silicon, titanium, magnesium, calcium, hafnium, zirconium, gallium, and niobium.

27. The method of claim 26, wherein the metal is aluminum.

28. A method for making a magnetic tunnel junction comprising a layer of metal oxide or semiconductor oxide on a first ferromagnetic layer, the method comprising:

(a) selecting a temperature and an O₂ partial pressure at which the oxidation of the metal or semiconductor is thermodynamically favored while the oxidation of the first ferromagnetic layer is not; and

(b) exposing a layer of the metal or the semiconductor deposited on the first ferromagnetic layer to a gas comprising a mixture of CO₂ and CO or a mixture of H₂ and

19

H₂O to oxidize the metal or semiconductor and provide a tunnel barrier oxide layer on the first ferromagnetic layer;

wherein $(p_{\text{CO}}/p_{\text{CO}_2})$ or $(p_{\text{H}_2}/p_{\text{H}_2\text{O}}) \cong (1/(p_{\text{O}_2} * K))^{1/2}$,

where p_{CO} is the partial pressure of CO in the gas mixture; 5

p_{CO_2} is the partial pressure of CO₂ in the gas mixture;

p_{H_2} is the partial pressure of H₂ in the gas mixture; $p_{\text{H}_2\text{O}}$

is the partial pressure of H₂O in the gas mixture; p_{O_2} is

the selected O₂ partial pressure; and K is an equilibrium 10

constant calculated from $\exp(-\Delta G^\circ_{\text{rxn}}/R * T)$, where R is

the gas constant, T is the selected temperature, and

$-\Delta G^\circ_{\text{rxn}}$ is the free energy of formation of CO₂ from CO

and O₂ or the free energy of formation of H₂O from

H₂ and O₂;

20

further wherein the selected O₂ partial pressure is no greater than 10⁻²⁰ torr, and the free energy for the pro-

duction of an oxide in the metal or semiconductor is less than the free energy for the production of an oxide in the

ferromagnetic layer at the selected temperature and O₂ partial pressure;

and further wherein a layer of a metal or metal alloy is deposited onto the first ferromagnetic layer and the

metal is yttrium or tantalum.

* * * * *