SUMMARY OF THE INVENTION

In view of the limitations associated with conventional designs of devices that use spin-momentum transfer, an object of the present invention is to provide a structure that is optimal for a magnetic memory or magnetic information processing device.

It is another object of the present invention to produce a magnetic device that has advantages in terms of speed of operation.

It is a further object of the present invention to produce a magnetic device that has advantages in terms of reliability.

It is a further object of the present invention to produce a magnetic device that requires lower power to operate.

It is a further object of the present invention to produce a magnetic device that has advantages in terms of the stability of the stored information.

It is a further object of the present invention to produce a magnetic device that has a large read-out signal.

These and additional objects of the invention are accomplished by a device that employs magnetic layers in which the layer magnetization directions do not lie along the same axis. For instance in one embodiment, two magnetic regions have magnetizations that are orthogonal.

The invention is a magnetic device comprised of ferromagnetic and non-magnetic layers through which current can flow. The magnetic device is comprised of a ferromagnetic layer with a fixed magnetization direction and another ferromagnetic layer separated from the first by a non-magnetic region that has a magnetization that is free to rotate in response to applied currents. A third ferromagnetic layer, again, separated from the others by a non-magnetic layer, has a fixed magnetization direction and can be employed to readout the magnetization direction of the free ferromagnetic layer. The magnetization directions of the ferromagnetic layers are not all along the same axis. In one of the preferred embodiments, the first fixed ferromagnetic layer's magnetization direction is perpendicular to the plane of the layer, while the free ferromagnetic layer's magnetization is in the plane of the layer. As described above, a current flow between the layers transfers spin-angular momentum from the fixed magnetization layer to the free

magnetization layer and produces a torque on the magnetization of the free layer. The torque is proportional to the vector triple product of the magnetization direction of the fixed and free layer, with a factor of proportionality that depends on the current and the spin polarization of the current. A large torque is produced when the magnetization directions of the fixed and free layers are orthogonal.

This large torque acting on the magnetization direction of the free magnetic layer causes the magnetization of the free magnetic layer to rotate out of the plane of the layer. Since the thickness of the free magnetic layer is less than the width and length dimensions, the rotation of the magnetization of the free magnetic layer out of the plane of the layer generates a large magnetic field, a 'demagnetizing' field, which is perpendicular to the plane of the layer.

This demagnetizing field forces the magnetization vector of the free magnetic layer to precess, i.e., for the magnetization direction to rotate around the direction of the demagnetization magnetic field. The demagnetizing field also determines the rate of precession. A large demagnetizing field results in a high precession rate, which is an optimal condition for fast magnetic switching. An advantage of this magnetic device is that random fluctuating forces or fields are not necessary to initiate or control the magnetic response of the layers.

A further aspect of the invention provides a magnetic device including a reference magnetic layer having a fixed magnetic helicity and/or a fixed magnetization direction, a free magnetic layer with at least one magnetization vector having a changeable magnetization helicity, and non-magnetic layer spatially separating said free magnetic layer and said reference magnetic layer. The magnetization helicity of the free magnetic layer can be changed using current induced spin-momentum transfer. In one preferred embodiment, the device has a substantially ring shaped structure, and the reference magnetic layer includes an easy axis substantially perpendicular to the reference layer and a fixed magnetization perpendicular to the plane of the reference layer. Alternatively, the reference layer includes an easy axis substantially perpendicular to the reference layer and a magnetic helicity substantially clockwise or counter-clockwise about the ring-shaped structure.

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In view of the limitations associated with conventional designs of devices that use spin-momentum transfer, an object of the present disclosure is to provide a structure that is optimal for a magnetic memory or magnetic information processing device.

It is another object of the present disclosure to produce a magnetic device that has advantages in terms of speed of operation.

It is a further object of the present disclosure to produce a magnetic device that has advantages in terms of reliability.

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It is a further object of the present disclosure to produce a magnetic device that has advantages in terms of the stability of the stored information.

It is a further object of the present disclosure to produce a magnetic device that has a large read-out signal.

These and additional objects of the disclosure are accomplished by a device that employs magnetic layers in which the layer magnetization directions do not lie along the same axis. For instance in one embodiment, two magnetic regions have magnetizations that are orthogonal.

The present disclosure provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator which is sufficiently thin such that electrons may traverse the insulator by quantum mechanical tunneling.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator including one or more of magnesium oxide, MgO, aluminum oxide, AlO or silicon oxide SiO, the proportion of oxygen to the first element need not be in the ratio of one to one.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator including magnesium oxide, MgO that has an epitaxial lattice arrangement with at least one of the magnetic layers, either the read-out magnetic layer or the free magnetic layer.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said pinned magnetic layer has a perpendicular

component of the magnetic anisotropy that is sufficient to orient that magnetization perpendicular to the layer.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said pinned magnetic layer has a perpendicular component of magnetic anisotropy and includes one or more of alloys of Fe and Pt, Co and Pt, Co and Pd, Co and Ni, Co and Au.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said pinned magnetic layer has a perpendicular component to the magnetic anisotropy achieved through the interfaces between dissimilar materials.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free

magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said free magnetic layer comprises one or more of Co, Ni and Fe and alloys of these elements, that are further alloyed with a non-magnetic element.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said free magnetic layer comprises one or more of Co, Ni and Fe and is alloyed with Ti, V, Cr, Mn or Cu.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said free magnetic layer comprises one or more of Co, Ni and Fe and alloys of these elements, that are further alloyed with an element which increases magnetization damping.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free

magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said free magnetic layer is doped with one or more of Pd or Pt.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said free magnetic layer is doped with rare earth atoms.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said first non-magnetic layer includes an insulator which is sufficiently thin such that electrons may traverse the insulator by quantum mechanical tunneling.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer

includes an insulator and wherein said first non-magnetic layer includes an insulator including one or more of magnesium oxide, MgO, aluminum oxide, AlO or silicon oxide SiO, the proportion of oxygen to the first element need not be in the ratio of one to one.

The present disclosure also provides a magnetic device comprising: a pinned magnetic layer with a magnetization vector having a fixed magnetization direction; a free magnetic layer with at least one magnetization vector having a changeable magnetization direction; a first non-magnetic layer spatially separating said free magnetic layer and said pinned magnetic layer; a read-out magnetic layer with a magnetization vector having a fixed magnetization direction; and a second non-magnetic layer spatially separating said free magnetic layer and said read-out magnetic layer, wherein the second non-magnetic layer includes an insulator and wherein said first non-magnetic layer includes an insulator including, MgO that has an epitaxial lattice arrangement with at least one of the magnetic layers, either the free magnetic layer or the pinned magnetic layer.

Also disclosed herein is a magnetic device comprised of ferromagnetic and non-magnetic layers through which current can flow. The magnetic device is comprised of a ferromagnetic layer with a fixed magnetization direction and another ferromagnetic layer separated from the first by a non-magnetic region that has a magnetization that is free to rotate in response to applied currents. A third ferromagnetic layer, again, separated from the others by a non-magnetic layer, has a fixed magnetization direction and can be employed to readout the magnetization direction of the free ferromagnetic layer. The magnetization directions of the ferromagnetic layers are not all along the same axis. In one of the preferred embodiments, the first fixed ferromagnetic layer's magnetization direction is perpendicular to the plane of the layer, while the free ferromagnetic layer's magnetization is in the plane of the layer. As described above, a current flow between the layers transfers spin-angular momentum from the fixed magnetization layer to the free magnetization layer and produces a torque on the magnetization of the free layer. The torque is proportional to the vector triple product of the magnetization direction of the fixed and free layer, with a factor of proportionality that depends on the current and the spin polarization of the current. A large

torque is produced when the magnetization directions of the fixed and free layers are orthogonal.

This large torque acting on the magnetization direction of the free magnetic layer causes the magnetization of the free magnetic layer to rotate out of the plane of the layer. Since the thickness of the free magnetic layer is less than the width and length dimensions, the rotation of the magnetization of the free magnetic layer out of the plane of the layer generates a large magnetic field, a `demagnetizing` field, which is perpendicular to the plane of the layer.

This demagnetizing field forces the magnetization vector of the free magnetic layer to precess, i.e., for the magnetization direction to rotate around the direction of the demagnetization magnetic field. The demagnetizing field also determines the rate of precession. A large demagnetizing field results in a high precession rate, which is an optimal condition for fast magnetic switching. An advantage of this magnetic device is that random fluctuating forces or fields are not necessary to initiate or control the magnetic response of the layers.

Further disclosed herein is a magnetic device including a reference magnetic layer having a fixed magnetic helicity and/or a fixed magnetization direction, a free magnetic layer with at least one magnetization vector having a changeable magnetization helicity, and non-magnetic layer spatially separating said free magnetic layer and said reference magnetic layer. The magnetization helicity of the free magnetic layer can be changed using current induced spin-momentum transfer. In one preferred embodiment, the device has a substantially ring shaped structure, and the reference magnetic layer includes an easy axis substantially perpendicular to the reference layer and a fixed magnetization perpendicular to the plane of the reference layer. Alternatively, the reference layer includes an easy axis substantially perpendicular to the reference layer and a magnetic helicity substantially clockwise or counter-clockwise about the ring-shaped structure.