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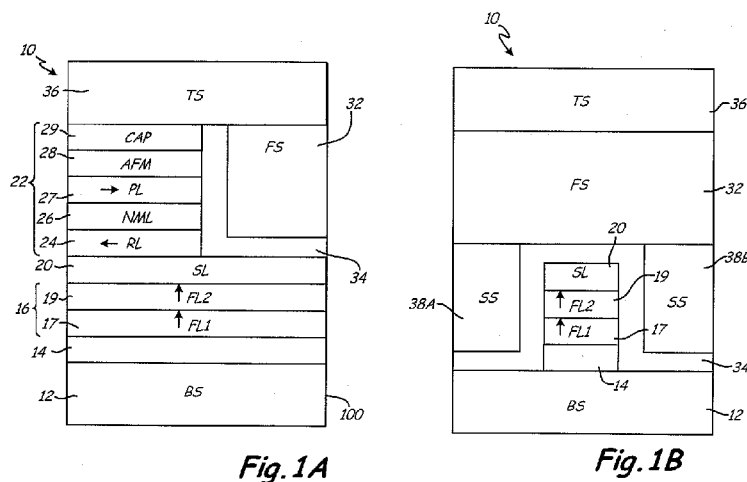


Fig. 1A

Fig. 1B

(57) Abstract: A magnetic sensor includes a freelay, a reference layer and a front shield. The freelay has a magnetization direction substantially perpendicular to the planar orientation of the layer and extends to the media confronting surface. The reference layer has a magnetization direction substantially in the plane of the layer and substantially perpendicular to the magnetization direction of the freelay. The reference layer is recessed from the media confronting surface and a front shield is positioned between the reference layer and the media confronting surface thereby reducing the shield-to-shield spacing and increasing the areal density of the reader.

MAGNETIC SENSOR WITH A RECESSED REFERENCE LAYER ASSEMBLY AND A FRONT SHIELD

BACKGROUND

In a magnetic data storage and retrieval system, a magnetic recording head typically includes a reader portion having a magnetoresistive (MR) sensor for retrieving magnetically encoded information stored on a magnetic disc. Magnetic flux from the surface of the disc causes rotation of the magnetization vector of a sensing layer or layers of the MR sensor, which in turn causes a change in electrical resistivity of the MR sensor. The sensing layers are often called “free” layers, since the magnetization vectors of the sensing layers are free to rotate in response to external magnetic flux. The change in resistivity of the MR sensor can be detected by passing a current through the MR sensor and measuring a voltage across the MR sensor. Depending on the geometry of the device, the sense current may be passed in the plane (CIP) of the layers of the device or perpendicular to the plane (CPP) of the layers of the device. External circuitry then converts the voltage information into an appropriate format and manipulates that information as necessary to recover the information encoded on the disc.

The essential structure in contemporary read heads is a thin film multilayer containing ferromagnetic material that exhibits some type of magnetoresistance. Examples of magnetoresistive phenomena include giant magnetoresistance (GMR), and tunneling magnetoresistance (TMR).

GMR sensors have a series of alternating magnetic and nonmagnetic layers. The resistance of GMR sensors varies as a function of the spin-dependent transmission of conduction electrons between the magnetic layers separated by the nonmagnetic layer and the accompanying spin-dependent scattering which takes place at the interface of the magnetic and nonmagnetic layers and within the magnetic layers. The resistance of a GMR sensor depends on the relative orientations of the magnetization in consecutive magnetic layers, and varies as the cosine of the angle between the magnetization vectors of consecutive magnetic layers.

A typical GMR read sensor configuration is the GMR spin valve, in which the GMR read sensor is a multi-layered structure formed of a nonmagnetic spacer layer positioned between a synthetic antiferromagnet (SAF) and a ferromagnetic free layer. The magnetization of the SAF is fixed, typically normal to an air bearing surface (ABS) of the GMR read sensor, while the magnetization of the free layer rotates freely in response to an external magnetic field. The SAF includes a reference layer and a pinned

layer which are magnetically coupled by a coupling layer such that the magnetization direction of the reference layer is opposite to the magnetization of the pinned layer. The resistance of the GMR read sensor varies as a function of an angle formed between the magnetization direction of the free layer and the magnetization direction of the reference

5 layer of the SAF.

TMR sensors have a configuration similar to GMR sensors, except that the magnetic layers of the sensor are separated by an insulating film thin enough to allow electron tunneling between the magnetic layers. The tunneling probability of an electron incident on the barrier from one magnetic layer depends on the character of the electron wave function and the spin of the electron relative to the magnetization direction in the other magnetic layer. As a consequence, the resistance of the TMR sensor depends on the relative orientations of the magnetizations of the magnetic layers, exhibiting a minimum for a configuration in which the magnetization of the magnetic layers are parallel and a maximum for a configuration in which the magnetizations of the magnetic

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15 layers are anti-parallel.

For all types of MR sensors, magnetization rotation occurs in response to magnetic flux from the disc. As the recording density of magnetic discs continues to increase, the width of the tracks on the disc must decrease, which necessitates smaller and smaller MR sensors as well. As MR sensors become smaller in size, particularly for sensors with dimensions less than about 0.1 micrometers (μm), the sensors have the potential to exhibit an undesirable magnetic response to applied fields from the magnetic disc. MR sensors must be designed in such a manner that even small sensors are free from magnetic noise and provide a signal with adequate amplitude for accurate recovery of the data written on the disc.

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MR sensors are designed with top and bottom shields that block undesirable magnetic fields from the recording medium from entering the sensing area of the reader. The active area of MR readers, as a result, is a function of the separation of the shield layers. Minimizing the shield-to-shield spacing in contemporary readers is a pressing design concern.

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SUMMARY

The present invention relates to a magnetic sensor including a freelay, a reference layer and a front shield. The freelay has a magnetization direction substantially perpendicular to the planar orientation of the layer and extends to a media confronting surface. The reference layer assembly has a magnetization direction

substantially in the plane of the layer and substantially perpendicular to the magnetization direction of the freelay and is recessed from the media confronting surface. A front shield is positioned between the reference layer and the media confronting surface.

5 BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A-12A are cross section views of magnetic sensors having a recessed reference layer, a front shield, and a freelay with magnetic anisotropy perpendicular to the plane of the layer.

10 FIGS. 1B-12B are media confronting surface views of the magnetic sensors of FIGS. 1A-12A, respectively.

FIG. 13A is a top view of a magnetic sensor showing the geometrical relationship of the side shield to the freelay and reference layer assemblies.

FIG. 13B is a top view of a magnetic sensor showing another aspect of the geometrical relationship of the side shield to the sensor stack.

15 DETAILED DESCRIPTION

FIG. 1A shows a schematic cross section of MR sensor 10, which is a current perpendicular to plane (CPP) GMR or TMR sensor stack. MR sensor 10 includes bottom shield 12, seedlayer 14, freelay assembly 16 (formed by freelayers 17 and 19), spacer layer 20, reference layer assembly 22 (formed by reference layer 24, nonmagnetic layer 26, pinned layer 27, antiferromagnetic layer 28, and cap layer 29), front shield 32, insulator layer 34, and top shield 36. Shields 12 and 36 also act as electrodes for CPP MR sensor 10. During operation in the presence of a bit field from recorded media, the magnetization direction of freelay assembly 16 will change in relation to the fixed magnetization of reference layer 24 of reference layer assembly 22 and will be detected as a change in electrical resistance (and voltage) between shields 12 and 36.

25 In the sensor stack, spacer layer 20 separates freelay assembly 16 and reference layer assembly 22. If spacer layer 20 is a conducting layer, MR sensor 10 is a GMR sensor. If spacer layer 20 is an electrically insulating layer, MR sensor 10 is a TMR sensor. Freelay assembly 16 comprises first freelay 17 under second freelay 19. 30 Second freelay 19 is separated from reference layer assembly 22 by spacer layer 20. Reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface (MCS) 100 is occupied by front shield 32. Front shield 32 is separated from reference layer assembly 22 and spacer layer 20 by insulator layer 34. Top shield 36 is on reference layer

assembly 22 and front shield 32. First freelay 17 is separated from bottom shield 12 by seedlayer 14. Reference layer assembly 22 comprises a synthetic antiferromagnetic stack comprising reference layer 24 and pinning layer 27 separated by nonmagnetic layer 24. Pinning layer 27 is exchange coupled to antiferromagnetic layer 28 which, in turn, is under cap layer 29.

The linear dimension of the down track sensing area of MR sensor 10 is, in this case, defined by the spacing between front shield 32 and bottom shield 12 at MCS 100. This distance is less than the distance between top shield 36 and bottom shield 12 due to the presence of front shield 32.

FIG. 1B shows the media confronting surface view of MR sensor 10. Side shields 38A and 38B are shown on both sides of the active sensor area containing seed layer 14, first freelay 17, second freelay 19 and spacer layer 20. Insulator layer 34 separates side shields 38A and 38B from the active area of the sensor. The track width of MR sensor 10 is defined by the lateral separation of the side shields.

First freelay 17 exhibits a magnetization direction perpendicular to the planar orientation of the layer and is comprised of, for example, TbFeCo. Other possible materials for freelay 17 are rare earth transition metal alloys such as GdFe, GdCoFe, TbCo, TbCoFe, or alloys of Co, Fe, Pt and Pd or single or multiple bilayers of Co, Fe, CoCr, CoFe coupled with Pt or Pd, such as (Co/Pt) n where n can be any number..

Second freelay 19 also exhibits magnetization direction perpendicular to the planar orientation of the layer and provides high spin polarization and tunneling magnetoresistance and is comprised of, for example, CoFeB other possible materials for freelay 19 are Co, Fe, Ni or their alloys or CoX, CoNiX, CoFeX where X=B, Ru, Rh or Pt. The perpendicular magnetization direction of freelay 19 is enforced by the exchange coupling with the freelay 17. Top shield 36, front shield 32, bottom shield 12, and side shields 38A and 38B are preferably made of soft magnetic material such as, but not limited to, NiFe, NiCoFe, and CoZrNb. In what follows, all like numbered layers are of identical materials to those named here.

Spacer layer 20 is a nonmagnetic layer disposed between freelay 19 and reference layer assembly 22. Spacer layer 20 may be a nonmagnetic conductive material such as Cu, Ag, Au, or Ru, making MR sensor 10 a giant magnetoresistive (GMR) sensor. Alternatively, spacer layer 20 may be a nonmagnetic insulator or semiconductor material such as oxides formed of Mg, Al, Hf, or Ti, making MR sensor 10 a tunneling magnetoresistive (TMR) sensor.

The magnetization direction of freelay assembly 16 is perpendicular to the fixed magnetization direction of reference layer 24 in reference layer assembly 22. Reference layer assembly 22 may be a single ferromagnetic layer having an anisotropy defined magnetization direction. Reference layer assembly 22 may also include various combinations of layers to provide magnetization having a fixed direction such as a ferromagnetic pinned layer with an antiferromagnetic pinning layer, a synthetic antiferromagnetic pinned layer (i.e. two ferromagnetic layers coupled by a nonmagnetic metal such as Ru), or a synthetic ferromagnetic pinned layer coupled to an antiferromagnetic pinning layer. Ferromagnetic layers of reference layer assembly 22 may be made of a ferromagnetic alloy such as CoFe, NiFe, or NiFeCo and the antiferromagnetic layer may be made of PtMn, IrMn, NiMn or FeMn. In what follows, all like numbered layers are of identical materials to those named here.

In operation, a sense current is passed through sensor stack 10 via leads/shields 12 and 36 such that the current passes perpendicular to the plane of the layers of sensor stack 10. The sense current may be a direct current (DC) bias current, an alternating current (AC) bias current, or a current with a combination of DC and AC bias components. As magnetization in freelay stack 16 rotates in response to external magnetic fields, the resistance of sensor stack 10 changes as a function of the angle between magnetizations in sensor stack 16 and reference layer 24. The voltage across sensor stack 10 is measured between leads/shields 12 and 36 by external circuitry (not shown) to detect changes in resistance to sensor stack 10.

As shown in FIG. 1B, the active area of sensor stack 10 is defined by the area between the front and bottom shields and the side shields which are electrically isolated from the freelay by insulator layer 34. The shield-to-shield spacing is defined by the distance between bottom shield 12 and front shield 32. In order to provide good electrical insulation, the thickness of insulating layer 34 is preferred to be about 4 to about 8 nm, preferably about 5 nm. The thickness of freelay assembly 16 is preferred to be about 4 to about 8 nm, preferably about 8 nm. The thickness of seedlayer 14 is preferred to be about 2 to about 5 nm, preferably about 2 nm. The thickness of spacer layer 20 is preferred to be about 1 nm to about 5 nm, preferably 1 nm. Under optimal conditions the shield-to-shield spacing can be about 16 nm for sensor configuration 10.

Free layer assembly 16, in this embodiment, has two layers. In other versions, the free layer assembly can have more than two layers. In a similar fashion, reference

layer assembly 22 is shown to have five layers here but could have a different number of layers in other versions.

FIGS. 2A and 2B show a schematic cross section and media confronting surface view of sensor 10', respectively. Sensor 10' is structurally similar to sensor 10 in FIGS. 1A and 1B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32'. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 10, seedlayer 14 is under freelay assembly 16 and the free and reference layer assemblies are between top shield 36, bottom shield 12, and side shields 38A' and 38B'. The shield materials in this sensor configuration are different. Front shield 32' and side shields 38A' and 38B' are made of magnetically soft insulating material such as nickel containing ferrite materials or laminated films. As a result, the requirement for electrical insulation is reduced due to the higher electrical resistivity of the ferrites and other equivalent materials. The role of the insulating material between the sensor stack and shields is mainly to break any magnetic coupling. As a result, the insulating layer can be thinner and can be about 1 nm to about 4 nm, preferably about 1 nm. The shield-to-shield spacing in sensor 10' is about 12 nm compared to the shield-to-shield spacing of about 16 nm in sensor 10.

FIGS. 3A and 3B show a schematic cross section and media confronting surface view of sensor 40, respectively. Sensor 40 is structurally similar to sensor 10 in FIGS. 1A and 1B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 10, seedlayer 14 is under freelay assembly 16 and free and reference layer assemblies 16 and 22 are between top shield 36, bottom shield 12, and side shields 38A and 38B. In comparison to sensor 10, front shield 32 and insulating layer 34 extend toward bottom shield 12 through freelay 19 such that the magnetic circuit from MCS 100 into sensor 40 is only through freelay 17 thereby reducing the active sensing area at MCS 100. As shown in the media confronting surface view in FIG. 3B, this has the result of decreasing the shield-to-shield spacing to the thickness of freelay 17 and seedlayer 14. Since the combined thickness of spacer layer 20 and freelay 19 can be about 2 nm, the shield-to-shield spacing can be as low as 14 nm in sensor 40.

FIGS. 4A and 4B show a schematic cross section and media confronting surface view of sensor 40', respectively. Sensor 40' is structurally similar to sensor 40 in FIGS. 3A and 3B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32'. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 40 seedlayer 14 is under freelay assembly 16 and the free and reference layer assemblies are between top shield 36, bottom shield 12 and side shields 38A' and 38B'. As in sensor 40, front shield 32' and insulating layer 34' extend toward bottom shield 12 through freelay 19 such that the magnetic circuit from MCS 100 into sensor 40' is only through freelay 17 thereby reducing the active sensing area at MCS 100 as shown in the media confronting surface view of FIG. 4B. This has the result of decreasing the shield-to-shield spacing to the thickness of freelay 17 and seedlayer 14.

The shield materials in sensor 40' are the same as those in sensor 10'. Front shield 32', bottom shield 12 and side shields 38A' and 38B' are made of magnetically soft insulating material such as nickel containing ferrite materials or laminated films. As a result, the requirement for electrical insulation is reduced due to the higher electrical resistivity of the ferrites and other equivalent materials. The role of the insulating materials between the sensor stack and shields is mainly to break any magnetic coupling. As a result, the insulating layer can be thinner and can be about 1 nm to about 4 nm, preferably about 1 nm. Since the combined thickness of spacer layer 20 and freelay 19 can be about 2 nm the shield-to-shield spacing can be as low as about 10 nm in sensor 40'.

FIGS. 5A and 5B show a schematic cross section and media confronting surface view of sensor 50, respectively. Sensor 50 is structurally similar to sensor 10 in FIGS. 1A and 1B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. Seedlayer 14 is under freelay assembly 16, and freelay and reference layer assemblies 16 and 22 are between top shield 36, bottom shields 12A, 12B and side shields 38A and 38B. Sensor 50 is distinguished from sensor 10 in that an additional shield layer 12B is deposited on bottom shield 12A and extends away from media confronting surface 100 until it stops and is replaced by insulating layer 13 distal from media confronting surface 100. The

purpose of insulating layer 13 is to restrict the electrical conduction path between top shield 36 and bottom shield 12 such that the current in the vicinity of MCS 100 is enhanced where magnetization rotation due to the bit fields from the media transitions are larger. In doing so, the increased current will increase signal amplitude from sensor 50. The shield-to-shield spacing of sensor 50 is defined in this case as the distance between additional shield layer 12B and front shield 32 which is the same as sensor 10 in FIGS. 1A and 1B, namely about 16 nm.

FIGS. 6A and 6B show a schematic cross section and media confronting surface view of sensor 50', respectively. Sensor 50' is structurally similar to sensor 40' in FIGS. 4A and 4B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32'. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 40', seedlayer 14 is under freelay assembly 16 and freelay and reference layer assemblies 16 and 22 are between top shield 36, bottom shields 12A, 12B, and side shields 38A' and 38B'. Front shield 32' and insulating layer 34' extend toward bottom shield 12 through spacer layer 20 and freelay 19 such that the shield-to-shield spacing extends from bottom shield 12B to front shield 33 and is on the order of 10 nm. As in sensor 50, bottom shield 12A has additional shield layer 12B extending back from MCS 100 until it confronts insulating layer 13. The purpose of insulating layer 13 is to restrict the electrical conduction path between top shield 36 and bottom shield 12B such that the current in the vicinity of MCS 100 is enhanced where magnetization rotation due to bit fields from the media transitions are larger. In doing so, the increased current will increase signal amplitude from sensor 50'.

The shield materials in sensor 50' are the same as those in sensor 40' in FIGS 4A and 4B. Front shield 32', bottom shields 12A and 12B and side shields 38A' and 38B' are made of magnetically soft insulating material such as nickel containing ferrite materials or laminated films. As a result, the requirement for electrical insulation is reduced due to the higher electrical resistivity of the ferrites and other equivalent materials. The role of the insulating materials between the sensor stack and shields is mainly to break any magnetic coupling. As a result, the insulating layer can be thinner and can be about 1 nm to about 4 nm, preferably about 1 nm. Since the combined thickness of spacer layer 20 and freelay 19 can be about 2 nm the shield-to-shield spacing can be as low as about 10 nm in sensor 51.

FIGS. 7A and 7B show a schematic cross section and media confronting surface view of sensor 60, respectively. Sensor 60 is structurally similar to sensor 10 in FIGS. 1A and 1B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 10, seedlayer 14 is under freelay assembly 16 and freelay and reference layer assemblies 16 and 22 are between top shield 36, bottom shield 12 and side shields 38A and 38B. The structure of sensor 60 is distinct from the structure of sensor 10 in that the back edge of front shield 32 is not vertical but is sloped which allows for gradual opening of the front shield into the sensor. As a result, the bit flux from the media can propagate further into the freelay and, in doing so, increase reader efficiency and output signal. All materials used in sensor 60 are identical to those in sensor 10. As a result, the shield-to-shield spacing of sensor 60 is approximately equal to the shield-to-shield spacing in sensor 10 or 16 nm.

FIGS. 8A and 8B show a schematic cross section and media confronting surface view of sensor 60', respectively. Sensor 60' is structurally similar to sensor 40' in FIGS. 4A and 4B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32'. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 40', seedlayer 14 is under freelay assembly 16, and freelay and reference layer assemblies 16 and 22 are between top shield 36, bottom shield 12 and side shields 38A' and 38B'.

The shield materials in this sensor configuration are different from the shield materials in sensor 60. Front shield 33 and side shields 40 and 41 are made of magnetically soft insulating material such as nickel containing ferrite materials or laminated films. As a result, the requirement for electrical insulation is reduced due to the higher electrical resistivity of the ferrites and other equivalent materials. The role of the insulating material between the sensor stack and shields is mainly to break any magnetic coupling. As a result, the insulating layer can be thinner and can be about 1 nm to about 4 nm, preferably about 1 nm. The structure of sensor 60' is similar to the structure of sensor 60, shown in FIG. 7A in that the front edge of the reference structure is not vertical, but is sloped which allows for gradual opening of the front shield into the sensor. In so doing, the magnetic flux from the bit fields on the media propagate further

into the freelay and, by doing so, increase the reader efficiency and output signal. In a fashion similar to sensor 40', in FIG 4A front shield 32' and insulating layer 34' extend toward bottom shield 12 through spacer layer 20 and freelay 19 to freelay 17 such that the magnetic circuit from MCS 100 into sensor 60' is only through freelay 17
5 thereby reducing the active sensing area at MCS 100 as shown in the media confronting surface view of FIG 8B. The shield-to-shield spacing of sensor 60' is similar to the shield-to-shield spacing of 40', namely about 10 nm.

FIGS. 9A and 9B show a schematic cross section and media confronting surface view of sensor 70 respectively. Sensor 70 is structurally similar to sensor 60 in FIGS.
10 7A and 7B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 60 in FIG 7A, seedlayer 14 is under freelay assembly 16 and the free and reference layer assemblies
15 are between top shield 36, bottom shield 12 and side shields 38A and 38B. As in sensor 60, sensor 70 has an additional shield layer 12B on shield layer 12A extending away from MCS 100 until it abuts insulating layer 13. A distinguishing feature of sensor 70 is that the front edge of the reference structure is not vertical but is sloped which allows for a gradual opening of the front shield into the sensor away from media confronting
20 surface 100. By doing so, the magnetic bit flux from the media transitions propagates further into the freelay and increases the reader efficiency and output signal. The shield-to-shield spacing of sensor 70 is similar to the shield-to-shield spacing of sensor 10 and is about 10 nm.

FIGS. 10A and 10B show a schematic cross section and media confronting
25 surface view of sensor 70', respectively. Sensor 70' is structurally similar to sensor 60' in FIGS. 8A and 8B in that reference layer assembly 22 is recessed from media confronting wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32'. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. Seedlayer 14 is under freelay
30 assembly 16, and freelay and reference layer assemblies 16 and 22 are between top shield 36, bottom shields 12A and 12B and side shields 38A' and 38B'. As in sensor 60', the front edge of the reference structure is not vertical but is sloped which allows for gradual opening of the front shield into the sensor. In doing so, the magnetic flux from the bit fields on the media propagate further into the freelay and increase the reader

efficiency and output signal. In addition, front shield 32' and insulating layer 34' extend toward bottom shield 12A through spacer layer 20 and freelay 19 to freelay 17 such that the magnetic circuit from media confronting surface 100 into sensor 70' is only through freelay 17 thereby reducing the active sensing area at MCS 100 as shown in the media confronting surface view of FIG. 10B.

The shield materials in sensor 70' are the same as those in sensor 10' in FIGS. 2A and 2B. Front shield 32', bottom shields 12A and 12B and side shields 38A' and 38B' are made of magnetically soft insulating material such as nickel containing ferrite materials or laminated films. As a result, the requirement for electrical insulation is reduced due to the higher electrical resistivity of the ferrites and other equivalent materials. The role of the insulating materials between the sensor stack and shield is mainly to break any magnetic coupling. As a result, the insulating layer can be thinner and can be about 1 nm to about 4 nm, preferably about 1 nm. Since the combined thickness of spacer layer 20 and freelay 19 can be about 2 nm, the shield-to-shield spacing can be as low as about 10 nm in sensor 70'. As in sensor 70 in FIG 9A, sensor 70' has an additional shield layer 12A on shield layer 12A extending away from MCS 100 until it abuts insulating layer 13. The purpose of insulating layer 13 is to restrict the electrical conduction path between top shield 36 and bottom shields 12A and 12B such that the current in the vicinity of MCS 100 is enhanced whereas the magnetization rotation due to the bit fields from the media transitions are larger. In doing so, the increased current will increase the signal output from sensor 70'.

FIGS. 11A and 11B show a schematic cross section and media confronting surface view of sensor 80, respectively. Sensor 80 is structurally similar to sensor 70 in FIGS. 9A and 9B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 70, seedlayer 14 is under freelay assembly 16 and the free and reference layer assemblies are between top shield 36, bottom shield 12 and side shields 38A and 38B. As in sensor 70, the front edge of the reference layer is not vertical but is sloped which allows for a gradual opening of the front shield into the sensor away from the media confronting surface. In doing so, the bit flux from the media transitions propagates further into the freelay and increases the reader efficiency and output signal. In contrast to sensor 70 wherein shield layer 12B and insulator 13 were on shield layer 12A and wherein insulator layer 13

abutted shield layer 12B distal from media confronting surface 100, bottom shield layer 12 is a single layer that gradually decreases in thickness distal from MCS 100 and is replaced by insulator layer 13. The purpose of insulating layer 13 is to restrict the electrical conduction path between top shield 36 and bottom shields 12A and 12B such that the current in the vicinity of MCS 100 is enhanced so that the magnetization rotation due to the bit fields from the media transitions are larger. In doing so, the increased current will increase the signal output from sensor 70'. The gradual sloping of bottom shield layer 12 away from media confronting surface 100 assists in concentrating the field and the magnetic circuit in freelay assembly 16 in response to bit flux from transitions written on the media. The shield-to-shield spacing of sensor 80 is similar to the shield-to-shield spacing of sensor 10 in FIGS. 1A and 1B, namely about 16 nm.

FIGS. 12A and 12B which show a schematic cross section and media confronting surface view of sensor 80', respectively. Sensor 80' is structurally similar to sensor 80 in FIGS. 11A and 11B in that reference layer assembly 22 is recessed from media confronting surface 100 wherein the space between reference layer assembly 22 and media confronting surface 100 is occupied by front shield 32'. Reference layer assembly 22 is separated from freelay assembly 16 by spacer layer 20. As in sensor 80, seedlayer 14 is under freelay assembly 16 and the free and reference layer assemblies are between top shield 36, bottom shield 12 and side shields 38A' and 38B'. As in sensor 80, the front edge of the reference structure is not vertical but is sloped which allows for a gradual opening of the front shield into the sensor away from the media confronting surface. By doing so the magnetic bit flux from the media transitions propagates further into the freelay and increases the reader efficiency and output signal. The shield-to-shield spacing of sensor 80' is similar to the shield-to-shield spacing of sensor 70' in FIGS. 10A and 10B and is about 10 nm. Bottom shield 12 in sensor 81 is a single layer that starts to decrease in thickness at a point distal from MCS 100 wherein the decreased thickness is replaced by insulating layer 13. The purpose of insulating layer 13 is to restrict the electrical conduction path between top shield 36 and bottom shield 12B such that the current in the vicinity of MCS 100 is enhanced where the magnetization rotation due to the bit fields from the media transitions are larger. In doing so, the increased current will increase signal amplitude from sensor 70. The sloped contour of bottom shield 12 away from media confronting surface 100 aids in magnetic circuit flow through freelayers 17 and 19 enhancing signal output of sensor 8D'.

FIG. 13A is a top view of the magnetic sensor layout showing the geometrical relation between the side shield and the sensor stack. The sides of the side shield, in this case, are straight and are parallel to the sides of reference layer assembly 22 and freelay assembly 16. This geometry is preferred from the standpoint of manufacturability. An enhanced geometry from the standpoint of performance is shown in FIG. 13B wherein the thickness of insulating layers 34 and 34' in the vicinity of reference layer assembly 22 is increased. This has the advantage of allowing easier flux penetration from the media transitions and resulting improved reader efficiency.

In summary, a number of configurations of a CPP magnetic sensor comprising a freelay assembly, a reference layer assembly, top, bottom, side and front shields are described. Magnetization orientation of the freelayers is substantially perpendicular to the planar orientation of the layers. A distinguishing characteristic of the reader designs is that a front shield is positioned between the reference layer assembly and the media confronting surface thereby reducing shield-to-shield spacing and increasing areal density of the reader. Configurations are described that enhance media flux flow into the reader and electrical current flow proximate the media confronting surface of the magnetic sensor.

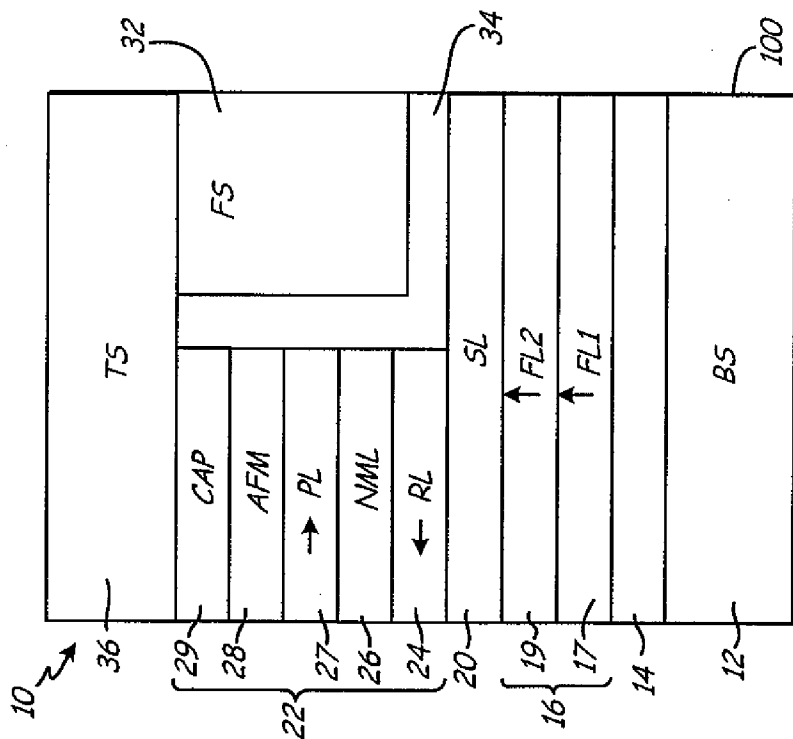
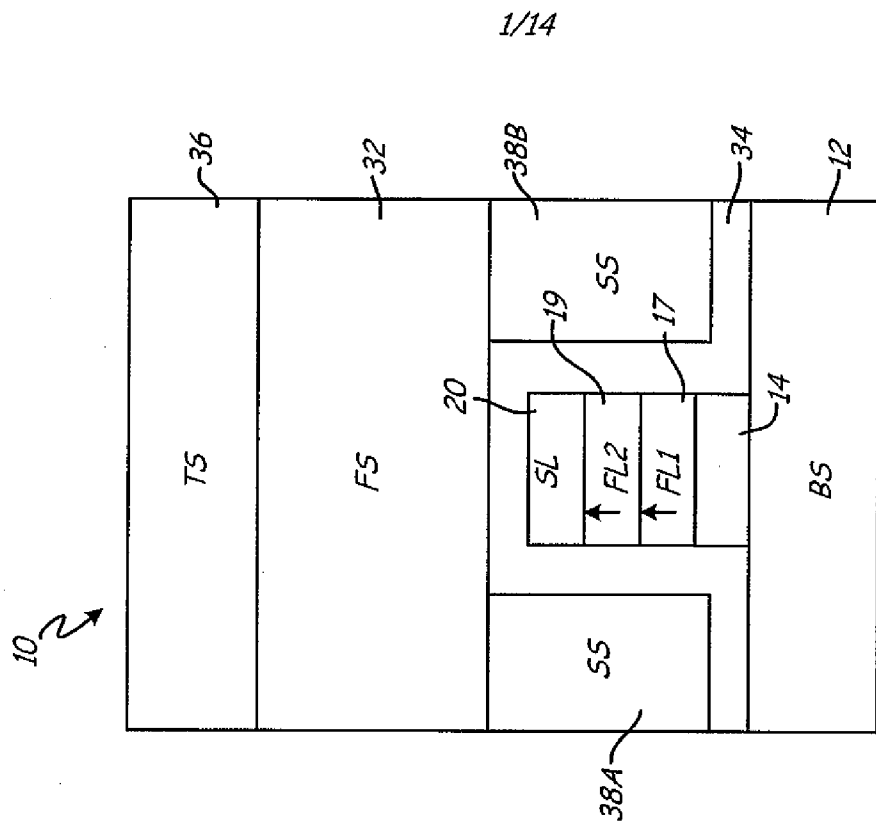
In other configurations, the relative positions of freelay assembly 16 and reference layer assembly 22 may be reversed, so that reference layer assembly 22 is closer to bottom shield 12. In that case, front shield 32 may be positioned adjacent bottom shield 12 rather than top shield 36.

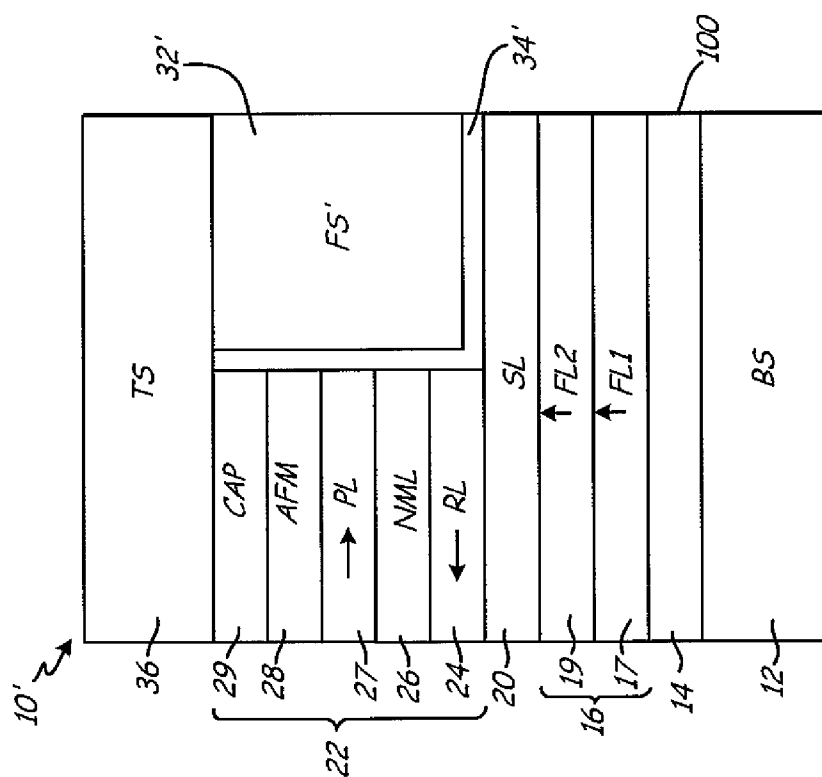
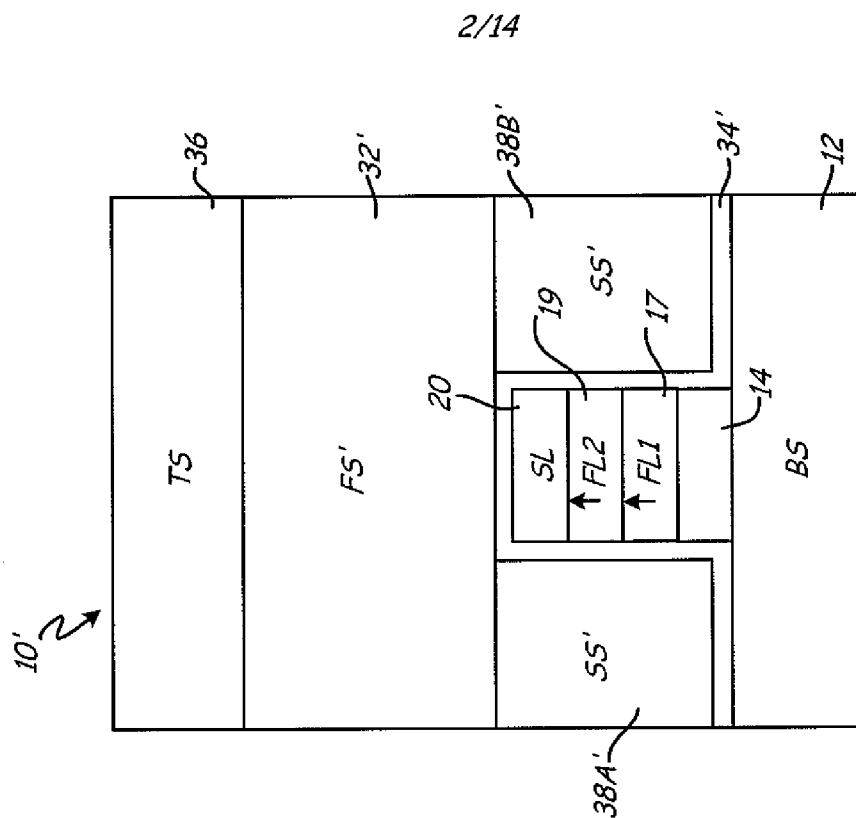
Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. The implementations described above and other implementations are within the scope of the following claims.

CLAIMS:

1. A magnetic sensor comprising:
 - a top shield;
 - a bottom shield;
 - a magnetoresistive stack positioned between the top and bottom shields and including:
 - a first freelay having a magnetization direction substantially perpendicular to a plane orientation of the first freelay, the first freelay extending to a media confronting surface;
 - a reference layer having a magnetization direction substantially in a plane of the reference layer and substantially perpendicular to the magnetization direction of the first freelay, the reference layer being recessed from the media confronting surface; and
 - a nonmagnetic spacer layer positioned between the first freelay and the reference layer; and
 - a front shield positioned between the reference layer and the media confronting surface.
2. The magnetic sensor of claim 1 and further comprising:
 - An insulating layer positioned between front shield and the magnetoresistive stack.
3. The magnetic sensor of claim 1 and further comprising:
 - first and second side shields positioned on opposite sides of the first freelay.
4. The magnetic sensor of claim 3, wherein the first and second side shields are in magnetic contact with the front shield.
5. The magnetic sensor of claim 4, wherein the front shield is in magnetic contact with one of the top and bottom shields.
6. The magnetic sensor of claim 5 and further comprising:
 - an insulating layer positioned between the magnetoresistive stack and the front shield, first side shield, and second side shield.
7. The magnetic sensor of claim 3, wherein the top shield and bottom shield and first and second side shields comprise a soft magnetic material.
8. The magnetic sensor of claim 3, wherein the top shield, bottom shield and first and second side shields comprise magnetically soft insulating material.

9. The magnetic sensor of claim 1, wherein the bottom shield is partially covered with an insulating layer such that sense current flow is confined to a region proximate the media confronting surface.
10. The magnetic sensor of claim 1, wherein a back wall of the front shield slopes away from the media confronting surface to facilitate increased magnetic flux flow from the media confronting surface into the magnetoresistive stack.
11. The magnetic sensor of claim 1, wherein the magnetoresistive stack further includes:
 - a nonmagnetic layer adjacent the reference layer;
 - a magnetic pinning layer adjacent the nonmagnetic layer; and
 - an antiferromagnetic layer adjacent the magnetic pinning layer.
12. The magnetic sensor of claim 11, wherein the nonmagnetic layer, magnetic pinning layer, and antiferromagnetic layer are recessed from the media confronting surface, and the front shield is positioned between the media confronting surface and the nonmagnetic layer, magnetic layer, and the antiferromagnetic layer.
13. The magnetic sensor of claim 1, wherein the front shield is also positioned between the nonmagnetic spacer layer and the media confronting surface.
14. The magnetic sensor of claim 1, wherein the magnetoresistive stack further includes a second freelay.
15. The magnetic sensor of claim 14 wherein the first freelay comprises GdFe, GdCoFe, TbCo, TbCoFe, or alloys of Co, Fe, Pt and Pd or single or multiple bilayers of Co, Fe, CoCr, CoFe coupled with Pt or Pd.
16. The magnetic sensor of claim 14 wherein the second freelay comprises CoFeB, Co, Fe, Ni, or their alloys or CoX where X=B, Ru, Rh or Pt.
17. The magnetic sensor of claim 14, wherein the second freelay is positioned between the first freelay and the nonmagnetic spacer layer.
18. The magnetic sensor of claim 17, wherein the second freelay is recessed from the media confronting surface.
19. The magnetic sensor of claim 18, wherein the second freelay is separated from the front shield by an insulating layer.
20. The magnetic sensor of claim 1, wherein the nonmagnetic spacer layer comprises at least one of Cu, Ag, Au, or Ru, and oxides of Mg, Al, Hf or Ti.





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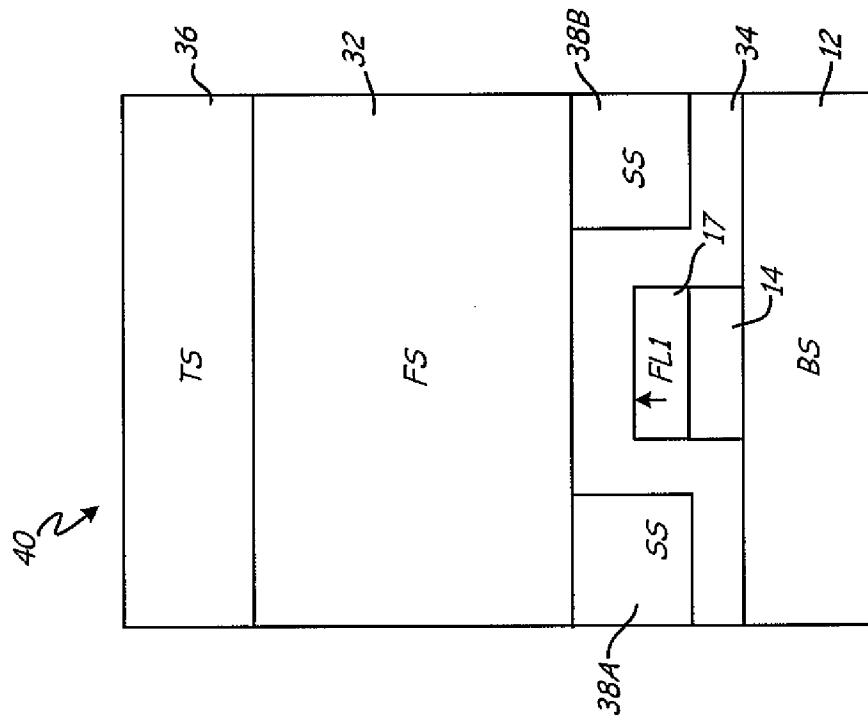


Fig. 3B

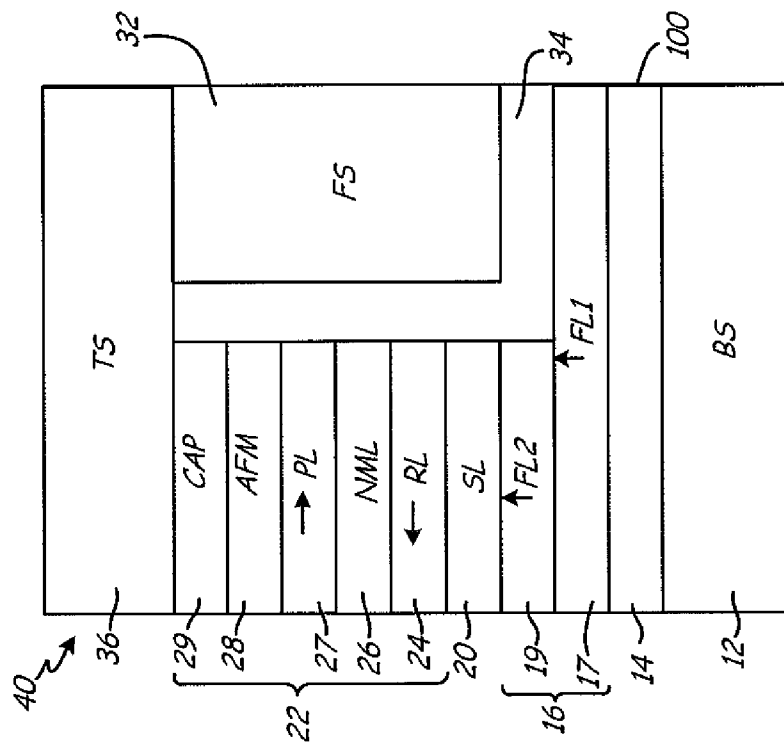


Fig. 3A

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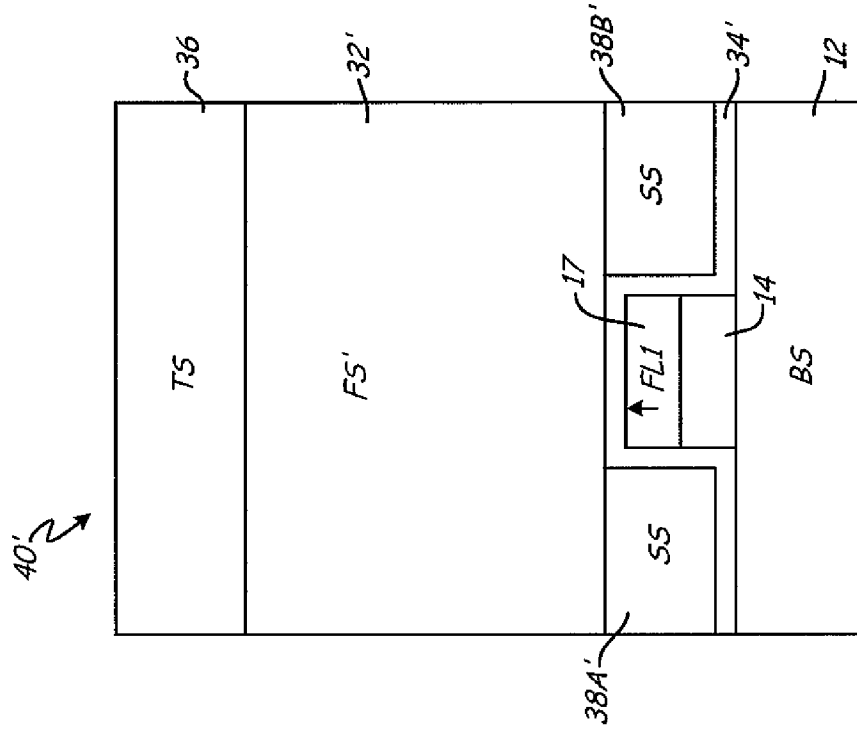


Fig. 4A

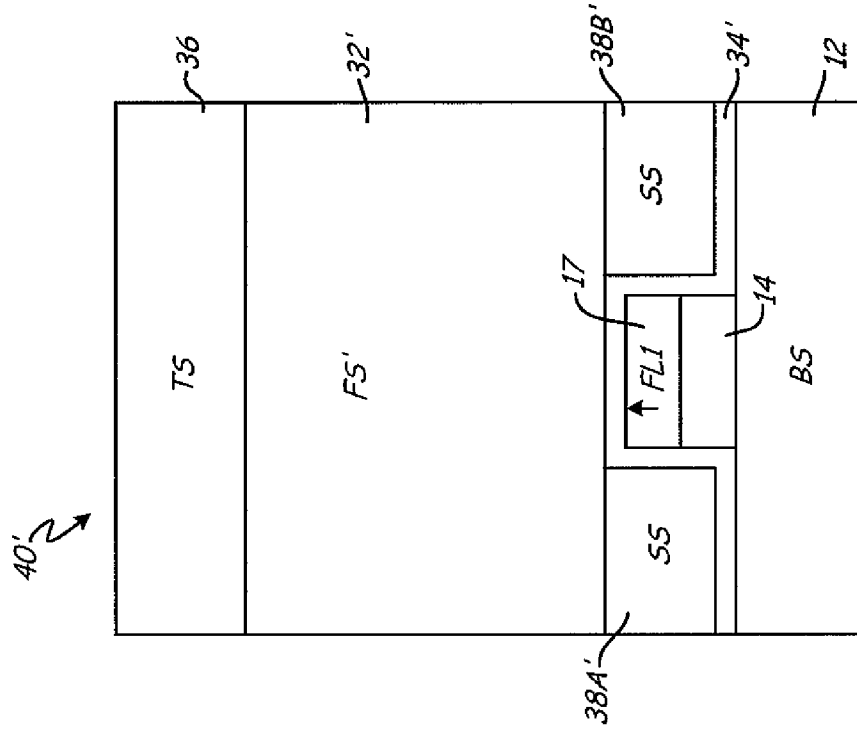


Fig. 4B

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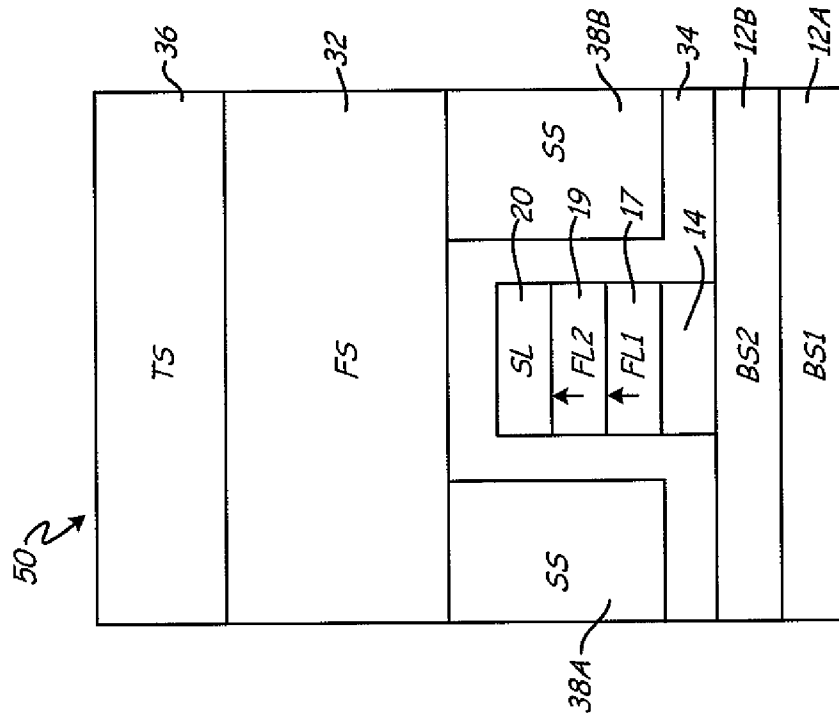


Fig. 5B

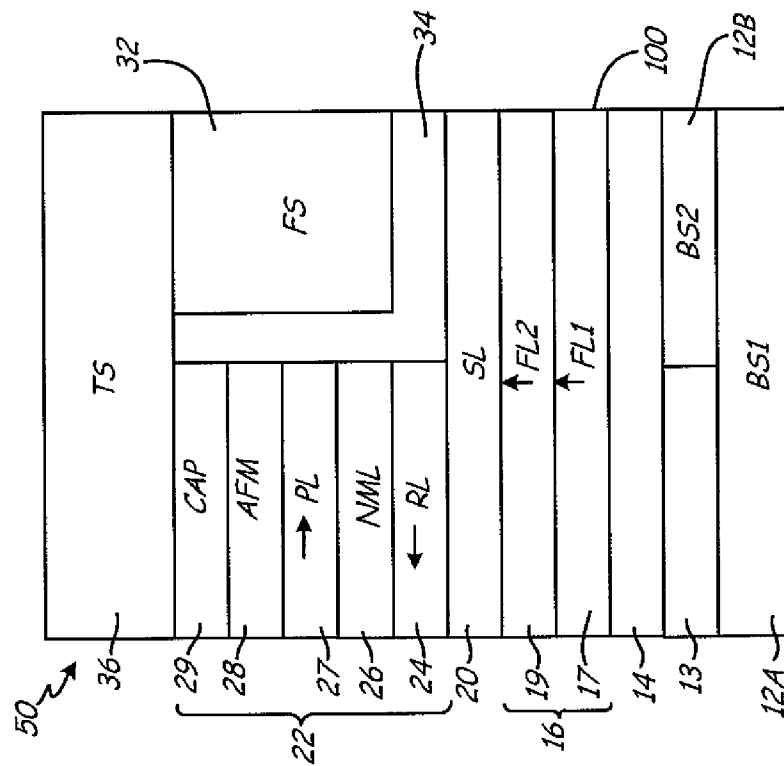


Fig. 5A

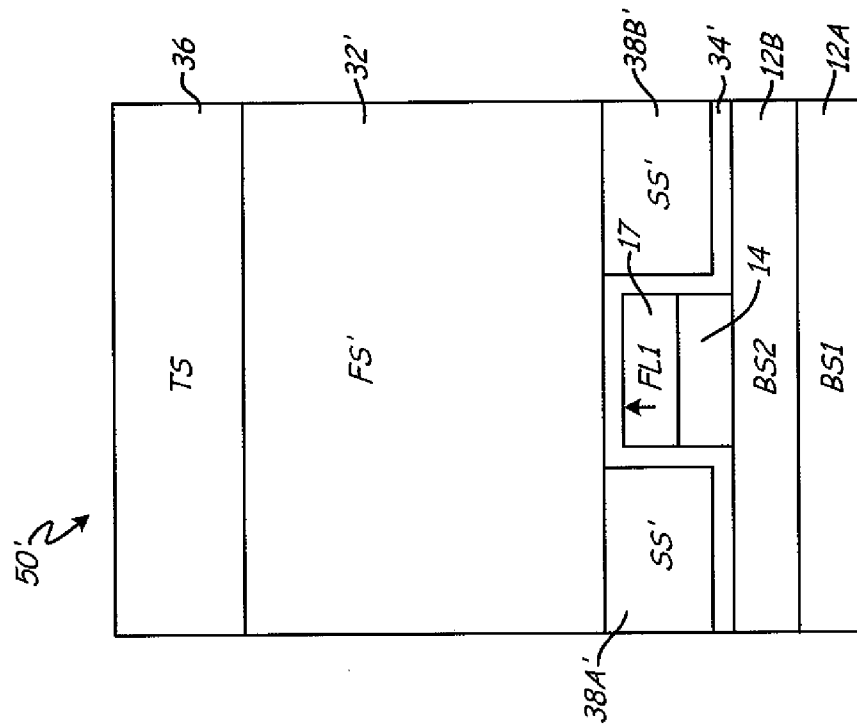


Fig. 6B

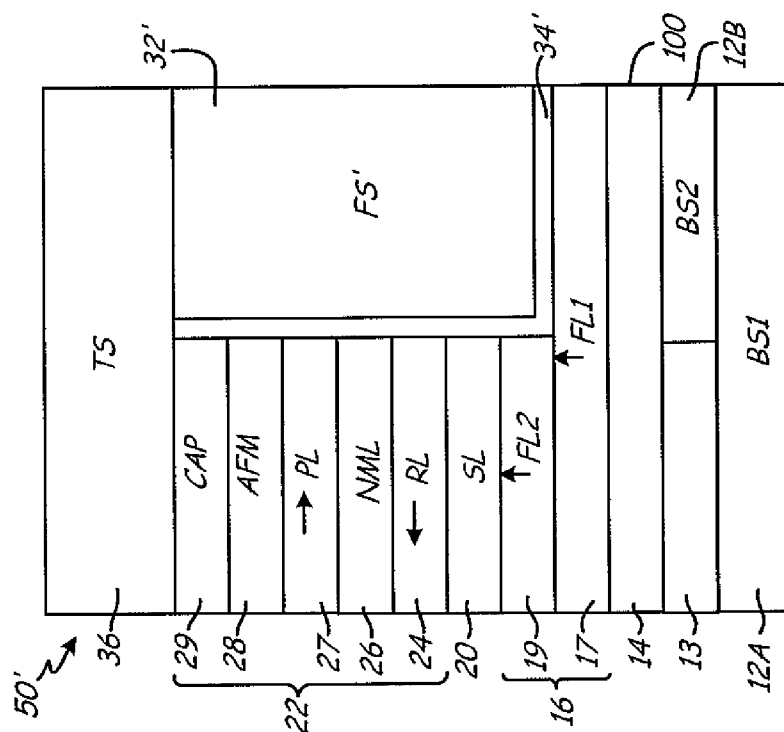


Fig. 6A

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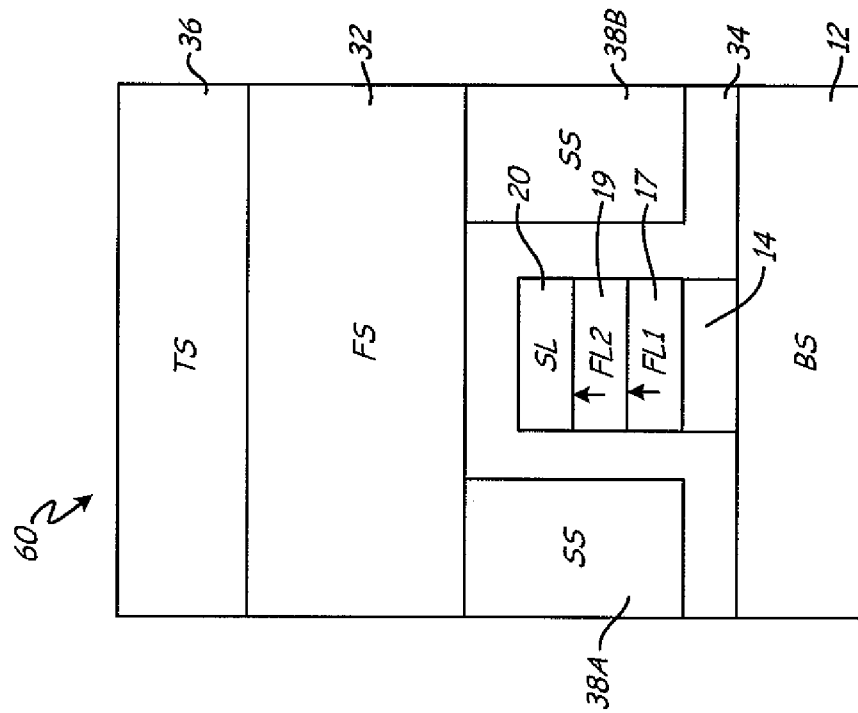


Fig. 7A

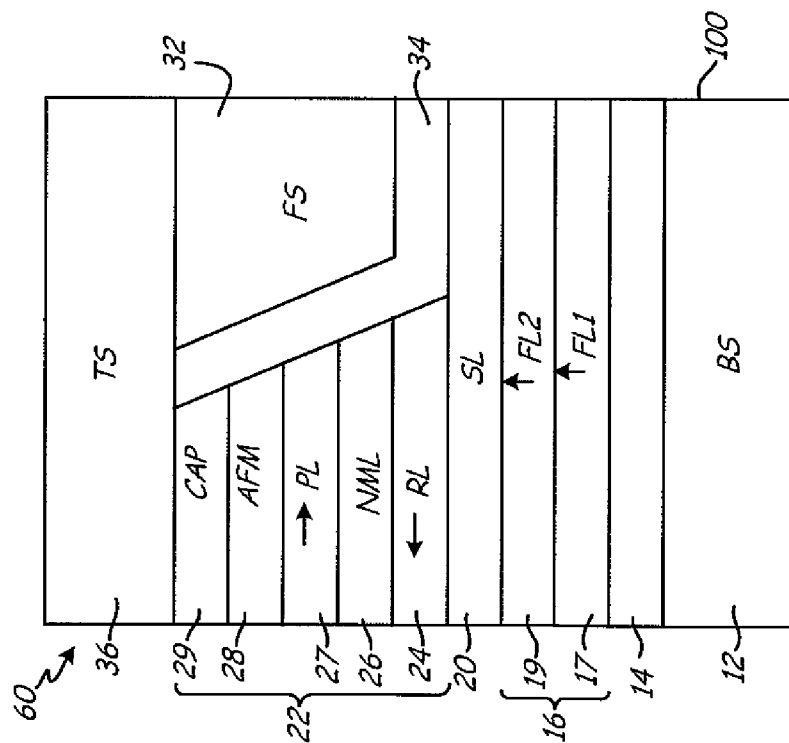


Fig. 7B

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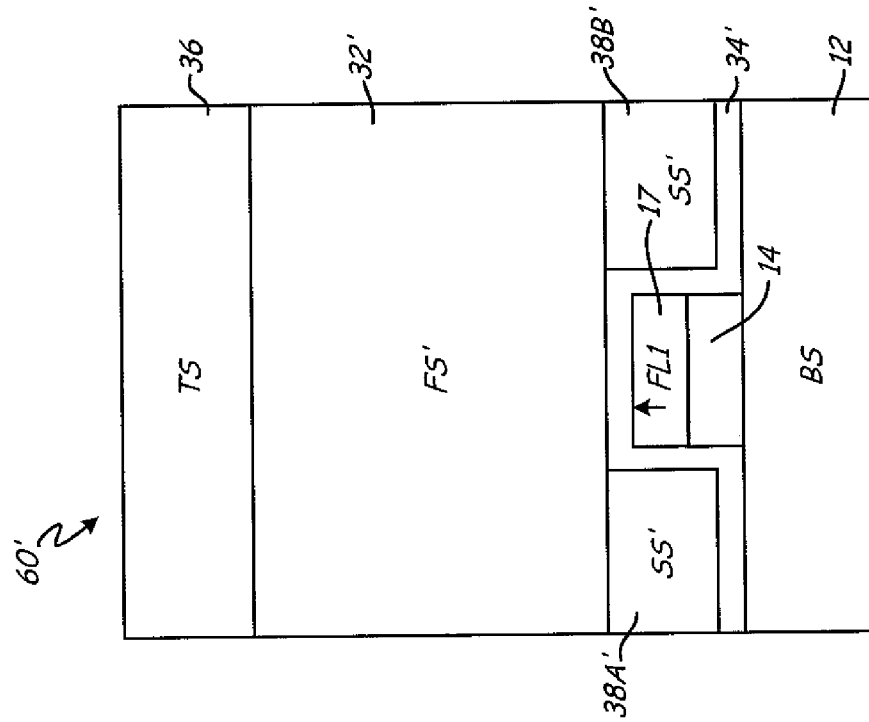


Fig. 8B

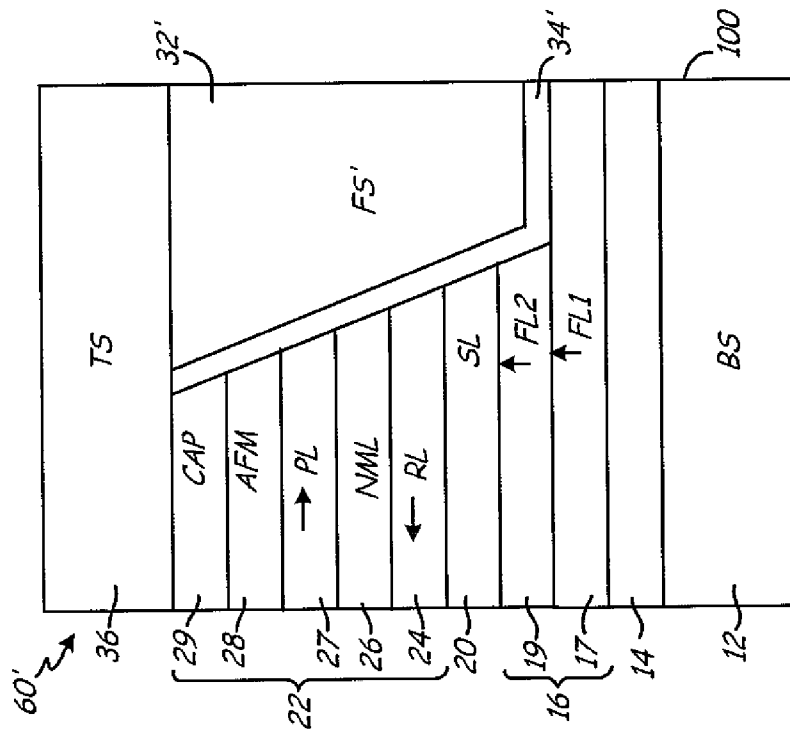


Fig. 8A

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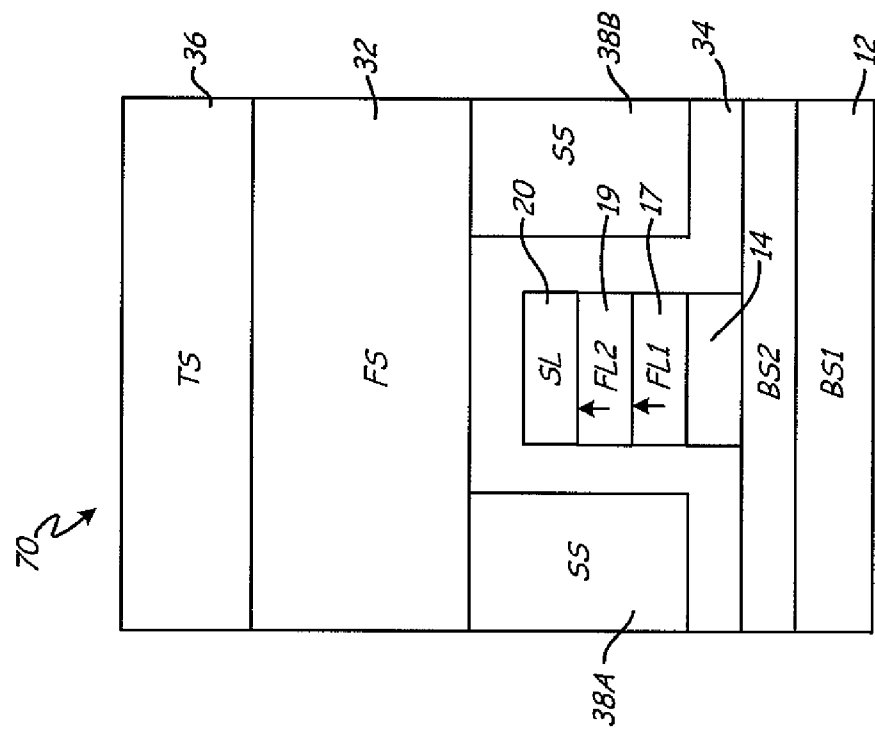


Fig. 9B

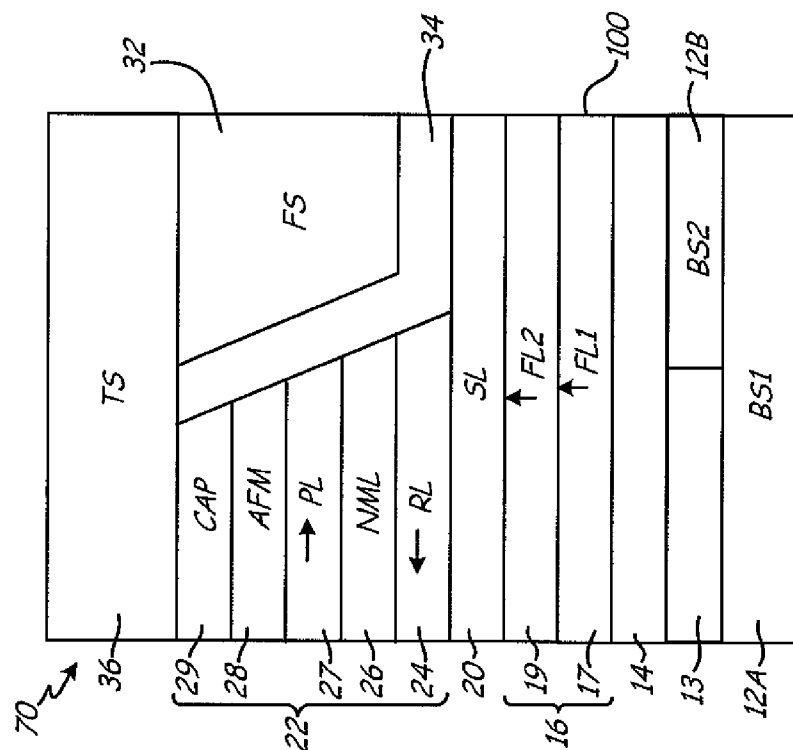


Fig. 9A

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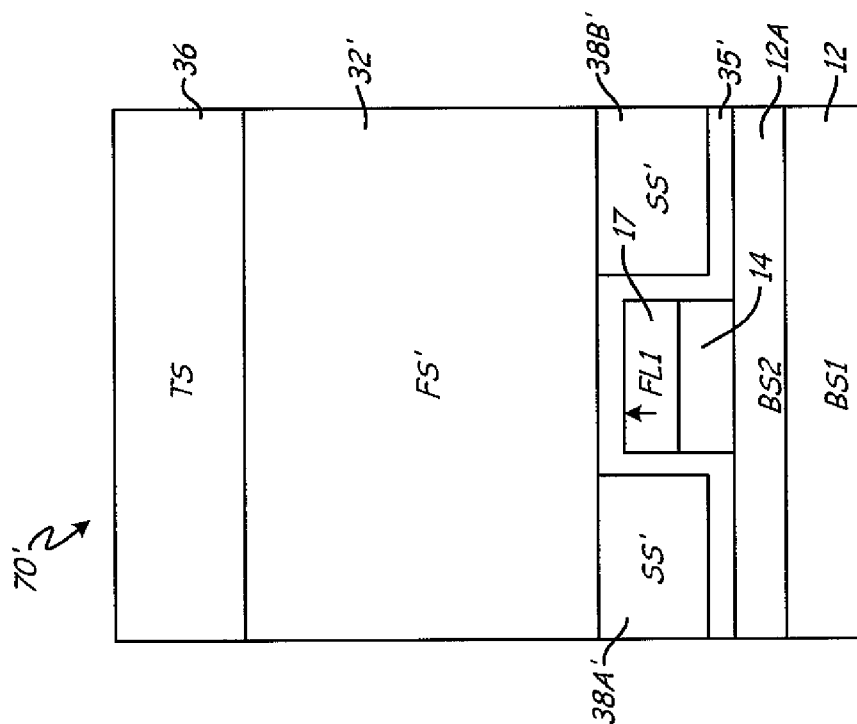


Fig. 10B

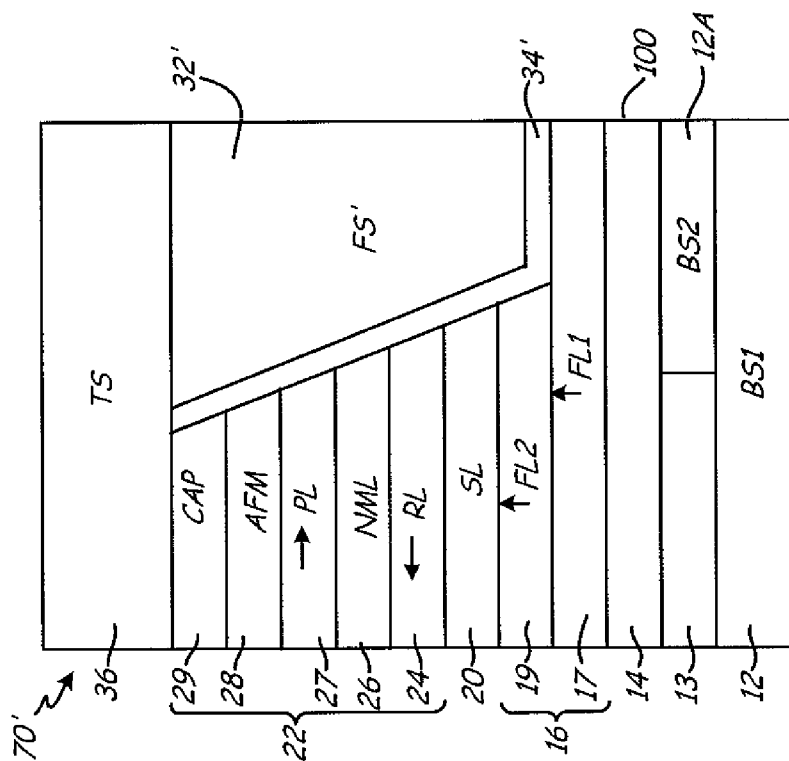


Fig. 10A

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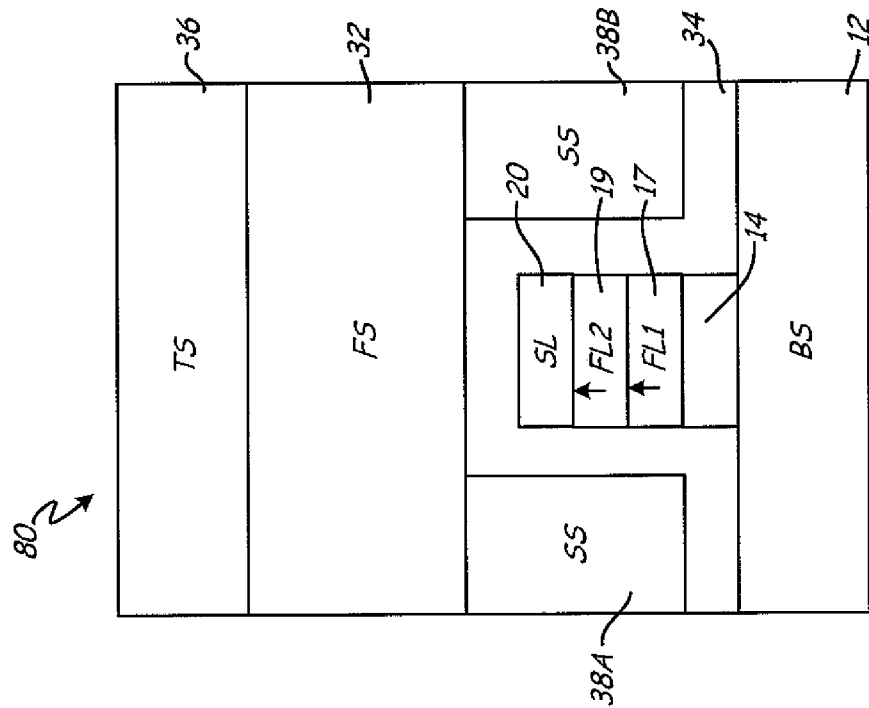


Fig. 11B

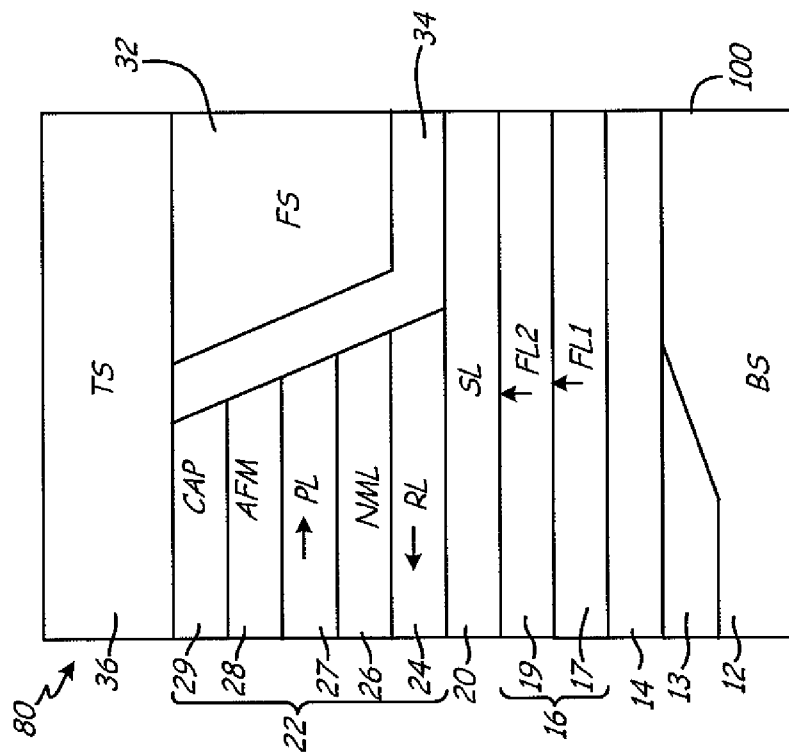


Fig. 11A

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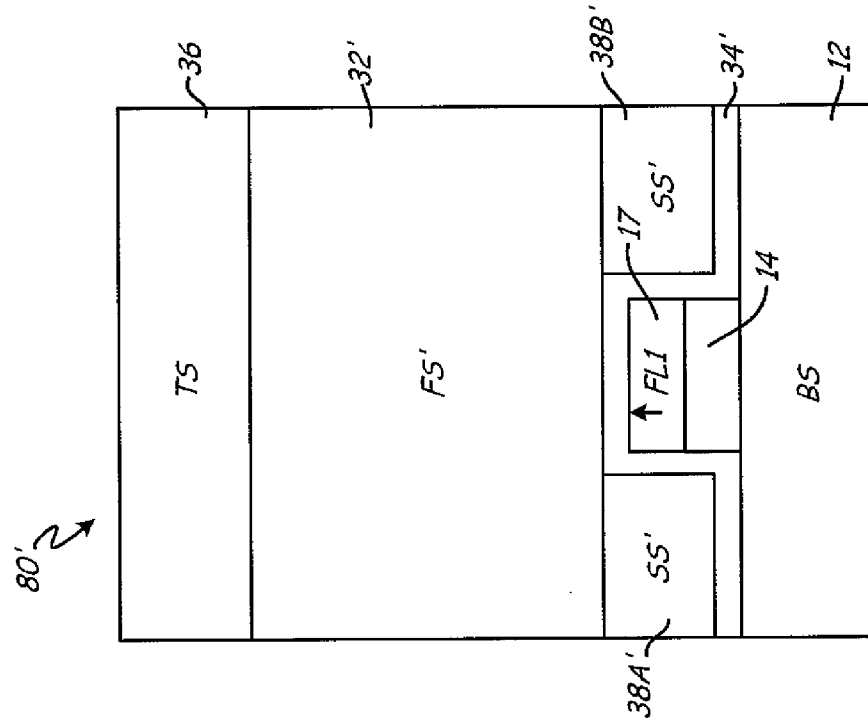


Fig. 12B

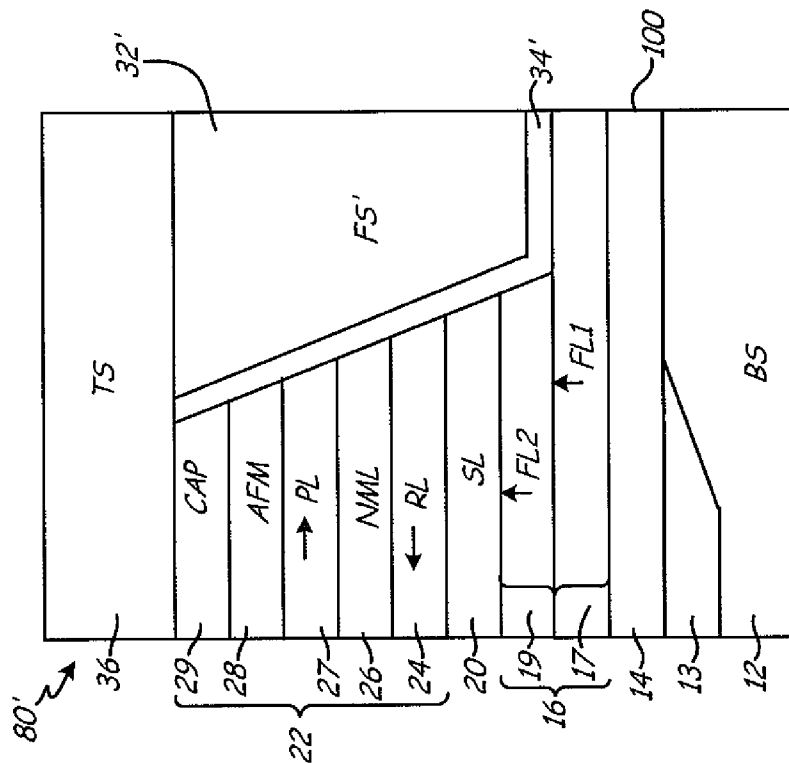


Fig. 12A

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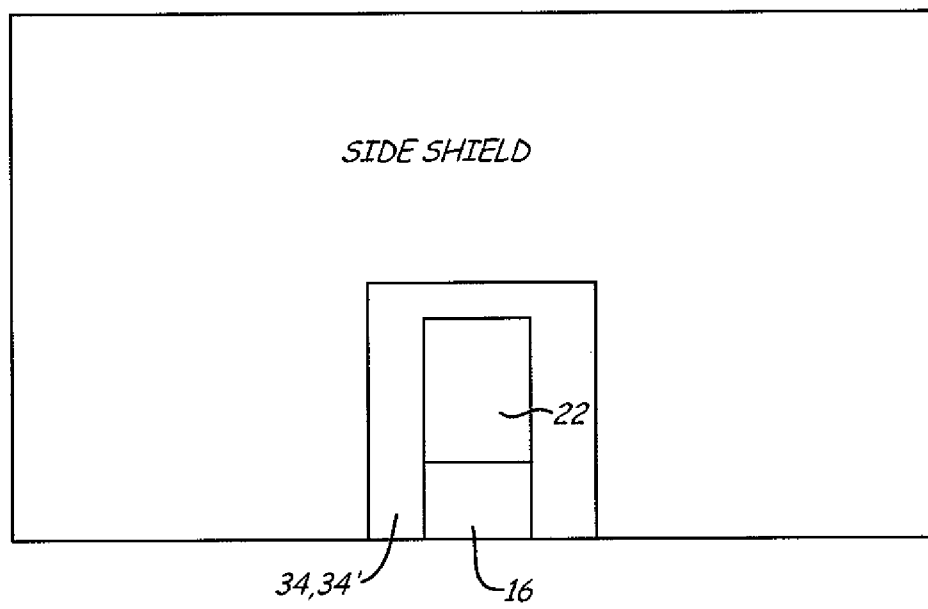


Fig. 13A

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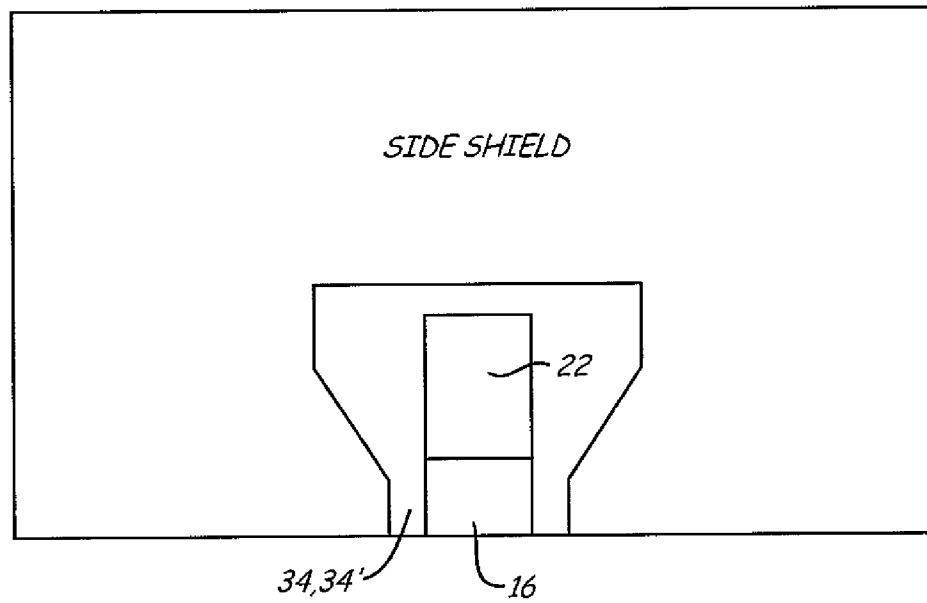


Fig. 13B

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/027510

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01R33/09
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2008/112087 A1 (CLINTON THOMAS WILLIAM [US] ET AL) 15 May 2008 (2008-05-15) abstract; figure 20 paragraph [0065] - paragraph [0067] -----	1-5, 8-20 6, 7
Y A	US 7 035 062 B1 (MAO SINING [US] ET AL) 25 April 2006 (2006-04-25) figures 2-6 -----	1-5, 8-20 6, 7

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search

28 May 2010

Date of mailing of the international search report

07/06/2010

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Authorized officer

Böhm-Pélissier, A

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2010/027510

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2008112087 A1	15-05-2008	CN 101261838 A	10-09-2008
		JP 4348389 B2	21-10-2009
		JP 2008123669 A	29-05-2008
US 7035062 B1	25-04-2006	NONE	