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BRIDGE CONFIGURATION FOR A MAGNETO-RESISTIVE LINEAR-DISPLACEMENT SENSOR

BACKGROUND OF THE INVENTION

The present invention relates to a giant magneto-resistance (GMR) film used, typically, in a magneto-resistive linear-displacement sensor.

Giant magneto-resistance, or GMR, is a relatively newly discovered phenomenon. Briefly stated, it has been discovered that a significant change in resistance ($\Delta R/R$ as much as 10% to 20% in some systems) can be obtained when the GMR films are subjected to a magnetic field, as compared to the $\Delta R/R \simeq 2\%$ typical of traditional magneto-resistive films. In general, GMR films are in a high resistance state when the magnetization in the GMR multilayers are predominately anti-parallel in consecutive magnetic layers, and can then be brought to a low resistance state by the action of an applied field which rotates each layer's magnetization in a predominately parallel orientation roughly along the applied field direction.

The known GMR effect (also known as the spin-valve effect) has been observed in a variety of magnetic multilayered structures, with a typical feature of the structures including at least two ferromagnetic metal layers separated by a non-ferromagnetic middle layer. For example, the GMR effect has been found in arrangements such as Fe/Cr, Co/Cu, or Co/Ru multilayers which exhibit strong antiferromagnetic coupling of the ferromagnetic layers, as well as in essentially uncoupled layered structures in which the magnetization orientation in one of the two ferromagnetic layers is fixed or pinned. The physical origin of the GMR effect is the same

1   in all types of structures: the application of an external magnetic field causes a variation in the

2   relative orientation of the magnetizations of neighboring ferromagnetic layers. This in turn causes

3   a change in the spin-dependent scattering of conduction electrons and thus the electrical resistance

4   of the structure. The resistance of the structure thus changes as the relative alignment of the

5   magnetizations of the ferromagnetic layers changes.

6   A known application of the GMR effect can be found in a sandwich structure or film

7   comprising two uncoupled ferromagnetic layers separated by a non-magnetic metallic layer in

8   which the magnetization of one of the ferromagnetic layers is pinned. The pinning may be

9   achieved by depositing the layer onto an iron-manganese layer to exchange couple the two layers.

10   This results in a spin valve magneto-resistive sensor in which only the unpinned or free ferro-

11   magnetic layer is free to rotate in the presence of an external magnetic field.

12   Stated alternatively, the known GMR film consists primarily of three ultra thin layers atop

13   a substrate: two ferromagnetic layers separated by a non-magnetic layer. One of the ferromagnet-

14   ic layers is biased, which is a condition that causes its magnetization to always point in one

15   direction. The other ferromagnetic layer is unbiased, with magnetization that changes direction

16   when a small field is applied. The resistance of this trilayer film changes as a magnetic field,

17   created for example by two magnets, is moved across it, thus allowing, for example, a position

18   determination of the film relative to the magnets to be made through a measurement of the

19   resistance.

1   Biasing of the one ferromagnetic layer can be achieved in several ways. For example, the

2   layer may be pretreated, i.e., annealed or grown in the presence of a magnetic field, which allows

3   the crystal structure of the material to orient in such a way that the internal anisotropies encour-

4   age the magnetization to stay along one direction. The bias would remain in this set direction

5   as long as the layer is not exposed to magnetic fields greater than the material's coercive fields.

6   It is therefore advantageous to use high coercivity or "hard" materials for the biased ferromagnet-

7   ic layer. A material may also be intrinsically hard, and/or have a carefully chosen adjacent layer

8   that will increase its coercivity. It is also possible to perform biasing or repair the biasing by

9   running appropriate currents in the layer. Conversely, the unbiased layer should be as "soft" as

10   possible, so that its magnetization will change under the application of small magnetic fields.

11   Typically, the harder magnetic layer includes hard ferromagnetic materials such as Co, Fe,

12   and alloys thereof, and antiferromagnetically-pinned materials. The harder magnetic layer will

13   typically have a thickness of about 20 Å to about 1,000 Å, and preferably about 45 Å.

14   Preferred materials for the softer magnetic layer will include Ni, Fe, permalloy, Co, and

15   combinations thereof (such as alloys and multilayer sandwiches). Typically, the softer magnetic

16   layer will be between 20 Å and about 1,000 Å thick, and preferably about 45 Å.

17   Preferred materials for the intermediate layer includes Cu, Pt, Ag, Au, and combinations

18   thereof. Typically, the intermediate layer will be between 20 Å and about 1,000 Å thick, and

19   preferably about 45 Å.

1   Preferably, layers are deposited with the greatest uniformity practicable, to maximize the

2   linearity of the device. If, e.g., an NiO layer is used as a pinning layer, this NiO layer preferably

3   would be deposited as an outside layer, without depositing any of the other magnetic layers on

4   top of it.

5   The substrate may be a substance such as glass, ceramic or a semiconductor upon which

6   the trilayer film is deposited. However, preferably the substrate will be a silicon or quartz

7   material. The properties of the substrate material should include non-conductivity. Further, the

8   selected substrate material should have a low coefficient of thermal expansion, and be rigid and

9   non-flexing. The material should also be capable of presenting a flat surface, and should allow

10   the other layers to be grown on it.

11   As noted, the GMR film can be used in various applications, for example, linear and

12   angular displacement sensors, such as disclosed in U.S. Patent 5,475,304 to Prinz, the subject

13   matter of which is incorporated herein by reference. As disclosed by this reference, the magneto-

14   resistive linear-displacement sensor measures the relative position of two workpieces by fixing

15   the first workpiece to a GMR film, and fixing the second workpiece to, for example, indexing

16   magnets whose movement relative to the GMR film will cause a change in resistance in the GMR

17   film, thus allowing a precise determination of the positions of the first and second workpieces.

18   One problem associated with the above described magneto-resistive linear-displacement

19   sensor is its sensitivity to changes in operating temperatures and the resulting decrease in its

20   measurement accuracy. It is known to compensate for changes in temperatures by providing a

1   thermobridge consisting of two strips of GMR film placed in line, and end-to-end with each

2   other, and in as close proximity as possible to one another to ensure both strips are at the same

3   temperature. These known bridge configurations use one strip of the GMR film as the sensor,

4   and the other strip as a reference, which allows the resistance changes due to material thermal

5   effects to be compensated for, as long as the reference strip is isolated from the magnetic fields

6   that will surround its neighboring sensor strip. However, to perform this magnetic shielding of

7   the reference strip, special material must be included between the two adjacent strips. This

8   results in an added length and further processing steps for the final device.

9   Temperature compensation of the above sensor is necessary because as the magnets are

10   moved across the strips, the resistance of the strips is directly related to any change in tempera-

11   ture that may occur since the magnets are first moved. However, this known temperature

12   compensation arrangement is problematic, i.e., requiring a device in which the GMR strips are

13   placed end-to-end, since the temperature of the reference strip may not be at the same tempera-

14   ture as the sensor strip.

15

16   <u>**SUMMARY OF THE INVENTION**</u>

17   It is an object of the present invention to provide a new bridge configuration which will

18   overcome the deficiencies of the prior art GMR arrangements.

1   It is a further object of the present invention to provide a bridge configuration that reduces

2   the fluctuations and drift in the resistance measurement that can arise from changes in the

3   temperature of the device.

4   It is a further object of the present invention to provide a bridge configuration that

5   compensates for thermal deviations using a smaller package.

6   It is yet a further object of the present invention to provide a bridge configuration that will

7   provide an increased signal strength over the prior art devices.

8   It is yet a further object of the present invention to provide a GMR device that will reduce

9   the impact of small inhomogeneities in the material.

10   The above and other objects are accomplished according to the invention by the provision

11   of a thermal bridge that includes a first Giant Magneto Resistance film having a layer with a

12   fixed bias pointing in a first direction, and a second Giant Magneto Resistance film superposed

13   on, and in thermal engagement with, the first Giant Magneto Resistance film. The second Giant

14   Magneto Resistance film has a layer with a fixed bias pointing in a second direction opposite to

15   the first direction.

16   The invention will now be described below in greater detail in connection with an

17   embodiment thereof that is illustrated in the drawing figures.

18

19   **BRIEF DESCRIPTION OF THE DRAWINGS**

1   Figure 1 is a cross-sectional view of a trilayer element with layers having aligned

2   magnetic fields.

3   Figure 2 is a cross-sectional view of a trilayer element with layers having opposing

4   magnetic fields.

5   Figure 3 is a cross-sectional side view of a trilayer element with a domain wall in one of

6   the magnetic layers, separating the regions of opposing magnetic fields in this layer.

7   Figure 3A is a cross-sectional side view of a trilayer element with a domain wall in one

8   of the magnetic layers, separating the regions of opposing magnetic fields in this layer, and with

9   an antiferromagnetically-pinned layer having a fixed magnetic state.

10   Figure 4 illustrates an enlarged sectional view of a GMR film atop a substrate.

11   Figure 5 is a cross-sectional side view of two trilayer GMR films arranged in accordance

12   with the present invention.

13   Figure 6 is an expanded view of the GMR bridge configuration according to the present

14   invention.

15   Figure 7 is an illustration of the bridge configuration shown in Figure 6 being passed

16   between two magnets.

17   Figure 8 is a graphical illustration of the change in the resistance of the two GMR strips

18   shown in Figure 7 relative to a position of the magnets.

19   Figure 9 is a schematic illustration of a known whetstone bridge circuit diagram.

1   Figure 10 is an illustration of the sensor using the bridge configuration shown in Figure

2   9.

3   Figure 11 is a further schematic view of the circuit used in the bridge shown in Figure

4   10.

5   Figure 12 is an alternative sensor configuration according to the present invention.

6   Figure 13 is a schematic of the circuit for the sensor shown in Figure 12.

7   Figure 14 is a schematic illustration of two bridges wired together according to the present

8   invention.

9

10   ## DETAILED DESCRIPTION OF THE INVENTION

11   Giant Magneto Resistance, or GMR, is a relatively newly discovered phenomenon.

12   Briefly stated, it has been discovered that there is a significant difference (on the order of

13   between 8% and about 20%) in electrical resistance between the structure shown in Fig. 1 and

14   the structure shown in Fig. 2.

15   Figure 1 shows a known trilayer element 10 having ferromagnetic layers 12, 14 which

16   have aligned magnetic fields. Layers 12, 14 are separated by and in contact with a non-magnetic

17   conductive layer 13. As carriers (generally electrons) are injected from a contact 16 into, for

18   example, the top ferromagnetic layer 12, the carriers are spin-polarized. The spin-polarized

19   carriers are free to travel through this ferromagnetic layer and the other conductive layer 13, 14

1   in trilayer 10. Consequently, the electrical resistance experienced by the current associated with

2   the flow of these carriers will be related to the thickness of the trilayer 10.

3·   In contrast, Fig. 2 shows a trilayer element 20 with ferromagnetic layers 22, 24 having

4   opposing magnetic fields, separated by and in contact with a non-magnetic conductive layer 23.

5   As carriers are injected from contact 16 into, for example, the top ferromagnetic layer 22, the

6   carriers are spin-polarized.   The spin-polarized carriers are free to travel through this

7   ferromagnetic layer 22 and the adjacent non-magnetic layer 23. However, when the spin-

8   polarized carrier strikes the interface with ferromagnetic layer 24 having a non-aligned magnetic

9   field, the carriers are scattered back, away from this layer, according to the GMR (i.e., spin-

10   valve) effect.

11   GMR is a function of the angle between the magnetic fields in the two layers. Scattering

12   is minimized when the fields are parallel (Fig. 1), and maximized when the fields are anti-parallel

13   (opposing) (Fig. 2). When the fields are opposing, the current associated with the flow of these

14   carriers is impeded from traveling through the entire thickness of trilayer 20, and thus the

15   electrical resistance experienced by this current will be higher, related to the thickness of only

16   the top two layers 22, 23 of trilayer 20.

17 .   Figure 3 shows another known trilayer element 30, which has a bottom layer 34 with a

18   fixed magnetic state, and a (relatively) soft magnetic top layer 32, with regions 35, 36 having

19   opposing magnetic fields. These regions 35, 36 are separated by a domain wall 37. Between and

20   contacting these two layers 32, 34 is a nonmagnetic conductive middle layer 33 for preventing

9

1   exchange coupling between the two magnetic layers 32, 34. As carriers are injected from contact

2   16 into, for example, the top ferromagnetic layer 32, the carriers are spin-polarized. The spin-

3   polarized carriers are free to travel through the ferromagnetic layer 32, the nonmagnetic layer 33

4   and the bottom ferromagnetic layer 34. Because the effective thickness of the conductor is

5   relatively large, electrical resistance will be relatively low on this side of the domain wall 37 (i.e.,

6   on the right hand side of the domain wall, as shown in the figure).

7   As the spin-polarized carriers travel further down this trilayer 30, to the far (left) side of

8   the domain wall 37, they will be confined to the bottom two layers 33, 34 of the trilayer element

9   30, in accordance with the GMR effect. Electrical resistance will be relatively high on this side

10   of the domain wall. Consequently, the overall electrical resistance of the trilayer element 30 will

11   be a linear function of the location of the domain wall 37. Positioning the domain wall 37

12   toward the left of the structure, away from the contact 16 injecting the carriers, will result in a

13   relatively low electrical resistance for the trilayer element 30. Positioning the domain wall 37

14   toward the right of the trilayer element 30, near the contact 16 injecting the carriers, will result

15   in a relatively high resistance for the trilayer element 30.

16   Figure 3A shows another embodiment of the known trilayer element 30', where the

17   bottom magnetic layer is fixed in its magnetic state using an antiferromagnetic pinning layer 81.

18

19   As shown, the spin-polarized carriers travel a non-reciprocal path. If the carriers are

20   injected from the left side of the domain wall 37, the spin-polarized carriers will be confined to

1   the top two layers 32, 33 of the trilayer element 30, 30' on the near side of the domain wall 37,

2   but will be free to travel through the entire thickness of the trilayer element 30, 30' on the far

3   side of the domain wall 37. In this case, moving the domain wall 37 to the left will decrease

4   electrical resistance, while moving it to the right will increase electrical resistance.

5   Accordingly, a magneto-resistive linear-displacement sensor can be used to measure the

6   relative position of two workpieces by fixing the first workpiece to a GMR film, and fixing the

7   second workpiece to means for inducing the domain wall in a relatively soft ferromagnetic layer

8   in the GMR film. The electrical resistance of the GMR film can thus be measured as a function

9   of the relative positions of the two workpieces. As used herein, workpieces are elements having

10   a relative displacement measured by the sensor. Examples of workpieces, as the term is used

11   herein, are machine parts having positions that need to be known with great accuracy and

12   precision.

13   Figure 4 shows a cross-sectional view of a known sensor 38 that uses the GMR effect.

14   In this known sensor, the trilayer element 30 is coupled to a first workpiece 40. The layer 34

15   with the fixed magnetic state (i.e., the magnetically harder layer) is disposed over the workpiece,

16   with the magnetic field lines oriented "into" the drawing sheet. Over, and contacted to, layer 34

17   is the non-magnetic metal buffer layer 33. Over and contacted to the buffer layer 33 is the

18   magnetically softer layer 32, with the magnetic field lines on one side 35 of the domain wall 37

19   oriented "into" the drawing sheet, and with the magnetic field lines on the other side 36 of the

20   domain wall 37 oriented "out of" the drawing sheet. A standard four probe configuration

1   connects the trilayer element 30 to a device 50 (for example, an ohmmeter that comprises a

2   constant current source 52 and a volt meter 54, connected in parallel) which provides the

3   operating current and measures the electrical resistance to the trilayer element 30.

4   Referring briefly to Fig. 7, a pair of indexing magnets 56, 58 with preferably opposing

5   magnetic moments are positioned to induce the domain wall 37 in the softer magnetic layer 32

6   where this domain wall 37 is perpendicular to the opposing magnetic moments. Magnets 56, 58

7   are coupled to the second workpiece (not shown), so that as the second workpiece is moved

8   relative to the first workpiece, the magnets will move along the element 30, thus changing its

9   resistance in a detectable manner. Skilled practitioners will recognize, however, that many

10   configurations for inducing a domain wall are known. In selecting a particular device for

11   inducing a domain wall, skilled practitioners will consider minimizing hysteresis and maximizing

12   domain wall definition, following known principles of ferromagnetism. It is preferred to

13   minimize hysteresis in the domain wall to improve two-way precision in the sensor.

14   Referring now to Figs. 5 and 6, a preferred embodiment of the present invention is

15   illustrated. In these figures, it is shown that two, preferably identically configured, trilayer

16   elements or films 30, 30" are arranged atop a substrate 60. As shown, the two trilayer elements

17   30, 30" form two equal size strips placed back to back, with the bias directions 62, 62' of their

18   biased layers 34, 34' opposing. In particular, the bias of the hard layer 34' of the upper trilayer

19   element 30' is in one direction 62', and the bias of the hard layer 34 of the other trilayer element

20   30 is in the opposite direction 62. Further, as is shown, the soft layers 32, 32' of each trilayer

1   element are essentially adjacent to one another and are separated only by the substrate 60, so that

2   soft layers abut against respective opposite surfaces of the substrate. The two trilayer elements

3   are in thermal engagement with one another, so that any thermal influence that may occur to one

4   of the trilayers, will equally occur to the other of the trilayers. Preferably, each trilayer element

5   is connected to device 50, for providing the operating current and measuring the electrical

6   resistance to the respective trilayer elements 30, 30".

7   As shown in Fig. 7, as the magnets 56, 58 are moved across the strips (constituted by

8   the respective trilayer elements 30, 30"), the resistance of the two trilayers will exhibit opposite

9   behavior patterns, because the biases of the hard layers are arranged in opposite directions. Thus,

10   as the magnets 56, 58 are moved from the left to the right in the direction of the arrow 64 in Fig.

11   7, the resistance of the upper trilayer element 30" will go, for example, from low to high, and

12   the resistance of the lower trilayer element 30 will go from high to low.

13   As shown in Fig. 8, the ideal resistance of the two elements 30, 30", which is shown

14   graphically, changes in a linear relationship, with the resistance of each trilayer element behaving

15   in a manner inverse to the behavior of the other trilayer element. However, as magnets 56, 58

16   are moved across the two strips, in the direction of arrow 64 shown in Fig. 7, the total resistance

17   of each strip is actually made of up three primary components. In particular, each strip includes

18   the resistance R_0, which is the material resistance of the strips measured when the magnets are

19   in their starting position, and which is a constant value. Further, each strip includes the resistance

20   R_T, which is the change in the resistance of the trilayer elements 30, 30" that occurs due to a

1   change in the temperature since the beginning of the movement of the magnets. Because the two

2   strips are arranged one above the other in thermal engagement with one another, this value is the

3   same for both strips. Further, each strip includes the resistance R_G, which is a proportionality

4   constant for the change in resistance created by the new position of the magnets.

5   The total resistance of each trilayer element 30, 30' can be determined in a known manner

6   by way of the following formulas:

$$R_1 = R_{01} + (x/x_0)R_G + R_T$$

$$R_2 = R_{02} - (1-x/x_0)R_G + R_T,$$

9   wherein x is the magnets' position, and x_0 is the length of the resistor, as measured in a long

10   dimension of the strips. When these two total resistances are subtracted from one another (using

11   for example a known difference circuit 66), i.e., $R_1 - R_2$, R_T is eliminated, thus eliminating any

12   effect that the change in resistance due to a change in temperature may have on the two strips.

13   Further, the measured effect due to moving the magnets, i.e., $(x/x_0)R_G$, is doubled, thus increasing

14   the total signal strength.

15   This configuration provides several distinct advantages over the prior art bridge

16   configurations. First, the particular geometry of the bridge does not require magnetic shielding

17   between two end-to-end strips, which results in a smaller package. Furthermore, the two double

18   strips provide twice as much signal. Moreover, the strips are much more certain to be at the

19   same temperature, since they are in physical contact with one another. Moreover, the averaging

1   of the signal from the two strips instead of one strip will reduce the impact of small inhomogene-

2   ities that may be present in the material.

3   In order to maximize the sensitivity and reduce the effects of temperature dependence, the

4   sensor can utilize a bridge configuration as shown in Figure 9, which illustrates a known

5   wheatstone bridge.

6   The output of such a bridge is given by:

7
$$V_0 = V_i[R_1/(R_1+R_4) - R_2/(R_2+R_3)]$$

8   This bridge will give a maximum and linear output if all four resistors are subject to

9   variation by a factor x. Here, x represents a fractional deviation of about zero.

10
$$R_1 = R_3 = R(1+x)$$

11
$$R_2 = R_4 = R(1-x)$$

12   For simplicity, it is assumed that all resistors are equal at $x = 0$. The output of the bridge

13   is then

14
$$V_0 = V_{ix}$$

15   In order to make practical use of a GMR-based linear displacement sensor, the temperature

16   dependence of both the resistance and the magnetoresistance cannot be ignored. If the form of

17   the overall resistance is taken to be:

18
$$R = R_0(T)[1+\alpha(T)x/x_0]$$

1   where $\alpha(T)$ is the GMR coefficient and typically is on the order of 0.01 to 0.05. $R_0(T)$ is the

2   resistance and $\alpha(T)R_0(T)$ is the magnetoresistance. The temperature dependence of α is roughly

3   linear varying by about 1%/K.

4   If the temperature of the device is fixed, then the absolute sensitivity of the sensor is

5   determined solely by the precision of the resistance measurement. However, absent temperature

6   control, the sensor output will be a function of temperature both in the resistance and the

7   magnetoresistance. To eliminate these effects a bridge circuit can be used.

8   Arranging two sensors biased in the opposite sense with respect to two other sensors

9   results in

10 $$R_1=R_3=R_0(T)[1+\alpha(T)x/x_0]$$

11 $$R_2=R_4=R_0(T)[1+\alpha(T)(x_0-x)/x_0]$$

12   since for $x=0$, R_1 and R_3 are in the low resistance (parallel) state, and R_2 and R_4 are in the high

13   resistance (antiparallel) state. The bridge then yields:

14 $$V_x(x,T)=[\alpha(T)(2x/x_0-1)/(2+\alpha(T))]V_i.$$

15   The output of the bridge is linear in displacement, but has temperature dependence

16   through the GMR term, $\alpha(T)$. Consequently, any temperature change that results in a 1% change

17   in α will result in an approximately 1% change in the bridge output, thereby producing a 1%

18   error. To eliminate this temperature dependence, the GMR temperature dependence should be

19   ratioed out.

1   By using a secondary bridge in which two elements are always biased in the high state

2   and the other two are always biased in the low state, i.e., no function of displacement, the output

3   as a function of temperature for this bridge will be

4
$$V_T(T) = \alpha(T)/(2+\alpha(T)).$$

5   Note that this secondary bridge should be magnetically shielded from the indexing magnets.

6   By ratioing the first bridge output by the second, the following results:

7
$$V_1(x,T)/V_2(T) = 2x/x_0 - 1$$

8   This ratio is now absolutely linear in displacement and independent of temperature.

9   The V_1 bridge can be fabricated by placing pairs of GMR elements back-to-back (Fig. 10)

10   such that the pairs are biased in an antiparallel configuration. The appropriate interconnects for

11   the bridge are then made to complete the circuit shown in Fig. 11.

12   The V_T bridge consists of elements R_5 and R_7 biased in the high resistive state while R_6

13   and R_8 are biased in the low state (no magnetoresistance). The biasing could be accomplished

14   by placing permanent magnets 70 as shown in Fig. 12. The appropriate interconnects for the

15   bridge are then made to complete the circuit shown in Fig. 13. In this case, the variable resistors

16   R_5 and R_7 vary with temperature and not displacement.

17   The two bridges are typically wired together as shown in Fig. 14. In this case the bridges

18   are in parallel and share the same excitation voltage V_i. The outputs of the two bridges can then

19   be ratioed by digital processing or some other means.

1   Although the present invention has been discussed in relation to trilayer elements, multiple

2   layer strips having more than three layers may also be used, which may further increase the

3   signal.

4   The invention now being full described, it will be apparent to one of ordinary skill in the

5   art that any changes and modifications can be made thereto without departing from the spirit or

6   the scope of the invention.

ABSTRACT OF THE DISCLOSURE

A thermal bridge includes a first Giant Magneto Resistance film having a layer with a fixed bias pointing in a first direction, and a second Giant Magneto Resistance film superposed on, and in thermal engagement with, the first Giant Magneto Resistance film. The second Giant

5   Magneto Resistance film has a layer with a fixed bias pointing in a second direction opposite to the first direction.

FIG. 1
(Prior Art)

10

12

13

14

16

FIG. 2
(Prior Art)

20

22

23

24

16

FIG. 3
(Prior Art)

30

37

32   35

36

33

34

16

FIG. 3A
(Prior Art)

30'

37

32   35

36

33

34

16

81
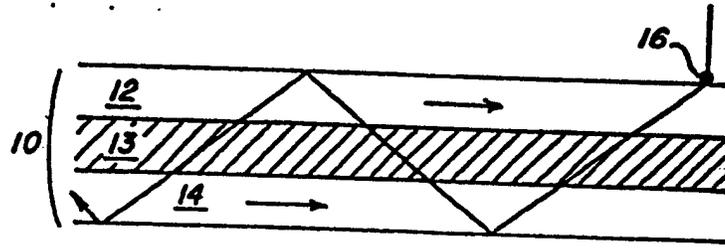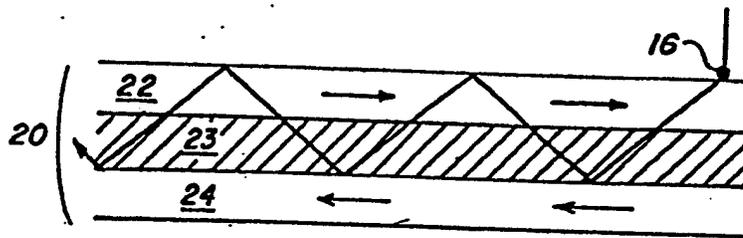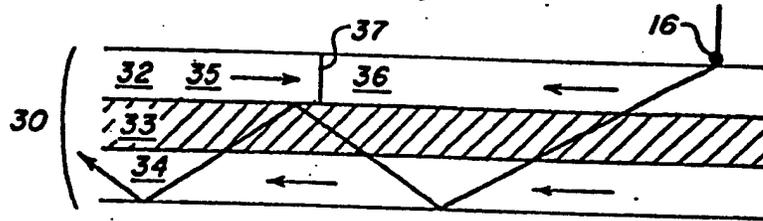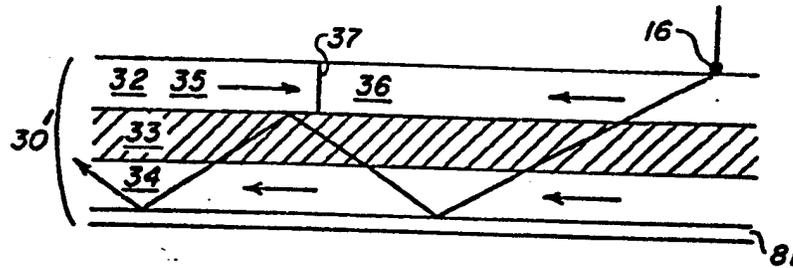
Fig. 4 (Prior Art)

Fig. 5

Fig. 6

Fig. 7

64

56
58

30"
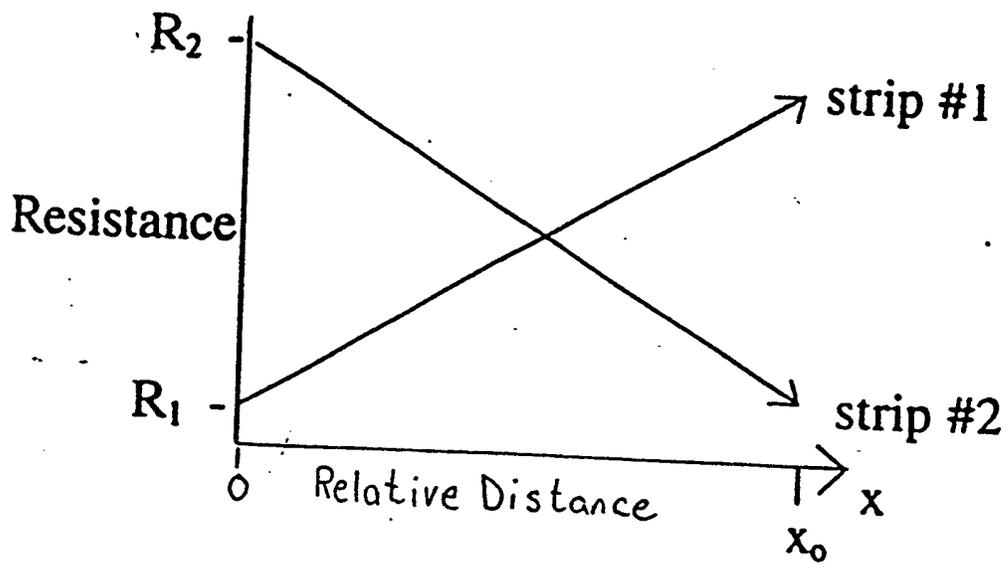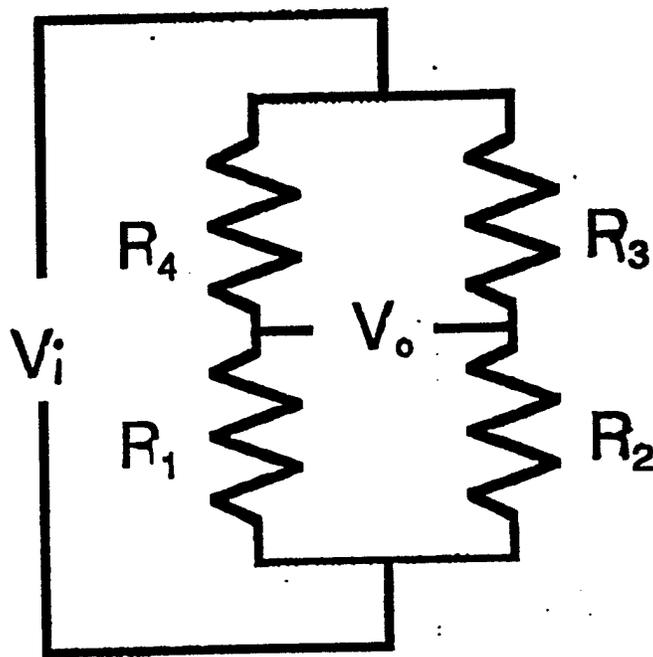30

Fig. 8

R_2

Resistance

strip #1

strip #2

R_1

0   Relative Distance x

x_0
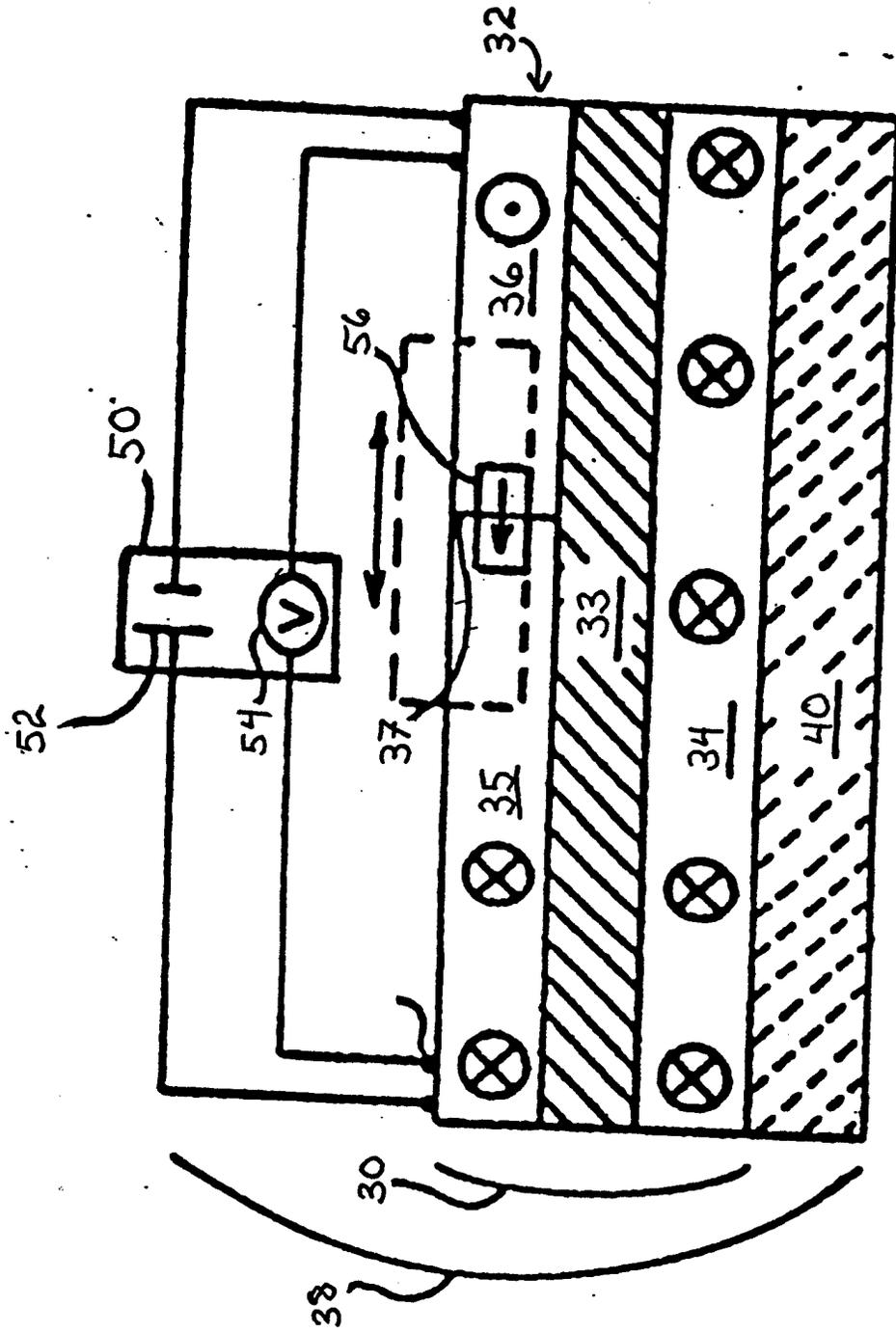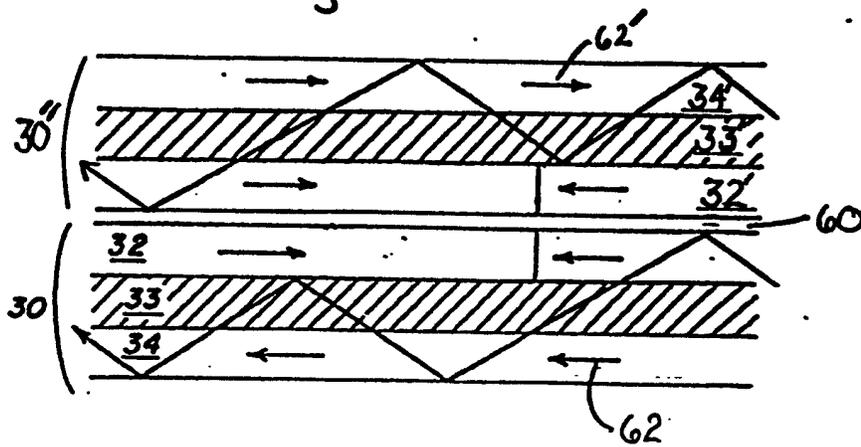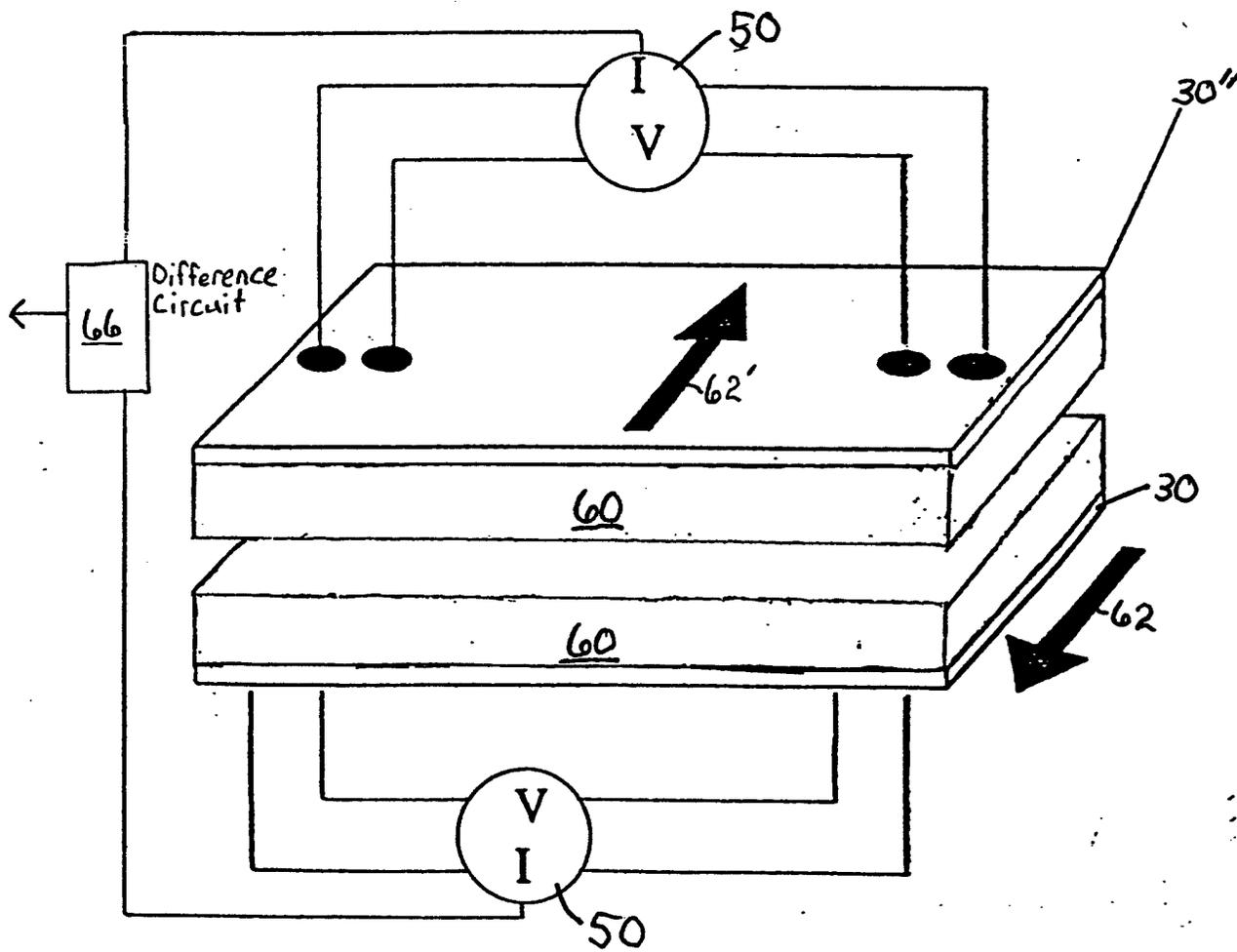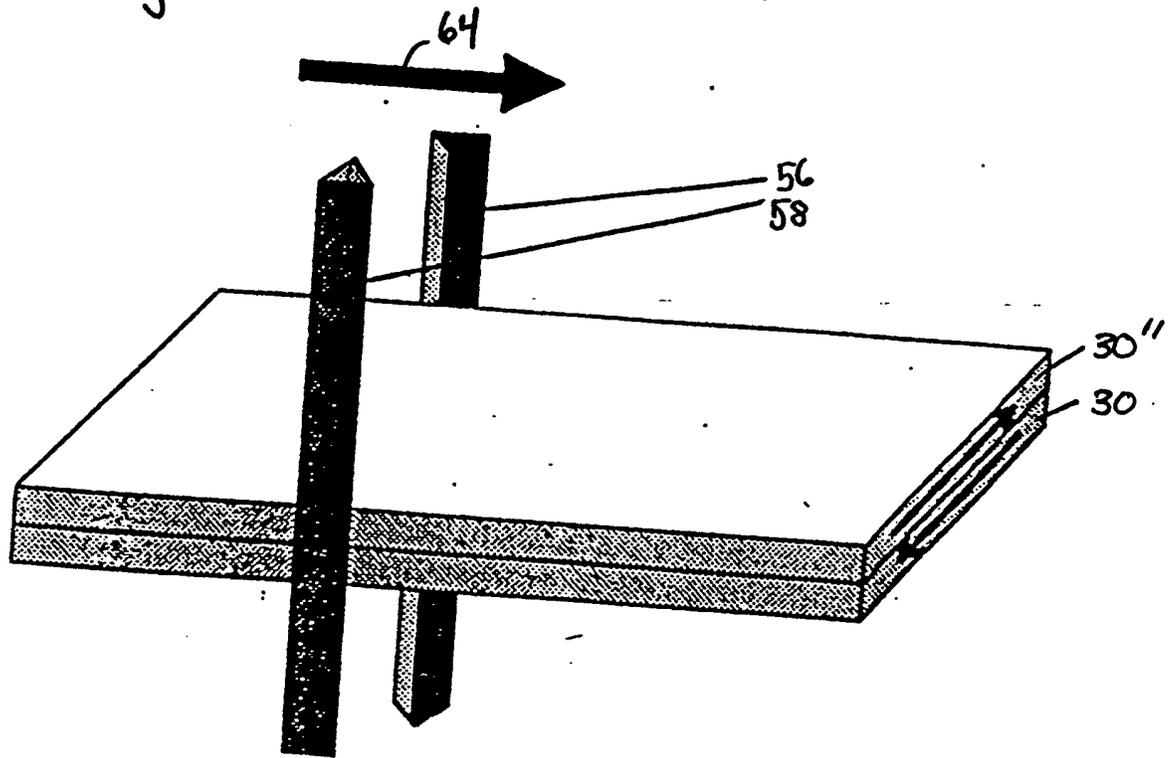
Fig. 9
(Prior Art)

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14