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(54) **GMR SENSOR**

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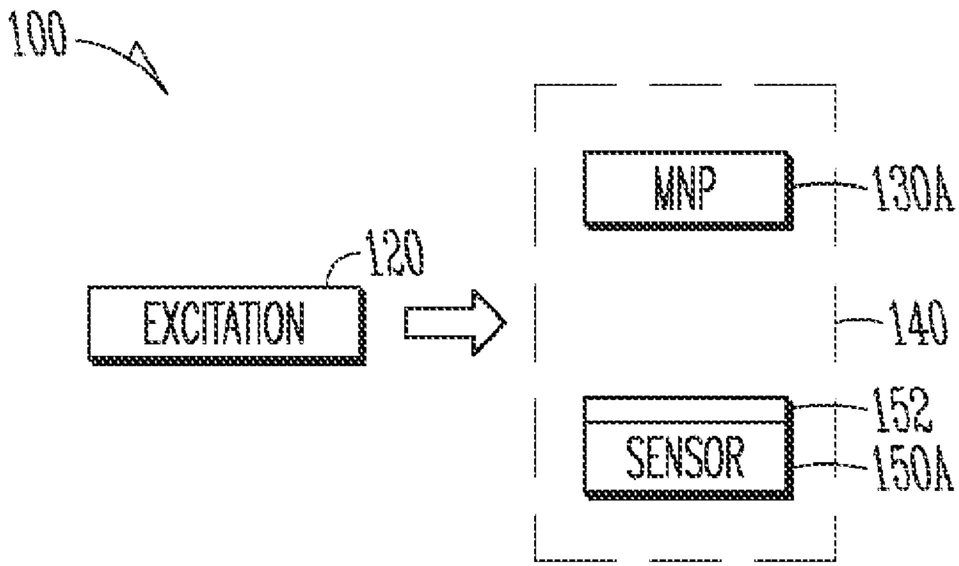
USPC .......................... **435/34**; 324/228; 435/287.1

(57) **ABSTRACT**

A system includes a first sensor, a field source, and a processor. The first sensor includes a surface and has an electrical resistance determined by a magnetic field at the surface. The field source is configured to provide a biasing magnetic field to the surface. The biasing magnetic field is aligned parallel to the surface and aligned perpendicular relative to the surface. The magnetic field has a frequency. The processor is coupled to the sensor and is configured to determine a parameter based on a measure of a change in the resistance. The change in the resistance corresponds to the resistance at a time before onset of a magnetic field perturbance at the surface and a time after the onset of the magnetic field perturbance at the surface.



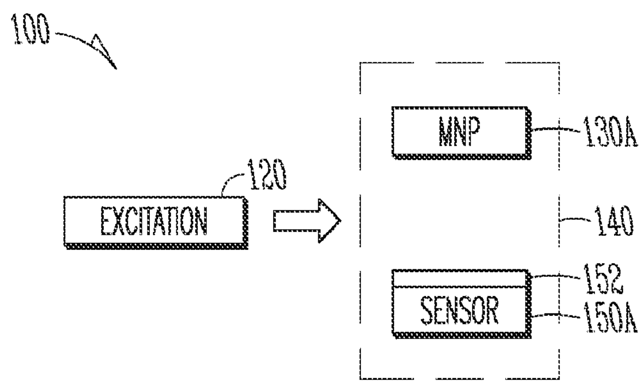

100
MNP
130A
120
EXCITATION
140
152
SENSOR
150A

*FIG. 1*

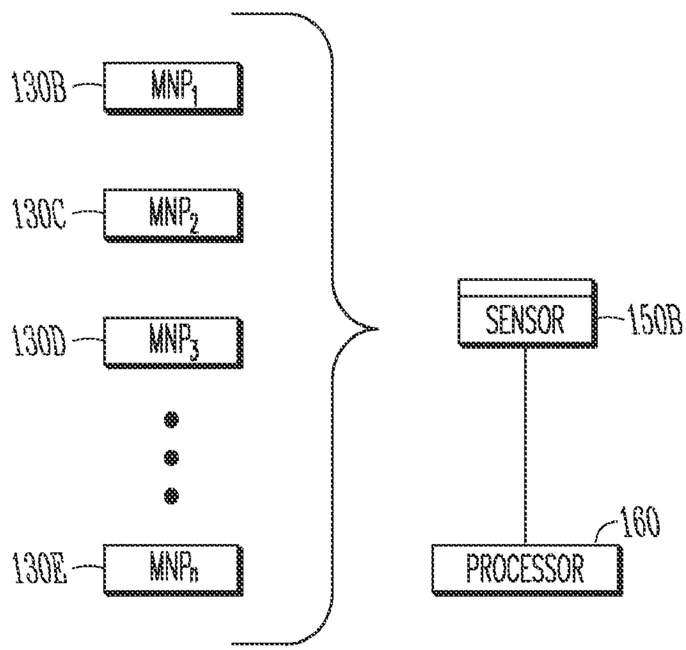

130B
MNP1
130C
MNP2
130D
MNP3
130E
MNPn
SENSOR
150B
160
PROCESSOR

*FIG. 2*

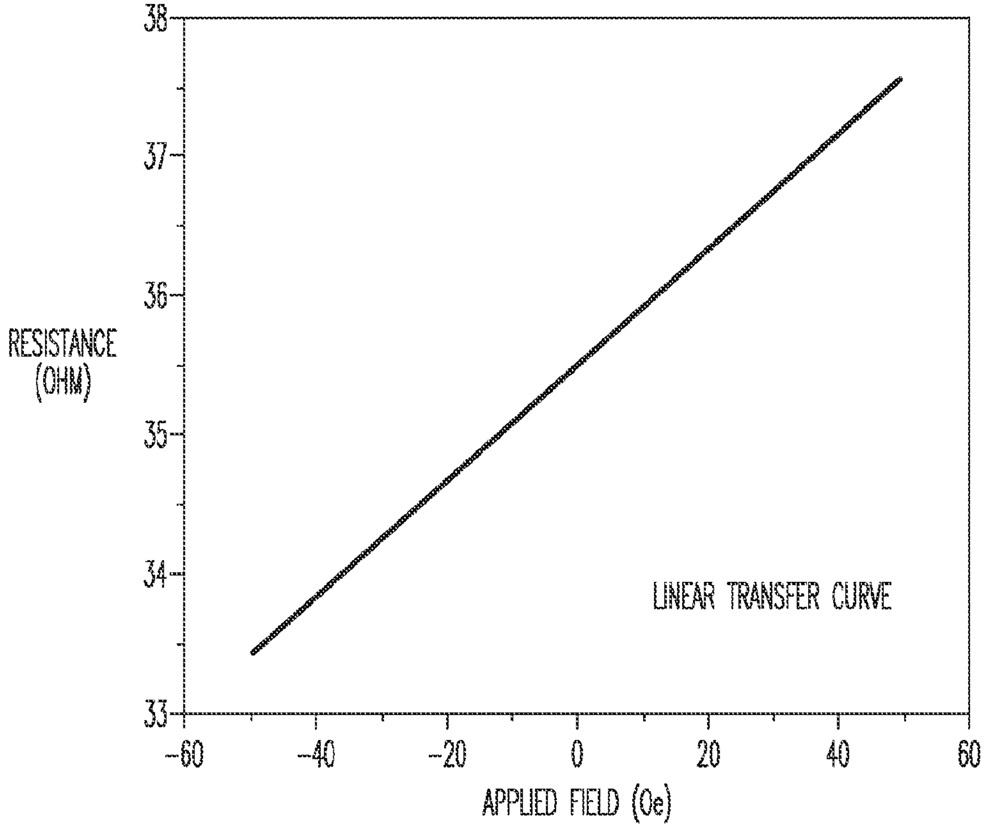

RESISTANCE
(OHM)
38
37
36
35
34
33
LINEAR TRANSFER CURVE
−60
−40
−20
0
20
40
60
APPLIED FIELD (Oe)

*FIG. 3*

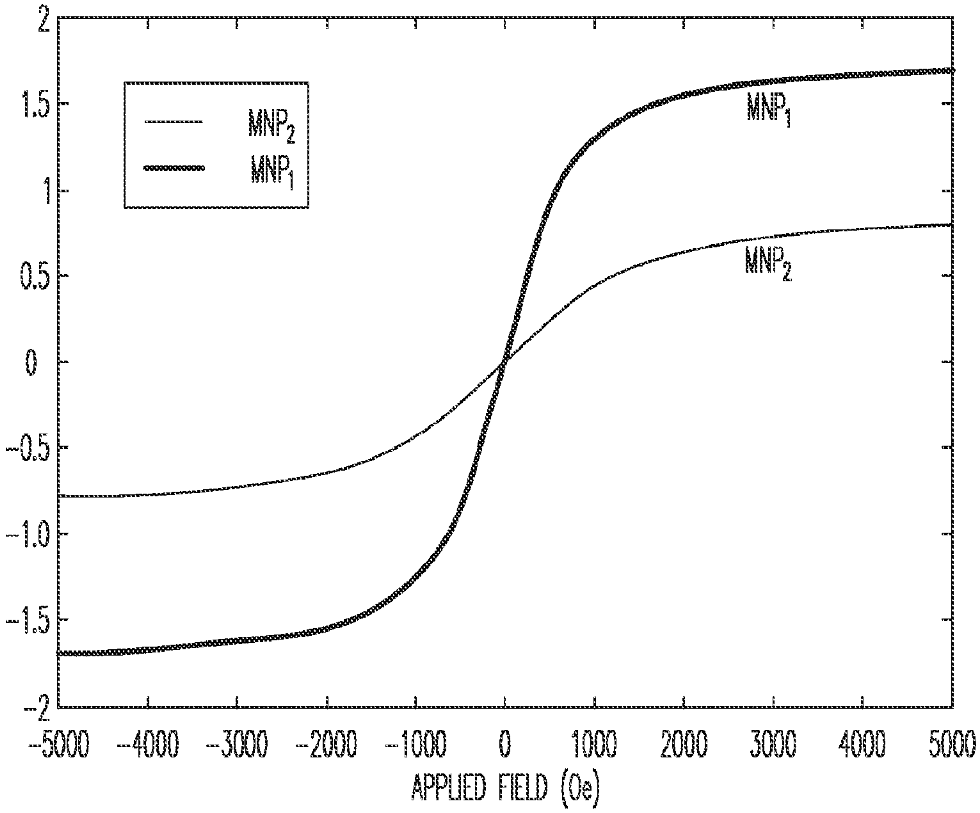

MNP2
MNP1
MNP1
MNP2
2
1.5
1
0.5
0
-0.5
-1.0
-1.5
-2
-5000
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
5000
APPLIED FIELD (Oe)

*FIG. 4*

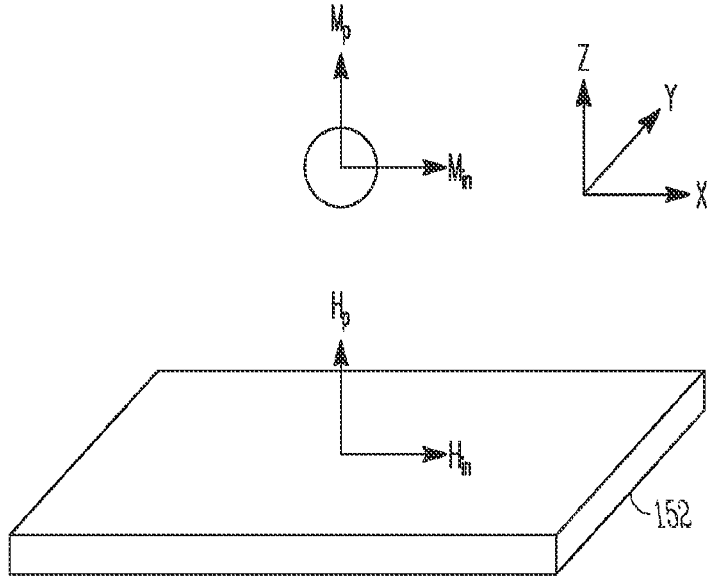

Mp
Mn
Z
Y
X
Hp
Hn
152

*FIG. 5*

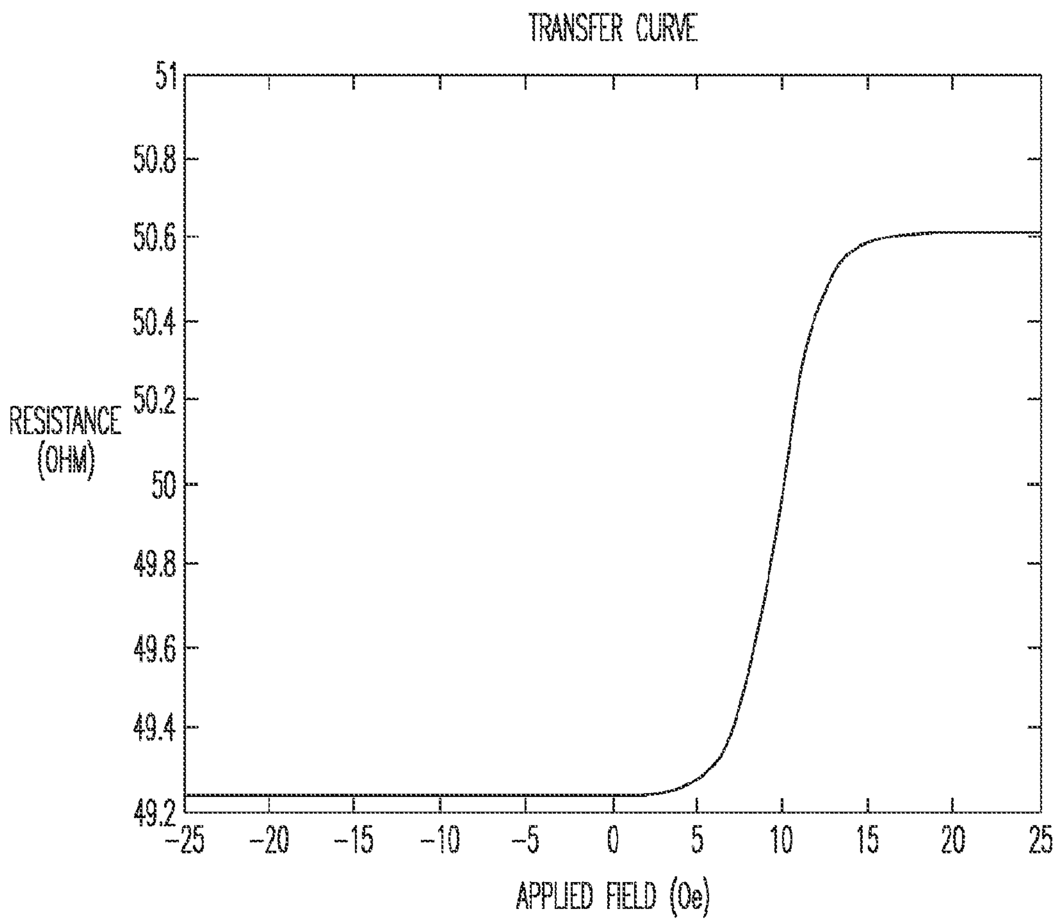

TRANSFER CURVE
RESISTANCE (OHM)
51
50.8
50.6
50.4
50.2
50
49.8
49.6
49.4
49.2
−25
−20
−15
−10
−5
0
5
10
15
20
25
APPLIED FIELD (Oe)

*FIG. 6*

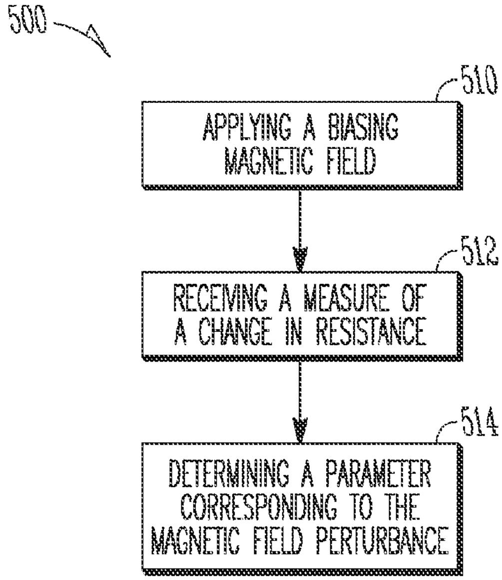

500
510
APPLYING A BIASING MAGNETIC FIELD
512
RECEIVING A MEASURE OF A CHANGE IN RESISTANCE
514
DETERMINING A PARAMETER CORRESPONDING TO THE MAGNETIC FIELD PERTURBANCE

*FIG. 7*

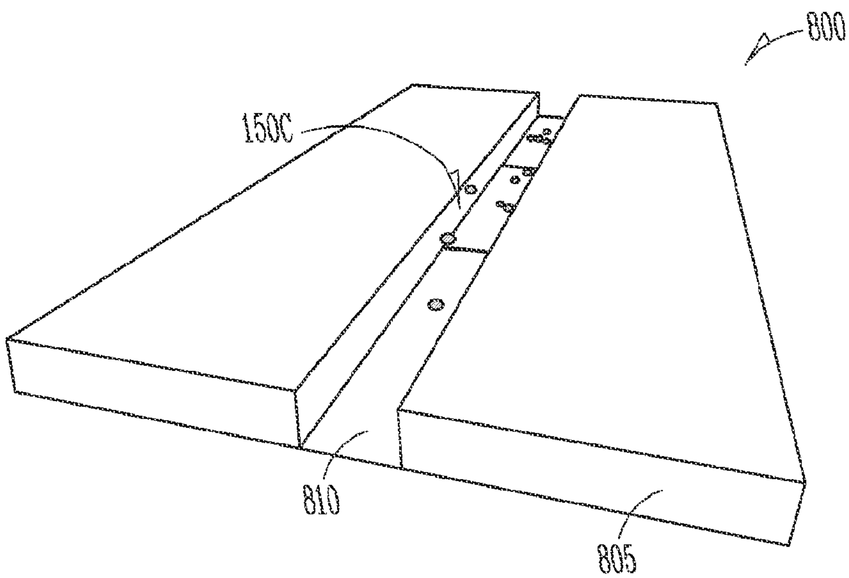

800
150C
810
805

*FIG. 8*

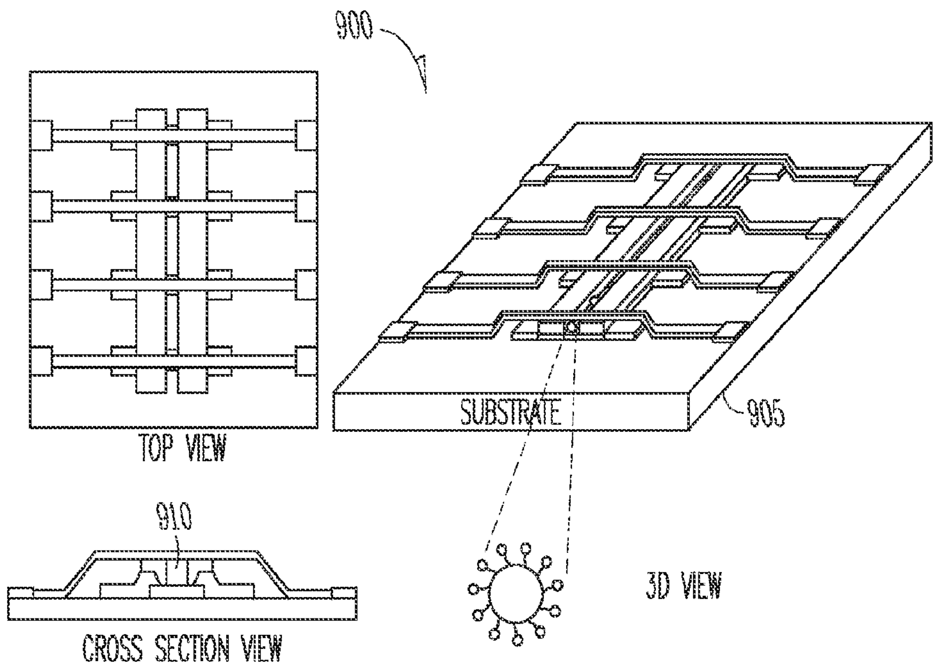

900
TOP VIEW
SUBSTRATE
905
910
CROSS SECTION VIEW
3D VIEW

*FIG. 9*

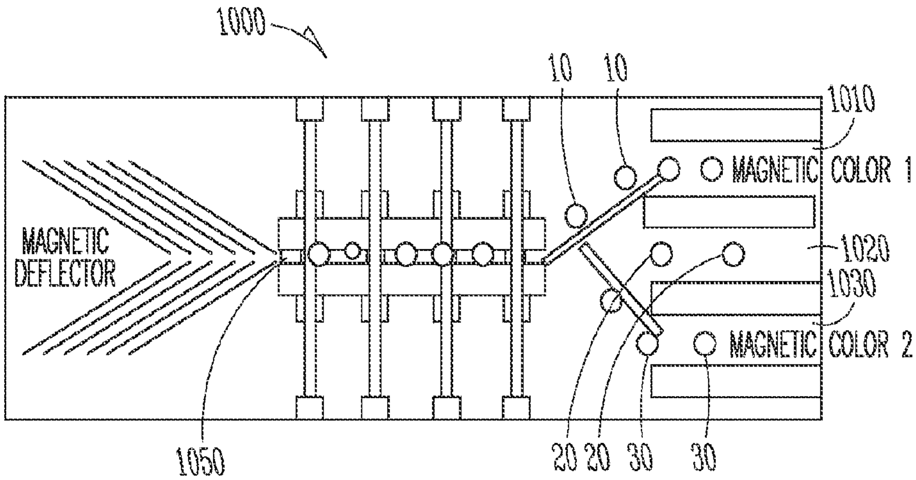

1000
10
10
1010
MAGNETIC COLOR 1
MAGNETIC DEFLECTOR
1020
1030
MAGNETIC COLOR 2
1050
20 20 30 30

*FIG. 10*

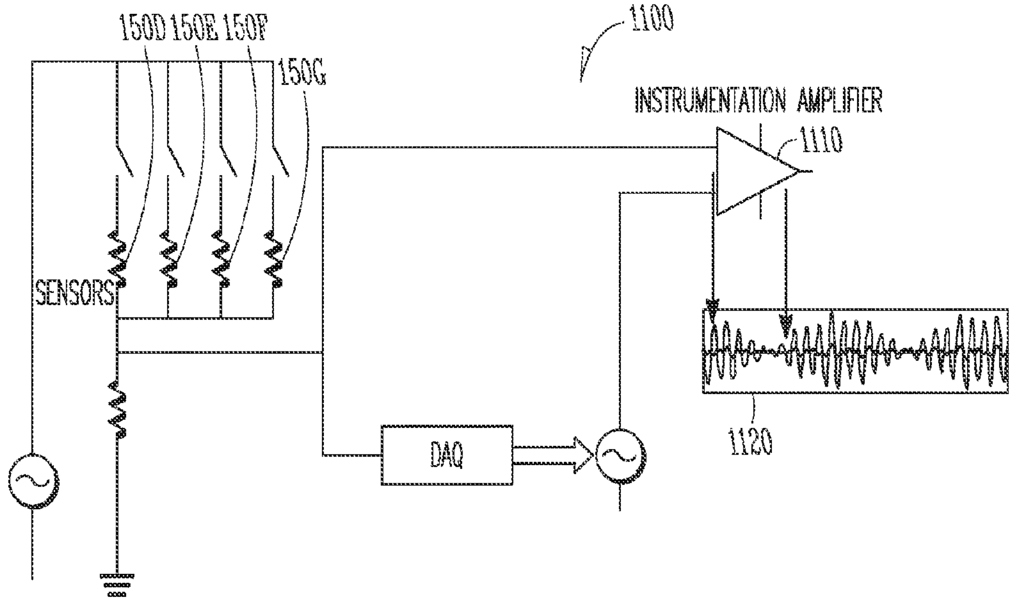

150D 150E 150F
150G
1100
INSTRUMENTATION AMPLIFIER
1110
SENSORS
DAQ
1120

*FIG. 11*

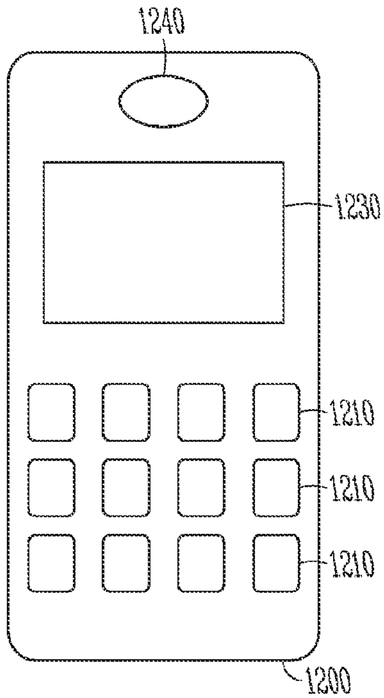

1240
1230
1210
1210
1210
1200

*FIG. 12*

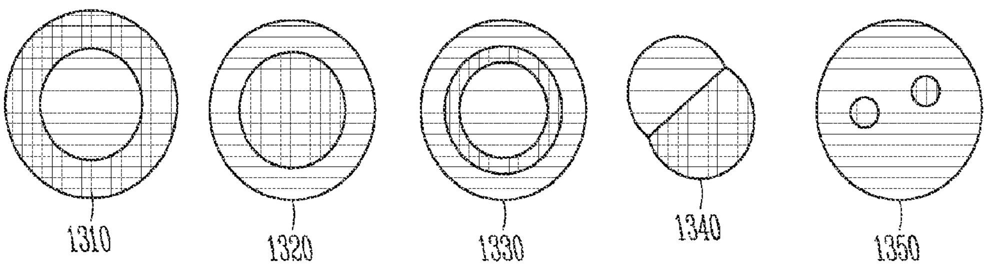

1310
1320
1330
1340
1350

*FIG. 13*

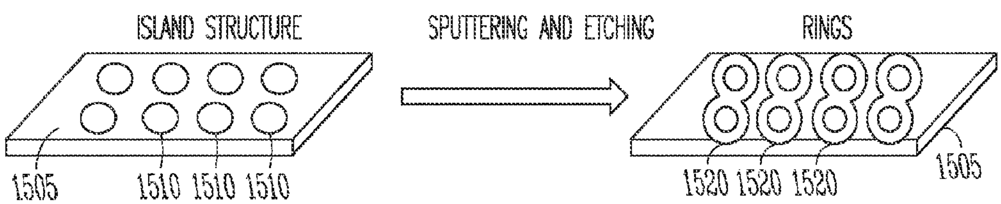

ISLAND STRUCTURE
SPUTTERING AND ETCHING
RINGS
1505
1510 1510 1510
1520 1520 1520
1505

*FIG. 14*

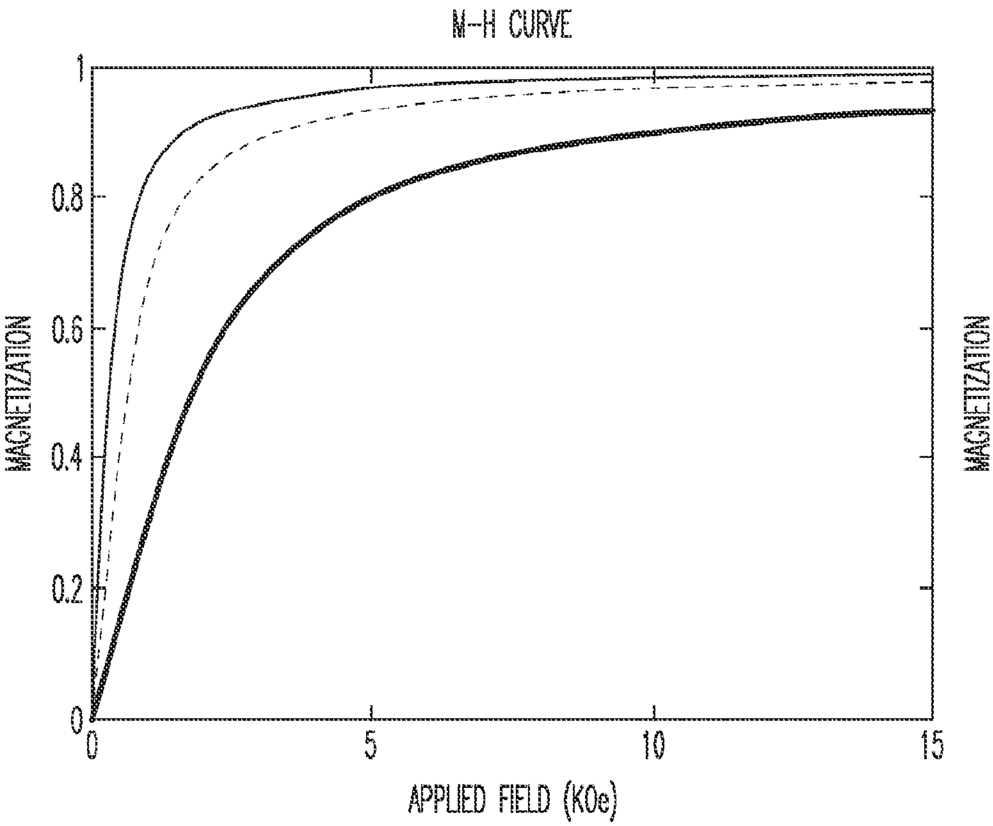

M-H CURVE
MAGNETIZATION
MAGNETIZATION
0
0.2
0.4
0.6
0.8
1
0
5
10
15
APPLIED FIELD (KOe)

*FIG. 15*

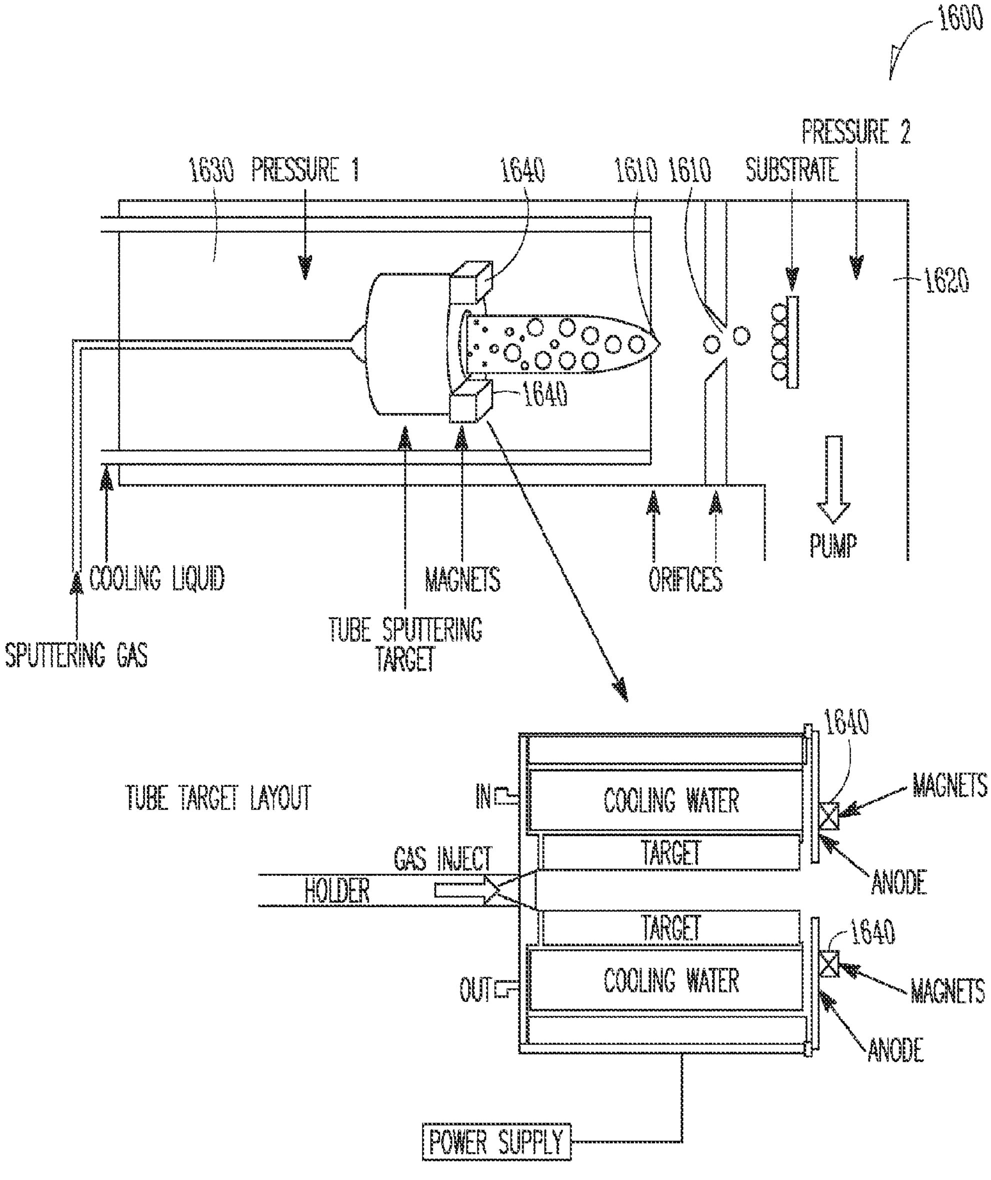

1600
PRESSURE 2
1630 PRESSURE 1
1640
1610 1610
SUBSTRATE
1620
1640
PUMP
COOLING LIQUID
MAGNETS
ORIFICES
TUBE SPUTTERING TARGET
SPUTTERING GAS
1640
TUBE TARGET LAYOUT
IN
COOLING WATER
MAGNETS
TARGET
GAS INJECT
ANODE
HOLDER
TARGET
1640
OUT
COOLING WATER
MAGNETS
ANODE
POWER SUPPLY

*FIG. 16*

# GMR SENSOR

## CLAIM OF PRIORITY

**[0001]** This patent application claims the benefit of priority to U.S. Provisional Patent Application Ser. No. 61/413,884, entitled "MAGNETIC NANOPARTICLE-BASED MAGNETIC COLORING," filed on Nov. 15, 2010 (Attorney Docket No. 600.831PRV), which is hereby incorporated by reference herein in its entirety.

## CROSS-REFERENCE TO RELATED PATENT DOCUMENTS

**[0002]** This patent application is also related to Wang et. al, PCT Application Serial Number ______, entitled "SEARCH COIL," filed on Nov. 15, 2011 (Attorney Docket No. 600.831WO2).

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

**[0003]** This invention was made with government support under award number 1717-522-6686 from National Science Foundation. The government has certain rights in this invention.

## BACKGROUND

**[0004]** Some biomedical detection systems, such as flow cytometry, are based on the principles of fluorescence. In the presence of high background noise, fluorescence-based detection devices have low signal-to-noise ratio. In addition, fluorescence-based detection devices are costly and complex to set-up. In addition, fluoresence-based detection devices are limited to a small number of individual colors.

## OVERVIEW

**[0005]** An example of the present subject matter includes magnetoresistance sensor that configured for detecting nanoparticles. The sensor, in one example, includes a giant magnetoresistance (GMR) sensor or other type of sensor exhibiting hysteresis behavior.

**[0006]** To detect different biomedical objects (e.g. proteins), the present subject matter applies different functionalization (e.g. specific capture antibody-antigen) of different sensors in an array format.

**[0007]** One example includes a linear GMR sensor and magnetic nanoparticle-based multiplex detection scheme. In addition, one example includes a non-linear GMR. Furthermore, a mixed-frequency detection scheme can be used with GMR sensor according to one example. A handheld device provides a system for magnetic multiplex sorting system of cells, proteins, DNA, RNA, small molecules, bacteria, virus and other objects in general. In one example, a magnetic coloring system allows monitoring of a biochemical reaction between proteins and cell membranes. A magnetic color sensing system can allow small molecule detection and sorting for new drug development. In one example, a magnetic color sensing library system can be used for small molecule detection and sorting and for monitoring and identifying reactions between molecules. In one example, a magnetic coloring system enables integration with micro-fluidic or nano-fluidic channels (e.g. PCR process).

**[0008]** Various examples are described with respect to a GMR sensor. However, the present subject matte can include other kinds of magnetic sensors, such as anisotropic magnetoresistance sensor (AMR), magnetic tunnel junction (MTJ), Hall sensor, giant magneto inductance (GMI), and magnetic optical sensor. In the various examples, a sensor surface is configured to detect a stray magnetic field and provide a change in electrical resistance.

**[0009]** As used herein, the term 'color' is used in a sense to correlate with color associated with flow cytometry. However, unlike the visual perceptual property corresponding in humans and associated with categories called red, green, blue and others, the term color is used herein to represent a system of classification and labeling that allows for ready identification and recognition of one group of elements relative to another.

**[0010]** The present inventors have recognized, among other things, that colored magnetic nanoparticles can solve the problems of identification and sorting that remain unmet by traditional flow cytometry.

**[0011]** This overview is intended to provide an overview of subject matter of the present patent application. It is not intended to provide an exclusive or exhaustive explanation of the invention. The detailed description is included to provide further information about the present patent application.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0012]** In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

**[0013]** FIG. **1** illustrates a sensor system, according to one example.

**[0014]** FIG. **2** illustrates a sensor relative to a number of magnetic nanoparticles.

**[0015]** FIG. **3** illustrates a linear transfer curve.

**[0016]** FIG. **4** illustrates an M-H curve for two types of magnetic nanoparticles, according to one example.

**[0017]** FIG. **5** illustrates a coordinate system relative to a sensor surface and a magnetic nanoparticle, according to one example.

**[0018]** FIG. **6** illustrates a non-linear transfer curve.

**[0019]** FIG. **7** illustrates a flow chart corresponding to a sensor, according to one example.

**[0020]** FIG. **8** illustrates a sensor in a channel, according to one example.

**[0021]** FIG. **9** illustrates views of a sensor, according to one example.

**[0022]** FIG. **10** illustrates views of a sensor configured to sort, according to one example.

**[0023]** FIG. **11** illustrates adaptive referencing, according to one example.

**[0024]** FIG. **12** illustrates a handheld system, according to one example.

**[0025]** FIG. **13** illustrates examples of magnetic nanoparticles.

**[0026]** FIG. **14** illustrates examples of magnetic nanoparticles formed as rings.

**[0027]** FIG. **15** illustrates M-H curves for three magnetic nanoparticles, according to one example.

**[0028]** FIG. **16** illustrates an example of a system for fabricating magnetic nanoparticles.

## DETAILED DESCRIPTION

**[0029]** FIG. **1** illustrates sensor system **100**, according to one example. Sensor system **100** includes sensor **150**A, excitation **120**A, and magnetic nanoparticle **130**A. Sensor **150**A includes sensor surface **152**. Sensor **152** is a planar surface having sensitivity to magnetic fields.

**[0030]** Sensor **150**A can include a giant magnetoresistance sensor or other type of magnetic sensor configured to generate a signal based on a magnetic field proximate surface **152**. In one example, sensor **150**A exhibits hysteresis. Sensor **150**A can include a free layer and a pinned layer. Surface **152** can have a rectangular shape having a length and a width.

**[0031]** Sensor **150**A can be but one element of a multi-element sensor. A multi-element sensor can be described as an array. In one example, an array includes **64** individual sensors.

**[0032]** The ratio of length to width can be described as an aspect ratio. For example, with a dimension of 40 μm×80 μm, the sensor has a relatively low aspect ratio of 2. Other aspect ratios are also contemplated, including a ratio greater than 100.

**[0033]** Sensor **150**A can include a linear or non-linear sensor. A linear sensor can have a relatively large aspect ratio, such as 100 or more, or such as 500. In a linear sensor, the free layer is elongate and does not allow easy rotation. On the other hand, a non-linear sensor has a relatively small aspect ratio, such as a ratio under 20, or a ratio of about 2. The small aspect ratio allows easy rotation of the free layer.

**[0034]** Proximity of magnetic nanoparticle **130**A to surface **152** produces an electrical signal from sensor **150**A. The electrical signal can be in the form of a resistance or in the form of a change in resistance.

**[0035]** Excitation **120** includes a driver configured to generate a magnetic biasing field. The biasing field can have a constant or varying amplitude, frequency, or phase. Excitation **120** can provide one or more frequencies to environment **140**. For example, excitation **120** can provide a low frequency signal at a first amplitude and a high frequency at a second amplitude different than the first amplitude. In one example, excitation **120** provides a swept frequency.

**[0036]** According to one example, sensor **150**A includes a linear GMR sensor, MNP **130**A includes superparamagnetic or ferromagnetic nanoparticles, and excitation **120** provides a mixed frequency. In a second example, sensor **150**A includes a non-linear GMR sensor, MNP **130**A includes superparamagnetic nanoparticles, and excitation **120** is configured to provide a mixed frequency. In a third example, sensor **150**A includes a linear GMR sensor, MNP **130**A includes superparamagnetic or ferromagnetic nanoparticles, and excitation **120** is configured to provide a swept or scanning frequency.

**[0037]** As shown at FIG. **2**, sensor **150**B can be configured to detect a number of magnetic nanoparticles, here shown to include $MNP_1$ **130**B, $MNP_2$ **130**C, $MNP_3$ **130**D and continuing to $MNP_n$ **130**E. Processor **160** is coupled to sensor **150**B. Processor **160** can include an analog-to-digital (ATD) converter, an amplifier, a filter, or a signal processor (analog or digital). In addition, processor **160** can be configured to communicate with a remote device or configured to provide a visual output to a user.

**[0038]** An example of the present subject matter is configured to detect a signal differentiating two kinds of magnetic nanoparticles. Unlike other sensing configurations that rely on an in-plane applied field, here referred to as the in-plane or parallel mode, the present subject matter includes an applied field delivered in the perpendicular direction relative to the sensor surface (plane). The vertical alignment of the excitation is referred to as the vertical mode. For a GMR spin valve, if a vertical magnetic field alone is applied, the stray field of the vertical magnetized nanoparticles is radially symmetric in the sensor plane. As such, the sensor does not generate a signal based on the proximity of the magnetic nanoparticles.

**[0039]** An example of the present subject matter uses an in-plane bias field to generate an in-plane stray field from the magnetic nanoparticles.

**[0040]** FIG. **3** illustrates an example of a linear transfer curve. In the figure, the horizontal axis is indexed to indicate the magnitude of an applied magnetic field, here in units of Oe. The vertical axis is marked to indicate electrical resistance in ohms.

**[0041]** FIG. **4** illustrates M-H curves for two types of magnetic nanoparticles, according to one example. The curves can be construed as representative of that for a $Fe_2O_3$ superparamagnetic MNP and for FeCo superparamagnetic MNP. The horizontal axis is marked to denote an applied field (in units Oe) and the vertical axis is marked to denote the magnetic moment (emu per nanoparticle).

**[0042]** FIG. **5** illustrates a coordinate system relative to sensor surface **152**. In addition, the figure illustrates a magnetic nanoparticle and the effective magnetization.

**[0043]** The figure illustrates a view of the detection scheme. Two applied field are used in this scheme, one denoted as $H_p$ and aligned in the vertical mode and one denoted as $H_{in}$ and aligned in the in-plane mode. Subsequently, two effective magnetization components are introduced, one denoted as $M_p$, the effective vertical magnetization and one denoted as $M_{in}$ aligned in the effective in-plane magnetization. Effective magnetization denoted as $M_{in}$ contributes to the in-plane stray field of the magnetic nanoparticles.

**[0044]** In the following description, the parameters are denoted as follows:

**[0045]** K1: susceptibility of magnetic nanoparticle A (obtained from the fitting of M-H curve)

**[0046]** K2: susceptibility of magnetic nanoparticle B (obtained from the fitting of M-H curve)

**[0047]** D: demag factor (here assume that two kinds of magnetic nanoparticles have the same D)

**[0048]** Ha-in: in-plane applied field (known parameter)

**[0049]** Hd: stray field from the magnetic nanoparticles

**[0050]** R=f(Ha-in): Boltzmann function (known parameter)

**[0051]** N: number of magnetic nanoparticle (here consider 10^13)

**[0052]** Equations modeling the system can be derived as follows:

**[0053]** Assume that a sensor without a magnetic nanoparticle will have a particular transfer curve and, in this case, the resistance of a GMR sensor is given by: $R=35.5+0.04H_{eff}$ where $H_{eff}$ is the effective field on the sensor.

**[0054]** Next, assume the sensor surface is loaded with one 12 nm $Fe_2O_3$ and one 12 nm FeCo magnetic nanoparticle on the sensor separately. A vertical mode excitation is applied on the sensor and magnetic nanoparticle:

$$H_p=A_0+A_1\sin(2\pi f_1)+A_2\sin(2\pi f_2)$$

At the same time, an in-plane bias field is applied in the sensor plane, which is $H_{in}$.

[0055] The total magnetization of all the magnetic nanoparticles is:

$$M = M_s L\left(\frac{m_0 \mu_0 H}{k_B T}\right)$$

where L is the Langiven function and $H_a$ is the total applied field.

[0056] As such, the average demag field on the free layer of the sensor is:

$$H_d = \frac{-8m_x}{(l^2 + 4d^2)\sqrt{l^2 + w^2 + 4d^2}} = \frac{-8m}{(l^2 + 4d^2)\sqrt{l^2 + w^2 + 4d^2}} \frac{H_{in}}{\sqrt{H_{in}^2 + H_p^2}}$$

where l is length of the GMR sensor, w is the width of the GMR sensor, d is the distance between the magnetic nanoparticle and the free layer of the GMR sensor. Therefore, the transfer curve after two kinds of magnetic nanoparticles deposition is then: $\Delta R = R - R_0$ which is the signal of magnetic nanoparticle.

[0057] Then the FFT of ΔR can be taken to examine the signal in frequency domain.

[0058] In addition to a linear transfer curve, one example of the present subject matter can also be used with a non-linear transfer curve, such as that shown in FIG. **6**. The transfer curve of FIG. **6** is depicted using applied field on the horizontal axis and resistance on the vertical axis.

[0059] Simulation and experimental data can be shown to allow determination of numerosity of magnetic nanoparticles of different types. For a system of two types of magnetic nanoparticles, the resulting two equations can be solved to determine values for N1 and N2 corresponding to the number of nanoparticles of each type.

[0060] As noted above, a non-linear GMR sensor (such as that shown in FIG. **6**) can be used with mixed frequency excitation. The number of MNPs that can be identified by a non-linear transfer curve is in the hundreds, while in the linear transfer case, it is 10ˆ6. There is a three order of magnitude improvement.

[0061] FIG. **7** illustrates method **500** that can be implemented using an example of the present subject matter. As shown, at **510**, method **500** includes applying a biasing magnetic field. The biasing magnetic field is applied to a surface of a magnetic sensor. The biasing magnetic field is aligned parallel to the surface and also aligned perpendicular relative to the surface. The biasing magnetic field has a frequency. The frequency can be held constant or the frequency can be swept.

[0062] At **512**, method **500** includes receiving a measure of a change in resistance from the sensor. The amount of change corresponds to the resistance at a time before onset of a magnetic field perturbance at the surface and a time after the onset of the magnetic field perturbance at the surface. The magnetic field perturbance can include the arrival or departure of a magnetic nanoparticle at the surface of the sensor.

[0063] At **514**, method **500** includes determining a parameter corresponding to the magnetic field perturbance. The parameter can include determining the number of magnetic nanoparticles. In one example, determining the parameter can include deterring a relaxation time for a magnetic nanoparticle. Applying the biasing magnetic field can include applying a first signal and applying a second signal wherein the first signal differs from the second signal. For example, the two signals can have differing amplitude. In one example, applying the biasing magnetic field includes applying an amplitude modulated signal at the frequency.

[0064] In addition, applying the biasing magnetic field can include sweeping the frequency through a range. Determining the parameter can include determining numerosity of a magnetic nanoparticle. In addition, determining the parameter can include solving a plurality of equations. In one example, the surface is configured to receive a fluidous medium. Furthermore, the method can include sorting magnetic nanoparticles flowing over the surface based on the parameter. Sorting can include applying a biasing force. The biasing force can be an electric field disposed transverse to the movement direction of the magnetic nanoparticles.

[0065] In one example, a linear GMR sensor, superparamagnetic or ferromagnetic nanoparticles, and a scanning frequency technique is implemented. The frequency can be swept over a range of frequencies.

[0066] FIG. **8** illustrates a view of system **800** including sensor **150**C disposed in fluid channel **810**. Fluid channel **810** is located in substrate **805** and can include a microfluidic channel or a nanofluidic channel configured to carry a liquid or a gas.

[0067] FIG. **9** illustrates system **900** having channel **910** in substrate **905**. Substrate **905** can include $SiO_2$ or PDMS. In the example shown, channel **910** is bridged by four transverse elements that can be configured to provide a biasing field. In the figure, sensors are in serial alignment, however, in other examples a parallel arrangement of sensor is also contemplated.

[0068] In one example, a magnetic coloring scheme utilizes the intrinsic magnetic relaxation time of nanoparticles that is measured by a series of GMR sensors. FIG. **9** illustrates an example of a series of GMR sensors. Magnetic nanoparticles with different anisotropy constant and volume product (KuV) will have different magnetic relaxation time at a given temperature, τ=f0−1exp (KuV/kBT), where f0 is the attempt frequency (109 Hz), kB is the Boltzmann constant and T is the testing temperature. As such, a magnetic nanoparticle with a given KuV value can appear to be superparamagnetic if τ<τM (i.e. the flipping of magnetic moment is fast compared to the measurement time), while if τ>τm, the flipping is slow and the particle appears to be ferromagnetic. By engineering magnetic nanoparticles with different anisotropy and volume product, which can be implemented by changing the composition of nanoparticles such as FeCox, each particle can exhibit different intrinsic relaxation time (or frequency), which is analogous to a color.

[0069] Each sensor works at a magnetic field having a different frequency, which can be implemented by the current lines above the channel sensor. Magnetic moment signal can be detected as a function of the magnetic field with different frequency.

[0070] If the KuV value of nanoparticles is selected with standard deviation about 10%, then at least four colors can be implemented based on the above scheme within a reasonable frequency range (DC—100 kHz). Three color schemes can be implemented with the frequency range (DC—1 kHz).

[0071] Additional techniques can be implemented to increase the number of colors available. For example, develop the nanoparticle with Ku very sensitive to temperature around room temperature range. As another example, increase the bandwidth of the device.

[0072] Noise may become a concern for testing. Noise may originate from the fluctuation of the height of the carrier of nanoparticles.

[0073] In one example, a magnetic dipole field is generated by 10 nm FeCo nanoparticles attached to 10 um bead (e.g. polymers, cells) relative to the distance to the sensor. Collecting the signal by passing the sample through a sensor array (10 s sensors) with the same working frequency can average out the fluctuation effect.

[0074] FIG. **10** illustrates microfluidic-channel **1000** configured as an integrated magnetic coloring sensing system for cell sorting and molecule identification. In the figure, different magnetic nanoparticles emerge on the right side of the channel and are steered to a selected corridor on the right edge based on a biasing voltage. For example, the nanoparticles are travelling rightward in channel **1050**. Upon discharge from channel **1050**, magnetic nanoparticles **10** are directed to corridor **1010**, magnetic nanoparticles **20** are directed to corridor **1020**, and magnetic nanoparticles **30** are directed to corridor **1030** based on a field aligned transverse to the direction of nanoparticle flow.

[0075] FIG. **11** illustrates schematic **1100** configured for adaptive referencing for a plurality of sensors, according to one example. In an example with a single sensor, a single resistor can be used to provide a reference signal level and configured to reduce common mode noise. For an array of sensors, the circuit of schematic **1100** can be used. In an array, resistance differences among the sensors of the array can lead to common mode noise arising from the excitation frequency. The adaptive referencing circuit shown can be used to compare the voltage difference between sensor signals and a reference signal (obtained either before or during the measurement). In the example shown, the data acquisition module (DAQ) can be selectively uncoupled from the reference source, and in which case, instrumentation amplifier **1110** receives a large differential at the input and will generate large output (denoted by the large amplitude sinusoid in data stream **1120**). With the DAQ coupled to the reference source, the switches at each of sensors **150**D, **150**E, **150**F, and **150**G are selectively actuated and, in which case, the instrumentation amplifier sees a small difference, thus yielding the small amplitude signal visible in data stream **1120**.

[0076] In one example, detection of magnetic nanoparticles entails frequency modulation of the excitation. For example, an excitation current signal ($f_s$) has a selected center frequency and an excitation field signal ($f_e$) is applied to the sensor. The resulting harmonics are seen at $f_2+f_e$ and $f_s-f_e$ and such harmonics can be filtered and processed to discern a parameter as to the magnetic nanoparticles.

[0077] FIG. **12** illustrates handheld device **1200** configured for detection, according to one example. Device **1200** includes user-operable keys **1210**, visual display **1230**, and sample receiving well **1240**. Device **1200** can be powered by a portable energy source such as batteries, solar cells or other means. Structure internal to device **1200** can include one or more sensors, an excitation source, and a processor. The results of the signal processing can include information as to type and amount of targeted elements and this can be displayed on the visual display **1230**.

[0078] MNP Colorization

[0079] Various magnetic nanoparticles having different magnetic behavior can be fabricated. The different behaviors are associated with magnetic coloring.

[0080] Magnetic nanoparticles with different magnetization behavior can be used as an identification signal.

[0081] A variety of magnetic nanoparticles having a selectable size, composition control, heterostructure, different morphology, etc., can be fabricated. These nanoparticles possess different magnetic properties and are able to be differentiated through their AC response.

[0082] Among other things, colorization of nanoparticles enables:

[0083] a) magnetic nanoparticles with magnetic coloring effect that can be applied in related biomedical applications, e.g. low cost and small-size or handheld magnetic cytometry (to sort, identify, and quantify the cells, proteins, or other molecules);

[0084] b) more than ten colors

[0085] c) identify multiple food contaminations, environment damage.

[0086] Magnetic nanoparticles can be non-toxic and exhibit high-magnetic-moment, and are tunable for selected magnetic behavior which can provide a differentiated AC response;

[0087] Examples of assorted magnetic nanoparticles are shown in FIG. **13**. Magnetic nanoparticle **1310** includes a first arrangement of core and shell elements and MNP **1320** includes a second arrangement. Magnetic nanoparticle **1330** includes a multi-shell example. Magnetic nanoparticle **1340** includes a pair of semispherical elements and MNP **1350** includes a pair of nodes embedded in a different element.

[0088] Superparamagnetic nanoparticles follow Langevin law.

[0089] For three kinds of superparamagnetic nanoparticles with different Langevin M-H curves, application of three AC fields can be used to differentiate the nanoparticles based on their magnetic response. Langevin M-H curves for three different nanoparticles are shown in FIG. **15**.

[0090] The ability to access magnetic nanoparticles with different M-H loops or Néel relaxation times enables "magnetic colors" to allow bio-lables for disease detection. Among other things, a magnetic signal is unaffected by the background from biological matters. In addition, a magnetic signal can penetrate tissue with negligible side-effects and Fe-based magnetic nanoparticles have improved biocompatibility compared to some quantum dots.

[0091] Others have attempted to fabricate magnetic particles. A top-down fabrication technique (based on lithography) has obstacles in scaling down the feature size with reasonable cost. In addition, the particle size is over 100 nm or larger. This dimension scale is not suitable for binding with molecules to be detected. Furthermore, the nanostructures may contain toxic materials unsuitable for biological use in order to achieve particular structure controlled magnetic property. In addition, chemical synthesis methods are able to provide very small magnetic nanoparticles, however, the process introduces other chemical residuals on the surface of the nanoparticles, which are difficult to remove.

[0092] An example of the present subject matter entails fabricating high-magnetic moment nanoparticles having a magnetic coloring effect. Size, composition, heterostructure and morphology of nanoparticles are designed and controlled to give different magnetic behavior. In one example, the materials have high saturation magnetization. A synthesis method can be implemented using physical gas condensation or other fabrication technique.

**[0093]** The magnetic moment of a nanoparticle will change with a change in size. The magnetic behavior will differ among each size category according to the Langevin theory. In one example, a high saturation magnetization material, such as FeCo, is selected. FeCo nanoparticles of differing size can be synthesized by physical gas condensation. Different sizes can be achieved by selection and control of the gas flow, sputtering current, and magnetic field strength.

**[0094]** FIG. **16** illustrates nanofabrication system **1600**, according to one example. As noted, pressure in region **1630** can be modulated to produce desired effects. In one example, the pressure is between 200 and 900 mTorr. Pressure in region **1620** is typically under 1 mTorr. Dimensions and profile of orifice **1610** can also be controlled to produce a desired effect. Furthermore, the field strength of magnets **1640** can be tailored for a particular purpose.

**[0095]** The specific magnetization change verses applied field for FeCo nanoparticles of different size shows observable differences. In addition, the composition of the nanoparticles can be changed. $Fe_xCo_{1-x}$ nanoparticles with different Fe:Co composition ratio can be fabricated by physical gas condensation method. Furthermore, magnetization and magnetic anisotropy differences caused by alloy composition change can play a role in the consequent loop difference. Examples of fabrication conditions are as follows:

| | $Fe_{10}Co_{90}$ | $Fe_{40}Co_{60}$ | $Fe_{70}Co_{30}$ |
|---|---|---|---|
| Sputtering pressure (mTorr) | 600 | 450 | 300 |
| Sputtering current (A) | 0.5 | 0.5 | 0.5 |
| Surface magnetic field strength (Oe) | 750 | 650 | 630 |
| Crystal structure | fcc | bcc | Bcc |
| Anisotropy constant (ergs/cm$^3$) | $5 \times 10^6$ | $3 \times 10^6$ | $1 \times 10^6$ |

**[0096]** Magnetic nanoparticles having heterostructure can lead to a special spin configuration confined in the nanodimension. This can lead to a more tunable M-H behavior. This can be fabricated by the gas phase synthesis method. Material choice and control of diffusion on the atomic scale can produce results.

**[0097]** The core-shell structure can be demonstrated by an EDX line scan across a single Co—Au nanoparticle synthesized by physical gas condensation method. In one example, the core is rich in Co and the shell is rich in Au. At room temperature, the nanoparticles show superparamagnetic behavior, which is consistent with Au covered Co.

**[0098]** Other types of heterostructure are also achievable through gas phase synthesis. These heterostructures can enrich the archive of magnetic colors. In one example, fabrication conditions include sputtering gas flow at 9.4 sccm and sputtering pressure at 200 mTorr. In another example, the fabrication conditions include sputtering gas flow at 16.7 sccm and sputtering pressure at 363 mTorr.

**[0099]** In one example, specific control of interparticle dipolar interaction through cluster ensemble type of heterostructure can provide a novel way to generate multiple magnetic colors. For example, the magnetization process of one small cluster is subject to influence from clusters in near proximity. It may be found that cluster ensemble types of particles are able to give differentiated magnetic behavior.

**[0100]** In one example, a tube target is provided in the gas phase deposition system. In one example, a tube target is used with a $Fe_{70}Co_{30}$ nanoparticles fabricated under conditions including: sputtering $Ar_2$ gas flow 21 sccm; sputtering gas pressure 400 mTorr, and sputtering current 0.6 A.

**[0101]** Morphology control of nanoparticles can modify the magnetic property in terms of the shape anisotropy, which is affected by the aspect ratio. In one example, magnetic energy barrier can be tuned to give different Neel relaxation time. Relaxation time difference is reflected by the phase of magnetization subject to AC field.

**[0102]** Nanometer scale magnetic rings may provide a tunable magnetic behavior. Ring diameter, ring aspect ratio and consisting materials are factors that can be changed to pursue a desired magnetic property.

**[0103]** Nanorings, such as those shown in FIG. **14**, can be fabricated by various methods. In one example, material is deposited onto substrates to form islands by selecting surface energy of the two. Sputtering ring material to form a thin layer and etch. Around the island where nucleation first occurs will have the thickest material and remains in a ring geometry after etching. Incomplete nanorings are shown at **1510** on substrate **1505** and, on substrate **1505** on the right side, completed nanorings **1520** are shown.

**[0104]** In another method, nanorings are fabricated by depositing ring material onto a substrate to form a thin film. In addition, place block copolymer rings onto the metal film and use ion etching to remove extra film material.

**[0105]** In sum, magnetic nanoparticle colors can be achieved by tuning magnetic behavior of nanoparticles. The colors are candidate labels or markers for detection, for example, multiple biological diseases diagnosis.

**[0106]** In one example, a magnetic flow cytometry system can be prepared. The system can include different size cells and each bonded to different nanoparticles. By using various combinations of nanoparticles, many different colors are available.

## Various Notes & Examples

**[0107]** Example 1 includes a system having a first sensor, a field source, and a processor. The first sensor having a surface and having an electrical resistance determined by a magnetic field at the surface. The field source configured to provide a biasing magnetic field to the surface. The biasing magnetic field aligned parallel to the surface and aligned perpendicular relative to the surface. The magnetic field having a frequency. The processor coupled to the sensor and configured to determine a parameter based on a measure of a change in the resistance. The change corresponding to the resistance at a time before onset of a magnetic field perturbance at the surface and a time after the onset of the magnetic field perturbance at the surface.

**[0108]** In Example 2, the subject matter of Example 1 can optionally include wherein the surface has dimensions corresponding to an aspect ratio of less than 50.

**[0109]** In Example 3, the subject matter of one or any combination of Examples 1 and 2 and optionally wherein the processor is configured to determine the parameter as a function of a dimensional size of the surface.

**[0110]** In Example 4, the subject matter of one or any combination of Examples 1 to 3 and optionally including a second sensor coupled to the processor.

**[0111]** In Example 5, the subject matter of one or any combination of Examples 1 to 4 and optionally wherein the first sensor and the second sensor are in serial alignment with a fluid channel.

[0112] In Example 6, the subject matter of one or any combination of Examples 1 to 5 and optionally including a channel in fluid communication with the surface.

[0113] Example 7 includes subject matter comprising method including applying a biasing magnetic field to a surface, receiving a measure of a change in resistance, and determining a parameter corresponding to the magnetic field perturbance. The biasing magnetic field is aligned parallel to the surface and aligned perpendicular relative to the surface. The magnetic field has a frequency. The method includes receiving the measure of a change in resistance from the sensor. The change corresponds to the resistance at a time before onset of a magnetic field perturbance at the surface and a time after the onset of the magnetic field perturbance at the surface. This Example includes determining a parameter corresponding to the magnetic field perturbance.

[0114] In Example 8, the subject matter of Example 7 can optionally include determining the parameter includes determining a relaxation time.

[0115] In Example 9, the subject matter of one or any combination of Examples 7 to 8 and can optionally include wherein applying the biasing magnetic field includes applying a first signal and applying a second signal, the first signal differs from the second signal.

[0116] In Example 10, the subject matter of one or any combination of Examples 7 to 9 and can optionally include applying the biasing magnetic field includes applying an amplitude modulated signal at the frequency.

[0117] In Example 11, the subject matter of one or any combination of Examples 7 to 10 and can optionally include applying the biasing magnetic field includes sweeping the frequency through a range.

[0118] In Example 12, the subject matter of one or any combination of Examples 7 to 11 and can optionally include determining the parameter includes determining numerosity of a magnetic nanoparticle.

[0119] In Example 13, the subject matter of one or any combination of Examples 7 to 12 and can optionally include determining the parameter includes solving a plurality of equations.

[0120] In Example 14, the subject matter of one or any combination of Examples 7 to 13 and can optionally include passing a fluidous medium over the surface.

[0121] In Example 15, the subject matter of one or any combination of Examples 7 to 14 and can optionally include sorting magnetic nanoparticles flowing over the surface based on the parameter.

[0122] In Example 16, the subject matter of one or any combination of Examples 7 to 15 and can optionally include sorting includes applying a biasing force.

[0123] These non-limiting examples can be combined in any permutation or combination.

[0124] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to herein as "examples." Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0125] In the event of inconsistent usages between this document any documents so incorporated by reference, the usage in this document controls.

[0126] In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In this document, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

[0127] Method examples described herein can be machine or computer-implemented at least in part. Some examples can include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device to perform methods as described in the above examples. An implementation of such methods can include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code can include computer readable instructions for performing various methods. The code may form portions of computer program products. Further, in an example, the code can be tangibly stored on one or more volatile, non-transitory, or non-volatile tangible computer-readable media, such as during execution or at other times. Examples of these tangible computer-readable media can include, but are not limited to, hard disks, removable magnetic disks, removable optical disks (e.g., compact disks and digital video disks), magnetic cassettes, memory cards or sticks, random access memories (RAMs), read only memories (ROMs), and the like.

[0128] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to comply with 37 C.F.R. §1.72(b), to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description as examples or embodiments, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

**1**. A system comprising:

a first sensor having a surface and having an electrical resistance determined by a magnetic field at the surface;

a field source configured to provide a biasing magnetic field to the surface, the biasing magnetic field aligned parallel to the surface and aligned perpendicular relative to the surface, the magnetic field having a frequency; and

a processor coupled to the sensor and configured to determine a parameter based on a measure of a change in the resistance, the change corresponding to the resistance at a time before onset of a magnetic field perturbance at the surface and a time after the onset of the magnetic field perturbance at the surface.

**2**. The system of claim **1** wherein the surface has dimensions corresponding to an aspect ratio of less than 50.

**3**. The system of claim **1** wherein the processor is configured to determine the parameter as a function of a dimensional size of the surface.

**4**. The system of claim **1** further including a second sensor coupled to the processor.

**5**. The system of claim **1** wherein the first sensor and the second sensor are in serial alignment with a fluid channel.

**6**. The system of claim **1** further including a channel in fluid communication with the surface.

**7**. A method comprising:

applying a biasing magnetic field to a surface of a magnetic sensor, the biasing magnetic field aligned parallel to the surface and aligned perpendicular relative to the surface, the magnetic field having a frequency;

receiving a measure of a change in resistance from the sensor, the change corresponding to the resistance at a time before onset of a magnetic field perturbance at the surface and a time after the onset of the magnetic field perturbance at the surface; and

determining a parameter corresponding to the magnetic field perturbance.

**8**. The method of claim **7** wherein determining the parameter includes deterring a relaxation time.

**9**. The method of claim **7** wherein applying the biasing magnetic field includes applying a first signal and applying a second signal, the first signal differs from the second signal.

**10**. The method of claim **7** wherein applying the biasing magnetic field includes applying an amplitude modulated signal at the frequency.

**11**. The method of claim **7** wherein applying the biasing magnetic field includes sweeping the frequency through a range.

**12**. The method of claim **7** wherein determining the parameter includes determining numerosity of a magnetic nanoparticle.

**13**. The method of claim **7** wherein determining the parameter includes solving a plurality of equations.

**14**. The method of claim **7** further including passing a fluidous medium over the surface.

**15**. The method of claim **7** further including sorting magnetic nanoparticles flowing over the surface based on the parameter.

**16**. The method of claim **15** wherein sorting includes applying a biasing force.

* * * * *