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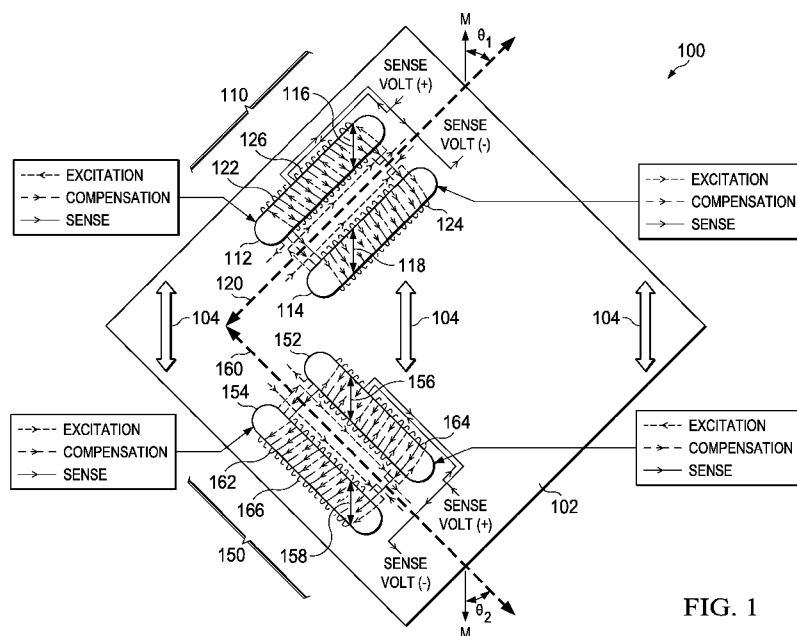


FIG. 1

(57) Abstract: In described examples, a fluxgate device (100) includes a first magnetic core (112, 114) and a second magnetic core (152, 154). The first magnetic core (112, 114) has a first magnetized direction (116, 118) that deviates from a first sense direction (120) by more than 0 degree and less than 90 degrees. The second magnetic core (152, 154) is arranged orthogonally to the first magnetic core (112, 114). The second magnetic core (152, 154) has a second magnetized direction (156, 158) that deviates from a second sense direction (160) by more than 0 degree and less than 90 degrees.

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DUAL-AXIS FLUXGATE DEVICE

BACKGROUND

[0001] A fluxgate device generally includes a magnetic core structure and coil members coiling around the magnetic core. A fluxgate device can be used as a magnetometer for detecting a change in magnetic flux in an environment adjacent to the magnetic core structure. Attempts have been made to interface a fluxgate device with an integrated circuit for adapting to various industrial applications. For example, a fluxgate device interfaced with a control circuit can be adapted as current measurement devices for use in motor control systems, or as position sensing device for use in robotic systems. Moreover, a fluxgate device may be adapted to perform dual-axis sensing applications, such as e-compass applications. However, these solutions typically involve tradeoffs between high sensitivity and low noise performances.

SUMMARY

[0002] In described examples, an integrated circuit includes a semiconductor substrate, a fluxgate device formed above the semiconductor substrate, and a sense circuit having transistors formed partially in the semiconductor substrate and under the fluxgate device. The fluxgate device includes a first magnetic core, a second magnetic core, a first sense coil, and a second sense coil. The first magnetic core has a first magnetized direction that deviates from a first sense direction by more than 0 degree and less than 90 degrees. The first sense coil includes first coil members that coil around the first magnetic core, and the first sense coil defines the first sense direction perpendicular to the first coil members. The second magnetic core is arranged orthogonally to the first magnetic core. Like the first magnetic core, the second magnetic core has a second magnetized direction that deviates from a second sense direction by more than 0 degree and less than 90 degrees. The second sense coil including second coil members that coil around the second magnetic core, and the second sense coil defines the second sense direction perpendicular to the second coil members. To process the signals received by the first and second sense coils, the sense circuit is coupled to the first sense coil and the second sense coil to receive these signals.

[0003] In another described example, a fluxgate device includes a first magnetic core and a

second magnetic core. The first magnetic core has a first magnetized direction that deviates from a first sense direction by more than 0 degree and less than 90 degrees. The second magnetic core is arranged orthogonally to the first magnetic core. The second magnetic core has a second magnetized direction that deviates from a second sense direction by more than 0 degree and less than 90 degrees.

[0004] In yet another described example, a method includes forming a first magnetic core along a first sense direction of a fluxgate device. The method also includes forming a second magnetic core along a second sense direction of the fluxgate device orthogonal to the first sense direction. The method further includes magnetizing the first and second magnetic cores according to a magnetization direction deviating from the first and second sense directions.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 shows a top view of an integrated fluxgate device according to an aspect of example embodiments.

[0006] FIG. 2 shows a top view of an integrated fluxgate device according to another aspect of example embodiments.

[0007] FIG. 3 shows a perspective view of a magnetic core film according to an aspect of example embodiments.

[0008] FIG. 4A shows a top view of the integrated fluxgate device detecting an external magnetic field according to an aspect of example embodiments.

[0009] FIG. 4B shows a voltage chart of the integrated fluxgate device detecting the external magnetic field according to an aspect of example embodiments.

[0010] FIG. 5 shows a schematic view of an integrated fluxgate device according to an aspect of example embodiments.

[0011] FIG. 6 shows a flow diagram of a method of fabricating an integrated circuit integrating a fluxgate device and a fluxgate processing circuit according to an aspect of example embodiments.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0012] Like reference symbols in the various drawings indicate like elements. The drawings are not drawn to scale. Example embodiments include systems and techniques relating to the fabrication of fluxgate devices, such as integrated fluxgate devices that are integrated with one or more circuits formed on a semiconductor substrate. More specifically, example embodiments

include a fluxgate device that delivers high sensitivity performance with a relatively low susceptibility to fluxgate noise in two-dimensional sensing applications, such as e-compass applications. The described fluxgate device includes at least two magnetic cores that are respectively aligned in two substantially perpendicular sensing direction. The magnetic cores are magnetized according to a magnetization direction that reduces the dependency on shape anisotropy of the magnetic cores while maintaining a low susceptibility to fluxgate noises. Advantageously, the magnetic cores can afford a wider range of geometric configurations, which may help reduce the overall size of the fluxgate device.

[0013] FIG. 1 shows a top view of an integrated fluxgate device (IFD) 100 according to an aspect of example embodiments. The IFD 100 can be formed on or above a semiconductor substrate 102, which is used for establishing circuitry that controls the operations of the IFD 100. The IFD 100 includes a first fluxgate 110 and a second fluxgate 150. For two-dimensional (2D) magnetic field sensing, the first fluxgate 110 is arranged orthogonally to the second fluxgate 150.

[0014] The first fluxgate 110 includes one or more first magnetic cores, such as first magnetic cores 112 and 114. The first fluxgate 110 also includes a first sense coil 122, a first excitation coil 124, and optionally, a first compensation coil 126. The first sense coil 122, the first excitation coil 124, and the first compensation coil 126 each includes coil members that coil around the first magnetic cores 112 and 114. For differential sensing, the first sense coil 122 and the first excitation coil 124 have the same coiling direction around the first magnetic core 112, whereas the first sense coil 122 and the first excitation coil 124 have the opposite coiling directions around the first magnetic core 114. When included, the first compensation coil 126 has the same coiling direction as the first sense coil 122 around both the first magnetic cores 112 and 114.

[0015] Likewise, the second fluxgate 150 includes one or more second magnetic cores, such as second magnetic cores 152 and 154. The second fluxgate 150 also includes a second sense coil 162, a second excitation coil 164, and optionally, a second compensation coil 166. The second sense coil 162, the second excitation coil 164, and the second compensation coil 166 each includes coil members that coil around the second magnetic cores 152 and 154. For differential sensing, the second sense coil 162 and the second excitation coil 164 have the same coiling direction around the second magnetic core 152, whereas the second sense coil 162 and the second excitation coil 164 have the opposite coiling directions around the second magnetic core

154. When included, the second compensation coil 166 has the same coiling direction as the second sense coil 162 around both the second magnetic cores 152 and 154.

[0016] The coil members of the first sense coil 122 define a first sense direction 120 that is substantially perpendicular (e.g., within a plus-and-minus 5% range of tolerance) to the coiling direction of these coil members. Because the first sense coil 122 coils around the first magnetic cores 112 and 114, the first sense direction 120 is substantially parallel to the longitudinal edges of the first magnetic cores 112 and 114. Likewise, the coil members of the second sense coil 162 define a second sense direction 160 that is substantially perpendicular (e.g., within a plus-and-minus 5% range of tolerance) to the coiling direction of these coil members. Because the second sense coil 162 coils around the second magnetic cores 152 and 154, the second sense direction 160 is substantially parallel to the longitudinal edges of the second magnetic cores 152 and 154. Because the first fluxgate 110 is arranged orthogonally to the second fluxgate 150, the first sense direction 120 is substantially orthogonal (e.g., within a plus-and-minus 5° of angular deviation) to the second sense direction 160.

[0017] To minimize the reception of fluxgate noise, a magnetic core may be magnetized according to a magnetization direction that is perpendicular to the sense direction of the fluxgate. In the application of 2D magnetic field sensing, the magnetization of the first magnetic cores 112 and 114 and the second magnetic cores 152 and 154 is generally performed under the same process steps in order to reduce the complexity and costs associated with the fabrication of the IFD 100. Under these conditions, the magnetization direction is substantially the same for the first magnetic cores 112 and 114 and the second magnetic cores 152 and 154. This means one set of magnetic cores is magnetized parallel to the respective sensing direction, whereas the other set of magnetic core is magnetized perpendicular to the respective sensing direction. Generally, the fluxgate with magnetic core magnetized perpendicular to the respective sensing direction (i.e., hard axis magnetization) is less susceptible to fluxgate noise than the fluxgate with magnetic core magnetized parallel to the respective sensing direction (i.e., easy axis magnetization). When the magnetization direction is perpendicular to one of the sense directions (e.g., 120 or 160), one of the orthogonally arranged fluxgates (e.g., 110 and 150) will likely experience higher fluxgate noise than the other one. This imbalance will lead to mismatch in sensitivity and noise susceptibility between the two orthogonally arranged fluxgates (e.g., 110 and 150).

[0018] An aspect of example embodiments provides a solution to reduce the noise and sensitivity mismatch between the fluxgates for use in 2D magnetic field sensing. The described solution involves magnetizing orthogonally arranged magnetic cores (e.g., 112, 114, 152, and 154) according to a magnetization direction (e.g., 104) that deviates from both of the orthogonally defined sense directions (e.g., 120 and 160) of the orthogonally arranged magnetic cores.

[0019] In one configuration, the magnetization direction (e.g., 104) is configured to deviate from each of the first sense direction 120 and the second sense direction 160 by more than 0 degree but less than 90 degrees. Accordingly, the magnetization direction (e.g., 104) is neither parallel, nor orthogonal, to either one of the first sense direction 120 and the second sense direction 160. Upon the magnetization process is completed, the first magnetic cores 112 and 114 have first magnetized directions 116 and 118 respectively. Each of the magnetized directions 116 and 118 deviates from the first sense direction 120 by more than 0 degree but less than 90 degrees (i.e., $0^\circ < \text{first deviation angle } \theta_1 < 90^\circ$). Likewise, the second magnetic cores 152 and 154 have second magnetized directions 156 and 158 respectively, both of which are substantially parallel to the first magnetized directions 116 and 118. Each of the magnetized directions 156 and 158 deviates from the second sense direction 160 by more than 0 degree but less than 90 degrees (i.e., $0^\circ < \text{second deviation angle } \theta_2 < 90^\circ$). Advantageously, this particular configuration helps reduce the imbalances in sensitivity and noise susceptibility between the first fluxgate 110 and the second fluxgate 150.

[0020] In one implementation, the magnetization direction 104 is configured to deviate from each of the first sense direction 120 and the second sense direction 160 by approximately 45 degrees. Accordingly, the magnetization direction 104 is aligned at approximately 45 degrees counterclockwise relative to the first sense direction 120 and 45 degrees clockwise relative to the second sense direction 160. Depending on variations in certain process parameters (e.g., deviations in size and/or shape among the first and second magnetic cores 112, 114, 152, and 154), the approximation in degrees may range from plus 10 degrees to minus 10 degrees. Advantageously, this particular configuration helps further reduce the imbalances in sensibility and noise susceptibility between the first fluxgate 110 and the second fluxgate 150. The approximation in degrees may also range from plus 7.5 degrees to minus 7.5 degrees for more optimized performance in 2D magnetic field sensing.

[0021] Upon the magnetization process is completed, the first magnetic cores 112 and 114 have first magnetized directions 116 and 118 respectively. Each of the magnetized directions 116 and 118 deviates from the first sense direction 120 by approximately 45 degrees counterclockwise (i.e., $-(45^\circ + \Delta) \leq \text{first deviation angle } \theta_1 \leq -(45^\circ - \Delta)$, where Δ represents the range of approximation). Likewise, the second magnetic cores 152 and 154 have second magnetized directions 156 and 158 respectively, both of which are substantially parallel to the first magnetized directions 116 and 118. Each of the magnetized directions 156 and 158 deviates from the second sense direction 160 by approximately 45 degrees clockwise (i.e., $(45^\circ - \Delta) \leq \text{second deviation angle } \theta_2 \leq (45^\circ + \Delta)$, where Δ represents the range of approximation). To that end, each of the first fluxgate 110 and the second fluxgate 150 may have a noise susceptibility (e.g., 2-3 μT) that is substantially lower than the magnetic field of the Earth (e.g., 20-50 μT).

[0022] Although FIG. 1 shows that the magnetization direction 104 is aligned at approximately 45 degrees counterclockwise relative to the first sense direction 120 and 45 degrees clockwise relative to the second sense direction 160, other magnetization directions are possible. For example, FIG. 2 shows a top view of an integrated fluxgate device 200 having a different magnetization direction 204. In this particular configuration, the magnetization direction 204 is aligned at approximately 45 degrees clockwise relative to the first sense direction 120 and 45 degrees counterclockwise relative to the second sense direction 160. Depending on variations in certain process parameters (e.g., deviations in size and/or shape among the first and second magnetic cores 112, 114, 152, and 154), the approximation in degrees may range from plus 10 degrees to minus 10 degrees. Advantageously, this particular configuration helps further reduce the imbalances in sensibility and noise susceptibility between the first fluxgate 110 and the second fluxgate 150. The approximation in degrees may also range from plus 7.5 degrees to minus 7.5 degrees for more optimized performance in 2D magnetic field sensing.

[0023] Upon the magnetization process is completed, the first magnetic cores 112 and 114 have first magnetized directions 216 and 218 respectively. Each of the magnetized directions 216 and 218 deviates from the first sense direction 120 by approximately 45 degrees clockwise (i.e., $(45^\circ - \Delta) \leq \text{first deviation angle } \theta_1 \leq (45^\circ + \Delta)$, where Δ represents the range of approximation). Likewise, the second magnetic cores 152 and 154 have second magnetized directions 256 and 258 respectively, both of which are substantially parallel to the first magnetized directions 216 and 218. Each of the magnetized directions 256 and 258 deviates

from the second sense direction 160 by approximately 45 degrees counterclockwise (i.e., $-(45^\circ + \Delta) \leq$ second deviation angle $\theta_2 \leq -(45^\circ - \Delta)$, where Δ represents the range of approximation). Like the IDF 100, the IDF 200 may have a noise susceptibility (e.g., 2-3 μ T) that is substantially lower than the magnetic field of the Earth (e.g., 20-50 μ T).

[0024] According to an aspect of example embodiments, the magnetic core (e.g., 112, 114, 152, and 154) includes soft magnetic alloys with high magnetic permeability, such as nickel iron (NiFe). These alloys can be magnetized spontaneously, and the direction of magnetization is determined by the net or overall anisotropy. Several anisotropies exist in nature, including induced anisotropies, shape anisotropies, magneto-crystalline anisotropies, and stress-induced anisotropies. Generally, soft magnetic alloys have relatively small magneto-crystalline anisotropies and stress-induced anisotropies. Accordingly, the net or overall anisotropy of a soft magnetic alloy is determined by the relative strength between the induced anisotropy and the shape anisotropy.

[0025] The strength of an induced anisotropy is controllable by the fabrication process because the magnetization direction (e.g., 104 or 204) applied during the deposition of the magnetic cores becomes the direction of the induced anisotropy. Accordingly, the magnetization direction may become the resulting magnetization (i.e., magnetized direction) of the magnetic cores where the induced anisotropy is the dominant anisotropy.

[0026] By comparison, the strength of a shape anisotropy is determined by the geometric dimensions of the magnetic core. For example, a demagnetizing field is the weakest along the longitudinal direction of a magnetic core. Thus, to minimize the magneto-static energy, a shape anisotropy prefers the magnetization to be aligned along the longitudinal direction of the magnetic core. For example, as shown in FIG. 3, a magnetic film 300 for constructing a magnetic core has a shape anisotropy H_{shape} that is dependent on the geometric dimensions of the magnetic film 300. These geometric dimensions include a thickness (t) of the magnetic film 300, a width (w) defined by a terminal edge 304, and a length (l) defined by a longitudinal edge 302. Generally, the shape anisotropy H_{shape} may be defined by Equation (1.0) hereinbelow (given in SI units), where M represents the magnetization of the magnetic alloy, N_w represents the demagnetizing factor along the terminal edge direction (e.g., 304), and N_l represents the demagnetizing factor along the longitudinal edge direction (e.g., 302).

$$H_{shape} = M(N_w - N_l) \approx M * \frac{2t}{\pi} * (\frac{1}{w} - \frac{1}{l}) \quad \text{Eq. (1.0)}$$

[0027] Accordingly, a fluxgate device with magnetic cores relying heavily on a shape anisotropy typically has a relatively large aspect ratio (i.e. the length divided by the width of a magnetic core). A relatively large aspect ratio (e.g., $AR \geq 30$) imposes certain size requirements on the magnetic cores. For example, a magnetic core having a shape anisotropy of 144 Oersted (Oe) may require a length of 990 μm and a width not greater than 33 μm , thereby resulting in an aspect ratio of 30. A fluxgate integrated circuit die incorporating this particular magnetic core may have limited options on sizing and placing the magnetic core. Thus, the size requirements imposed by shape anisotropies increase the overall size of a fluxgate die and restricting the placement of circuitry around the magnetic cores.

[0028] Example embodiments provide a solution to the size restrictions imposed by shape anisotropies. More specifically, the IFD 100 and the IFD 200 are both dominated by induced anisotropies such that the magnetic cores of these devices may have a flexible range of aspect ratios. In one example implementation, the aspect ratio of each of the magnetic cores 112, 114, 152, and 154 may be set at a value that is less than 30. To that end, the difference between the length and the width of each magnetic core (e.g., 112, 114, 152, or 154) become less drastic that the overall size of the fluxgate device (e.g., 100 or 200) may be reduced. At the same time, the placement of other circuitry may also become less restrictive. For example, the length of each magnetic core (e.g., 112, 114, 152, or 154) may be reduced to 700 μm while adjusting the corresponding width to 50 μm or more. In this case, the aspect ratio of each magnetic core (e.g., 112, 114, 152, or 154) may be reduced to 14.

[0029] FIG. 4A shows a top view of the integrated fluxgate device 100 detecting an external magnetic field 410, and FIG. 4B shows a sense output chart 420 representing the results of such a detection. The first sense output signal 422 corresponds to the magnetic field 410 detected by the first fluxgate 110, whereas the second sense output signal 424 corresponds to the magnetic field 410 detected by the second fluxgate 150. The voltages of first sense output signal 422 and the second sense output signal 424 have a phase difference of 90 degrees because of the orthogonal arrangement between the first fluxgate 110 and the second fluxgate 150. Generally, the first sense output signal 422 has a voltage V_{FG1} defined by Equation (2.1), and the second sense output signal 424 has a voltage V_{FG2} defined by Equation (2.2).

$$V_{FG1} = V_{Max} * \sin \theta \quad \text{Eq. (2.1)}$$

$$V_{FG2} = V_{Max} * \cos \theta \quad \text{Eq. (2.2)}$$

[0030] As recited in Equations (2.1) and (2.2), V_{Max} represents the normalized output voltage corresponds to the strength of the external magnetic field 410 and θ represents the alignment of the external magnetic field 410. To determine the angular position of the external magnetic field 410, the IFD 100 includes a circuit that calculates the value of θ by applying Equation (3.0).

$$\theta = \tan^{-1} \left(\frac{V_{FG1}}{V_{FG2}} \right) \quad \text{Eq. (3.0)}$$

[0031] To determine the strength of the external magnetic field 410, the IFD 100 includes a circuit that calculate the normalized output voltage V_{Max} by applying the calculated value of θ to either Equation (4.1) or Equation (4.2).

$$V_{Max} = \frac{V_{FG1}}{\sin \theta} \quad \text{Eq. (4.1)}$$

$$V_{Max} = \frac{V_{FG2}}{\cos \theta} \quad \text{Eq. (4.2)}$$

[0032] The IFD 100 and the IFD 200 includes a sense circuit having transistors formed partially in the semiconductor substrate 102. The sense circuit can be formed under the first fluxgate 110 and the second fluxgate 150. To detect and generate the fluxgate sense voltages V_{FG1} and V_{FG2} , the sense circuit is coupled to the first sense coil 122 and the second sense coil 162. FIG. 5 shows a schematic view of an integrated fluxgate device 500 according to an aspect of example embodiments. The integrated fluxgate device 500 can be realized by an integrated circuit die incorporating a fluxgate device 510 and a fluxgate processing circuit 530.

[0033] The fluxgate device 510 is manufactured by modeling each of the first fluxgate 110 and second fluxgate 150 as shown and described in FIGS. 1-4. Thus, the fluxgate device 510 incorporates the structural and functional features of the first fluxgate 110 and the second fluxgate 150 even though some of these features are not explicitly shown in FIG. 5. For example, the fluxgate device 510 is for use in 2D magnetic field sensing applications, even though the structures shown therein are simplified to illustrate only unidirectional sensing.

[0034] The fluxgate device 510 includes a magnetic core 511, an excitation coil 512, a sense coil 514, and a compensation coil 516 arranged in substantially the same ways as their counterparts as shown in FIGS. 1-4. The magnetic core 511 is oriented parallel to the first

sensing direction 504 and the second sensing direction 506 of the integrated fluxgate circuit 500. The excitation coil 512 is extended between a first excitation terminal 521 and a second excitation terminal 522. The excitation coil 512 coils around the longitudinal edge of the magnetic core 511. The sense coil 514 is extended between a first sense terminal 523 and a second sense terminal 524, and the sense coil 514 coils around the longitudinal edge of the magnetic core 511. To enable 2D magnetic field sensing, multiple instances of the fluxgate device 510 can be arranged and configured according to the illustrations and descriptions of FIGS. 1-4.

[0035] The fluxgate processing circuit 530 includes an excitation circuit 532, a sense circuit 534, and an output stage 550. The excitation circuit 532 is coupled to the excitation coil 512 via the first excitation terminal 521 and the second excitation terminal 522. The excitation circuit 532 is configured to generate an excitation signal including an excitation current to be conducted by the excitation coil 512. In a consecutive and alternating pattern, the excitation current may flow from the first excitation terminal 521 to the second excitation terminal 522 via the excitation coil 512 during a first time period, and from the second excitation terminal 522 to the first excitation terminal 521 via the excitation coil 512 during a second time period. By applying the alternating excitation current, the excitation circuit 532 is configured to drive the magnetic core 511 in and out of magnetic saturation during consecutive time periods. The change in magnetic saturation due to the presence of an external magnetic field is detected by the sense coil 514, and the output voltage is generated by the sense circuit 534.

[0036] The sense circuit 534 includes a fluxgate front-end (FFE) circuit 536 and an integrator circuit 538. The FFE circuit 536 is coupled to the sense coil 514 via the first sense terminal 523 and the second sense terminal 524. The FFE circuit 536 is configured to receive a sense signal from the sense coil 514 and demodulate the sense signal based on a synchronization scheme that synchronizes with the movement of the excitation current. In one example implementation, the FFE circuit 536 is coupled to the excitation circuit 532 to receive a synchronization signal 533. The synchronization signal 533 may indicate, during a certain period of time, whether the excitation current is flowing from the first excitation terminal 521 to the second excitation terminal 522 via the excitation coil 512, or from the second excitation terminal 522 to the first excitation terminal 521 via the excitation coil 512. Based on the synchronization signal 533, the FFE circuit 536 is configured to demodulate the sense signal using two or more switches, such as

chopper switches.

[0037] The integrator circuit 538 is coupled to the FFE circuit 536 to receive the demodulated sense signal. The integrator circuit 538 is configured to integrate the demodulated sense signal to generate a sense voltage across a first integrator output 542 and a second integrator output 544. The sense voltage drives the compensation coil 516 via the first compensation terminal 525 and the second compensation terminal 526 to conduct a compensation current. The compensation current helps reset the magnetic field detected by the sense coil 514 within a closed-loop configuration. This reset process enables the sense circuit 534 to operate within a linear region so as to optimize the sensitivity of the integrated fluxgate device 500.

[0038] The output stage 550 is coupled to the first integrator output 542 and the second integrator output 544. The output stage 550 includes a matching impedance 552, a feedback impedance 554, and a differential amplifier 560. The matching impedance 552 provides matching between the differential inputs of the differential amplifier 560. The differential amplifier 560 is configured to generate a fluxgate output voltage (e.g., V_{FG1} or V_{FG2}) to be delivered at the output port 502. The feedback impedance 554 provides a feedback path from the output of the differential amplifier 560.

[0039] FIG. 6 shows a flow diagram of a method 600 of fabricating an integrated circuit (e.g., 500) integrating a fluxgate device (e.g., 510) and a fluxgate processing circuit (e.g., 530) according to an aspect of example embodiments. The method 600 begins at step 602, which involves forming a sense circuit (e.g., 534) having transistors defined partially in a semiconductor substrate (e.g., 102). Then, the method 600 proceeds to step 604, which involves integrating the sense circuit and a fluxgate device (e.g., 110 and 150 as shown in FIGS. 1 and 2, and/or 510 as shown in FIG. 5) to a single integrated circuit having the fluxgate device positioned above the sense circuit.

[0040] Then, the method 600 proceeds to step 612, which involves forming a first magnetic core (e.g., 112 and/or 114) along a first sense direction (e.g., 120) of the fluxgate device. Step 612 includes the alternating depositions of a magnetic alloy, such as nickel iron, and an insulation material, such as silicon nitride. Step 612 also includes the patterning of the deposited magnetic alloy and insulation material. The patterning process defines an aspect ratio of the first magnetic core (e.g., 112 and/or 114), which has a width that can be greater than or equal to 50 μm across the first sense direction (e.g., 120). In one implementation, the aspect ratio is less than

30. In another implementation, the aspect ratio is less than or equal to 14.

[0041] The method 600 may proceed to step 614 after step 612. Alternatively, the method 600 may perform step 612 simultaneously with step 614. Like step 612, step 614 involves forming a second magnetic core (e.g., 152 and/or 154) along a second sense direction (e.g., 160) of the fluxgate device. Step 614 includes the alternating depositions of a magnetic alloy, such as nickel iron, and an insulation material, such as silicon nitride. Step 614 also includes the patterning of the deposited magnetic alloy and insulation material. The patterning process defines an aspect ratio of the second magnetic core (e.g., 152 and/or 154), which has a width that can be greater than or equal to 50 μm across the second sense direction (e.g., 160). In one implementation, the aspect ratio is less than 30. In another implementation, the aspect ratio is less than or equal to 14. When step 614 is performed simultaneously with step 612, the first magnetic core and the second magnetic core are formed under the same deposition and patterning process flows.

[0042] Then, the method 600 proceeds to step 616, which involves magnetizing the first and second magnetic cores according to a magnetization direction (e.g., 104 or 204) that deviates from the first and second sense directions (e.g., 120 and 160). Alternatively, the method 600 may perform step 616 simultaneously with steps 612 and 614. The deviation can be based upon and thus consistent with the description of FIGS. 1-4. In one example implementation, the magnetization direction may deviate from the first sense direction by approximately 45 degrees clockwise and from the second sense direction by approximately 45 degrees counterclockwise. In another example implementation, the magnetization direction may deviate from the first sense direction by approximately 45 degrees clockwise and from the second sense direction by approximately 45 degrees counterclockwise. Consistent with the description of FIG. 3, the magnetizing step includes induced anisotropy magnetizing the first and second magnetic cores. Moreover, the magnetizing step of the first and second magnetic cores may be performed simultaneously.

[0043] Then, the method 600 proceeds to step 622, which involves forming a first sense coil (e.g., 122) including first coil members coiling around the first magnetic core (e.g., 112 and/or 114) to define the first sense direction (e.g., 120), which is perpendicular to the first coil members. The method 600 may proceed to step 624 after step 622. Alternatively, the method 600 may perform step 622 simultaneously with step 624. Like step 622, step 624 involves

forming a second sense coil (e.g., 162) including second coil members coiling around the second magnetic core (e.g., 152 and/or 154). The second sense coil defines the second sense direction (e.g., 160), which is perpendicular to the second coil members.

[0044] In this description, the term “configured to” describes structural and functional characteristics of one or more tangible non-transitory components. For example, a “configured to” component has a particular configuration that is designed or dedicated for performing a certain function. Accordingly, a device is “configured to” perform a recited function if the device includes tangible non-transitory components that can be enabled, activated or powered to perform that recited function. The term “configured to” may encompass being configurable, but it is not limited to such a narrow definition. Thus, when used for describing a device, the term “configured to” does not require the described device to be configurable at any given point of time.

[0045] For various functions performed by components (such as elements, resources, etc.) described hereinabove, the terms used for describing such components correspond, unless otherwise indicated, to any component that performs the specified function of the described component (e.g., which is functionally equivalent), even though not structurally equivalent to the described structure. Also, although a particular feature may have been described herein with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as desired and advantageous for any particular application

[0046] Certain features that are described herein in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described herein in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described hereinabove as acting in certain combinations, one or more features from a combination can in some cases be excised from the combination, and the combination may be directed to a subcombination or variation of a subcombination.

[0047] Similarly, although operations are depicted in the drawings in a particular order, such operations are not required to be performed in the particular order shown or in sequential order (and not all illustrated operations are required to be performed) to achieve desirable results, unless such order is recited as being required. In certain circumstances, multitasking and parallel

processing may be advantageous. Moreover, the separation of various system components in the embodiments described hereinabove does not require such separation in all embodiments.

CLAIMS

What is claimed is:

1. An integrated circuit, comprising:
 - a semiconductor substrate;
 - a fluxgate device formed above the semiconductor substrate, the fluxgate device having:
 - a first magnetic core having a first magnetized direction deviating from a first sense direction by more than 0 degree and less than 90 degrees;
 - a first sense coil including first coil members coiling around the first magnetic core, the first sense coil defining the first sense direction perpendicular to the first coil members;
 - a second magnetic core arranged orthogonally to the first magnetic core, the second magnetic core having a second magnetized direction deviating from a second sense direction by more than 0 degree and less than 90 degrees; and
 - a second sense coil including second coil members coiling around the second magnetic core, the second sense coil defining the second sense direction perpendicular to the second coil members; and
 - a sense circuit having transistors formed partially in the semiconductor substrate and under the fluxgate device, the sense circuit coupled to the first sense coil and the second sense coil.
2. The integrated circuit of claim 1, wherein:
 - the first sense direction is orthogonally to the second sense direction.
3. The integrated circuit of claim 1, wherein:
 - the first magnetized direction deviates from the first sense direction by approximately 45 degrees clockwise; and
 - the second magnetized direction deviates from the second sense direction by approximately 45 degrees counterclockwise.
4. The integrated circuit of claim 1, wherein:
 - the first magnetic core has a first aspect ratio less than 30; and
 - the second magnetic core has a second aspect ratio less than 30.

5. The integrated circuit of claim 1, wherein:
 - the first magnetic core has a first width equal to or greater than 50 μm across the first sense direction; and
 - the second magnetic core has a second width equal to or greater than 50 μm across the second sense direction.
6. A fluxgate device, comprising:
 - a first magnetic core having a first magnetized direction deviating from a first sense direction by more than 0 degree and less than 90 degrees; and
 - a second magnetic core arranged orthogonally to the first magnetic core, the second magnetic core having a second magnetized direction deviating from a second sense direction by more than 0 degree and less than 90 degrees.
7. The fluxgate device of claim 6, wherein the first sense direction is arranged orthogonally to the second sense direction.
8. The fluxgate device of claim 6, wherein the first magnetized direction is parallel to the second magnetized direction.
9. The fluxgate device of claim 6, wherein the first magnetized direction deviates from the first sense direction by approximately 45 degrees.
10. The fluxgate device of claim 6, wherein the second magnetized direction deviates from the second sense direction by approximately 45 degrees.
11. The fluxgate device of claim 6, wherein:
 - the first magnetic core has a first aspect ratio less than 30; and
 - the second magnetic core has a second aspect ratio less than 30.
12. The fluxgate device of claim 6, wherein:
 - the first magnetic core has a first width equal to or greater than 50 μm across the first sense direction; and
 - the second magnetic core has a second width equal to or greater than 50 μm across the second sense direction.
13. The fluxgate device of claim 6, further comprising:
 - a first sense coil including first coil members coiling around the first magnetic core, the first sense coil defining the first sense direction perpendicular to a first plane of coiling; and
 - a second sense coil including second coil members coiling around the second magnetic

core, the second sense coil defining the second sense direction perpendicular to a second plane of coiling.

14. A method, comprising:

forming a first magnetic core along a first sense direction of a fluxgate device;

forming a second magnetic core along a second sense direction of the fluxgate device orthogonal to the first sense direction; and

magnetizing the first and second magnetic cores according to a magnetization direction deviating from the first and second sense directions.

15. The method of claim 14, wherein the magnetizing includes induced anisotropy magnetizing the first and second magnetic cores according to the magnetization direction.

16. The method of claim 14, wherein the magnetizing includes simultaneously magnetizing the first and second magnetic cores according to the magnetization direction.

17. The method of claim 14, wherein:

the magnetization direction deviates from the first sense direction by approximately 45 degrees clockwise; and

the magnetization direction deviates from the second sense direction by approximately 45 degrees counterclockwise.

18. The method of claim 14, wherein:

the forming the first magnetic core includes forming the first magnetic core having a first width greater than or equal to 50 μm across the first sense direction; and

the forming the second magnetic core includes forming the second magnetic core having a second width greater than or equal to 50 μm across the second sense direction.

19. The method of claim 14, wherein:

the forming the first magnetic core includes forming the first magnetic core having a first aspect ratio less than 30; and

the forming the second magnetic core includes forming the second magnetic core having a second aspect ratio less than 30.

20. The method of claim 14, further comprising:

forming a first sense coil including first coil members coiling around the first magnetic core and perpendicular to the first sense direction;

forming a second sense coil including second coil members coiling around the second

magnetic core, the second sense coil defining the second sense direction perpendicular to the second coil members; and

forming a sense circuit having transistors defined partially in a semiconductor substrate;
and

integrating the sense circuit and the fluxgate device to a single integrated circuit having the fluxgate device positioned above the sense circuit.

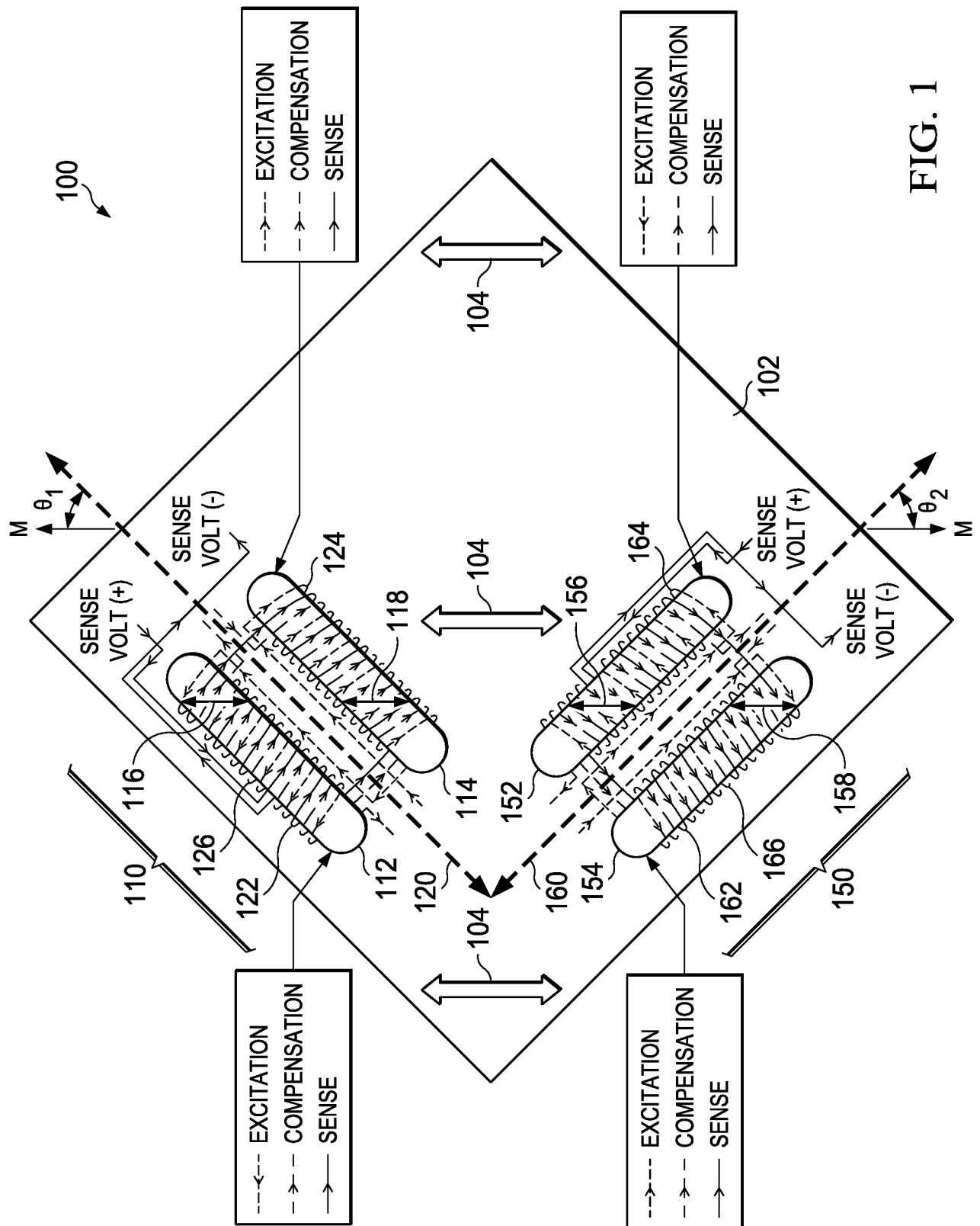


FIG. 1

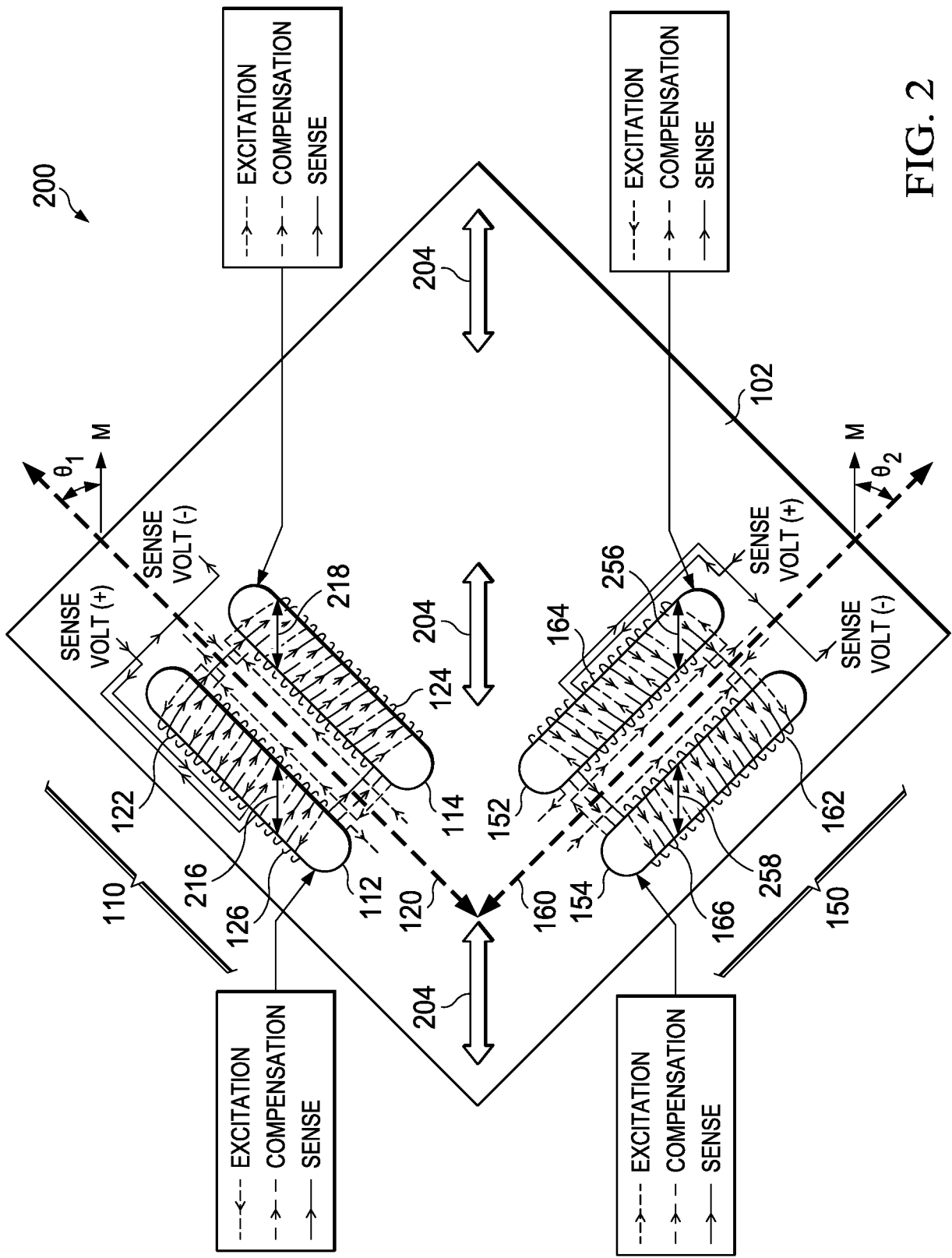


FIG. 2

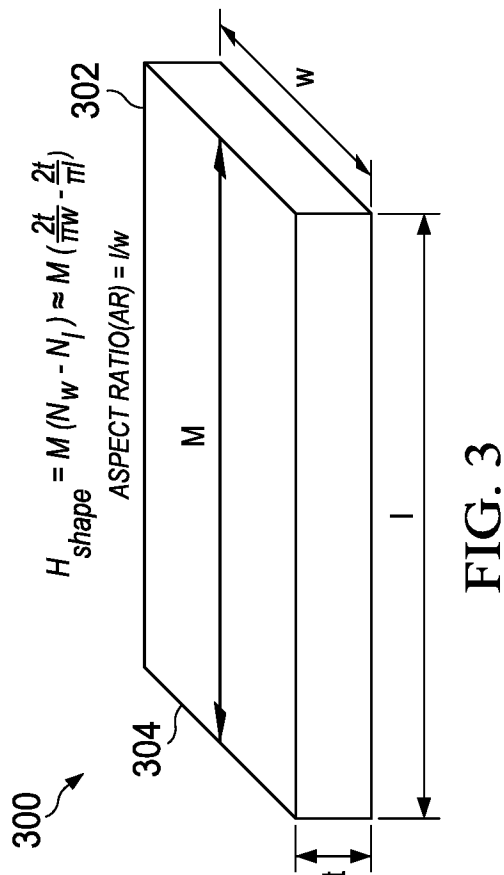
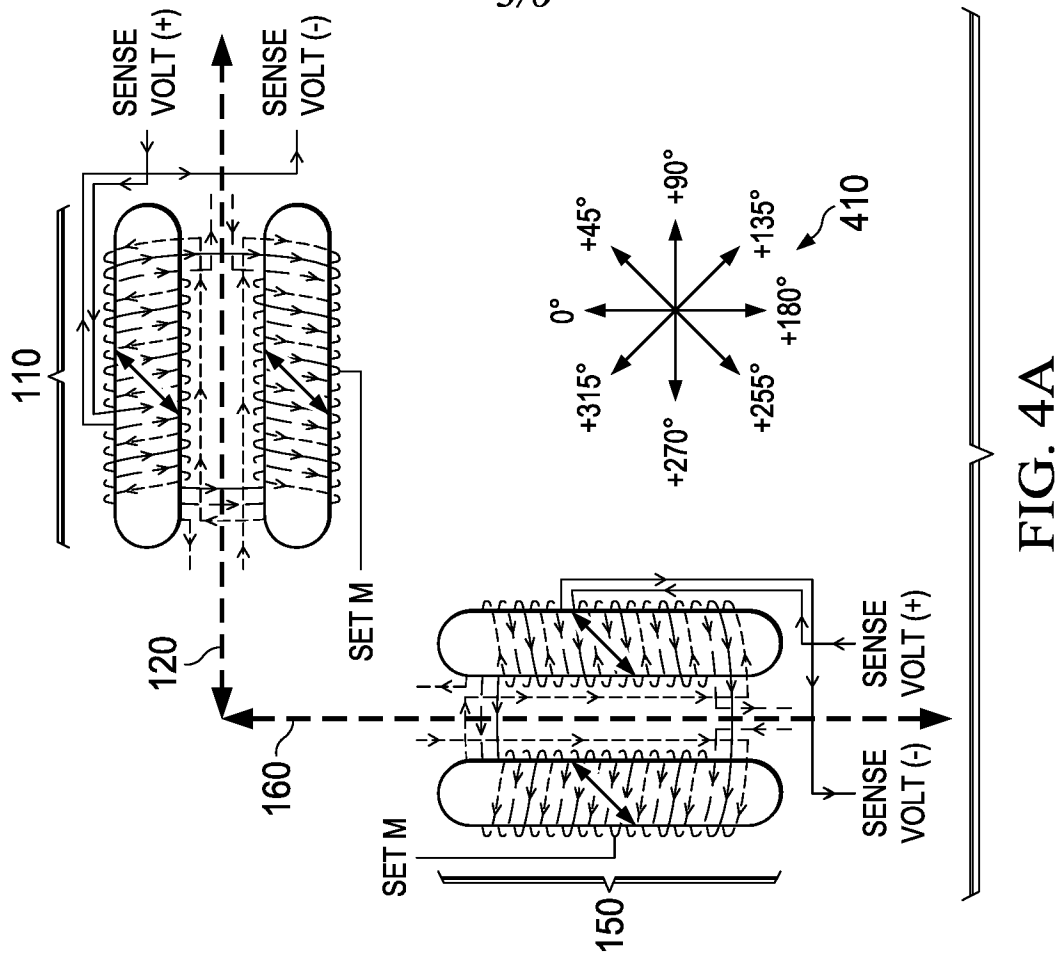
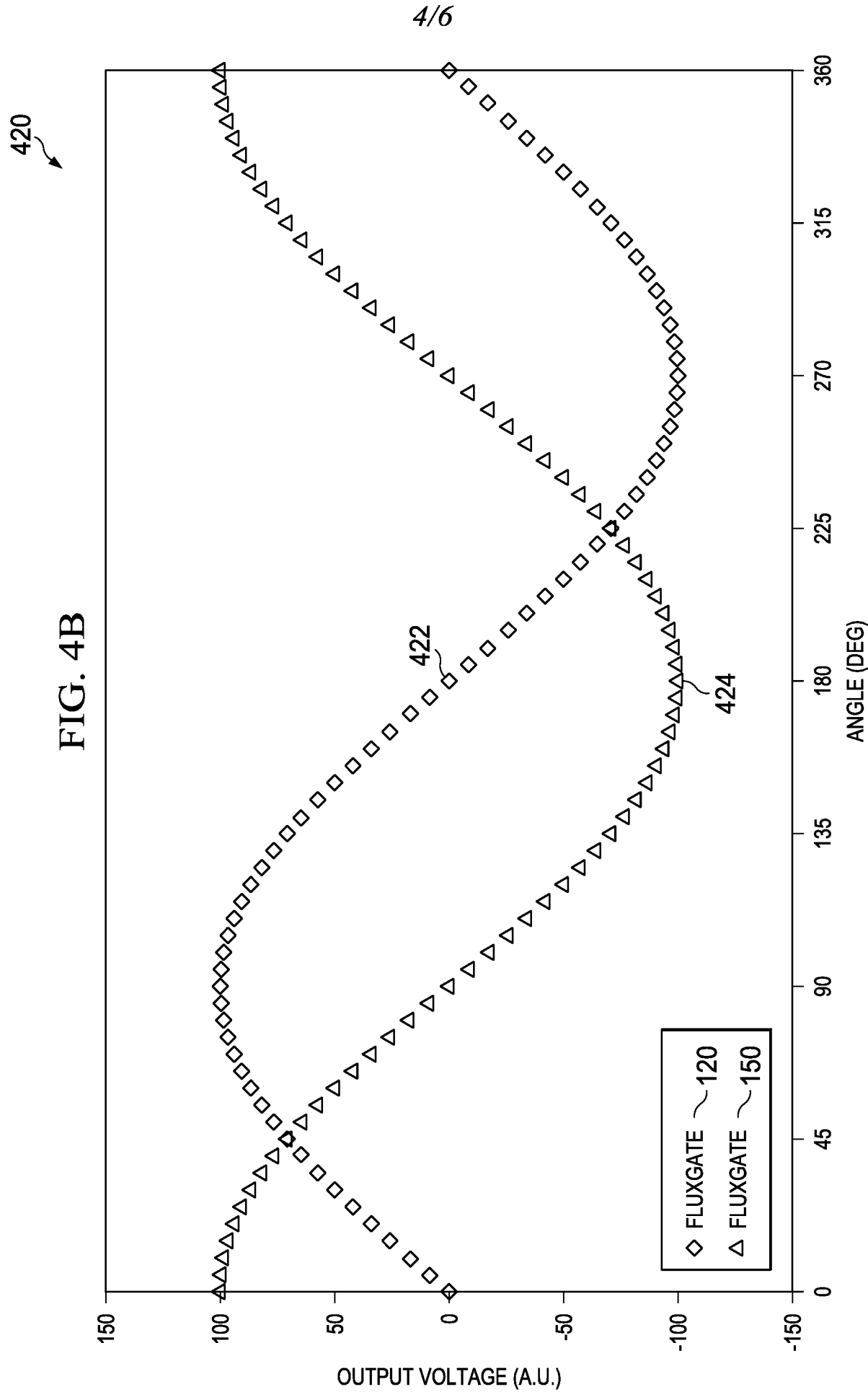


FIG. 3



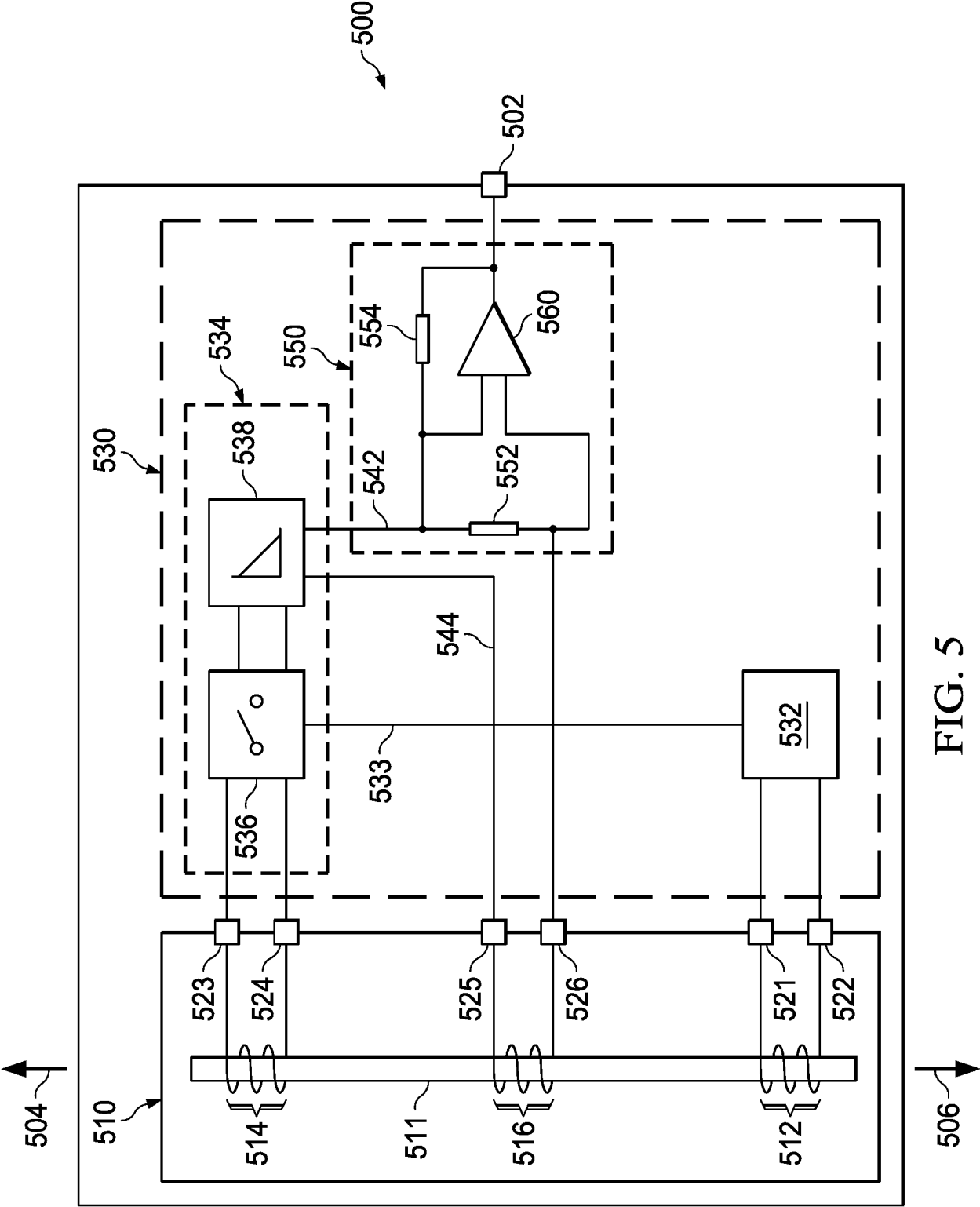


FIG. 5

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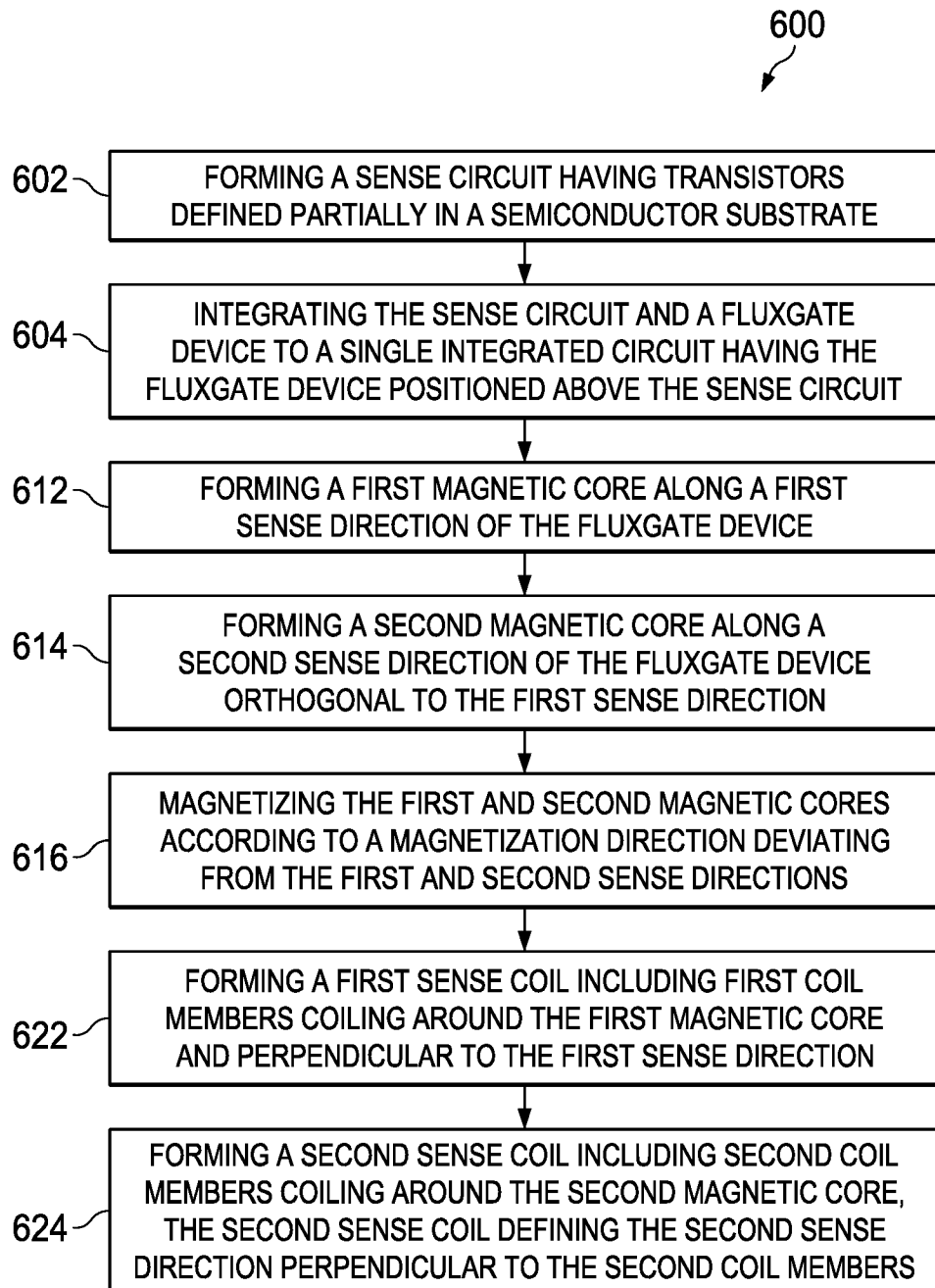


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2017/032245

A. CLASSIFICATION OF SUBJECT MATTER		
G01R 33/09 (2006.01)		
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 33/00, 33/02, 33/04, 33/06, 33/09, H01L 43/00, 43/12, 29/00, 29/26		
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 practicable, search terms used)		
PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, DWPI, EAPATIS, PATENTSCOPE, Information Retrieval System of FIPS		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1387179 A2 (SAMSUNG ELECTRO-MECHANICS CO., LTD.) 04.02.2003	1-20
A	US 2015/0048820 A1 (TEXAS INSTRUMENTS DEUTSCHLAND GMBH) 19.02.2015	1-20
A	US 2015/0338474 A1 (TEXAS INSTRUMENTS INCORPORATED) 26.11.2015	1-20
A	US 7737687 B2 (SAMSUNG ELECTRONICS CO., LTD.) 15.06.2010	1-20
A	US 7414399 B2 (COMISSARIAT A L'ENERGIE ATOMICUE) 19.08.2008	1-20
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "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 "I" 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 "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "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		Date of mailing of the international search report
28 August 2017 (28.08.2017)		14 September 2017 (14.09.2017)
Name and mailing address of the ISA/RU: Federal Institute of Industrial Property, Berezhkovskaya nab., 30-1, Moscow, G-59, GSP-3, Russia, 125993 Facsimile No: (8-495) 531-63-18, (8-499) 243-33-37		Authorized officer M. Adireeva Telephone No. (499) 20-25-91