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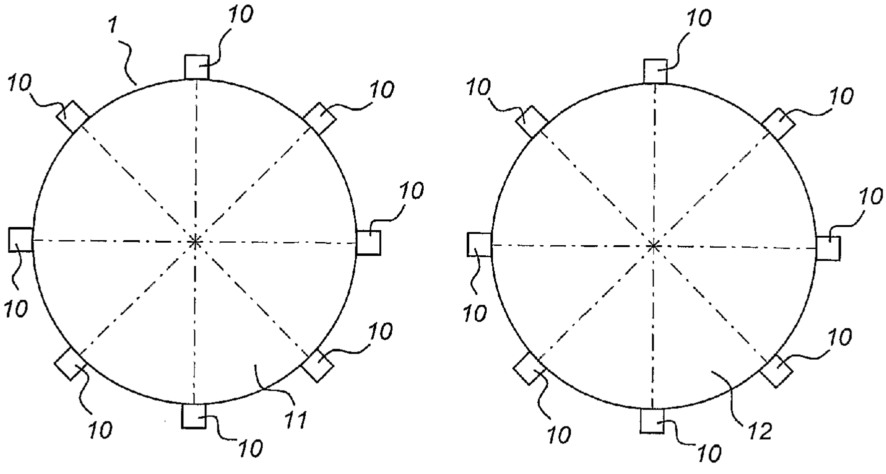
**(54) Title:** MAGNETIC FIELD SENSOR, SUPPORT FOR SUCH A MAGNETIC FIELD SENSOR AND A COMPASS PROVIDED WITH SUCH A MAGNETIC FIELD SENSOR



**(57) Abstract:** The invention relates to a magnetic field sensor (1) with at least two Hall plates (11, 12, 13, 14). The magnetic field sensor (1) is equipped to generate measuring currents in a number of directions in the Hall plates (11, 12, 13, 14) and to measure a potential difference over the Hall plates (11, 12, 13, 14) in a direction in the plane of the Hall plate (11, 12, 13, 14), wherein the direction is always essentially perpendicular to the direction of the measuring current. The measured potential difference is a measure for the magnetic field through the Hall plate (11, 12, 13, 14) in a direction that is essentially perpendicular to the direction of the measuring current and the measured potential difference. The magnetic field sensor (1) is equipped to generate a measuring current in at least eight directions in each Hall plate (11, 12, 13, 14).

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# MAGNETIC FIELD SENSOR, SUPPORT FOR SUCH A MAGNETIC FIELD SENSOR AND A COMPASS PROVIDED WITH SUCH A MAGNETIC FIELD SENSOR

## FIELD OF THE INVENTION

The invention relates to a magnetic field sensor, comprising at least two Hall plates, wherein the magnetic field sensor is equipped to generate measuring currents in a number of directions in the Hall plates and to measure a potential difference over the Hall plates in a direction in the plane of the Hall plate, wherein the direction is always essentially perpendicular to the direction of the measuring current and wherein the potential difference measured is a measure for the magnetic field through the Hall plate in a direction that is essentially perpendicular to the direction of the measuring current and the measured potential difference, wherein the magnetic field sensor is equipped to generate a measuring current in each Hall plate in at least eight directions.

The invention furthermore relates to a support for such a magnetic field sensor and a compass provided with such a magnetic field sensor.

For a calibration-free electronic compass in small portable, battery-powered applications there is a need for magnetic field sensors with ultra-low offset (for example less than one μT). Preferably, the sensor produces a digital output signal. Sufficient resolution can be achieved with such a low offset (a few degrees, in the Netherlands the earth's magnetic field is 30 - 50 μT) and no external electronics are needed other than the microprocessor which often is already present in the application.

Sensors based on the magnetoresistive principle can be made with ultra-low offset. However, because of the technology these sensors cannot be combined with electronics on the sensor, as a result of which external electronics have to be added. Moreover, these sensors are not able to withstand high magnetic fields; they then cease to function well.

Hall plates can be combined with electronics on one and the same silicon chip, as a result of which the desired digital output signal can be produced. And the sensors cannot be overloaded. However, the magnetic field sensors based on Hall plates that are known at present do not meet the offset requirement; they display an offset of tens of μT or more, which, moreover, changes over time. There is therefore a need for a magnetic field sensor based on silicon Hall plates that has an ultra-low offset (of the order of a few μT). Moreover, such a sensor can produce digital output signals.

A magnetic field can be measured with the aid of a Hall plate. If a current is passed in a first direction through a Hall plate placed in a magnetic field, a potential difference will then be created over the Hall plate in a second direction, perpendicular to the first direction, which is dependent on the current intensity and the strength of the magnetic field in a third direction, which is perpendicular to the first and the second direction. However, for various reasons such a measurement device suffers from a certain offset, which makes it impossible to measure relatively small magnetic fields.

Attempts have already been made for a very long time to lower the offset of Hall plates because this brings the applications in which relatively small fields have to be measured nearer. Single silicon or other semiconductor Hall plates easily have an offset of 10 mT. The main cause of the offset is mechanical stress in the semiconductor Hall plate. Stress in a semiconductor crystal gives rise to a direction-dependent change in the resistance of the material, which is also known as piezoresistivity. The change in resistance in current directions that differ from one another by 90° (are orthogonal) are opposed and thus compensate each other.

This mechanical stress is temperature- and time-dependent and can hardly be improved by calibration. Various methods for lowering this offset by compensation techniques have been proposed in the state of the art.

## STATE OF THE ART

Various magnetic field sensors that make use of Hall plates are known from the state of the art.

Known methods for Hall offset compensation are frequently based on orthogonal compensation.

The geometric orthogonal compensation technique uses two different well-coupled Hall plates, the current direction in the one plate being orthogonal to that in the other. As a result the offset error caused by stress in the one Hall plate will be opposed to the error in the other. Although this compensation is instantaneous, it is, however, fundamentally restricted by dissimilarity in the Hall plates and by the dissimilarity in the mechanical stress to which they are subjected.

US Patent 5,621,319 ("Chopped Hall sensor with synchronously chopped sample and hold circuit", April 15, 1997) describes a temporal orthogonal compensation technique that makes use of a single Hall plate, where, viewed in terms of time, the currents are switched round orthogonally in four directions. Since the offset originates from the same plate, a much more accurate offset compensation is achieved in this way, provided the offset sources do not change in the switch-round period.

However, changes in the offset sources, caused by external mechanical stress, external temperature influences or by internal temperature modulation in the chip are appreciable. In order to achieve adequate suppression the requisite frequency with which the current is switched round over all current directions is fairly high (100 kHz - 400 kHz). However, this rapid switching also itself introduces dynamic offset, which limits the gain achieved in lowering the offset. The four offset signals from the four switching directions are also measured and averaged by the electronics and thus there is no instantaneous compensation, which demands a high dynamic voltage range for the electronics.

On the basis of the techniques described above, magnetic sensors with an offset of a few hundred μT can be made. Furthermore, the above techniques have the major limitation that they only remove the offset that is caused by mechanical stress. At least two further important causes of offset can be indicated that cannot be eliminated by orthogonal compensation. The first is the junction FET effect, where the sensitivity of the Hall plate changes by changing the (electrically effective) thickness, caused by changing electrical voltage between the Hall plate and the underlying layer. The second effect is the production of thermocouple voltages by thermal gradients induced by Joule heating and/or Peltier heating/cooling. As a result of these causes the offset in the Hall plates with offset compensation based on current in four directions is still above 100 μT. These other sources of offset in the Hall plate are eliminated with Hall plates where the current is not switched or does not run orthogonally (in four directions) but is switched or runs in at least eight directions.

A first technique that makes use of this is described in US Patent 5,406,202 ("Offset-compensated Hall sensor having plural Hall detectors having different geometrical orientations and switchable directions", April 11, 1995). This technique is also described in Hohe, in "Hall sensor array for measuring a magnetic field with offset compensation", PCT Application no. 01/18556, 8 September 2000. In these publications a configuration of Hall plate pairs is proposed in which the currents in the individual plates are switched round orthogonally. The angle between the pairs is not orthogonal but, for example, 45 degrees. The 8 possible current directions can then be achieved with, for example, 4 Hall plates (2 pairs) that are switched round. Such a configuration has good instantaneous compensation and the required dynamic range of the electronics can remain small. However, the offset compensation is limited. Only 4 directions are possible per Hall plate, as a result of which the compensation per Hall plate is thus incomplete. Moreover, the structures proposed involve thermal self-modulation, the (thermal) offset in one Hall plate being influenced by spinning of the current in the other. As a result, offset is caused by the structure itself.

Another method is described by Munter in "Electronic circuitry for a smart spinning Hall plate with low offset", Proceedings of Eurosensors IV, 1991, Vol. 2, pages 747 to 751, karlsrule October 13, 1990. The method uses one circular Hall plate with 16 contacts that are uniformly distributed around the outer edge of the Hall plate. The current is switched round in circles by electronic switches. After adding up the 16 different Hall voltages the resulting offset is lowered to an order of tens of μT (10 - 20 μT).

Another method is described in US Patent 6,064,202 ("Spinning current method of reducing the offset voltage of a Hall device", 16 May, 2000). In this patent a Hall plate with 4 contacts is described. Each pair of contacts is connected to a periodic signal, the phase shift in the currents corresponding to the geometrical phase shift, i.e. 90°. The various features result in a continuously spinning current vector in the Hall plate. The reported resulting offset after demodulation was of the order of 10 μT.

However, the methods described by Munter and in US Patent 6,064,202 have the limitation that there is no instantaneous compensation of external offset sources and, in order to prevent dynamic switching offset, it is necessary to operate at relatively low spinning frequencies, which leads to unstable offset compensation. Internal mutual modulations between Hall plate and electronics are also not avoided, which once again introduces offset.

US 5,747,995 describes a Hall sensor for use in an alternative application, specifically for determining the relative position of two objects. The sensor has a number of Hall plates, each with 8 contacts. For example, a sensor that consists of four Hall elements (Fig. 6a) is discussed in the document. The first and third Hall elements carry a current in a first direction and the second and fourth Hall elements carry a current in a second direction. The distances between the Hall elements are so chosen that these correspond to the period of the object for which the relative position is determined, for example a gear wheel, as is indicated by the phases mentioned in the figure. The Hall plates thus each measure a different magnetic field. The accuracy of this sensor is far from being sufficient to measure, for example, the earth's magnetic field.

US 2003/0155912 A1 describes a Hall sensor consisting of a first and a second Hall plate. Each Hall plate is equipped to generate measuring currents in 8 directions and the associated potential difference in a direction perpendicular to the measuring currents can be measured. These measured potential differences are a measure for the magnetic field. US 2003/0155912 A1 describes that the measuring currents can be spun over the various directions. This takes place in a first direction in the first Hall plate and in a second direction in the second Hall plate, the first and the second spin directions being opposed. Such a measurement method suppresses the dynamic offset because these are more or less opposed in the two plates and thus compensate one another. However, the signals from the two Hall plates offer relatively moderate instantaneous suppression. Moreover, the measurement method according to US 2003/0155912 A1 will suffer from self-modulation. An offset of 200 uT is reported in a recent article on the measurement method according to US 2003/0155912 A1 (A programmable Hall sensor for camshaft applications, Mario Motz et all, proceedings, IEEE sensors, October 24-27, 2004.).

It is clear that the known techniques are not suitable for the measurement of weak magnetic fields, such as the earth's magnetic field, for, for example, compass applications or other applications where a low offset, for example less than a few μT, is required. This has led to the shift of research into other directions, such as on-chip integrated flux gates.

All magnetic field sensors known from the state of the art that make use of a Hall plate exhibit a relatively high offset, i.e. of 10 μT or more. Such sensors are thus unsuitable for applications in which a high degree of accuracy is required, for example when measuring the earth's magnetic field, where an offset of less than 10 μT, for example 1 μT, is required. The aim of the invention is thus to provide a magnetic sensor based on Hall plates that provides increased accuracy. US Patent 5,406,202 is regarded as the closest prior art in the context of this invention and the invention will be delimited with respect to this invention.

## BRIEF DISCUSSION OF THE INVENTION

The said aim is achieved with a magnetic field sensor as described in the preamble, characterised in that the measuring current in the first Hall plate is at an essentially constant angle to the measuring current in the second Hall plate. Using a magnetic field sensor according to the invention it is possible to measure a magnetic field in a manner that is many times more accurate than was possible on the basis of the state of the art. By providing several Hall plates with at least eight current directions it has proved possible to achieve an offset that is many times smaller than the existing magnetic field sensors that make use of Hall plates.

Using such a magnetic sensor it is possible to measure a magnetic field with an offset that is clearly lower than the magnetic sensors described in the state of the art. On the basis of the data known from the state of the art it did not appear to be possible to make a magnetic sensor with such an accuracy with the aid of Hall plates. Many publications on the topic are known, a few of which have been discussed in the preamble, but none of the magnetic field sensors described that make use of Hall plates achieved the accuracy that is achieved with the magnetic field sensor according to the invention. For this reason the development in the field in recent years was also oriented strongly towards making magnetic field sensors based on the magnetoresistive or the flux gate principle. However, although magnetic field sensors with ultra-low offset can be made by this means, because of the technology these sensors can be less well combined with electronics on the sensor, as a result of which external electronics have to be added. When such sensors are exposed to relatively strong magnetic fields such sensors no longer function well.

The invention provides a method that enables instantaneous and temporal compensation of internal and external offset sources with a geometrical combination of Hall plates with spinning current direction with at least eight current directions. As a result the influence of changing external sources and of the mutual influencing of electronics and Hall plate is substantially suppressed. Depending on the configuration chosen, self-modulation of the various Hall plates on one another is also suppressed. Moreover, the circuit can be operated at an increased spinning frequency. With the aim that the entire magnetic field sensor is less sensitive to rapid changes or (self) modulations in the various offset sources, which ultimately will lead to a magnetic field sensor with reduced offset.

In practice it has already been demonstrated that a much smaller and stable offset than the other reported methods is possible.

The method is combined with on-chip electronics which are needed for accurate control and sampling of the Hall signals. Moreover, additional electronic functions for or improvements in the Hall plate are described, as can be used with conventional Hall plates.

According to one embodiment the invention relates to a magnetic field sensor wherein the magnetic field sensor is equipped to direct the measuring current per Hall plate in the at least eight directions in accordance with a predetermined sequence. By choosing a suitable sequence it is possible to compensate for specific causes of offset.

According to one embodiment the invention relates to a magnetic field sensor wherein the measuring current is directed successively in a first sequence through the at least eight directions and is then directed in a second sequence through the at least eight directions, wherein the first sequence is the reverse of the second sequence. It is, for example, possible to choose the first sequence such that the measuring current to be directed clockwise through the at least eight directions, followed by a second sequence in which the measuring current is directed anticlockwise through the at least eight directions. Thermal effects can be compensated by this means.

According to one embodiment the invention relates to a magnetic field sensor in which the magnetic field sensor comprises at least one pair of Hall plates, consisting of a first and a second Hall plate, wherein the angle between the measuring current in the first Hall plate and the measuring current in the second Hall plate is 45°, 90° or 180°. Such a Hall plate has the advantage that the offset caused by mechanical stress or thermal gradients is always compensated instantaneously and the resulting offset is compensated after spinning.

According to one embodiment the invention relates to a magnetic field sensor wherein each Hall plate is provided with at least eight contacts for feeding the measuring current to the Hall plate.

According to one embodiment the invention relates to a magnetic field sensor wherein each Hall plate is provided with four contacts and the magnetic field sensor is equipped to feed a periodic signal to each of the contacts, which periodic signals are, respectively, shifted in phase by essentially 90° with respect to one another. In this way a continuously spinning measuring current is created with a limited number of contacts. This continuously spinning measuring current can be used not only to measure in eight directions but also to measure in more than eight directions.

According to one embodiment the invention relates to a magnetic field sensor, wherein the magnetic field sensor is provided with at least four Hall plates, each of which is equipped to carry a measuring current in at least eight directions. With this arrangement the Hall plates are preferably geometrically identical and thermally and spatially coupled to one and the same substrate, whilst the Hall plates individually cycle through their possible current directions, wherein the mutual direction of the currents has a compensating effect on external and internal influences. The combination of the Hall voltages for individual spinning currents will ultimately yield an ultra-low offset with an interference-free signal.

According to one embodiment the invention relates to a magnetic field sensor, wherein the magnetic field sensor is equipped to direct the measuring currents in a predetermined sequence through the at least eight directions of the at least four Hall plates, wherein:

- a measuring current in a first Hall plate runs essentially perpendicularly with respect to a measuring current in a second Hall plate,
- the measuring current in the second Hall plate runs essentially perpendicularly to a measuring current in a third Hall plate,
- the measuring current in the third Hall plate runs essentially perpendicularly to a measuring current in a fourth Hall plate, and
- the measuring current in the fourth Hall plate runs essentially perpendicularly to the measuring current in the first Hall plate.

This embodiment compensates instantaneously for both thermal and mechanical offset.

According to one embodiment the invention relates to a magnetic field sensor comprising a first group of Hall plates, comprising a first, second, third and fourth Hall plate, and a second group of Hall plates, comprising a fifth, sixth, seventh and eighth Hall plate, wherein the magnetic field sensor is equipped to select the direction of the measuring current in the first, second, third and fourth Hall plate essentially perpendicular with respect to the fifth, sixth, seventh and eighth Hall plate, respectively. By this means even better (instantaneous) compensation of offset sources can take place. By this means 2nd and 3rd order effects, such as second order built-in stress, can also be compensated.

According to one embodiment the invention relates to a magnetic field sensor wherein the Hall plates are positioned on the same support. This is advantageous in connection with thermal and mechanical coupling. A good coupling generally ensures good compensation because the effects are identical in all Hall plates.

According to one embodiment the invention relates to a magnetic field sensor wherein the support is a semiconductor and the support furthermore has a demultiplexer that is equipped to take a current and to distribute this over the at least eight directions of the Hall plates, and the support furthermore has a multiplexer that is equipped to take the measurement voltages over the Hall plates and to output these via an output and the support is furthermore provided with a control unit for driving the demultiplexer and the multiplexer. The support is preferably a silicon plate where supplementary electronics can be installed in a simple manner. Silicon support is also particularly suitable for making Hall plates. Supplementary a demultiplexer and a multiplexer can easily be installed on such a support, which demultiplexer and multiplexer, respectively, are particularly suitable for distributing the measuring currents over the various directions and Hall plates and subsequently sampling the various measurement signals.

According to one embodiment the invention relates to a magnetic field sensor wherein the support furthermore has a summing unit that is connected to the output of the multiplexer, for summing the various voltages measured. By summing the various voltages measured a value can be obtained that is a measure for the strength of the magnetic field and that is not sensitive to a wide variety of types of offset.

According to one embodiment the invention relates to a magnetic field sensor, wherein the support is furthermore provided with a sigma/delta converter, for digitising the output signal from the multiplexer, and an amplifier for amplifying the output signal from the multiplexer.

According to one embodiment the invention relates to a magnetic field sensor, wherein the magnetic field sensor is furthermore provided with a flux concentrator that essentially is in the third direction of the Hall plates. The flux concentrator draws magnetic field lines towards it. At the edge of the flux concentrator deflection of the magnetic field lines lines will be produced, as a result of which it is possible nevertheless to measure field lines in three dimensions with Hall plates that are in one plane. This has the advantage that with one magnetic field sensor a magnetic field can measure three directions. In this embodiment a subtraction operation is often done on the signals from two Hall plates. This subtraction operation gives a particular form of instantaneous compensation in which identical (instead of opposed) offset of Hall plates is compensated. This can lead to current direction choices that differ from those for the other types of instantaneous compensation.

According to one embodiment the invention relates to a magnetic field sensor, wherein the magnetic field sensor is provided with at least one coil for generating a magnetic field that can be measured by the magnetic field sensor. With such a coil it is possible to generate a magnetic field of a known strength and direction, by means of which the magnetic field sensor can be calibrated easily.

According to one embodiment the invention relates to a magnetic field sensor, wherein the coil can be driven to demagnetise flux concentrator. By this means any troublesome magnetisation of the flux generator can be eliminated in a simple manner.

This can be effected, for example, by applying a damping sinusoidal signal to the coil, for which purpose the electronics necessary for this can easily be integrated as well.

According to one embodiment the invention relates to a magnetic field sensor, wherein the magnetic field sensor is equipped to ignore at least one measurement signal for measurement of the potential difference over the Hall plates for a specific period. This makes it possible to ignore equilibrating fluctuations, as a result of which a reliable measurement can be made within a relatively short time. Specifically, it is then not necessary to measure over a relatively long period in order to average out the equilibrating fluctuations.

According to a further aspect the invention relates to a support provided with a magnetic field sensor as described above.

According to a further aspect, the invention relates to a compass provided with a magnetic field sensor as described above.

## BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be explained in more detail below with reference to a few drawings in which a few illustrative embodiments are shown. The drawings are intended solely for illustrative purposes and do not serve to restrict the scope of protection that is defined by the claims.

Figure 1 shows, diagrammatically, two Hall plates according to one embodiment of the invention;

Figures 2a to 2e show, diagrammatically, various configurations of Hall plates according to various embodiments of the invention;

Figures 3a to 3h show various directions of the current directions according to one embodiment of the invention;

Figures 4a to 4h show temperature profiles for various measuring current directions in one embodiment of the invention;

Figures 5a to 5d show the effect of the temperature of electronics on the Hall plates;

Figure 6 shows various signals as a function of time according to one embodiment of the invention;

Figures 7a and 7b show various spin directions of the measuring current;

Figure 8 shows, diagrammatically, a chopper loop according to one embodiment of the invention;

Figure 9 shows, diagrammatically, a magnetic field sensor with processing electronics according to one embodiment of the invention;

Figures 10a and 10b show a plan view and a side view, respectively, of a magnetic field sensor according to one embodiment of the invention.

## DETAILED DESCRIPTION OF THE INVENTION

A magnetic field sensor 1 according to the invention, as is shown in Fig. 1, comprises, for example, two Hall plates 11, 12, provided with a number of connections 10, by means of which currents can be directed through each Hall plate in at least eight directions. This makes it possible to achieve temporal compensation in at least eight current directions, which, as has been described in the preamble, is necessary for complete offset compensation. A magnetic field sensor with several Hall plates, in which only four current directions can be controlled in each Hall plate, as previously described in US Patent 5,406,202, is not sufficient to eliminate all offset sources to an adequate extent.

The Hall plates 11, 12 as shown in Fig. 1 each have eight connections 10. Of course the invention also relates to a magnetic field sensor 1 provided with Hall plates with more than eight connections or in which more than eight current directions can be obtained. The invention also relates to a Hall plate with a continuously spinning current vector, in which not eight, but four contacts 10 are needed in order to achieve at least eight current directions. Such a Hall plate 11, 12 has four contacts, which are positioned equidistantly around the edge of the Hall plate 11, 12. The two pairs of contacts 10 located opposite one another are connected to a periodic signal (for example a sinusoidal signal), the phase shift in the currents corresponding to the geometrical phase shift of the pairs of contacts, i.e. 90°. The various features result in a continuously spinning current vector in the Hall plate. The at least eight required current directions can also be achieved with such a device.

Optimum technology, such as, for example, the technique that makes use of so-called implanted, buried or deposited layers, is preferably used for each Hall plate 11, 12. The choice of the position on the chip (minimum stress gradients) and measures to minimise the value of the stress (etched channels around the Hall plates, packing in elastic materials such as silicones) can also be employed.

After a complete cycle through at least eight current directions, the individual Hall plates 11, 12 will be completely temporally compensated provided the external and internal offset sources are constant. In general this requirement will not be met and there will be residual offset after a complete cycle, depending on the behaviour of the these offset sources, which will be explained later. In order to suppress these effects the invention makes use of geometric instantaneous compensation, where the magnetic field sensor 1 consists of various Hall plates 11, 12 that are connected in parallel, such that the magnetically induced signals are summed and the internal and external (instantaneous) offset sources always eliminate one another as far as possible. With the aim that the entire magnetic field sensor becomes less sensitive to rapid changes or (self-)modulations in the various offset sources, which ultimately will lead to a magnetic field sensor with lowered and more stable offset.

Various internal and external sources can be identified and described here.

External sources which may be mentioned are: mechanical stress and temperature (drift) effects. Internal sources which may be mentioned are: modulation of electronics on the Hall plates 11, 12, thermal or mechanical stress of Hall plates 11, 12 and their contacts and connections to one another, hereinafter termed self-modulation;

Change of external sources can lead to unstable offset compensation and therefore have to be compensated. Internal sources, moreover, have the characteristic of displaying a degree of correlation with the current direction state and are therefore able to generate offset themselves.

The said effects and their geometric compensation will now be described in more detail.

As mentioned previously, mechanical stress compensation preferably takes place with the aid of current directions that are at an angle of approximately 90°, but in a number of cases this can also take place with an angle of approximately 45°. Hall plate pairs with current directions at 90° (or possibly 45°) thus compensate for the mechanical stress.

Thermal compensation preferably takes place with an angle between the current directions of approximately 180°. One of the main reasons for thermal offset is, specifically, the thermocouple effect that generates a voltage over the measurement contacts if there is a temperature difference between these contacts. For current directions at an angle of 180° a precisely opposed temperature difference and thus opposed offset voltages are generated, which will cancel one another out. Hall plate pairs with current directions at 180° thus have a thermally compensating effect.

It will be clear that at least four Hall plates 11, 12, 13, 14 are needed in order to employ both thermal compensation and stress compensation.

The above compensations apply for compensation of internal and external effects. However, internal effects demand a more detailed explanation because incorrect choices can lead to built-in offset.

As an example we take the influence of a changing temperature profile as a consequence of heat generation in the electronics. The electronics are preferably integrated on the semiconductor plate and will be discussed further later. The heat generation by the electronics is, by definition, correlated to the current direction that is set and sampled at that point in time, for example by a changed signal in the read out electronics and a changed position of the current switches and connecting wires. This effect is sufficiently suppressed by a thermally compensating geometrical configuration. This will be explained in more detail below with reference to Fig. 5.

The (self-)modulating effects of the Hall plates 11, 12, 13, 14 on one another are described below.

In the same way as described above, the Hall plates 11, 12, 13, 14 will see each other thermally and modulate each other's offset. If the plates are switched to another current direction simultaneously and at the same frequency, the thermal offset of the individual Hall plates 11, 12, 13, 14 will, by definition, change at the same time. This will be explained in more detail in Fig. 4 below.

The Hall plates 11, 12, 13, 14 and their connection patterns will also create a mechanical stress field on each other, which is not necessarily corrected instantaneously. This can lead to high offset peaks per current direction, which normally are compensated after a complete spin cycle unless a thermal modulation of this stress pattern takes place.

It will also be possible for the Hall plates to be modulated by the changing magnetic fields that are generated by the currents in the other Hall plates 11, 12, 13, 14.

The configuration of compensating Hall plates 11, 12, 13, 14 is preferably so chosen that these effects are either completely avoided, the effects in the various Hall plates 11, 12, 13, 14 compensate geometrically instantaneously or the effects at least in the Hall plate combination compensate temporally after a complete switch-round cycle. If these conditions are not met, a residual offset will remain.

Depending on the sources to be compensated there are now a number of degrees of freedom in the choice of the geometrical instantaneous compensation and the temporal compensation. For instance, inter alia, the following can be varied:

- the position and the number of Hall plates 11, 12, 13, 14;

- the current directions and spin patterns of the various current directions in the various Hall plates 11, 12, 13, 14;
- the spin speeds for the individual current directions in the various Hall plates 11, 12, 13, 14.

A number of different possibilities for constructing the magnetic field sensor 1 from several Hall plates 11, 12, 13, 14 so that geometrical compensation can be obtained are shown in Fig. 2a to Fig. 2e.

The double Hall plates 11, 12 shown in Fig. 2a, the individual current directions of which always run at approximately 90° with respect to one another, is a sub-optimum solution as far as the offset is concerned because even though offset as a result of mechanical stress is compensated the offset as a result of thermal gradients is not compensated. An embodiment with only two Hall plates 11, 12 does, however, have a favourable current consumption. The Hall plates 11, 12 that are shown in Fig. 2a are positioned a relatively large distance apart to prevent instantaneous offset by thermal self-modulation. There is thus a trade-off between optimum coupling of the Hall plates and optimum prevention of (self-)modulation.

Analogously, a Hall plate pair can be set to a difference of 180° in current direction in order to obtain thermal suppression. It will thus be clear to those skilled in the art that in order to employ both thermal compensation and stress compensation at least four Hall plates 11, 12, 13, 14 are needed, with Hall plate currents at 90° and at 180° degrees with respect to one another.

The magnetic field sensor 1 with two Hall plates can then be supplemented by another (or a number of) pair(s), the external influences being better suppressed. In this case the currents can still be freely chosen because the choice is not limited by the prevention of self-modulation. Fig. 2b shows an example of a magnetic field sensor 1 that comprises four Hall plates 11, 12, 13, 14 that have been positioned a relatively large distance away from one another so that self-modulation is prevented.

Better instantaneous compensation takes place when the Hall plates are better coupled in pairs and offset-generating effects such as temperature and stress are thus also better coupled. This can be achieved by positioning the Hall plates in pairs a relatively short distance apart. In this case self-modulation can no longer be adequately prevented and it is necessary to work with an equivalent pair with opposing thermal or mechanical stress, so that instantaneous compensation is nevertheless obtained.

This is achieved with a so-called double pair quad, which is shown in Figure 2c. With this arrangement the one pair must not have a systematic influence on the other. Fig. 2c shows such a magnetic field sensor 1, in which two pairs of Hall plates 11, 12, 13, 14 are shown. The Hall plates are, per pair, positioned a relatively small distance apart, but the pairs are a greater distance from one another.

Even better compensation will take place and less of the chip surface will be used if four Hall plates are combined. However, because of self-modulation this construction allows less freedom for the choice of direction of the currents, but does compensate best for all effects mentioned.

According to one embodiment the magnetic field sensor is made up of four Hall plates 11, 12, 13, 14, all four of which are positioned a relatively small distance apart. This embodiment is referred to as the coupled quad configuration and is shown in Fig. 2d. With correct choice of the current directions in the Hall plates 11, 12, 13, 14 very good compensation of offset resulting from mechanical stress, the JFET effect and internal and external thermocouple effects can be obtained. In particular, feedback from electronics in the vicinity to the magnetic field sensor 1 via a time-dependent temperature gradient that is created by the electronics is compensated with the coupled quad configuration. The embodiment shown in Fig. 2d is a preferred embodiment and will be described in detail further below.

Fig. 2e shows a further alternative embodiment of the magnetic field sensor 1 that comprises two coupled quad configurations. In total, the magnetic field sensor 1 thus comprises eight Hall plates 11, 12, 13, 14, 15, 16, 17, 18. By choosing the current directions such that the current directions in the one coupled quad configuration 11, 12, 13, 14 are at an angle of 90° to the current directions in the corresponding Hall plates 15, 16, 17, 18 of the other coupled quad configuration, even better (instantaneous) compensation of offset sources can take place. 2nd and 3rd order effects can also be compensated by this means. As a result the requisite dynamic range of the sampling electronics is then reduced, as a result of which non-linearities in the electronics give rise to a smaller offset from the electronics. This embodiment makes it possible to lower the offset of the magnetic field sensor 1 even further and thus to make an even more accurate magnetic field sensor 1.

The embodiment of the magnetic field sensor 1 that is shown in Fig. 2d makes it possible to obtain very good compensation of various causes of offset. The Hall plates 11, 12, 13, 14 are, for example, placed on a semiconductor support, for example a silicon plate, and are closely linked thermally and mechanically. This configuration provides instantaneous compensation for mechanical stress and thermal gradients.

Each Hall plate 11, 12, 13, 14 has at least eight current directions, referred to as the north, north-east, east, south-east, south, south-west, west and north-west direction below. These current directions can be obtained in various ways, as has already been indicated in the description of Fig. 1.

An example of a choice of the mutual current direction in a coupled quad configuration is shown in Figs 3a to 3h. In Fig. 3a the current runs north in the first Hall plate 11, west in the second Hall plate 12, south in the third Hall plate 13 and east in the fourth Hall plate 14.

The current directions in Fig. 3b are obtained by turning the current directions of all Hall plates 11, 12, 13, 14 45° clockwise from the position in Fig. 3a. In this way state 2 is thus defined as follows: the current in the first Hall plate 11 runs north-east, the current in the second Hall plate 12 runs north-west, the current in the third Hall plate 13 runs south-west and the current in the fourth Hall plate 14 runs south-east. The current directions in the further Figures 3c to 3h can be obtained by in each case turning the current directions through 45° from the previous state. The current directions of the quad from states 1 to 8 in Figure 1 are thus shown.

It will be understood by a person skilled in the art that the sequence shown is one of the many possible sequences, the sequence of the states being important in particular for dynamic phenomena, which are discussed later. There are many other possible sensible sequences, the one sequence of which compensates the best thermally and another the best electrically for switching phenomena. This is discussed further later. By, for example, keeping the sequence programmable, the best sequence can always be set.

Because there are always two currents 180° apart and all are 90° apart, the combination of Hall plates described gives instantaneous suppression of (changing) external interference factors, such as packaging stress and temperature gradients as a result of external influences. This has the result that the instantaneous offset is lower and more stable, as a result of which the resulting offset is lower and more stable. As a result the requisite dynamic range for the electronics can be lower.

The specific choice of current directions for the Hall plates 11, 12, 13, 14 per state compensates for the mutual (thermal) influence of the Hall plates 11, 12, 13, 14 on one another, as a result of which self-modulation and self-induced offset of the quad configuration is avoided.

Other specific choices of current directions have a similar effect and are not precluded in the implementation of the invention. As indicated above, the following effects, inter alia, are of importance for this: self-induced thermal gradient, self-induced magnetic field and self-induced voltage.

Figs 4a to 4h show a specific example of a quad configuration in which the temperature effect has been further elaborated. Here the temperature gradient as a consequence of the heat generation and the Peltier effect in the Hall plates themselves is shown diagrammatically in Fig. 4. Here heat is generated in each Hall plate and the Peltier effect ensures that the heat profile per Hall plate 91 is not entirely point symmetrical. As first order compensation it can be argued that two Hall plates always see the direction of the complete thermal gradient 90 as positive (the + towards the middle of the configuration) and the other two Hall plates see this as negative (the – towards the middle of the configuration), so that there is thus instantaneous compensation of thermal effects. However, as can be seen the thermal gradient of the entire magnetic sensor 90 is not precisely 90° rotationally symmetrical. It can be seen from further analysis that the situations in Figs 4a and 4e and Figs 4c and 4g are rotationally identical, but that the situations in Figs 4a and 4c are opposed. Furthermore, it is known that states in Figs 4b, 4d, 4f and 4h are symmetrical and thus are not sensitive to second order effects.

Because patterns 4a and 4c and 4e and 4g yield results that are opposed to one another, complete compensation can be achieved by using a second identical quad Hall plate that always has current directions 90° in advance of the first, as shown in Fig. 3, so that the first quad is in state 4a whilst the second is in the opposing state 4c.

Similar reasoning can be established for the compensation of the magnetic field and the integral mechanical stress profile. This also applies for possible modulations of the temperature profile on the stress profile. However, this can lead to other mutual current choices. Starting from Fig. 4, the current in Hall plates 12, 14 could, for example, be turned through 90° or 180°.

The Hall plates 11, 12, 13, 14 are preferably placed on a semiconductor plate, on which the electronics 20, which will be discussed in more detail later, have been installed for driving, sampling and processing the Hall plates 11, 12, 13, 14. Such electronics 20 generate heat that can influence the Hall plates 11, 12, 13, 14. The offset that is created as a result can also be compensated in a relatively simple manner with the aid of a magnetic field sensor 1 according to the invention.

In Figs 5a, 5b and 5c it is shown how a single Hall plate 11 and electronics 20 can be installed on a semiconductor plate (not shown). The current direction is always different in the various figures and it can be seen how the centre point for heat generation in the electronics 20 is always positioned somewhere different within the electronics 20. The temperature profile that is thus produced in the semiconductor plate is thus always different (indicated by the concentric circles) and the Hall plate 11 is always subjected to a different temperature effect. Because the offset that causes the temperature profile will now also always be different, the residual offset per individual Hall plate will not be compensated after a complete cycle. With the aid of the quad configuration discussed, where two currents are always at 180° with respect to one another, this thermal modulation of the electronics 20 towards the Hall plates 11, 12, 13, 14 can be suppressed instantaneously, as a result of which the thermal modulation of the offset voltages is avoided and the linear dynamic range of the entire system is increased, as is shown Fig. 5d. In this example plate 11 and 13 and 12 and 14 will exhibit opposing thermal modulation. This suppression can be even further assisted by the choice of class A electronics, which have a better constant heat emission, as will be discussed further later.

The reduction in the thermal feedback can also comprise measures such as active thermal compensation. This means that the heat generated by the electronics is compensated using heat sources of equal size, which are positioned on the other side of the Hall plates so as to reduce thermal gradients in this way.

With the temporal compensation technique the electric currents that pass through the Hall plates 11, 12, 13, 14 are distributed over the various contacts 10 of the Hall plates 11, 12, 13, 14 and the electrical voltages that the Hall plates 11, 12, 13, 14 generate are measured from other contacts by means of integrated switches, such as MOSFET switches. Switching of these switches gives rise to strong electrical switch transition phenomena that can lead to offset, assuming that these – parasitic – phenomena will never be perfectly identical for all switches. In addition, the temperature profile in the magnetic field sensor 1 changes when the current direction is switched over, because the Hall current generates a great deal of heat. This change in the temperature profile leads to a changing thermocouple effect.

In Figure 6 it is described how transition phenomena are completely avoided. The signals from the Hall plates 11, 12, 13, 14 are ignored for a certain period and only after stabilisation of all transition phenomena are fed to the electronics by a logical combination of the switching signal and a (transition phenomenon) switch-off signal. Fig. 6 shows 4 signals, the upper signal of which is a switching signal 31. The switching signal 31 indicates that a first current direction and associated measuring direction is switched to a second current direction and measuring direction. The third signal is the Hall signal 33 generated in the second measuring direction. It can clearly be seen that this generated Hall signal 33 initially fluctuates substantially before assuming an essentially constant value. This fluctuation can be the consequence of switching effects and/or thermal equilibrating processes. In order to avoid the adverse effects of this fluctuation, a switch-off signal 32 is provided that interrupts the measurement for some time. This is done, for example, for at least 1 μs, required in order to avoid the large electrical switching peaks, up to a period of the order of 1 ms, in order to achieve a stable situation from the thermal standpoint as well.

Thus, a portion of the Hall signal 33 produced is not used and a used Hall signal 34 remains that is essentially free from undesired equilibrating fluctuations. Whilst only a minimal portion of the signal is discarded, the major advantage of such a method is that fundamentally it is possible to spin more rapidly because the portion that generates offset has been eliminated and a pure signal remains. Without this method the offset must be reduced by averaging with a long time for the pure signal. The offset will then thus become greater the more rapid the switching because a larger fraction of the signal is compromised by switching phenomena.

The thermal switching effect can furthermore be compensated by first switching clockwise and then anticlockwise. In Fig. 7 it is shown that as a result of the thermal inertia of the magnetic field sensor 1 a temperature profile that runs somewhat behind the measurement will spin in the magnetic field sensor on rapid switching of the current direction. In Fig. 7a a Hall plate 11 is shown in which the current (indicated by the continuous arrow) is turned clockwise. The thermal profile that is produced in the Hall plate 11 however corresponds to a direction of the current in which the current was running just beforehand (indicated by the broken arrow). Fig. 7b shows the reverse situation.

If the current is switched clockwise this profile will be thermally mirrored with respect to the situation in which switching is anticlockwise. As a result the thermal offset will be opposed. By alternately switching clockwise and anticlockwise and summing the signals, compensation of the dynamic offset can be obtained. In this case too the electrical switching transition phenomena can be eliminated to lower the offset.

It is obvious that several switching patterns are possible that thermodynamically have an opposed residual error and by using these switching patterns after one another or mixed with one another over time this error can thus be compensated temporally. Even instantaneous thermodynamic compensation is a possibility if the various Hall plate combinations allow, for example, two Hall plates to spin clockwise and two anticlockwise.

The two above methods for avoiding dynamic offset enable more rapid switching of the current. In the case of changing external offset causes, this is advantageous because these changes are better suppressed, which makes even stable offset suppression possible.

The electronics 20 for signal processing and driving the Hall plates is preferably of the best type. A few details are very important.

It is important that the layout of the electronics 20 is so chosen that offset in the Hall plates 11, 12, 13, 14 by (asymmetric) generation of heat in the electronics is avoided as far as possible. For this purpose the electronics 20 are run in so-called class A operation, where the output stages of the analogue amplifier(s) are associated with continuous heat emission. This is in contrast to class B operation, where the aim is for minimal heat emission, which is associated with fluctuations in the heat emission.

Measures are also taken in the layout of the electronics 20 to minimise offset in the electronics as a result of the generation of heat in the Hall plates 11, 12, 13, 14, specifically by positioning the input stages of the amplifiers such that the (changing) heat emission by the Hall plates 11, 12, 13, 14 gives rise to only minimal temperature differences between the transistors of the input stages, for example by means of a quad input stage.

The residual influence of the Hall plate on the electronics can be even further reduced by a slow chopper loop that reverses after every eight measurements (a complete rotation over the Hall plates 11, 12, 13, 14). This is shown diagrammatically in Fig. 8. With this arrangement a residual offset Vmod is created in the electronics by the thermal effect and modulation of the Hall plate. Reversing the choppers 21 will have no influence on this thermal modulation, as a result of which the modulation offset caused for the two periods of eight measurements thus remains the same. Because the Hall signals do spin, the offset is thus eliminated after demodulation (subtraction of the results of both sets of eight measurements). After 16 measurements all signals have been summed, but the offset that is created by the influence of the Hall plates 11, 12, 13, 14 on the electronics 20 has been eliminated by the chopper loop.

Further points for consideration when designing the electronics are: very substantial linearity because of the nevertheless high dynamic still present in the signal; ultra-low offset, because 50 nV direct current offset is already equivalent to 1 μT; and driving of the Hall plates 11, 12, 13, 14 via power sources that are optionally temperature-compensating and identical multiplexer switches so as not to have disrupted the chance of a pure signal even before measurement of the magnetic field.

Finally, there is also the option of connecting the Hall plates to one another directly before or after the multiplexers and of amplifying the resulting signal using one amplifier, or of giving each Hall plate its own amplifier and A/D converter and summing the signals digitally. The former leads to a smaller circuit and is thus more efficient; the latter leads to a larger signal and thus better bandwidth or signal/noise ratio. A person skilled in the art will have to make a choice here on the basis of the specific application of the magnetic field sensor 1.

In order to keep the size of the circuit restricted, the output signal from the Hall plates 11, 12, 13, 14 can be digitised using a sigma/delta A/D converter, integrated over 16 measurements with a counter and then put in a digital register as output signal. This limits the speed of the sensor to 16 switching times. A possible improvement is to keep track of a running average by using more digital registers. In combination with prediction techniques, the speed of the sensor can be improved in this way.

Fig. 9 shows the diagrammatic set-up of a magnetic field sensor 1 that has been implemented on a chip. A stable current source 35 is fed to a demultiplexer 40. The demultiplexer has eight outputs 41, 42, ..., 48 which are connected to eight different contacts 51, 52, ..., 58, respectively, of the Hall element 50. In the situation shown in Fig. 9, the Hall element 50 has a quad configuration consisting of four Hall plates 11, 12, 13, 14. Each Hall plate 11, 12, 13, 14 also has 8 contacts 10 that have been connected in a desired manner to the contacts 51, 52, ..., 58 of the Hall element 50. This can be done in various ways, as will be understood on the basis of the description given above.

The contacts 10 of the Hall plates 11, 12, 13, 14, in turn, are connect to eight inputs 61, 62 ..., 68, respectively, of a multiplexer 60. Both the multiplexer 60 and the demultiplexer 40 are connected to a control unit 73 that ensures that the correct contacts are sampled or, alternatively, current is applied to the correct contacts, at the correct points in time.

The Hall voltages are sampled via the multiplexer 60. These are then amplified using a differential amplifier 70 that is in a chopper loop. The common-mode control (CM control) ensures, inter alia, that the junction FET effects are minimised. The output from the differential amplifier 70 can then be digitised, for example using a sigma/delta converter 71. The digitised measurement signal is then summed by a summing unit 72. This can be done in various ways, as has already been discussed above. The digital signal can be then be fed to further processing electronics (not shown).

It will be clear that the switching scheme described here is only one of the many possible schemes. For instance, the amplified signal can, for example, also first be summed by an analogue summer 71 and only then digitised by the sigma/delta converter 72. The digitised signal can optionally also be digitally filtered before being output.

The magnetic field signal can be output in the form of a digital and/or analogue signal. The control unit 73 is responsible for driving the demultiplexer and multiplexer and optionally makes sophisticated switching schemes possible.

It will be clear to those skilled in the art that the control unit and the multiplexers can easily be organised such that the various current directions in the individual Hall plates 11, 12, 13, 14 and in the various current sequences and speeds are completely programmable, as a result of which the configuration can be put to flexible use.

The circuit can optionally be expanded with logic units, for example with an on-chip microprocessor, in order to perform signal calculations, such as calculation and calibration of the magnetic vector, temperature compensation, auto-calibrations and to control compensation for magnetic materials in the surroundings. In this context relevant calibration data can be stored in on-chip EEPROM or other memory facilities. Specific forms of output signal (buses, field buses, etc.) can thus also be implemented.

Figs 10a and 10b show a magnetic field sensor 1 with four Hall plates 11, 12, 13, 14 in a plan view and a side view, respectively. The magnetic field sensor 1 shown in Figures 10a and 10b is more sensitive as a result of the use of an amplifier and a modulator, in the form of a flux concentrator 80. The flux concentrator 80 is a magnetically active layer which, as the name already indicates, draws the field lines of the magnetic field from the surroundings to it and in that way locally amplifies the field (at the expense of a slight attenuation elsewhere). Preferably a so-called soft magnetic material is used that does draw in the field lines but has no permanent magnetisation properties.

By arranging the flux concentrator 80 precisely above the Hall plates 11, 12, 13, 14 a stronger magnetic field is detected at this point and the signal (and thus the signal/noise ratio and the signal/offset ratio) is stronger. This can yield a gain of a factor of 5 - 10. Of course, the offset is still approximately 1 μT. However, for example, the earth's magnetic field is now no longer experienced as 30 - 50 μT but as 150 - 500 μT. This leads to a more accurate determination of the magnetic field or, alternatively, the speed of the magnetic field sensor 1 can be increased without reducing the original accuracy.

The flux concentrator 80 draws magnetic field lines to it. Deflection of the magnetic field lines will be produced at the edge of the flux concentrator 80, as is indicated in Fig. 10b. This effect makes it possible nevertheless to measure field lines in three dimensions with Hall plates 11, 12, 13, 14 that are in one plane, because at the edge of the flux concentrator the field lines that run in the plane of the Hall plates 11, 12, 13, 14, the plane that is spanned by the X axis and Y axis, in Fig. 10a, are deflected in the Z direction. This has the advantage that we are able to make one chip with three (or more) Hall plate configurations that can measure the (earth's) magnetic field in three directions (X, Y and Z). According to the state of the art three chips that are positioned in the three directions X, Y and Z are needed for this. Three chips are more expensive than 1 and positioning in three directions is an unusual and thus expensive technique.

In conclusion, the flux concentrator 80 can ensure that the signal is stronger and also that we are able to determine a magnetic field in three dimensions with 1 chip. The latter was not previously possible with Hall elements, simply because the offset of the Hall elements was still too great. This makes the invention very suitable for use in a compass for determining the strength and/or direction of the earth's magnetic field. The fact that the magnetic field sensor 1 can easily be made on a semiconductor plate, on which further processing electronics can also be installed, makes it possible to incorporate the magnetic field sensor 1 in a simple manner in electronic equipment such as, for example, a watch or GPS device.

Fig. 10b shows a possible configuration with flux concentrator 80. Magnetic fields in the X and Y direction are deflected by the flux concentrator 80 so that the magnetic field lines in the Z direction run through the Hall plates 11, 12, 13, 14. The magnetic field lines now run inwards on one side of the flux concentrator 80 and outwards on the other side. As a consequence of the flux concentrator 80, the magnetic field lines in, for example, the direction of the X axis run in a first direction through a first Hall plate 11 and in a second direction, that is opposed to the first direction, through a second Hall plate 13. By subtracting the two signals from the two Hall plates 11, 13 on the X axis from one another the magnetic field in the X axis is measured, because the two Hall plates experience the signal in the X direction in opposite directions as a result of the specific deflection characteristics of flux concentrator 80.

The Y components of the magnetic field are determined in an identical manner, but using the Hall plates 12, 14 that are located on the Y axis. For the Z component the system works as described above and the signals from the various Hall plates 11, 12, 13, 14 are summed. By summing and subtracting the signals digitally it is easy (digitally) to correct for differences in sensitivity between the X and Y direction on the one hand and the Z direction on the other hand.

In this embodiment of the invention only two Hall plates are now used for the X and Y components and geometrical instantaneous compensation takes place in a different manner to that described above. Since there is subtraction of the signals from two Hall plates, the instantaneous offset compensation now takes place to a significant extent by subtraction of identical offset components from the first and third Hall plate 11, 13. In Fig. 10, for example, the stress component will be identical and thus be lost, but the external thermal components will be opposed. Thus, different results can be obtained with different current choices in the four Hall plates 11, 12, 13, 14. Optionally, a further offset compensation can be achieved by replacing all single Hall plates in the configuration 11, 12, 13, 14 by one of the compensating Hall plate configurations discussed above. For example 11 by a double Hall plate.

In Figs 10a and 10b a coil 81 is furthermore also shown. The coil 81 is positioned in the plane of the Hall plates 11, 12, 13, 14 (X-Y plane) and is located around the Hall plates 11, 12, 13, 14. The coil 81 makes it possible to perform auto-calibration. By passing a known current through the coil 81 the latter will generate a magnetic field, the strength of which is known. This magnetic field can be measured by the magnetic field sensor 1. Because the size and direction of this generated magnetic field is known, the coil can thus be used to perform auto-calibration. Of course, several coils 81 can also be used for this purpose.

The magnetic field strength that can be achieved with such a coil 81 on a chip is very low. However, because the offset and offset drift of the invention have now become so small, calibration of the sensitivity of the sensor can be carried out by this means. This is important if the sensitivity changes over time or as a function of the temperature.

If the flux concentrator does exhibit magnetisation, the coil 81 can also be used to demagnetise (degauss) or to magnetise or to set/reset the abovementioned flux concentrator

80 if necessary in order to compensate for the magnetisation of the flux concentrator. Usually a damping sinusoidal signal is applied to the coil for demagnetisation, it, of course, easily being possible for the electronics necessary for this to be integrated as well.

The coil 81 that is run around the flux concentrator 80 on the chip can serve for calibration of the sensor's sensitivity and to bring the flux concentrator into a desired magnetic state.

The flux concentrator 80 and the coil 81 can be used either in combination or independently.

In the description of the invention given above various measures are mentioned for achieving an offset that is lower than the offset known in the state of the art. However, in order to obtain an offset of 1 μT it is also possible to employ only temporal compensation in a minimum of 8 directions by using one Hall element that consists of a single Hall plate 11, in combination with the sophisticated electronics that have also been described above. This has the advantage that less power is consumed (one hall plate 11 consumes less energy than two or more Hall plates). This can be a significant advantage for battery-powered applications. Because, however, the (instantaneous) geometrical compensation is lacking, the offset will increase in the case of changing stress or temperature effects, which is not the case with a Hall element that consists of several Hall plates.

It will be clear that the embodiment described below has been described only by way of example and not with any limiting significance and that various modifications and adaptations are possible without going beyond the scope of the invention and that the scope is determined only by the appended claims.

Furthermore, it will be clear to a person skilled in the art that the various measures described in this text that have been described in combination with the invention are suitable for possible independent use. This applies in particular for the various aspects that have been described with regard to the positioning and operating conditions of the electronics, the use of the flux concentrator 80, the coil 81.

# CLAIMS

1. Magnetic field sensor (1), comprising at least two Hall plates (11, 12, 13, 14), wherein the magnetic field sensor (1) is equipped to generate measuring currents in a number of directions in the Hall plates (11, 12, 13, 14) and to measure a potential difference over the Hall plates (11, 12, 13, 14) in a direction in the plane of the Hall plate (11, 12, 13, 14), wherein the direction is always essentially perpendicular to the direction of the measuring current and wherein the potential difference measured is a measure for the magnetic field through the Hall plate (11, 12, 13, 14) in a direction that is essentially perpendicular to the direction of the measuring current and the measured potential difference, wherein the magnetic field sensor (1) is equipped to generate a measuring current in each Hall plate (11, 12, 13, 14) in at least eight directions, characterised in that the measuring current in the first Hall plate is at an essentially constant angle to the measuring current in the second Hall plate.

2. Magnetic field sensor (1) according to Claim 1, wherein the magnetic field sensor (1) is equipped to direct the measuring current per Hall plate (11, 12, 13, 14) in the at least eight directions in accordance with a predetermined sequence.

3. Magnetic field sensor (1) according to Claim 2, wherein the measuring current is directed successively in a first sequence through the at least eight directions and is then directed in a second sequence through the at least eight directions, wherein the first sequence is the reverse of the second sequence.

4. Magnetic field sensor (1) according to one of the preceding claims, in which the magnetic field sensor (1) comprises at least one pair of Hall plates, consisting of a first and a second Hall plate (11, 12), wherein the angle between the measuring current in the first Hall plate (11) and the measuring current in the second Hall plate is 45°, 90° or 180°.

5. Magnetic field sensor (1) according to one of the preceding claims, wherein each Hall plate (11, 12, 13, 14) is provided with at least eight contacts (10) for feeding the measuring current to the Hall plate (11, 12, 13, 14).

6. Magnetic field sensor (1) according to one of Claims 1 - 4, wherein each Hall plate (11, 12, 13, 14) is provided with four contacts and the magnetic field sensor (1) is equipped to feed a periodic signal to each of the contacts, which periodic signals are, respectively, shifted in phase by essentially 90° with respect to one another.

7. Magnetic field sensor (1) according to one of the preceding claims, wherein the magnetic field sensor (1) is provided with at least four Hall plates (11, 12, 13, 14), each of which is equipped to carry a measuring current in at least eight directions.

8. Magnetic field sensor (1) according to Claim 7, wherein the magnetic field sensor (1) is equipped to direct the measuring currents in a predetermined sequence through the at least eight directions of the at least four Hall plates (11, 12, 13, 14), wherein:

- a measuring current (1) in a first Hall plate (11) runs essentially perpendicularly with respect to a measuring current in a second Hall plate (12),
- the measuring current in the second Hall plate (12) runs essentially perpendicularly to a measuring current in a third Hall plate (13),
- the measuring current in the third Hall plate (13) runs essentially perpendicularly to a measuring current in a fourth Hall plate, and
- the measuring current in the fourth Hall plate (14) runs essentially perpendicularly to the measuring current in the first Hall plate (11).

9. Magnetic field sensor (1) according to one of the preceding claim, comprising a first group of Hall plates, comprising a first, second, third and fourth Hall plate (11, 12, 13, 14), and a second group of Hall plates, comprising a fifth, sixth, seventh and eighth Hall plate (15, 16, 17, 18), wherein the magnetic field sensor (1) is equipped to select the direction of the measuring current in the first, second, third and fourth Hall plate (11, 12, 13, 14) essentially perpendicular with respect to the fifth, sixth, seventh and eighth Hall plate (15, 16, 17, 18), respectively.

10. Magnetic field sensor (1) according to one of the preceding claims, wherein the Hall plates (11,12,13,14) are positioned on the same support.

11. Magnetic field sensor (1) according to Claim 10, wherein the support is a

semiconductor and the support furthermore comprises a demultiplexer (40) that is equipped to take a current and to distribute this over the at least eight directions of the Hall plates (11, 12, 13, 14), and the support furthermore has a multiplexer (60) that is equipped to take the measurement voltages over the Hall plates (11, 12, 13, 14) and to output these via an output and the support is furthermore provided with a control unit (73) for driving the demultiplexer (40) and the multiplexer (60).

12. Magnetic field sensor (1) according to Claim 11, wherein the support furthermore has a summing unit (71) that is connected to the output of the multiplexer (60), for summing the various voltages measured.

13. Magnetic field sensor (1) according to one of Claims 11 or 12, wherein the support is furthermore provided with a sigma/delta converter (72), for digitising the output signal from the multiplexer (60), and an amplifier (70) for amplifying the output signal from the multiplexer (60).

14. Magnetic field sensor (1) according to one of the preceding claims, wherein the magnetic field sensor (1) is furthermore provided with a flux concentrator (80) that essentially is in the third direction of the Hall plates (11, 12, 13, 14).

15. Magnetic field sensor (1) according to one of the preceding claims, wherein the magnetic field sensor (1) is provided with at least one coil (81) for generating a magnetic field that can be measured by the magnetic field sensor (1).

16. Magnetic field sensor (1) according to Claim 15, wherein the coil (81) can be driven to demagnetise flux concentrator (80).

17. Magnetic field sensor (1) according to one of the preceding claims, wherein the magnetic field sensor (1) is equipped to ignore at least one measurement signal for measurement of the potential difference over the Hall plates (11, 12, 13, 14) for a specific period.

18. Support provided with a magnetic field sensor (1) according to one of the preceding

claims.

19. Compass provided with a magnetic field sensor (1) according to one of Claim 1 - 17.

Fig 1

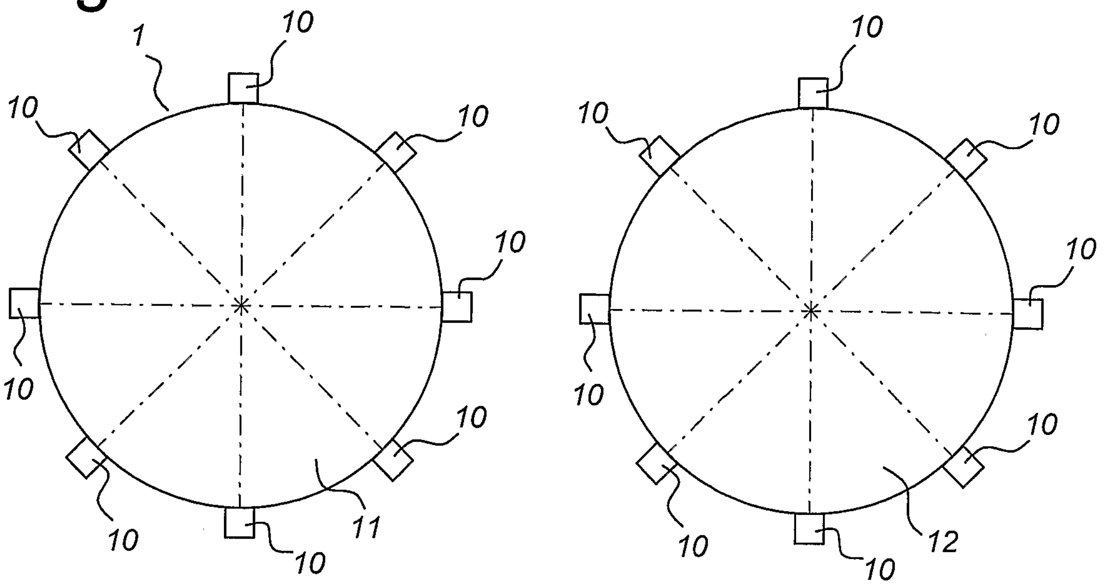


Fig 2a

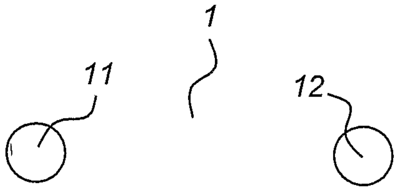


Fig 2b

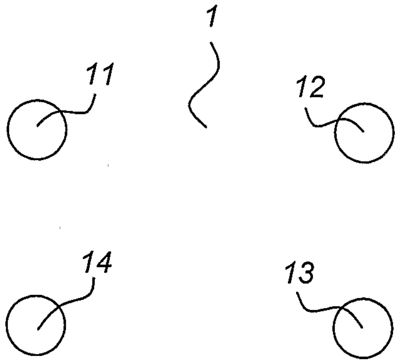


Fig 2c

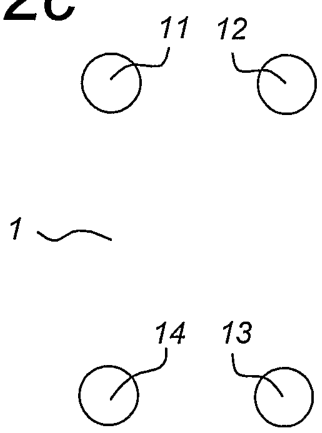


Fig 2d

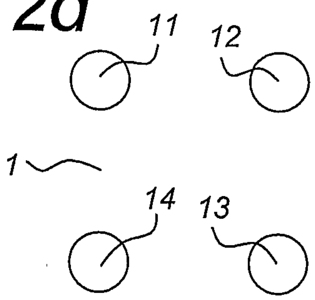


Fig 2e

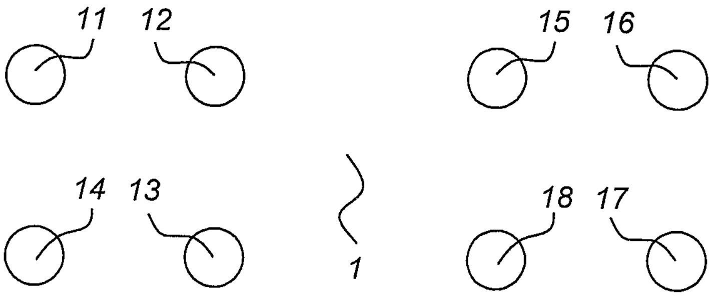


Fig 3a

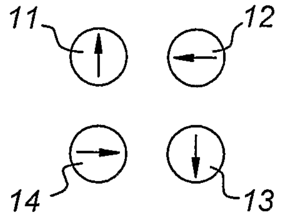


Fig 3b

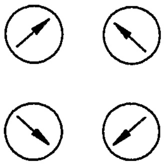
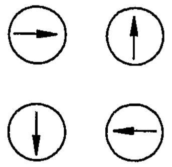


Fig 3c



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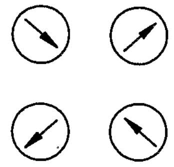

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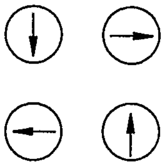


Fig 3f

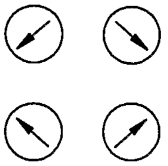


Fig 3g

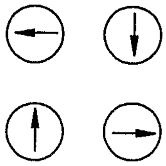


Fig 3h

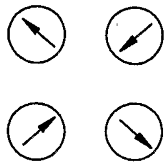


Fig 4a

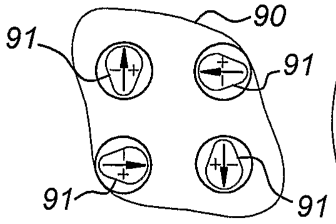


Fig 4b

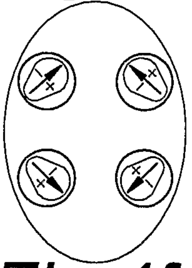


Fig 4c

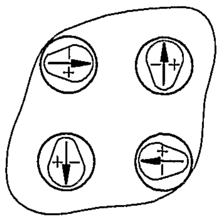
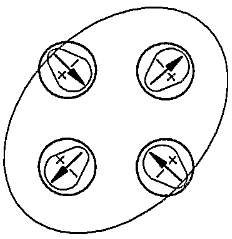


Fig 4d



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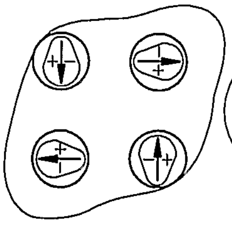


Fig 4f

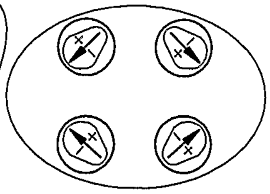


Fig 4g

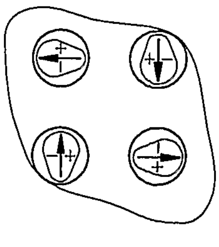


Fig 4h

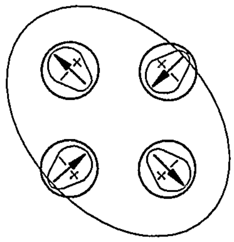


Fig 5a

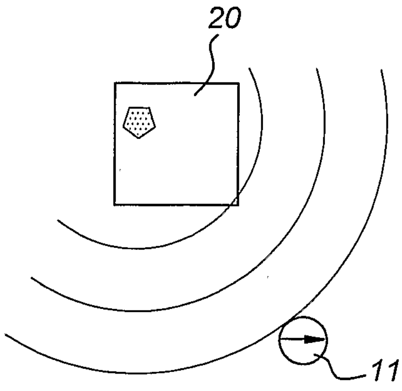


Fig 5b

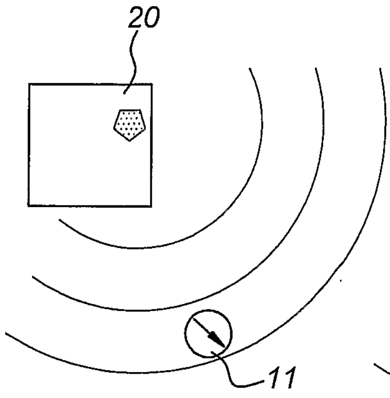


Fig 5c

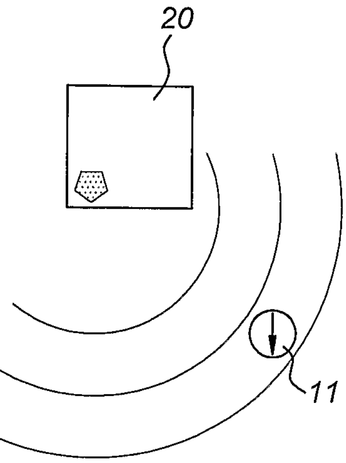


Fig 5d

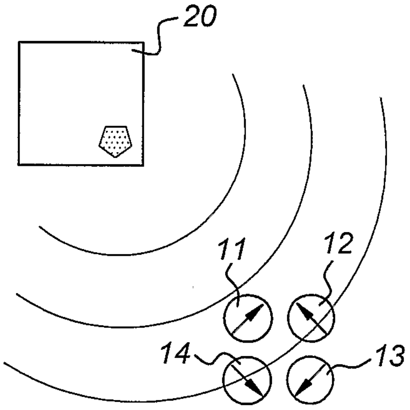


Fig 6

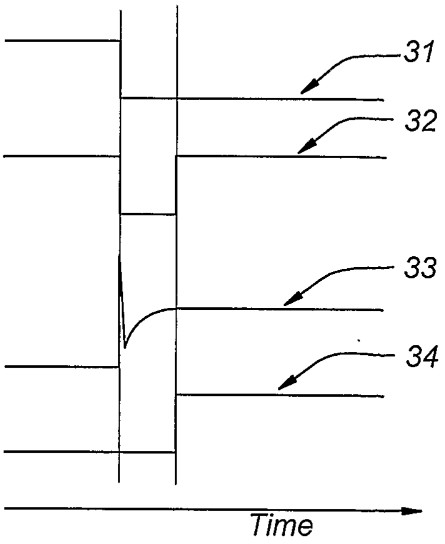


Fig 7a

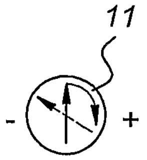


Fig 7b

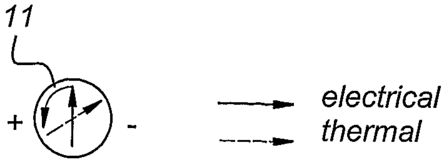


Fig 8

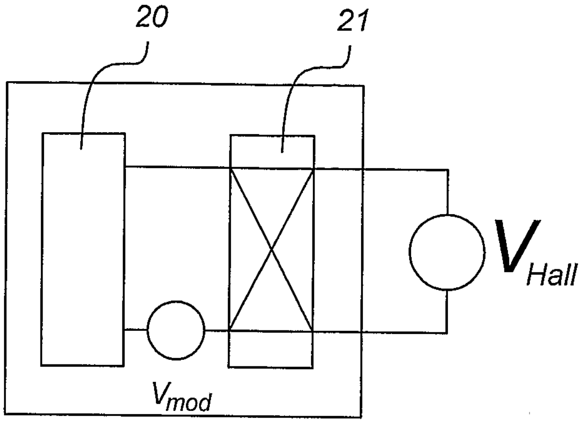


Fig 9

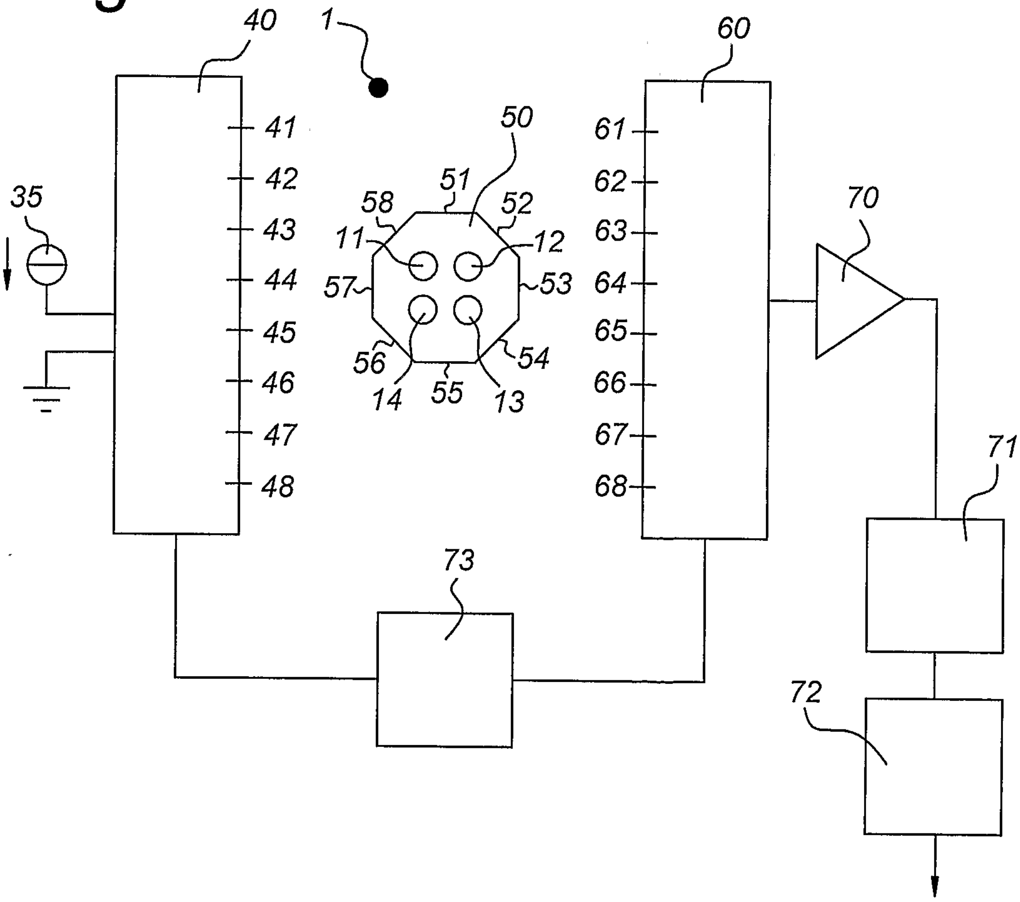


Fig 10a

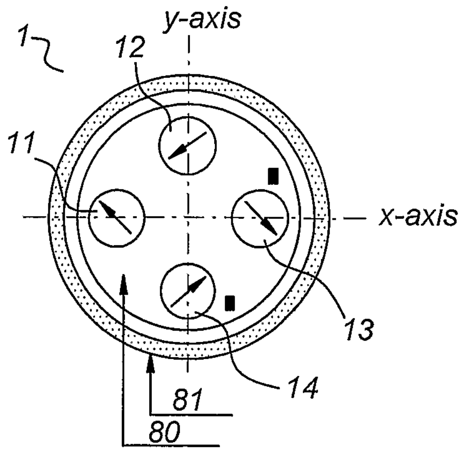
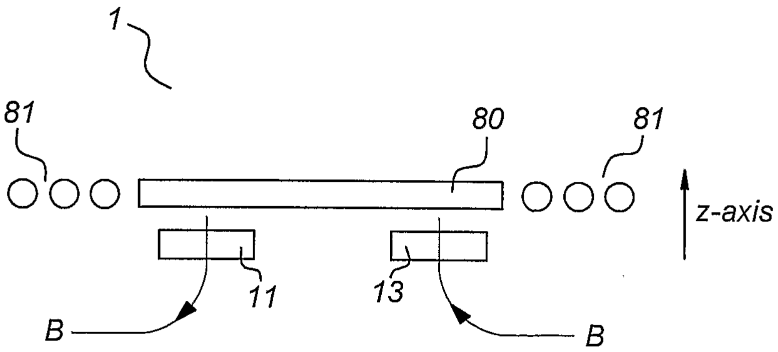


Fig 10b



# INTERNATIONAL SEARCH REPORT

International Application No
PCT/NL2004/000871

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7 G01R33/07

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)
IPC 7 G01R

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

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

EPO-Internal, INSPEC, COMPENDEX, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| X | US 5 747 995 A (SPIES ALFONS)<br>5 May 1998 (1998-05-05)<br>column 4, line 26 - line 50<br>column 5, line 4 - line 27<br>column 6, line 17 - line 24<br>figures 4,5 | 1,2,<br>4-11,<br>15-19 |
| Y | | 13,14 |
| X | US 2003/155912 A1 (MOTZ MARIO)<br>21 August 2003 (2003-08-21)<br>page 2, paragraph 16<br>page 3, paragraph 37<br>page 3, paragraph 40 - page 4, paragraph 45<br>figures 3A,3B,4 | 1-3,5,<br>10-12,<br>17,18 |

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☒ Patent family members are listed in annex.

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| Date of the actual completion of the international search<br>11 May 2005 | Date of mailing of the international search report<br>19/05/2005 |
| Name and mailing address of the ISA<br>European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,<br>Fax: (+31-70) 340-3016 | Authorized officer<br>Swartjes, H |

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PCI/NL2004/000871

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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