Sense & Control

Designing a Disc Magnet for use with Infineon GMR Sensors

Application Note

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Designing a Disc Magnet for use with Infineon GMR Sensors Revision History: V1.0, 2011-10-15	
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1 Abstract

There are many applications in the automotive, industrial control, medical, and other markets where it is desired to monitor the angular position or speed of a rotating shaft. The majority of the techniques used to perform these measurements are based on the use of magnetic sensors, of which there are two main technology types: Hall effect and magnetoresistance (MR) effect.

Infineon manufactures a wide range of Hall effect and GMR (giant magnetoresistance) sensors with a variety of different programming, package, and interface options. For many applications, GMR is the preferred sensor technology because of its accuracy, small size, low cost, and ability to provide 360º contactless angle measurement. Also, GMR sensors support a larger air gap between the magnet and the sensor as compared to their Hall effect counterparts.

This application note introduces the concepts underlying the use of GMR sensors, including discussions on potential sources for errors and how to mitigate them. The application note then details the process of designing and analyzing a disc magnet for use with Infineon GMR sensors. The three main attributes to consider when selecting or creating a disc magnet are its material from which it is manufactured, its diameter, and its thickness. This application note describes a specific recommended disc magnet design using sintered SmCo5 material with a *Br* value of 0.9T, a diameter of 10mm, and a thickness of 1.7mm. The application note also provides the information necessary to analyze alternative disc magnet designs if required.

2 Introducing GMR Sensors

2.1 Terms and Meanings

The terms used in this application note along with their meanings are shown in Table 1.

Table 1 Terms and Meanings

Term	Meaning
Magnetic Flux	A measure of the strength of a magnetic field over a given area
Magnetic Flux Density	Amount of magnetic flux in a unit area perpendicular to the direction of magnetic flow
Magnetic Circuit	One or more closed loop paths containing a magnetic flux
Remanence (*Br*)	The measure, or strength, of the magnetization associated with a magnetic material

Note: Disc and disk are alternative spellings of the descriptive word for things of a (generally) thin and circular geometry. These variations are due to the way in which the words originated. The earlier word is ***disk****, which came into the English language in the middle of the 17th century. The more recent spelling* ***disc*** *was introduced in the 18th century, following an increasing tendency to base the spelling of words on their roots (in this case the Latin word "discus").*

2.2 Example GMR Sensor Application

A GMR-based angular sensor requires the presence of a homogeneous magnetic field. For the purposes of this application note, it is assumed that the magnetic field is provided by a disc magnet that is attached to a rotating shaft. The GMR sensor detects the direction of the magnetic field and reports this information to a microcontroller. An example GMR sensor application is illustrated in Figure 1.

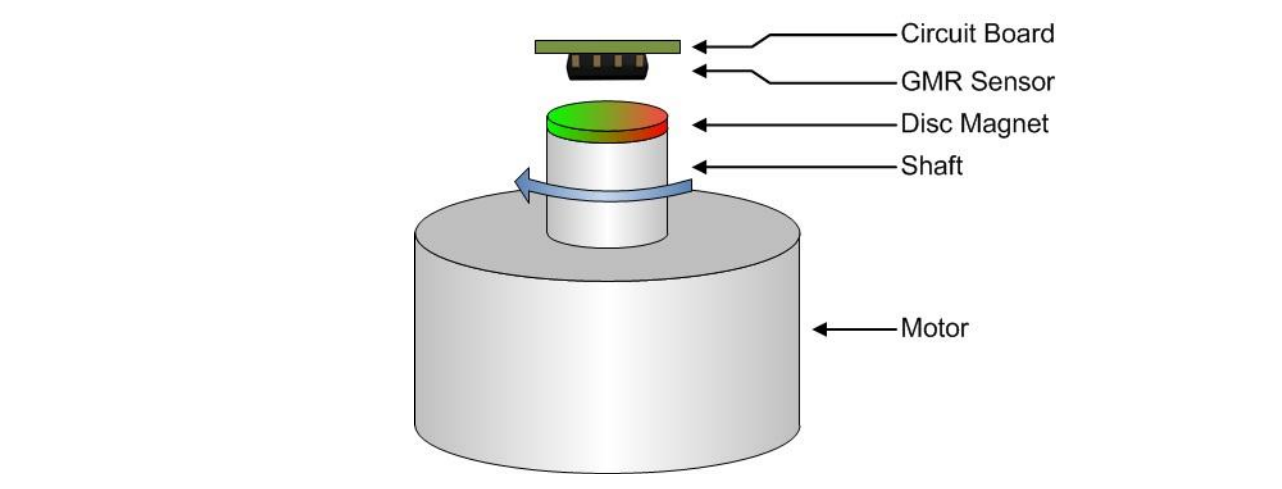

Figure 1 Example GMR sensor application

2.3 Mode of Operation

Infineon's GMR sensors are manufactured in PG-DSO-8 packages. In fact, each package contains two GMR-sensitive areas as illustrated in Figure 2.

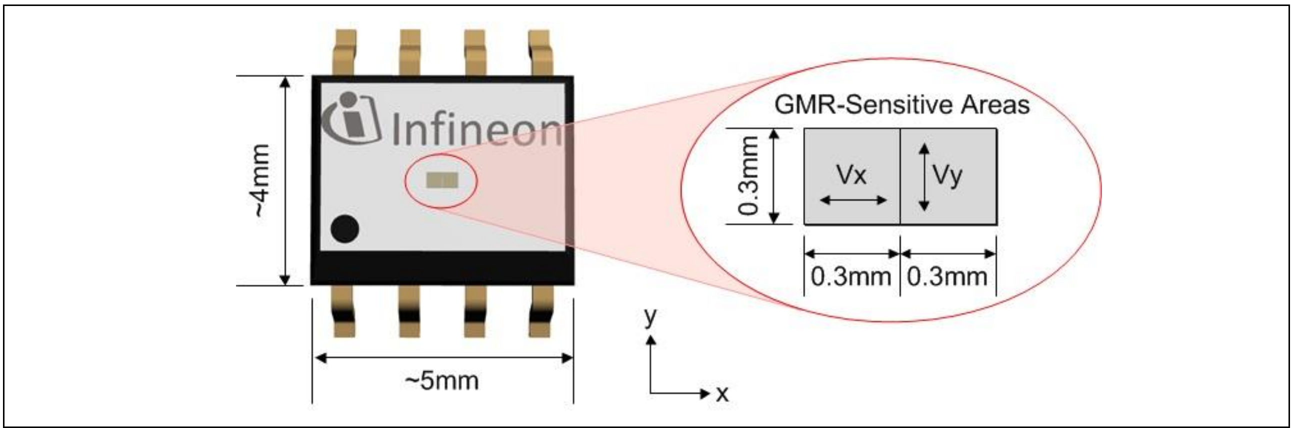

Figure 2 The Vx and Vy GMR-sensitive areas

Note: The Vx GMR-sensitive area comprises four GMR elements that are connected to a Wheatstone bridge (similarly for the Vy GMR-sensitive area). The advantage of using a full-bridge structure is that the amplitude of the GMR signal is doubled and temperature effects are cancelled out.

Note: Throughout this application note, the outputs from the GMR-sensitive areas are considered to be in terms of voltage, because this is their initial realization inside the device. However, different sensors may process the signals in different ways internally; also different sensors may use a variety of interface options to communicate with an external microcontroller.

The output from the Vx GMR-sensitive area reflects the cosine of the magnetic field, so this output is at its maximum when the magnetic flux lines are parallel to the x-axis as shown in Figure 2. By comparison, the output from the Vy GMR-sensitive area reflects the sine of the magnetic field, so this output is at its maximum when the magnetic flux lines are parallel to the y-axis as shown in Figure 2.

Consider a GMR sensor located above a disc magnet such that the package body and Vx GMR-sensitive area are initially aligned with the magnetic field as illustrated in Figure 3.

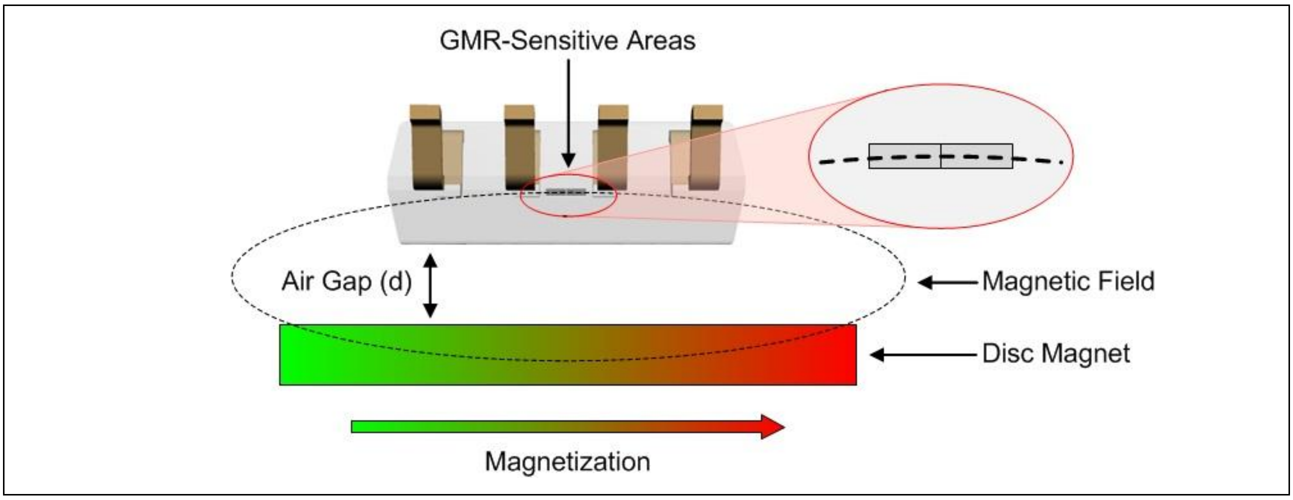

Figure 3 Side view of the sensor package relative to the disc magnet

If the disc magnet now begins to rotate – assuming an ideal setup with no sources of error – the outputs from the Vx and Vy GMR-sensitive areas will be as illustrated in Figure 4.

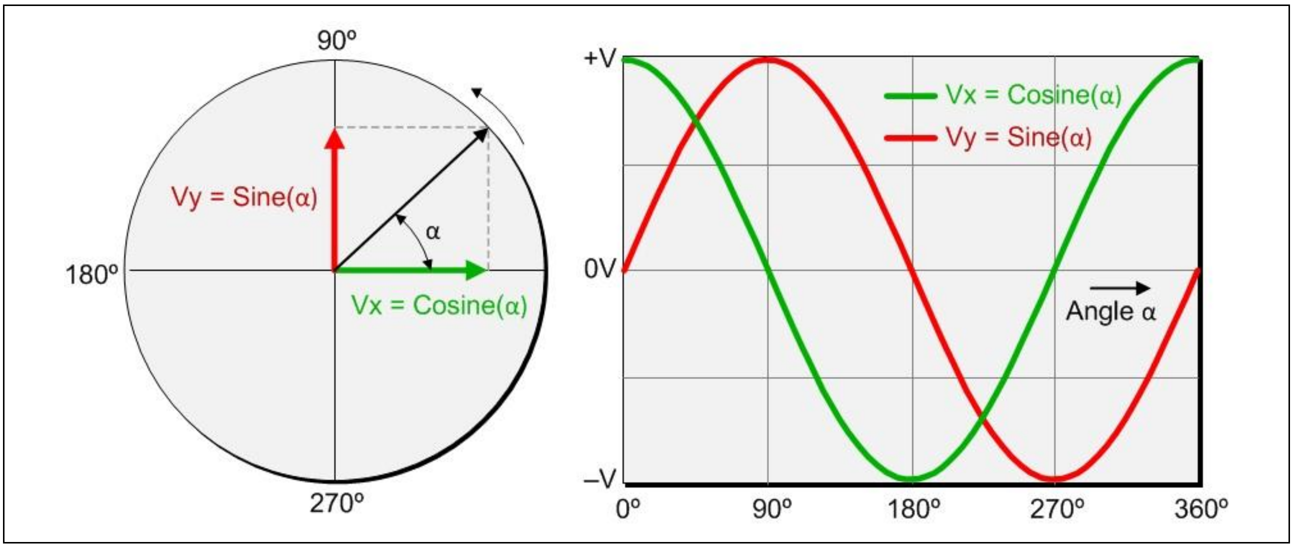

Figure 4 Ideal outputs from the GMR-sensitive areas

2.4 Sources of Error

There are several potential sources of system errors, in addition to the intrinsic sensor error, which are summarized as follows:

- The disc magnet may vary in thickness
- The disc magnet may be positioned eccentrically on the rotating shaft (or off center)
- There may be a positioning tolerance of the sensor package on the circuit board
- There may be a positioning tolerance of the circuit board over the disc magnet
- There may be positioning tolerances of the GMR-sensitive areas within the sensor package

These sources of error will be specified as tolerances in applicable data sheets or determined during the design phase. For the purposes of this application note, the sum of these errors (excluding variations in the thickness of the disc) will be referred to as the alignment error (a) as illustrated in Figure 5.

Note: The sources of potential system errors listed above do not consider tilt of the magnet as that topic is beyond the scope of this application note.

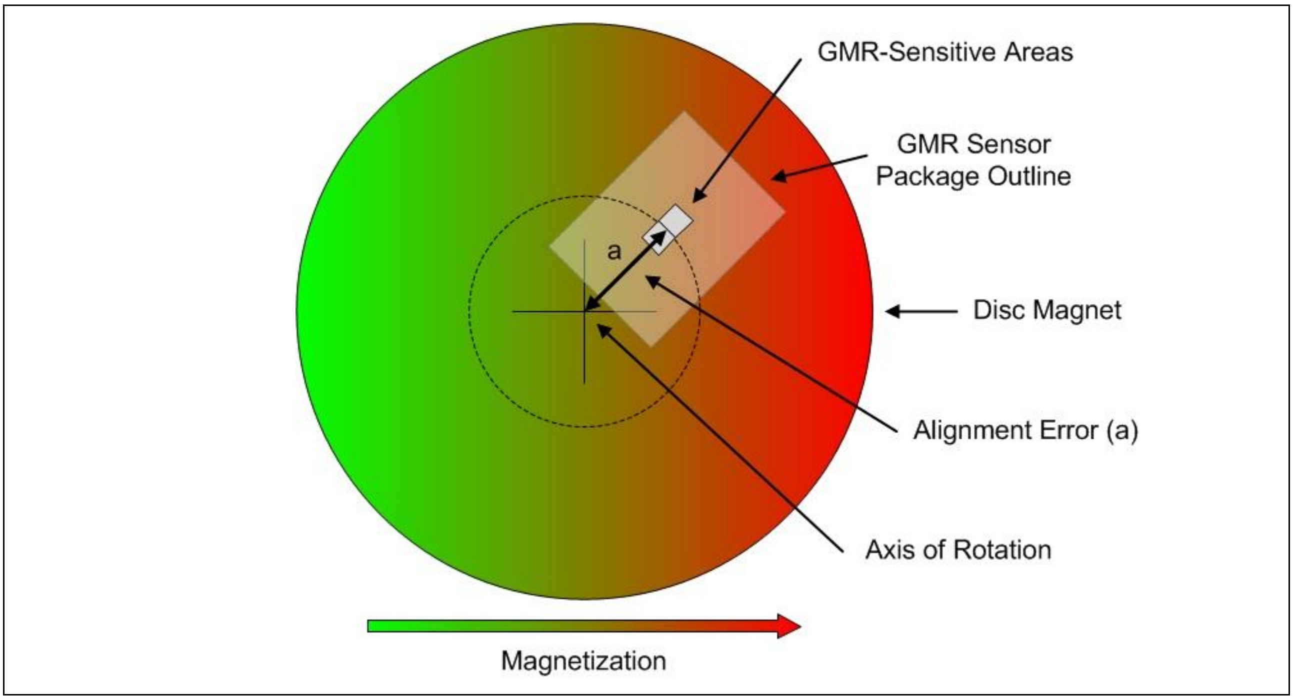

Figure 5 Top view of GMR-sensitive areas displaced (misaligned) with respect to the axis of rotation

It should be noted that when the shaft is rotating, a displaced (misaligned) disc magnet combined with a perfectly aligned sensor will give identical results to a perfectly aligned disc magnet combined with a displaced sensor.

For the majority of this application note, the two GMR-sensitive areas will be assumed to be so small as to occupy a single point (this assumption will be tested in Section 3.4.4 of this application note).

To understand why a displacement (misalignment) of the disc magnet / sensor combination causes errors with GMR-based sensors, first consider a disc magnet with an idealized magnetic field as illustrated in Figure 6.

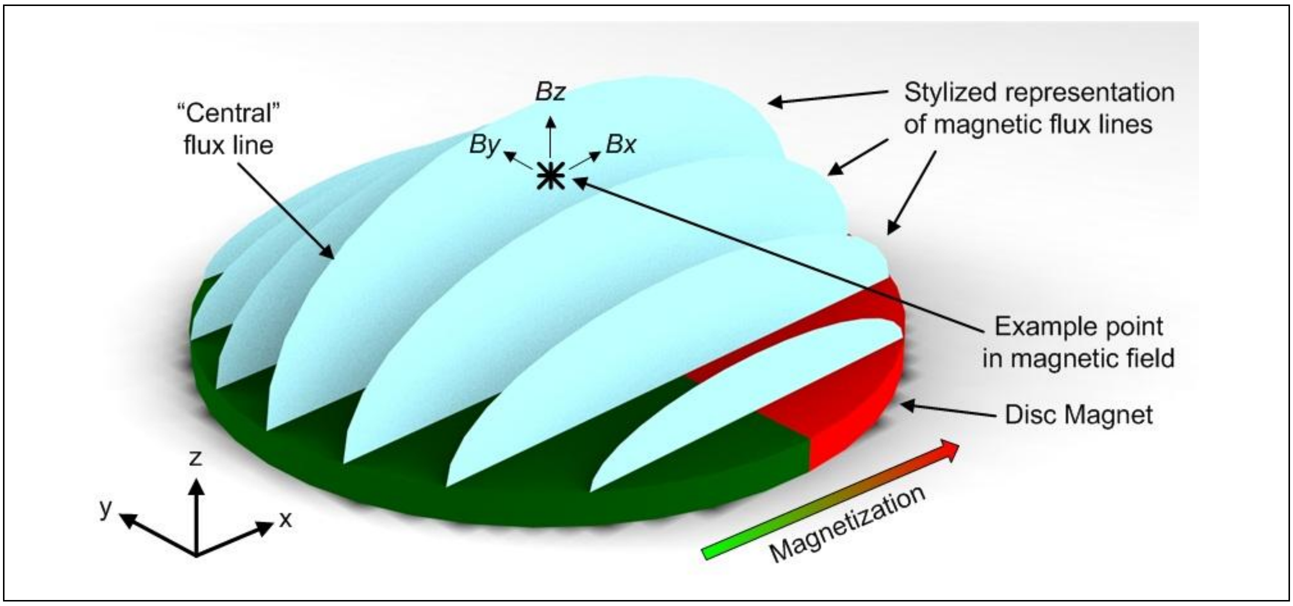

Figure 6 Stylized representation of an ideal magnetic field

Any point in the magnetic field can be represented by three magnetic components *Bx*, *By*, and *Bz*. As an example, consider the "central" flux line shown in Figure 6. At the point where this flux line exits the magnetic pole on the left-hand side of the green area of the magnet, it will have both *Bx* and *Bz* components. The *By* component will be zero anywhere on the central flux line. By comparison, the *Bz* component will vary across the flux line; at the central point in the flux line's arc (half way between the magnet's poles), the *Bz* component will have fallen to zero. However, as per the discussions associated with Figure 2, the two GMR-sensitive areas in the sensor package can only be affected by the *Bx* and *By* magnetic components; they will not be affected by any *Bz* component.

If all of the magnetic flux lines were to be "vertically orientated" as illustrated in the ideal representation shown in Figure 6, then regardless of where the GMR-sensitive areas were to be placed in the field, the magnetic component *By* would always be zero and the GMR-sensitive areas would only be presented with a magnetic component *Bx* (again, unaffected by the component *Bz*). Since this example is ideal and there are no *By* components, any displacement of the disc magnet or GMR-sensitive areas from the main axis of rotation would *not* result in any errors.

Now consider a more realistic representation of the magnetic field as illustrated in Figure 7. In this case, the magnetic flux lines increasingly depart from a vertical orientation (that is, perpendicular to the plane of the face of the disc magnet) the further they are located from the central flux line.

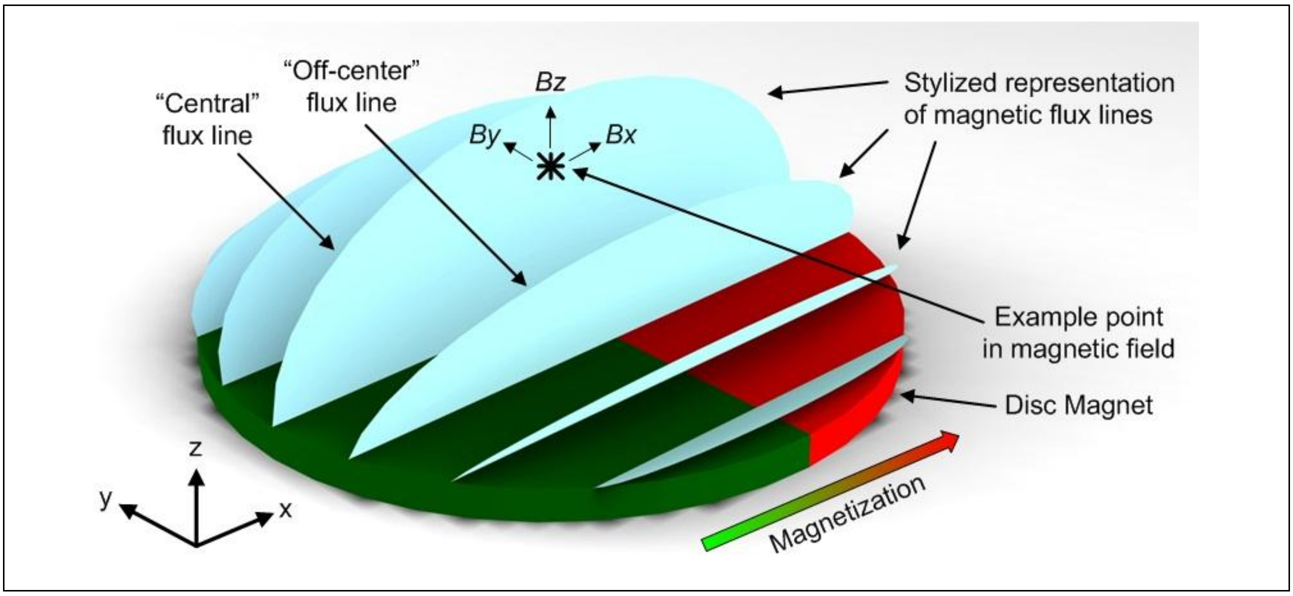

Figure 7 Stylized representation of realistic magnetic field

First consider the "central" flux line illustrated in Figure 7. Since this flux line *is* perpendicular to the plane of the face of the disc magnet, the *By* magnetic components will be zero anywhere on the line.

By comparison, consider the "off-center" flux line shown in Figure 7. This flux line departs from a vertical (perpendicular) orientation, which means that it may have non-zero *By* magnetic components. To be more specific, at the point where this flux line exits the magnetic pole on the left-hand side of the green area of the magnet, it will have non-zero *Bx*, *By*, and *Bz* components. Both the *By* and *Bz* components will vary across the flux line; at the central point in the arc, both of these components will have fallen to zero.

Since the magnetic flux lines increasingly depart from a vertical (perpendicular) orientation the further they are from the central flux line, their corresponding *By* components will also increase. The problem is that any non-zero *By* components will result in errors in the angles calculated using the outputs from the GMR-sensitive areas in the sensor.

Note: Increasing the diameter of the disc magnet will reduce the size of errors caused by the displacement of the disc and/or the GMR-sensitive areas from the axis of rotation.

3 Analysis of a 10mm Diameter Disc Magnet

This section presents an example disc magnet design and discusses the decisions to be made and the types of analysis that should be performed.

The three main attributes that can be controlled when creating a disc magnet are its diameter, its thickness, and the magnetic material from which it is manufactured.

3.1 Diameter Selection

For the purposes of this application note, we will begin by specifying a diameter of 10mm. As noted in Section 2.4 of this application note, increasing the diameter of the disc will reduce the size of any errors caused by the displacement of the disc magnet and/or the GMR-sensitive areas with respect to the axis of rotation, but this will also increase the size and mass of the magnet.

3.2 Material Selection

The material selection for a disc magnet may depend on the intended application and operating environment. For automotive applications, it is common to specify minimum and maximum values for the strength of the magnetic field used with a GMR sensor for an ambient temperature of 25ºC and junction temperatures ranging between –40 to +150ºC. The relevant section from a representative GMR sensor data sheet is illustrated in Figure 8 (the actual sensor datasheet should be referenced to determine specific values).

Magnetic Induction at T_A= 25°C [4) 5)]	B_{XY}	30	-	50	mT	-40°C < T_J<150°C
	B_{XY}	30	-	60	mT	-40°C < T_J<100°C
	B_{XY}	30	-	70	mT	-40°C < T_J<85°C
Expanded Magnetic Induction at T_A = 25°C [4) 5)]	B_{XY}	25	-	30	mT	Additional angle error of 0.1° [6)]

Figure 8 Minimum/maximum magnetic field values from a representative GMR sensor data sheet

Note: See also the Infineon application note GMR Accuracy Extension.

To minimize errors, the magnetic material should maintain its magnetic properties as constant as possible over the full temperature range. The *Br* (remanence) value is typically specified at room temperature (20ºC) and varies as a function of the temperature coefficient, Δ*B*/ΔT (normally specified in %/K). Assuming that the temperature coefficient is constant over the required temperature range, the formula for calculating the remanence value at a particular temperature is presented in Equation (1):

Equation (1) $Br_{T(NEW)} = Br_{T(20C)} * (1 + T_{CE} * \Delta T)$

Where: $Br_{T(NEW)}$ is the remanence value at the new temperature, $T_{(NEW)}$

$Br_{T(20C)}$ is the remanence value at room temperature (20ºC)

T_{CE} is the temperature coefficient of the magnetic material

$\Delta T = T_{(NEW)}$ – 20ºC (the new temperature minus room temperature)

Thus, the change in *Br* can be calculated using the appropriate temperature coefficient; for example:

- T_{CE} = –0.2%/K for Ferrite
- T_{CE} = –0.05%/K for SmCo5
- T_{CE} = –0.035%/K for Sm2Co17

Note: The temperature coefficients for the magnetic materials discussed in this application note have negative values. This means that the strength of the field will increase as the temperature decreases; conversely, the strength of the field will decrease as the temperature increases.

For the purposes of this application note, an automotive application is assumed. In this case, all of the materials listed above can be safely used over the operating temperature range of –40 to +150ºC and the temperature coefficient can be assumed to be more or less constant over this range. Also, plastic-bonded versions of these materials are stable over the long term.

An alternative material is NdFeB, but only high temperature grades can be used up to +150ºC. Furthermore, the temperature coefficient of NdFeB is not constant over the full automotive temperature range (assuming -0.12%/K at room temperature, the coefficient may increase to –0.25%/K or more at +150ºC). Also, plastic-bonded NdFeB magnets will slowly degrade at high temperatures, so careful material selection and analysis should be performed if NdFeB is to be considered for the target application.

The material with the lowest cost considered in this application note is ferrite, but due to its temperature coefficient of –0.2%/K, the disc magnet’s strength will vary by approximately 38% over the full temperature range from –40 to +150ºC. This is more variation than can be tolerated in an automotive application.

Out of the three main materials noted above, sintered SmCo is recommended. In particular, a SmCo5 grade, which has a $\Delta B/\Delta T$ of –0.05%/K and whose field strength varies by less than 10% over the full –40 to +150ºC operating temperature range. Another type of Samarium Cobalt material, Sm2Co17, has a better thermal consistency, but it also has a stronger magnetic field. The stronger field would require a thinner disc which would be very fragile for use in an automotive environment; therefore, not recommended.

3.3 Disc Thickness Determination

Once the strength of the magnetic material has been determined, the next step is to calculate the thickness of the disc. Increasing the thickness of the magnet will make it stronger and less susceptible to bending or breaking, but this will also increase the strength of the magnetic field, and GMR sensors have a maximum value of the magnetic field they can tolerate as discussed earlier in this application note.

Samarium Cobalt is a brittle material, so making it too thin will cause increased risk of damage during handling. Taking into account the SmCo5 grades that are readily available, a *Br* value of 0.9T is recommended for this application. In this case, a disc thickness of 1.7mm is required. This is relatively thin, so the resulting magnet will be somewhat fragile.

For the purposes of this application note, the air gap between the disc magnet and the sensor is assumed to have minimum and maximum values of 0.5mm and 4.5mm, respectively. The flux density at room temperature (20°C) on the rotation axis of the proposed disc magnet (diameter = 10mm, thickness = 1.7mm, material = sintered SmCo5 with a *Br* value of 0.9T) for this air gap range is illustrated in Figure 9.

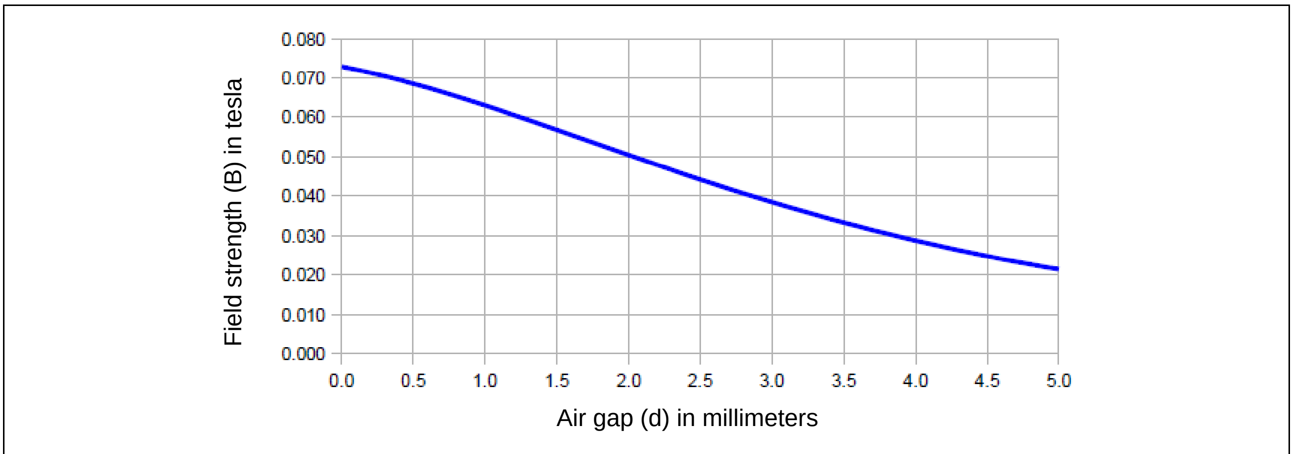

Figure 9 Variation of flux density *B* on the rotation axis of the proposed disc magnet at 20°C

From Figure 9, it can be seen that the flux density at room temperature (20°C) ranges between a maximum value of 68mT for an air gap of 0.5mm, and a minimum value of 25mT for an air gap of 4.5mm. From Equation

(1), using a temperature coefficient of –0.05%/K, the maximum value increases to 70mT at –40°C while the minimum value decreases to 23mT at 150°C. Additional variation comes from the tolerance of the magnetic material´s remanence, which is approximately ±4%.

3.4 Modeling and Analysis

3.4.1 Creating a 3D Model

To analyze the proposed disc magnet, it must be modeled using an appropriate 3D package. Creating this model is not complicated as it only consist of the magnet and the surrounding air – no other magnetic material is present in the system.

Note: For the purposes of these evaluations the GMR sensor elements are assumed to be non-magnetic.

In order to reliably extract very small field values, the accuracy of the analysis must be high, which requires very fine meshing in the important areas of the model.

3.4.2 Analyzing Displacement Errors

As discussed in Section 2.4, due to the limited size of the disc, *By* magnetic components may be present if there is any displacement (misalignment) of the disc magnet and/or the GMR sensor with respect to the axis of rotation. Any non-zero *By* components will result in output angle errors from the GMR sensor. Figure 10 shows the intensity and distribution of the *By* components in a plane 0.5mm above the surface of the magnet (green hues indicate low *By* component values, while yellow, orange, red, cyan, and blue hues indicate increasing *By* component values).

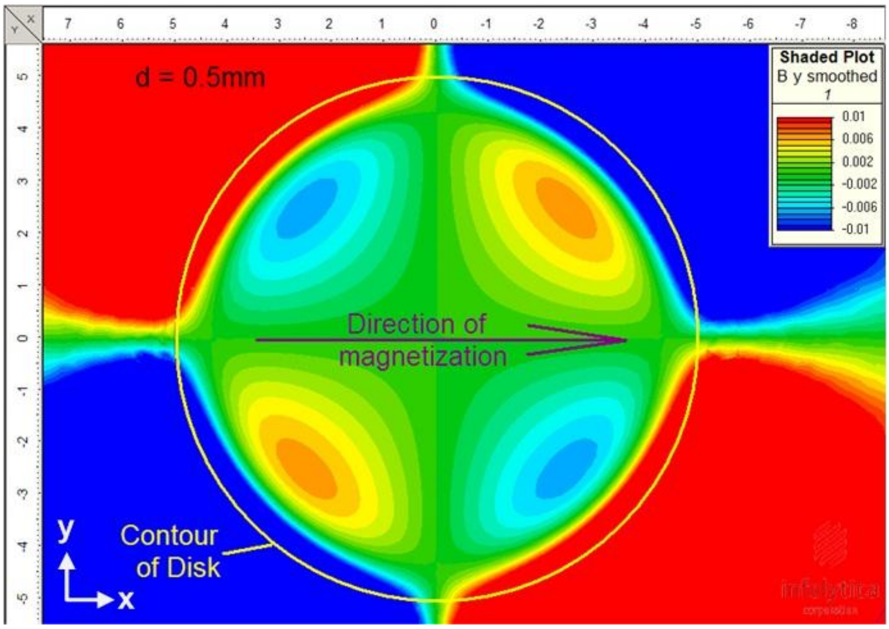

Figure 10 Distribution of *By* components in a plane 0.5mm above the surface of the disc magnet

For reasons of symmetry, there are four directions from the center of the disc magnet that have minimal *By* components: 0°, 90°, 180°, and 270°. By comparison, the worst-case *By* components occur at 45°, 135°, 225°, and 315°.

Therefore, when the disc magnet is rotating, and assuming that the disc magnet and/or GMR-sensitive areas are displaced from the axis of rotation, the results from the GMR sensor will be accurate four times per revolution. Similarly, worst-case errors caused by the *By* components will occur four times per revolution. Figure

11 shows the resulting angle error generated by the GMR sensor when it is displaced 0.3, 0.6, 0.9, 1.2, 1.5, and 1.8mm from the axis of rotation (these simulations were performed using an air gap of 0.5mm).

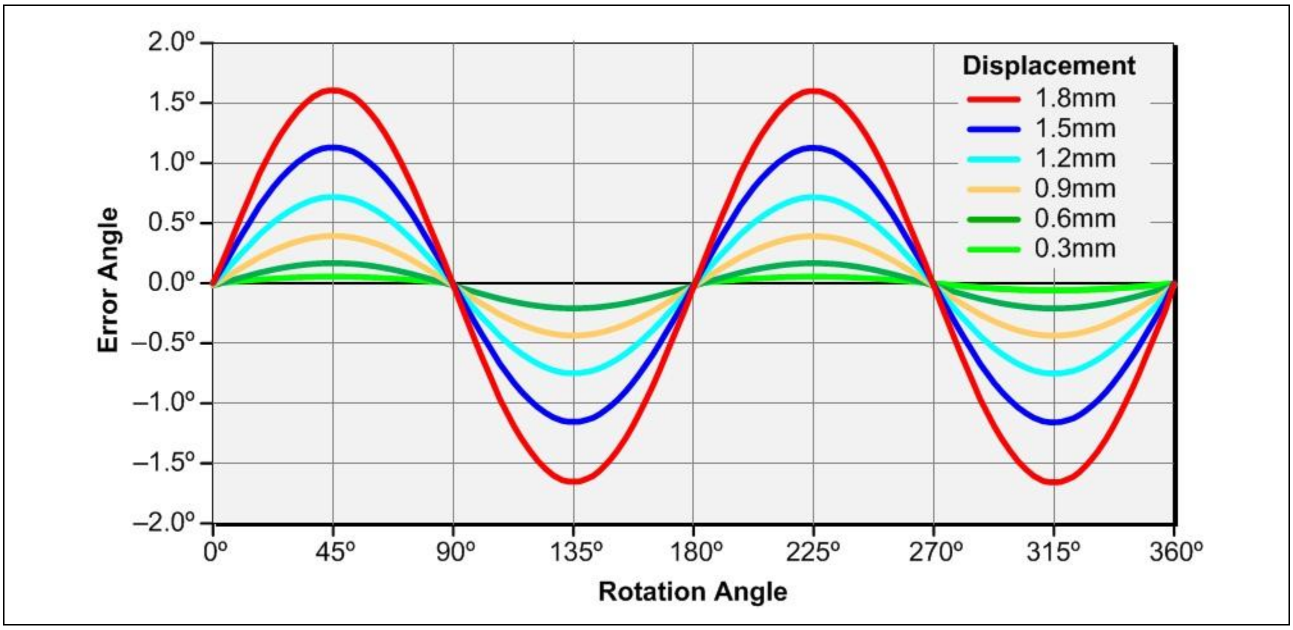

Figure 11 Resulting error angles associated with increasing displacement from the axis of rotation

An alternative view of the data from Figure 11 is presented in Figure 12, which plots the maximum error angles versus the displacement from the axis of rotation.

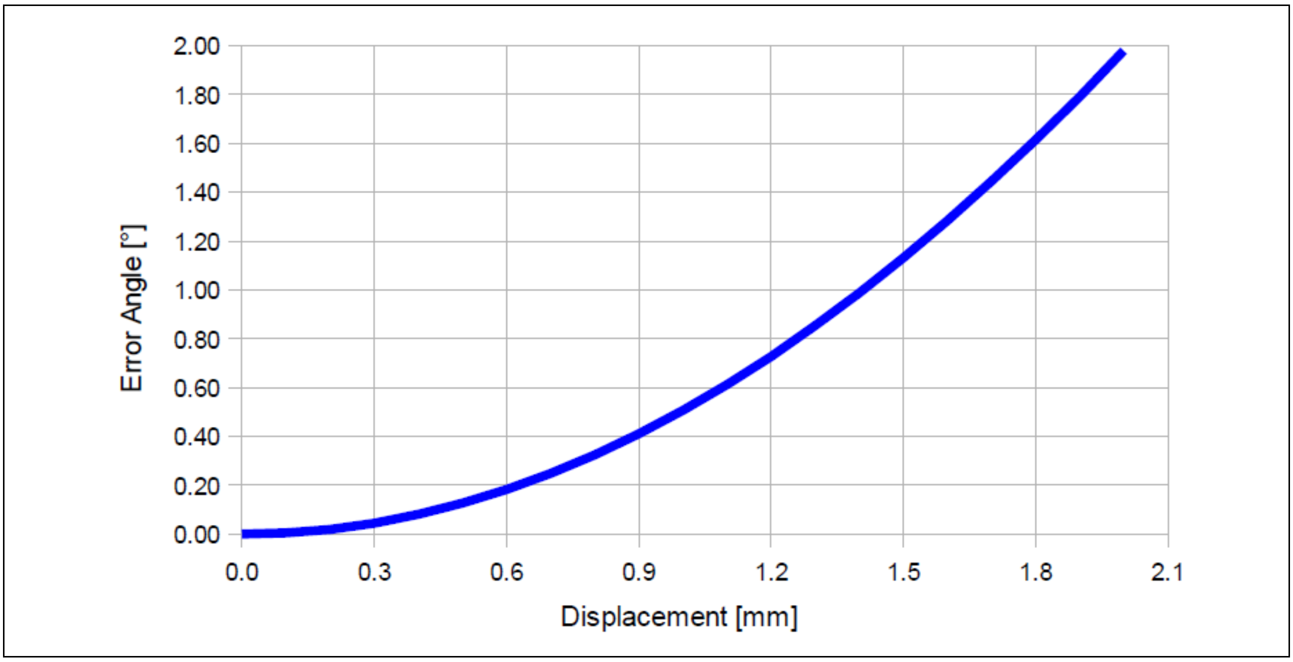

Figure 12 Maximum error angles associated with increasing displacement from the axis of rotation

3.4.3 Field Characteristics Associated with Different Air Gaps

As previously mentioned, the air gap between the disc magnet and the GMR sensor is assumed to have minimum and maximum values of 0.5mm and 4.5mm, respectively. The analyses in section 3.4.2 were all performed using an air gap of 0.5mm. Figure 13 shows the maximum error angles associated with increasing displacement from the axis of rotation for air gaps of 0.5, 2.5, and 4.5mm.

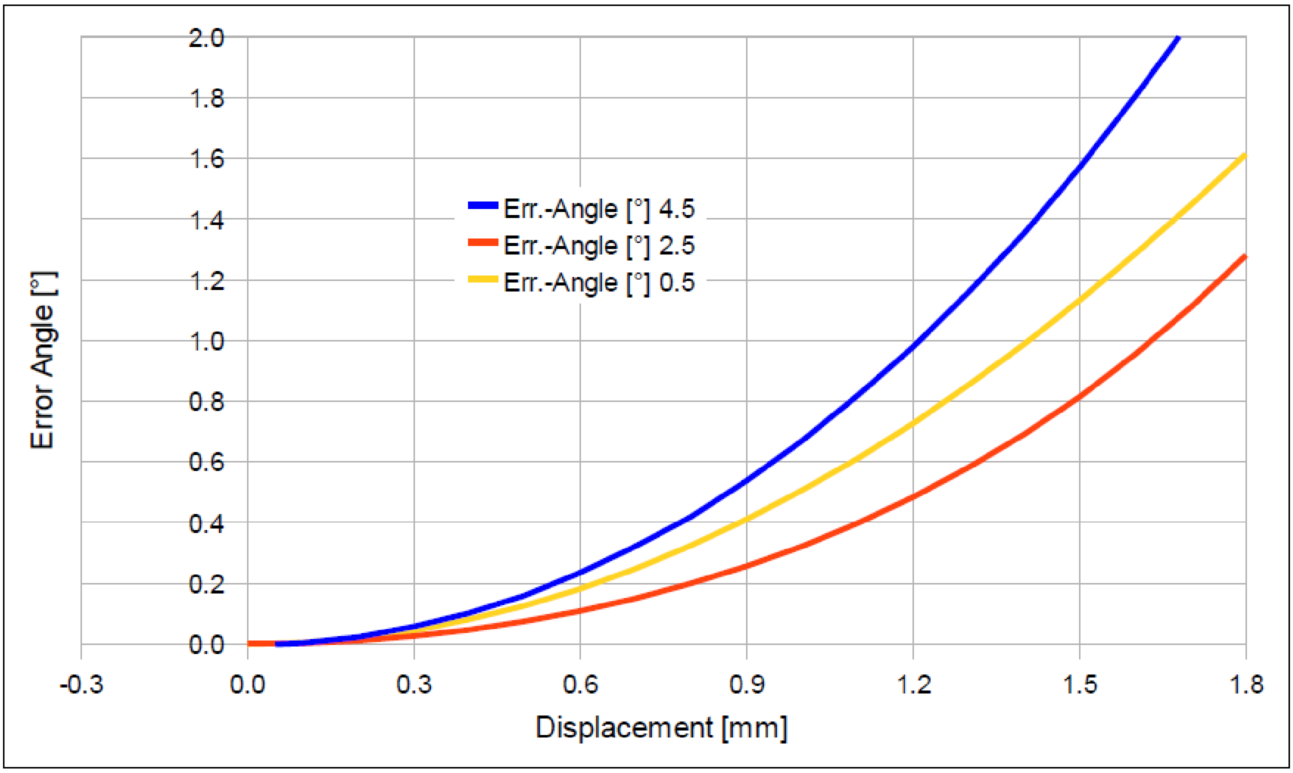

Figure 13 Maximum error angles associated with different air gaps

The quality of the magnetic field close to the surface of the disc magnet (at the minimum air gap value of 0.5mm) is not the best. Also, the flux lines diverge more and more as the air gap increases. Thus, the minimum and maximum air gap values of 0.5mm and 4.5mm reflect worst-case conditions; the optimum conditions are found between these extremes with an air gap of 2.5mm. The order of magnitude of the error angle for an air gap of 2.5mm and a maximum displacement of 1.8mm can reach about 1°. Better results can be achieved by modifying the shape of the disc magnet, but such modifications are beyond the scope of this application note.

Note: See the Infineon application note GMR-Based Angular Sensors Magnet Design for optimized magnet shape design and discussions.

The intensity of the magnetic flux density within a plane is not perfectly constant, but the variation is relatively small. The errors caused by the angle of the magnetic field are more significant than errors associated with changes in flux density, which does not vary by more than ±2mT over the specified area.

The following illustrations show the intensity of the flux density (the sum of the vectors *Bx* and *By*) for different air gap values; Figure 14 reflects an air gap of 0.5mm, Figure 15 reflects an air gap of 2.5mm, and Figure 16 reflects an air gap of 4.5mm.

As discussed with Figure 10, there is symmetry of errors around the x-axis and y-axis of the disc magnet. Thus, only the upper-right-hand quadrant of the disc is shown in Figure 14, Figure 15, and Figure 16 to magnify the details.

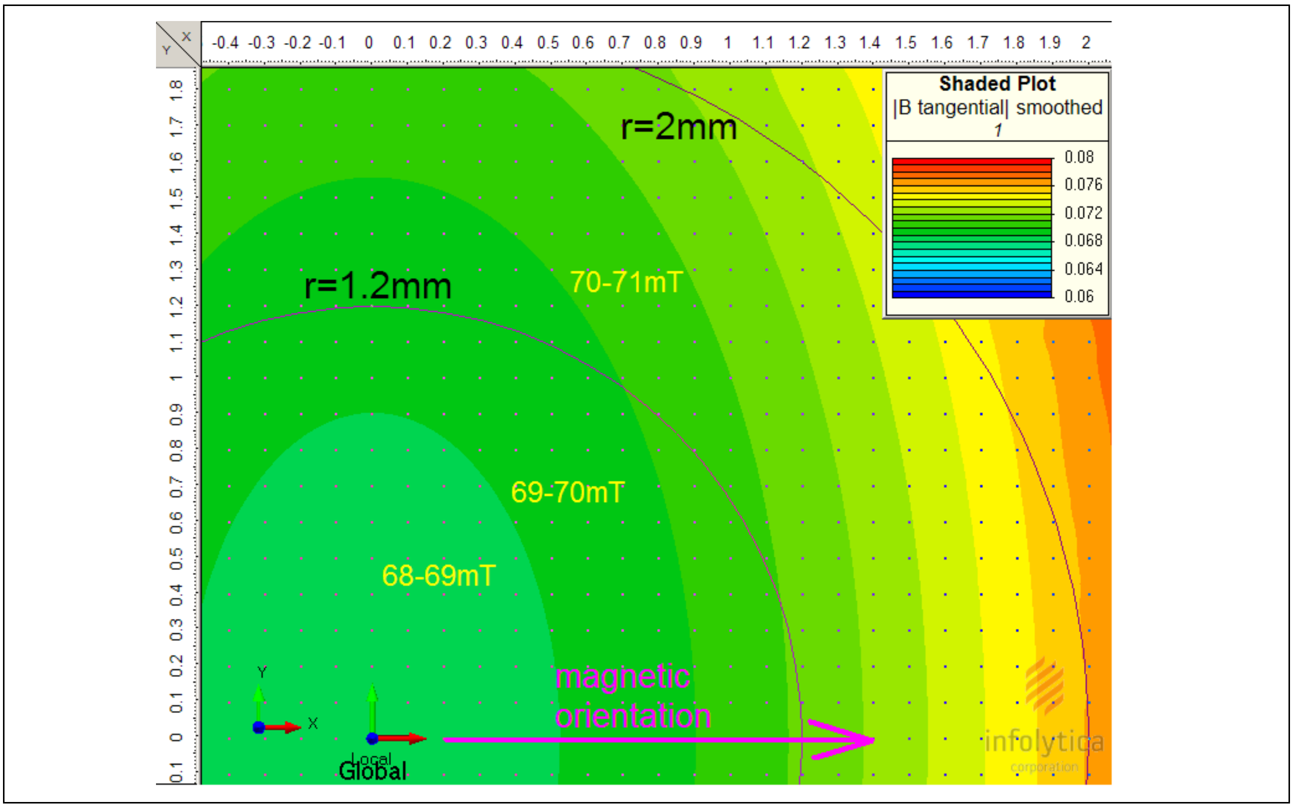

Figure 14 Distribution of tangential induction in the *Bx-By* plane with an air gap of 0.5mm

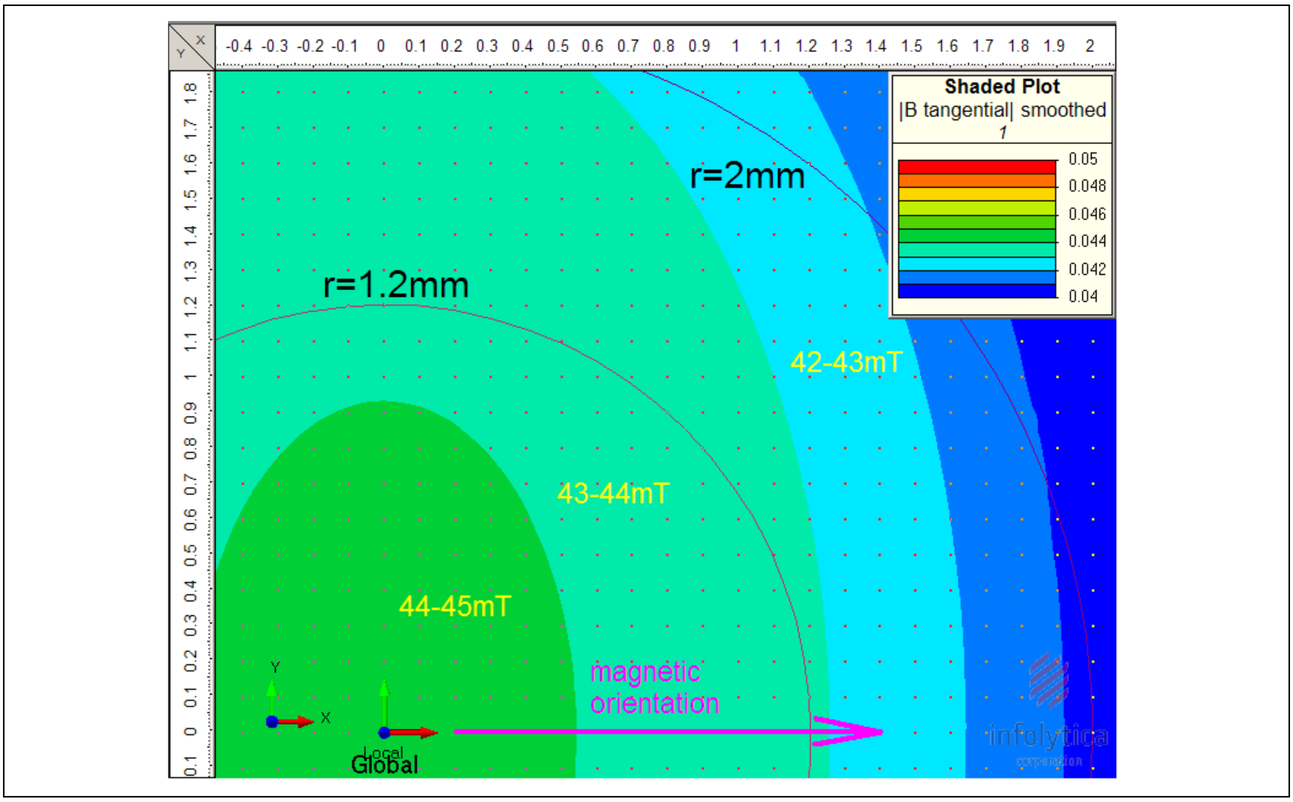

Figure 15 Distribution of tangential induction in the *Bx-By* plane with an air gap of 2.5mm

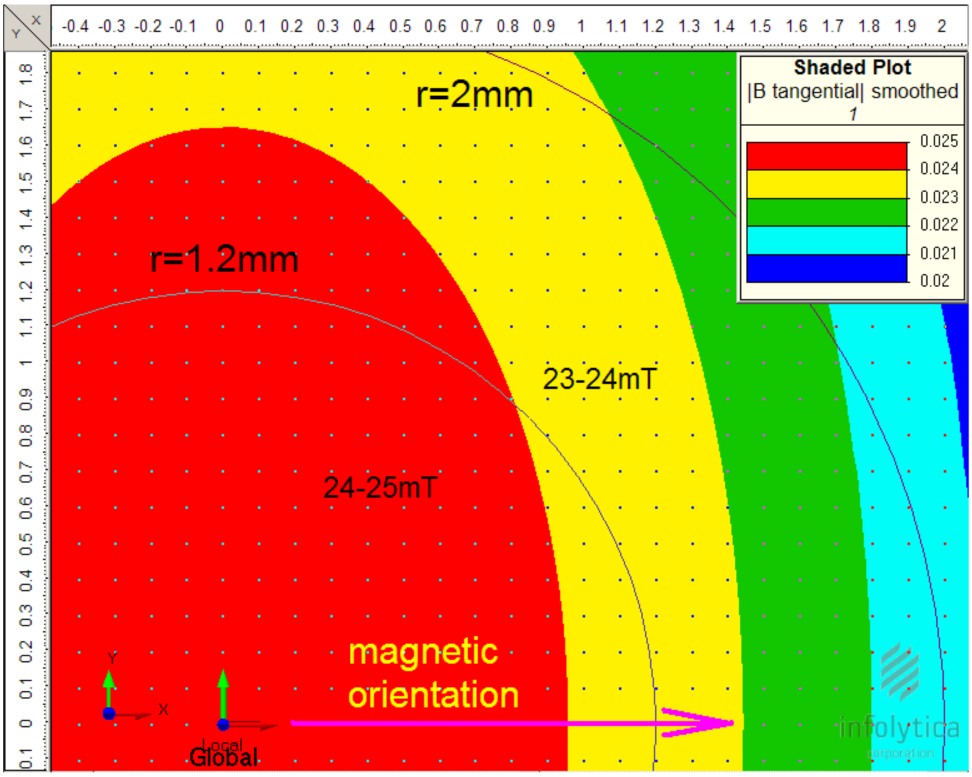

Figure 16 Distribution of tangential induction in the *Bx-By* plane with an air gap of 4.5mm

3.4.4 Flux Distribution Across the Sensor's Active Area

In Section 2.4, an assumption was made that the two GMR-sensitive areas within the sensor package have a minuscule area and that they essentially occupy a single point. However, as was illustrated in Figure 2, each GMR-sensitive area actually occupies an area of 0.3mm x 0.3mm.

Figure 13 illustrated how a significant difference in field direction may exist across the active sensor area at an elevated degree of displacement. However, the gradient across the small area of the GMR-sensitive areas is close to linear.

In order to obtain worst-case values, the center of the two GMR-sensitive areas is considered to be 1.2mm from the axis of rotation. Also, the air gap is assumed to have its maximum value of 4.5mm because this provides the maximum errors. Using these values, the *Bx*, *By*, and *Bz* magnetic components were simulated for the corners of the GMR-sensitive areas and for the center of each area as illustrated in Figure 17.

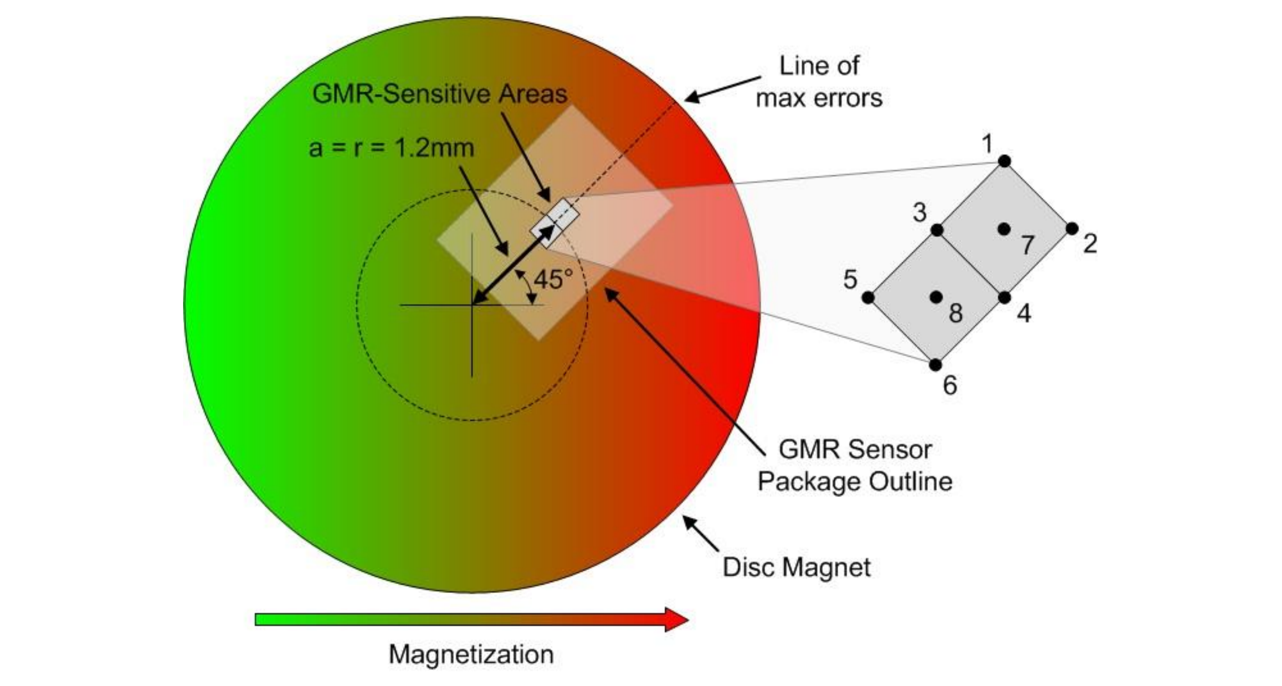

Figure 17 Configuration for evaluation of the field distribution across the two sensor areas

The results are presented in Figure 18. The “Err. simulated” column shows the error angle values for the eight points shown in Figure 17. The “Err. Averaged” column shows the error values at the center point of each GMR-sensitive area. Those values were calculated using the linear averaging of the errors associated with the four corners for each GMR-sensitive area. As can be seen, the deviation between the real values and the linear averages is negligible.

Point	Coord. x	Coord. y	Coord. z	Bx [T]	By [T]	Bz [T]	Err. simulated	Err. averaged
1	0.95	1.17	-4.5	-0.0236	0.00063	-0.0068	-0.99	
2	1.17	0.95	-4.5	-0.0233	0.00064	-0.0084	-1.00	
3	0.74	0.95	-4.5	-0.0241	0.00040	-0.0053	-0.76	
4	0.95	0.74	-4.5	-0.0239	0.00040	0.0069	-0.77	
5	0.53	0.74	-4.5	-0.0244	0.00022	0.0039	-0.48	
6	0.74	0.53	-4.5	-0.0242	0.00022	-0.0054	-0.49	
7	0.95	0.95	-4.5	-0.0237	0.00051	-0.0068	-0.89	-0.88
8	0.74	0.74	-4.5	-0.0242	0.00031	-0.0054	-0.64	-0.62

Figure 18 Error angle values associated with the sensor elements

Figure 18 shows that the gradient across each GMR-sensitive area is approximately linear. Therefore, it is only necessary to consider the center point of each GMR-sensitive area when calculating the corresponding output signal.

4 Conclusion

Infineon offers excellent GMR sensor solutions for accurate contactless 360º angle measurement. To realize the advantages of these sensors at the system level, designers must use a corresponding disc magnet that supports the technology utilized by the sensor. Designers may choose to use an off-the-shelf disc magnet or to design and build their own disc magnet. In either case, it is necessary to fully analyze the disc magnet to ensure that it will function as required.

The three main attributes to consider when selecting or creating a disc magnet are its material from which it is manufactured, its diameter, and its thickness. This application note described a specific recommended disc magnet design using sintered SmCo5 material with a *Br* value of 0.9T, a diameter of 10mm, and a thickness of 1.7mm. It also provided the information necessary to analyze alternative disc magnet designs if required. The application note provided the analysis and simulation results associated with the specified disc magnet design illustrating the increased air gap benefits of using Infineon GMR sensors. Furthermore, the application discussed the sources of errors along with mitigation techniques that can be used to address these errors.

This application note showed how, with the specified disc magnet design, the order of magnitude of the error angle for an air gap of 2.5mm and a maximum displacement of 1.8mm can reach about 1°. This ~1° of additional misalignment error is in addition to any intrinsic sensor error, so the total error might be slightly higher. Better results can be achieved by modifying the shape of the disc magnet, but such modifications are beyond the scope of this application note. Finally, the technology and accuracy discussed in this application note emphasizes why Infineon's GMR sensors offer the best solution for angular position or speed monitoring applications in the automotive, industrial control, medical, and other markets.

5 Additional Information

For further information please visit http://www.infineon.com

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