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An Integrated on-chip flux concentrator for galvanic current sensing

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***Abstract*— On-chip integration of a magnetic flux concentrator with a galvanic current sensor is proposed. Our layout utilizes a discontinuity in a magnetic via, resulting in penetration of the magnetic field into the substrate. A conversion factor of 96mT/A is predicted via simulations corresponding to a magnetic gain x1.8 in comparison to air. The permeability of the magnetic core required is 500, much lower than that reported in off-chip concentrators, resulting in a significant easing of the specifications of the material properties of the core.**

***Index Terms*—Magnetic cores, Magnetostatics, Magnetic flux leakage, Magnetic films, Soft magnetic materials, Galvanic sensors, MagFET, GaN, Smart IC, Power management IC.**

I. Introduction

On-chip current sensors are desirable components to provide inbuilt protection of power devices against current overshoot and to enhance the short circuit capability of smart power ICs. Galvanic current sensors, such as the MagFET [1] and hall-effect sensors [2], detect the magnetic field generated by current, without any direct electrical connection with the sensor. Such a non-invasive method of current monitoring is highly attractive in a wide range of applications [2].

The sensitivity of a galvanic current sensor to the magnetic field depends on the carrier mobility, hall factor and its geometry[3][4]. In this context, inherent polarization in GaN gives rise to a high density 2DEG even without the application of an external bias. Despite a bulk mobility lower than that of silicon, electrons in this 2DEG have a mobility of up to 2000 cm^2/Vs, approximately 50% higher than that in silicon [5]. This lends itself to extremely sensitive MAGFETs[6] and Hall devices [7] in GaN that are attractive on account of their compatibility with integrated CMOS drivers for power management ICs in GaN [8].

The resolution and sensitivity of a galvanic current sensor to current can be increased further by an arrangement consisting of two [3][9] or more magFETs [10][11] at the cost, however, of increasing the chip area. Therefore, increasing the magnetic field induced by the current to be sensed is more favorable and achievable either by routing the metal line around the hall device [12][13] or by a magnetic concentrator[14][15] which acts as a passive amplifier of the magnetic field.

In this letter, we propose a structure to increase the magnetic field strength in a galvanic current sensor, such as a MagFET or a Hall sensor, which relies on a combination of both the above approaches: routing a copper line around a sensor as well as a magnetic concentrator. Moreover, this structure is much easier to fabricate than a conventional inductor[16].

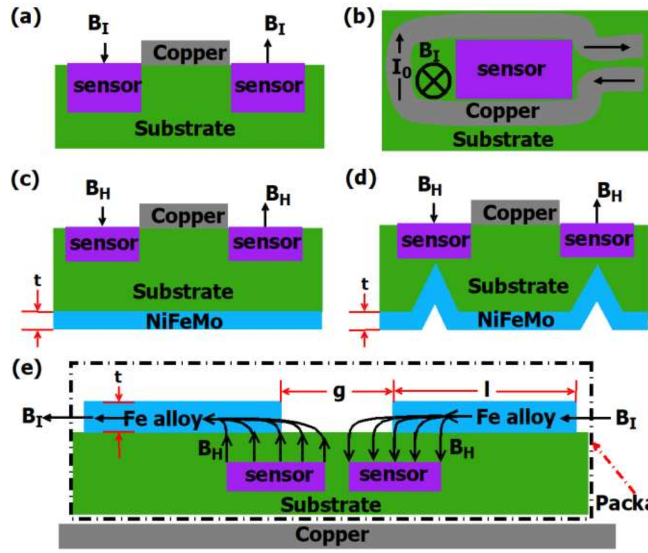

Fig. 1. Arrangement of Galvanic current sensors in on-chip implementations (a) On-chip integrated current sensor [3][10] (b) Conductor loop [13] (c) Sheet magnetic concentrator [14] (d) Tip magnetic concentrator [14]. (e) Integrated magnetic concentrator (IMC) at the top [15].

II. Background and Methodology

Fig. 1 describes implementations of conventional sensors for on-chip current sensing. In Fig. 1 (a), sensors surrounding a conductor carrying a current (I_0) to be sensed, rely on its magnetic field, (B_I), in a direction normal to the surface as [3]

$$B_I = F_I I_0 \tag{1}$$

Where, F_I the conversion factor of the structure depends on the relative position of the sensor with respect to the conductor. In Fig. 1 (b) the current circles around the sensor increasing the magnetic field, resulting in higher F_I than in Fig. 1 (a). F_I can be further improved by increasing the number of loops of the copper line around the sensor in Fig. 1 (b) [13][17]. Alternatively, a magnetic material is used to increase the field strength by concentrating the magnetic flux at the sensor in Figures 1 (c), (d), and (e). The magnetic thin film shown in Fig. 1 (c) increases the component of the magnetic field along the normal direction, whereas its tip implemented via a groove increases the flux density in Fig. 1 (d) even further. Integrated magnetic concentrators (IMC)[15], shown in Fig. 1 (e), utilize the fringing magnetic field at the edge to convert the applied

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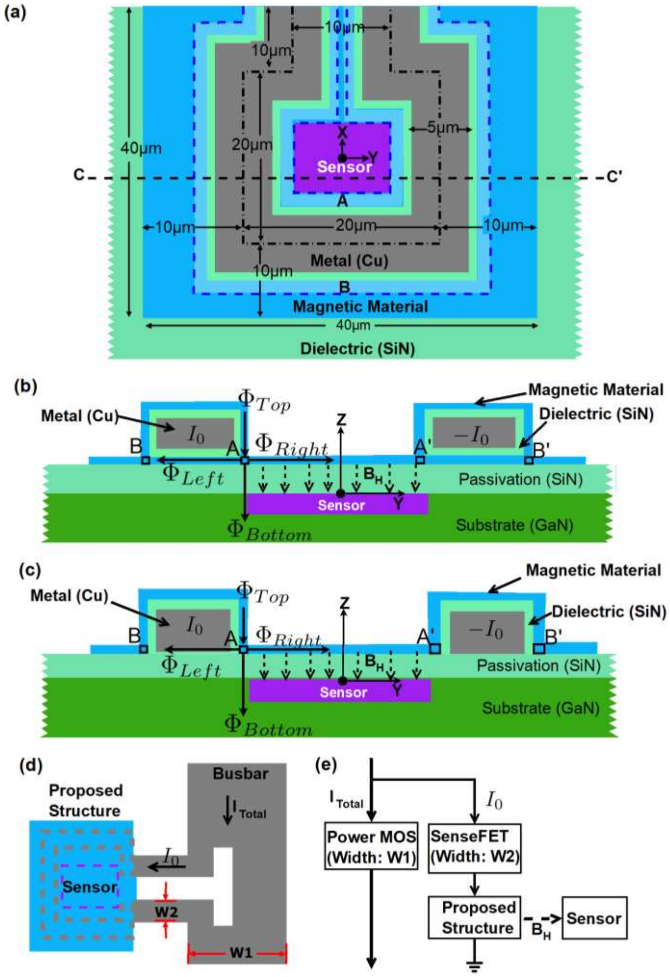

Fig. 2. (a) Top view of a loop inductor integrated with a galvanic current sensor i.e. (a MagFET or a hall-effect sensor). (b) Cross-sectional view across C-C' assuming a conventional loop inductor with magnetic film below the Cu wire (c) Cross-sectional view across C-C' of the proposed structure without magnetic film below the Cu wire. (d) A schematic of a busbar with a notch to divert a portion of the total current (I_{Total}) into the proposed structure. (e) A schematic using senseFET to divert a portion of the total current (I_{Total}) into the proposed structure.

uniform magnetic field parallel to the surface into the vertical direction. The effective conversion factor (F_c) in these cases can be expressed as

$$F_c = (B_H/I_0) = F_I G_M = (B_H/B_I)(B_I/I_0) \qquad (2)$$

Where, $G_M = B_H/B_I$, and B_H and B_I denote the normal component of the magnetic field at the sensor with and without field concentrators. G_M denotes the magnetic gain that depends on the shape and dimension of the magnetic concentrator.

In comparison to the above, we propose a novel structure in Fig. 2 (a) with an underlying sensor, in this case on a GaN substrate, which improves both F_I and G_m. Fig. 2 (b) depicts how a conventional loop inductor, with a copper line surrounded by a laminate of magnetic material or an air core, might typically be integrated with the sensor [18]. Fig. 2 (c) shows the cross-sectional view of our novel structure in which the magnetic core does not extend beneath the copper line (A-B). Φ_{Top}, Φ_{right}, Φ_{left} and Φ_{bottom} in figures 2(b) and (c) denote magnetic fluxes in the directions identified as top, right, left, and bottom, respectively, at the junction where the magnetic via meets the magnetic layer at the surface "A" identified in the figures. The magnetic field in both structures is normal to the sensor as required because of the structural symmetry around the X-Z plane. Typically a small proportion of the total current (I_{total}) to be sensed is diverted into the conductor using a busbar with a notch [19] or a SenseFET [20] shown in figures 2(d) and 2(e) respectively. In the former, a proportion of the current flowing through the loop inductor is determined by the ratio of the width of the copper in the inductor and the bus bar i.e., the ratio of the series resistance of the inductor and bus bar. In the latter case, the ratio of the widths of the SenseFET and the power device determine the proportion of current flowing through the loop inductor. In both cases, since the proportion is fixed and known, the overall current can be estimated from the measured I_0.

Two geometries of the loop inductor are compared using magnetostatic simulations in ANSYS EM suite (Maxwell) on a GaN substrate of thickness 80μm with relative permittivity and resistivity set to 9.5 and 6 Ω-cm respectively [21]. We find that the resistivity of the substrate does not affect the results within a range of 0.1-100 Ω-cm. The passivation consists of 300 nm of SiN of relative permittivity 7 [22]. The width and thickness of the copper line of the inductor are 5 and 1 μm respectively. The thickness of the magnetic film is 200 nm. Soft magnetic alloys, CoZrO, CoTaZr and CoTaZrB, which are widely considered for on-chip inductors in CMOS, have reported permeability in the range 67-83 [23], 1000 [18], and 665-1080 [22]. Their corresponding resistivity is 600Ω-cm [23], 99 Ω-cm [18], and 115 Ω-cm [22] respectively. Therefore, the permeability of the magnetic material is varied from 10 to 1080 in simulations, whereas resistivity is set to a nominal value of 100 μΩ-cm, representing the worst-case scenario for eddy current losses. The current through the inductor (I_0) is set to 20mA.

III. Results and Discussion

A change in the field distribution due to the removal of the magnetic material below the Cu wire between A and B is illustrated by a ratio of fluxes from the left, right and bottom, with respect to the flux at the top viz., $\Phi_{\mathrm{Left}}/\Phi_{\mathrm{Top}}$, $\Phi_{\mathrm{Right}}/\Phi_{\mathrm{Top}}$, and $\Phi_{\mathrm{Bottom}}/\Phi_{\mathrm{Top}}$ respectively, plotted in Fig. 3(a). In the conventional structure, as μ_r is increased, Φ_{Left}

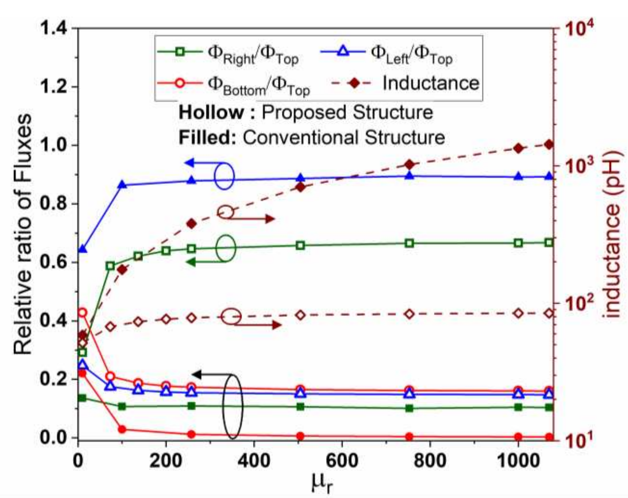

Fig. 3. The ratio of fluxes ($\Phi_{\mathrm{right}}/\Phi_{\mathrm{Top}}$, $\Phi_{\mathrm{left}}/\Phi_{\mathrm{Top}}$, and $\Phi_{\mathrm{bottom}}/\Phi_{\mathrm{Top}}$) and inductance of the proposed and conventional structures versus μ_r.

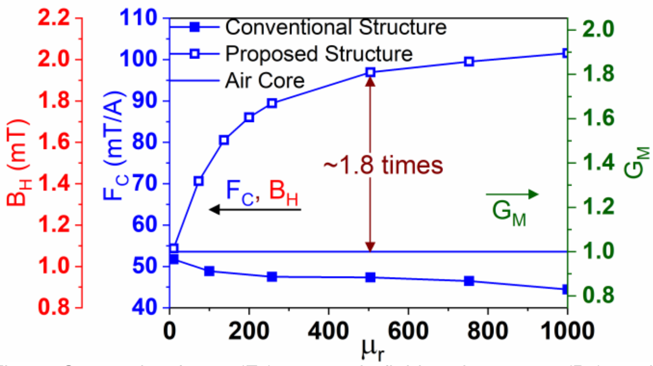

Fig. 4. Conversion factor (F_C), magnetic field at the sensor (B_H), and magnetic gain (G_M) of the conventional, air core, and proposed structures versus permeability.

increases at the expense of Φ_{Bottom}, and saturates beyond μ_r =200. For μ_r>200, most of the flux induced by the current I_0 is concentrated within the magnetic material with nearly 90% looping around the copper winding, resulting in an increase of inductance with μ_r while only 10% leaks into the magnetic film between the conductors. This is because the magnetic material around the metal layer offers a low reluctance path to the field lines through the copper with very little available to the underlying sensor. On the other hand, in the proposed structure, due to the presence of the magnetic material on the right coupled with an absence of magnetic material between A-B causes the field distribution to shift towards the right and bottom as evident from Fig. 3; Φ_{Bottom} and Φ_{Right} are 80% of Φ_{Top} showing an opposing distribution of the field. Φ_{Bottom} is still a considerable percent (at least 18%) of the overall flux induced in the magnetic via (Φ_{Top}) for all values of μ_r. Hence, the magnetic field in the substrate is enhanced by the current flowing through the copper as well as field penetration at the discontinuity A-B for all values of μ_r.

Conversion factors (F_c) of the conventional, proposed and air core structures with the permeability of the magnetic material are plotted in Fig. 4, indicating an increase of G_m, and thereby F_c, of the proposed structure by the factor of 1.8. On the other hand, F_c of the conventional structure reduces from 52mT/A to 45 mT/A.

Table I shows an improvement in the conversion factor of our structure in comparison to reported structures also evaluated via simulation alone, by a factor of 12. The major drawback of the tip and sheet concentrator is the fabrication processing required at the bottom surface of the substrate including substrate thinning. The IMC requires a large chip space (in the range of mm) and thicker magnetic material, typically in the range of 20um, ideally equal to gap marked as "g" in Fig. 1 (e), in the magnetic material near the sensor. The permeability of the magnetic material should be greater than 1500 and a minimum length is 250um to achieve G_m of 1.5 [25]. On the other hand, the proposed structure achieves a gain of 1.8 at a fraction ($\sim\frac{1}{60}$) of chip space and much lower permeability. Another major drawback of the IMC is a requirement of a constant B field to be applied throughout requiring the width of the conductor to be of a similar order as that of the IMC.

Even though IMCs achieve higher G_m than other structures,

TABLE I
A COMPARISON OF THE CONVERSION FACTOR FROM THIS WORK WITH REPORTED LITERATURE

structure	Ref.	F_I (mT/A)	G_M	F_c (mT/A)	μ_r	t (um)
Magnetic sheet	[14]	0.05-0.1	1.5	0.075-0.15	~2x10^4	1.5
Tip concentrator	[14]	0.05-0.1	3*	0.15-0.3	~2x10^4	1.5
On-chip Metal line	[10]	4.95	--	4.95	--	--
	[3]	8	--	8	--	--
Integrated Magnetic concentrator	[15][(a)]	--	5*	--	~10^4	20
	[24][(b)]	--	21	--	10^5	22
	[25][(c)]	0.02-0.5[26]*	8*	0.16-4	>1500	20
Proposed Structure	**This work[(d)]**	**53.7**	**1.8**	**96.6**	**>500**	**0.2**

*experimental [(a)] Tanga shape; Length:1.1mm; width:0.5mm [(b)] Tanga shape; Length:2mm; Width:1mm [(c)] Two Circular IMCs; diameter: 1mm. [(d)] Square shape; Length:40um; Width:40um

they suffer from low F_I because they are designed to measure the current in off-chip conductors. The proposed structure and on-chip metal line perform better because the current conductor is separated from the B sensor by passivation alone. It is to be emphasized that the proposed structure is intended only for on-chip current detection, whereas the IMC is also versatile in angular sensing, e-compass, position sensing.

IV. Conclusion

This work demonstrates a method to improve the detection limit of a current sensor and its sensitivity in a form factor that is compact and can be easily integrated. The magnetic gain 1.8 is achieved with the permeability as low as 500 via simulations, much lower than other flux concentrators reported by simulation, requiring less stringent specifications on the magnetic material. This is mainly due to the way by which a portion of the field induced in the magnetic material is diverted into the substrate via a combination of the current conductor and the magnetic film. This combination is unsuitable for high inductance structures but works well for sensors by diverting the field into the substrate to improve the sensitivity.

References

[1] Bin Xue and D. M. H. Walker, "Built-in current sensor for IDDQ test," in *Proceedings. 2004 IEEE International Workshop on Current and Defect Based Testing (IEEE Cat. No.04EX1004)*, 2001, pp. 3–9. DOI: 10.1109/DBT.2004.1408945.

[2] J. Lenz and S. Edelstein, "Magnetic sensors and their applications," *IEEE Sens. J.*, vol. 6, no. 3, pp. 631–649, Jun. 2006. DOI: 10.1109/JSEN.2006.874493.

[3] O. Aiello and F. Fiori, "A new MagFET-based integrated current sensor highly immune to EMI," *Microelectron. Reliab.*, vol. 53, no. 4, pp. 573–581, Apr. 2013. DOI: 10.1016/j.microrel.2012.10.013.

[4] H. Lu, P. Sandvik, A. Vertiatchikh, J. Tucker, and A. Elasser, "High temperature Hall effect sensors based on AlGaN/GaN heterojunctions," *J. Appl. Phys.*, vol. 99, no. 11, p. 114510, Jun. 2006. DOI: 10.1063/1.2201339.

[5] M. Shur, B. Gelmont, and M. Asif Khan, "Electron mobility in two-dimensional electron gas in AIGaN/GaN heterostructures and in bulk GaN," *J. Electron. Mater.*, vol. 25, no. 5, pp. 777–785, May 1996. DOI: 10.1007/BF02666636.

[6] P. Igic, N. Jankovic, J. Evans, M. Elwin, S. Batcup, and S. Faramehr, "Dual-Drain GaN Magnetic Sensor Compatible With GaN RF Power Technology," *IEEE Electron Device Lett.*, vol. 39, no. 5, pp. 746–748, May 2018. DOI: 10.1109/LED.2018.2816164.

[7] T. P. White, S. Shetty, M. E. Ware, H. A. Mantooth, and G. J. Salamo, "AlGaN/GaN Micro-Hall Effect Devices for Simultaneous Current and Temperature Measurements From Line Currents," *IEEE Sens. J.*, vol. 18,

no. 7, pp. 2944–2951, Apr. 2018. DOI: 10.1109/JSEN.2018.2794264.

[8] A. Kumar and M. M. De Souza, "An E-Mode p-Channel GaN MOSHFET for a CMOS Compatible PMIC," *IEEE Electron Device Lett.*, vol. 38, no. 10, pp. 1449–1452, 2017. DOI: 10.1109/LED.2017.2747898.

[9] M. Donoval, M. Daricek, J. Marek, and V. Stopjakova, "Power devices current monitoring using horizontal and vertical magnetic force sensor," in *2009 12th International Symposium on Design and Diagnostics of Electronic Circuits & Systems*, 2009, pp. 124–127. DOI: 10.1109/DDECS.2009.5012111.

[10] F. C. Castaldo, P. Rodrigues, and C. A. Reis Filho, "Shunt-zero based on CMOS split-drain: A practical approach for current sensing," *IEEE Annu. Power Electron. Spec. Conf.*, vol. 2005, no. 3, pp. 1745–1749, 2005. DOI: 10.1109/PESC.2005.1581866.

[11] G. Busatto, R. La Capruccia, F. Iannuzzo, F. Velardi, and R. Roncella, "MAGFET based current sensing for power integrated circuit," *Microelectron. Reliab.*, vol. 43, no. 4, pp. 577–583, 2003. DOI: 10.1016/S0026-2714(03)00024-6.

[12] N. Jankovic, O. Kryvchenkova, S. Batcup, and P. Igic, "High Sensitivity Dual-Gate Four-Terminal Magnetic Sensor Compatible With SOI FinFET Technology," *IEEE Electron Device Lett.*, vol. 38, no. 6, pp. 810–813, Jun. 2017. DOI: 10.1109/LED.2017.2693559.

[13] M. Donoval, M. Daricek, V. Stopjakov, and D. Donoval, "Magnetic Fet – Based on – Chip Current Sensor for Current Testing of Low – Voltage Circuits," *J. Electr. Eng.*, vol. 59, no. 3, pp. 122–130, 2008.

[14] R. Steiner, M. Schneider, F. Mayer, U. Munch, T. Mayer, and H. Baltes, "Fully packaged CMOS current monitor using lead-on-chip technology," in *Proceedings MEMS 98. IEEE. Eleventh Annual International Workshop on Micro Electro Mechanical Systems. An Investigation of Micro Structures, Sensors, Actuators, Machines and Systems*, 1998, pp. 603–608. DOI: 10.1109/MEMSYS.1998.659826.

[15] H. Blanchard, L. Chiesi, R. Racz, and R. S. Popovic, "Cylindrical Hall device," in *International Electron Devices Meeting. Technical Digest*, 1996, pp. 541–544. DOI: 10.1109/IEDM.1996.554041.

[16] D. S. Gardner, G. Schrom, F. Paillet, B. Jamieson, T. Karnik, and S. Borkar, "Review of on-chip inductor structures with magnetic films," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4760–4766, 2009. DOI: 10.1109/TMAG.2009.2030590.

[17] A. Ajbl, M. Pastre, and M. Kayal, "A fully integrated hall sensor microsystem for contactless current measurement," *IEEE Sens. J.*, vol. 13, no. 6, pp. 2271–2278, 2013. DOI: 10.1109/JSEN.2013.2251971.

[18] D. S. Gardner, G. Schrom, P. Hazucha, F. Paillet, T. Karnik, and S. Borkar, "Integrated on-chip inductors with magnetic films," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2615–2617, 2007. DOI: 10.1109/TMAG.2007.893794.

[19] Allegro MicroSystems LLC, "Application note 295045: Application Information Recent Trends in Hall Effect Current Sensing." pp. 1–7, 2013.

[20] P. Igic, O. Kryvchenkova, S. Faramehr, S. Batcup, and N. Jankovic, "High sensitivity magnetic sensors compatible with bulk silicon and SOI IC technology," in *Proceedings of the International Conference on Microelectronics*, 2017, pp. 55–59. DOI: 10.1109/MIEL.2017.8190068.

[21] R. K. Crouch, W. J. Debnam, and A. L. Fripp, "Properties of GaN grown on sapphire substrates," *J. Mater. Sci.*, vol. 13, no. 11, pp. 2358–2364, Nov. 1978. DOI: 10.1007/BF00808049.

[22] K. Koh, D. S. Gardner, C. Yang, K. P. O'brien, N. Tayebi, and L. Lin, "High frequency microwave on-chip inductors using increased ferromagnetic resonance frequency of magnetic films," in *28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, 2015, pp. 208–211. DOI: 10.1109/MEMSYS.2015.7050923.

[23] P. Dhagat, S. Prabhakaran, and C. R. Sullivan, "Comparison of Magnetic Materials for V-groove Inductors in Optimized High-Frequency DC-DC Converters," *IEEE Trans. Magn.*, vol. 40, no. 4, pp. 2008–2010, 2004. DOI: 10.1109/TMAG.2004.832480.

[24] P. M. Drljača, F. Vincent, P. A. Besse, and R. S. Popovic, "Design of planar magnetic concentrators for high sensitivity Hall devices," *Sensors Actuators, A Phys.*, vol. 97–98, pp. 10–14, 2002. DOI: 10.1016/S0924-4247(01)00866-4.

[25] C. Schott and S. Huber, "Modern CMOS hall sensors with integrated magnetic concentrators," in *Lecture Notes in Electrical Engineering*, vol. 21, S. C. Mukhopadhyay and Y.-M. Huang, Eds. Berlin: Springer, 2008, pp. 3–21. DOI: 10.1007/978-3-540-69033-7_1.

[26] R. S. Popovic and C. Schott, "Hall ASICs with Integrated Magnetic Concentrators." GMW Associates, San Carlos, California, USA, Tech. Report. TN Hall IMC, pp. 1–12, 2002.