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High-Accuracy Teslameter with Thin Three-Axis Hall Probe

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***Abstract* – The new digital teslameter system incorporates a 3-axis Hall probe, analog electronics based on the spinning-current technique, 24-bit analog-to-digital converter, computer, and 7-digit touch-screen display. The Hall probe is a single silicon chip with monolithically integrated horizontal and vertical Hall magnetic sensors and a temperature sensor. The Hall sensor chip is encapsulated in a robust ceramic package, a version of which is only 250µm thick. The spinning-current eliminates most of the Hall probe offset, low-frequency noise, and the planar Hall voltage. The errors due to the Hall element non-linearity and the variations in the probe electronics temperatures are eliminated by a calibration procedure based on a three-variable second-order polynomial. The errors due to the angular errors of the Hall probe are eliminated by a calibration of the sensitivity tensor of the probe. These new developments resulted in a teslameter that can measure magnetic field vectors from about 1µT to 30T, with the spatial resolution 100 µm, magnetic resolution ±2ppm of the range, the accuracy ±0.0001% of reading + 0.001% of range, temperature coefficient less than 5ppm/°C, and angular errors less than 0.1°.**

Keywords - Gaussmeter, teslameter, magnetic measurement, three-axis Hall probe, thin Hall probe

I. INTRODUCTION

Hall-effect-based teslameters are currently the mostly applied instruments for measuring DC and AC magnetic flux densities in the range from about 1mT to about 30T. The best published characteristics of modern Hall teslameters include the resolution as high as 0.1ppm (typically not batter than several ppm) and the accuracy of up to 50ppm of the measurement range. Though, the measurement accuracy of a teslameter is usually strongly deteriorated by temperature variations, at AC measurement conditions, and when measuring non-homogeneous magnetic fields.

Modern science and industry have steadily increased need in accurate measurement of highly non-homogeneous magnetic fields. This trend introduces a number of additional requirements for good teslameters, particularly for their Hall probes. The additional requirements include the following:

a) Small and compact sensitive volume of the Hall probe, which allows for high spatial resolution of the magnetic measurement;
b) (Often) The necessity to measure all three components of a magnetic field simultaneously at the same spot;
c) Small overall dimensions of the probe, so that it can be inserted into a small space, such as a narrow air gap between the poles of a magnet;
d) Accurate spatial positioning of the probe with respect to a coordinate system;
e) Accurate angular positioning of the probe with respect to a coordinate system;
f) High degree of conformity of the sensitivity vector(s) of the probe with the axes of the coordinate system;
g) No planar Hall effect;
h) High frequency response.

The importance of the requirements (a), (c) and (d) is obvious for accurate measurement and mapping of non-homogeneous magnetic fields. The requirements (b) and (e) to (g) are related to the fact that the magnetic field is a divergence-free vector field; therefore, in a non-homogeneous magnetic field, not only the amplitude, but also the orientation of the magnetic flux density vector is position-dependent; therefore, all three components of the magnetic field should be measured at the same spot and with respect to a well-defined coordinate system. In particular, the requirement (g) is needed for the measurement of a small component of a strong magnetic field vector. The requirement (h) shall enable a rapid scanning of a non-homogeneous magnetic field.

The above requirements are either poorly met or simply neglected in most of the commercially-available teslameters.

In this paper, we present a novel Hall teslameter, which features not only among the best conventional characteristics, including high magnetic resolution, high accuracy and low temperature dependence, but also meets to a high degree all the above additional requirements.

II. NOVEL THREE-AXIS HALL PROBE CHIP

The requirements (a) and (b) of Section I are met by integrating miniaturized horizontal and vertical Hall

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devices (see, for example, [1]) on a square 100µm by 100µm of a single silicon chip, Figs. 1 and 2.

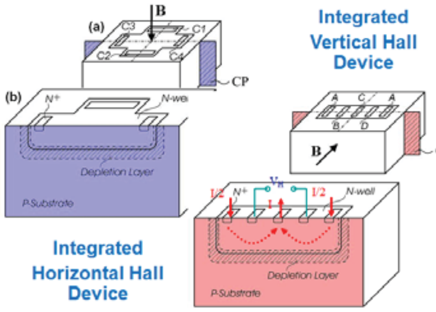


Fig. 1. Integrated horizontal (left) and vertical (right) Hall devices in a single silicon chip.

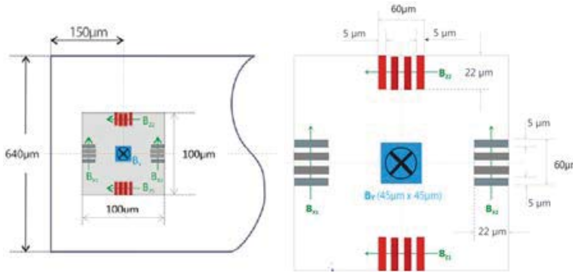


Fig. 2. The spatial distribution of the Hall devices of Fig. 1 on the Hall probe chip. The novel SENIS integrated Hall probes have the magnetic field sensitive volume) of 100µm x 10µm x 100µm (By: 45µm x 5µm x 45µm; Bx and Bz: 100µm x 10µm x 100µm).

The structures of the Hall devices are similar to that, previously published [2]. But the latest generation of the SENIS' CMOS integrated Hall devices is much improved; it features a voltage-related magnetic sensitivity of about 0.04V/VT and low flicker noise, which allows a near-to-physical-limit magnetic resolution [3], Fig. 3.

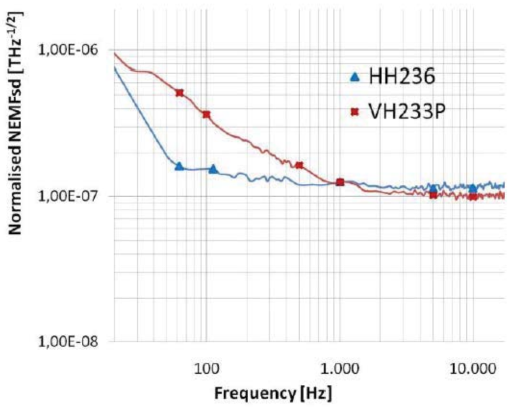


Fig. 3. Measured noise-equivalent magnetic field spectral density of the SENIS' Hall devices [4] implemented in 0.35µm CMOS technology, normalized to biasing power of 1mW. HH236: horizontal Hall device (SV = 0.038T^{-1}, R = 3kΩ); VH233P: vertical Hall device (SV = 0.043T^{-1}, R = 1.9kΩ); Bias voltage (both): 1V. The sensitivity of both, horizontal and vertical Hall devices approaches the physical limits of silicon Hall magnetic sensors.

For each measurement axis, eight equal parallel-connected Hall devices are used, as illustrated in Fig. 2. With reference to Fig. 3, this allows reducing the noise-equivalent magnetic field spectral density of the thermal noise of each group of Hall devices to about 40nT/√Hz.

A temperature sensor, which is also integrated on the Hall probe chip, enables an efficient temperature compensation of the influences of the probe temperature.

III. ULTRA-THIN CERAMIC PACKAGE OF THE PROBE

The package materials around the silicon Hall IC die shall meet the requirements (c) to (e) of Section I. Moreover, it shall be non-magnetic, rigid, shall have thermal expansion coefficient similar to that of silicon and shall be electrically isolating but still a good thermal conductor; and it shall have no thick and/or large metalized layers (to avoid eddy currents) and shall be nontransparent. SENIS developed a few new ceramic probe cases that meet all that requirements– see Figs. 4-6.

Fig. 4a. Photograph of the standard ceramic package of SENIS three-axis Hall probes. This package is suitable for the temperature range -55°C to +155°C.

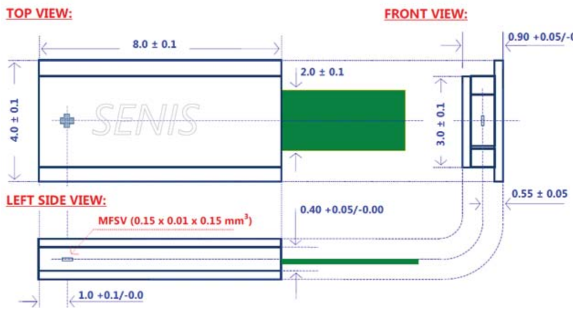


Fig. 4b. The dimensions of standard ceramic package of SENIS three-axis Hall probes (length x width x thickness): 8.0mm x 4mm x 0.9mm.

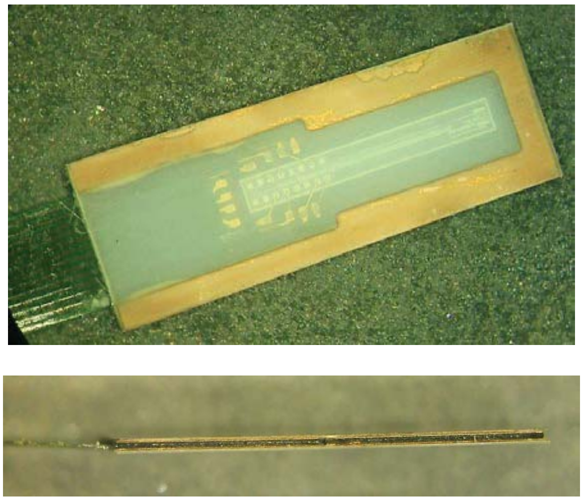


Fig. 5a. Photograph of the ultra-thin ceramic package of SENIS three-axis Hall probes. The dimensions (length x width x thickness): 8.0mm x 3mm x 0.25mm. This Hall probe is suitable for the industrial temperature range - from -20°C to +85°C.

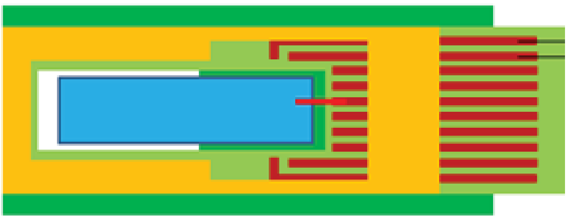


Fig. 5b. Structure of the ultra-thin SENIS ceramic package for three-axis Hall probes: the bottom and the cover plate are 40µm thin machinable ceramic plates. The substrate is a 100µm flex-PCB. The sensor IC die is Si CMOS IC, 50µm thin, with 20µm bonding wire loops.

The ceramic package helps achieve fairly uniform temperature within the enclosure of the Hall IC die; and provides for a stable positioning and referencing of the Hall probe for magnetic field mapping.

The Hall probe is connected with the electronics module via a 2m (or longer) thin and flexible cable.

IV. ELECTRONICS FOR BIASING, SIGNAL CONDITIONING, AND A/D CONVERSION

The analog front-end part of the electronics of the new teslameter is based on the earlier developed SENIS low-noise magnetic field-to-analogue-voltage transducer [4], Fig. 6. A thoroughly optimized “spinning current” method is applied to efficiently cancel offset, 1/f noise, and the planar Hall voltage (requirement (g) of Section I). The analog electronics provides at its output a high-level differential signal for each of the three components of the measured magnetic field. The bandwidth (-3dB) of the analog signal conditioning module can be as high as 4kHz (requirement (h) of Section I). A temperature sensor is incorporated in the electronic module and measures its local temperature.

Fig. 6. SENIS Low-Noise magnetic field-to-analogue-voltage Transducer[4].

Fig. 7 shows the low-frequency noise and short-term drift of the analog front-end part of the teslameter. The drift is due to a temperature change during the measurement. The temperature dependence of the offset, as well as other imperfections of the raw transducer signal are corrected by the software of the teslameter.

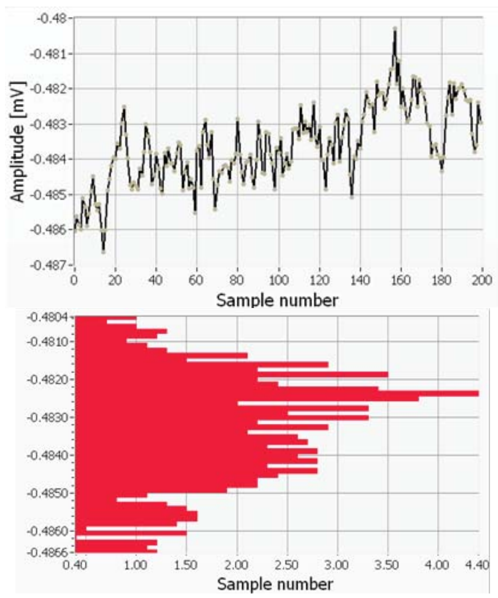


*Fig. 7. The graphs show the offset fluctuation of the SENIS Low Noise Transducer, with the Hall probe placed in a Zero Gauss Chamber, over a time period of 10 seconds. The upper graph shows the offset in the time domain and the lower graph shows the related histogram. The sensitivity of the transducer is 1.25V/T and full scale 2T (FS). The measured fluctuation is 5µVp-p. This corresponds to the magnetic resolution (5µVp-p/1.25V/T)/2T =***2ppm***(p-p)(FS).*

A digital module is added to the analog transducer to form the digital Teslameter, Fig. 8. The digital module incorporates a 24-bit analog-to-digital converter, computer with dedicated software for signal treatment, display; and provides the possibility of automatic data acquisition via a USB serial interface by a host computer.

Fig. 8. SENIS High-Accuracy Teslameter with a very thin three-axis Hall Probe encapsulated in ceramic package

V. EMBEDDED SOFTWARE

All other functions of the teslameter, including the digital signal treatment, calibration, calculations, analysis of the measurement results, interface with the user and communication, are fulfilled by the embedded software of the teslameter.

High measurement accuracy of each of the components of a magnetic field is enabled by the software module, which, based on the calibration data, corrects the nonlinearity and temperature coefficients of the whole measurement system, including the Hall probe, analog signal conditioning, and A/D converter.

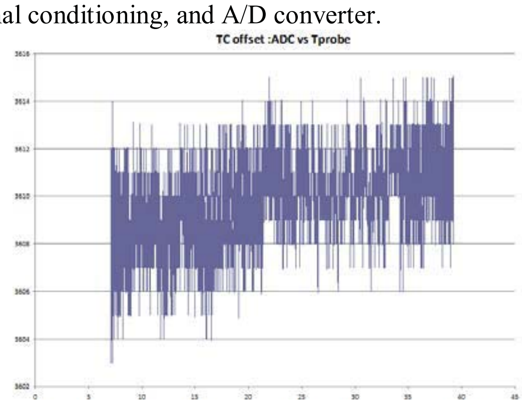


Fig. 9. The graph shows the AD-convertor (ADC) reading during the Hall probe temperature change in the range of 30°C. The change is 6LSB (least significant bits), which corresponds to the temperature coefficient (TC) related to the Hall probe temperature of 0.1µV/°C. The TC related to the electronic module of Teslameter is.0.5µV/°C.

A. Correction of non-linearity and influence of temperature

The problems to be solved are illustrated in Figs. 7 (upper part), 9 and 10 (upper part). The hardware means for temperature compensation, applied in SENIS analog magnetic transducers, are efficient only in a limited magnetic measurement range [5], since the temperature coefficients vary with the measured magnetic field.

The new teslameter corrects the nonlinearity error and the temperature influences in the following way:

- The Hall voltage is a function of three independent variables – of the measured magnetic field *B*, the temperature of the Hall probe *Th*, and the temperature of the electronics *Te*. The function *Vh*(*B, Th, Te*) is approximated by a polynomial function of 2nd degree, which corresponds to the first 10 terms of a Taylor series:

$$\begin{aligned} Vh(B, Th, Te) \approx\ & C0 \\ & + C1\,(B - B0) + C2\,(Th - Th0) + C3\,(Te - Te0) \\ & + C4\,(B - B0)^2 + C5\,(Th - Th0)^2 + C6\,(Te - Te0)^2 \\ & + C7\,(B - B0)(Th - Th0) + C8\,(B - B0)(Te - Te0) \\ & + C9\,(Th - Th0)(Te - Te0) \qquad (1) \end{aligned}$$

where *B0*, *Th0*, and *Te0* are the coordinates of a point in the (*B, Th, Te*) - space around which the approximation (1) is valid.

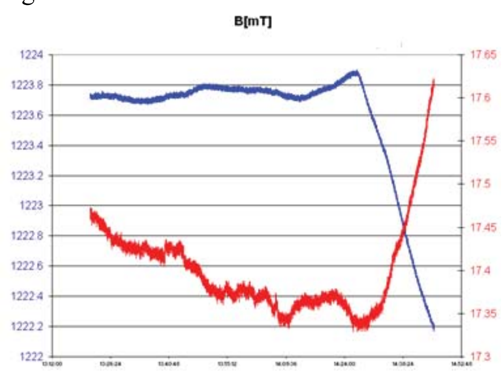
- During the calibration of the teslameter, the teslameter’s probe and the electronics are exposed to 10 different sets of the variables *B, Th, Te*, near the point (*B0, Th0, Te0*), and the each resulting function *Vh* is measured. These values are substituted in Eq. (1); so a set of 10 linear equations with 10 unknowns (the coefficients C0, C1, …, C9 of (1)) are obtained and then solved.

- In the application of the teslameter, the instantaneous values of the variables *Vh, Th, Te* are measured, and then substituted into Eq. (1). Since now all other parameters in (1) are known, (1) reduces to a quadratic equation with one unknown (*B*):

$$a\,B^2 + b\,B + c = 0 \qquad (2)$$

The real and reasonable solution of this equation is the final result of the measurement of a component *B* of a magnetic field.

The result of this procedure is an (almost) temperature-independent correction of all nonlinearities, which enables a measurement accuracy of quasi DC magnetic field better than 50ppm. This is illustrated in Fig. 10.



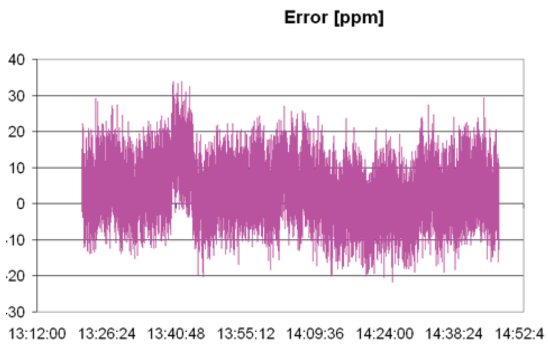


Fig. 10. The upper graph shows the magnetic field measured by SENIS Teslameter, which strictly follows the temperature changes. The lower graph shows the measurement error (in ppm) that remains very stable in spite of the temperature range.

B. Correction of angular errors of the probe

To the first approximation, the Hall voltage of a single Hall element is given by the scalar product

$$Vh \approx \boldsymbol{S} * \boldsymbol{B} \qquad (3)$$

where $\boldsymbol{S}$ denotes the sensitivity vector of the Hall element, and $\boldsymbol{B}$ denotes the magnetic flux density vector. For a three-axis Hall probe, Eq. (3) can be generalized to

$$\boldsymbol{Vh3} \approx [\boldsymbol{S}] * \boldsymbol{B} \qquad (4)$$

where $\boldsymbol{Vh3}$ denotes "the Hall voltage vector" (a list of the three output voltages of the three-axis Hall probe); and $[\boldsymbol{S}]$ is the probe's sensitivity tensor, a 2^{nd} order tensor, whose 9 components consist of the components of the sensitivity vectors of the Hall elements for the x, y, and z axis. Ideally, the sensitivity tensor of a 3-axis Hall probe should have the form

$$[\boldsymbol{S'}] = S\,[\boldsymbol{I}] \qquad (5)$$

where S denotes the probe's sensitivity magnitude (equal for all three axis), and $[\boldsymbol{I}]$ denotes the identity (unit) 3x3 matrix.

The Hall sensor dice cannot be glued to the probe substrate so as to be perfectly parallel with the reference plane and edges of the probe package; moreover, the sensitivity vectors of the integrated 3-axis Hall magnetic sensors are not perfectly oriented with respect to the dice planes and edges. The resulting accumulated angular errors of the Hall probe sensitivity vectors with respect to the probe package reference axes is of the order of 1°, which does not comply with the requirement (f) of Section I. The angular errors of about 1° produce the off-diagonal terms of about 0.02 in what should be identity matrix $[\boldsymbol{I}]$ of Eq. (5).

The teslameter corrects the probe's angular errors in the following way:

- During the calibration of the teslameter, the teslameter's probe is placed at 3 precisely known angular positions in the magnetic field $\boldsymbol{B}$ with precisely known components; and Hall output voltages $\boldsymbol{Vh}$ are read. These values are substituted in Eq. (3); so, for each sensitivity axis, a set of 3 linear equations with 3 unknowns (the components of the sensitivity vector) are obtained; which is then solved. This gives all 9 components of the sensitivity tensor $[\boldsymbol{S}]$. The sensitivity tensor, taken as a matrix, is then inverted, and the inverse matrix $[\boldsymbol{S}]^{-1}$ is stored in the teslameter's memory.
- In the application of the teslameter, the instantaneous values of the components of the "vector" of the Hall voltages $\boldsymbol{Vh3}$ are measured. With reference to Eq. (4), the measured magnetic field vector is then calculated as

$$\boldsymbol{B} = [\boldsymbol{S}]^{-1} * \boldsymbol{Vh3} \qquad (6)$$

By this procedure, the effective angular errors of the Hall probe can be reduced to below 0.1°, and so the requirement (f) of Section I is met.

VI. OTHER FEATURES, SUMMARY OF PERFORMANCE, AND CONCLUSION

The high-accuracy teslameter with three-axis Hall probe can measure magnetic fields in the range of about a µT up to 30T. The measurement ranges are selectable and the auto-range option is available. The Hall probes are equipped with an EEPROM for storing the probe calibration data, which makes the probes interchangeable on a running teslameter. The teslameter also provides the analog outputs - three differential voltages that are proportional to the three components of the measured magnetic flux density and a single-ended voltage output that is proportional to the chip temperature.

A user can easily integrate a measurement routine into its measurement system while using its programming tools such as Basic, C, C++, LabVIEW, etc.

The magnetic resolution is ±2ppm of the range and the magnetic field measurement accuracy is ±0.0001% of reading + 0.001% of range. The probe can measure the magnetic fields with the highest resolution in the bandwidth from dc to 10Hz; and with a slightly lower resolution up to 1kHz; and further up to 4kHz.

The compensation of temperature drifts and nonlinearities are very efficient due to the use of the voltage signal that is proportional to the real probe and electronics temperatures. The probe temperature resolution is 0.001°C. The temperature compensation method, implemented in the digital module of the teslameter allows a temperature coefficient of sensitivity less than 5ppm/°C and a temperature coefficient of the offset of ±0.1µT/°C. The long-term instability of sensitivity is less than 1% over 10 years of operation.

The performance figures here refer to the measurement range 2T.

The applied "spinning-current" method in the analog part of the teslameter cancels offset, 1/f noise, and the planar Hall voltage. The teslameter has virtually no crosstalk between the channels. The spinning-current and the tightly twisted thin probe cable make the teslameter immune to electromagnetic disturbances.

The teslameter operates with the low-noise (high magnetic resolution) integrated three-axis Hall probe. The probe integrates horizontal and vertical Hall devices on a single CMOS Si-chip. The integrated Hall probe allows a very small magnetic field sensitive volume of 100µm x 100µm x 10µm.

The three-axis Hall probe is enclosed in a ceramic package. A version of the probe is only 250µm thick, which allows magnetic field measurement in a very small air-gaps (<300µm). The ceramic package is very rigid and robust and allows for a precise positioning of the probe during the measurement.

Some additional measures were introduced that significantly increase the instrument stability, reduce the long-term drift in the electronics and Hall probe, and reduce the required instrument and Hall probe re-calibration rate.

This performance allows a very accurate measurement of the homogeneous and nonhomogeneous magnetic flux densities in research and development laboratories.

The new teslameter technology presented here pushes the current limits in magnetic and spatial resolution and in the accuracy of the Hall-effect based magnetic field measurements.

ACKNOWLEDGEMENT

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