The Hall Voltage Nonlinearity: a Surface Layer Formation with the Lorentz Force

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Abstract – **A new galvanomagnetic source for the Hall voltage nonlinearity related to conductive surface layer formation by the Lorentz force is experimentally proved. This nonlinearity appears as tendency saturation in output characteristics. This behaviour occurs under certain values of the magnetic induction depending on the bias current and the magnetic-field polarity.**

Keywords – **Hall effect, Orthogonal Hall microsensor, Nonlinearity, Conductivity surface layer formation, Device performance.**

I. INTRODUCTION

Sensor output characteristics, magnetotransducers including, are a functional dependence of the output parameter, for example the Hall voltage $V_H(\boldsymbol{B})$ related to the input influence, in this case the magnetic field $\boldsymbol{B}$, defined in steady-state conditions. In most of the cases in control-measurement technologies, the output signal is preferred to be a straight line in order to use a constant sensitivity S = const. The voltage $V_H(\boldsymbol{B})$ of Hall elements with finite sizes is not an ideal straight line, as it is theoretically said about this phenomenon, $V_H(I_s,\boldsymbol{B}) = GR_HI_sB/t$, where $R_H = -1/qn$ or $R_H = 1/qp$ is the Hall coefficient, I_s is the bias current, t is the thickness of the structure in direction of the magnetic field $\boldsymbol{B}$, and G is the geometrical correction factor [1], [2], [3], [4], [5]. The reasons for the non-linearity of the Hall output V_H have different origin. One of the possible sources is the dependence of G parameter from the induction B. Another reason is the influence of the field $\boldsymbol{B}$ on the Hall coefficient R_H by modulation of the carrier concentration n or p, etc. These negative factors in the common case exert quadratic influence on the voltage $V_H(B) \sim B^2$. In the CMOS Hall sensors, especially parallel-field CMOS Hall devices, the cause for the non-linearity is the dependence of the effective thickness t_{eff} confining the transducer zone with p-n junction by the field $\boldsymbol{B}$ [4]. Other factors, disturbing the linearity, are the high values of the magnetic induction ΔB, working temperature range ΔT

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and the dependence of the sensitivity S from the strength and strain of the field $\boldsymbol{B}$. The highest linearity is achievable when the magnetic induction has small values $B \leq 1$ T and the temperature T is near to room conditions, $15 \leq T \leq 40$ °C. In this cases the nonlinearity NL, defined as NL = ($V_H(B)$ - V_{Hideal})/V_{Hideal}, is up to 0.2 - 0.4 % for silicon Hall sensors, where $V_H(B)$ is the actual measured Hall voltage on the output with fixed current I_{s0} and induction B_0, and V_{Hideal} is the point (with the same current I_{s0} and field B_0) of the best linear fit to the experimentally measured values [2], [4].

In Hall sensors, it is often observed a typical, well reproducible nonlinearity, manifested as a tendency of saturation of the characteristic $V_H(\boldsymbol{B})$ at one polarity of the magnetic field $\boldsymbol{B}$, and in the other direction of the vector $\boldsymbol{B}$ this peculiarity is missing [6]. This irregularity is strongly visible at high values of the magnetic inductance B. It makes worse the metrological qualities of the signal $V_H(\boldsymbol{B})$, so a software linearization is needed when it is electronically processed at the next step. In our opinion the main cause for this negative property of the Hall sensor output is a galvanomagnetic process, which is not sufficiently clarified so far. The present publication extends the scope of investigations of this regularity with samples of batch fabricated Hall devices.

II. SAMPLES AND MEASUREMENT METHODS

Figure 1 illustrates a sketch of the Hall sensor fabricated by one corporation. The substrate semiconductor material is n-type silicon with majority carriers' concentration $n \sim 10^{15}$ cm^{-3}. The design is symmetrical with quadratic shape and the bias contacts C_1 and C_2, and Hall terminals H_1 and H_2 are in the middle of the four sides and are electrically interchangeable.
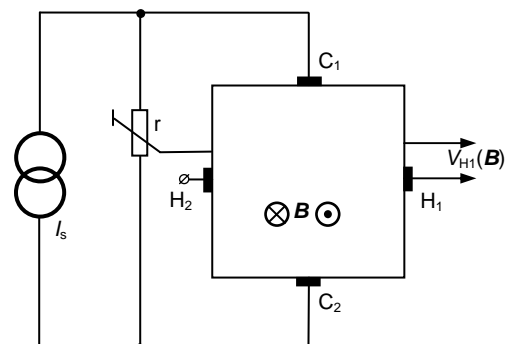

Fig. 1. Sketch of the investigated orthogonal Hall device, the circuitry containing a trimmer r for compensation of the quadratique magnetoresistance is shows too.

The Si chips are fixed on four terminal packages with a plastic coverage. The power-supply of the samples is accomplished in mode of operation constant current I_s = const. The output voltage $V_{H1,2}$ (B) is measured with both high quality voltmeter, type Hewlett Packard, and with a curve tracer, too. The inevitable offset $V_{H1,2}(B = 0) \neq 0$ can be compensated by trimming. This approach is described in [1], [2], [3], [7]. The controlled external magnetic field B is generated by an electromagnet with water cooling. When the supply power is 1.2 kW and the distance between the poles is 20 mm, the value of the magnetic inductance is B = 2 T. The vector B is normal to the sensor plane, Fig. 1. According to the results in [6], the effect of nonlinear behavior of the output signal is better visible in Hall element with minimal design complexity [7], [8]. These devices have only three contacts: two bias electrodes and one output contact. The Hall effect and the magnetoresistance coexist at the output terminal H. Because the Hall voltage is the parameter of interest, the sensors are investigated as three contacts, as shown in Figure 1. The overall measurement error is no more than 2 %.

The inevitable geometrical quadratic magnetoresistance MR ~ B^2 between the supply contacts C_1 and C_2 introduces on terminal H a MR-component, which value is the half of the whole $V_{C1,2}(B)$ voltage on electrodes C_1 and C_2. Hence, on the terminal H sinergetically attend a Hall voltage V_H and a MR signal. The circuitry in Fig. 1 realizes precise extraction of the Hall voltage V_H only at a fully compensation of the magnetoresistance MR. The main conclusion of this analysis is that the half of the Hall voltage $V_H = 0.5\ V_{Hall}$ generated in the sensor from Fig. 1 posses the same physical and metrological characteristics as the well known classical Hall devices. This circuitry gives the opportunity the Hall signal to be investigated without the so called "differential contamination". The differential Hall voltage $V_{H1,2}(B)$ to a great extend disguises details about the galvanomagnetic processess in the structures.

III. EXPERIMENTAL RESULTS. INTERPRETATION

Figure 2 illustrates a typical behaviour of the investigated Hall sensors, registered with the arrangement from Fig. 1. For one polarity of the magnetic field B, depending on the bias current $I_{C1,2}$ and after a fixed value of the magnetic induction B_0, the Hall signal goes to saturation. For the other polarity of the field - B, the linearity of the dependence $V_H(B)$ remains the same, by analogy with [6]. It is clearly established by a further experiment, that the nonlinearity NL at a field $B > 0$ appears when the Lorentz force F_L deflects the carriers to the respective side with contact H. For the other direction of the force F_L, when the carriers are deflected to the substrate bulk, the linearity is maintained. Figure 3 shows the experimental dependence of the threshold induction $B_0(I_{C1,2})$ as a function of the bias current $I_{C1,2}$. The resulting curve can be approximated as B_0 ~ $1/I_{C1,2}$. As bigger the bias current $I_{C1,2}$ is, as earlier the nonlinearity NL is visible for the Hall voltage $V_H(B)$.
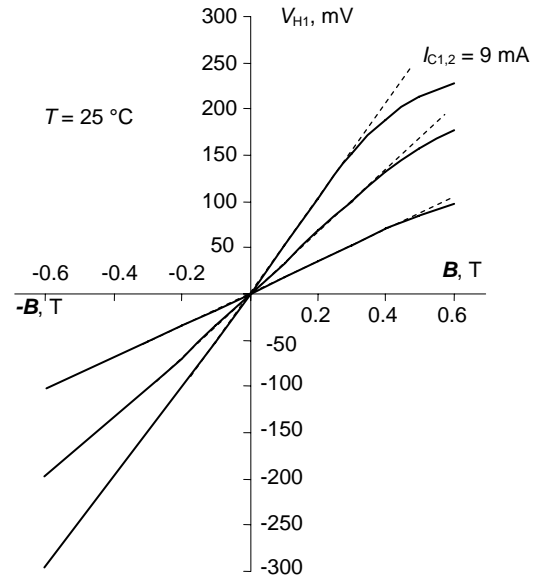

Fig. 2. Output sensor characteristics $V_H(B)$, the bias current is as a parameter, T = 25 °C. The nonlinearity occurs when the Lorentz force deflects the carriers toward the surface with the Hall contact H.

Comparing our results with these in [6], we can conclude that the nonlinear behavior of the Hall voltage V_H has a regular character. Such nonsymmetrical behavior of the Hall voltage is not a consequence of the existing theory of this phenomenon [2], [3], [4], [5], [9], [10], [11], [12], [13].
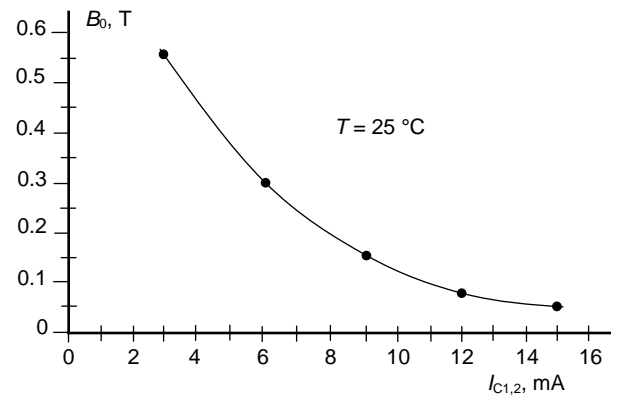

Fig. 3. Dependence of the threshold induction B_0 as a function of the bias current $B_0(I_{C1,2})$.

Therefore the interpretation of this property is based on a new physical mechanism. We think that in the theory of the Hall effect, there are essential gaps. It is believed that the charges which are accumulated by the Lorentz force F_L to the respective boundary with Hall contact H are immovable and generate a Hall field E_H and voltage $V_H(B)$. This clearly contradicts to the fact that the supply voltage V_s is applied not only to the bulk of the structure, but also to its surface! Therefore, the additional electron concentration to the side

with contact H increases the conductivity of the surface layer. So, after a concrete value of the field B_0, i.e. of the additional electrons of the boundary, the Hall voltage V_H on contact H is shunted from the reduced surface resistance. At the dependence $V_H(\boldsymbol{B})$ this is observed as a saturation. For the opposite direction of the field - $\boldsymbol{B}$, the Lorentz force $\boldsymbol{F}_L$ impoverishes the boundary with contact H from movable electrons. Thus, positive donor ions remain and generate positive potential, directly proportional to the induction B [14].

Especially, the stronger is the bias current $I_{C1,2}$, the higher the Lorenz deflection, and the shunting role of the formed high-conductive surface n^+ layer, depending on the voltage $V_H(\boldsymbol{B})$ is better expressed. The saturation behavior of the curve $B_0(I_{C1,2})$, Fig. 3, is most probably related to an upper limiting density value of the electrons on the Hall surface caused by the repulsing Coulomb forces. For the opposite direction of the magnetic field -$\boldsymbol{B}$, the depletion of the surface region from moving carriers is proportional to the Lorentz force $\boldsymbol{F}_L$ value. In this case a tendency of saturation within the magnetic fields range used is not experimentally observed. We can presume that the dimension of the depletion zone, induced by the Lorentz force with respect to the thickness of the structure is negligible. Therefore, for +$\boldsymbol{B}$ field, the generated by the Hall effect high-conductive surface layer directly exert a shunting action on the voltage $V_H(\boldsymbol{B})$. This is accompanied by a tendency of saturation on the dependence $V_H(+\boldsymbol{B})$. The new property is better experimentally pronounced at a field $\boldsymbol{B} > 0$ when a high-conductive surface n^+ - layer under the interface Si-SiO$_2$ already exists. This effect arises when in the oxide SiO$_2$ positive charge exists, emerging there during technology realization. This initial n^+-layer at a field polarity $\boldsymbol{B} > 0$ grows and its influence on the surface conductivity becomes decisive after induction $B > B_0(I_{C1,2})$, Fig. 2. At negative polarity $\boldsymbol{B} < 0$ the n^+-layer remains unchanged like at induction $B = 0$ and the dependencies $V_H(-\boldsymbol{B})$ remain linear. The behavior of the samples with linear characteristics $V_H(\boldsymbol{B})$ at two magnetic-field polarities is most probably caused by the higher quality of technology realization. In this case, for the asymmetry of the Hall contact dependencies to be observed, substantially higher magnetic-field inductions are necessary [14]. Consequently the linear character of the Hall voltage remains the same. The described sensor's effect undoubtedly explains the reason for this polar nonlinearity in the investigated batch fabricated Hall devices.

IV. CONCLUSION

The main question, related to the metrology of Hall effect sensoric is the possibility to eliminate the reason for this drawback. We consider that it can be done with an appropriate gate, located on the surface with the Hall contact. Applying negative voltage we can maintain the Fermi level in flat bands mode, analogously to MOST. In such a way the accumulation of carriers from the Lorentz force will not dominate, and the linearity will be maintained in two polarities of the magnetic field.

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