A NONLINEARITY INDUCED BY THE LORENTZ FORCE IN HALL DEVICES

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Abstract

An unknown so far phenomenon in sensorics has been established experimentally, expressed in the strictly linear dependence on the magnetic field of Hall’s potential on the boundary of Hall devices, which is deprived of carriers by Lorentz force, irrespective of the value of the supply current and the magnetic induction, and non-linear potential of the opposite surface with the augmented electron concentration. With increase of the supply current, nonlinearity is expressed better and starts at lower induction values. The new property is due to the magnetically controlled surface current in conducting materials, whereas nonlinearity is caused by the additional voltage drop generated by this current on the respective Hall boundary. The experiments were carried out using unique measuring circuitry and batch-fabricated Hall sensors. The results will be used to construct a new variety of high-precision magnetometers and to develop a method characterizing the surface of semiconductor materials.

Key words: nonlinearity, Hall devices, magnetically controlled surface current, Lorentz force, Debye length

Introduction. Among the variety of sensor phenomena, converting magnetic field into electronic signal, the mechanism used most often in modern technology is Hall effect. The main reason for such expansion is its physical simplicity, unambiguousness, and last but not least, the linear and odd dependencies of information Hall voltage on magnetic field $B$ and supply current $I_0$ [1-4]. Contactless

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applications determine the significance of this effect, especially in robotics and mechatronics, and mostly, in their plane and space orientation systems. Since its invention in 1879 until recently, Hall effect was interpreted in a largely common way for devices with both orthogonal and in-plane activation \[^{1-6}\]. The developed sophisticated theory and all simulation models related with the phenomenon were reduced to generation of increased concentration of additional, but statically localized opposite-sign charges on both Hall boundaries of the sample. The reason for such separation is the lateral carriers deflection by the Lorentz force \( \mathbf{F}_L \). The transversal electric field \( \mathbf{E}_H \) thus appeared in the structures, recorded experimentally as Hall voltage \( V_H \), compensates for this deviation in the plates.

An unknown so far galvanomagnetic phenomenon – magnetically controlled surface currents \( i_s(\mathbf{B}, I_0) \) on Hall’s boundaries in conducting materials, simultaneously with Hall voltage, was identified recently \[^7\]. This dependence was proven by experiments based on specially implemented in-plane magnetosensitive silicon samples, provided with measuring probes appropriate for current \( i_s(\mathbf{B}, I_0) \) registration. In order to avoid the suspicion of purposeful use of appropriate structures proving this property, we made experiments with the most widespread in practice Hall sensors – batch-fabricated orthogonal Hall devices with rectangular shape. During the investigation, however, unexpectedly, strongly expressed nonlinearity of one of Hall potentials \( \varphi_{H2} \) was identified on the Hall surface to which Lorentz force deflects the carriers. The potential \( \varphi_{H1} \) on the opposite boundary was strictly linear, irrespective of the supply current and the maximal experimentally obtained magnetic induction. At the same time, this nonlinearity, as a sensor defect, seriously deteriorates metrology, notwithstanding that the differential Hall voltage \( V_{H1,2}(\mathbf{B}) \) compensates it to a certain extent. So far, various reasons have been pointed out for the origin of nonlinearity – all of them technological and geometrical \[^3, 4, 6\]. This paper contains the results which prove the new dependence as a fundamental property of Hall sensors generated by magnetically controlled surface current in conducting materials.

**Samples.** Usually, the linear Hall devices offered on the market are supplied with scarce data about the elements themselves and/or the used semiconductor. Probably, this is commercial know-how. Anyhow, a number of sensor and operational characteristics are available, which are useful for the relevant final produce, which in our case is of no particular significance. A substantial part of the firms offer basically digital, trigger-type integrated circuits with Hall plates incorporated inside, which makes it impossible to carry out the planned experiments. The structures we use are industrially produced silicon structures with rectangular shape (Fig. 1). Actually, all Hall chips are mounted onto respective nonmagnetic lead frames placed in plastic bodies. The resistances between contacts \( C_1, C_2, H_1 \) and \( H_2 \) are, as follows: \( R_{C1,2} \approx 1000 \, \Omega \), \( R_{C1,H1} = R_{C1,H2} = R_{C2,H1} = R_{C2,H2} \approx 700 \, \Omega \) and \( R_{H1,2} \approx 700 \, \Omega \). The differential magnetosensitivity of the Hall devices is \( S_l = 170 \, \text{V}/\text{AT} \). The experimental
data are based on a series of 45 samples chosen randomly out of 100 pieces, which is a sufficient guarantee of the results’ reproducibility.

**Measurement setup.** The requirement towards the metrological circuitry is universal applicability for various modifications of Hall devices for the purpose of obtaining information about the individual potentials $\varphi_{H1}$ and $\varphi_{H2}$ at contacts $H_1$ and $H_2$ on both Hall boundaries. Our idea to investigate these potentials was triggered by the fact that the commercial Hall elements lack additional contacts for measurement of current $i_s(B, I_0)$, as what has been achieved in [7].

On each of Hall surfaces there is one electrode $H_1$ and $H_2$, and it is impossible to measure directly the current $i_s(B, I_0)$ (Fig. 1). Moreover, on contacts $H_1$ and $H_2$ in magnetic field $B$, two signals are generated – one is half of Hall voltage, $\pm 0.5V_{H1,2}(B, I_0)$, and the other – quadratic (even) bulk magnetoresistance $V_{MR} \sim B^2$. Therefore, relation $V_{H1} = | - V_{H2} | = \pm 0.5V_{H1,2}(B, I_0) + V_{MR}$ holds.

Therefore, the measurement of the potentials $\varphi_{H1}$ and $\varphi_{H2}$ will be correct, if the circuitry compensates fully the voltage $V_{MR}$. The working hypothesis is that potentials $\varphi_{H1}(I_0, B)$ and $\varphi_{H2}(I_0, B)$ contain information for both the additional electric charges generated by Hall effect, as well as for the influence the non-equilibrium current $\pm i_s(B, I_0)$ has on them.

Figure 1 presents also the measuring circuitry used in the experiments. It operates in constant current mode, $I_0 \equiv I_{C1,2} = \text{const}$, implemented by load resistor $R = 15 \text{ k}\Omega$. There is also a trimmer $r$, whose both contacts are connected.
with the supply electrodes C_1 and C_2. Its resistance r is by at least one order greater than the resistance R_{C1,2} of the structure, r = 10 kΩ ≫ R_{C1,2}. This condition guarantees that the current through the trimmer r will be sufficiently low. The circuit thus composed (Fig. 1) provides for full compensation of the magnetic field B decreases. The stronger the induction semiconductor, i.e. the silicon. As a result, the current remaining. These are dopant donor atoms in the regular crystal lattice of the basic semiconductor, \( \phi \). The experiments were carried out at room temperature \( T = 300 \text{ K} \). The overall measurements’ resulting error did not exceed \( \pm 2.0\% \).

**Effect of the current \( i_s(B, I_0) \) on Hall potentials.**

a) The processes in Hall effect, related with the generation of field \( E_H \) by the additional charges through force \( F_L \) take place in the near-to-surface zone (the interface), whose size is equal to the screening length \( L_D \) named Debye length, \( L_D = (\varepsilon_0\varepsilon_\text{r}kT/q^2n_0)^{1/2} \), or \( L_D \sim 1/(n_0)^{1/2} \). To get a clearer quantitative idea of the size of the regions, commensurate with the parameter \( L_D \), let us consider an n-Si sample having rectangular shape, with orthogonal activation (Fig. 1) and for example, electron concentration \( n_0 = N_D \approx 4.5 \times 10^{21} \text{ m}^{-3} \), temperature \( T = 300 \text{ K} \), resistivity \( \rho \approx 0.01 \text{ Ω.m} \), with supply currents \( I_0 = 5 \times 10^{-3} \text{ A} \) and induction \( B = 1.6 \text{ T} \). With these parameters, Debye length is \( L_D = (\varepsilon_0\varepsilon_\text{r}kT/q^2n_0)^{1/2} \approx 61.7 \times 10^{-9} \text{ m} \approx 62 \text{ nm} \), whereas with silicon \( \varepsilon_0\varepsilon_\text{r} \approx 12 \) [6].

When Lorentz force \( F_L \) deflects the electrons from the right side to the opposite one with contact \( H_2 \) (Fig. 1) in the right interface zone with contacts \( H_1 \), the uncompensated electric charges or the “stripped” positive donor ions remain. These are dopant donor atoms in the regular crystal lattice of the basic semiconductor, i.e. the silicon. As a result, the current \( i_s(B, I_0) \) in this region decreases. The stronger the induction \( B \) and/or the current \( I_0 \), the more donor layers without compensating electrons will remain and the greater the length \( L_D \) will become. The total positive charges \( N_+ \) determines the \( +E_H \) components of the Hall field [1]. The pure mechanism of the Hall effect’s arising is namely this. Therefore, the total positive charges \( N_+ \) thus generated in the right zone of width \( L_D \) is directly proportional to the force \( F_L \), i.e. to the product \( I_0B \). The thus decreasing the current \( i_s(B, I_0) \) in increasing magnetic field \( B \) and/or current \( I_0 \) does not change the linearity of the positive potential \( +\varphi_{H1}(B) \), determined by the charge-state of the interface. The positive sign of the Hall potential \( \varphi_{H1}(B) \) is with respect to the electroneutral central part of the structure.
b) The situation on the left boundary with contact H₂ is different. The force $F_L$ concentrates on it additional electrons whose total charges $N_-$ coincides with charges of the donor ions, $N_{D+}$, $N_-$ = $N_{D+}$. The stronger the current $I_0$ and/or the induction $B$, the higher the concentration of the non-equilibrium electrons in the near-to-surface layer (interface) with width $L_D$. On this side, however, another process takes place as well. The surface is sure to contain defects, inclusions into the crystal lattice and others. These result in various scattering mechanisms for the electrons moving in the layer. Up to a certain concentration level of the carriers pressed by the force $F_L$ (value of induction $B_0$), the electrons are expected to cover “electrostatically” these various defects, i.e. “to level” the relief of the crystal disturbances on the surface. Actually, such a mechanism should not have effect on the linearly increasing negative component of Hall field, $-E_H$, i.e. overall charge formation of pure Hall field. Moreover, the current $i_s(B, I_0)$ also increases as a function of the field $B$ and the supply $I_0$. That is why, up to induction values $B \leq B_0$ with parameter $I_0 \equiv I_{C1,2} = \text{const}$, the current $i_s(B, I_0)$ does not change the linearity of the negative Hall potential $-\varphi_{H2}(-B)$. Within this induction range, $B_0 > \pm B$, the dependencies of the potential $\varphi_{H2}(-B)$ and the differential Hall voltage $V_{H1,2}(B)$ are strictly linear. With further increase of the induction, $B > B_0$, the current $i_s(B, I_0)$ starts to increase substantially. The reason lies in the electrically neutralized in first approximation interface defects from the increasing concentration of the electrons pressed by force $F_L$. The resistance $R_S$ of the layer with contact H₂ decreases naturally, whereas the growth of the electron concentration $n_S$ results in even more substantial current $i_s(B, I_0)$. It creates voltage drop $-V_{H2}(B)$, $| -V_{H2} | \sim i_s(B, I_0)$ in the near-to-surface region. It has the same sign as the Hall potential $-\varphi_{H2}$ and is algebraically summed up with it, $\varphi_{H2} = | -\varphi_{H2}(B) - V_{H2}(B) |$. The dependence of the voltage $-V_{H2}$ on the magnetic induction $B$ is not expected to be linear since it is not formed by pure Hall effect, but is generated by the specific kinetics of the moving surface charges. Actually, the interface electron velocities in the zone with width $L_D$ should not have the same value. The inevitable dispersions of the velocities and the concentrations depend on the current $I_0$, the induction $B$, i.e. on the force $F_L$ and on the profile of the impurity surface states. This is why the nonlinearity of the potential $\varphi_{H2}(B)$ is experimentally recordable when the average velocity $v_S$ of the electrons forming the current $i_s(B, I_0)$ in the near-to-surface zone becomes equal to and greater than the bulk velocity $v_0$ of the supply current $I_0$, $v_0 \leq v_S(B)$. For this reason, after a certain critical value of the magnetic induction $B_0$, the total potential $\varphi_{H2}(B)$ on contact H₂ should change nonlinearly. It will increase more quickly than the standard Hall signal, $-\varphi_{H2}(B)$, on account of the specifics of decreasing the resistance $R_S$ of the surface layer. It should be noted that the critical induction $B_0$, under otherwise the same conditions, depends on the quality (defects) of the surface of the semiconductor (silicon) material. This means that the values of the induction $B_0$, at which the
deviation of the potentials $\varphi_{H1}(B)$ or $\varphi_{H2}(B)$ from the straight line starts (the force $F_L$ concentrates the current carriers on the boundaries with contacts $H_1$ or $H_2$) may be different.

**Experimental.** Figure 2 shows this part of the experimental potential dependencies $\varphi_{H2}(-B)$ at different values of the supply current $I_0 \equiv I_{C1,2}$ when Lorentz force $F_L$ presses the charges to the boundary with contact $H_2$ for one of the samples. The potential $\varphi_{H2}(-B)$ is negative and, after certain values of the induction $B_0$, depending on the current $I_{C1,2}$, is non-linear. The behaviour of the potential $\varphi_{H1}(B)$ of the same sample, if the force $F_L$ concentrates the electrons to the surface with contact $H_1$, is similar. Under the specified condition for the directions of the force $F_L$, all examined structures demonstrate the same behaviour as in Fig. 2. The stronger the current $I_0$, the more profoundly expressed the nonlinearity, whereas it occurs at lower value of the induction $B_0$. Another important specific is that the nonlinearity in the individual sample starts at different values of the induction $B_0$. When Lorentz force $F_L$ takes away electrons from the respective Hall surface, it naturally gets positively charged. The potentials $+\varphi_{H1}(B)$ or $+\varphi_{H2}(B)$ in the same Hall element, at the respective polarity of the

![Figure 2](image_url)

Fig. 2. Dependencies of the potential $\varphi_{H2}(-B)$ with the current $I_0 \equiv I_{C1,2}$ as a parameter; the force $F_L$ presses the electrons to the boundary with contact $H_2$; the sensitivity at field $+B$ reaches $S_1 \approx 85$ V/AT (dot lines)
field \( B \), are also positive, whereas their linearity is preserved up to the maximally high induction \( B \) in the experiments. The recorded magnetosensitivity in the linear range of the potentials \( \varphi_{H1}(+B) \) and \( \varphi_{H2}(-B) \) of the series of samples is \( S_1 \approx 85 \) V/AT.

Figure 3 presents the dependencies \( B_0(I_0) \) of the critical induction \( B_0 \), when nonlinearity in potentials \( \varphi_{H1}(B) \) and \( \varphi_{H2}(B) \) arises at respective polarity of field \( B \) for both Hall boundaries. The essential fact is that in the structure the inductions \( B_0 \) practically decrease linearly in first approximation, whereas for both Hall surfaces, they are shifted to each other. The rest of sensors of the series demonstrate similar behaviour. In some of them, the graph of potential \( \varphi_{H1} \) features lower values than the graph of potential \( \varphi_{H2} \).

**Comments.** The nonlinearity of Hall devices is their immanent property generated by the magnetically controlled surface current \( i_s(B, I_0) \). The other reasons for the nonlinearity of the characteristics \( V_{H1,2}(B) \) described in literature \([4, 6]\) are not excluded, however, the new dependence is a key one in Hall effect. The critical induction value \( B_0 \) (Fig. 3) contains information about the surface defects, specifics in dopant atoms and growth of the semiconductor, disturbances of the crystal lattice, possible deformations or strains and so on. The unexpected conclusion here is that the surface with better quality is the surface for which the inductions \( B_0 \) feature lower value. However, from the viewpoint of Hall devices, the better version of the applications is the “relief” boundary. With it, the values of the induction \( B_0 \) are higher, which defines a wider linear range of the Hall voltage \( V_{H1,2}(B) \).
Conclusions. The obtained experimental results corroborate with the proposed model of the effect of the current $i_s(B, I_0)$ on Hall potentials. The advantage of the investigation is that it has been implemented using batch-fabricated structures and not purposefully implemented samples, which determines the practical significance of the results. The universal nature of the new phenomenon provides for it to be used as a basis of a new surface research method in material science. Moreover, the asymmetry of Hall potentials with respect to the polarity of the magnetic vector $B$ prompts the idea for constructing a new type of magnetometers with drastically increased accuracy and expanded induction range. They will operate with this direction of the field $B$, at which the output characteristics are strictly linear. The new property regardless the varieties of Hall sensors, is always reproducible. Another challenge is the influence of the temperature factor, especially the cryogenic conditions, on the galvanomagnetic properties of the potentials on both boundaries, inclusive of the quantum Hall effect. The activity in these research guidelines is in progress.

REFERENCES


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