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ON THE MAGNETICALLY CONTROLLED SURFACE CURRENT AT THE HALL STRUCTURE SIDES

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Abstract

The experimentally observed new phenomenon in conducting materials – the magnetically controlled surface current was examined again with an original measuring method and new silicon samples. The obtained results corroborate very well with the previously acquired data. The proposed registration approach utilizes the nulling compensation technique guaranteeing full offset compensation in all operating modes. The connection of the Ettingshausen effect with the new effect is clear demonstrated. A novel pressure sensor using the surface current dependence on external mechanical strain is developed and tested. The output characteristics of this transducer are very well reproducible and are suitable for measurement technologies.

Key words: magnetically controlled surface current, Hall and Ettingshausen effects, presure sensor

1. Introduction. The Hall effect is one of the best aquired and technologically utilized phenomena available up to now. The numerous varieties of orthogonal and parallel-field Hall sensors and microsensors with universal applicability, multidimensional magnetometry as well as robotics are a categorical evidence thereof [1, 2]. This phenomenon to researchers in sensorics has been experienced to such an extent that the modelling and design of magnetosensitive elements has already become a routine procedure. The discovery of quantum Hall effect in 1980 by K. von Klitzing [3] constituted another contribution of this classical

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event. Notwithstanding the foregoing, until recently, Hall effect theory did not provide clear answers to the questions: 1) How the Hall field $\boldsymbol{E}_{\mathrm{H}}$ is generated, after its complete compensation by the Lorentz forces $\boldsymbol{F}_{\mathrm{L}}$ in conducting structure $\boldsymbol{E}_{\mathrm{H}} \approx \boldsymbol{F}_{\mathrm{L}}$. Moreover, the homogeneity of the current paths in the samples has been restored, as in the case with missing magnetic field, $B = 0$. This question may as well be redefined as follows: given the carriers' deflection has been fully compensated, $\boldsymbol{F}_{\mathrm{L}} \approx 0$, what is the mechanism of the positive/negative charges generated additionally on the opposite Hall structure sides, which maintain field $\boldsymbol{E}_{\mathrm{H}}$; and 2) What is the reason for the additional charges from Lorentz deflection, generating the Hall field $\boldsymbol{E}_{\mathrm{H}}$ to be statically locallized on Hall's sides, like a capacitor in the presence of accelerating supply electric field $\boldsymbol{E}_{\mathrm{s}}$ in the samples for bulk and surface charges. The field $\boldsymbol{E}_{\mathrm{s}}$ is by about two orders greater than Hall field, $\boldsymbol{E}_{\mathrm{H}}$. Another fact is the lack of a direct method to measure the surface current along the conducting material probes. An unexpected and unknown so far galvanomagnetic phenomenon – the magnetically controlled surface current in conducting materials [4], provides an answer to the above-mentioned problems. This paper provides additional experimental results and develops ideas about this effect.

2. Measurement methods for surface current. The magnetically controlled surface current observation became possible after a measurement method for the longitudinal surface current in conducting material structures. Figure 1*a* shows the experimental surface current registration setup used in [4]. It is similar to the standard electrical resistance and magnetoresistance measurement circuit [1, 5].

In these cases, a voltage V is recorded, i.e. the measuring device should necessarily feature input resistance many times greater than the resistance between

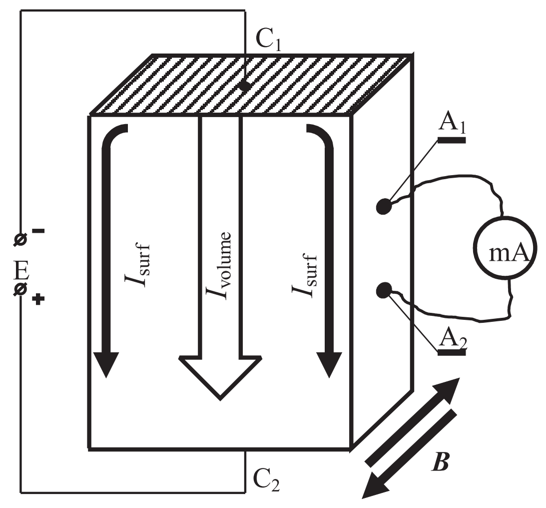


Fig. 1*a*. Orthogonal Hall element with two side contacts A_1 and A_2 for measuring the surface current I_{S}. The bulk and surface components of the supply $I_{\mathrm{C}_{1,2}}$ are shown too

contacts A_1 and A_2. However, in our case, Fig. 1*a*, the arrangement has been modified to measure electric current I. A key requirement for this purpose is that the input resistance of the measuring device is many times greater than the resistance of the region between points A_1 and A_2. This simple change in the circuitry has not been used so far, but it resolves in principle the problem of the surface current measurement. Since both contacts A_1 and A_2 are ohmic, the switching of the ammeter shunts the area between terminals A_1 and A_2. Actually, the surface current I_S in the boundary region near to points A_1 and A_2 has been taken out of the structure to be measured and then returned again, $\alpha I_S/I_{C_{1,2}}$ whereas $\alpha \ll 1$. As it can be seen from Fig. 1*a*, the surface current I_S is formed in the two regions, $C_1 - A_1$ and $A_2 - C_2$. Initially, the surface current $I_S(B = 0)$ with $I_{C_{1,2}} = \mathrm{const}$ in the absence of a magnetic induction, $B = 0$, is measured, after which the field $\boldsymbol{B}$ is switched-on. The magnetically controlled surface current $I_m(\boldsymbol{B})$ is given by the relation $\Delta I_m(\boldsymbol{B}) = I_S(\boldsymbol{B}) - I_S(0)$. For additional verification of the observed property in conducting materials, we propose and test a novel modification of the measurement method.

Figure 1*b* shows an alternative arrangement to the circuitry from Fig. 1*a*. A typical feature of the circuitry is that, in the lack of field $B = 0$, it maintains equipotentiality of points A_1 and A_2. This is achieved by the two variable resistors R_1 and R_2, thus connected to supply E, to establish in all cases the potential equity $V_{A1} = V_{A2}$.

The condition in this case is that the values of the load resistors are many times greater than the internal resistances of the respective zones in the semiconducting structure, $R_1, R_2 \gg R_{A_{1,2}}, R_{C_1,A_1}, R_{C_2,A_2}$. The circuit tuning is achieved in two stages. In position 1 of the switch, using a standard voltmeter and variation of resistors R_1 and R_2, equipotentiality at zero field $B = 0$, of points A_1 and A_2

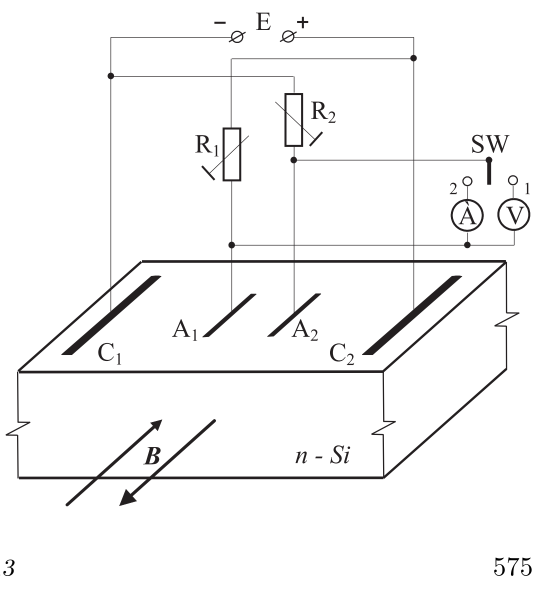


Fig. 1*b*. Original nulling potentiometric arrangement used for surface current measurements on semiconductor Hall samples. The offset cancelation is registered by the voltmeter V – position 1 of the switch SW; the galvanometer A was introduced in the circuit by closing the switch SW – position 2. The contacts A_1 and A_2 were kept at the same potential and the surface current in a magnetic field $\boldsymbol{B}$ is displayed by the ammeter A

is established. Then, the switch is turned to position 2, and magnetic field $\boldsymbol{B} \neq 0$ is established. According to the ammeter readings, the value of the magnetically controlled current, $I_{\rm m}(\boldsymbol{B})$, is recorded. Various modifications, including electronic ones, may be used as ammeters. The presented circuitry in Fig. 1*a* is similar to the one used during the measurement of the Hall current $I_{\rm H}$, as described in [1, 5]. In our case, equipotentiality may always be achieved, notwithstanding the supply current $I_{\rm C1,2}$, flowing in the structure. Another advantage of the arrangement from Fig. 1*b* is the possibility for automation of the measurement process, thus eliminating the need to determine the difference between the starting current $I_{\rm S}$ and its value in a magnetic field $\boldsymbol{B}$. As well as with Hall effect experiments, the obligatory condition to achieve high precision is the offset compensation.

3. Experimental. To test the circuitry from Fig. 1*b*, the experimental results previously obtained with the scheme in Fig. 1*a* [4], have been compared with those obtained using the setup from Fig. 1*b*. To provide data comparability, the same device design and sizes of the *n-Si* chips, as those described in detail in [4] were used, but the samples were new and unstudied. Since the internal resistance $\rm R_{int}$ characteristic of the individual regions between contacts $\rm C_1$, $\rm C_2$, $\rm A_1$ and $\rm A_2$ is about 420–450 Ω, the chosen nominal value of both resistors, $\rm R_1$ and $\rm R_2$, is $\rm R_1 = R_2 = 10$ kΩ. Our experiments use an electronic pA ammeter type HP 4140B featuring relative error of 0.5% in the range $I_{\rm S} \leq 10^{-2}$ A. The errors for such a comparative investigation are as follows: the voltages have been measured with approximate accuracy of 0.15% and resolution of 0.05%; the currents have been determined with the same typical accuracy of 0.5% whereas the resolution of the current measurement is no more than 0.1% or no more than about 40–50 pA. It should be noted that the ultimate error in our experiments is determined not by their electric part, but by the magnetic measurements. Our electromagnet is of Weiss type, with water cooling, whereas with supply power of 1.2 kW and distance between the poles of 20 mm, the induction $B = 2.0$ T; the diameter of the poles was 60 mm. The magnetic field was measured and regulated using an orthogonal KSY type Hall sensor, which was calibrated using a Metrolab magnetometer. The magnetic measurement errors introduced by the used Hall sensor and the calibrating Metrolab instrument are no more than 0.5%. The inevitable hysteresis of the electromagnet with magnetic field commutation $\pm\boldsymbol{B}$ is accounted for, which is about 0.2–0.3% of the maximal value, $B_{\max} = 2$ T. Therefore, the magnetic measurements' resulting error did not exceed $\approx \pm 2.0\%$. The experiments were carried out under dark conditions, at room temperature $T = 23\,^\circ$C, which is maintained constant with accuracy of $\pm 0.3\,^\circ$C within the range $18 \leq T \leq 28\,^\circ$C. A suitable minithermostat was used, controlled by the base-emitter voltage $V_{\rm EB}(T)$ of $n-p-n$ Motorola MTS 102 silicon transistor as a diode temperature sensor, operating in constant current mode, as the method described in [1].

Figure 2 shows the typical experimental dependences of the surface current

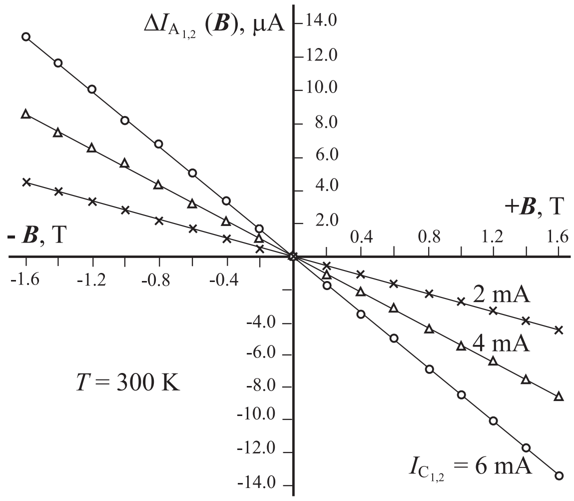


Fig. 2. Linear and odd magnetic control of the surface current as a function of the magnetic field $\boldsymbol{B}$, the supply $I_{C_{1,2}}$ is as a parameter

$I_m(\boldsymbol{B})$ as a function of the magnetic field $\boldsymbol{B}$ obtained using the arrangement in Fig. 1*b*, with the supply $I_{C_{1,2}}$ as a parameter. The ratio of the surface current $I_m(0) \equiv I_S$ to the supplying $I_{C_{1,2}}$ in the lack of a magnetic field is about $\alpha I_S/I_{C_{1,2}} \approx 8\%$. Ten probes, collected from two sample series implemented at two different times, coming from different fabrication batches have been examined.

The comparison of the obtained dependences in Fig. 2 in our paper with those from Fig. 2 in [4] shows that, in the first approximation, they are identical, regardless of the measurement method and samples. Therefore, the key conclusion is that the experimental facts from [4] have been confirmed by another measurement approach and new samples. In our opinion, at this stage, such verifications are obligatory, since the new phenomenon should be approbated many times minding its fundamental impact on magnetic-field sensorics.

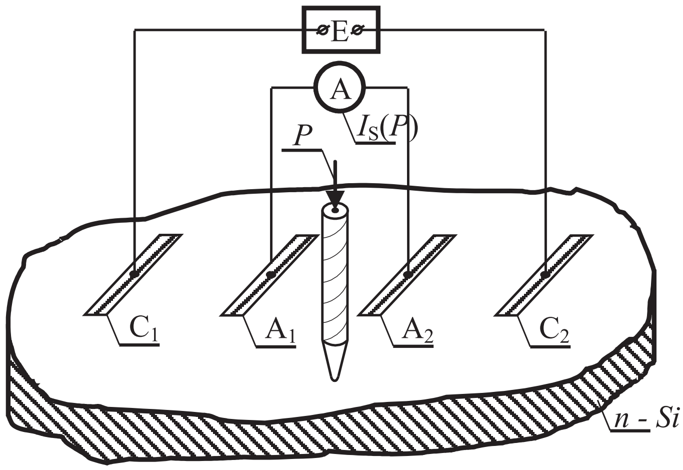
4. The new phenomenon and the Ettingshausen effect. Let us recall the discussion of the new phenomenon from [4]. The magnetically controlled surface excess-current $\Delta I_m(\boldsymbol{B}) = I_m(\boldsymbol{B}) - I_S(0) > 0$ results from the increased carriers density on Hall's side, to which the Lorentz force, $\mathbf{F}_L$ accumulates moving electrons (if the structure features *n*-type conductivity). The drop of the current I_S on the opposite side, $\Delta I_m(\boldsymbol{B}) = I_m(\boldsymbol{B}) - I_S(0) < 0$, results from the decreased surface concentration of the carriers with respect to their equilibrium value caused by Lorentz deflection, such as the influence of the immovable lattice ions grow. The keeping of non-steady state on both Hall sides in a magnetic field is similar to the minority carrier injection by $p - n$ junction in the base region. The disturbed electric neutrality on the respective Hall side is maintained by the majority electrons coming additionally from one of the supply contacts. Exactly the same number of electrons leave simultaneously this surface from the opposite ohmic supply contact. This mechanism keeps the disturbed electric neutrality on the respective surface layer with thickness about the Debye length

$L_D \approx 10^{-5} - 10^{-4}$ cm (in silicon at a carrier concentration n_0 $10^{14} - 10^{15}$ cm^{-3}) [6] at a fixed level, defined by the current I_S (the drift velocity $\boldsymbol{v}_{dr}$), and the magnetic induction B. Namely, the control of the surface current I_S at a supply $I_{C_{1,2}}$ = const is carried out by the field $\boldsymbol{B}$.

The galvanothermomagnetic Ettingshausen effect is a generation of temperature gradient ΔT between the Hall structure sides as a result of the Hall phenomenon [7]. The origin of this transversal gradient ΔT in solids, according to the commonly adopted interpretation so far, is due to the statistical distribution of the carrier drift velocities $\boldsymbol{v}_{dr}$ around their Boltzmann statistic mean value. Thus, the Lorentz force $\boldsymbol{F}_L = q\boldsymbol{v}_{dr} \times \boldsymbol{B}$, which acts individually on each electron differs from carrier to carrier while the electrostatic force of the integrated Hall field $\boldsymbol{E}_H$ in the semiconductor specimen (for instance) is the same for all electrons. Moreover, the two forces $\boldsymbol{F}_L$ and $\boldsymbol{E}_H$ are oppositely directed. With faster carriers, the force $\boldsymbol{F}_L$ exerts stronger effect on them, while with slower carriers it is the field $\boldsymbol{E}_H$. This separation, according to their kinetic energies, i.e. their drift velocity values, results in the generation of the temperature gradient ΔT between the Hall sides. Consequently, on this boundary edge, to which the Lorentz force $\boldsymbol{F}_L$ is directed, "hotter" electrons are concentrated and this boundary edge should have higher temperature T_1, while the side, to which the Hall field concentrates the slower carriers (with lower kinetic energy) have lower temperature T_2, $T_1 > T_2$. Within the new phenomenon, the Ettingshausen effect unexpectedly obtains quite a clear explanation. The transversal temperature gradient ΔT between the Hall structure sides results from the different values of the two surface currents $I_m(\boldsymbol{B})$ in a magnetic field $\boldsymbol{B}$. Thus, the side to which the Lorentz force $\boldsymbol{F}_L$ is directed features higher value of the current $I_m(\boldsymbol{B})$, and therefore, it also features higher temperature T_1. The opposite side features lower value of the current $I_m(\boldsymbol{B})$, and therefore, its temperature T_2 is lower, i.e. $T_1 > T_2$. An experimental confirmation is the temperature difference ΔT on the boundary surfaces of Hall elements in a magnetic field [8], recently observed with infrared thermography. This method for registration of the transversal gradient ΔT in a magnetic field $\boldsymbol{B}$, i.e. the Ettingshausen effect, is convenient for surface current behaviour in complex electronic devices. The performed analysis shows that the primary reason for both Hall effects, as well as the Ettingshausen phenomenon is the magnetically controlled surface current. The development of this hypothesis has a great innovative potential.

5. On the application of the $\boldsymbol{I_S(B)}$ current. Reference [4] provides an overview of some of the advanced applications of the magnetically controlled surface current as a means for characterization of materials and their surfaces. The possibilities to obtain express information on the conductivity type, carriers concentration, and the mobility of semiconductor (silicon) materials have been approbated. The data do not differ, within the experimental error, from the data obtained using the classical Hall effect. Since the surface current, according to

Fig. 3. Pressure sensor utilizing the surface current as operation principle. The needle-like intender transfers the external force $\boldsymbol{P}$ on the n-Si substrate. The output is the ammeter A



the new phenomenon, is highly sensitive to external influences, we will present the first results on the action of a pressure sensor based on it. A sketch of the new n-type silicon transducer is shown in Fig. 3 [9].

The external force $\boldsymbol{P}$ is applied on the upper side of n-Si substrate. In the middle zone, the ohmic supply contacts C_1–C_2 are formed and by the current terminals A_1 and A_2 the surface current I_S is measured. The information signal here is $\Delta I_S(\boldsymbol{P}) = I_S(\boldsymbol{P}) - I_S(0)$. The dependence of the output signal $\Delta I_S(\boldsymbol{P})$ as a function of the measure and $\boldsymbol{P}$ is shown in Fig. 4.

The obtained curve is reproducible for a given sample and is suitable for metrological purposes. In the first approximation it is similar to the dependences in silicon structures a subject to uniaxial deformation. Experimentally no hys-

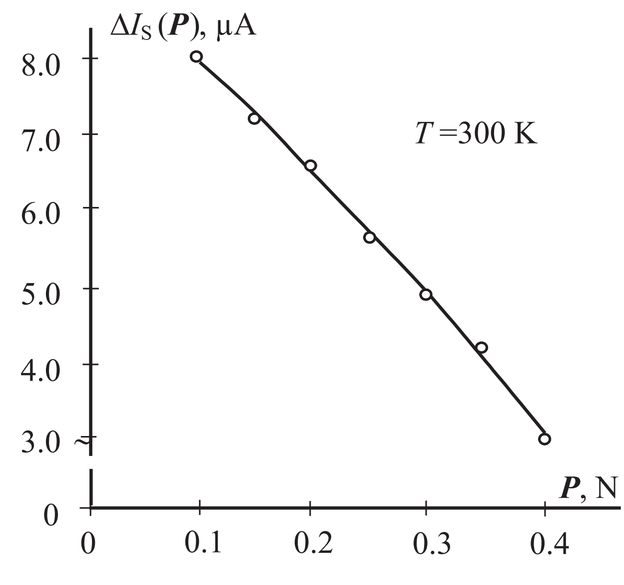


Fig. 4. Output characteristic $\Delta I_S(\boldsymbol{P})$ of the new pressure sensor as a function of the external force $\boldsymbol{P}$ at a supply $I_{C_{1,2}} = 8$ mA and $T = 300\,\mathrm{K}$

teresis is observed for values $\boldsymbol{P} \leq 0.4$ N. The strain induced by the needle like indenter changes the surface conductivity through the effective mass and carrier mobility and as a result, the current $\Delta I_{\mathrm{S}}(\boldsymbol{P})$ drops. An important conclusion on the properties of the surface current generated by external non-electric measurements (magnetic field and deformation) is that this phenomenon appears to be a prospective sensor agent. The influence of the radiant flux Φ with different light spectrum and nuclear-particle radiation on the behaviour of the surface current I_{S} would be of interest.

6. Conclusion. The experimental and theoretical studies of the magnetically controlled surface current and related sensor mechanisms, associated with parameters, such as pressure, light flux, temperature, nuclear-particle radiation, chemical signals, etc. will provide new abundant information on the properties of the surface. The key conclusion from the performed analysis and the data obtained so far is that the surface current, as a function of various external influences, is a powerful characterization method with multidisciplinary impact. Apart from supplementing the already known methods, it provides new information on the surface and interface, which may be regarded rather as unstudied "devices", than as pure boundary.

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