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Steady current skinning in uncompensated metals

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Abstract

We discuss charge transfer effects in the case of Hall coefficient that varies along the transport direction and changes its sign. This situation takes place in contacts of the serially joined materials having electron and hole types of conductivity. Spatial inhomogeneity of conductivity and inversion of Hall coefficient sign are analyzed in terms of electric potential and current density distribution. Magnetic field varies along transport direction of model plate conductor. Two reasons stimulate the inhomogeneity of conductivity: the contact of the serially joined materials having electron and hole types of conductivity and the topology of transverse magnetic field itself. Spatial inhomogeneity of conductivity and inversion of Hall coefficient sign are modeled by the method of curving the electric current lines in such manner that normal local projection of magnetic field varies along transport direction of plate sample. The curving of current lines takes place in the bent plate sample that being placed in an homogeneous magnetic field. It is shown that under inhomogeneous conductivity via contact region the steady current skinning takes place in plate sample so that at one side of plate sample the current density is high and at another side the current density is small. The degree of current skinning and the localization of current density extreme near one of sides is defined with conductivity gradient level and its direction.

1. Introduction

Metal heterogeneous contact between the conductors having different types of conductivity occur in low temperature energetic devices and electric cryogenic machine circuits. Under zero magnetic field there is no any problems with current flowing through such contacts because usually used normal metal conductor materials aluminum and copper have cubic crystal symmetry and their electron kinetic coefficients are scalars. Copper and aluminum have an electron and hole types of conductivity respectively and a contact of Cu and Al plate samples connected in series is an example of heterogeneous medium if an action of an external strong magnetic field is present. The inhomogeneity is a result of opposite signs of Hall coefficients in Al and Cu and as a consequence such a contact has a transformation of conducting properties from the hole type to the electron that along transport direction. This transformation may be represented as a charge transfer process via medium having gradient type of conductivity. So an action of an external magnetic field being even homogeneous that on to charge flow via heterogeneous-contact made of materials having electron and hole type of conductivity stimulates gradient relations. The excessive resistance connected with current lines redistribution is a result of conductivity inhomogeneity stimulated by magnetic field. Homogeneous magnetic field may be a reason of current density redistribution and excessive resistance and heat generation. It is known that an external homogeneous field applied to polycrystalline conductor stimulates current flow rearrangement and respective resistivity being different from that of single crystal specimen [1-4].

However the inhomogeneity is not determined with only the electron and crystal structure via contact. The magnetic field topology itself (for example due to its own technological inhomogeneity taking place in any magnetic system of restricted geometrical dimensions) is a reason of gradient conductivity and an additional respective electric potential picture rearrangement too. The problem of steady current and heat skinning at low temperature transfer have already been discussing in the number of articles [5-15], where both homogeneous and inhomogeneous magnetic field is analysed as a reason of appearance the current lines redistribution in metal, semi-metal and semiconductor samples on the base of taking into account of conductivity inhomogeneities of different nature (crystallite disorientation, geometrical due to grooves, volume density due to porous , charge density in semimetals due to impurity concentration gradient .., own magnetic field inhomogeneity,.. etc.)

In this paper the double type of inhomogeneity of electric conductivity stimulated both by heterocontact and by magnetic field gradient is investigated. In other words the processes taking place in metal heterogeneous contacts placed both in inhomogeneous and in homogeneous magnetic field are modeled experimentally and analitically. Here we analyse the peculiarities of charge transfer under more complicated case of spatial topology of conductivity inhomogeneity in sample volume than before. The study is done on the base and in accordance with the experimental data that has been obtained for model approximation of heterogeneous contact consisted of two plate samples connected in series. The real energy structure and peculiarities of Fermi surface of intermediate type suitable for both aluminum and copper polycrystalline conductors are used.

2. Experimental and theoretical approach

The procedure of modeling of hetero-contact and magnetic field inhomogeneity is based on the method of curving of electric current lines so that the normal local component of an external magnetic field has a variation along the transport direction in accordance with definite law [10, 11]. For the simplicity the heterogeneous contact under the experiment have been chosen as a symmetric that in electron energy structure and consisted of materials Al^{+}-Al^{-} type. Here Al^{+} is a usual widely used aluminum of hole type of conductivity and Al^{-} is a farfetched electron analogue of Al^{+} which has an electron type of conductivity in magnetic field. That is Al^{-} has negative Hall coefficient R that is equal $-|R|$ instead of positive R for usual aluminum. So Al^{+} (aluminum) and Al^{-} (anti-aluminum) type components used in experimental modeling process have the same electric resistivity tensors excluding the sign of Hall coefficients. Both components of heterogeneous contact are realized on the base of plate sample made of aluminum. For this aim the aluminum plate sample was bent to acquire the form of U letter of Latin alphabet. After annealing and mounting of current and potential probes the U shaped sample was oriented in specimen holder so that an external homogeneous magnetic field was parallel ($U \parallel B$) or normal ($\subset \perp B$) to double bent sample. It is clear that for parallel orientation ($U \parallel B$) the magnetic field normal local component varies along sample length from zero value on one branch (far from the bent section) up to maximal that in the center line and farther to zero that on another branch of double sample. For normal orientation ($\subset \perp B$) the local normal component of magnetic field varies along one of branch from maximal value when point is far from bent section up to zero that when point is in the center line of bent section and farther up to maximal that on another branch of double bent specimen. For aluminum – anti-aluminum heterogeneous-contact modeled on the base of U shaped specimen in parallel to magnetic field orientation the magnetic field local component topology corresponds to the picture that is shown at Fig.1a. This topology is called as inversion type of inhomogeneity. It is important that for this type of current flow the dimension along contact where the magnetic field changes its sign is very small. In experiment this dimension is of zero length whereas on the Fig.1a this dimension is finite. Respectively the same heterogeneous-contact modeled on the base of the same U shaped specimen in normal orientation to magnetic field has the normal local magnetic field component topology that corresponds to the picture of Fig.1b. This topology is called as symmetric type of inhomogeneity. Following the Fig.1b it is seen that the magnetic field of value 7 –8 T decreases up to zero on the length of 2 – 3 mm.

Plates of rectangular cross section having a size 7×0.4×38 mm were prepared by electric erosion technique. The required shape was obtained by bending the samples in preliminary prepared moulds. Deformation defects were eliminated by a 48-hours annealing at temperatures 500 K. As a result the parameter determining the ratio of resistance at 300 K and at 4.2 K RRR was 8000 for all samples. Both sides of double bent sample were prepared for potential probe mounting. The separation between the contacts for the measuring signal was about 5 – 6 mm. The magnetic field was generated by a superconducting solenoid in a helium cryostat with working field up to 8.5 T. The electric potential picture was measuring along transport direction whereas current was flowing through double U shaped bent specimen from one branch to another that. The current value through the cross section of U shaped sample was chosen so to precisely measure electric potential picture on both sides without any heating of sample. The current density averaged through the sample cross section was such that a thermal flux through the sample surface was less than $2 \cdot 10^{-5}$ W/mm^2. The self magnetic field of current was rather small in comparison with field of solenoid and was neglected in measurement data and analysis. Far from bent section of U shaped sample the potential picture was symmetric in the sense that both sides of any branch of sample had the same potential value in accordance with the homogeneous current flow through this region of conductor. This principle was used for correct orientation of U shaped sample in magnetic field before measurement. As the traditional manner of orientation of samples is not valid for inhomogeneous current flowing the sample in magnetic field of helium cryostat was rotating until the potential picture on the both sides of both branches in the region spacing far from bent section becomes totally symmetric. Respectively in the region of bent section the potential data on opposite sides are most different in behavior and value.

3. Results and analysis

For two types of magnetic field inhomogeneity in contact two sets of electric potential distribution pictures along transport direction has been measured. For the first type of magnetic field topology (inversion type of in-homogeneity) the heterogeneous abrupt model contact is placed in inhomogeneous along transport direction magnetic field. The potential picture for this contact is represented in Fig.2a. Fig.2a is placed under the spatial topology of magnetic field represented in Fig.1a. For the second type of magnetic field topology (symmetric type of inhomogeneity) the heterogeneous not very abrupt model contact having transition dimension of 3-4 mm is placed into homogeneous magnetic field. The respective potential picture is represented in Fig.2b. Electric field potential picture in Fig.2 are measured on opposite Hall sides along sample length L .The potential picture is shown for contact region (the center of bent section corresponding to zero magnetic field line) and for region near to heterogeneous boundary.

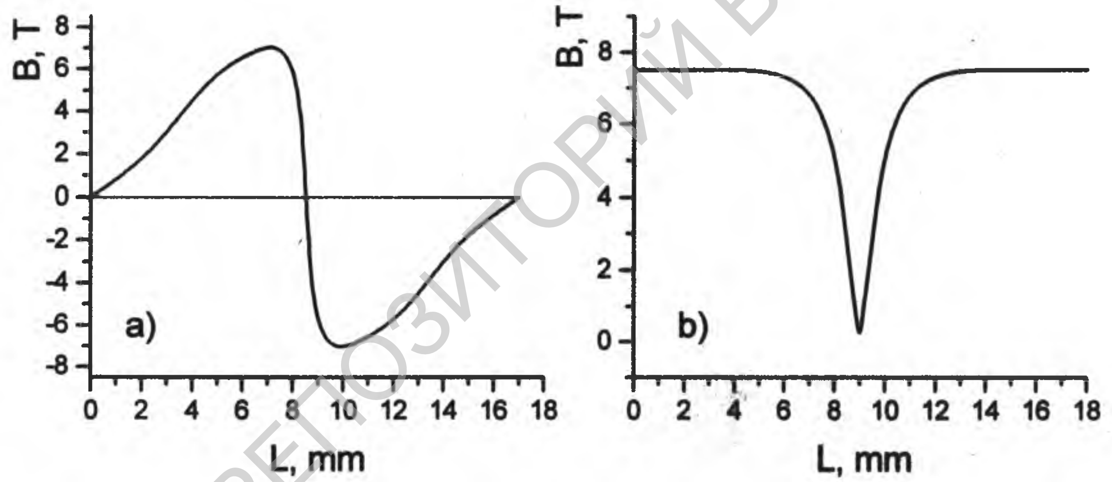

Fig.1. The topology of magnetic field B (up double block):
a) the inversion type of inhomogeneity; the orientation of B is parellel to U shaped sample, (U || B);
b) the symmetric type of inhomogeneity, the orientation of B is normal to Ushaped sample ($\subset \perp$ B).

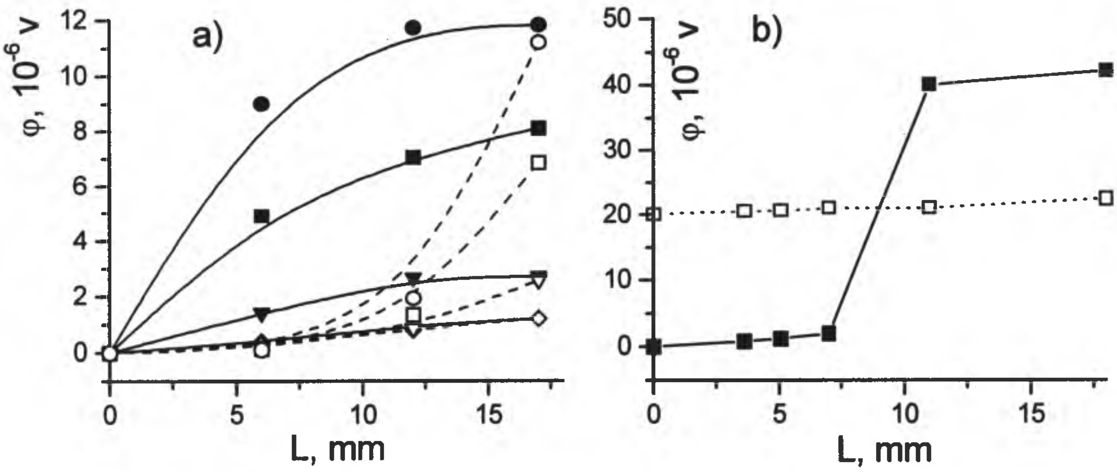

Fig.2. The potential picture along sample length on opposite sides (solid and dashed lines) in inhomogeneous magnetic field (down double block):
a) field topology corresponds to Fig.1a ; where the maximal field B, T is: 0.14 (diamonds), 1.4 (triangles), 4.3 (squares), 7.1 (circles);
b) field topology Fig.1b), where the maximal field is 7.5 T.

It is interesting that for inversion type of inhomogeneity the potential picture is symmetric near zero field line. A strong and a weak spatial dependence of potential on *L* (from left to right, solids lines of Fig.1 a) takes place at the one of side whereas at an opposite side the weak and a strong spatial dependence of potential on transport coordinate L is observed respectively. At zero normal component of magnetic field (far fromt heteroregion) the potential magnitudes on opposite sides are the same and as a result the curves coincide indicating that electric Hall voltage difference is zero. For symmetric type of magnetic field inhomogeneity (Fig.1b). the potential dependence on transport direction L at opposite sides is essentially different on behavior. One side of sample has abrupt jump of potential in contact region but another side shows very weak dependence on coordinate along transport direction including the contact region. It is seen that far from inhomogeneous region the magnetic local component is the same and voltage difference between opposite sides is a constant along coordinate *L* in accordance with magnetic topology From Fig.2 it is clear that under inhomogeneity of conductivity both due to heterogeneous contact and magnetic field gradient the current density reallocation takes place.

Here we continue to analyze the peculiarities of charge transfer under conductivity inhomogeneity, and the real energy structure and peculiarities of isoenergetic surface of intermediate type are taken into account. Intermediate type of isoenergetic surface is valid as it is suitable to analyse the transfer peculiarities through heterocontact aluminum-copper for some partial cases. To analyze the problem the macroscopic equations of field based on continuity conditions for current density and the potentiality of steady electric field have been used to write the basic equation for electric potential φ:

$$div j = 0; j_i = -\sigma_{ik} \partial\varphi / \partial x_k ,$$

here j is a current density vector, j_i is current density component along i-direction, σ_{ik} – is a component of conductivity tensor.
The next differential equation describes the transfer process through the inhomogeneous region near metal heterogeneous contact:

$$\left(\frac{1}{\beta^2}+\frac{\alpha}{\beta}\right)'_x \varphi'_x+\left(\frac{1}{\beta^2}+\frac{\alpha}{\beta}\right)\varphi''_{xx}-\frac{\beta'}{\beta^2}\varphi'_y+\left(\frac{1}{\beta^2}+\frac{\alpha}{\beta}\right)\varphi''_{yy}-\frac{\beta'}{\beta^2}\varphi'_z+\varphi''_{zz}=0 \qquad (1)$$

Here φ'_x , φ''_x , $(\ldots)'_x$ and so on – are the derivatives of respective order with coordinates x or y, z; $\beta' = \partial\beta/\partial x$; $\beta = \omega\tau$, ω is Larmor frequency, τ is a relaxation time.
To get the equation (1) the modified type of electric conductivity tensor is used that takes into account the peculiarities of charge transfer via polycrystalline sample. Polycrystalline high pure aluminum conductor has no classical asymptotic saturation of electrical resistance in transverse magnetic field. Only very dirty aluminum sample shows the correspondence to Koller rule. So these peculiarities connected with the aluminum energy structure are to be taken into analysis. For this aim a more complicated type of conductivity tensor containing both a contribution from closed electron trajectories and a contribution to conductivity from electrons belonging to open and elongated trajectories have been used in phenomenological manner.

$$\sigma_{ik}=\sigma_0\begin{pmatrix} \frac{\alpha}{\beta}+\frac{1}{\beta^2} & \frac{1}{\beta} & \frac{1}{\beta} \\ -\frac{1}{\beta} & \frac{\alpha}{\beta}+\frac{1}{\beta^2} & \frac{\alpha}{\beta}+\frac{1}{\beta} \\ -\frac{1}{\beta} & -\frac{\alpha}{\beta}-\frac{1}{\beta} & 1 \end{pmatrix} \qquad (2)$$

Here σ_0 is a scalar – conductivity in zero magnetic field. Magnetic field is oriented along z coordinate. The component $\sigma_{xx} = 1/\beta^2 + \alpha/\beta$ has such view after taking into account of the existence of a layer of open electron orbits. This layer appears in strong magnetic field. The contribution into resistivity of this layer via its thickness is proportional to parameter of effective magnetic field β^{-1}. Usual view of diagonal component of conductivity tensor for closed anisotropy Fermi surface is $\sigma_{xx} = 1/\beta^2$. However effective thin layer of open orbits due to magnetic break down and umklapp processes exists in polycrystalline sample. The term responsible for this layer is α/β which must be accepted in modulo, (for aluminum $1/\beta^2 >> \alpha/\beta$). Following such a presentation the diagonal component of resistivity tensor of pure aluminum plate sample is $\rho_{xx} \propto 1/\sigma_0(1+\alpha\beta)$. That is it has not very strong slope in linear dependence on magnetic field because the parameter α/β describing the quantity of open electron trajectories is rather small. Respectively the magneto-resistance ρ_{xx} for polycrystalline copper sample may be represented as the same expression where the strong linear Kapitza law takes place because the parameter describing the width of open electron trajectories is very great and closed to unit, ($1/\beta^2 <<$ α/β , $\alpha \cong 1$). At the absence of open trajectories the parameter α is zero and the tensor (2) acquires the properties of anisotropy classic electron gas. Isotropy free electron gas has conductivity tensor components of next type:

$\sigma_{xx} = \sigma_0/(1+\beta^2)$, $\sigma_{xy} = \sigma_0\,\beta/(1+\beta^2)$… etc.

To analyze the equation (1) it is necessary to indicate that potential derivatives with longitudinal coordinate and its contribution to the total picture of distribution is not dominant. These derivatives are to satisfy the condition:

$$-(\beta'/\beta^2)\,\varphi'_z + \varphi''_{zz} \cong 0 \tag{3}$$

It means that $\varphi(z) = C\,(\beta'/\beta^2)^{-1}\exp((\beta'/\beta^2)z)$, if β'/β^2 = Const, We analyze high magnetic fields that is $\beta \gg 1$, respectively the parameter $\beta' L/\beta^2 \ll 1$ (here L is a dimension of inhomogeneous region of sample), and both components of (3) are to be very small in comparison with other components of (1). That is the dependence of electric potential on *z*-coordinate have to be very slow in comparison with respective dependence along other transverse coordinates. Exponential dependence of potential on *z*-coordinate deals that on the thickness of sample (*z* varies from zero to *d*, *d* is equal to sample thickness) the exponential parameter $(\beta'/\beta^2)d$ is so small ($(\beta'/\beta^2)d \ll \beta' L/\beta^2$) that only first term of expansion is real. So taking into account that the thickness of samples in *z* direction is small in comparison with other dimensions the approximation that the current flow picture in normal to magnetic field plane is not influenced by movement of charges along *z*-direction is rather correct. As the carrier motion along magnetic field is neglected, the electric potential φ is accepted as a function of *x* and *y* coordinates only. For the two-dimensional geometry the potential equation is:

$$\left(\frac{1}{\beta^2}+\frac{\alpha}{\beta}\right)'_x \varphi'_x + \left(\frac{1}{\beta^2}+\frac{\alpha}{\beta}\right)\varphi''_{xx} - \frac{\beta'}{\beta^2}\varphi'_y + \left(\frac{1}{\beta^2}+\frac{\alpha}{\beta}\right)\varphi''_{yy} = 0 \tag{4}$$

The separation of variables allows to obtain the total decision of equation (2) for some particular cases:

$$\varphi = C_1\left(\int \frac{\beta^2}{1+\alpha\beta}\,dx\right) exp\left(\beta'\frac{1}{1+\alpha\beta}\,y\right) + C_2 \tag{5}$$

This expression is valid when $\beta'/(1+\alpha\beta)$ = Const. So for the limit case $\alpha \to 0$ one can obtain the potential distribution in approximation of free electron gas. Following the approximation $\alpha = 0$ the potential picture under linear law of spatial dependence of magnetic field can be easily obtained. It is essential that β' indicates a magnetic field gragient direction along transport flow. This approximation ($\alpha = 0$) is not only abstract that. It may be applied to aluminum sample too if the magnetic field gradient is not very large that in comparison with unvariable part of magnetic field. It means that: $\beta' = K$; $\beta = \beta_0 + Kx$; $KL \ll \beta_0$., L is the sample length along charge transport via inhomogeneous

region. Our own study of potential picture distribution in aluminum samples under linear law of magnetic field variation and above mentioned small values of magnetic field gradient has indicated the correctness of applied approximation (of course the condition of strong magnetic field ($\beta_0 >> 1$) is to be realized).
Following Eq.(3) the potential dependence on sides of sample placed in inhomogeneous magnetic field has strong (at $y = b$, where b is the sample width) and weak (at $y = 0$) dependence on coordinate along transport direction. The direction of magnetic field gradient plays very important role in the potential distribution on the reason that magnetic gradient participates in the governing of transport process via strong exponential dependence on transverse y-coordinate. The transverse dependence of potential on y-coordinate is much higher of that along transport x-coordinate. Here under inhomogeneity the definite correspondence between transport electric field and Hall field is similar to homogeneous situation. So for this particular case of aluminum type conductor placed in magnetic field having small gradient as result non-large influence of elongated trajectories on to the total potential picture takes place. The respective current density distribution along transport direction is:

$$\varphi = C_1 \int \beta^2 dx exp(\beta' y) + C_2 ; \quad j_x = C\beta' exp(\beta' y); \quad \beta' = const \qquad (6)$$

Following this expression the potential dependence on coordinate in transverse magnetic field is rather complicated than that belonging to the actions of homogeneous magnetic field. For inhomogeneous case the potential dependence on x-coordinate is quasi-linear and the dependence on transverse y-coordinate is exponential. Under homogeneous magnetic field action the potential dependence is:

$$\varphi = C(x+\beta y). \qquad (7)$$

Respectively from (5,6) it follows that the steady current skinning takes place. Namely near one of side the current density is large and near opposite side the current density is small. Magnetic field gradient inversion transforms the potential picture and the current skinning center to opposite side. This type of dependence takes place in Fig.2a where the effective inversion of magnetic field gradient sign occurs near zero field line.
For Fig.2b the dependence of φ is governed with the effective magnetic field action which has the same sign via total model contact and sample. The opposite type of Hall conductivity near central zero line transforms the effective magnetic actions and the abrupt increase of potential corresponds to an action of exponent in Eq.(4) whereas the weak potential growth on opposite side is a result of the absence of an exponential contribution to potential.. For this type of contact the direction of gradient is the same via inhomogeneous region and through the contact line. As a result the current density maximum locates near the same side of bent sample.
It is necessary to stress the potential picture on Fig.2 has only qualitative similarities with behavior described by (6). The gradient value on Fig.1 is not small. A law of magnetic field variation along charge transport is more complicated than linear that. Respectively the law of potential change is not a linear that as follows both from (6) and Fig.2. For this case a nonzero parameter α for conductivity tensor and the potential picture (5) is suitable

for the description of charge transfer. The (5) describes charge transfer through both aluminum-anti-aliminum and aluminum-copper contact. For symmetric inhomogeneity (Fig.1b) the region of magnetic field variation that is the contact dimension is so short that the intermediate potential probes on sample sides via inhomogeneous region have not been arranged. As a result the abrupt potential increase is shown by line connecting two points on the edge of contact. Linear smooth law of potential increase from left to right (far from zero field line) indicates the influence of homogeneous magnetic field.
As to copper type conductor in heterocontact (experimental results we have no yet), the analysis of Eq.(3) allows to conclude that the potential picture redistribution due to double inhomogeneity also can be estimated. So for copper type conductor the width of layer of open trajectories is large, these particles are basic in charge transfer. The respective expression for the electric potential is:

$$\varphi = C_1 \int \frac{\beta}{\alpha} dx exp\left(\frac{\beta'}{\alpha\beta} y\right) + C_2 \,; \quad \frac{\beta'}{\alpha\beta} = const \qquad (8)$$

The equation (8) is valid only for exponential law of magnetic field variation along transport direction. Respectively the integration of (8) with variable *x* leads to exponential type of spatial variation of electric potential along transport direction: $\varphi \propto C\ exp(k_1 x + k_2 y)$, here k_1 and k_2 are the *Constants* The analysis shows that for copper type conductor the potential redistribution due to inhomogeneity is not so high as for aluminum type conductor. The reason of this is the large number of elongated orbits on isoenergetic surface. The carriers of these orbits are not so free to drift in transverse direction in gradient magnetic field. As a result the more complicated movement of carriers leads to more weak degree of electric potential reallocation and current skinning'

4. Conclusion

The method of modeling of magnetic field inhomogeneity via curving of current lines allowed to create a physical picture of current flow through the model aluminum based heterogeneous contact. Aluminum based heterocontact consists of pure aluminum sample that have been bent and situated in magnetic field in such manner that an effective magnetic field action is equal to the presence of two heterogeneous components having opposite in sign Hall coefficients. The influence of homogeneous magnetic field on to charge flow via metal hetero-contact is modeled on Fig.1b and Fig.2b where steady current skins near one of sides. Double type of inhomogeneity due to heteroconductivity in magnetic field and due to magnetic field action itself is modeled on Fig.1a and Fig.2a. Here the inhomogeneity generates current density redistribution via contact region and skinning of steady current near one of sides of plate contact before zero field line. The inversion of magnetic field gradient inverses the current skinning picture to opposite side after zero field line. Of course the skinning score is a function of magnitude of total local gradient of task including both magnetic field and electron structure conductivity inhomogeneity. Moreover, the investigation shows that under strong magnetic field both heterogeneous contacts and homogeneous plate conductors situated in such manner that current changes its direction (for example plate conductor is bent technologically as in our experiment) are undergone to the action of forces stimulated with magneto generated inhomogeneity of conductivity. Respective current density redistribution and skinning of charge flow takes place. It means that effective cross section of conductor is less than that in other parts. As a result excessive resistance and heat generation are to be overcome via a correct conjunction of conducting materials and a correct placing of conductors in magnetic field.

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