DOI 10.31489/2022Ph1/111-116

UDC 621.315.592

O.D. Bigozha[1], A.Zh. Seitmuratov[2], L.U. Taimuratova[1*],
B.K. Kazbekova[1], Z.K. Aimaganbetova[3]

[1]Caspian University of Technology and Engineering named after Sh. Yessenov, Aktau, Kazakhstan
[2]Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan
[3]K.Zhubanov Aktobe Regional University, Aktobe, Kazakhstan
(E-mail: taimuratova@mail.ru.)

Longitudinal magnetoresistance of uniaxially deformed n-type silicon

The study of Galvano-magnetic effects (as well as tensoeffects) in silicon under extreme conditions allows not only to identify the mechanisms of these effects but also to identify the possibility of creating gaussmeters, infrared detectors, sensitive strain gauges, amplifiers and generators of a wide frequency range. The reliability of the mechanism of negative magnetoresistance was verified using uniaxial elastic deformation of the studied crystals. Uniaxial deformation excludes interline transitions of electrons, as a result of which negative magnetoresistance disappears with an increase in uniaxial pressure. When cubic symmetry is violated, anisotropic phenomena occur in such crystals. The multipath of the isoenergetic surface of the bottom of the silicon conduction band causes anisotropies of the effective mass and relaxation time, which are associated with the features of the transfer phenomenon. In particular, magnetoresistance (piezoresistance), which is the most sensitive to the anisotropy of the iso energy surface. The influence of the latter on magnetoresistance is most clearly revealed in the region of strong magnetic fields, where the magnetoresistance is saturated since the longitudinal magnetoresistance is entirely due to the anisotropy of electron mobility.

Keywords: galvano-magnetic effects, piezoresistance, negative magnetoresistance, uniaxial pressure, isoenergetic, multivalley model, valley crossing, silicon magnetoresistance.

Introduction

The longitudinal magnetoresistance of n-type silicon on crystals is investigated $d = n_e = 3{,}1 \cdot 10^{12} cm^{-2}$ in the temperature range 77–300K and the observed negative magnetoresistance due to interband transitions of electrons in J∥ H ∥ [110].

The reliability of the mechanism of negative magnetoresistance was verified using uniaxial elastic deformation of the studied crystals.

Uniaxial deformation excludes interline transitions of electrons, as a result of which negative magnetoresistance disappears with an increase in uniaxial pressure.

According to the classical theory, the magnetoresistance should be saturated in strong magnetic fields when μH >>1, where (μ – electron mobility, H – magnetic field strength). To test this theory, we investigated the longitudinal magnetoresistance of n-type silicon in the case of J∥ H ∥ [110].

The isoenergetic surface of the bottom of the silicon conduction band consists of six ellipsoids of rotation (energy minima) located along the axis of type [100] at a distance of $k = 0{,}85k_{\max}$ (k$_{\max}$ is the value of the wave vector corresponding to the boundary of the Brillouin zone) from the center of the Brillouin zone. These energy minima in silicon crystals at six equivalent points are sometimes called valleys [1].

The energy in the vicinity of the extreme point is related to the wave vector by the following relation:

$$\varepsilon = \frac{\hbar^2}{2}\left\{\frac{(k_x + k_{ox})^2}{m_{\Pi}} + \frac{(k_y - k_{oy})^2}{m_{\perp}} + \frac{(k_z - k_{oz})^2}{m_{\perp}}\right\}$$

where $m_{\Pi}, m_{\perp}$ – longitudinal and transverse effective masses of electrons, k_{ox}, k_{oy}, k_{oz} – coordinates of the center of the ellipsoid, $T = 77{,}4K : m_{\Pi} = 0{,}911m_0\, , m_{\perp} = 0{,}191m_0$ m_0 – free electron mass, and the attitude $\frac{m_{\text{Ц}}}{m_{\perp}} = 4{,}72$ characterizes the anisotropy of isoenergetic surfaces. Thus, in silicon, the total electric current comprises currents caused by carriers located in different valleys and, consequently, the total conductivity of the crystal is the sum of the conductivities of individual valleys.

If there are no external influences that violate the cubic symmetry of the crystal (for example, uniaxial deformation, heating electric field, quantizing magnetic field), then the electrons are evenly distributed across the valleys. In this case, the total conductivity of the crystal is an isotropic value, despite the anisotropic nature of the conductivity of each valley separately.

Experimental and Results and Discussion

The saturation of the longitudinal magnetoresistance of silicon in a classically strong magnetic field (μH>>1), in the case of J∥ H ∥ $[110]$ is determined by the formula [2].

$$\left[\frac{\rho_H}{\rho_0}\right]_{sat} = \frac{(2k+1)(k+1)}{k(k+5)} \qquad (1)$$

where $\rho_{\text{н}}$ – resistivity silicon crystal in a magnetic field, ρ_0 – specific resistance of the crystal in the absence of magnetic field, $k = \frac{m_{\text{Ц}} \prec \tau_{\text{Ц}} \succ}{m_{\perp} \prec \tau_{\perp} \succ}$ is the parameter of anisotropy ($\tau_{\text{Ц}}, \tau_{\perp}$ – longitudinal and transverse relaxation time, respectively).

Taking k=4.72, we make numerical estimates of magneto resistance

$$\left[\frac{\Delta\rho_H}{\rho_0}\right]_{sat} = 1{,}315$$

which gives a good agreement with the experimental values in the temperature range of 150–300 K obtained on a sample with a concentration of current carriers $n_e = 4{,}1 \cdot 10^{12} sm^{-3}$.

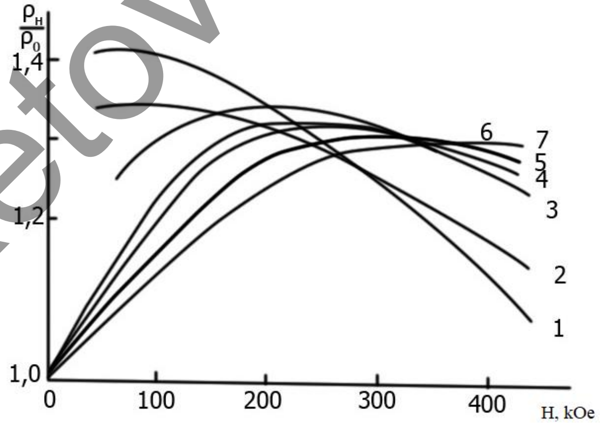

Figure 1. Temperature dependence of the longitudinal magnetoresistance of n-type silicon for a sample with $\rho_{300Ke} = 150 Om \cdot sm\ J\text{II}H\text{II}[110]T^0K$ 1 – 77, 2 – 102, 3 – 150, 4 – 204, 5 – 240, 6 – 270, 7 – 300

$$\left[\frac{\rho_H}{\rho_0}\right]_{sat} = 1{,}31$$

This indicates that in this temperature range $k_\tau = \frac{\prec \tau_{\perp} \succ}{\prec \tau_{\text{Ц}} \succ} = 1$ the interline scattering mechanism dominates.

However, with a decrease in temperature, the discrepancy between the experimental results and the calculated ones increases, so, for example, for $T = 77{,}4K$, it reaches

$$\left[\frac{\rho_H}{\rho_0}\right]_{sat} = 1{,}4.$$

This is due to the contribution of the anisotropy of the scattering mechanism (in this case, acoustic phonons, for which $k_\tau = 0{,}76$) [3].

As can be seen from Fig. 1, in strong magnetic fields, in addition to saturation of magnetoresistance, the manifestation of quantum effects is also observed. The latter, in turn, are associated with a number of features, in particular, the redistribution of electrons between valleys having effective electron masses of $0{,}26m_0$ and $0{,}422m_0$ respectively, leading to the appearance of negative magnetoresistance. This phenomenon was first experimentally observed in [3] in Germany when studying the longitudinal magnetoresistance at 20, 4 K, and its theoretical interpretation was given in the work [4].

We observed this effect on n-type silicon when studying both longitudinal and transverse magnetoresistance (at 77.4 K) in the following cases H‖[001], H‖[110], which is caused by the redistribution of electrons between valleys, that is, interline transitions of electrons.

Fig.1 (Curves 1 and 2) shows that the magnetoresistance after saturation has a decline area, which is associated with a multi-valley model of the isoenergetic surface of the silicon conduction band, and it can be easily understood from the following.

In the quantum limit, due to the nonequivalence of different valleys relative to the magnetic field, their bottoms in the magnetic field rise differently due to the different effective mass in these valleys and the migration of electrons from the upper valley to the lower ones begins, as a result of which the conductivity increases, that is, the resistance decreases and a decrease in the magnetoresistance curves is observed.

The complete migration of electrons from the upper valley to the lower ones is carried out only in the ultra-quantum region (when$\hbar\omega_{\text{H}} \leq 3\text{к}_{\text{Б}}\text{T}$),

where $\hbar$ – is the Planck constant of division by 2π, $\omega_H = \dfrac{e \cdot H}{m \cdot c}$, e – is the electron charge, H – is the magnetic field strength, m is the effective mass of the electron, c – is the speed of light, $k_{\text{Б}}$ – is the Boltzmann constant, T – is the absolute temperature) only a part of the electrons moves.

Electron migration between valleys at H-400 kOe reaches

$$\frac{n_i}{n_j} = 0{,}51.$$

Thus, the results of the experiment in n-type silicon clearly demonstrate the reliability of the mechanism of negative magnetoresistance caused by the actual pumping of current carriers between the valleys of the conduction band, shifting along the energy scale in a quantizing magnetic field at different "speeds".

Note that with the help of uniaxial elastic deformation, the energy gap between the valleys can be changed to a wider range than is achieved in quantizing magnetic fields and thereby verify the validity of this interpretation of the observed negative magnetoresistance of n-type silicon at orientation J‖ H ‖ [110].

The results of such experiments are shown in Figure 2. The data obtained on a uniaxially deformed n-type silicon crystal proves that the decline in magnetoresistance (Fig.2, curve 1) is due to the interline transition of electrons, which gradually disappears with an increase in mechanical stress (Fig.2, curves 4,6). In this case, the magnetoresistance is doubled in magnitude and the negative part of the curve disappears completely. A low-amplitude magnetic resonance is observed on these crystals.

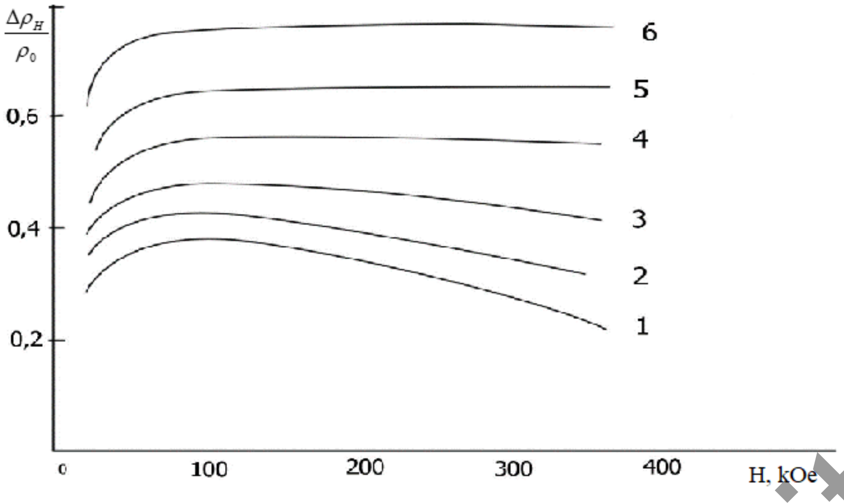

Fig.2 Effect of uniaxial pressure X on the negative part of the magnetoresistance of n-type silicon at X∥ J ∥ H ∥ [110]($n_e = 4{,}1\cdot 10^{13} sm^{-3}, T = 77{,}4K$); $X\cdot 10^{-3}\,\frac{Pa}{sm^2} : 1 - X = 0;2 - 1;2 - 3;4 - 5;5 - 6$

Conclusions

The increase in the magnetoresistance of silicon with uniaxial pressure is explained as follows.The saturation of the longitudinal piezoelectric resistance of n-type silicon in the case of XJ ∥ [110] is determined by the formula derived by one of the authors [5–7]:

$$\left[\frac{\rho_X}{\rho_0}\right]_{sat} = \frac{2(2k+1)}{3(k+1)} \tag{2}$$

Using this formula, $\left[\frac{\rho_X}{\rho_0}\right]_{sat} = 1{,}35$ was calculated, which is in good agreement with the experimental value of magnetoresistance $\left[\frac{\rho_X}{\rho_0}\right]_{sat} = 1{,}354$ (Figure 2, curve 1)

Combining the ratio (1) and (2), we obtain an expression that allows us to calculate the longitudinal magnetoresistance in saturation by the magnetic field according to the measurement data of the longitudinal piezoresistance at strong single-bearing deformations [8, 9]:

$$\frac{\rho_{H\to\infty}}{\rho_{X\to\infty}} = \frac{3(k+1)^2(k+2)}{2k(2k+1)(k+5)}. \tag{3}$$

The calculated value according to the formula (3) $\frac{\rho_{H\to\infty}}{\rho_{X\to\infty}} = 0{,}73$, which gives a good agreement with the experimental value – 0.732, shown in Fig.2 (curve 5,6). This proves the increase in magnetoresistance with uniaxial pressure.

References

32 Proskuryakov Y.Y. Linear in-plane magnetoconductance and spin susceptibility of a two-dimensional electron gas on a vicinal silicon surface / Y.Y. Proskuryakov, Z.D. Kvon, A.K. Savchenko // *Physical review b: condensed matter and materials physics*, 2004. — Vol. 69 (3). – P. 333041–333044. DOI: 10.1103/PhysRevB.69.033304

33 Toshinori Taishi. Heavily Boron-Doped Silicon Single Crystal Growth: Constitutional Supercooling // Toshinori Taishi, Xinming Huang, Masayoshi Kubota, Tomio Kajigaya, Tatsuo Fukami and Keigo Hoshikawa // *Japanese Journal of Applied Physics*, 2000. — Vol. 39. — P. 5-8.

34 Kolomoets V. Application of piezoresistance effect in highly uniaxially strained pSi and n-Si for current-carrier mobility increase / V. Kolomoets, V. Baidakov, A. Fedosov, A. Gorin, V. Ermakov, E. Liarokapis, G. Gromova, B. Kazbekova, L. Taimuratova, B. Orazgulyev // Physica Status Solidi, 2009. — Vol. 246, No. 3. — P.652–654.

35 Kolomoets V., Baidakov V. Orazgulyev B., Taimuratova L.U. et al. Strain-induced Nonlinear Behaviour of Electron Effective Mass in Degenerately Doped n-Si (P) Under High Uniaxially Pressure X‖[111] // Phys. Status Solidi, 2009. — Vol. 246, No. 3. — P. 612–614.

36 Orazguliev B. Longitidinal magnetoresistance of uniaxially deformed p-silicon J‖B‖[001] / B. Orazguliev, L.U. Taimuratova // *Ukrainian Journal of Physics*, 2008. — Vol. *53(3).* — P. 246–249.

37 Баранский П.И. Механизмы рассеяния носителей тока, ответственные за формирование магнитопьезосопротивления N-SI в области сильных упругих деформаций / В.М. Бабич, В.Л. Борблик, Ю.П. Доценко, В.Б. Ковальчук // Физика и техника полупроводников. — 1983. — Т. 17. — В. 6. — С. 67 0-671.

38 Taimuratova L.U., Bigozha O.D., Seitmuratov A.Zh., Kazbekova B.K., Aimaganbetova Z.K. Negative longitudinal magnetoresistance silicon on interline electron transitions // News of the National Academy of Sciences of the Republic of Kazakhstan, Physico-Mathematical series. ISSN 1991-346X Vol. 6, No. 340 (2021), 37–41. https://doi.org/10.32014/2021.2518-1726.99

39 Almagambetova A.A. Problem on the distribution of the harmonic type relay wave / A.A. Almagambetova, S.S. Tileubay, L.U. Taimuratova, A. Seitmuratov, K. Kanibaikyzy // News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 2019. — 1(433). — P. 242–247.

40 Seitmuratov A. Approximate equation plate oscillation for transverse displacement of points of the median plane / A. Seitmuratov, Z.T. Seylova, K. Kanibaikyzy, A.K. Smakhanova, S.M. Serikbol // News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 2018. — 3(429). — P. 258–265.

О.Д. Биғожа, А.Ж. Сейтмұратов, Л.У. Таймуратова, Б.К. Казбекова, З.К. Аймаганбетова

Деформацияланған бір осьті n-типтес кремнийдің бойлық магниттіккедергісі

Төтенше жағдайларда кремнийдегі гальваномагниттік әсерлерді (сонымен қатар тензоәсерлерді) зерттеу бұл әсерлердің механизмдерін анықтап қана қоймай, гауссметрлерді, инфрақызыл детекторларды, сезімтал тензобергішті, күшейткіштерді және кең жиілік диапазонының генераторларын құруға мүмкіндік береді. Теріс магниттіккедергі механизмінің беріктілігі зерттелетін кристалдардың біросьті серпімді деформациясы арқылы тексерілді. Біросьті деформация электрондардың аңғарааралық ауысуын болдырмайды, нәтижесінде теріс магниттіккедергісі біросьті қысымның жоғарылауымен жойылады. Мұндай кристалдардың кубтық симметриясы бұзылған жағдайда анизотропты құбылыстар пайда болады. Кремнийдің өткізгіштік зонасынан изоэнергиялық беттің көпаңғарлы сипаты тиімді массасы мен релаксация уақытының анизотропиясын анықтайды, бұл тасымалдау құбылысының ерекшеліктерімен байланысты. Атап айтқанда, магниттіккедергі (пьезокедергі) изоэнергетикалық беттің анизотропиясына ең сезімтал болып табылады. Соңғысының магниттіккедергіге әсері магниттіккедергі қаныққан күшті магниттік өрістер аймағында айқын көрінеді, өйткені бойлық магниттіккедергісі толығымен электрон қозғалтғышының анизотропиясына байланысты.

Кілт сөздер: гальваномагниттік эффекттер, пьезокедергісі, теріс магнитті кедергісі, біросьті қысым, изоэнергетикалық аймақаралық өтулер, аймақтық қиылысулар, кремнийлі магниттік кедергі.

О.Д. Бигожа, А.Ж. Сейтмуратов, Л.У. Таймуратова, Б.К. Казбекова, З.К. Аймаганбетова

Продольное магнитосопротивление односно-деформированного кремния *n*-типа

Изучение гальваномагнитных эффектов (а также тензоэффектов) в кремнии в экстремальных условиях позволяет не только выявить механизмы этих эффектов, но и возможность создания гауссметров, инфракрасных детекторов, чувствительных тензодатчиков, усилителей и генераторов широкого частотного диапазона. Надежность механизма отрицательного магнетосопротивления проверена с помощью одноосного упругого деформирования исследуемых кристаллов. Одноосная деформация исключает междолинные переходы электронов, вследствие чего исчезает отрицательное магнетосопротивление с увеличением одноосного давления. При нарушении кубической симметрии в таких кристаллах возникают анизотропные явления. Многодолинность изоэнергетической поверхности дна зоны проводимости кремния обусловливает анизотропии эффективной массы и времени релаксации, с которой связаны особенности явления переноса. В частности, магнетосопротивление (пьезосопротивление), которое является наиболее чувствительным к анизотропии изоэнергетической поверхности. Влияние последней на магнетосопротивление наиболее отчетливо выявляется в области сильных магнитных полей, где магнетосопротивление насыщается, так как продольное магнетосопротивление всецело обусловлено анизотропией подвижности электронов.

Ключевые слова: гальваномагнитные эффекты, пъезосопротивление, отрицательное магнитосопротивления, одноосное давление, изоэнергетическое междолинные переходы, пересечение долины, кремниевое магнитосопротивление.

References

1 Proskuryakov, Y.Y., Kvon, Z.D., & Savchenko, A.K. (2004). Linear in-plane magnetoconductance and spin susceptibility of a two-dimensional electron gas on a vicinal silicon surface. *Physical review b: condensed matter and materials physics*, 69(3), 333041-333044. DOI: 10.1103/PhysRevB.69.033304

2 Toshinori Taishi, Xinming Huang, Masayoshi Kubota, Tomio Kajigaya, Tatsuo Fukami & Keigo Hoshikawa (2000). Heavily Boron-Doped Silicon Single Crystal Growth: Constitutional Supercooling. *Japanese Journal of Applied Physics,* 39, 5-8.

3 Kolomoets, V., Baidakov, V., Orazgulyev, B., & Taimuratova, L.U. et al. (2009). Application of piezoresistance effect in higlyUniaxially Strained p-Si and n-Si for current-carrier mobility increase. *Phys. Status Solidi, Вып. 246, 3,* 652-654.

4 Kolomoets, V., Baidakov, V., Orazgulyev, B., & Taimuratova, L.U. et al. (2009). Strain-induced Nonlinear Behaviour of Electron Effective Mass in Degenerately Doped n-Si (P) Under High Uniaxially Pressure X‖[111]. *Phys. Status Solidi, 246(3),* 612–614.

5 Orazguliev, B., Taimuratova, L.U. (2008). Longitidinal magnetoresistance of uniaxially deformed p-silicon J‖B‖[001]. *Ukrainian Journal of Physics, 53(3),* 246-249.

6 Baranskii, P.I., Babich, V.M., & Borblik, V.L. (1983). Mekhanizmy rasseianiia nositelei toka, otvetstvennye za formirovanie magnitopezosoprotivleniia N-SI v oblasti silnykh uprugikh deformatsii [Mehanisms of carrier scattering responsible for the magnetopiezoresistance of n-type si in tne range of strong elastic def ormations]. *Fizika i tekhnika poluprovodnikov — SOVIET PHYSICS SEMICONDUCTORS-USSR, Vol. 17, B. 6,* 67 0-671 [in Russian].

7 Taimuratova, L.U., Bigozha, O.D., Seitmuratov, A.Zh., Kazbekova, B.K., & Aimaganbetova, Z.K. (2021). Negative longitudinal magnetoresistance silicon on interline electron transitions. *News of the National Academy of Sciences of the Republic of Kazakhstan, Physico-Mathematical series.* ISSN 1991-346X, 6 (340), 37–41. https://doi.org/10.32014/2021.2518-1726.99

8 Almagambetova, A.A., Tileubay, S.S., Taimuratova, L.U., Seitmuratov, A., & Kanibaikyzy, K. (2019). Problem on the distribution of the harmonic type relay wave. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 1(433),* 242–247.

9 Seitmuratov, A., Seylova, Z.T., Kanibaikyzy, K., Smakhanova, A.K., & Serikbol, S.M. (2018). Approximate equation plate oscillation for transverse displacement of points of the median plane. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 3(429),* 258–265.