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HALL EFFECT AND MAGNETORESISTANCE INVESTIGATION OF FAST ELECTRON IRRADIATED SILICON

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A set of n-type silicon samples has been irradiated by 6.6 MeV electrons with doses from 1 to 5 ($\times 10^{16}$) e/cm^2, and temperature dependences of Hall and magnetoresistance mobilities were measured. The ratio of magnetoresistance and Hall mobilities was found equal to 1.15 ± 0.25. The correspondence of the data measured by both methods opened the possibility of measurement of electron mobility in semiconductors with microinhomogeneities by magnetoresistance effect investigation.

Keywords: magnetoresistivity, silicon, electron irradiation, mobility

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1. Introduction

The free carrier transport properties are important for performances of many semiconductor devices, and they become very relevant for the analysis of changes of the device parameters induced by ionizing radiation. This is important both for the degradation of ionizing radiation detectors [1] and for their performance in the magnetic field environment [2]. Hall and magnetoresistance (MR) effects come in parallel as valuable for carrier transport characterization. In principle, both methods reveal carrier mobility directly and including conductivity measurements the carrier density may be found. A certain disadvantage of these techniques is the lack of knowledge about Hall and MR factors [3] related to the type of the carrier scattering, but more important is the information about the dependence of carriers' mobility on interaction with irradiation defects, the dependence of mobility on temperature or relation with different annealing behaviour. The Hall and MR factors are well known only for separate carrier scattering mechanisms like phonon or impurity scattering, but usually a multiple of these mechanisms participate simultaneously

The geometry of the sample under investigation is very important because it introduces another discrepancy related to the electric field redistribution and the electric current leakage, but as different types of samples are used, it is necessary to test what is the correspondence of data obtained by Hall and MR analysis in the samples fabricated in different geometry.

The main difference between the Hall and MR effects appears if the sample is non-uniform. Many papers have demonstrated a complicated character of the Hall effects in inhomogeneous materials [4–7] that hid the true change of the Hall mobility. Preliminary investigations have already presented how the irradiation with fast neutrons changes Hall and MR effects in silicon [7], but as they were performed in the samples with the extended defects, the methods have to be compared in homogeneous samples. The preliminary results were promising: the Hall voltage lowered significantly with the fluence that was interpreted as the influence of the radiation defects induced inhomogeneities. At the same measurement MR changed only slightly with the dose that was interpreted as its direct proportionality to a change of the mobility of carriers [8]. The irradiation lowers the total number of free carriers but the MR effect is proportional not to the absolute value of resistivity but to its relative change in the presence of the magnetic field. When the irradiation creates isolated regions, the free carriers mostly go around them into the less affected regions, so less information is extracted about the irradiation damage. However, the boundaries of the defective regions are not abrupt and single point defects may appear after irradiation in the free carrier paths. This shows the promises of the MR effect to provide information about the mobility of carriers in the irradiated samples. Both methods allowed calculating carrier mobility only in some limited cases. In crystal materials the high energy neutrons mostly create large-scale defective regions, which act as macroinhomogeneities, while the energy of electromagnetic or electron irradiation dissipates into the crystal mostly forming point defects, which may merge into larger-scale crystal irregularities when certain high doses are being absorbed.

In this work we apply both mentioned carrier mobility measurement techniques simultaneously for the silicon samples irradiated by electrons to show the difference of the measurement revealed characteristics and discuss the ability for further application. The main aim of this comparison is related to revealing a range of possibilities to apply the MR effect to the free carrier mobility control in the samples fabricated primarily for the Hall effect measurement.

2. Experimental details

A set of Hall-bar silicon samples (2 mm width, 6 mm length, and 0.375 mm thickness) was used in our experiments having electron (phosphorous-doped about 10^{15} cm^{-3}) conductivity type with the electric contacts geometry as shown in Fig. 2(a)) inset. The electric contacts were placed on one side (face) of the samples by using surface lithography technique. To avoid the influence of the surface conductivity (and the leakage at the corners) all the sides of the samples were processed to be isolating. One initial sample was prepared for van der Pauw (VDP) type measurements of the same thickness (10 mm × 10 mm area). The magnetic field induction in the experiments was up to 1.75 T. The electric current sourcing and measurement was performed with a Keithley 6430 multimeter, and the Hall voltage was measured with a Keithley 6514 multimeter, which both have 5 to 7 digit measurement precision and 200 TΩ input resistance (voltmeter). At first, the four point probe experiments were carried out to make sure the contacts were good (ohmic) enough to perform temperature dependent measurements. The electron irradiation by 6.6 MeV electrons was performed in cyclotron set-up in Byelorussian State University. The irradiated samples were sensitive to the annealing so only cooling experiments were performed this time. The samples were characterized using stationary Hall and MR measurement techniques simultaneously. Electric current was sourced at two mostly distant bigger contacts (1, 2), while the smaller ones were used for Hall voltage probing (3, 4) and for the control of the electric field drop along the sample (4, 5). The magnetic field was perpendicular to the sample face surface, and the field's opposite directions have been switched in the same data acquiring cycle to eliminate the permanent electric potential on the Hall contacts. The specific conductivity was calculated considering the samples as rectangular shape resistors with the same length as the distance between the contacts. This sample geometry is commonly used for the magnetoresistance measurements and the effect is known as geometrical magnetoresistivity (GMR) [3]. In such geometry the Hall field influences the MR values. The relations between the GMR, the Hall mobility, and the carrier mobility are tied with factors which we treat in these experiments as 1. Moreover, this sample geometry includes a partially longitudinal GMR effect, because the electric current also flows into the sample bulk from the contact islands on the surface.

The MR mobility in this work was calculated using the following classical relation:

$$\mu_{\mathrm{m}} = \frac{1}{B}\left(\frac{I_0}{I_B} - 1\right)^{1/2}. \quad (1)$$

Here B is the magnetic field induction, I_0 is the electric current in the sample when magnetic field is not present, and I_B is the same current with the presence of the magnetic field. Figure 1 presents the dependence of resistivity on the magnetic field induction to demonstrate the correctness of proportionality to the B^2. It was not trivial to observe the linear dependence in such geometry samples.

The Hall mobility was calculated using

$$\mu_{\mathrm{H}} = \frac{1}{B}\frac{l}{w}\frac{U_{\mathrm{H}}}{U_X}. \quad (2)$$

Here l is the distance between the electric current contacts (1, 2), U_X is the voltage applied, w is the distance

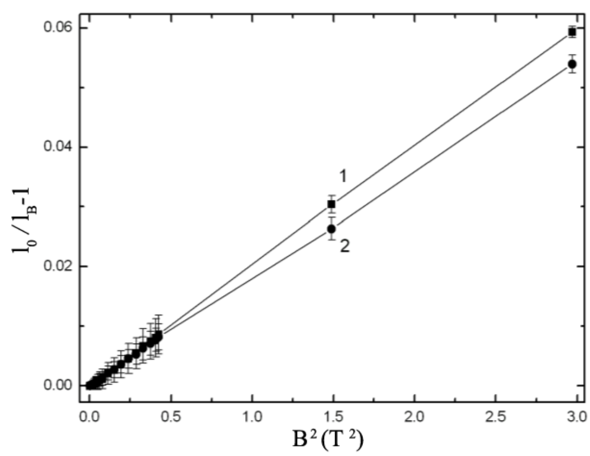

Fig. 1. Magnetoresistance dependence on squared magnetic field induction for the nonirradiated sample (1) and the sample irradiated with the highest fluence (2). The error corresponds to statistical variation of a few measurement times and its magnitude is the difference between the average and the most distant value.

between the Hall contacts (3, 4). It appeared that the electric field distributed along the samples as in Ohmic resistor and the probing of the sourcing field near the Hall contacts was unnecessary. The last relation is suitable for only strong one type conductivity, which was held in our experiments. The values of the Hall and MR mobilities in the following calculations were multiplied by 10000 to obtain [cm^2/Vs] measurement units.

3. Results and discussion

In the initial samples the Hall mobility temperature dependence at a first glance is similar to phonon limited as one can see in Fig. 2(a). However, the Hall factor is required to be know in the whole temperature range to calculate the drift mobility. In these experiments the geometry factor may also give discrepancy, so to make more clearance the sample of VDP geometry was measured and the results were compared to the bar-shape samples results. It was found that the Hall mobility calculated from VDP geometry and MR mobility in the whole temperature range are within 93% of their ratio, which varies from 0.98 at low temperature to 1.12 near 225 K and 1.1 at 300 K. For example, the phonon limited mobility in pure silicon at room temperature is about 1560 cm^2/Vs [9] but we obtained the Hall mobility is 1500 cm^2/Vs or 1214 cm^2/Vs in VDP geometry. Introducing VDP geometry factor 0.97 [10] (for samples with dimensions used in this work) the actual Hall mobility is found 1250 cm^2/Vs. The phonon scattering factor in this case may be 1.18 [3], which gives a reasonable drift mobility value of 1060 cm^2/Vs indicating the presence of scattering other than only phonon limited. In these samples the mobility temperature dependence at high temperature suggests the intervalley scattering.

Irradiation should lower the carrier mobility in the crystal samples because it creates the scattering centres but it also may create compensating dopants [11]. By

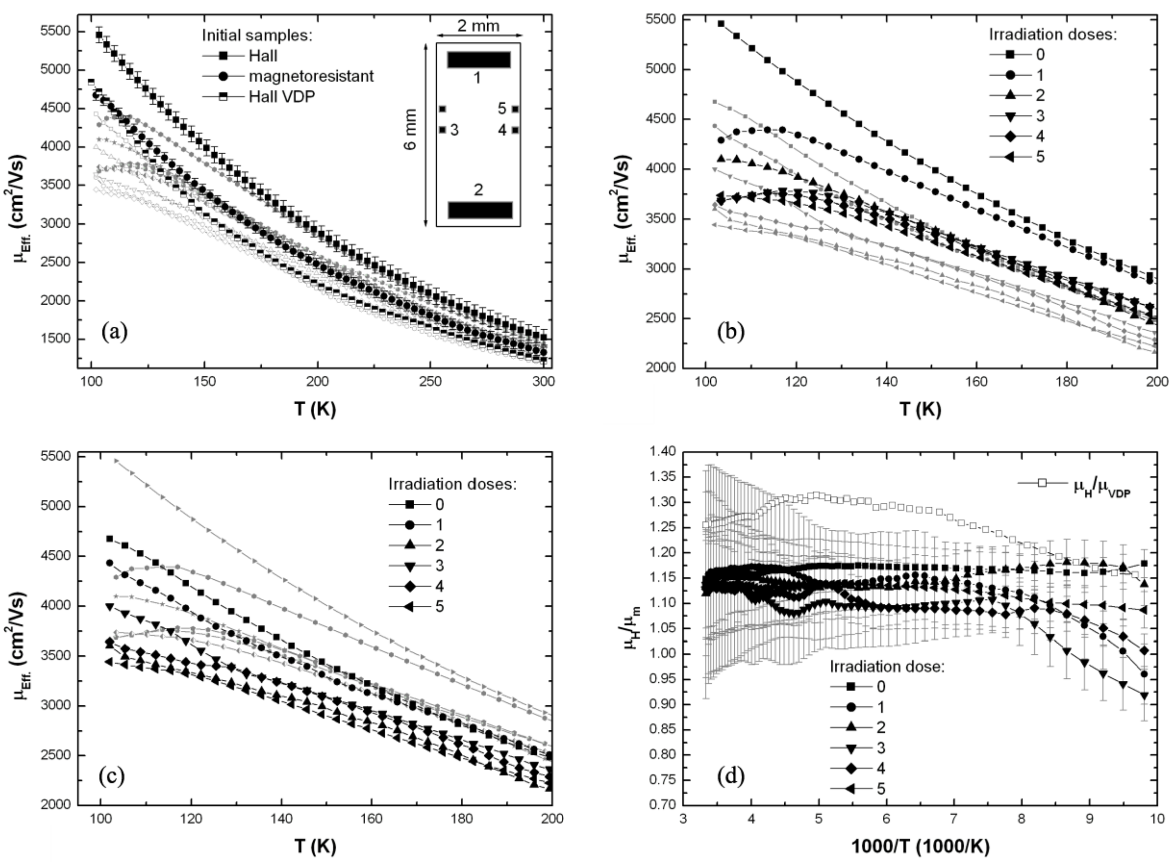

Fig. 2. Hall and magnetoresistance mobility ($\mu_{Eff.}$) for the samples irradiated with corresponding different doses as shown: 0, 1, 2, 3, 4, 5 times 10^{16} e/cm^2. The measurement errors in these graphs were calculated as the maximum difference between the experimental values and the fitting curves to these values. The fitting included the phonon and the ionized impurity scattering terms in the mobilities: (a) curves of the initial samples highlighted and compared to the van der Pauw geometry sample, (b) the Hall data highlighted at lower temperatures, (c) the magnetoresistivity data highlighted, and (d) the ratio of the Hall and magnetoresistance mobilities (in addition, the ratio between Hall-bar type and Hall van der Pauw type mobilities is displayed).

comparison of the free carrier mobility values from the Hall effect (Fig. 2(b)) and MR (Fig. 2(c)) we determined the ratio of MR and Hall mobilities approximately equal to 1.15 ± 0.25 (Fig. 2(d)), and as both effects showed the same dependence on temperature it is possible to conclude that the MR effect can be used to analyse the free carrier mobility in the samples of chosen geometry.

Therefore, the MR effect can be applied to the analysis of free carrier mobility dependence on irradiation also in the cases when the extended defects created the bulk inhomogeneity of samples as it was observed in [8], as well as in [12, 13], where the Hall voltages are anomalously reduced by cellular-structure related nonuniformities, while the MR mobility still remained high.

The measured mobility dependence on the irradiation fluence at different temperature allows analysing the free carrier scattering nature. It was also assumed that the scattering events of different scattering mechanisms do not influence each other and may be treated separately. This allows us to use Matthiessen's rule for the mobility:

$$1/\mu = 1/\mu_1 + 1/\mu_2 + \ldots \quad . \tag{3}$$

As it is known, the temperature dependence of electron mobility in silicon [14] may follow the power law $T^{-2.4}$. This reciprocal dependence (found from the experiment at higher temperature) presented in Fig. 3 can be subtracted from the general reciprocal mobility dependence at lower temperature. It was found that

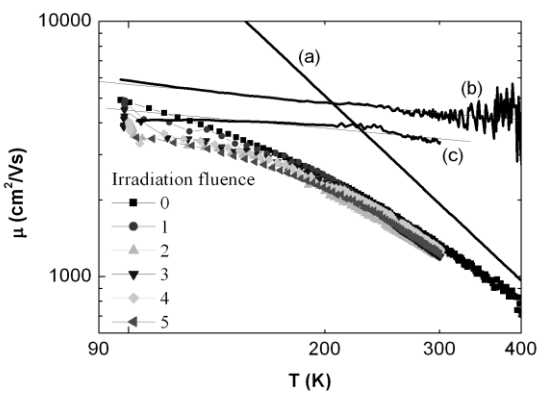

Fig. 3. Temperature dependence of magnetoresistance mobility in the samples irradiated with corresponding different doses as shown: 0, 1, 2, 3, 4, 5 times 10^{16} e/cm^2, and the simulated (extrapolated from the experiment) electron mobility according the $T^{-2,4}$ dependence (a), and the electron mobility temperature dependence if the dependence (a) was subtracted for in the initial sample (b) and irradiated to 5 10^{16} e/cm^2 (c).

the remaining part of mobility has a weak dependence on temperature and a linear fit gave the value (–0.234 ± 0.016) and (–0.233 ± 0.013) in the nonirradiated and irradiated to $5 \cdot 10^{16}$ cm^{-2} fluence, respectively. This result can be explained proposing that this contribution is related to the conductivity via surface states and be similar to the Mott dependence in the disordered materials. Further analysis of the scattering centres requires analysing the dependence of free carriers' mobility on the passivation of the surface and on the scattering centres' filling, which is possible to implement by excitation of semiconductors by an intense light pulse [15] that will be performed.

4. Summary

The Hall and magnetoresistance (MR) mobility measurements were carried out simultaneously for the silicon samples irradiated with fast electrons and the temperature dependences correlated. The ratio of MR and Hall mobilities was found equal to 1.15 ± 0.25. The MR effect is less sensitive than the Hall effect to microinhomogeneities and it can be used for analysis of properties of semiconductors with the extended defects.

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GREITAISIAIS ELEKTRONAIS APŠVITINTO SILICIO HOLO REIŠKINIO IR MAGNETOVARŽOS TYRIMAI

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Santrauka

Darbe tyrinėti n-tipo silicio bandiniai, apšvitinti 6,6 MeV energijos elektronais, pasitelkiant Holo ir magnetovaržos reiškinius. Bandinių geometrija išskirtinai tinka Holo reiškiniui, tačiau norėta išsiaiškinti, ar prasmingus rezultatus galima gauti matuojant ir magnetovaržą. Ankstesniais tyrimais buvo nustatyta, kad Holo įtampos signalas ženkliai iškraipomas, kai medžiagoje yra stambesni nevienalytiškumai, pvz., atsiradę dėl švitinimo (iki 10^{16}/cm^2) greitaisiais neutronais, o magnetovaržos signalas išlieka panašus, kaip ir nešvitintų bandinių. Šiame darbe silicis buvo apšvitintas elektronais, kurie daugiausiai kuria taškinius defektus. Išmatuotos temperatūrinės judrio ir laidumo priklausomybės nuo 100 iki 300 K intervale parodė, kad nors ir nesilaikoma magnetovaržos matavimams keliamų bandinių geometrijos reikalavimų, galima atlikti pakankamai kokybišką krūvininkų judrio analizę.