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The 40th RD50 Workshop (CERN)

Charge carrier mobility investigation in p-type Si after 6MeV electron irradiation

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Motivation

- The demand of radiation detectors!
- Which results in available material sorting, analysis and engineering for a better detector fabrication

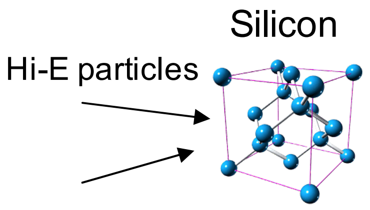
Indirect

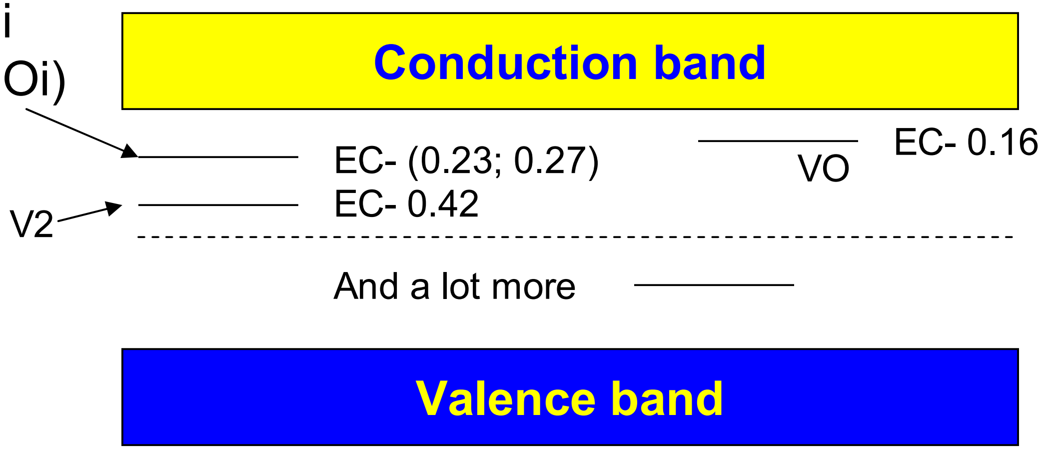
Direct

This work was performed as a part of CERN RD50 collaboration and the Vilnius University contribution was supported by the Lithuanian Academy of Sciences CERN-RD50 grants. The collaboration between Vilnius and Belarusian State universities was supported by Research Council of Lithuania under contract No. TAP-10066 and by National Academy of Sciences of Belarus.

In more detail:

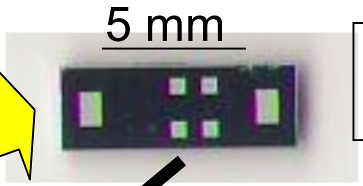
Recent interest in p-type Si and related defects (like BiOi)




Adey et al 2003, A. HIMMERLICH et al 2021 …

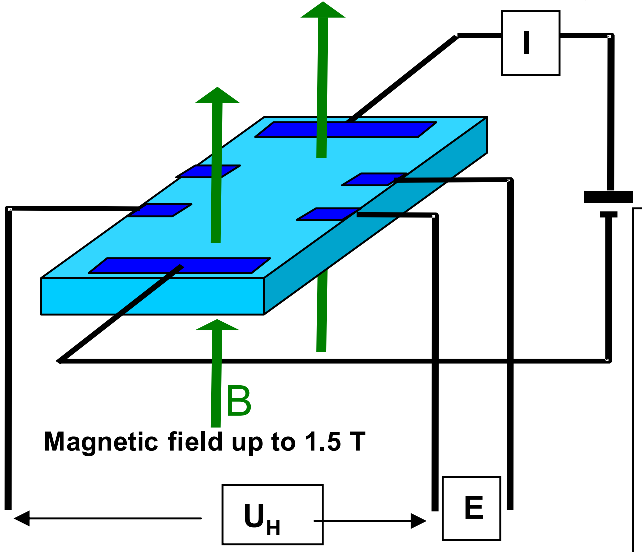
Kitchen

Samples from our partners



Irradiated with 6MeV (or 4MeV) electrons
Fluence from 0.4 to 5 x 10^{16}e/cm^2

Plugging into equipment



Magnetic field up to 1.5 T

$$r_H = \mu_H / \mu_C = \langle \tau^2 \rangle / \langle \tau \rangle^2$$

Equipment **SHOULD** give:

$$\mu_H = f\,\frac{r_H V_H}{B V_X}$$

$$\mu_M = \frac{r_M}{B}\sqrt{\frac{\rho_B - \rho_0}{\rho_0}}$$

Measuring:
conductivity and **mobility**
Calculating:
charge carrier **density**

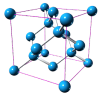
Theory states:

$$\frac{1}{\mu_{tot}} = \frac{1}{\mu_{ph}} + \frac{1}{\mu_{ion}} + \frac{1}{\mu_0}$$

$$\mu_{ph} = aT^{-3/2}$$

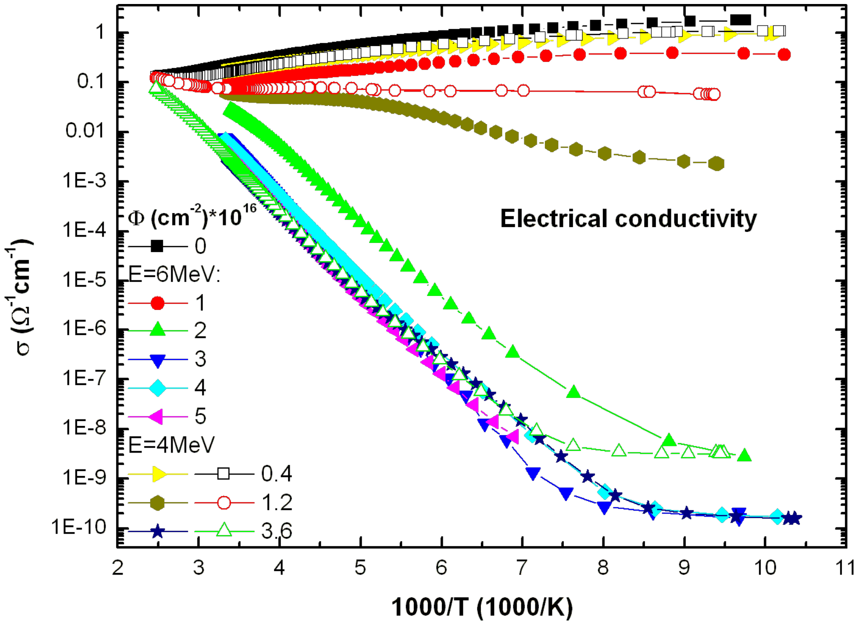
$$\mu_{ion} = b(T, N, n)\,T^{+3/2}$$

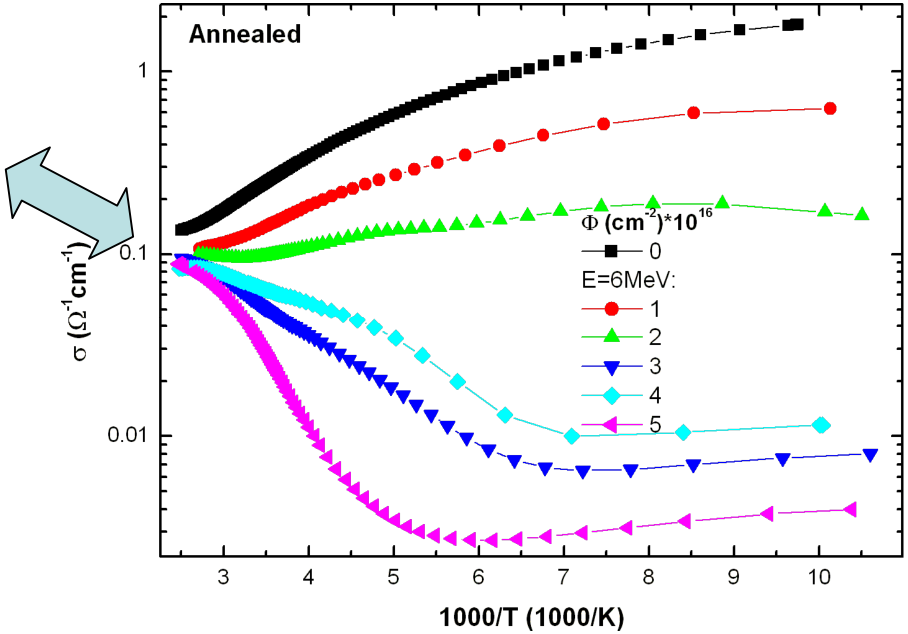
Number of electrically active Scattering centers ~ number of irradiation defects.

The quality of the 

The results

Electrical conductivity dependence on T and Φ evaluation.



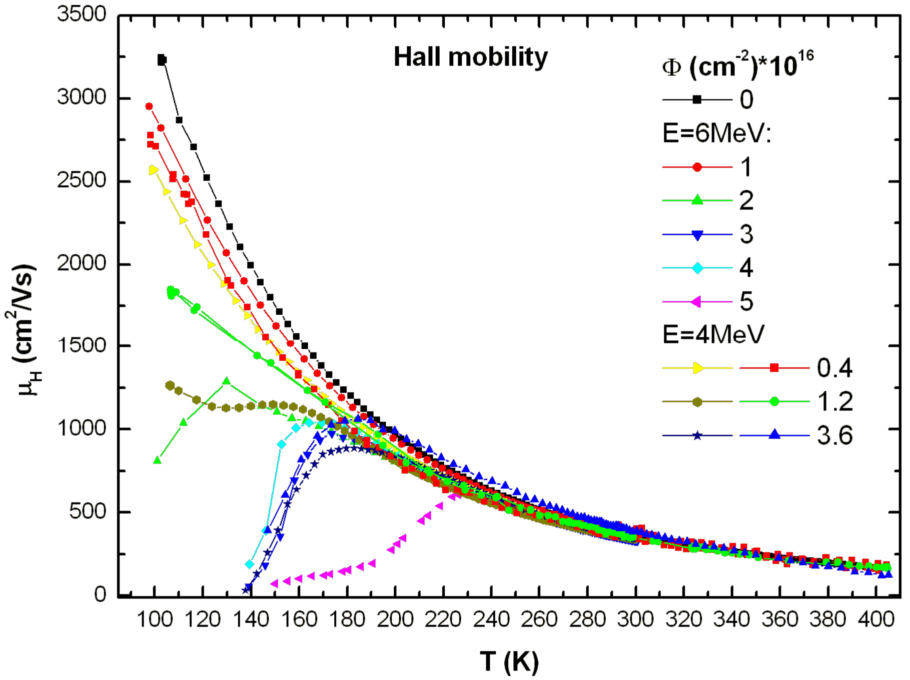


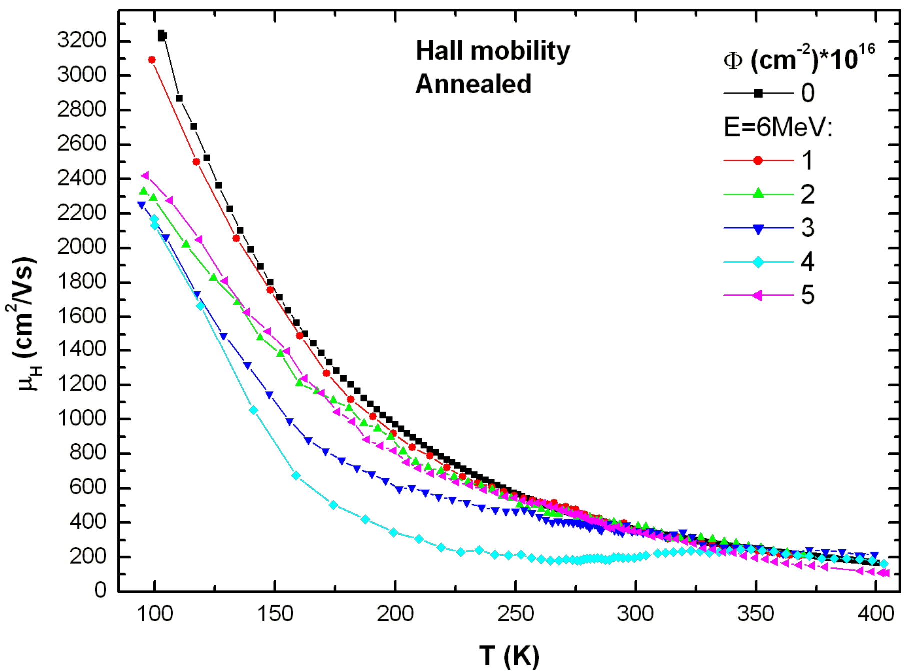
- The method is simple and reliable. Ohmic contacts, 2 point probe method is suitable.
- It is sensitive enough to distinguish the difference between irradiated/not irradiated sample.
- The difference between the samples is very well seen even after the annealing @350C 2h.
- At that T the defects of V2 and VO already anneal.

Thermal activation may give opportunity to calculate the slope from Arhenius plots,
but it is more reliable to do that from the charge carrier density dependencies.

The results

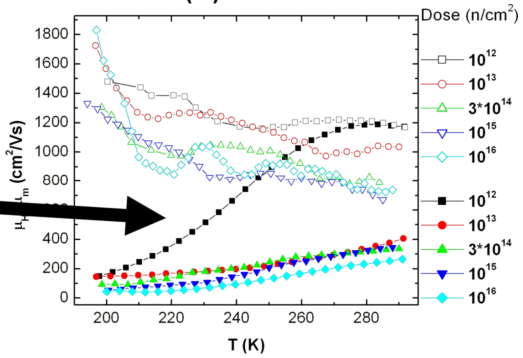
Hall mobility thermal dependency





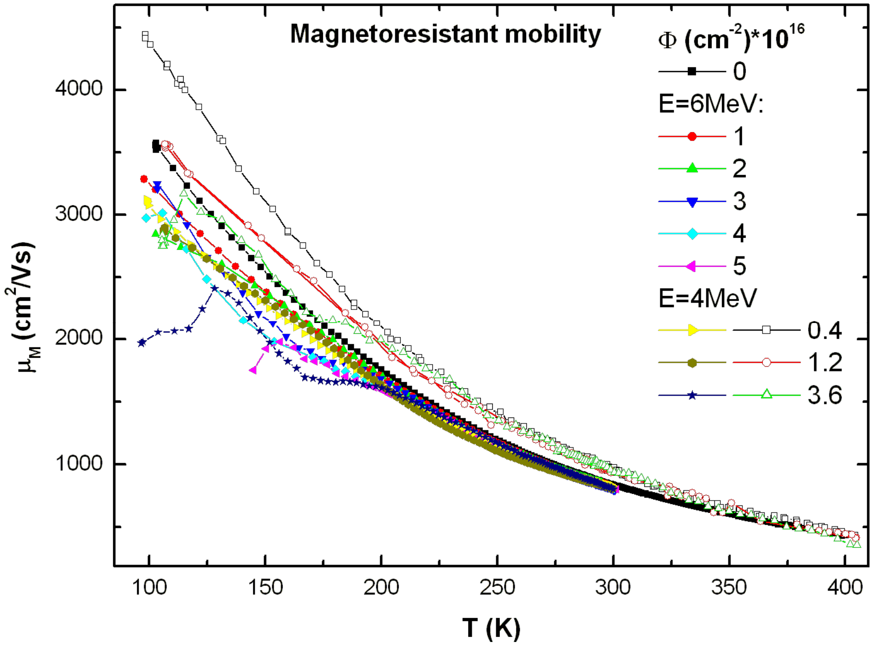
All the changes are mostly seen at lower T.
Expected behavior: greater fluence = lower mobility

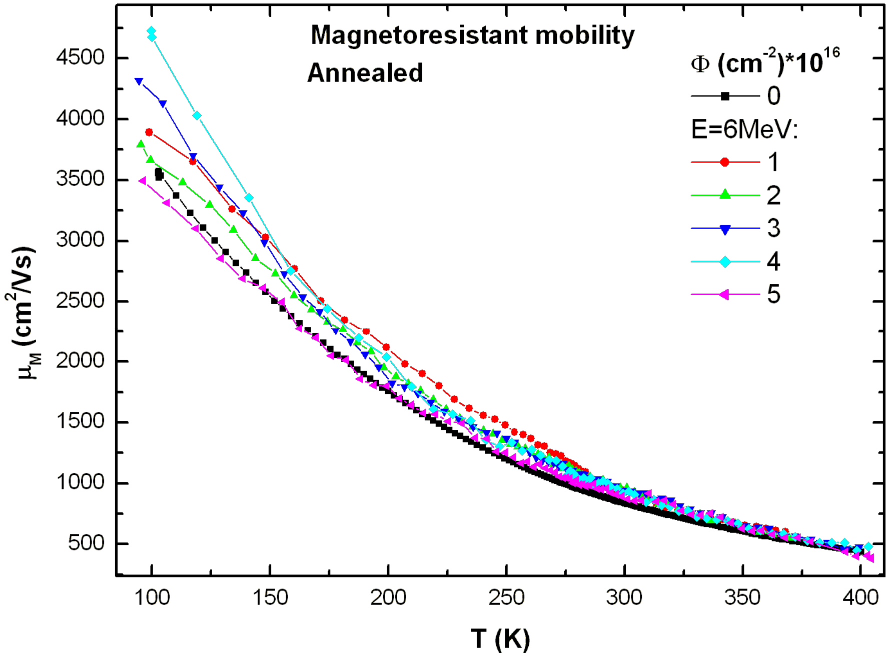
Unexpected behavior: Hall signal drop like for neutron irradiation.
This is not bipolarity effect because holes are slower than electrons.
And the sign of Hall voltage remains the same.



The results

Magnetoresistant mobility thermal dependency





Less sensitive than conductivity or Hall mobility, the signal is obtained as a second order perturbation and more suffers from electrical noise.

However, the irradiation impact is greater than the sensitivity threshold and the samples show difference between.

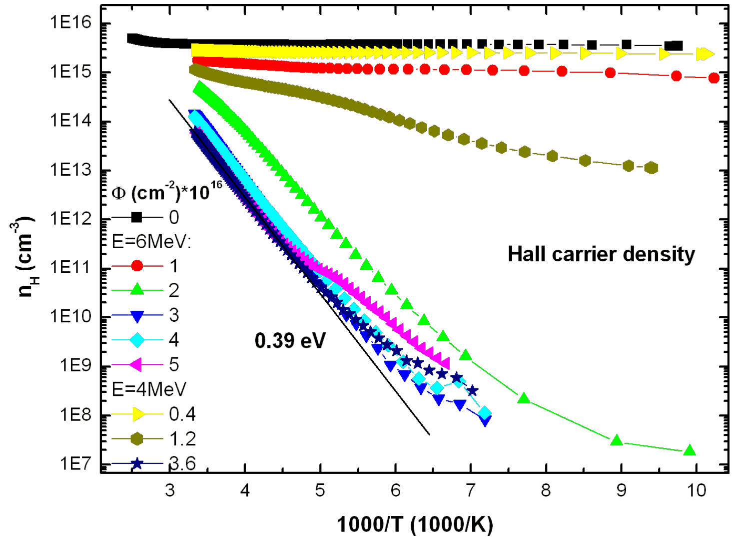
In contrast to Hall mobility, there is no such significant signal drop at lower T.

This once more show similarity to the irradiation with neutrons.

Unusual is the fact that at the lowest fluence the mobility is higher than for non-irradiated one and after annealing, almost in all the samples the mobility increases more than the reference (except with the highest fluence).

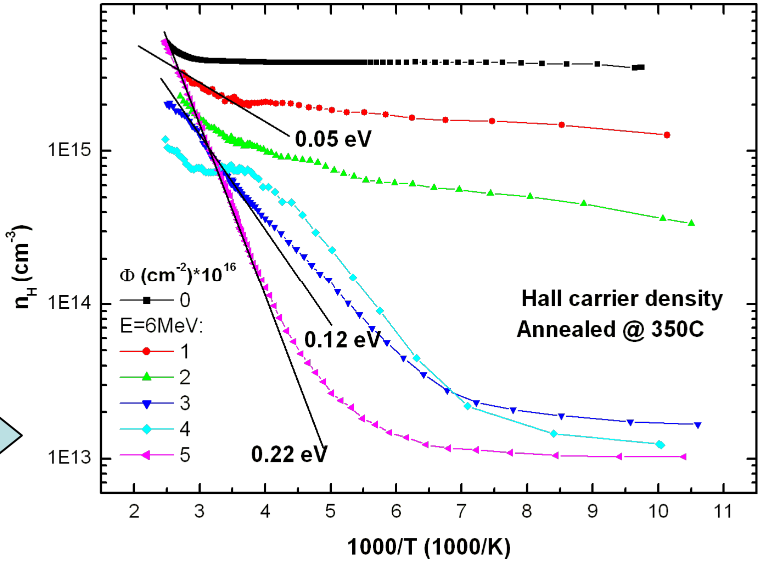
The results

Carrier density thermal dependency

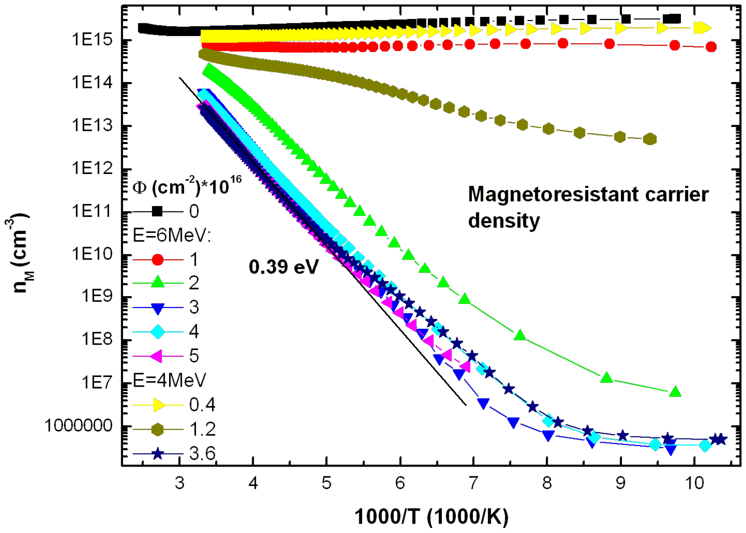


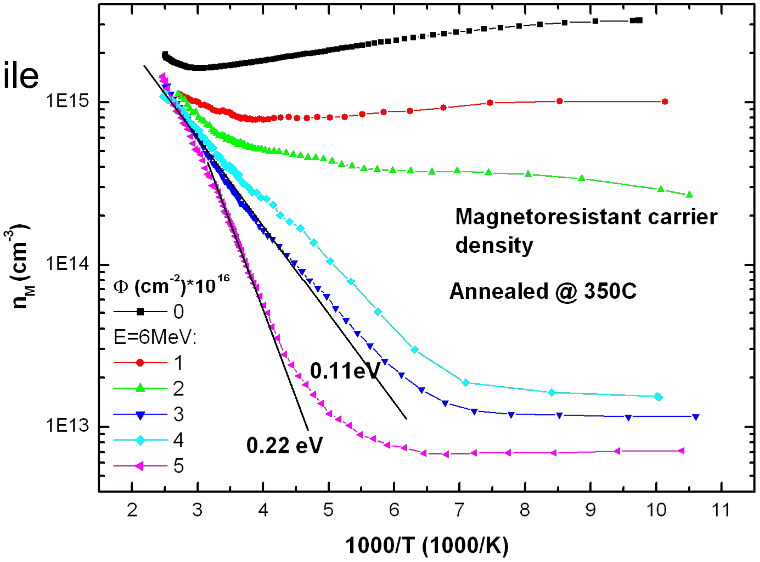
0.39 eV
V2 perhaps

0.22 eV
BiOi perhaps



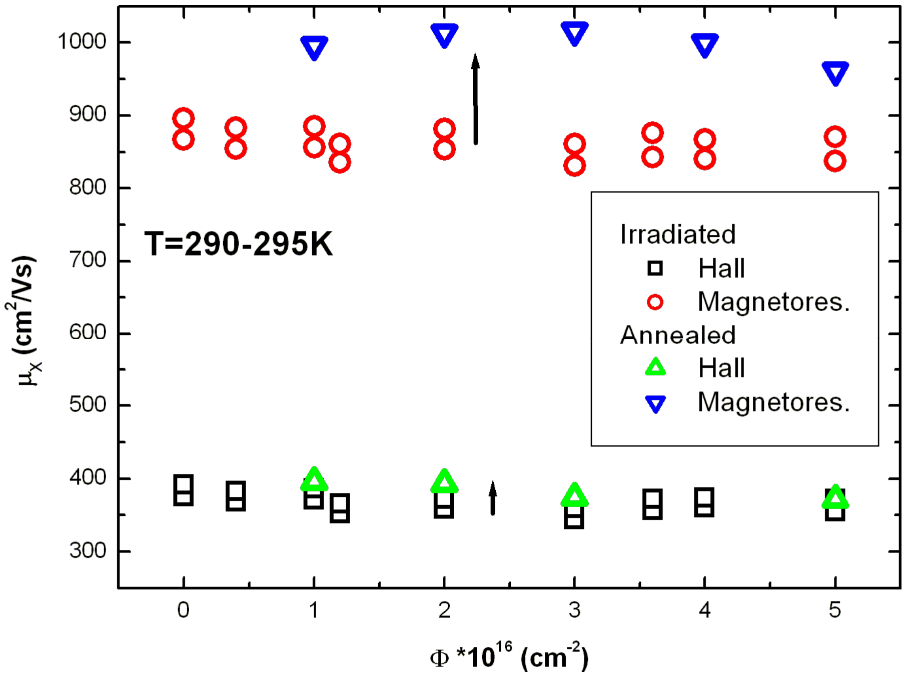
But the annealing T
For BiOi is above
160C only, meanwhile
here T is 350C.

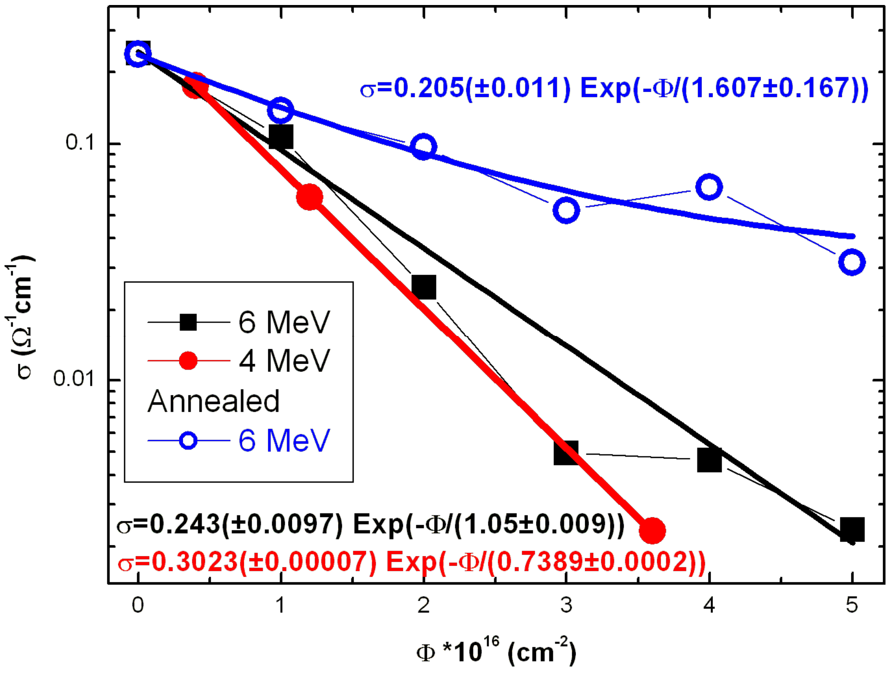




The results

Changes in more detail at RT. Dependence on the fluence

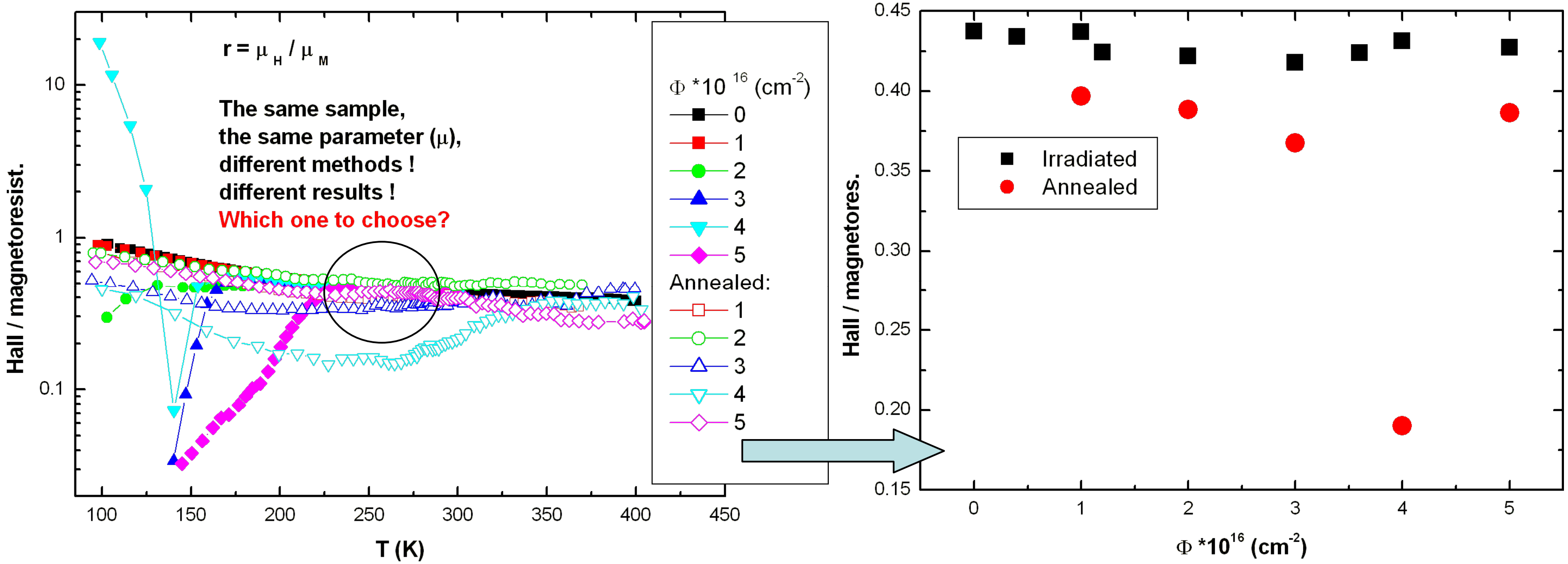




At RT the mobility changes with the fluence only slightly, almost independent.
The conductivity changes exponentially several orders with the fluence.

The results

The intervals of the coincidence of Hall and magnetoresistant mobility



The different mobilities give information from the different places of the material. Magnetoresitivity is sensible to the places, where most of the electric current flows (the best part of the material), meanwhile the Hall voltage is formed with the carriers, which are capable to reach the contact going around the damaged places, which may block the fluent transport.

Calculating N

For the further calculations Hall mobility was chosen in the T range, where it is suitable. The Hall method is more popular and this results in the available references for the phonon scattering term. This time the reference is from Ioffe Institute.

The steps:

$$\frac{1}{\mu_{tot}} = \frac{1}{\mu_{ph}} + \frac{1}{\mu_{ion}} + \frac{1}{\mu_0}$$

Known from the experiment

Known from the literature

Has to be calculated

Temperature independent term, so should be obtainable by correct fitting giving the N also independent on T.

From the theory:

$$\mu_{ph} = aT^{-3/2}$$

$$\mu_{ion} = b\left(T, N, n\right) T^{+3/2}$$

Simple fitting to find **a** and **b** does not work, because the curves do not converge to the experimental ones good enough.

$$b\left(T, N, n\right) = \frac{128\sqrt{2\pi}\left(\varepsilon\varepsilon_0\right)^2 k^{3/2}}{\sqrt{m^*}Z^2e^3N} X\left(T, n\right)$$

With Brooks-Herring (overlapping potentials) model for X:

$$X\left(T, N\right) = \left(ln\left[1 + \left(\frac{12\pi\varepsilon\varepsilon_0 kT}{Ze^3N^{1/3}}\right)^2\right]\right)^{-1}$$

Or screening potential model for X:

$$X\left(T, n\right) = \left(ln\left(1 + \xi\left(T, n\right)\right) - \frac{\xi\left(T, n\right)}{1 + \xi\left(T, n\right)}\right)^{-1}$$

$$\xi\left(T, n\right) = \frac{96\pi^2\varepsilon\varepsilon_0 m^*}{n}\left(\frac{kT}{he}\right)^2$$

However, the calculated N appears as strongly dependent on T. So, the assumptions for the calculation direct using Ioffe data are not suitable. The geometry/scattering Hall factors are not exactly known or something else is missing.

$$\mu_{ph\_Experiment} = aT^{-2.8}$$

And T power in Ioffe data is not 1.5, but ~2.4

Calculating N

Difficulty to choose the phonon scattering term prompts to search for the alternatives

Masetti model. Used in RD50 or related collaboration.
[taken from Juan Pablo Balbuena Valenzuela thesis]

Input from the experiment

$$\mu_{dop} = \mu_{\min 1} e^{-\frac{P_c}{N_i}} + \frac{\mu_{const} - \mu_{\min 2}}{1 + \left(\frac{N_i}{C_r}\right)^{\alpha}} - \frac{\mu_1}{1 + \left(\frac{C_s}{N_i}\right)^{\beta}}$$

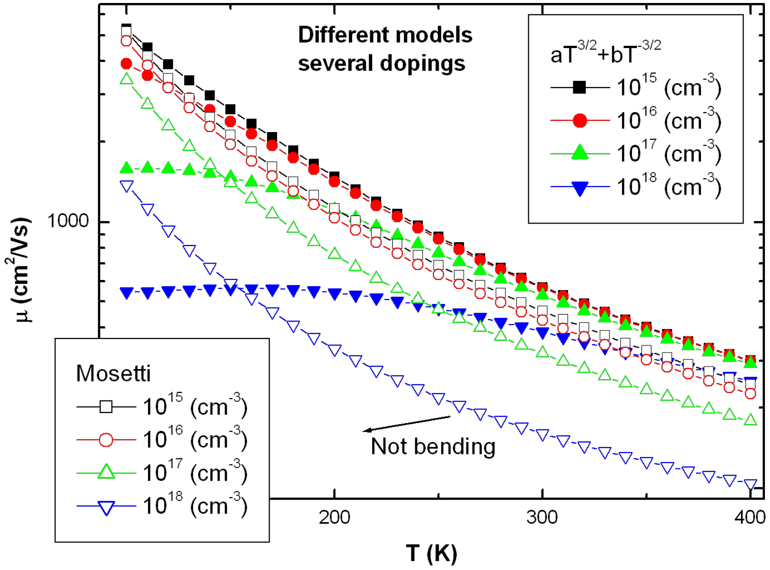
Terms with N. Not solvable analytically.

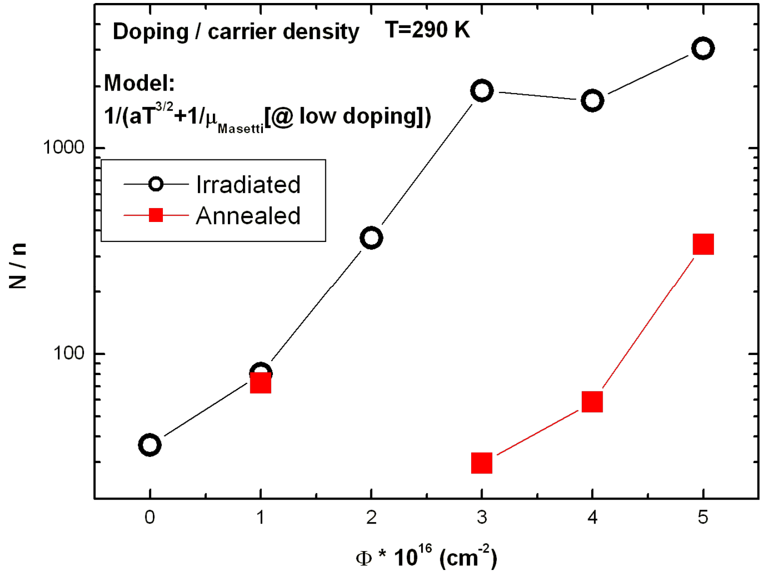
	Holes	**Unit**
μ_L	470.5	$cm^2/(Vs)$
ζ	2.2	1
μ_{min1}	44.9	$cm^2/(Vs)$
μ_{min2}	0	$cm^2/(Vs)$
μ_1	29.0	$cm^2/(Vs)$
P_c	9.23×10^{16}	cm^{-3}
C_r	2.23×10^{17}	cm^{-3}
C_s	6.10×10^{20}	cm^{-3}
α	0.719	1
β	2.0	1

Numerical solver (in Wolfram Mathematica) takes too long to find the solutions
So fitting is done only for RT points, giving N~$5*10^{16}/cm^3$ (later in these slides).
This value is 10 x higher than a free carrier density (~$5*10^{15}$).

The calculation results

Searching for the density of the scattering centers. Another option for Masetti.





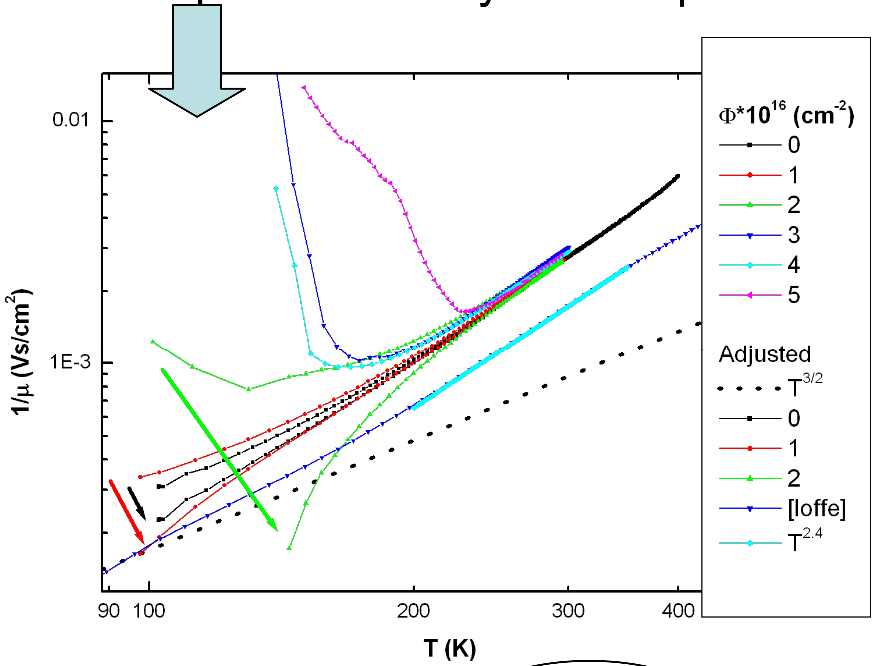
Masetti empirical model is attractive because it already includes all the required terms representing phonon and impurity scattering.

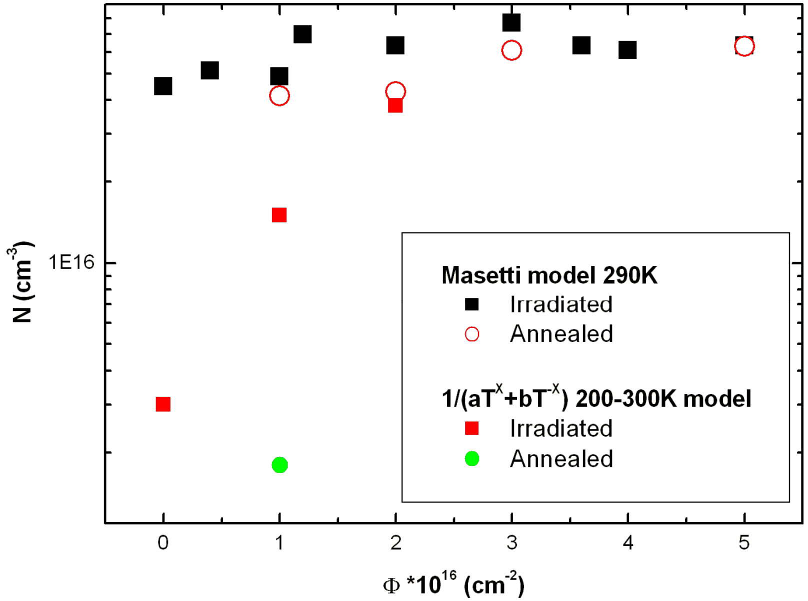
So it was used to find the mobility term of the undoped material and the term of ionized impurity scattering could be estimated. Still, N is much higher than n.

However, the model fails with higher doping at low T

The calculation results

A reciprocal mobility term of phonon scattering ONLY with unknown Hall factor





$$\frac{1}{\mu_{tot}} = \frac{1}{\mu_{ph}} + \frac{1}{\mu_{ion}} + \frac{1}{\mu_0}$$

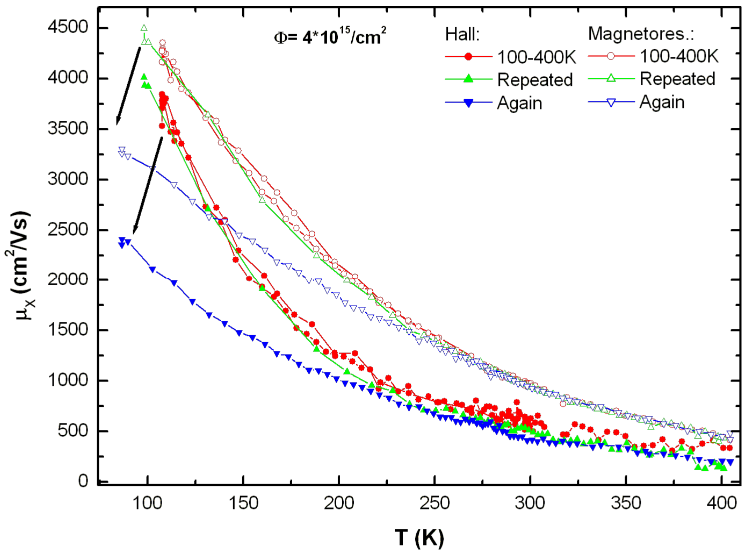
Ioffe data is used as the reference not with absolute values, but only its T power.

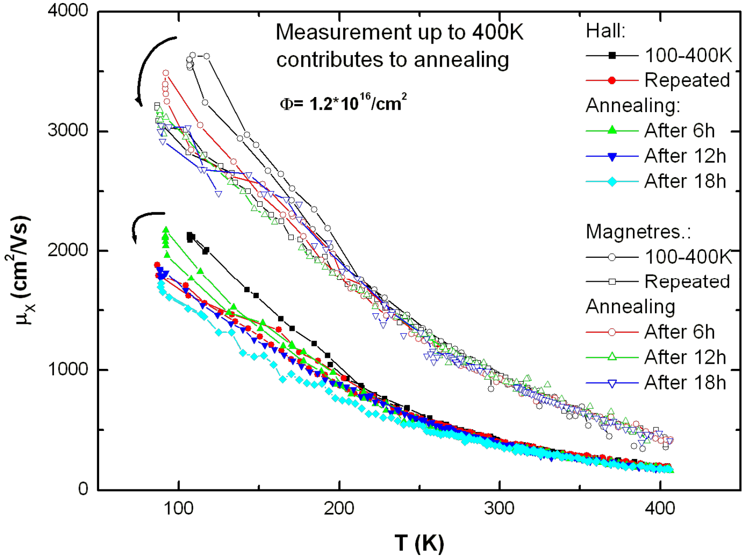
These terms are tuned. With the assumption that not irradiated sample has N=n, so only last term is fitted. For the irradiated samples N is also fitted.

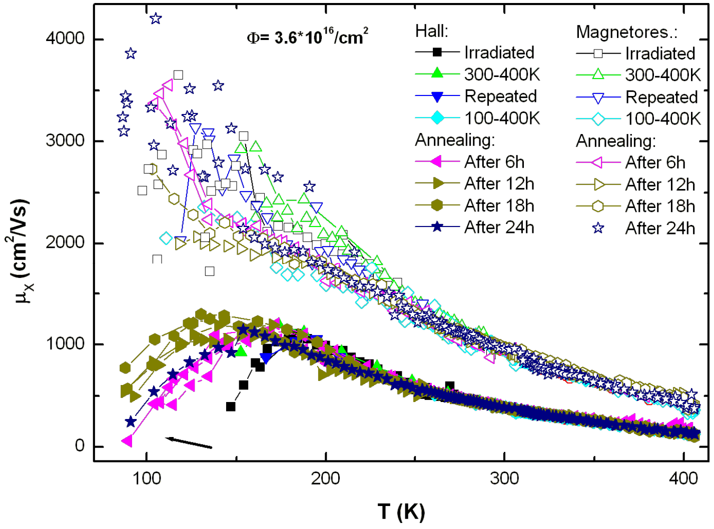
This term has to be the same for all the samples

Still needs revision

4 MeV samples and 80C isothermal annealing

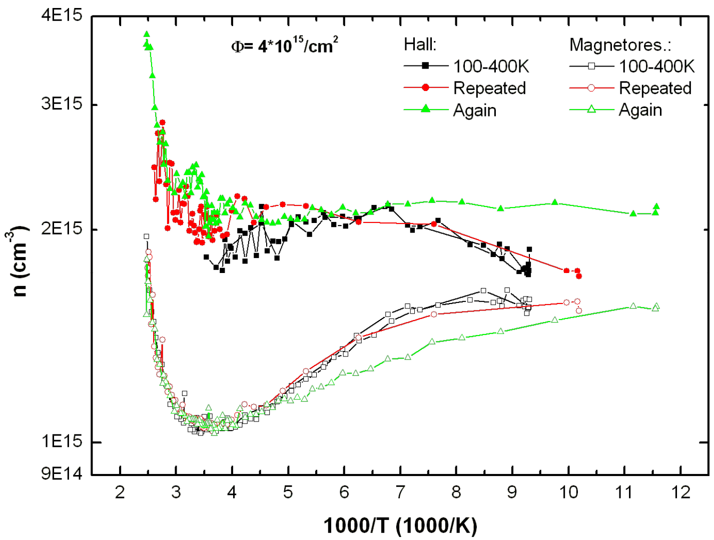


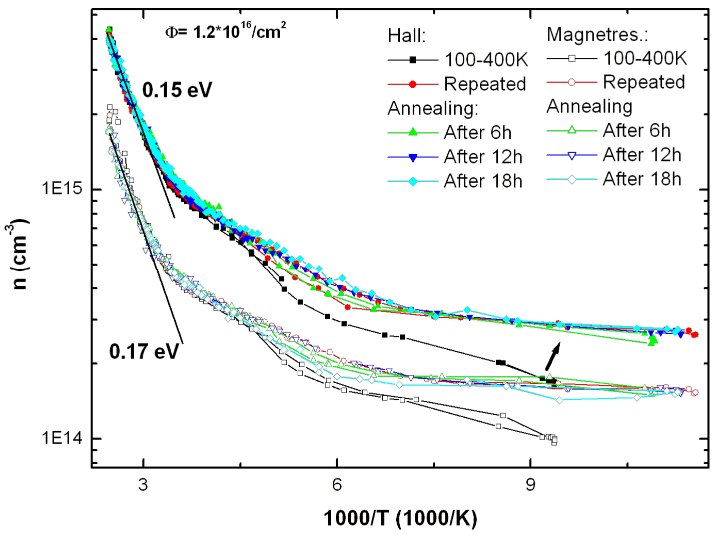

Measurement up to 400K contributes to annealing

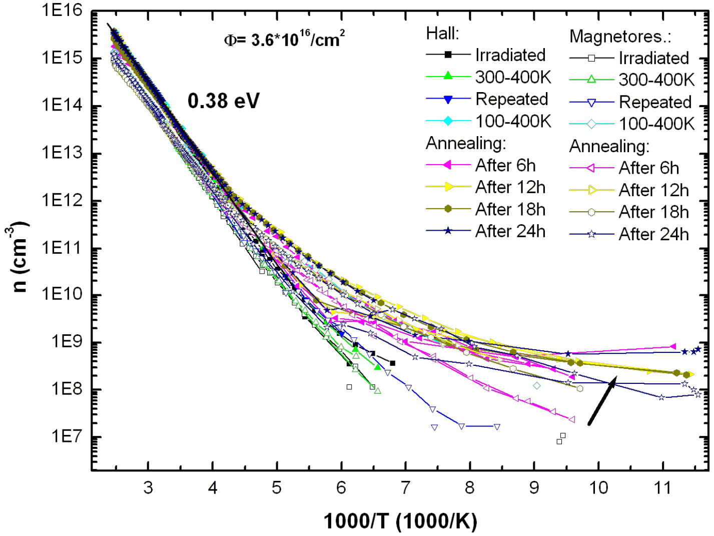


The mobility (Hall and magnetores.) both decreases after annealing for the lower fluence and increases for the higher fluence.

4 MeV samples and 80C isothermal annealing



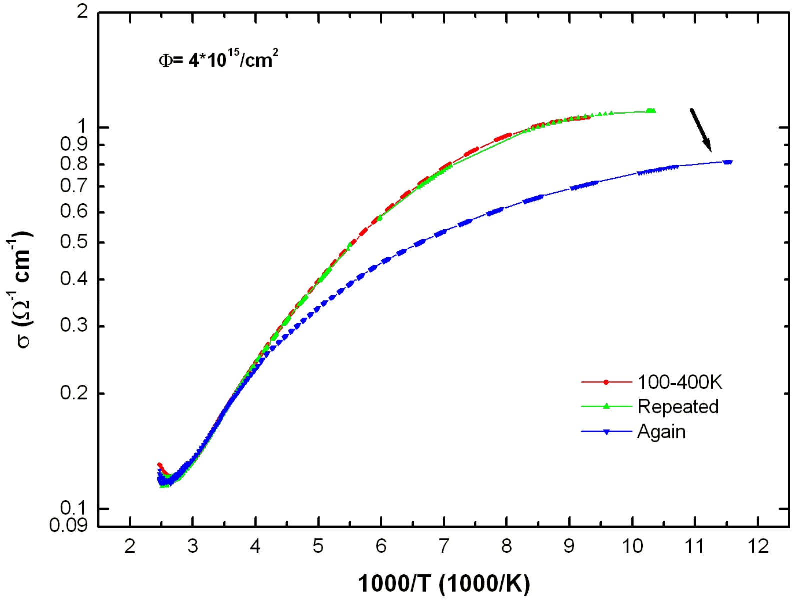


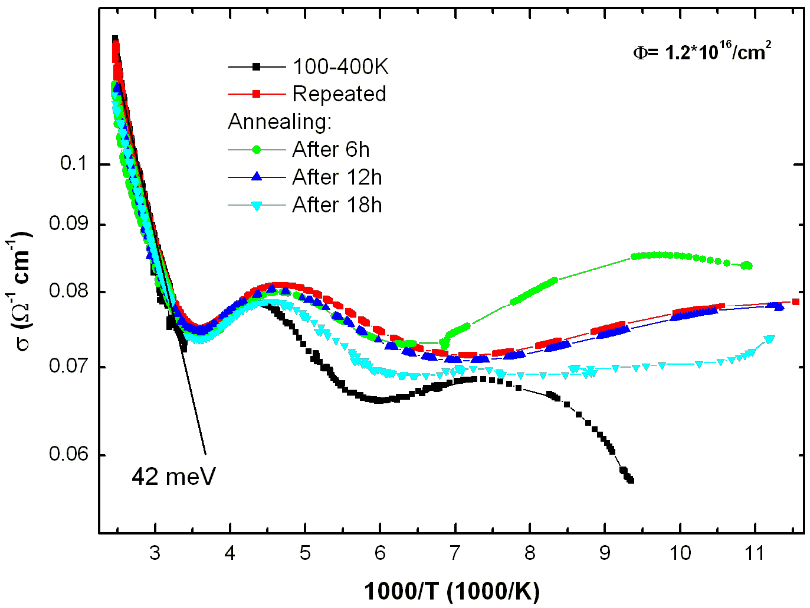


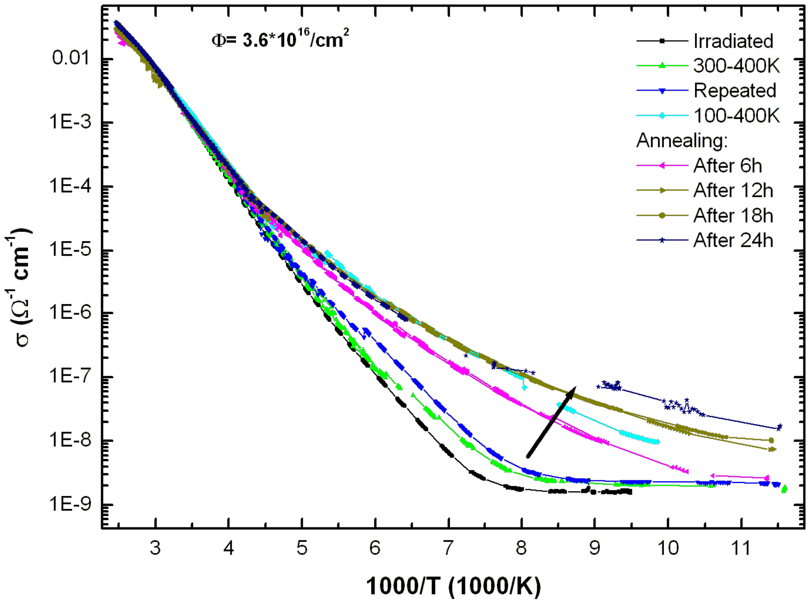
The free carrier density increases during the annealing, meaning that new electrically active dopants appear or decreases the compensation.

Further research is planned for the charge neutrality equation fitting.

4 MeV samples and 80C isothermal annealing



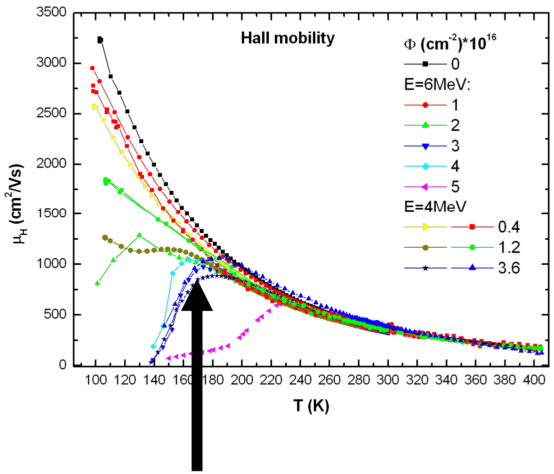




During the annealing, the electrical conductivity covers the cases:

1. Decreases (lowest fluence Φ)
2. Increases at the beginning of the annealing, then decreases (intermediate fluence Φ)
3. Decreases (highest fluence Φ)

The screening of the charge carriers



What if the drop of Hall voltage is a result of charge carrier blocking from the contact because the potential of the impurities overlap?

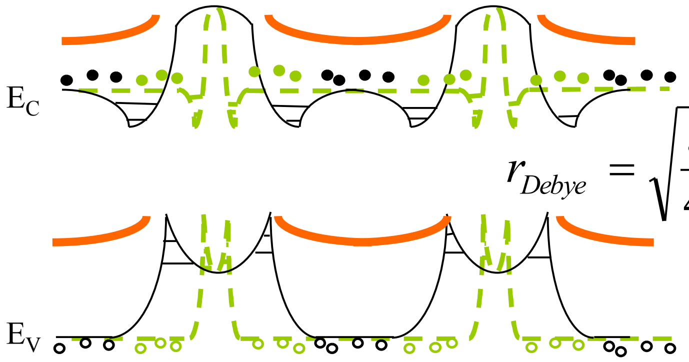
Then the screening functions in the mobility terms have to give the same values:

$$X\left(T,N\right)=\left(ln\left[1+\left(\frac{12\pi\varepsilon\varepsilon_0 kT}{Ze^3N^{1/3}}\right)^2\right]\right)^{-1}$$

$$X\left(T,n\right)=\left(ln\left(1+\xi\left(T,n\right)\right)-\frac{\xi\left(T,n\right)}{1+\xi\left(T,n\right)}\right)^{-1}$$

For lower n, the screening has to be reconsidered as probably changing into abrupt potential model.

However, these X values are far away from each other (ratio ~ 0.2) even for non reasonably high Z values.



$$r_{Debye}=\sqrt{\frac{\varepsilon\varepsilon_0 kT}{4\pi e^2 n'}}$$

Another evaluation is for the Debye screening radius:

For **n=10^{15}/cm^3** ; @ 290K ; r = 36nm A cell of 1/r^3
Results in density **2.1*10^{16}/cm^3**
Meaning that at least for **20** times greater n the screening radius may overlap.

Overview

- P type Si samples irradiated with 6 MeV energy electrons with fluence range (1,2,3,4,5) x 10^{16}/cm^2 (and 4 MeV with (0.4, 1.2, 3.6) x 10^{16}/cm^2) were investigated.
- Hall and magnetoresistivity temperature dependencies were used for the material damage characterization.
- Hall mobility revealed that at lower carrier densities the electric potentials between the charged impurities do not overlap, the cause of a drop of Hall voltage signal is not explained completely.
- Annealing of the samples revealed that the most of the changes in mobility appear at lower T.
- Isothermal annealing of the samples at 80C show that the electrically active impurities density increases and causes the lowering of the mobility.
- Further research is intended to continue the annealing of the samples with increasing time and temperature.

Thank you