Charge carrier mobility evaluation in Silicon Microstrips detectors exploiting photoconductivity phenomena

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Motivation

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

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.
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The 43rd RD50 Workshop (CERN, Zurich 2023-11-28 / 12-01)
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The samples

Irradiated with 1MeV neutrons
Most recent batch:
Fluence from $10^{15}$ to $10^{17}$ n/cm$^2$

Top contacts
Bottom contact

n in p or p in n

Ichiro Shibasaki and Naohiro Kuze, Molecular Beam Epitaxy. 2013

Similar to B sensor

Magnetic density B
Terminal electrode Short bar electrode

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Experimental setup
The experimental results

Photo current spectral dependencies with different applied electric potential.

Spectral shape is sensitive to the external electric field and near band-to-band transition, when the absorption is weak at the surface.
The method

Light absorption:
\[ I_{\text{photo}} = I (1 - R) e^{-\alpha x} \]

Charge carrier generation:
\[ p = n \]
\[ D \frac{d^2 p}{dx^2} - \frac{p}{\tau} = -G \]
\[ p = \frac{C \tau_p e^{-\alpha x}}{\alpha^2 L^2 - 1} + c_1 e^{x/L} + c_2 e^{-x/L} \]

Introduced variables:
\[ D = 2 \frac{D_n D_p}{D_n + D_p} \]
\[ G = \eta \alpha I (1 - R) e^{-\alpha x} \]
\[ L = \sqrt{D \tau} \]
\[ \frac{d...}{dt} = 0 \]
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\[ D = \frac{\mu k T}{e} \]

\[ G = \eta \alpha I (1 - R) e^{-\alpha x} \]

\[ L = \sqrt{D \tau} \]

\[ \frac{d...}{dt} = 0 \]

Boundary conditions:

\[ D \frac{dp(0)}{dx} = sp(0) \quad c_1 = 0 \]

Surface recombination rate

The detected signal:

\[ i = e \mathcal{E} (\mu_p + \mu_n) w \int_0^{\infty} pdx \]
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Surface

\[ \alpha \text{ from [Macfarlane et al. (1959)]} \]
\[ R \sim 0.3 \text{ from [Chelikowsky and Cohen (1976)]} \]
The method

Light absorption: 
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[Smith. Semiconductors]

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\[ \alpha \quad \text{from [Macfarlane et al. (1959)]} \]
\[ R \sim 0.3 \quad \text{from [Chelikowsky and Cohen (1976)]} \]

The profile is similar, but…

Not fitting
The idea

1. The Si/SiO2 interface may be the cause of the surface mobility degradation.

2. At the surface generated carriers are less mobile, which causes the decrease of the recombination rate.

3. The applied voltage causes the carriers to drift to the clusters in the bulk and recombine faster.
The idea

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Double layer model: the surface and the bulk

- The variation of mobility is enough to have the desired tuning of the spectral shape.


[J.V.Vaitkus et al, LJP, 2023]
The double layer model

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\[ \frac{D}{dx^2} \frac{d^2 p}{dx^2} - \frac{p}{\tau} = -G \]
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Introduced variables:
\[ \mu_p \tau = M_p \quad \mu_n \tau = M_n \]
\[ M_{n1} + M_{p1} = K_1 \quad \tau_{1s} = S_1 \]
\[ M_{n2} + M_{p2} = K_2 \quad \tau_{2s} = S_2 \]
\[ S_1 / S_2 = S_{12} \]
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Boundary conditions:

\[ D \frac{dp(0)}{dx} = sp(0) \quad p_2(x_1) = p_1(x_1) \quad D_1 \frac{dp_1(x_1)}{dx} = D_2 \frac{dp_2(x_1)}{dx} \]

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The detected signal:
\[ \frac{i}{\omega eEI (1 - R)} = \frac{\eta_1 K_1}{(\alpha^2 L_1^2 - 1)} \left( \alpha L_1^2 + S_1 \right) \frac{1}{S_1 + L_1} \alpha L_1 \left( 1 - e^{-\frac{x_1}{L_1}} \right) - 1 + e^{-\alpha x_1} \]
\[ + K_2 \left( \frac{\eta_2 e^{-\alpha x_1}}{\alpha^2 L_2^2 - 1} + \right. \left. \frac{\eta_1 S_1}{\alpha^2 L_1^2 - 1} \left( S_1 + \alpha L_1^2 e^{-\frac{x_1}{L_1}} - e^{-\alpha x_1} \right) \right) \alpha L_2 \left( 1 - e^{-\frac{x_1}{L_2}} \right) \]
\[ + K_2 \eta_2 \frac{e^{-\alpha x_2} - e^{-\alpha x_1}}{\alpha^2 L_2^2 - 1} \]...not complete, much bigger

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The detected signal:
\[ \frac{i}{\omega \varepsilon I (1 - R)} = \frac{\eta_1 K_1}{(\alpha^2 L_1^2 - 1)} \left( \frac{\alpha L_1^2 + S_1}{S_1 + L_1} \right) \alpha L_1 \left( 1 - e^{-\frac{x_1}{L_1}} \right) - 1 + e^{-\alpha x_1} \]
\[ + K_2 \left( \frac{\eta_2 e^{-\alpha x_1}}{\alpha^2 L_2^2 - 1} + \frac{\eta_1 S_{12}}{\alpha^2 L_1^2 - 1} \left( \frac{S_1 + \alpha L_1^2}{L_1 + S_1} e^{-\frac{x_1}{L_1}} - e^{-\alpha x_1} \right) \right) \alpha L_2 \left( 1 - e^{-\frac{x_1 - x_2}{L_2}} \right) \]
\[ + K_2 \eta_2 \frac{e^{-\alpha x_2} - e^{-\alpha x_1}}{\alpha^2 L_2^2 - 1} \]
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\[ S_1 / S_2 = S_{12} \]

Deeper analysis:
Mobility and lifetime here always comes as a product \((\mu \tau)\). The increase of \(\tau\) because of decrease of \(\mu\) have an opposite effect on the surface.

Meanwhile, the irradiation decreases \(\mu\) and \(\tau\) both. And at some fluence its product in the bulk may become smaller than on the surface? Is surface affected by irradiation in a similar way?
The double layer model

Double layer

(S) is bigger at the top

Single layer

(S) is bigger at the bottom

Experiment

Which one fits better?
The fitting steps

The fitted curve is very sensitive to the initial values!
The algorithm uses variable error evaluation to maintain the required curve shape.
The fitting steps

The fitted curve is very sensitive to the initial values!
The algorithm uses variable error evaluation to maintain the required curve shape.

Some fits:

Could be better
The fitting results

$\mu_p \tau = M_p$  $\mu_n \tau = M_n$

$M_{n1} + M_{p1} = K_1$

$M_{n2} + M_{p2} = K_2$

$L = \sqrt{D \tau}$

The fitting confirms the order of the layers:

Top layer is “better” than bottom ($\mu \tau$ is bigger).

$K_1 >> K_2$ (x100 and more for 1E+15/cm$^2$)

$L_1 >> L_2$

$X_1 << X_2$
The fitting results

\[ \mu_p \tau = M_p \quad \mu_n \tau = M_n \]

\[ M_{n1} + M_{p1} = K_1 \]

\[ M_{n2} + M_{p2} = K_2 \]

\[ L = \sqrt{D\tau} \]

Top layer is “better” than bottom (\(\mu \tau\) is bigger).

\[ K_1 \gg K_2 \text{ (x100 and more for 1E+15/cm}^2) \]

\[ L_1 \gg L_2 \]

\[ X_1 \ll X_2 \]

Next steps:

1. Obtain \(\tau\) or \(\mu\) from other experiments at required \(T\).
2. Reduce the fitting parameter distribution by simultaneous fitting of the several dependencies.
3. Complete more photoconductivity experiments.

[L. Deveikis et al]
The experimental results

**Exceptional** case for sample S25: **negative** photo current. The photo carrier density is positive, so the current has to be. The mobility may decrease because of the band structure (excitation to the valley of higher effective mass?) But the slower carriers still contribute as addition to the total photo current. The effect is related to the **deeper layer** (less photo absorption) and is sensitive to the external electric field. The explanation is that the presence of internal electric field or the current blockade work like in FET. Perhaps, this is related to the defect charge separation of dipole type or Photo-Volt effect?
The previous results

At low fluence the double layer is not observed. If the surface quality is defined by the surface oxide, then at a certain fluence the product of ($\mu t$) may become the same in the whole sample. Then the second layer would not show up too. Meanwhile the experiments show the opposite: the double layer appears at higher fluence.

Difficult to compare the surface of the samples, because the low fluence was applied for the other batch.

For this reason older batch was included for the analysis (next slide).
The previous results

The previous analysis was mostly concentrated at the bandgap. The later effect is best expressed above the bandgap.

![Graph showing I (nA) vs Photon energy E (eV)]

[10^{14} \text{n/cm}^2, 36 \text{K; } U = 50 \text{V}]

- Experiment
- (1) 0.495 eV
- (2) 0.768 eV
- (3) 0.850 eV
- (4) 0.945 eV
- (5) Total defects

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The effect of double layer is observed at higher electric potential.
The previous results

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The effect of double layer is observed at higher electric potential.

Too high potential hides the effect again!
Relation to the magnetoresistance (MR)

From 41\textsuperscript{st} RD50:

MR top to bottom shows a good quality material

MR measurement is separated from $\tau$, so “good quality” means bigger $\mu$, but not $\mu\tau$.

The 41st RD50 Workshop (CERN, Zurich 2023-11-28 / 12-01)

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MR top to top shows an irradiated material (or like degraded at the Si/SiO2 interface?)

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From 41\textsuperscript{st} RD50:

MR top to bottom shows a good quality material

MR measurement is separated from $\tau$, so “good quality” means bigger $\mu$, but not $\mu\tau$.

MR top to top shows an \textbf{irradiated} material
(or like degraded at the Si/SiO\textsubscript{2} interface?)

Only perpendicular to B electric current experiences MR.

What if the irradiated device still has another layer of better quality material?

Irradiation with neutrons increases R in the bulk, so what remains more conductive? Surface?

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Summary

Silicon STRIP detectors were investigated by photo conductivity effect in range 0.45 eV to 3.5 eV with constant photon number.

The model of good crystal quality on sample top and irradiated material below was proposed and parameter extraction procedure estimated.

Negative photo response in sample irradiated to 1E+17/cm² was observed and its origin was discussed.
Thank you