Electric Fields in Irradiated Silicon Pad Detectors

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- deconvolution of measured pulse shapes
- deep level concentrations
- simulation of pulse shapes

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Charge Collection in Silicon Sensors

- charge $dQ$ induced on electrodes by drifting charge $q$ (Ramo’s theorem):

$$dQ = \frac{q(t)}{d} \; dx = \frac{q(t)}{d} \; v(t) \; dt$$

- trapping leads to charge carrier loss:

$$dq(t) = -\frac{1}{\tau_{eff}} q(t) dt, \quad \text{with } \tau_{eff} = \tau_{eff} (\Phi_{eq})$$

- resulting (measured) signal current:

$$i_m(t) = \frac{q_0}{d} v(t) \exp(-t / \tau_{eff})$$

- injection with short range laser from one side allows to distinguish between electron and hole signal
Aim

• task: find model for numeric simulation of charge drift

• two models for electric field are compared:

1. electric field depends linearly on substrate depth $x$

\[ N_{\text{eff}}(x) = \text{const.} \]

2. deep level model as proposed by V. Eremin et al., see 3rd RD50 workshop / NIM A 476 (2002) 556-564

\[ N_{\text{eff}}(x) = F^+ N_{DD} - F^- N_{DA} + N_{sh} \]

parameters are extracted from TCT measurements
Transient Current Technique, Set-up

- 672nm red laser (3.6\(\mu\)m absorption length, FWHM = 44ps),
- applicable bias voltage range 0-1200V
- fast pulse amplifier (10\(\times\), 100 kHz - 1.8 GHz), (current sensitive!)
- oscilloscope (Tektronix TDS 784D, band width 1 GHz)
- rise time of system (incl. detector) about 1 ns
- PC readout system (LabVIEW)
- cooling system (-20°C - +20°C, rms 0.2°C)
Oxygenated Silicon Samples

- 5×5 mm² n-bulk pad detectors, thickness 250-300 μm, manufactured by CiS (Erfurt/Germany)
- ⟨111⟩ crystal orientation, oxygenation 24h at 1200°C
- proton irradiation with 24 GeV protons at CERN-PS
  (0.92 - 5.00) · 10^{14} \text{n}_{eq}/\text{cm}^2 \text{ or}
  neutron irradiation at TRIGA reactor, Ljubljana
  (1 - 4) · 10^{14} \text{n}_{eq}/\text{cm}^2
- no biasing during irradiation
- detectors annealed to minimum $V_{dep}$ at 60°C

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Deconvolution: \( i(t) \rightarrow v(x), E(x) \)

\[ v_{dr}(t) = a \cdot i(t) \]

\[ \int_{0}^{t_c} v_{dr}(t) \, dt = a \int_{0}^{t_c} i(t) \, dt = d \]

\[ \Rightarrow a = d \left/ \int_{0}^{t_c} i_c(t) \, dt \right. \]

\[ \Rightarrow v_{dr}(t), x(t) \]

\[ \rightarrow v_{dr}(x) \rightarrow E(x) \]
Drift Velocities → Carrier Densities

Use deep level model for further analysis:

- use drift velocities obtained from deconvolution
- carrier densities $n_{e,h}$ calculated from drift velocity with

$$n_e = \frac{j_e(x)}{q_0 \nu_{dr,e}(x)}, \quad n_h = \frac{j_h(x)}{q_0 \nu_{dr,h}(x)}$$

$$j_e = Gx, \quad j_h = G(d - x)$$

carrier densities

- $\Phi_{eq} = 5.00 \cdot 10^{14} \text{n}_e / \text{cm}^2$
- $V_{dep} = 120 \text{V}$
- $V_{bias} = 170 \text{V}$
- $T = 273 \text{K}$

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Carrier Densities $\rightarrow$ Charged Deep Levels

- free carriers are trapped by deep levels
  $\Rightarrow$ additional space-charges
- deep level model uses only two deep level defects
- with $F^+/F^-$ as charged fraction of deep donors/acceptors

\[
F^- = \frac{F}{1 + F}, \quad F^+ = \frac{1}{1 + F}
\]
with
\[
F = \frac{n_t}{N_t - n_t} = \frac{c_e n_e + v_{th,h} \sigma_h N_V \exp\left(-\left(E_t - E_V\right)/kT\right)}{c_h n_h + v_{th,e} \sigma_e N_C \exp\left(-\left(E_C - E_t\right)/kT\right)}
\]

deep acceptor:

\[
E_t = E_C - 0.52 \text{ eV}, \quad \sigma_e = 10^{-15} \text{ cm}^2, \quad \sigma_h = 10^{-15} \text{ cm}^2
\]

deep donor:

\[
E_t = E_V + 0.53 \text{ eV}, \quad \sigma_e = 10^{-15} \text{ cm}^2, \quad \sigma_h = 3 \times 10^{-14} \text{ cm}^2
\]
Charged Deep Levels $\rightarrow$ Contribution to $E$-Field

\[ N_{\text{eff}}(x) = F^+ N_{DA} - F^- N_{DD} + N_{sh} \]

$\rightarrow\ E(x) = E(x_1) - \frac{q_0}{\varepsilon_0 \varepsilon_{\text{Si}}} \int_{x_1}^{x} N_{\text{eff}}(x') \, dx'$ is fitted to measured $E(x)$

- $N_{DA}, N_{DD}$ are fit parameters,
- $N_{sh}$ is calculated from Hamburg model (stable damage)

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Deep Level Concentrations vs. $V_{\text{bias}}$

$N_{DA}$, $N_{DD}$ are obtained from p- and n-side signals for various $V_{\text{bias}}$:

- $N_{DA}$, p-side
- $N_{DA}$, n-side
- $N_{DD}$, p-side
- $N_{DD}$, n-side

$N_{DA}$, $N_{DD}$ are obtained from p- and n-side signals for various $V_{\text{bias}}$:

- variation with $V_{\text{bias}}$
- incompatible results from p- and n-side

$N_{DA}= (63.55 \pm 0.73) \cdot 10^{15} \text{cm}^{-2}$

$N_{DD}= (11.31 \pm 0.19) \cdot 10^{15} \text{cm}^{-2}$

$V_{\text{dep}} + 50 \text{V} \leq V_{\text{bias}} \leq V_{\text{dep}} + 100 \text{V}$

$N_{DA}$, $N_{DD}$ are averaged over $V_{\text{dep}} + 50 \text{V} \leq V_{\text{bias}} \leq V_{\text{dep}} + 100 \text{V}$
Deep Acceptor Concentration vs. Fluence

24 GeV protons

- no linear dependence or saturation visible
- \( N_{DA} = \text{const.} \) assumed \( (N_{DA} \text{ strongly correlated with fluence dependent } N_{sh}) \)

\[
N_{DA} = \begin{cases} 
(80 \pm 17) \cdot 10^{12} / \text{cm}^3 & \text{for protons, p - side} \\
(120 \pm 9.2) \cdot 10^{12} / \text{cm}^3 & \text{for neutrons, p - side}
\end{cases}
\]
Deep Donor Concentration vs. Fluence

- Data suggest linear introduction of deep donors:
  \[ N_{DD} = g_{DD} \cdot \Phi_{eq} \]

\[ g_{DD} = \begin{cases} (3.08 \pm 0.10) \cdot 10^{-2} / \text{cm} & \text{for protons, p - side} \\ (2.87 \pm 0.35) \cdot 10^{-2} / \text{cm} & \text{for neutrons, p - side} \end{cases} \]
• simulation of charge drift with two models for electric field
  - $V_{bias} = V_{dep} + 100V$
  - red laser on pad-detector, sample-fluences and -thicknesses
  - simulation considers diffusion, trapping, signal distortion
  - measured signals are corrected for bandwidth limitation (adding of derivative)

**linear E-field**

- p-side
  - Sample P
  - $\phi_e = 3.6 \times 10^{10} \text{cm}^{-2}$
  - $V_{bias} = 90V$
  - $V_{dep} = 150V$
  - p-side signal
  - simulated
  - measured

- Sample P
  - $\phi_e = 3.6 \times 10^{10} \text{cm}^{-2}$
  - $V_{bias} = 900V$
  - $V_{dep} = 150V$
  - p-side signal
  - simulated
  - measured

- Sample D
  - $\phi_e = 1.0 \times 10^{11} \text{cm}^{-2}$
  - $V_{bias} = 60V$
  - $V_{dep} = 160V$
  - p-side signal
  - simulated
  - measured

- Sample D
  - $\phi_e = 1.0 \times 10^{11} \text{cm}^{-2}$
  - $V_{bias} = 60V$
  - $V_{dep} = 160V$
  - p-side signal
  - simulated
  - measured

- Sample Q
  - $\phi_e = 2.0 \times 10^{11} \text{cm}^{-2}$
  - $V_{bias} = 220V$
  - $V_{dep} = 220V$
  - p-side signal
  - simulated
  - measured

- Sample Q
  - $\phi_e = 2.0 \times 10^{11} \text{cm}^{-2}$
  - $V_{bias} = 220V$
  - $V_{dep} = 220V$
  - p-side signal
  - simulated
  - measured

**deep level model**

- p-side
  - Sample P
  - $\phi_e = 3.6 \times 10^{10} \text{cm}^{-2}$
  - $V_{bias} = 90V$
  - $V_{dep} = 150V$
  - p-side signal
  - simulated
  - measured

- Sample P
  - $\phi_e = 3.6 \times 10^{10} \text{cm}^{-2}$
  - $V_{bias} = 900V$
  - $V_{dep} = 150V$
  - p-side signal
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  - measured

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  - $\phi_e = 2.0 \times 10^{11} \text{cm}^{-2}$
  - $V_{bias} = 220V$
  - $V_{dep} = 220V$
  - p-side signal
  - simulated
  - measured

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Pulse Shape Simulation: Temperature

- temperature dependent properties:
  - leakage current $\rightarrow$ carrier densities
  - occupation probabilities $\rightarrow$ charged fractions of deep levels
- temperature dependence checked with two neutron irradiated samples

\[ 1 \cdot 10^{14} n_{eq}/cm^2, \ V_{bias} = V_{dep} + 80V \]

\[ 2 \cdot 10^{14} n_{eq}/cm^2, \ V_{bias} = V_{dep} + 120V \]
CCE vs. $V_{\text{bias}}$, proton irradiation

- simulation of CCE vs. $V_{\text{bias}}$ with linear field and deep level model
- measured CCE from TCT, charge crossing method
- proton-irradiated samples
- $V_{\text{bias}} \geq V_{\text{dep}} + 50\text{V}$
CCE vs. $V_{bias}$, neutron irradiation

- simulation of CCE vs. $V_{bias}$ with linear field and deep level model
- measured CCE from TCT, charge crossing method
- neutron-irradiated samples
- $V_{bias} \geq V_{dep} + 50V$

$1 \cdot 10^{14} n_{eq}/\text{cm}^2$

$2 \cdot 10^{14} n_{eq}/\text{cm}^2$
Conclusions

- parameters for deep level model obtained from pulse shapes (TCT)
  - parameter values depend strongly on $V_{\text{bias}}$, illuminated side
- $N_{DA}$ shows strange behaviour, either
  - fluence dependence is „shadowed“ by stable shallow defects or
  - saturation already at low fluences
- $N_{DD}$ shows linear introduction

⇒ values for $N_{DA}, N_{DD}$ should only be used within this model!

- two models for electric field have been used for simulation
- deep level model is superior to linear model in describing pulse shape, especially towards low bias voltages,
  but: (mathematical?) problems below $V_{\text{dep}} + 50\text{V}$
Finally...

THE END
Calculation of Electric Field

\[ j_e = Gx, \quad j_h = G(d - x) \]

\[ n_e = \frac{j_e(x)}{q_0 v_{dr,e}(E(x))}, \quad n_h = \frac{j_h(x)}{q_0 v_{dr,h}(E(x))} \]

- starting with linear field
- 10-15 iterations

\[ F = \frac{n_i}{N_t - n_i} = \frac{c_e n_e + v_{th,h} \sigma_h N_v \exp\left(-\frac{(E_i - E_V)}{kT}\right)}{c_h n_h + v_{th,e} \sigma_e N_C \exp\left(-\frac{(E_C - E_i)}{kT}\right)} \]

Gauss' law

leakage current

electric field

carrier density

filling factors

charged fractions

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Pulse Shape Simulation: Electric Fields, Fluence

- simulation of charge drift with linear field and deep level model (p-side data)
- red laser on pad-detector, fluences and thicknesses same as in samples
- simulation considers diffusion and trapping
- simulated signals are convoluted with gaussian ($\sigma=400\text{ps}$)
- measured signals are corrected for bandwidth limitation (adding of derivative)

2.04 / 1.06 / 0.92 × 10^{14} \text{eq}/\text{cm}^2
Pulse Shape Simulation: Electric Fields, Fluence (2)

- simulation of charge drift with linear field and deep level model (p-side data)
- red laser on pad-detector, fluences and thicknesses same as in samples
- simulation considers diffusion, trapping, sim. signals are convoluted with gaussian ($\sigma$=400ps)
- measured signals are corrected for bandwidth limitation (adding of derivative)

linear E-field

red laser on pad-detector, fluences and thicknesses same as in samples

5.00 / 4.46 / 3.22 $10^{14}$ $n_{eq}$/cm$^2$

deep level model
Pulse Shape Simulation, $V_{bias} = V_{dep} + 50V, +150V$

$p$-irradiated, $V_{bias} = V_{dep} + 50V, +150V$
Pulse Shape Simulation, $V_{bias} = V_{dep} + 50V - 150V$
CCE: Fluence Dependence

protons

neutrons

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