Updated double junction simulation of CMS pixel test beam data


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2004 CMS Pixel Beam Test

All results are based upon 125μm x 125μm CiS pspray test sensors:

- 22x32 cells on each chip
- 285μm thick doped substrate from Wacker:
  - n- doped with ρ = 2-5 kΩ-cm, <111> orientation
  - oxygenated at 1150°C for 24 hours
- irradiated with 24 GeV protons at PS to fluences: (5.9, 2.0, 0.47)×10^{14} n_{eq}/cm^{2}
- annealed for 3 days at 30°C
  - all sensors are “Standard Annealed”
- bump-bonded at 20°C, stored at -20°C
Readout Chip

- sensors bump-bonded to PSI30 ROC from Honeywell
  - doesn’t sparsify data, permits readout of small signals
  - good linearity to 30k e (at 15°, mp charge deposit is ~10k e)
  - not very rad-hard
- irradiated sensors bump-bonded “cold” to unirradiated ROCs

supply of PSI30 now exhausted!
Test Beam Layout

Beam tests performed in SPS H2 beam:

- 150-225 GeV $\pi^+/p$
- 3T open geometry magnet with field along beam axis
- 4xy plane Si strip beam telescope
  - 1 $\mu$m resolution
  - hybrid platform rotates
  - platform cooled to: $-15^\circ C$, $-30^\circ C$
  - ROC heat load increases sensor T to: $-10^\circ C$, $-25^\circ C$
Charge Collection (V. Chiochia+M.S.)

Charge collection was studied from the signal profiles in a row of pixels illuminated by a 15° beam and B=0,• each pixel samples Q deposited at a different depth
• precise beam telescope info is used to refine profile
• collected charge profiles are sensitive to trapping
  – trap rates measured by Ljubljana + Dortmund groups
  – need a simulation to interpret the data
• profiles at several V provide enormous information/contraints on E-field profiles
Over the last several years, we have constructed a detailed sensor simulation, Pixelav [NIM A511, 88 (2003)]

- Particle tracking: e-h pairs are generated according to x-sections of Bichsel [RMP 60, 663 (1988)]
  - E<1 MeV delta rays propagated according to range/energy relation (density of e-h pairs from dE/dx)
Electric field calculation: uses TCAD 9.0 software

- simulate 1/4 pixel cell to keep mesh size ~25,000 nodes. This requires 4-fold symmetry (no bias dot)
- no process simulation, use MESH w/ analytic doping profiles to generate grid and doping files

![Doping Profiles](image1.png)

![Potential Distribution](image2.png)
Transport calculations are done by integrating the fully saturated equation of motion for the carriers:

\[
\frac{d\vec{r}}{dt} = \mu \left[ q\vec{E} + \mu r_H \vec{E} \times \vec{B} + q\mu^2 r_H^2 (\vec{E} \cdot \vec{B}) \vec{B} \right] \frac{1}{1 + \mu^2 r_H^2 B^2}
\]

- 4th-order R-K calc is vectorized for G4 processor
- incorporates diffusion and trapping
- signal induced from displaced, trapped charge is calculated from segmented parallel plate cap. model

Electronics Simulation:
- includes leakage current and electronic noise
- readout chip analog response from measurements
- ADC digitization
- reformat data to look like test beam data
Comparing the charge collection profiles of real and simulated data at $\Phi_1=5.9 \times 10^{14}$ $n_e/q/cm^2$

-300V data are well described by $N_{\text{eff}}=4.5 \times 10^{12}$ $cm^{-3}$ p-

- width of -150V peak requires $N_{\text{eff}}=24 \times 10^{12}$ $cm^{-3}$ p-
  - tail not described

- Constant $N_{\text{eff}}$/linear E-fields ruled out!
Space charge in irradiated sensors can be produced by ionized traps. The SRH description is based on **ALL** trapping states:

\[ \rho_{\text{eff}} = e \left( \sum_{D} N_D f_D - \sum_{A} N_A f_A \right) + \rho_{\text{dopants}} \]

\[ \approx e \left[ N_D f_D - N_A f_A \right] + \rho_{\text{dopants}} \]

- \( N_D \) and \( N_A \) are the densities of h- and e-traps
- \( f_D \) and \( f_A \) are the trap occupation probabilities
- follow Eremin, Verbitskaya, Li and use single h/e-traps
  - D and A states **don’t have to be physical states**: they represent average quantities!
  - model parameters are not physical
The trap occupation probabilities are given in terms of the usual SRH quantities:

\[ f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kT}}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})} \]

\[ f_A = \frac{v_e \sigma_e^A n + v_h \sigma_h^A n_i e^{-E_A/kT}}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})} \]

- \( E_D, E_A \) are defined relative to the mid-bandgap energy
- \( \sigma_e, \sigma_h \) are not well-known in general
- rescaling \( \sigma_{e/h} \Rightarrow r \sigma_{e/h} \) leaves \( f_D \) and \( f_A \) invariant. They depend upon \( \sigma_h / \sigma_e \) only! [key point]
- rescaling \( n/p \Rightarrow r(n/p) \) does not leave \( f_D \) and \( f_A \) invariant (\( f_D \) and \( f_A \) depend on \( I \) and \( E_D, E_A \))
Eremin, Verbitskaya, Li create double junctions from the trapping of the generation current,

\[ \rho_{\text{eff}} = N_D f_D - N_A f_A \]

- the trap parameters (3rd RD50 Workshop) are:

<table>
<thead>
<tr>
<th>trap</th>
<th>( E ) (eV)</th>
<th>( g_{\text{int}} ) (cm(^{-1}))</th>
<th>( \sigma_e ) (cm(^2))</th>
<th>( \sigma_h ) (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>donor</td>
<td>( E_V + 0.48 )</td>
<td>6</td>
<td>( 1 \times 10^{-15} )</td>
<td>( 1 \times 10^{-15} )</td>
</tr>
<tr>
<td>acceptor</td>
<td>( E_C - 0.525 )</td>
<td>3.7</td>
<td>( 1 \times 10^{-15} )</td>
<td>( 1 \times 10^{-15} )</td>
</tr>
</tbody>
</table>
EVL separates the trap dynamics from the leakage current. In Dessis, any attempt to add current-generating defects also traps charge. Solution:

- rescale $\sigma_{e/h} \Rightarrow r\sigma_{e/h}$ (leaves $f_D, f_A$ invariant) but increases SRH generation current by a factor of $r$,

$$U = \frac{r v_h v_e \sigma_h^D \sigma_e^D N_D (np - n_i^2)}{v_e \sigma_e^D (n + n_ie^{E_D/kT}) + v_h \sigma_h^D (p + n_ie^{-E_D/kT})} + \frac{r v_h v_e \sigma_h^A \sigma_e^A N_A (np - n_i^2)}{v_e \sigma_e^A (n + n_ie^{E_A/kT}) + v_h \sigma_h^A (p + n_ie^{-E_A/kT})} = rU_0$$

- can adjust leakage current without appealing to external sources
- EVL fix $\sigma_e = \sigma_h = 10^{-15}$ cm$^{-2}$, keeping $\sigma_e = \sigma_h$ is mathematically equivalent
What current should we use? \( I \) is larger than one would expect for a 2.75x4x0.285 mm\(^3\) volume: try 2 values

\[ \Phi_1 = 5.9 \times 10^{14} \, \text{n}_e/\text{cm}^2 \]

- Model ere5 is normalized to produce 30% of \( I_{\text{obs}} \) [saturates \( \alpha = I(20\, \text{C})/(V\Phi) = \alpha_0 = 4 \times 10^{-17} \, \text{A/cm} @300\, \text{V} \)]
- Model ere6 is normalized to produce 100% of \( I_{\text{obs}} \)

Neither of these can describe the data!
“Fitting” the Data

- parameters $N_A, N_D, \sigma^A_e, \sigma^A_h, \sigma^D_e, \sigma^D_h$ are varied keeping the same $E_A, E_D$ as EVL
- signal trapping rates $\Gamma_e, \Gamma_h$ are uncertain ($\pm 10\%$ level due to $\Phi$ uncertainties and $\pm 30\%$ level due to possible annealing) and were also varied in the procedure
- very slow and tedious: 8-12hr TCAD run + 4x(8-16)hr Pixelav runs + test beam analysis
- “eyeball” fitting only - no $\chi^2$ or error matrix
  - parameters varied by hand (no Minuit)
- strong correlations between parameters
Best fit to $5.9 \times 10^{14} \text{ n}_\text{eq}/\text{cm}^2$:
labelled dj44

- $\sigma_h/\sigma_e = 0.25, N_A/N_D = 0.40$
- scale $\Gamma_e/h$ by 0.8 as compared with rate $\Gamma_0$ expected for $\Phi$
- E-field is quite symmetric across sensor
There is a contour in $N_D$ vs $\sigma_e$ space ($\sigma_e \propto N_D^{-2.5}$) that produces (more or less) the same efield in the detector:

- large $z$, -150V tail becomes too large for $N_D < 35 \times 10^{14}$
- large $z$, -300V signal becomes too small for $N_D > 70 \times 10^{14}$
- $I \propto N_D \sigma_e$ so any $I$ from $\alpha_0/2$ to $\alpha_0$ fits data
- $\Gamma_e \sim v_e N_A \sigma_e \propto N_D \sigma_e$ so observed $\Gamma_e$ is just OK
Temperature Dependence

Use $T$-dependent recombination in TCAD and $T$-dependent quantities in Pixelav ($\mu_{e/h}, D_{e/h}$, and $\Gamma_{e/h}$):

- $T=-10\,^\circ C$

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>$\Phi_1=6\times10^{14} \text{ n}_\text{eq}/\text{cm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td><img src="image1" alt="Graph" /></td>
</tr>
<tr>
<td>200</td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>300</td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>450</td>
<td><img src="image4" alt="Graph" /></td>
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</tbody>
</table>

- $T=-25\,^\circ C$

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th><img src="image5" alt="Graph" /></th>
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</thead>
<tbody>
<tr>
<td>200</td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>300</td>
<td><img src="image7" alt="Graph" /></td>
</tr>
<tr>
<td>450</td>
<td><img src="image8" alt="Graph" /></td>
</tr>
</tbody>
</table>

- $\text{dj-model is predictive!}$
The “Wiggle”

The charge collection profiles show a “wiggle” at low bias:

- signature of a doubly-peaked electric field:
  - e-h pairs deposited near field minimum separate only a little before trapping, produces local minimum
  - the apparently “unphysical” bump is caused by collection of holes in the higher field region near the p+ implant (e’s drift into low field region and trap)
Scaling to Lower Fluences

Scale densities + trapping rates of $d_{j44}$ linearly by fluence:

\[
\begin{align*}
N_A(\Phi_2) &= R_A \cdot N_A(\Phi_1) \\
N_D(\Phi_2) &= R_D \cdot N_D(\Phi_1) \\
\Gamma_{e/h}(\Phi_2) &= R_\Gamma \cdot \Gamma_{e/h}(\Phi_1)
\end{align*}
\]

\[
R_A = R_D = R_\Gamma = \frac{\Phi_2}{\Phi_1}
\]

$T=-10^\circ C$

$\Phi_2=2 \times 10^{14}$

✧ linear scaling of the trap densities doesn’t work!

✴ too much field on the p+ side

✧ the “wiggle” is still present at $\Phi_2=2 \times 10^{14}$ $n_{eq}/cm^2$

✴ a doubly-peaked field persists at lower fluences
Why doesn’t linear $\Phi$ scaling work?

✦ scaling of $f_{A/D}$ with $n$, $p$ is wrong (wrong $E_{A/D}$)?

✦ quadratic $\Phi$ scaling of $V_{2X}$ states?

Can increase n+ side field and decrease p+ side by increasing $N_A/N_D$ but keeping $\Gamma_{e/h}$ and $I$ linear in $\Phi$

$$R_{\Gamma} = \frac{\Phi_2}{\Phi_1}, \quad R_A = R_{\Gamma}(1 + \delta), \quad R_D = R_{\Gamma}(1 - \delta)$$

✦ $R_{\Gamma} = (R_A + R_D)/2$, keeps $I$ linear

✦ increase $N_A/N_D$ from 0.4 to 0.68 (closer to EVL value of 0.62)

✦ must scale the “full” $I_{\text{leak}}$ point (range is $\pm 10\%$ in $N_D$)

✦ net donor $\sigma_h/\sigma_e$ also prefers to increase (not very sensitive)

✦ took 3 months of tuning!
Best fit to $2.0 \times 10^{14}$ $n_{eq}/cm^2$: labelled dj57a

- $N_A/N_D = 0.68$
- $\sigma_{Ah}/\sigma_{Ae} = 0.25$, $\sigma_{Dh}/\sigma_{De} = 1.00$,
- E-field still doubly-peaked (more than EVL prediction)
- Also compare with PMP model
Petasecca, Moscatelli, and Pignatel showed a 3-state model of irradiated n-type silicon at the 5th RD50 workshop:

- dominant acceptor traps e- creating net negative space charge (effective p-type doping)
  - model of linear charge inversion
  - no double junctions or doubly-peaked E-fields

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<th>$g_{int}$ (cm$^{-1}$)</th>
<th>$\sigma_e$ (cm$^2$)</th>
<th>$\sigma_h$ (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>donor</td>
<td>$E_v+0.36$</td>
<td>1</td>
<td>$1\times10^{-15}$</td>
<td>$1\times10^{-16}$</td>
</tr>
<tr>
<td>acceptor</td>
<td>$E_c-0.42$</td>
<td>26</td>
<td>$1\times10^{-16}$</td>
<td>$8\times10^{-15}$</td>
</tr>
<tr>
<td>acceptor</td>
<td>$E_c-0.50$</td>
<td>0.1</td>
<td>$1\times10^{-16}$</td>
<td>$1\times10^{-15}$</td>
</tr>
</tbody>
</table>
$2.0 \times 10^{14} \text{ } n_{eq}/\text{cm}^2$ compared with EVL and PMP

- EVL is adjusted to produce expected leakage current
- PMP produces more or less correct leakage current (a bit low)

What about the $0.47 \times 10^{14} \text{ } n_{eq}/\text{cm}^2$ point?
Scaling to Even Lower Fluences

Scale dj57a to increase $N_A/N_D$ at $\Phi_3=0.47 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$

$$R_{\Gamma} = \frac{\Phi_3}{\Phi_2}, \quad R_A = R_{\Gamma}(1 + \delta'), \quad R_D = R_{\Gamma}(1 - \delta')$$

✦ $N_A/N_D = 0.75, \sigma_{Ah}/\sigma_{Ae} = 0.25, \sigma_{Dh}/\sigma_{De} = 1.00$

✴ charge drift times now comparable to preamp shaping (simulation may not be reliable)

✧ the data “wiggle” is still present at $\Phi_3=0.47 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$

✴ a doubly-peaked field persists at lowest fluence!!!
We can still see evidence of a doubly-peaked electric field near the “type-inversion” fluence:

✦ profiles are not described by thermodynamically ionized acceptors alone
✦ trapped leakage current can describe everything

Scale factor summary:

✦ trapping rates are linear in $\Phi$
✦ $N_A/N_D$ increases from 0.40 at $\Phi_1=5.9 \times 10^{14}$ $n_{eq}/cm^2$ to 0.75 at $\Phi_3=0.47 \times 10^{14}$ $n_{eq}/cm^2$
Conclusions

- It is clear that a two-peak electric field is necessary to describe our charge collection data even at low fluence.
- A two-trap double junction model can be tuned to provide reasonable agreement with the data.
  - \( \frac{N_A}{N_D} \) must vary with fluence.
  - Describes non-trivial \( T \) and \( \Phi \) dependence of E-field.
• Assuming that the “chemistry” of irradiated doped silicon is independent of initial dopant
  - suggests that there is no advantage of n/n over n/p at high $\Phi$ (n/p is much cheaper to build)

$\Phi = 5.9 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$

$N_{dop} = 1.2 \times 10^{12} \text{ cm}^{-3}$

• Model will be important to calibrate the hit reconstruction after irradiation in LHC
Charge Sharing in 4T CMS After Irradiation

The Lorentz angle is linear in the mobility $\mu(E)$

$$\tan \theta_L \simeq \frac{er_H v_B \sin \theta_{vB}}{eE} = r_H \mu(E) B \sin \theta_{vB}$$

- $\mu(E)$ varies by ~3 across the detector thickness in irradiated sensors
  - creates very non-linear charge sharing
  - largest in middle and smallest near implants
- trapping also causes non-linear response in irradiated sensors