Radiation Damage in Silicon Detectors

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Outline

• Prelude
• Basics of silicon detector operation
• Radiation fields at hadron colliders
• Radiation damage
  – Displacement damage
  – Ionization
• Operation of irradiated silicon detectors
• From LHC to HL-LHC
• Conclusions and outlook
• Position sensitive silicon detectors are an indispensable ingredient of any collider experiment
  – mostly as tracking detectors, but also for calorimetry
• Physics requirements in terms of integrated luminosity and the resulting particle fluences are ever escalating
  – for LHC $10^{15}$ n$_{eq}$/cm$^2$ considered extremely difficult
    • design was 730/fb @14TeV...
  – HL-LHC takes it to nx$10^{16}$ (vertex) or even $10^{17}$ (FW calo)
    • 4000/fb @14TeV
  – FCC is dreaming of towards $10^{18}$ for the tracker
    • 30/ab @100TeV
• Ratio $\sim$1:20:600!
• What is the limit of silicon sensors?
Pushing the Limits

• Progress in radiation hardness is astounding
  – evolution, spiced up by a couple of revolutions
  – hard work of the whole community
  – many new ideas and concepts developed

• R&D mostly by individuals/groups
  – resources needed moderate in HEP terms

• Streamlined by collaborations/projects
  – CERN RD-48 and RD-50
  – EC sponsored:
    • AIDA, AIDA2020 (IP)
    • MC-PAD, STREAM (MC)
Si material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic number</td>
<td>14</td>
</tr>
<tr>
<td>atomic mass</td>
<td>28.09</td>
</tr>
<tr>
<td>distance between lattice atoms</td>
<td>$5.34 \times 10^{-10}$ cm</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>11.9</td>
</tr>
<tr>
<td>density</td>
<td>$2.328 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>density (SiO$_2$)</td>
<td>$2.33 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>density of atoms</td>
<td>$5.0 \times 10^{22} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>intrinsic carrier concentration at $T = 300$ K ($n_i$)</td>
<td>$1.45 \times 10^{10} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>effective density of states ($T = 300$ K):</td>
<td></td>
</tr>
<tr>
<td>in conduction band ($N_c$)</td>
<td>$2.80 \times 10^{19} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>in valence band ($N_v$)</td>
<td>$1.04 \times 10^{19} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>energy gap ($T = 300$ K) ($E_g$)</td>
<td>1.12 eV</td>
</tr>
<tr>
<td>average minimum ionizing particle energy</td>
<td></td>
</tr>
<tr>
<td>loss ($dE/d(\rho x)$)</td>
<td>166 keV kg$^{-1}$ m$^2$</td>
</tr>
<tr>
<td>electron mobility $\mu_{0,e}$</td>
<td>1380 cm$^2$/Vs</td>
</tr>
<tr>
<td>hole mobility $\mu_{0,h}$</td>
<td>480 cm$^2$/Vs</td>
</tr>
<tr>
<td>$m_e^*$ (at bottom of conduction band)</td>
<td>0.558 $m_e$</td>
</tr>
<tr>
<td>$m_h^*$ (at top of valence band)</td>
<td>1.08 $m_e$</td>
</tr>
<tr>
<td>$v_{th,e}$ (at $T = 300$ K)</td>
<td>$2.3 \times 10^7$ cm/s</td>
</tr>
<tr>
<td>$v_{th,h}$ (at $T = 300$ K)</td>
<td>$1.65 \times 10^7$ cm/s</td>
</tr>
</tbody>
</table>

in thermal equilibrium

Electrically Neutral Bulk (ENB)

$$np = n_i^2 = N_C N_V e^{-\frac{E_g}{k_B T}}$$

$$N_{C,V} = 2 \left( \frac{2\pi m_{e,h}^* k_B T}{\hbar^2} \right)^{\frac{3}{2}}$$
Fermi Level

- Carrier density governed by Fermi-Dirac statistics

\[ F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)} \]

\[ n = N_C e^{-\frac{E_C - E_F}{k_B T}} \]

\[ p = N_V e^{-\frac{E_F - E_V}{k_B T}} \]

- Extrinsic (doped): \( E_F \) adapts closer to \( E_C (E_V) \)
  - \( n \approx N_D \) (donors, n-type) or \( p = N_A \) (acceptors, p-type)
Drift and Conductivity

- In electric field charge carriers drift
- mobility $\mu = \mu(E)$
  - zero field mobility $\mu_0$
  - saturation velocity $v_{sat}$
    - $v_{sat} \approx 100 \, \mu m/\text{ns}$
    - transit times $D/\nu > n s$
- resulting resistivity
  \[
  \rho = \frac{1}{e_0(\mu_e n + \mu_h p)}
  \]
  - for intrinsic ($n=p=n_i$): $\rho \approx 230 \, k\Omega \cdot cm$ ($T=300 K$)
  - high resistivity 5 k$\Omega \cdot cm$ $n(p)$-type: $N_D(N_A) = 0.9(2.6) \times 10^{12} \, \text{cm}^{-3}$
- Impossible to see particle signal in presence of current
**p-n Junction**

- Join *n*-doped and *p*-doped Si
  - mobile carriers diffuse across junction and recombine
  - ions stay constituting **space charge region** (SCR) depleted of carriers
  - resulting electric field opposes diffusion
    - resulting $V_{bi} \approx 1$ V
  - added reverse bias provokes further diffusion, widening SCR

- **Simplification** – abrupt junction in 1-D
  - solve Poisson equation
  - space charge constant, junction neutral ($N_A D_A = N_D D_D$)
  - electric field linear, peaked at junction
  - electric potential quadratic
  - usually $N_{A(D)} \gg N_{D(A)}$, so $w_{SCR} \approx w_{SCR, D(A)}$

$$- \frac{d^2 V}{dx^2} = \frac{\rho_e(x)}{\varepsilon_s \varepsilon_0}$$
Space Charge Region

- Single sided abrupt junction
  - $p^+n$ or $n^+p$ ($N_D -> N_A$)
  - compensated material
    - $N_D \rightarrow N_{\text{eff}} = |N_D - N_A|$
  - $w=D$ full depletion voltage $V_{FD}$
    - scales with $N_{\text{eff}}$ (or $1/\rho$) and $D^2$
    - $V_{FD} = 70$ V @ $N_{\text{eff}} = 10^{12}$ cm$^{-3}$ for $D = 300$ μm
  - for high resistivity silicon (5 kΩ.cm) and $D = 300$ μm
    - $V_{FD} \approx 65$ V(n) or 180 V(p)
    - $E_{\text{max}} \approx 0.2$ or 0.6 V/μm at junction
  - $V > V_{FD}$ add constant $E_c = (V - V_{FD})/D$ to linear field @ $V_{FD}$
    - field slope ($N_{\text{eff}}$) independent of $V$

\[ w(V) = \sqrt{\frac{2\epsilon_S\epsilon_0}{e_0 N_D}} V \]
Segmented Detectors

- 1-D approach adequate for pad detectors or when lateral dimension $L \gg D$
  - often also used for first estimates
- Realistic detectors 2-D (strips) or 3-D (pixels) with electrode segmentation (single/double sided, 3D)
  - solve Poisson equation in 3-D to obtain el. field
  - doping profile can deviate from abrupt
- Numerical simulations, often using TCAD package
**$V_{FD}$ measurement: $I$-$V$ and $C$-$V$**

- 1-D pad detector
  - $I$ dominated by generation in SCR
    - surface current contribution
      - guard ring
  - $1/C^2$ of SCR linear in $V$ up to $V_{FD}$
    - ENB: $R$ or $1/\omega C$?
    - surface $R$?
    - $V_{FD}$ from “kink” in $1/C^2$ vs. $V$

\[
C \propto \frac{1}{w} \propto \sqrt{\frac{V_{FD}}{V}}
\]

\[
\frac{1}{C^2} = \frac{2}{\varepsilon_0 \varepsilon_{Si} \varepsilon_0 N_{eff} S^2} V
\]
Signal Formation

- Charged particle ionizes silicon along its path
  - Landau fluctuations of ionization
    - mean $dE/dx$ ill-defined
  - MIP creates 108 e-h pairs/μm on average (72e MPV for 300 μm Si)
  - in SCR the charges start moving towards electrodes
    - in absence of field the charges rapidly recombine
  - promptly current gets induced on electrodes – mirror charge
    - no need to wait until charge gets “collected”
- Induced current given by Ramo-Shockley theorem

\[ I(t) = \frac{q \cdot v \cdot E}{w} = q \cdot \mu(E) \cdot E \cdot E_w \]
Weighting Field

\[ I(t) = q \cdot \mu(E) \cdot \vec{E} \cdot E_w \]

- \( E_w \) is the weighting (Ramo) field
  - solve Laplace equation (no space charge!) for weighing potential \( V_w \) with
    - readout electrode at unit potential (\( V_w = 1 \))
    - all other electrodes grounded (\( V_w = 0 \))
  - fraction of induced charge given by \( \Delta V_w \)
  - \( E_w = -\text{grad}(V_w) \)
  - in 1-D \( E_w = 1/w \)
  - numerical simulation with many cells required for a realistic \( E_w \) of pixel/strip

- Resulting \( I(t) \) subject to transfer function of the electronics

\[ I(t) = q \cdot \mu(E) \cdot \vec{E} \cdot E_w \]
Radiation Field at (HL)-LHC

- At $L=10^{34}$ cm$^{-2}$s$^{-1}$ LHC produces $R = \sigma. L = 800$ MHz of inelastic 13 TeV $pp$ collisions
- Each collision yields $\sim$14 primary charged particles, mostly pions, with $p_T > 0.5$ GeV/c in the tracker ($|\eta|<2.5$)
- $\sim$same flux of high energy gammas is created from $\pi^0 \rightarrow 2\gamma$
- Detector material produces
  - $e^+e^-$ pairs from conversions, $\sim$doubling every $X_0$
  - additional hadrons (pions) from nuclear interactions
    - interaction length $\Lambda_i$; for detector material $\Lambda_i > X_0$
  - fast neutrons from spallation in calorimeters
    - very long-lived
    - bounce around until captured or thermalized
    - reach back tracker – albedo neutrons
Radiation Effects - Ionization

• Total Ionization Dose (TID) \([\text{Gy} = \text{J/kg}, (= 100 \text{ rad})]\]
  – charged particles ionize matter
    • neutrons through ionization KERMA \((p, \text{fragments})\)
    • gammas through pair production \(\rightarrow e^+e^-\)
  – produces \(e-h\) pairs in Si at 3.6 eV per pair \(\rightarrow\) signal
  – positive charges remain in oxide \(\rightarrow\) sensor surface, electronics

• Bethe-Bloch formula
  – function of \(\beta\gamma (\nu)\) only
    • small modification for \(e\)
  – shallow minimum around \(\beta\gamma \approx 3\) \(\rightarrow\) MIP
    • \(dE/(\rho dx) \approx 2 \text{ MeV}/(\text{g/cm}^2)\)
    • \(dE/dx_{\text{Si}} = 390 \text{ eV}(108 \text{ e-h})/\mu\text{m}\)
  – relativistic rise at high \(\beta\gamma\)
    • limited by: polarization (density), restricted loss (escape)
Radiation Effects - Displacement

• Non-Ionizing Energy Loss (NIEL) \( \frac{n_{eq}}{cm^2} \)
  – heavy particles displace Si atoms from lattice – bulk damage
    • primary knock-on atom (PKA), threshold \( \sim 20 \) eV
    • interstitial atom (I) and vacancy (V) in Si lattice – primary defects
    • PKA knocks out further atoms until \( E < 20 \) eV
  – about 50 % of NIEL ends up in displacements, rest in phonons

• NIEL normalized to 1 MeV neutrons
  – 95 MeV.mb per Si atom
    • \( 10^{17} \) n/cm\(^2\) displaces \( \sim 2 \times 10^{-4} \) of atoms
    • \( dNIEL/(\rho dx) \approx 2 \text{ keV}/(g/cm^2) \)
  – particles fluences converted to 1 MeV neutron equivalent fluence
  – hardness factor \( \kappa = \frac{\Phi_{eq}}{\Phi} \)
    • fast pions, protons \( \kappa \leq 1 \)
    • electrons, thermal neutrons \( \kappa \ll 1 \)
Defect Dynamics

- Vastly different topologies
  - 10 MeV $p$ – point defects
  - 1 MeV $n$ – clusters
  - 24 GeV $p$ – in-between
- Number of $V$ scales with NIEL
- Basis of NIEL hypothesis: All bulk damage scales with NIEL

- Most (~90%) of $I-V$ recombine within cluster
  - or form $V_2/V_3$ (Group B)
- The rest diffuses and interacts with each other and impurities to form stable defects in lattice (Group A)
- Stable defects have their own long term dynamics - annealing
Bulk damage to Si Sensor

- Some of stable defects electrically active
  - energy levels in band-gap
  - deep
    - donors
    - acceptors
    - multi-charge states
- Defects neutralize initial shallow dopants
  - donor, acceptor removal
    - exponential with fluence: $N = N_0 e^{-c\Phi}$
    - removal constant scales with initial doping ($c \approx 2.10^{-13}$ cm$^2$ for high $\rho$)
    - mechanism not fully understood

- Shockley-Read-Hall statistics
  - thermal equilibrium (ENB)
    - Fermi-Dirac statistics for level occupancy
    - $e$ and $h$ capture/emission balanced for each defect
    - Fermi level adapts to ensure overall neutrality
  - SCR
    - $\approx$no $e/h$ to capture, only emission remains
    - $E_i \approx$ mid-gap instead of Fermi level
    - donor/acceptor ionized in SCR if few $k_B T$ above/below $E_i$
Manifestations of Bulk Damage

- Ionized deep traps contribute to space charge
  - deep acceptors prevail – **negative space charge**
- States close to mid-gap have ∼equal $e/h$ emission rates

\[
U = \frac{\sigma_n \sigma_p v_{th} N_t (pn - n_i^2)}{\sigma_n [n + n_i \exp\left(\frac{E_i - E_t}{kT}\right)] + \sigma_p [p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)]}
\]

- generation leakage current
- Defects trap signal (and current) charge – **trapping**
  - ionized/neutral acceptors trap holes/electrons
  - ionized/neutral donors trap electrons/holes
    - trapping cross sections usually larger for ionized traps
  - emission times long on signal collection time-scale – charge lost
- ENB: if $N_t >> N_{D,A}$ - defects pin $E_F$ close to deep levels: $\rho \rightarrow \rho_i$

$U=R-G$
ENB: $U=0$
SCR: $p=n\approx 0; U=-G$
Bulk Damage: Space Charge

- Hamburg model
  - effective acceptor introduction
    - stable – $g_c \approx 0.015$ cm$^{-1}$
    - short term (beneficial) annealing - $g_a \approx 0.018$ cm$^{-1}$
    - long term (reverse) annealing – $g_{ra} \approx 0.052$ cm$^{-1}$
  - (incomplete) shallow donor removal

\[
\frac{\Delta N_{eff}(t)}{\Phi_{eq}} = g_c + \sum_{\text{annealing}} g_a e^{-t/\tau_a} + \sum_{\text{rev. annealing}} g_{ra} (1 - e^{-t/\tau_{ra}}) +
\]

\[
\frac{(N_D(0) - N_D(\Phi_{eq})) - (N_A(0) - N_A(\Phi_{eq}))}{\Phi_{eq}}
\]

- $\tau_{ra} O(y)$ and $\tau_a O(d)$ at R.T
- can optimize operation to stay close to shallow minimum between the two
  - 80 min annealing @60°C

- Effectively $N_{eff} = -\beta \Phi$ for $\Phi > 10^{13-14} \text{ n}_{eq}/\text{cm}^2$
  - $\beta \approx 0.02$ cm$^{-1}$ -> $N_{eff} \approx 10^{12} \text{ cm}^{-3}$ @ $\Phi \approx 5 \times 10^{13} \text{ n}_{eq}/\text{cm}^2$
• (HL)-LHC experiments last for \(O(10\,\text{y})\)
  – Cannot ignore annealing
  – Annealing scenario needed
  – Time constants exponentially dependent on \(T\) – Arrhenius relation

\[
\tau(T) = \tau(T_0) \cdot \exp \left(- \frac{E_a (T - T_0)}{k_B T_0 T} \right)
\]

– \(E_a\) – activation energy
  • annealing: \(\tau(20^\circ C) = 55\, \text{h}; E_a = 1.1\, \text{eV}\)
  • reverse annealing: \(\tau(20^\circ C) = 475\, \text{d}; E_a = 1.3\, \text{eV}\)

• Morale: always keep detector cold!
Bulk Damage: Leakage Current

- Leakage (reverse bias) current consequence of generation by mid-gap level(s) in SCR
- Strictly scales with NIEL (material, particles)
  - in fact used to measure $\Phi_{eq}$!
- Annealing reveals many components
  - most relevant component
    - $\tau \approx 10 \text{ d}, E_a = 1.1 \text{ eV}$
    - slow annealing afterwards
- $\alpha_{80\text{min},60^\circ\text{C}} \approx \alpha_\infty \approx 4 \times 10^{-17} \text{ A/cm}^3$
  - @20°C, scaling to other $T$
    - $\sim$doubles every 8°C

\[ \alpha(T) \propto T^2 \exp\left(-\frac{E_g}{2k_B T}\right) \]

- fitted $E_g \approx 1.2 \text{ eV}$ instead of 1.12 eV
  - level(s) not exactly mid-gap
Measurement: Charge Collection

- Signal mostly measured as time integral – charge
- Simplest: $^{90}\text{Sr}$ (β~MIP), pad detector, CSA, shaper ($\tau \sim 25$ ns) -> signal
  - signal spectrum: Landau×Gaussian (noise)
- Signal MPV (or mean) vs. bias voltage
  - absolute calibration difficult
  - normalize to non-irradiated, fully depleted detector
    - Charge Collection Efficiency - CCE
- Expect charge collection from SCR
  - indeed observed in non-irradiated
  - for irradiated $CCE(V)$ linear ?!
  - ENB highly resistive, $E_w = 1/D$ not $1/w$
  - Charge drifts $w$ only: CCE reduced by $w/D$
- For pixels, strips, two cases
  - SCR grows from collecting electrode
    - e.g $p+$ strips on n-bulk before type inversion
    - smaller correction from $E_w$ since $E_w$ peaked at pixel strip, $CCE(V)$ therefore closer to $v(V)$
  - after inversion SCR growth from backplane
    - need $V > V_{FD}$ for ~any $CCE$, otherwise charge distributed over many strips/pixels

\[
CCE \propto w \propto \sqrt{\frac{V}{V_{FD}}}
\]
\[
CCE_{irr} \propto \frac{w \cdot w}{D} \propto \frac{V}{V_{FD}}
\]
**Transient Current Technique**

- **Transient Current Technique (TCT)**
  - Generate charges by fast (<300 ps) laser pulse
  - Measure induced signal $I(t)$ with fast amplifier with sub-ns rise-time

- **Laser**
  - Red laser with $\sim 3$ $\mu$m penetration on top surface
    - Need opening in metallization
  - Generates induced currents for
    - Electrons (p+-side injection)
    - Holes (n+ side injection)
  - IR laser (1060 nm), penetration $\sim$mm
    - Ionizes through detector; $\sim$MIP equivalent
  - From top or side – Edge-TCT
    - Detector edge polished
  - Focus laser, move detector to scan
  - Maps detector response in $(x,y,z)$

- **Analyze $I(t)$ to extract detector parameters**
Bulk Damage: Trapping

- Defects capture charge carriers

\[ Q(t) = Q_0 \exp\left(- \frac{t}{\tau}\right) \]

\[ \frac{1}{\tau} = \frac{v_{th}}{\langle l \rangle} = v_{th} \sum_t \sigma_t N_t = v_{th} \sum_t \sigma_t g_t \cdot \Phi = \beta \cdot \Phi \]

- Visible in TCT as charge deficit above \( V_{FD} \)
- Can correct \( I(t) \) with \( \exp(\frac{t}{\tau}) \) until charge flat for all \( V > V_{FD} \)
  - Charge correction method
- Measured \( 1/\tau(\Phi) \) linear up to \( 2 \times 10^{14} \) \( n_{eq}/cm^2 \)
  - \( \beta \) values around \( 5 \times 10^{-16} \) \( cm^2/ns \)
    - \( \tau \approx 20 \) ns@\( 10^{14} \) \( n_{eq}/cm^2 \)
    - trapping important (limiting) beyond \( 10^{15} \) \( n_{eq}/cm^2 \)
  - holes > electrons by \( \sim 40 \% \)
    - more after annealing
  - charged hadrons > neutrons
    - NIEL violation at 30 \% level
Résumé for LHC

• Operate Si at ~500 V
  – copes with $V_{FD}$ up to $\sim 6 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$
    • strips ($< 2 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$) safe with $p+n$ ($n^+n$ too expensive)
    • pixel (inner $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$) go $n^+n$ and 700 V

• At the limit of the then technology
  – previous generation of Si operated at $\leq 100$ V!
  – push on sensor design and manufacturing
  – even services non-trivial (Ta caps for $> 300$ V!)

• So far, big success in operation!
  • caution, was planned for 730/fb, we are at $\sim 100$/fb now
HL-LHC Radiation Field

- Maximum fluences
  - pixels \( \sim 2 \times 10^{16} \text{n}_{eq}/\text{cm}^2 \)
  - strips \( \sim 10^{15} \text{n}_{eq}/\text{cm}^2 \)
  - \( \sim \) charged hadrons for pixels, up to 80% neutrons for (outer) strips

- TID up to 10 MGy

- About 20x planned for LHC

### Table: 1 MeV neutron equivalent fluence

<table>
<thead>
<tr>
<th>Location</th>
<th>1 MeV n. eq. (cm(^{-2}))</th>
<th>Protons</th>
<th>Pions</th>
<th>Neutrons</th>
<th>Dose (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r=28 cm; z=0 cm)</td>
<td>6.9e+14</td>
<td>7.8%</td>
<td>38.5%</td>
<td>53.7%</td>
<td>329</td>
</tr>
<tr>
<td>(r=28 cm; z=117 cm)</td>
<td>8.9e+14</td>
<td>13%</td>
<td>31.8%</td>
<td>55.2%</td>
<td>418</td>
</tr>
<tr>
<td>LS (r=100 cm; z=0 cm)</td>
<td>1.7e+14</td>
<td>6%</td>
<td>13%</td>
<td>61%</td>
<td>34</td>
</tr>
<tr>
<td>LS (r=100 cm; z=117 cm)</td>
<td>2.1e+14</td>
<td>6.2%</td>
<td>10%</td>
<td>83.8%</td>
<td>38</td>
</tr>
</tbody>
</table>

### Diagram: 1 MeV neutron equivalent fluence over ATLAS ITK 3000/fb.
• Linear extrapolation from low fluence data
  – Current: $I_{\text{leak}} = 0.8 \text{ A/cm}^3 \ @ 20^\circ\text{C}$
    • $0.4 \text{ mA/cm}^2$ for 300 $\mu$m thick detector @ -20°C
  – Depletion: $N_{\text{eff}} \approx 4 \times 10^{14} \text{ cm}^{-3}$
    • $FDV \approx 30 \text{ kV}$
  – Trapping $\tau_{\text{eff}} \approx 1/8 \text{ ns} = 125 \text{ ps}$
    • $Q \approx Q_0/d \nu_{\text{sat}} \tau_{\text{eff}} \approx 80 \text{ e/}\mu\text{m} 200 \mu\text{m/ns} 1/8 \text{ ns} = 2000 \text{ e in very high electric field (>>1 V/}\mu\text{m)}$

• Looks much like Mission Impossible (part n...)
• Need a(?) miracle... better a revolution or two...
Pre-Revolution: Material Engineering

• Major achievement of ROSE (RD-48)
  – oxygenated FZ silicon (DOFZ) exhibits ~3x smaller $g_c$ for charged hadrons
    • benefits also in reverse annealing
  – unlucky enough, no effect with neutron irradiation
    • [O] too small in clusters?
  – no effect on trapping
• Used by LHC pixel detectors
  – neutron share small, trapping not yet a big issue

• Trials with many more materials
  – MCz exhibited some benefit, but not conclusive
1st Revolution: Beef up Voltage

- Rather obvious, but definitely not trivial
  - detectors break down
  - engineering needs special care in components, materials, clearances, services...
    - does not scale linearly with $V$
  - ATLAS SCT started with 350, then 500 V
    - services foresightedly designed to latter value
  - ATLAS Pixel went to 700 V
  - IBL (Phase-0 pixel upgrade) extended to 1000 V
- R&D now routinely use $V$ to 1000 (even 2000) $V$
• For segmented detectors with trapping e collection (\(n^+\) electrodes) is better
  – faster drift (\(\mu_e \approx 3.\mu_h\) but \(v_{sat,h} \approx \frac{3}{4}.v_{sat,e}\))
  – less trapping
  – high electric field coincident with high weighting field after inversion
• Expense of \(n^+n\) overcome by turning to \(n^+p\)
  – shallow dopant benefit hardly noticeable
  – no inversion, if that matters...
• A major surprise (beneficial !) came later...
3rd Revolution: Charge Multiplication

- Used in APD for ages, but never considered in segmented Si detectors
  - remember, electric fields used to be $E_{\text{max}} < 1 \text{ V/\mu m}$!
    - and we were collecting holes...

- Results with $n^+p$ looked encouraging
  - $CCE$ of $\geq 50 \%$ @ $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$
  - $CCE \sim \text{linear in } V$

- Then somebody decided to turn the bias voltage knob
  - $CCE > 100 \%$ up to $3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$
  - $CM$ “discovered” in Si sensors
• Multiplication is textbook physics
  – e.g. S.M. Sze, Physics of Semiconductor Devices, Wiley, New York, 1981
    - Ch 1.6.4 High-Field Property
      – Velocity saturation, impact ionization
    - Ch 2.5.3 Avalanche Multiplication
      – Junction break-down
• Measured impact ionization
  – Electrons create 1 pair in 10 µm at $E \sim 20$ V/µm (100 µm at 14 V/µm), holes need $E \sim 40$ V/µm
  – Holes need ~1 mm for pair creation at $E \sim 20$ V/µm
    • Neglect hole multiplication in signal creation altogether
    • Need to invoke hole multiplication for junction breakdown
• $\alpha_e >> \alpha_h$ - Nature gentle to us (in silicon)
  – Large range in $E$ where electrons multiply without inducing breakdown
  – But beware of (too) high electric fields!

\[ \alpha_{e,h}(E) = \alpha_{e,h}^\infty e^{-b_{e,h}/E} \]

\[
\int_0^w dx \alpha_e(x) e^{-x} = 1
\]
Breakdown condition, can swap $\alpha_e$ with $\alpha_h$
• Generation current accumulates, increasing $p$ and $n$ in opposite directions through SCR

• $e$ and $h$ trap, contributing to space charge
  – new (dynamic) configuration
  – observed as “double junction” in e-TCT
    • modelled also in TCAD
  – most prominent in $p$ irradiated Si around $10^{15} \text{n}_{eq}/\text{cm}^2$ – $E$ nearly flat, good for CCE
  – much less effect after $n$ irradiation
• *n*-irradiated Si behaves almost “by the book”
  – no [O] benefit
  – little double junction
  – good SCR/ENB separation
• But at extreme fluences there appears a substantial field in ENB
  – $E_{ENB}$ up to 3 V/μm!
• Interpreted as Ohmic $E=j.\rho$
  – $j$ generated in SCR
  – $\rho$ must be larger than $\rho_i$
  – possible because of 6x smaller mobility, also take $\rho_i(E)$, not $\rho_i(0)$
Nothing is Linear

- Linear behaviour is just the first term in Taylor series
  - sooner or later expected to break down
    - saturation – lower than linear prediction
    - breakdown – higher than linear prediction
- So far saturation effects observed in
  - leakage current (maybe just SCR effect...)
  - trapping
  - $g_c$ for neutrons
- Looks like the odds are on our side
  - so far?
Where are we now?

• We are confident to build Si trackers for HL-LHC
  – TDR’s in writing (ATLAS Strip TDR approved)
  – some sensor options (can) remain open (3-D, CMOS)
  – inner Pixel part exchangeable (headroom for sensors, electronics (design) issue above 5 MGy)

• Many other ingenious and important developments I had no time to elaborate on
  – sensor technologies
    • 3-D detectors, depleted CMOS, thin detectors, LGAD’s, ...
  – characterization
    • microscopic defects, device simulation, TPA TCT, test-beams, ...
  – surface damage
    • electronics, sensor design
  – single event effects
Can Si Serve in FCC

- Maximum radiation in tracker $6 \times 10^{17} \, n_{eq}/cm^2$ and 500 MGy
- From first sight this looks plain *impossible*
  - except for exchanging inner tracker each ~month
    - robots!
- But remember
  - HL-LHC ($2 \times 10^{16} \, n_{eq}/cm^2$ and 10 MGy) looked *impossible* from LHC perspective
  - even LHC looked *impossible* from LEP perspective
Measurements up to $1.6 \times 10^{17} \text{n}_{\text{eq}}/\text{cm}^2$

- Measurement with ganged $n^+ p$ strip (spaghetti) detectors
  - Above $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ linear $\text{CCE}(V_{\text{bias}})$
  - Power law scaling with fluence, $b \approx -\frac{2}{3}$
  - Leakage current “saturating”

$$Q_{\text{MPV}}(V, \Phi) = k \cdot (\Phi/10^{15} \text{n}_{\text{eq}}/\text{cm}^2)^b \cdot V$$

$k = 26.4 \text{e}_0/\text{V}$

$b = -0.683$

From: G. Kramberger et al., *JINST 8 P08004 (2013).*
Summary

• Radiation hardness of Si has been reviewed with focus on bulk damage in Si
• Road travelled from LEP over LHC to HL-LHC outlined
• The paramount difficulties successfully surmounted from LHC to HL-LHC awaken aspirations for Si at FCC
• Pions, neutrons, hadrons
  – Pions, hadrons peak at ~5 GeV
  • 90% above 500 MeV
  – Neutrons flat to ~30 GeV
Facilities Matching

- **IRRAD2 (PS) protons**
  - A bit on the high side
  - ~same damage expected
  - KIT & UoB well below

- **JSI neutrons**
  - Cover spectrum up to 5 MeV

- **Not really ideal, but that’s what we have**

- **Believe in NIEL scaling?**
  - violations observed in Si
  - KIT & UoB scaling verified, but surprises possible
Weighting field

• Weighting field sharply peaked at strips, pixels (3-D!)
• Will affect signal when $v \tau_{\text{eff}} \ll d$
  – $v_{\text{sat}} \tau_e \approx 30\mu m @ 10^{16}$
  ➢ Thin detectors
➢ Inclined tracks
  – Skewed distributions
  – Algorithms ?
➢ Non-homogeneous detectors ?


Top 25% yield
80% of signal,
top 10% give 50%

<table>
<thead>
<tr>
<th>$U_w$</th>
<th>$x$</th>
<th>$\Delta x$</th>
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<tbody>
<tr>
<td>0.0</td>
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<tr>
<td>0.1</td>
<td>145</td>
<td>145</td>
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<td>0.2</td>
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<tr>
<td>0.8</td>
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<td>4</td>
</tr>
<tr>
<td>0.9</td>
<td>276</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>280</td>
<td>4</td>
</tr>
</tbody>
</table>

M.Mikuž: Radiation Damage in Si
Thin detectors

- Seen to provide more signal after heavy irradiation at “low” $V$
  - Less charge sharing for inclined tracks
- But beware:
  - Less ionization signal, more fluctuations
    - Additional fluctuations from trapping, CM
      - Rely on Central Limit Theorem?
      - Best measure $MPV \rightarrow S/N \rightarrow$ spectrum on actual device in test beam
- Efficiency vs. noise occupancy as function of threshold - ultimate info for (binary) tracking

\[ FWHM \geq 4\xi = 2K \cdot (Z/A) \cdot (x/\beta^2) \text{ MeV} \]
Linear $CCE(V)$?

- What could be linear
  - SCR governed $CCE(V)$ after irradiation ($VV$), highly resistive ENB ($VV$), without trapping
  - Trapping dominated with non-saturated drift velocity

- What is *not* linear
  - velocity saturation
  - charge multiplication
  - double junction
  - field in ENB
  - ...

- Just a nice coincidence or some physics behind?
  - look *into* silicon to search for an answer
Edge TCT

- **Edge-TCT**
  - Generate charges by edge-on IR laser perpendicular to strips, detector edge polished
  - Focus laser under the strip to be measured, move detector to scan
  - Measure induced signal with fast amplifier with sub-ns rise-time (Transient Current Technique)
  - Laser beam width 8 µm FWHM under the chosen strip, fast (40 ps) and powerful laser

  - Caveat – injecting charge under all strips effectively results in constant weighting (albeit not electric !) field

\[
\begin{align*}
I(y,t) &= I_e(y,t) + I_h(y,t) \\sim e_0 A N_e h v_e(y) + v_h(y) W
\end{align*}
\]

\[
I(y,t) \sim e_0 A N_e h v_e(y) + v_h(y) W
\]

Figure 1. Schematic view of the Edge-TCT technique.

Figure 2. Induced current pulses at \(y = 50 \mu m\) for different bias voltages in a non-irradiated detector.

Figure 3. Velocity profiles of neutron-irradiated detector to different fluences.
Electric Field Measurement

- Initial signal proportional to velocity sum at given detector depth
- Caveats for field extraction
  - Transfer function of electronics smears out signal, snapshot taken at ~600 ps
    - Problematic with heavy trapping
    - Electrons with \( v_{sat} \) hit electrode in 500 ps
  - Mobility depends on \( E \)
    - \( v \) saturates for \( E >> 1V/\mu m \)

\[
I(t = 0) = q \cdot \vec{v} \cdot \vec{E}_w =
= N_{e-h} e_0 \cdot (v_e + v_h) / d =
= N_{e-h} e_0 \cdot (\mu_e + \mu_h) \cdot E(x) / d
\]

![Graphs showing electric field vs. velocity for electrons and holes.](image1)

Measured signal non-irradiated 50 \( \mu m \) from strip

- \( V_{bias}=500 \text{ V} \)
- \( V_{bias}=400 \text{ V} \)
- \( V_{bias}=300 \text{ V} \)
- \( V_{bias}=200 \text{ V} \)
- \( V_{bias}=100 \text{ V} \)
- \( V_{bias}=0 \text{ V} \)
Selected Results from Neutrons

- Hamamatsu ATL07 n⁺ mini-strip, FZ p-type, neutron irradiated at JSI TRIGA reactor
  - In steps up to $10^{16} \text{n}_{eq}/\text{cm}^2$

- Very instructive regarding qualitative electric field shape
  - Non-irradiated “by the book” for abrupt junction n⁺p diode
    - SCR and ENB nicely separated, small double junction near backplane
  - Medium fluence ($\Phi=10^{15}$ neutrons): some surprise
    - Smaller space charge than expected in SCR, some field in “ENB”
  - Large fluence ($\Phi=10^{16}$): full of surprises
    - Still lower space charge, sizeable field in “ENB”
    - Charge multiplication (CM) additional trouble for interpretation at large $V$

- Nice, but let’s get quantitative!

Published in:
G. Kramberger et al., JINST 9 P10016(2014).

STREAM WS, CERN, 6/11/2017
M. Mikuž: Radiation Damage in Si
Extending the Reach

• In 2014 added $5 \times 10^{16}$ and $10^{17}$ n$_{eq}$/cm$^2$ measurements of the same detector
  – $10^{16}$ of this fluence fully annealed, the rest 80 min @ 60°C

• Intrinsic feature – signal oscillations
  – period $\sim 5/4$ ns
  – LRC (C$\sim 2$pf $\Rightarrow$ L$\sim 20$ nH $\sim 1$cm of wire)
  – velocity (slope) and charge (integral) yield consistent results
  – should be, as $Q \approx Q_0 \nu_{sum} \tau_{eff}/d$

☹ Cannot use $I(t)$ to measure trapping...
... shall take a closer look
Absolute Field Measurement

- Solution: concurrent forward bias $v_{sum}$ measurements
  - Ohmic behaviour with some linear (field) dependence
    - constant (positive) space charge
  - can use $\int E(y)\,dy = \bar{E} d = V$ to pin down field scale
    - corrections from $v(E)$ non-linearity small
- Use same scale for reverse bias!
- FW measurements up to 700 V
  - know $E$ scale up to 2.33 V/$\mu$m
  - can reveal $v(E)$ dependence
Proton Irradiations

- 5 sample pairs of ATL12 mini-strips irradiated at CERN PS during summer 2015
  - got 0.5, 1.0, 2.9, 11, 28e15 protons/cm$^2$, no scanning
  - NIEL hardness factor 0.62
  - thanks to CERN IRRAD team
    - took 41 PS days to reach the highest fluence

- Covers HL-LHC tracker range well
- Samples back in September 15, 2 per fluence investigated by E-TCT for all fluences
  - concurrent forward and reverse bias measurements
Mobility Considerations FW bias

- For forward bias can extract \( v(E) \) up to a scale factor
- Observe less saturation than predicted
- Model with

\[
v_{\text{sum}}(E) = \frac{\mu_{0,e} E}{1 + \frac{\mu_{0,e} E}{v_{e,\text{sat}}}} + \frac{\mu_{0,h} E}{1 + \frac{\mu_{0,h} E}{v_{h,\text{sat}}}}
\]

- keep saturation velocities at nominal values @-20°C (\( v_{e,\text{sat}} = 107 \, \mu\text{m/ns} \); \( v_{h,\text{sat}} = 83 \, \mu\text{m/ns} \))
- float (common) zero field mobility degradation
- fit \( v(E) \) for \( \phi_n \geq 5 \times 10^{15} \) and \( \phi_p \geq 3 \times 10^{15} \)

n.b. FW profiles less uniform for lower fluences and for protons, but departures from average field still small, corrections \( O(\%) \)
Mobility Fits

- Data follow the model perfectly
  - $\mu_0$ degradation the only free parameter, scale fixed by $v_{\text{sum,sat}}$
  - although $E$ range limited, $v_{\text{sum,max}}$ still $> 1/3$ of $v_{\text{sum,sat}}$
Mobility Results

- Fit to $\nu_e + \nu_h$ with common mobility degradation factor
  - factor of 2 at $10^{16}$ $n_{eq}/cm^2$
  - factor of 6 at $10^{17}$ $n_{eq}/cm^2$
  - need $2x/6x$ higher $E$ to saturate $\nu$

<table>
<thead>
<tr>
<th>$\Phi n$</th>
<th>$\mu_{0,sum}$</th>
<th>$\Phi p$</th>
<th>$\mu_{0,sum}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[10^{15} n_{eq}/cm^2]$</td>
<td>$[cm^2/Vs]$</td>
<td>$[10^{15} n_{eq}/cm^2]$</td>
<td>$[cm^2/Vs]$</td>
</tr>
<tr>
<td>non-irr (model)</td>
<td>2680</td>
<td>1.6</td>
<td>2063± 188</td>
</tr>
<tr>
<td>5</td>
<td>1661 ± 134</td>
<td>1.6</td>
<td>2063± 188</td>
</tr>
<tr>
<td>10</td>
<td>1238 ± 131</td>
<td>6.1</td>
<td>1337± 47</td>
</tr>
<tr>
<td>50</td>
<td>555 ± 32</td>
<td>15.4</td>
<td>817± 42</td>
</tr>
<tr>
<td>100</td>
<td>407 ± 40</td>
<td>$T$=-20°C</td>
<td></td>
</tr>
</tbody>
</table>
Mobility Analysis

- Mobility governed by hard scattering on acoustic phonons and traps
  \[ \frac{1}{\tau} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_{trap}} \]

- Fit mobility dependence on fluence with a power law
  \[ \mu_{0,\text{sum}}(\Phi) = \frac{\mu_{0,\text{sum,phonon}}}{1 + \left( \frac{\Phi}{\Phi^{1/2}} \right)^\alpha} \]

- Fits perfectly, value of \(\alpha\) close to linear
- At same NIEL, mobility decrease worse for protons
  - NIEL violation? Large errors?

<table>
<thead>
<tr>
<th>Irradiation particle</th>
<th>(\alpha)</th>
<th>(\sigma_\alpha)</th>
<th>(\Phi^{1/2}/10^{15})</th>
<th>(\sigma_{\Phi^{1/2}}/10^{15})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor neutrons</td>
<td>-0.74</td>
<td>0.07</td>
<td>9.8</td>
<td>1.7</td>
</tr>
<tr>
<td>PS protons</td>
<td>-0.90</td>
<td>0.19</td>
<td>6.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Mobility Comparison

- Dependence on shallow dopant concentration
  - Measured in the roaring 60’s
- Characteristic trap concentration $N \sim 10^{17}$ cm$^{-3}$
  - Looks out of reach for typical $g = O(10^{-2})$
- But $g$ refers to $N_{\text{eff}} = |N_a - N_d|$
- While $N$ is more like $N_a + N_d$
  - $x$-sections for deep and shallow?
- Power law looks compatible: $a \leq 1$
Velocity and Field Profiles

• Knowing $v(E)$ can set scale to velocity profiles
  – assumption: same scale on FW and reverse bias
    • protons: for $5 \times 10^{14}$ and $10^{15}$ use same scale, fixed by average field for $5 \times 10^{14}$ at 1100 V (no good FW data)

• Invert $E(v)$ to get electric field profiles
  – big errors when approaching $v_{sat}$ i.e. at high $E$
    • exaggerated by CM in high field regions
    • $v > v_{sat}$ not physical, but can be faked by CM
Velocity Profiles Neutrons

$\nu = 190 \, \mu\text{m/ns}$

Velocity profile $5 \times 10^{15}$

Velocity profile $1 \times 10^{16}$

Velocity profile $5 \times 10^{16}$

Velocity profile $1 \times 10^{17}$
Current Characteristics

- Smooth behaviour in both directions
  - Highly resistive Si limits FW injection
- Reverse current smaller than predicted by an order of magnitude
- Both currents rising with bias
Reverse Bias Field Profile

- Two distinct regions at high biases
  - Large region from backplane with (small) slope in the field
    - constant (small, negative) space-charge
    - $E = j \cdot \rho$ at junction ? like “ENB” ?
    - indication of thermal (quasi)equilibrium: $np = n_i^2$ ?
    - thus no current generation ?
  - Small region at junction building up with bias
    - depleted space-charge region ?
    - source of generation current ?
SCR Consistency

- Hard to estimate SCR extent, especially at lower bias and highest fluence
- A crude estimate
  - $5 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$: ~80 µm @ 600 V; ~120 µm @ 1000 V
  - $10^{17} \text{n}_{\text{eq}}/\text{cm}^2$: ~60 µm @ 600 V; ~80 µm @ 1000 V

- Predicted/measured currents
  - $5 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$: 300/300 µA @ 600 V; 400/500 µA @ 1000 V
  - $10^{17} \text{n}_{\text{eq}}/\text{cm}^2$: 400/300 µA @ 600 V; 500/600 µA @ 1000 V

- Reasonable agreement with current generated exclusively in SCR
  - n.b. - current “saturation” observed @1000V in *JINST 8 P08004 (2013)*

- Acceptor introduction rates: $g_c \approx 6/4 \times 10^{-4} \text{ cm}^{-1}$
  - substantial part (up to 80 %) of voltage drop “spent” in “ENB”
  - matches well data in *JINST 9 P10016(2014)* (up to $10^{16}$)
“ENB” Consistency

• Space charge in “ENB” rising with bias, e.g. for $10^{17} \text{n}_{\text{eq}}/\text{cm}^2$
  – $1.6 \times 10^{11} @ 100 \text{ V}$, $9.2 \times 10^{11} \text{ cm}^{-3} @ 500 \text{ V}$
  – c.f. $\sim 4 \times 10^{13} \text{ cm}^{-3}$ in SCR
  – negative space charge, like in SCR

• Resistivity from $\rho = j/E @ 100 \text{ V}$
  – maximum $\rho(p) \approx 2.8 \times 10^7 \text{ } \Omega \text{cm}$ using nominal mobilities @ $p \sim 2 \times 10^8 \text{ cm}^{-3}$
  • all measured values exceed this limit
  – compatible with measured mobility sum and $p \sim O(10^9) \text{ cm}^{-3}$

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\rho$</th>
<th>$p$</th>
</tr>
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<tbody>
<tr>
<td>$[n_{\text{eq}}/\text{cm}^2]$</td>
<td>$[10^7 \Omega \text{cm}]$</td>
<td>$[10^9 \text{ cm}^{-3}]$</td>
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<tr>
<td>$1 \times 10^{16}$</td>
<td>3.3</td>
<td>0.5</td>
</tr>
<tr>
<td>$5 \times 10^{16}$</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>$1 \times 10^{17}$</td>
<td>2.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Trapping Considerations

- Extrapolation from low fluence data with $\theta_{e,h}(-20^\circ C)=4.4,5.8 \times 10^{-16} \text{ cm}^2/\text{ns}; \ 1/\tau=\theta\Phi$

<table>
<thead>
<tr>
<th>$\Phi$ [1e15]</th>
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<th>10</th>
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<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ [ps]</td>
<td>400</td>
<td>200</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>$mfp@v_{sat}$ [\mu m]</td>
<td>95</td>
<td>48</td>
<td>9.5</td>
<td>4.8</td>
</tr>
<tr>
<td>$MPV$ [e$_0$]</td>
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<td>3800</td>
<td>760</td>
<td>380</td>
</tr>
<tr>
<td>$MPV@1000$ V</td>
<td>8900</td>
<td>5500</td>
<td>1800</td>
<td>1150</td>
</tr>
<tr>
<td>$CCD_{1000}$ V [\mu m]</td>
<td>110</td>
<td>70</td>
<td>23</td>
<td>14</td>
</tr>
</tbody>
</table>

- Measured data exceeds (by far) linear extrapolation of trapping
  - n.b.1: $E\sim3$ V/\mu m by far not enough to saturate velocity
  - n.b.2: little sign of CM at highest fluence
More Considerations

• More realistic: take $v_{sum}$ at average $E = 3.3 \text{ V/}\mu\text{m}$

<table>
<thead>
<tr>
<th>$\Phi$ [1e$15$]</th>
<th>5</th>
<th>10</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{sum}(3.3 \text{ V/}\mu\text{m})$</td>
<td>137</td>
<td>126</td>
<td>90</td>
<td>77</td>
</tr>
<tr>
<td>$CCD_{1000v}$ [$\mu\text{m}$]</td>
<td>110</td>
<td>70</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>$\tau \approx CCD/v$ [ps]</td>
<td>800</td>
<td>560</td>
<td>260</td>
<td>180</td>
</tr>
<tr>
<td>$\tau_{ext}$ [ps]</td>
<td>400</td>
<td>200</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

• Implies factor of 6-9 less trapping at highest fluences
  – lowest fluence still x2 from extrapolation
  – weak dependence on fluence as anticipated
  – CM would effectively shorten trapping times
  – not good when large $E$ variations ($v(E)$ saturates)
  – not good when $CCD \approx$ thickness (less signal at same $\tau$)
Exploiting TCT Waveforms

- Waveforms at $y=100 \, \mu m$, 800 V, $5\times10^{16}$ and $10^{17}$
  - $E \approx 3 \, V/\mu m$, CCD/2 implies signal within $\sim 10 \, \mu m$ or <0.2 ns
    - the rest you see is the transfer function of the system
- Still distinct signals from the two fluences
  - treat $10^{17}$ waveform as transfer function of the system
    - convolute with $e^{-t/\tau}$ to match $5\times10^{16}$ response
    - $\tau = 0.2$ ns provides a good match
- In fact, measure $\sim \Delta \tau$, as “transfer” already convoluted with $e^{-t/\tau(1e17)}$ !

\[ \tau = 0.2 \, \text{ns} \]
Waveforms: How sensitive?

- $\Delta \tau = 0.2$ ns certainly best fit, 0.1 too narrow, 0.3 too broad
- precision $\sim 50$ ps
Trapping – position dependence?

- Waveforms plotted every 50 um in detector depth for reverse bias at 1000 V
- Forward bias in middle of detector added at 600 V
- Very little, if any, wf dependence on position observed
- Trapping not position (even not bias) dependent !?
Velocity Profiles Protons

$\nu = 190 \mu m/\text{ns}$

Same scale as for neutrons
Field Profiles Protons

Smaller peak fields than for neutrons
Scale 0-7 V/μm