Radiation hard APD’s for CMS ECAL

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Talk Outline

- Objectives
- Characteristics
- Radiation Hardness
- How to reach a high reliability
The APD’s (EG&G) with “reverse” structure have improved characteristics:

- **High speed**, good visible and blue response, **reduction of nuclear counter effect**, lower dark current and radiation resistance
1993 first test with a prototype APD from Hamamatsu *(there was no Beaune 1993)*

- Dark current: 800 nA, \( \Phi \) 5mm, 320 pF,
- Gain/ Bias: \( (dM/dV \times 1/M \text{ @ } M=50) \) 15 \%

- Difficult operation, but very promising

- Single 18 cm PbWO\(_4\) crystal in a 80 GeV electron beam

\[ \sigma/E = 1.5\% \]
Compact Muon Solenoid

Total mass: 12,500t
Overall Diameter: 15.0m
Overall Length: 21.6m
Magnetic field: 4T
~80000 crystals
Lead Tungstate Properties

Advantages:
• Fast, Dense
• rel. cheap
• Radiation hard
• Emission in visible

Disadvantages:
• Temperature dependence
• Low light yield (Nuclear Counter Effect)

Photos detector with gain
(in a strong magnetic field)

Density [g/cm³] 8.28
Rad length, $X_0$ [mm] 8.9
Interaction length [mm] 224
Molière radius [mm] 21.9
Decay time [ns] 5(39%) 15(60%) 100 (1%)
Refractive index 2.30
Max emission [nm] 425
Light yield [photon/MeV] ~50
Temp coeff [%/°C] -2

PWO Radioluminescence Spectrum

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>0</td>
</tr>
<tr>
<td>380</td>
<td>0</td>
</tr>
<tr>
<td>420</td>
<td>20</td>
</tr>
<tr>
<td>460</td>
<td>15</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
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<tr>
<td>540</td>
<td>5</td>
</tr>
<tr>
<td>580</td>
<td>5</td>
</tr>
<tr>
<td>620</td>
<td>0</td>
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</tbody>
</table>
Today’s APD is a result of about 10 years R&D with (EG&G and) Hamamatsu Photonics KK.

APD’s will be operated at a gain of 50

(→ 100)

- Active area of 2 x 25mm²/crystal (400mm²)
- Q.E. ~ 75% for PbWO₄ emission (420nm)
- Excess noise factor is F ~ 2 @ M=50
- Capacity = 80pF
- Insensitive to shower leakage particles (d_eff ~ 6 µm) *(nuclear counter effect)*
- Irradiation causes bulk leakage current to increase ⇔ electronic noise doubles after 10 years - acceptable

Delivery from Hamamatsu started last year: ~37 000 APD`s delivered so far
**Structure**

- Si$_3$N$_4$, SiO$_2$, contact
- p$^{++}$ photon conversion
- p $\rightarrow$ e$^-$ acceleration
- n $\rightarrow$ e$^-$ multiplication
- n$^-$ e$^-$ drift
- n$^{++}$ e$^-$ collection
- Reduce volume effects: C and dM / dV

APD is grown epitaxially on a n$^{++}$ wafer $\rightarrow$ **Individuality of APDs**
ECAL Resolution

Resolution:

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E\text{(GeV)}}} \oplus b \oplus \frac{c}{E}
\]

where,

- \( a \) : due to intrinsic shower fluctuations & photo statistics
- \( b \) : related to stability and reproducibility
- \( c \) : noise contributions

**CMS design goal**: \( a \sim 3\% \), \( b \sim 0.5\% \), \( c \sim 200 \text{ MeV} \)

APD contributions:

- \( a \) - photo statistics (area, QE) & excess noise factor
- \( b \) - gain variation with bias voltage and temperature
- \( c \) - capacitance as series noise and dark current as parallel noise

We optimised all these parameters to reach the design goal
APD Noise Contribution

\[ \sigma_{total} = \sqrt{\sigma_{parallel}^2 + \sigma_{series}^2} \]

\[ \sigma_{parallel} = \sqrt{(I_{ds} + I_{db} M^2 F) \cdot q \tau} \]

\[ \sigma_{series} = \sqrt{\frac{4kT \cdot C^2}{2\tau} \cdot \left( \frac{0.7}{g} + R \right)} \]

M = APD gain
F = excess noise factor
\( \tau \) = shaping time constant
q = electron charge
\( I_{ds} \) = dark surface current
\( I_{db} \) = dark bulk current
R = series resistance
C = capacitance of APD and amplifier
k = Boltzmann constant
T = absolute temperature
g = transconductance of amplifier

first stage
$V_B$ – breakdown voltage $V_R$ – operating voltage (Gain = 50)

$V_B - V_R > 40 \Rightarrow M \gg 1000$
Gain Stability

Bias Voltage

\[
\frac{dM}{dV} \times \frac{1}{M} = 3.0\% / V
\]

Temperature

\[
\frac{dM}{dT} \times \frac{1}{M} = -2.2\% / ^\circ C
\]

Photo multiplier has 1 - 2\% / V

Energy loss in phonon interaction

![Graphs showing gain stability with respect to bias voltage and temperature.](image)
Excess Noise Factor

statistical fluctuations of the avalanche multiplication

\[ F = k \times M + (2 - 1/M) \times (1-k) \]  \text{[McIntyre]}

\( k \) - ratio of the ionisation coefficients for holes and electrons
\( M \) - gain

Contributes to stochastic term \( b \)
\[ \sqrt{F/N_{p.e.}} \]

\( F \sim 2 \) \text{ at } M=50
Quantum Efficiency

Quantum Efficiency [%]

Wavelength [nm]

Beaune 2002

K. Deiters Paul-Scherrer-Institute
Demanding Contrainst

- APDs are not accessible at all
- Integrated neutron flux for 10 years of LHC operation is $2 \times 10^{13}$ 1MeV neutrons/cm²
- We connect one HV channel to 50 capsules (=100 APDs) and 10 crystals built one trigger tower. There is still a probability, that one faulty APD infects all 50 connected to the same HV channels and respectively 5 towers
- We ordered about 130 000 APDs. All are equal but …

We need an operation reliability of the APDs of 99.9%
• Hadron irradiation could cause displacements of atoms in the silicon lattice resulting in a change of the doping profile in the bulk
  – High dark current, gain modifications

• Gamma irradiation causes modifications in the surface region
  – QE changes (Epoxy), surface currents due to SiO₂ break-up

From extensive tests we know:
• Irradiation does not significantly change gain, QE, ΔT and ΔM
• Hadron irradiation only creates high dark current in the bulk. 5 µA dark current is acceptable
VB – VR > 37 V → first look criterion for radiation hardness

Absolute value should be large

Spread in $V_B - V_R$ is small

Stable since one year
~ 15% of APD`s “died” (change of $V_B > 37$V) due to $^{60}$Co irradiation and during the accelerated ageing.

- Problems at the APD surface (bad contacts of metallisations, mask defects)

- Surface modifications

- But still ~ 3 % die during $^{60}$Co irradiation and accelerated ageing
  (Mask, alignment, dust ..)

![Diagram of APD with labels for junction, groove, antireflecting coating, and surface leakage current]
“Defect” is seen on all APD`s from the same position on the wafer - defect of the mask (hot electron photo)
Solution: Screen APD`s to reject unreliable APD`s

Gamma irradiation causes change of $V_B$ for faulty APD`s,

It does not change the most of other APD parameters ($V_R$, QE, F, $dM/dV$, $dM/dT$, capacitance, ...). Changes of the APD dark current and noise (surface currents) are small and will not cause degradation of the ECAL resolution. This kind of effects anneal away.

**Method:**

- Irradiate 100% of all APD`s (0.5 Mrad) with $^{60}$Co gamma source (at PSI);
- Measure $V_B$ and $I_d(V)$ of all irradiated APD`s 1 day after irradiation (at PSI);
- Anneal all APD`s in an oven (for 4 weeks at $T=80^\circ$C and bias, at CERN APD Lab);
- Measure $V_B$, $I_d(V)$ and noise after annealing/ageing (at CERN APD Lab);
- Reject potentially non-reliable APD`s

$\rightarrow$ Finally sort 50 APD pairs in bins of $-2 < V_R < +2$
Change of $V_B$ 1 day after irradiation

Lot 34 Breakdown Voltage Comparison

$V_B$ (irradiated) - $V_B$ (Hamamatsu) [V]

Rejected
Dark Current

![Graph showing the relationship between noise irradiated and gain, with the y-axis labeled ldOverGain, nA and the x-axis labeled Gain.](image)
Rejection criteria

1 day after $^{60}$Co irradiation:
- $V_B - V_R < 37$ V
- change of $V_B > 5$V
- dark current $3\sigma$ above wafer mean ($\text{mean} \sim 200\text{nA}$)

After annealing respectively during annealing (4 weeks at $80^\circ$C @ bias)
- change of $V_B > 5$V
- dark current $4\sigma$ above wafer mean ($\text{mean} \sim 50\text{nA}$ was $\sim 10\text{nA}$)
- Noise $4\sigma$ above wafer mean
- $I_D/M$ vs. $M$, slope below $M=400$

“bad” positions (>30% APD`s “died”after irradiation and ageing) should be rejected

Neutron irradiation of “lot release” APDs to verify the whole lot
Efficiency of the screening method

Double irradiation (225 APDs from lot##33,34)

225 APD`s which passed 1st irradiation and annealing were irradiated the 2nd time. No change of VB>2V was found for all APD`s !!!
CMS APD summary

- ~37,000 APD’s received from Hamamatsu
- Most of them have been irradiated, annealed & aged
- We reject now 1-5% (going down, 1‰)
- We are confident, that the “Screening method” gives us a reliability of 99.9%
- 5000-6000 APD’s per month ➔ happy end in 2 years
- There will be no talk on this subject in „Beaune 2005“
  (Cognac 2005)