Avalanche PhotoDiodes
for CMS electromagnetic calorimeter

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(on behalf of the CMS Collaboration)
To detect the Higgs boson in the mass range 90-130 GeV, CMS Collaboration will build a homogeneous electromagnetic calorimeter

80,000 PWO scintillating crystals
Lead tungstate
is a fast and compact
scintillating crystal
limited by a low light yield
(~ 100 photons/MeV in 23 cm crystals)

Photon detectors for PbWO₄ in CMS

- not sensitive to 4 Tesla magnetic field
- high $\varepsilon_0$ for $\lambda \sim 400 \div 500$ nm
- internal amplification
- fast and good for high rate
  (1 bunch crossing every 25 ns)
- radiation hard
- not (too much) sensitive to charged particles
AVALANCHE PHOTODIODES

- fast
- not affected by magnetic field
- high quantum efficiency
- internal amplification (50 ÷ 100)
- small area

Strong R&D activity to develop APD
in collaboration with
EG&G and Hamamatsu
APD Working Principle

REVERSE STRUCTURE
⇒ Improve Quantum efficiency at short λ
reduce nuclear counter effect
NUCLEAR COUNTER EFFECT

Charged particles crossing a silicon layer generate:

\[ \frac{dn}{dx} = \frac{dE}{dx} \times \rho \times \frac{1}{E_{e/h}} \approx 100 \text{ e/h pairs/\mu m} \]

In a reverse structure APD only electrons
produced in p+ layer (few \(\mu\)m)
are fully amplified by gain M

\[ \Rightarrow \text{Effective thickness } d_{\text{eff}} \]

comparing radioactive source peak \((^{90}\text{Sr})\)
measured in PIN and APD

\[ d_{\text{eff}} = \frac{d_{\text{PIN}}}{\text{peak(PIN)}} \cdot \text{peak(APD)} \]

\[ \Rightarrow \left( \frac{\text{MIP}}{\text{light}} \right)_{\text{APD}} = \frac{d_{\text{eff}}}{d_{\text{PIN}}} \left( \frac{\text{MIP}}{\text{light}} \right)_{\text{PIN}} = \]

\(d_{\text{eff}} \approx 5\mu\text{m}, \ d_{\text{PIN}} = 200 \mu\text{m}\)

\[ = \frac{1}{40} \left( \frac{\text{MIP}}{\text{light}} \right)_{\text{PIN}} \]
Noise in homogeneous electromagnetic calorimeter

\[ \frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \]

\[ \frac{a}{\sqrt{E}} \Rightarrow \text{intrinsic term } \oplus \text{ photo-statistics} \]
\[ b \Rightarrow \text{calibration } \oplus \text{ stability} \]
\[ \frac{c}{E} \Rightarrow \text{electronic noise} \]

CMS design goal:
\[ a \sim 3\%, \ b \sim 0.5\%, \ c \sim 200 \text{ MeV} \]

The APD contributes to all the terms
Statistical fluctuations increased by avalanche multiplication: Excess noise factor

\[ \frac{\sigma(\text{MeV})}{E} = \sqrt{\frac{F}{N_{pe}E}} \rightarrow a \]

Stability

\[ \frac{\partial M}{\partial V} \quad \text{and} \quad \frac{\partial M}{\partial T} \rightarrow b \]

APD capacitance, resistance and preamplifier noise: Series Noise

\[ \frac{\sigma(\text{MeV})}{E} \propto \frac{(C_D+C_{PA})}{\sqrt{\frac{R_s}{M}}} \sqrt{\frac{C_D^2}{g_m} + 0.7} \frac{1}{\sqrt{\tau N_{pe} ME}} \rightarrow c \]

APD leakage current: Parallel Noise:

\[ \frac{\sigma(\text{MeV})}{E} \propto \frac{1}{\sqrt{\frac{1}{N_{pe} ME}}} \sqrt{(I_s+FM^2I_B)} \sqrt{\tau} \rightarrow c \]
During R&D special prototypes were developed by Hamamatsu and EG&G and tested by the collaboration.

GOALS:

- low capacity
- small Dark Current
- improve stability in gain and temperature
- increase the sensitive area
- match scintillation spectrum and quantum efficiency
- reduce excess noise factor $F$
- improve radiation hardness
New prototypes \((M = 50)\) \(T \simeq 20^\circ C\)

<table>
<thead>
<tr>
<th>APD</th>
<th>C(pF)</th>
<th>(V_b)(V)</th>
<th>(I_D)(nA)</th>
<th>F</th>
<th>(\varepsilon_Q) (450 nm)</th>
<th>N.C.E. (d_{eff}) ((\mu m))</th>
<th>(1\ \frac{dM}{M\ dV}) (%/V)</th>
<th>V spread</th>
<th>(1\ \frac{dM}{M\ dT}) (%/°C)</th>
<th>Area (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ham.</td>
<td>110</td>
<td>400÷420</td>
<td>2-3</td>
<td>2</td>
<td>85%</td>
<td>5</td>
<td>5</td>
<td>5%</td>
<td>-2.0</td>
<td>0.25 (\rightarrow) 2(\times)0.25</td>
</tr>
<tr>
<td>EG&amp;G</td>
<td>25</td>
<td>350÷450</td>
<td>30-50</td>
<td>2.3</td>
<td>75%</td>
<td>10</td>
<td>0.6</td>
<td>25%</td>
<td>-2.7</td>
<td>0.25 (\rightarrow) 2(\times)0.25 or 0.5</td>
</tr>
<tr>
<td>ideal CMS request</td>
<td>&lt; 100</td>
<td>&lt; 500</td>
<td>~ 10 nA</td>
<td>2</td>
<td>big</td>
<td>small</td>
<td>&lt; 2</td>
<td>&lt; 5%</td>
<td>&gt; -2</td>
<td>&gt; 0.5</td>
</tr>
</tbody>
</table>
\[ a = \sqrt{\frac{F}{N_{pe}}} = \sqrt{\frac{2}{5000}} = 2\% \]

b < 0.5% require Voltage regulation better than 100 mV

c \sim 30 \text{ MeV (measured with prototype electronics)}

not irradiated APD contribution negligible but

\( I_d \) increases with radiation damage
RADIATION DAMAGE
occurs through two mechanisms:

- The surface damage causes defects in the front layers.
  - increase surface current
  - could reduce quantum efficiency

- The bulk damage is due to displacement of atoms from their lattice sites.
  - increase bulk current
  - could change the gain

To preserve Quantum Efficiency

⇒ passivation layer from SiO₂ to Si₃N₄ (γ damage)

(plot)

No (or little) change in gain observed

(plot)
Gain before and after irradiation

with $2.7 \cdot 10^{12}$ protons/cm$^2$
At high gain, the main effect is the increase of the bulk current due to neutrons damage.

\[ I_B(\alpha A) \]

\[ 1 \leq 10 \leq 10^2 \]

\[ 10^2 \leq 10^3 \leq 10^4 \]

\[ 10^2 \leq \Phi(10^{11} n/cm^2) \]

The increase in $I_B$ is linear:

\[ I_B = I_B^0 + \alpha \cdot V \cdot \Phi \]

$\alpha = (10 \pm 1) \cdot 10^{-17}$ A/cm per neutron after 2 days from irradiation

$V \approx d_{eff} \times \text{Area} = 9 \cdot 10^{-5}$ cm$^2$
Behaviour of the **DARK CURRENT**

after irradiation

The dark current depends on temperature

\[ I_d = T^2 \ e^{-E_t/KT} \]

in a model with a single trap with energy \( E_t \)

The dark current recovers with time

\[ I_{d}^{\text{irr}} (t) = I_{d}^{\text{irr}} (0) \sum_i g_i \ e^{-t/\tau_i} \]

where \( g_i \) is the weight of different levels

induced by neutrons in the semiconductor

The recovery depends on temperature

Each \( \tau_i \) depends on the ratio \( E_i/KT \)
Recovery of the dark current at 20°C

Fit by 3 exponentials + constant

- $\tau_1 = 1.3$ days \hspace{1cm} weight $\sim 35\%$
- $\tau_2 = 7$ days \hspace{1cm} weight $\sim 25\%$
- $\tau_3 = 70$ days \hspace{1cm} weight $\sim 17\%$
- constant term \hspace{1cm} weight $\sim 23\%$
Recovery of the dark current at 0°C

Recovery of the dark current at higher temperatures
Noise Model for LHC

Assuming a schedule with 180 days of run per year divided in three periods of 60 days each and separated by 10 days of pause.

First 3 years at low luminosity

2 hypothesis:

(a) run at 18°C

(b) run at 12°C stand by at 40°C during shut-down
Summary:

Intense R&D activity lead to prototypes very close to CMS ECAL specifications.

Next step: large sample production to test stability and reproducibility.

Second half 1998: start of pre-production.