Avalanche Photodiode Investigation for Fast Scintillators
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Abstract
Hamamatsu S-8664 series Si Avalanche Photodiodes were considered as a possible photodetector candidates for Belle II Electromagnetic Calorimeter upgrade. Five experimental samples of two photodiode sizes were investigated for their dark current, gain and capacitance. These parameters can be used for optimal working bias voltage and filter time constant estimation for a better signal to noise ratio.

1 Introduction
CP symmetry violation is one of the conditions to explain matter-antimatter asymmetry in the present universe. Two asymmetric electron positron B factories at Belle and BaBar experiments confirmed the presence of CP violation in B meson decay and indicated the Kobayashi-Maskawa mechanism to be the main source of the observed CP violation. Measuring a number of B meson decay modes at Belle and BaBar provided the data for precise measurement of Cabibbo-Kobayashi-Maskawa matrix elements and other new observables. Despite the success, some questions are still unresolved since some of the results showed deviations from the SM predictions and may be hints for the new physics. However, to enhance precision and to collect more statistics the present B factories need a significant luminosity upgrade. This is the main task of the future Super B-factories: Belle II and SuperB [1].

One of the challenges of the Belle upgrade is high resolution Electromagnetic Calorimeter (ECL) able to provide high precision coordinates and energy measurements of gamma quanta, signal for the neutral trigger of the detector and to provide information for particle identification in the increased luminosity and background environment. High resolution calorimeter is very important since one third of B-decay products are \( \pi^0 \)’s and other neutral particles that provide photons in a wide energy range from 20MeV to 4GeV. In Belle calorimeter, Thallium doped CsI(Tl) scintillation crystals were chosen for their high light output, relatively short radiation length, good mechanical properties and moderate price.

In increased noise environment fast scintillation counters with pure CsI crystals can be used to suppress pileup noise and random clusters. However, pure CsI crystals have 10 times smaller light output than the present CsI(Tl) crystals. But for Si photodiodes electronic noise gives essential contribution to the energy resolution of scintillation counter. Therefore, to improve signal to noise ratio we should use electronic devices with internal amplification. One of the possibilities is to use Hamamatsu S-8664 series Si Avalanche Photodiodes (APD). Apart from internal signal amplification it has other advantages such as stability, insensitivity to electric field and its small size (wit sensitive area of up to 1×1 cm²) allows to place several APDs (2 or 4) on a single scintillator crystal to provide redundancy. There are several other ECL configuration possibilities such as the use of Photopentode, but its sensitivity to magnetic field is still a problem [2].
2 Avalanche Photodiode Parameters

Photodiodes are semiconductor devices that can generate voltage or current when the PN junction is irritated by light. APDs have internal avalanche multiplication, when at high applied reverse bias voltage carriers gain enough energy to release new electron–hole pair through impact ionization. Number of carriers increases by a chain of these impact ionizations [3].

Figure 1 shows a not to scale typical APD cross section with corresponding electrical field, net carrier concentration and impact ionisation factor as a function of depth. Electron-hole pairs are generated by photons penetrated into the Si. Electric field forces the electrons in the depleted volume to drift towards n layer. Avalanche multiplication by impact ionisation occurs in the high field metallic zone. It is a statistical process that leads to the distribution of signal from \( n \) photoelectrons with \( \sigma = F \sqrt{n} \), where \( F \) is called excess noise factor [4].

\[
\text{ENC}^2 = 2q \left( \frac{I_{ds}}{g^2} + I_{db} F \right) \tau + 4kTR_s \frac{C_{tot}^2}{g^2} \frac{1}{\tau},
\]

\( \text{ENC} \) = equivalent noise charge,
\( q \) = electron charge,
\( g \) = avalanche gain,
\( I_{ds} \) = component of the dark current that is not amplified (surface leakage and n-layer bulk current),
\( I_{db} \) = component of dark current that is amplified (bulk current from p-layer),
\( F \) = excess noise factor,
\( \tau \) = filter time constant, we assume \( \tau = \tau_{\text{diff}} = \tau_{\text{int}} \),
\[ k \] = Stefan-Boltzmann constant,
\[ T \] = absolute temperature,
\[ R_s \] = amplifier series noise resistance,
\[ C_{tot} \] = parallel capacitance (APD + cable + preamp) [4].

Surface leakage current term is suppressed by a factor of gain squared and has insignificant contribution for the accuracy of measurements, so it can be neglected. The two main contributions are short noise \( 2qI_{dc}F\tau \) and thermal noise \( 4kTR_s \frac{C_{tot}^2}{g^2} \). The purpose of the carried investigation was measurement of APD characteristics required for the calculation of noise level with other parameters being chosen.

3 Photodiodes Measured

Nowadays commercially available APDs have relatively large sensitive area of up to 1\( \times \)1 cm\(^2\) but have low quantum efficiency for the scintillation light of pure CsI crystals (\( \lambda \approx 310 \)nm). Hamamatsu issued 10 experimental samples of S8664 series Si APD with 5x5mm and 10x10mm sensitive areas, 5 of them were investigated during this laboratory work. To test the experimental setups two Hamamatsu Si PIN S2744-08 photodiodes with no internal amplification were investigated for the same parameters. Photodiodes used in this investigation are shown in Figure 2.

![Figure 2: Left to right: Hamamatsu Si PIN S2744-08, APD S8664-55 and APD S8664-1010.](image)

4 Dark current

One of the noise sources is dark current, a current passing through the photodiode in the absence of any external light. For this purpose special care was taken to isolate the setup from any external light. An electronic scheme constructed for the measurement is shown in Figure 3.

![Figure 3: Electronic setup scheme for measuring the dark current.](image)

To suppress any current induced in the wires the scheme was shielded by extending the grounding around the scheme and adjacent wires. A photo of the setup is shown in Figure 4.
Figure 4: Electronic setup for measuring the dark current.

The source voltage was monitored by additional voltmeter and the actual voltage applied to the photodiode was calculated using formula $U = U_{source} - I_{dark} R_{total}$. From this formula we can see why it was necessary to have second resistance. At some point the applied voltage of the source will be greater than the breakdown voltage of the diode while on the diode the actual voltage will be still below it. In this situation accidental shut of the voltmeter contacts would shortcut the circuit and burn the diode. So the second resistance is there to prevent this possibility. The resistances taken for this measurement were 10.11MΩ each and one of them combined parallel with voltmeter internal resistance was measured to be 5.26MΩ giving the total resistance of the scheme to be $R_{total} = 15.37$MΩ. Voltage on one of the resistors was measured as a function of applied source voltage and known resistances were used to calculate the actual voltage on the photodiode and dark current. The scheme was tested with two PIN photodiodes and then the measurement was done for two big and three small APD photodiode samples. The results are plotted in Figures 4, 5 and 6.

Figure 5: Si PIN S2744-08 photodiodes dark current vs bias voltage.
All samples showed consistency with manufacturer supplied characteristics information. For all 5 APD samples the breakdown voltage was estimated to be around 420V.

5 Photocurrent, Gain
Same electronic scheme as for the dark current measurement was used for the measurement of photocurrent gain. The only modification to the initial setup was addition of a LED pointing on the photodiode inside the light-isolating box containing the setup. The setup was again tested with PIN photodiode and the results are shown in Figure 7.
As expected, after a certain voltage (~0.5V) the photocurrent in PIN photodiodes saturated and had no significant change with increasing the applied voltage.

For APD photodiodes current at small voltages up to 10V was found to be constant within the accuracy of the performed measurements and was assumed as gain of 1. Gain was calculated using the following formula (2):

\[
G(U) = \frac{I_{total}(U) - I_{dark}(U)}{I_{total}(10V) - I_{dark}(10V)}
\]  

(2)

Photocurrent gain as a function of applied voltage for APD photodiodes is shown in Figures 8 and 9.
Figure 10: Si APD S8664-55 photodiodes gain vs bias voltage.

6 Capacitance

For the measurement of capacitance the scheme was modified to include additional source of alternating voltage as shown in Figure 10. An extra $C = 5\text{nF}$ capacitance was added to the scheme to protect the alternating voltage source from direct bias voltage. In this scheme photodiode is represented by a capacitance $C_d$. Voltmeter here is an oscilloscope to measure alternating voltage amplitude change on the $201.1\text{k}\Omega$ added resistance with the change of voltage applied to the photodiode.

\[
C_{\text{total}} = \frac{1}{\omega R \sqrt{\left(\frac{U_0}{U}\right)^2 - 1}}.
\]

Where $\omega$ is the angular frequency of the alternating voltage source, $R = 165.9\Omega$, $U_0$ is alternating voltage source amplitude when it is not connected to the scheme and $U$ is voltage amplitude.
measured by the oscilloscope. Capacitance of the photodiode can be extracted from the total capacitance using formula

$$C_d = \frac{CC_{total}}{C - C_{total}} = \frac{C_{total}}{1 - C_{total}/C}.$$  \hspace{1cm} (4)

Where $C = 5\text{nF}$. Measurements with the scheme and formulas above were performed for each type of the photodiodes and the resulting graphs are shown in Figures 11, 12 and 13.

Photodiode junction capacitance can be approximated as a parallel plate capacitor where the distance between the plates (depletion layer depth) is a function of applied voltage. A simplified formula for this can be written as $d = d_0 + \alpha \sqrt{U_{bias}}$, where $d$ is the distance between the plates (depletion layer depth) while $d_0$ and $\alpha$ are some constants. Since capacitance is inversely proportional to the distance between the plates the following dependence on the bias voltage is expected:

$$C(U_{bias}) = \frac{A}{B + \sqrt{U_{bias}}}.$$  \hspace{1cm} (5)

$A$ and $B$ are some parameters. A fit for the capacitance measurement results was performed according to formula (5).

For PIN photodiode fit was performed up to 35V applied voltage. Capacitance after this voltage was approximated by a straight line since saturation was reached as depletion layer width is limited by the dimensions of the photodiode.

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**Figure 12: Electronic setup scheme for measuring the dark current.**
Figure 13: Electronic setup scheme for measuring the dark current.

Figure 14: Electronic setup scheme for measuring the dark current.
7 Summary

The main properties of APDs have been measured. The values of dark current will be used to evaluate the short noise contribution and together with values of gain and capacitance it well allow to evaluate optimal shaping time $\tau$ needed to reach the lowest electronic noise of scintillation counter.

At the measured temperature of 24-26°C the breakdown voltage was estimated to be around 420V. However, APDs have high temperature dependence of the breakdown voltage and hence gain and dark current, that have exponential increase close to the breakdown, are very temperature-sensitive in that region. That makes it impractical to operate APDs close to the breakdown voltage. A good working point for APDs was estimated to be $U_{\text{bias}} = 370$V at 25°C. This value was found to be optimal since it is close enough to the breakdown voltage of 420V to give low capacity and reasonably high gain of 30 (both needed for low noise level) and far enough from it to avoid very steep temperature dependence of gain and dark current.

References