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Studies of Silicon Photo-Multipliers at cryogenic temperatures

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Multicell Geiger-mode APDs (SiPMs) experienced a fast development in the last years. SiPM based detectors where multiphoton detection is involved are becoming common, but the use of SiPMs for single photon applications is still problematic due to their high dark rate, which can be reduced by several orders of magnitude only by cooling. SiPM operation at low temperature is also very interesting for scintillation detection in low T systems.

We investigated the behavior of different kind of SiPM at different T in the range 10K<T<350K. I-V characteristics, breakdown voltage, dark noise, after-pulsing, cross-talk, pulse shape, gain and photon detection efficiency were studied as a function of T and as a function of bias voltage, both in proportional (below breakdown) and in Geiger operation mode. The discussion of the results is based on the physical properties of silicon and on models related to avalanche and tunnel breakdown in high field regions and carrier generation, transport and freeze-out at low T. In particular we are able to explain the following phenomena: decrease of breakdown voltage at low T, strong dark rate suppression at low T, increase of after-pulsing below T=100K, no dependence of cross-talk on T and the evolution of the signal pulse shape, photon detection efficiency and gain as functions of T.

In conclusion we show how our studies might result in enhancements of SiPM performances at low temperatures and we discuss some possible applications to new detectors.

Summary (Additional text describing your work. Can be pasted here or give an URL to a PDF document):

SiPM based detectors are becoming more and more common in High Energy, Medical and Space physics, mainly where multi-photon detection is involved (eg Calorimetric applications). In contrast, the use of SiPM' s in few-photons applications (e.g. Cherenkov detectors) is problematic for their high dark count rate which is produced by single carriers (at typical rates of 1MHz). Cooling is mandatory for reducing the dark rate by several orders of magnitude. Furthermore, SiPM operation at low temperature is very interesting because they are good candidates for scintillation detection in low temperature systems.

We investigated the behavior of different kind of SiPM (Hamamatsu, FKB-IRST, CPTA and MEPHY) at different temperatures in the range 10K < T < 350K. Current-voltage characteristics (forward and reverse polarization) and breakdown voltage were measured as a function of temperature; dark noise, after-pulsing, cross-talk, signal pulse shape, gain and photon detection efficiency were studied as a function of temperature and as a function of bias voltage (at fixed temperature) both in proportional (below break-down) and in Geiger operation mode.

Our measurements in will be discussed, after a brief introduction about the physics of the device, focusing on the phenomena related to breakdown (avalanche and tunnel) in high field regions and to carrier generation, transport and freeze-out in silicon, which are crucial to explain the device characteristics. The results of our studies are summarized in the following.

We find that the breakdown voltage (Vbr) is decreasing at low temperature in fair agreement with Baraff (Phys. Rev. 128 p.2507, 1962) and Ridley (Solid State Phys. 16 p.3375, 1983) models, predicting the change of Vbr as a consequence of the temperature dependence of the carrier mean free path for optical phonon scattering and the mean energy loss per collision.

Dark count rate is also decreasing at low temperature. It is dominated by field-enhanced generation-recombination (SRH) noise above 200K, while at lower T band to band tunnel noise becomes the main contribution in agreement with Hurkx model (IEEE TED 39, p.2090, 1992). The model which includes band-to-band tunneling, trap-assisted tunneling, SRH recombination and avalanche breakdown is based on the solution of continuity equations in the depletion region and contains a few parameters that can be determined at one temperature. Basically the different noise mechanisms are distinguished by the analysis of the activation energy, obtained by fitting the dark count rate against 1/T.

After-pulsing probability is measured with an autocorrelation technique. After-pulsing probability versus time is fitted and trap characteristic time can be extracted for various traps. It is found that after-pulsing probability is increasing at low temperature, due to increasing trap lifetimes. Our modeling of after-pulses compares well with the measured after-pulsing probability as a function of over-voltage at fixed temperature. As a consequence we can reasonably subtract the after-pulsing contribution from the dark noise in order to analyze the dark noise only in terms of field enhanced SRH and band-to-band tunneling contributions.

Concerning the signal shape, two exponential waveform components with different time constants can be discriminated. They are related to different contributions to the internal current, respectively through the poly-silicon quenching resistor (Rq) whose value shows dependence on temperature, and through the pixel parasitic capacitance in parallel with Rq. We observe that at low temperature the quenching resistance is increasing (from few hundred KΩ to few MΩ), with the consequence of enhancing the device dead-time. Pixel capacitance doesn't show any dependence on temperature, which is the reason for the gain being constant at fixed over-voltage (Gain ˜ Over-Voltage x Pixel Capacitance). Cross-talk shows no dependence on T because it depends mainly on the gain.

Preliminary measurements with LED and scintillation light sources indicate a moderate enhancement (up to 15%) of the photon detection efficiency (PDE) with decreasing temperature for short wavelengths, above freeze-out temperature (˜30K). This is probably related to the smaller energy gap in silicon at low temperature and to the increase of avalanche probability due to the enhancement of impact ionization coefficients at low temperature. Below freeze-out temperature PDE is dramatically decreasing.

We show how the fair quantitative agreement of our data with models is promising for the possibility of tuning the SiPM production parameters (e.g. doping profiles) in order to further reduce the single carrier noise in the development of future devices.

In conclusion we briefly discuss applications of SiPM's as attractive alternative to PMT's in systems at low temperature like Noble liquids scintillation detectors or Cherenkov light imaging systems for fundamental physics studies.

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