Linear mode photon counting with HgCdTe APDs

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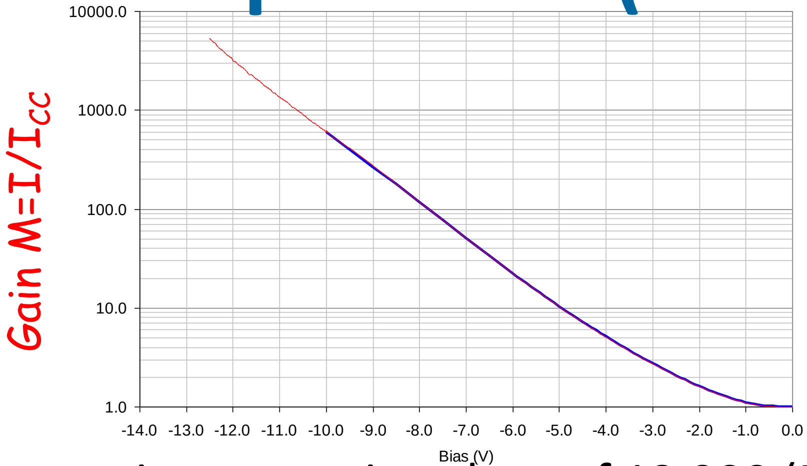
Gautier Vojetta
LETI: J. Rothman
IPAG: P. Feutrier

MINATEC CAMPUS

Outline

- HgCdTe APD basics
- How to count photons with HgCdTe APDs ?
- Linear mode photon counting with MWIR (and SWIR) HgCdTe APDs

HgCdTe APDs: A first example of single carrier multiplication (SCM) APDs



MWIR HgCdTe e-APD

cut-off wavelength λ_c=5.3 µm

T=80K

- Linear gain up to gain values of 13 000 (MWIR) and 600 (SWIR)
- $F_{electric}$~1-1.5 (DRS, SELEX, LETI, BAE, TELEDYNE)
- Response time independent of gain GBW= 2.1 THz (LETI, 2008)
- Noise equivalent input counts N... < 12 e/s (SWIR λ...=3 µm)

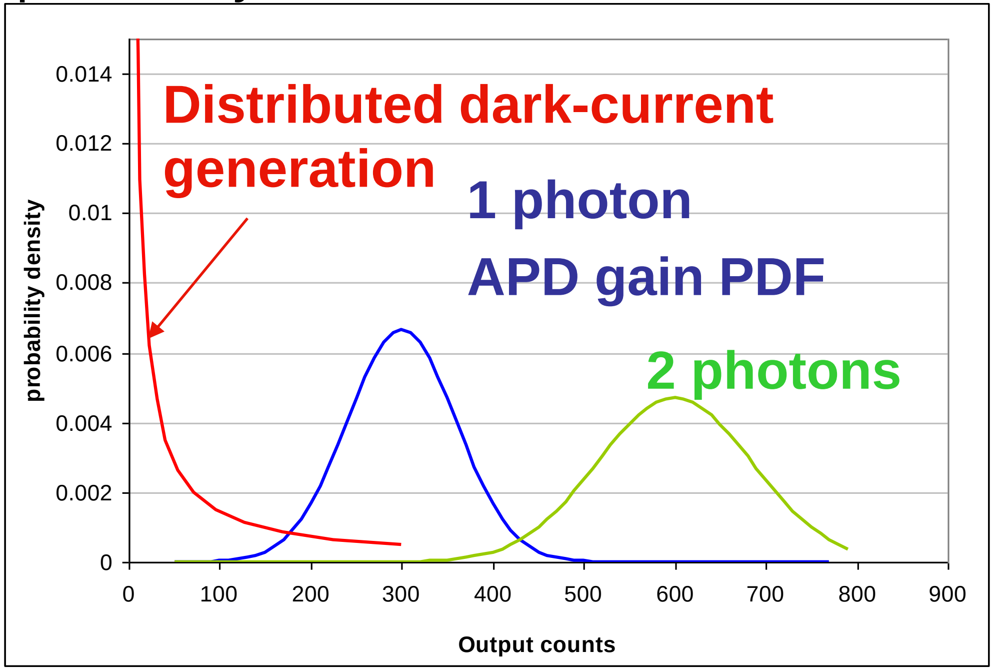
- PLUS all the standard pr...
  - High quantum efficiency (inte...
  - **Detect wavelengths from UV ...**
  - Low operating temperatures ...
- Photo detector arrays 80...

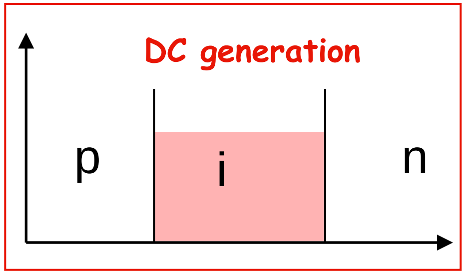
Linear mode photon counting with :
-High photon detection efficiency (PDE)
-Photon number resolution in each APD
-Large dynamic range per APD
-Low dark count rate (DCR)
-High rate (no dead time/zero afterpulsing)
-Large detector arrays

SCM (HgCdTe) APDs for linear mode proportional photon counting

Output count probability distribution for <M>=300 and F=1.04

$$F = 1 + \frac{\sigma_M^2}{\langle M \rangle^2}$$



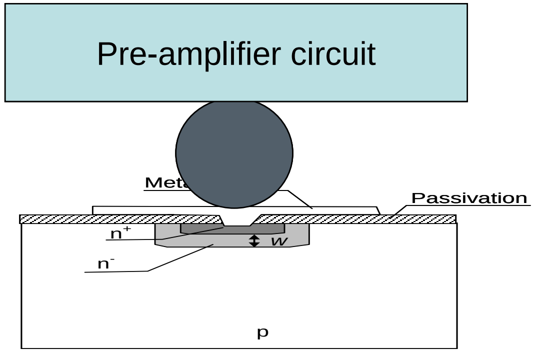


- Linear mode with low F
  - Photon number resolution at high PDE
  - Discrimination of non-amplified dark current events ➔ Low DCR
    - Depends on the distribution of the dark current generation

HgCdTe APDs for linear mode single photon detection

Useful gain is lower than the record values : M=30-500 (operability, dark currents)
Same order as the noise of free standing current amplifiers (>300 electrons)

Close coupling (hybridization) of the APD and a pre-amplifying read-out integrated circuit (ROIC) to limit stray capacitances

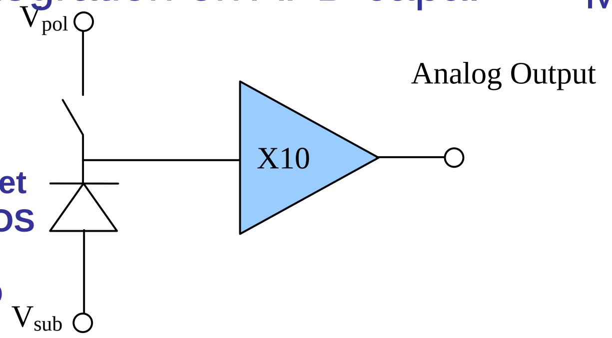


- Raytheon (2008): hetero-structure APD ? CTIA ? Noise ? 1 GHz BW
  - Poisson statistics at MxQE=200 for *m*=1
- DRS (2011): HDVIP APDs, RTIA with BW ~1GHz and 30 electrons of noise
  - Average photon signal to noise ratio MNR>10 for M>300
  - PDE=50 % measured at M=1000
  - DCR~1MHz (residual thermal photons, ROIC glow ?), high power consumption, large foot print

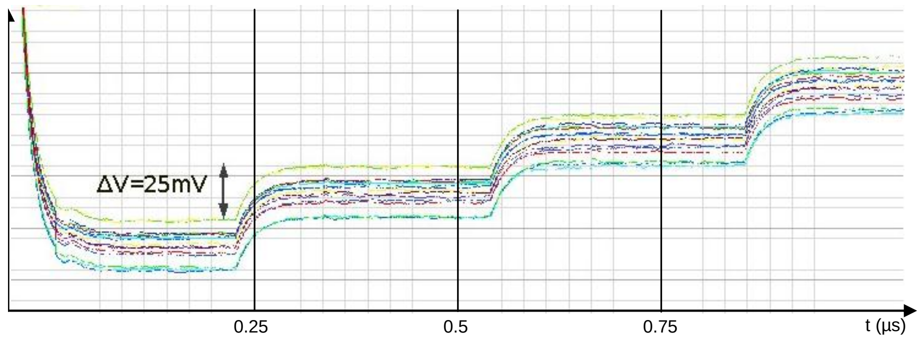
Pre-amplifier design

- Our goal: minimized noise, low power, limited constraint on BW
  - Enable photon counting at lowest possible gain
    - Facilitate the use of SWIR APDs → lower DCR and/or higher operating temperature
  - Large format small pixel FPAs
  - Tool to study the probability distribution function of the APD gain
    - APD architecture and geometry, Cd composition, temperature

Amplified source follower: Integration on APD capa.

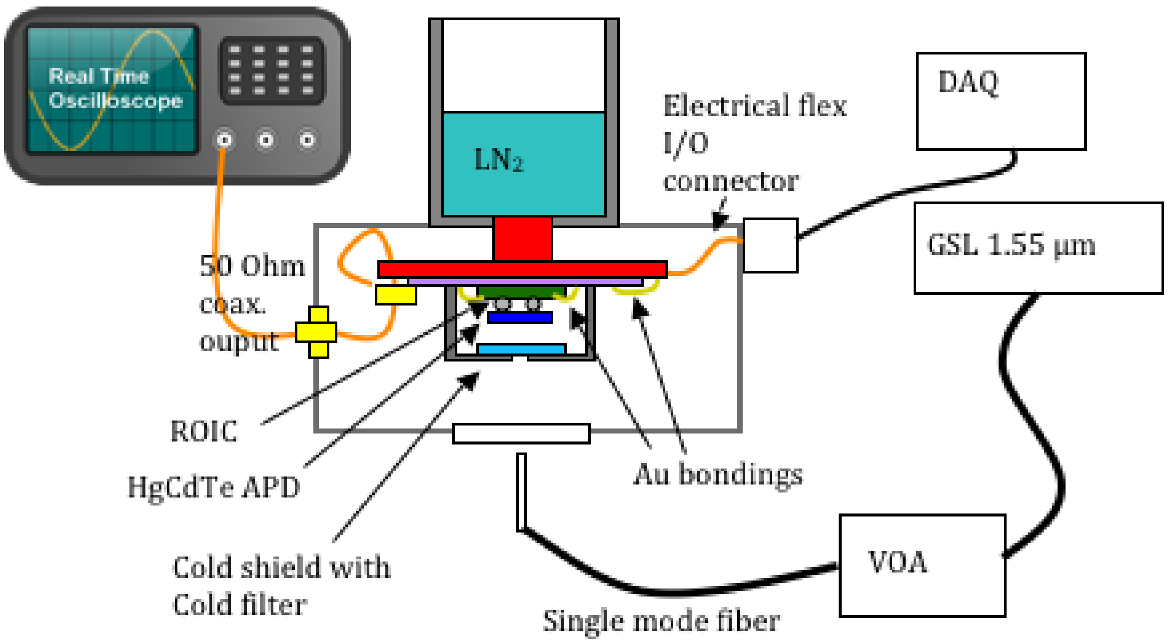


Simulated responses for three consecutive photons M=100 and F=1



- Noise ~ 10 electrons and BW=7 MHz (50 ns risetime)
  - Temporal jitter 3 ns of read-out circuit (F=1)
- *Mg*=25 mV → amplifier gain *g*=0.25 mV/electron
- Reset noise of 15 mV due to charge injection from the reset switch
- Low power consumption (13 µW) and foot print → Large area arrays

Experimental set-up

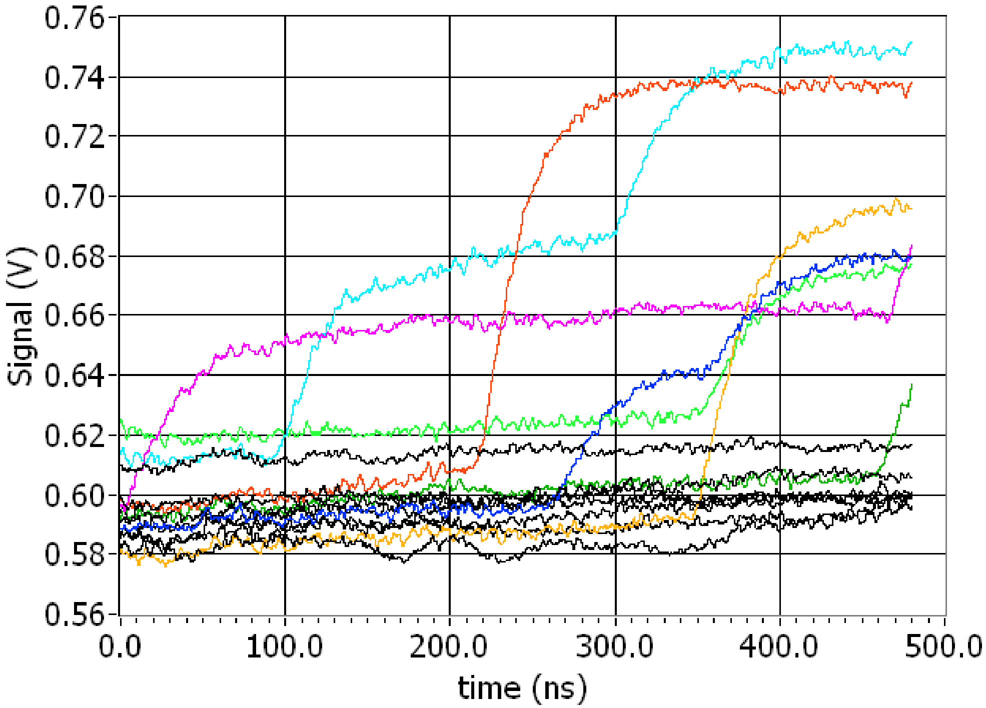


- Cold shield and filter leakage yields a residual thermal flux of 200 fA (MWIR APD)
- Pulsed laser at 1.55 µm : Ep=1.2 pJ (10^7 photons/pulse) FWHM=40 ps
- Fiber to sample distance is 3 cm
  - An attenuation of 100 yields ~ 3 photons/ pulse at the APD

Output signal with continuous thermal flux

Output signals with internal buffer amplifier (x2)

MWIR HgCdTe APD at V_{sub}=-10V and 80 K, constant flux (residual, laser off)

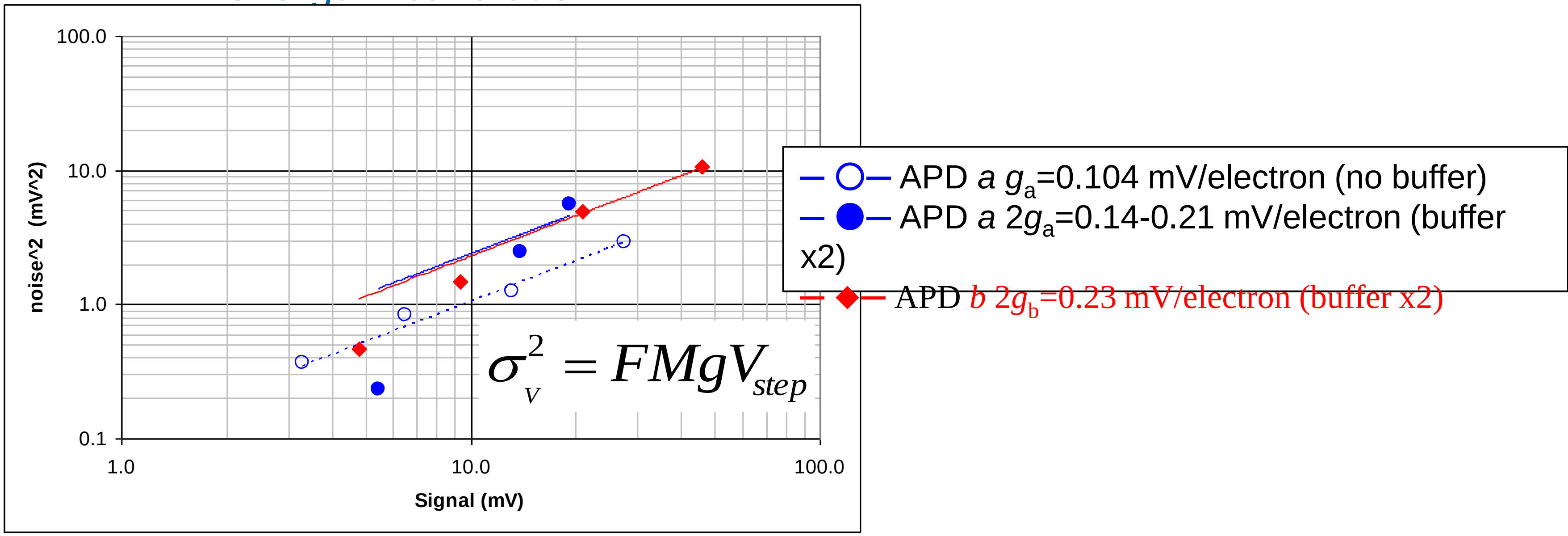


Photon counting ?
→ ROIC and APD
Gain calibration !

- Detection of events → Single photon detection ?
- Rise time 60 ns : BW=6 MHz // nominal value of 7 MHz
- Base line noise ~ 2.3 mV (APD b)- 3.7 mV (APD a) (with buffer gain x2)
- Reset noise close to nominal value (~10 mV rms)

ROIC characterization

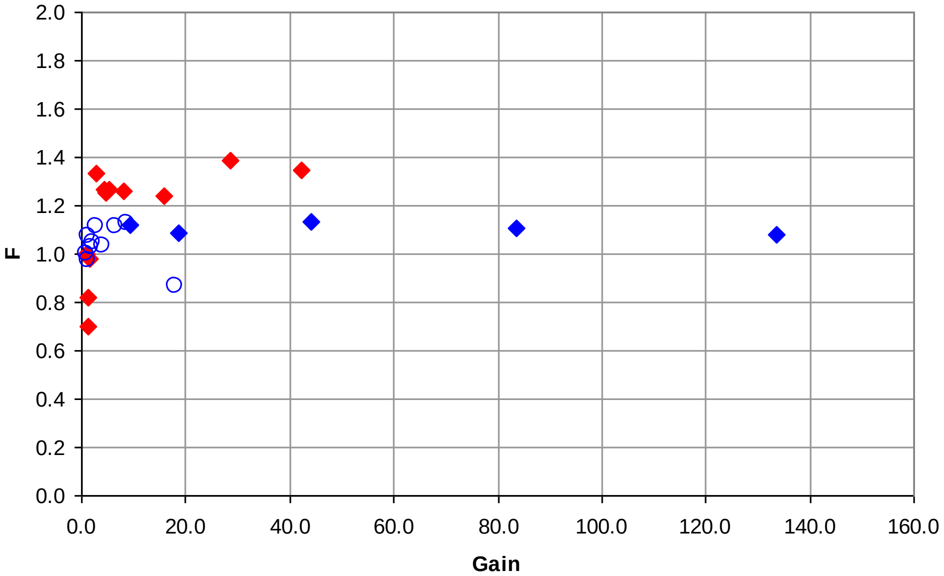
Photon noise
ROIC gain calibration

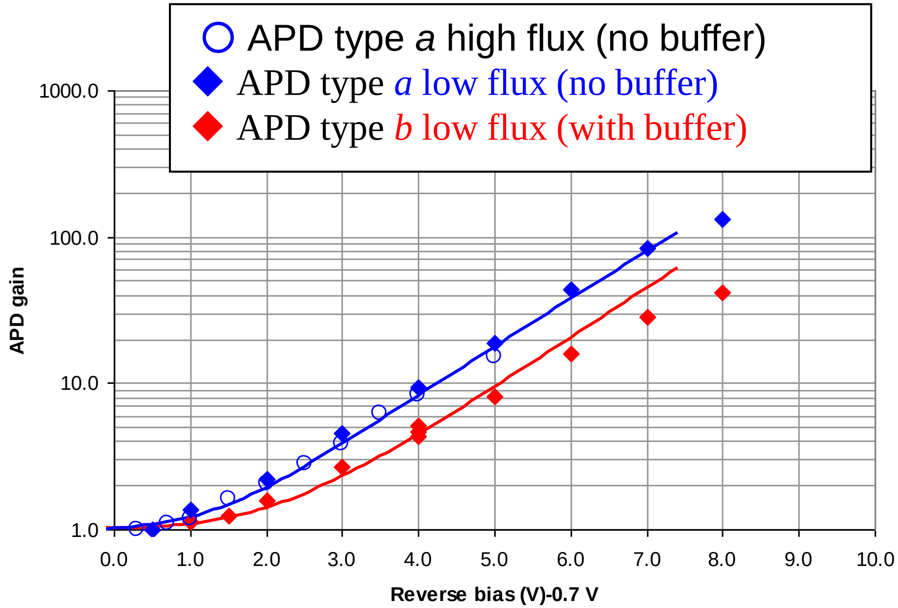


- ROIC gain calibration **M,F =1** → *g*=0.11 mV/e
  - factor 2 lower than the simulations (APD capacitance and/or ROIC gain)
- Base line noise ~ 2.3 mV (APD b)- 3.7 mV (APD a) (with buffer gain x2)
  - ROIC noise = 10 - 20 electrons → Photon counting at M> 30-40

ROIC and APD characterization

Signal and noise as a function of reverse bias



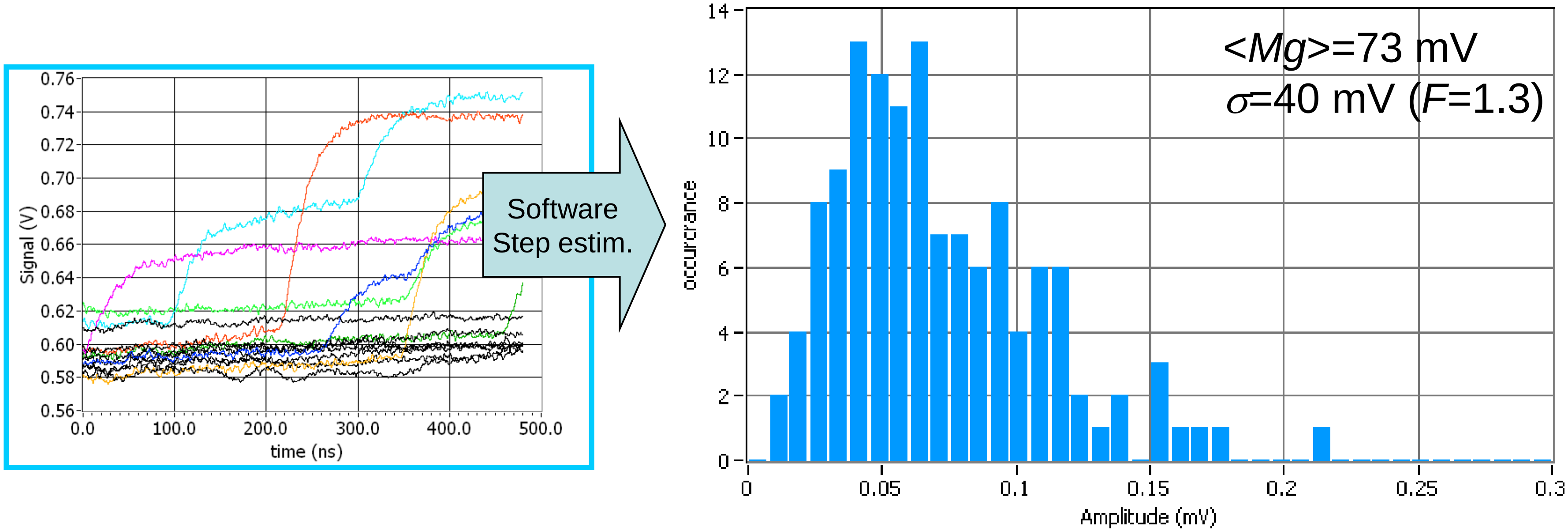


- Signal levels between 3 and 4000 electrons
- Estimated avalanche gains close to the expectations
- Saturation of signal and noise is observed at output signals >1000 electrons
  - Proportional photon counting up to 10 photons at M=100
  - Higher photon number can be detected with non-linear penalties which can be calibrated
- F= 1.1 - 1.3 (depending on the APD geometry)

Estimation of the APD gain probability distribution (PDF) using residual thermal flux (I_{res}=200fA)

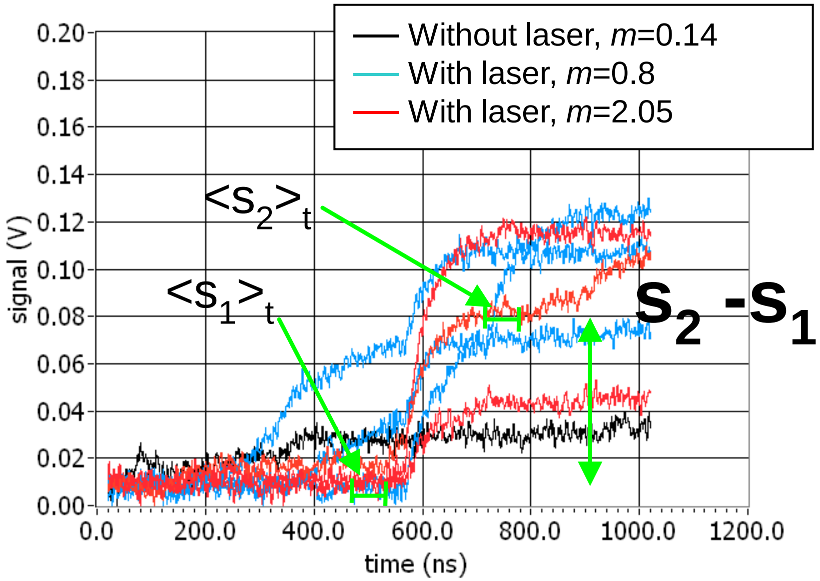
Analysis of 50 samples of a duration of 2 µs

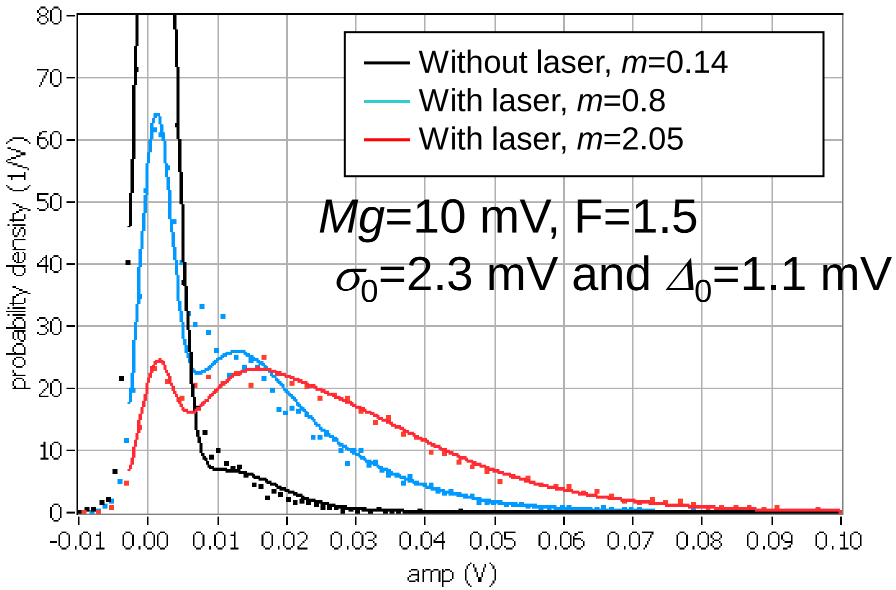
MWIR (λ_c=4.6 µm) HgCdTe APDa at 80 K, V_{sub}=-10V, APD gain ~230



- <Mg>≈$M_{APD}g_0$ → Single photon detection + estimation of the APD gain PDF
- 130 events was detected with a threshold of 10mV → *I*=200 fA
  - Equal to the measured residual photon current → PDE close to 100 %
- Asymmetry and low excess noise F=1.3 favors high PDE at high thresholds
  - Threshold at 40 % of <*Mg*> yields a reduction of 10 % in events (PDE = 90 %)

Proportional photon counting using MWIR HgCdTe APDs (V_{sub}=- 8V, M_{APD}=40, Attn.>100)

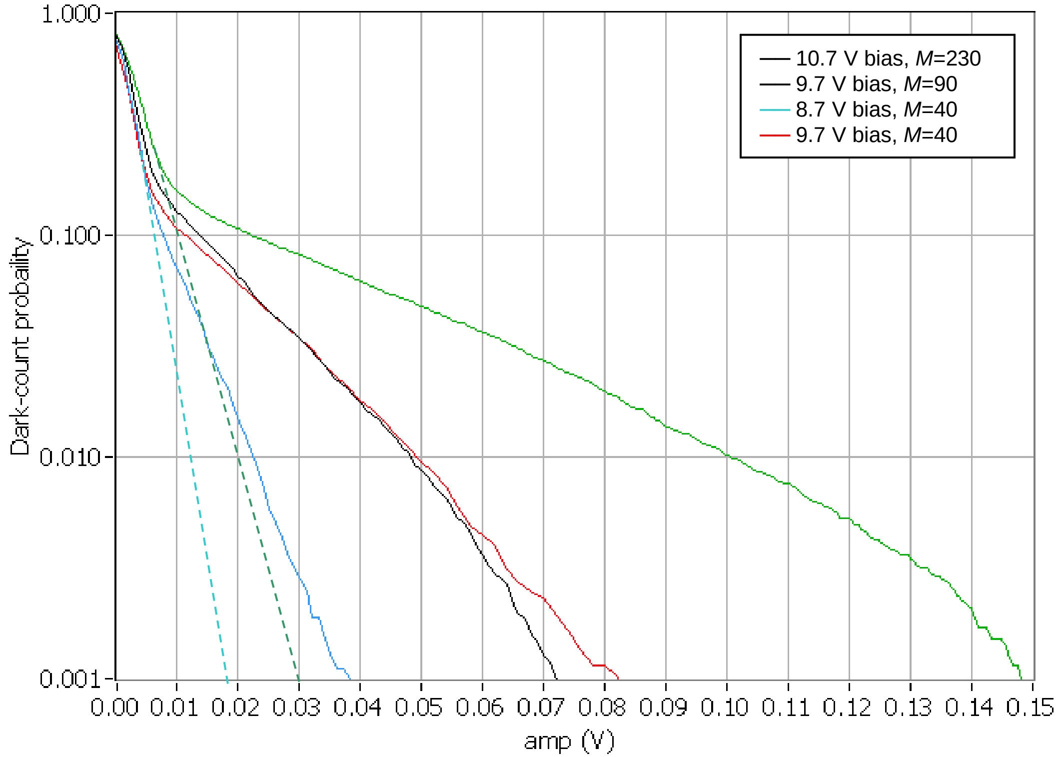




- Observation of laser events and residual thermal photons and/dark current events
- The results is consistent with photon Poisson statistics
  - Linear photon counting at Mg/g_0=40 for m=0.8 to 8
  - m=0.14 with no light, I(residual flux)=200 fA (DCR=1 MHz)
  - F=1.5 is too large for photon number resolution
- High probability density between zero and one photon average <*Mg*>
  - Measurement artefact attributed to laser jitter (coherent with gain PDFs)

Estimation of DCR in MWIR HgCdTe APDs

Dark count distribution function estimated using fixed s_2-s_1 estimator and laser off



- Low amplitude events :ROIC noise and low gain dark current
  - Increases at high reverse bias
- High amplitude events due to residual (thermal) photons (DCR=1 MHz)
- DCR without residual photons can *be estimated by an exponential interpolation* of the ROIC/low gain DC noise
  - **DCR = 8 kHz at -10V (M=230) at 30 mV (40% of <Mg> and PDE =90 %)**
  - DCR increases at low bias (800kHz at – 8 V, M=40) due to the influence of ROIC noise

Conclusions/perspectives

- Linear mode proportional photon counting has been demonstrated in MWIR and SWIR HgCdTe APDs hybridized with an ultralow noise ROIC (10 to 20 electrons)
  - Linear mode single photon detection at record low gain M=40
  - Rise time 60 ns (BW=6 MHz)
  - Dynamic range of between DCR and 10-20 photons per observation time (between two resets of the ROIC)
  - A low amplitude tail was observed with the laser pulses :
    - Correlated with the observation of a temporal instability between the laser and the signal capture
  - Count photons from UV to IR
- The analysis of the amplitude of residual thermal photons gave a first estimation of the PDF of the avalanche gain in HgCdTe APDs
  - High asymmetry and low F → estimation of a PDE of 90 % at 40% of the average single photon amplitude
- The measured DCR was limited by residual photon flux in MWIR APDs (1 MHz) and ROIC noise in SWIR APDs (80 kHz)
  - DCR down to 8 kHz was estimated at 90 % estimated PDE
- Direct measurements of PDE and DCR at controlled and zero flux
- Characterization of APD PDFs using the present ROIC (Cd, geometry, hetero-structure)

- Optimization of the ROIC (BW) and APDs (BW>10 Ghz, F=1.05, Top up to 200K, DCR below 100 Hz) → high speed photon number resolved detection
  - 1 ROIC with 1 GHz BW, 30 electrons noise and low power consumption and variants with thresholding circuits are waiting for characterization
- Photon counting arrays: pitch size down to 10 µm