Requirements and Candidates for Ladar Single-Photon Detector Arrays

KECK Institute for Space Studies
California Institute of Technology
Jet Propulsion Laboratory

Single-Photon Counting Detectors Large Scale Study
1st Workshop, January 25-29, 2010

William Cottingame, PhD

Photodetector User – Lidar Remote Sensing

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Miniature Aerosol Lidar

1-µm IR Enhanced Si APD

248- to 308-nm Excitation, PMTs

Fluorescence Lidar

Eye-Safe Autonomous Aerosol Lidar

1.5-µm InGaAs APD

0.5- & 1-µm Si APD, 1.5-µm InGaAs APD

Mobile Backscatter Lidar Facility

280- to 450-nm Monochromators

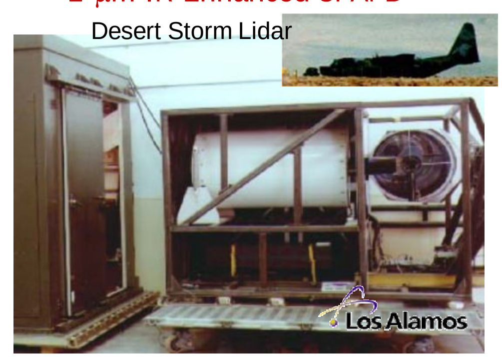
UV Differential Absorption Lidar

9- & 10-µm CO_2 Bands, Heterodyne

248- to 351-nm Excitation, PMTs

1-µm IR Enhanced Si APD

Desert Storm Lidar



Laser-Based Remote Sensing (Lidar/Ladar)

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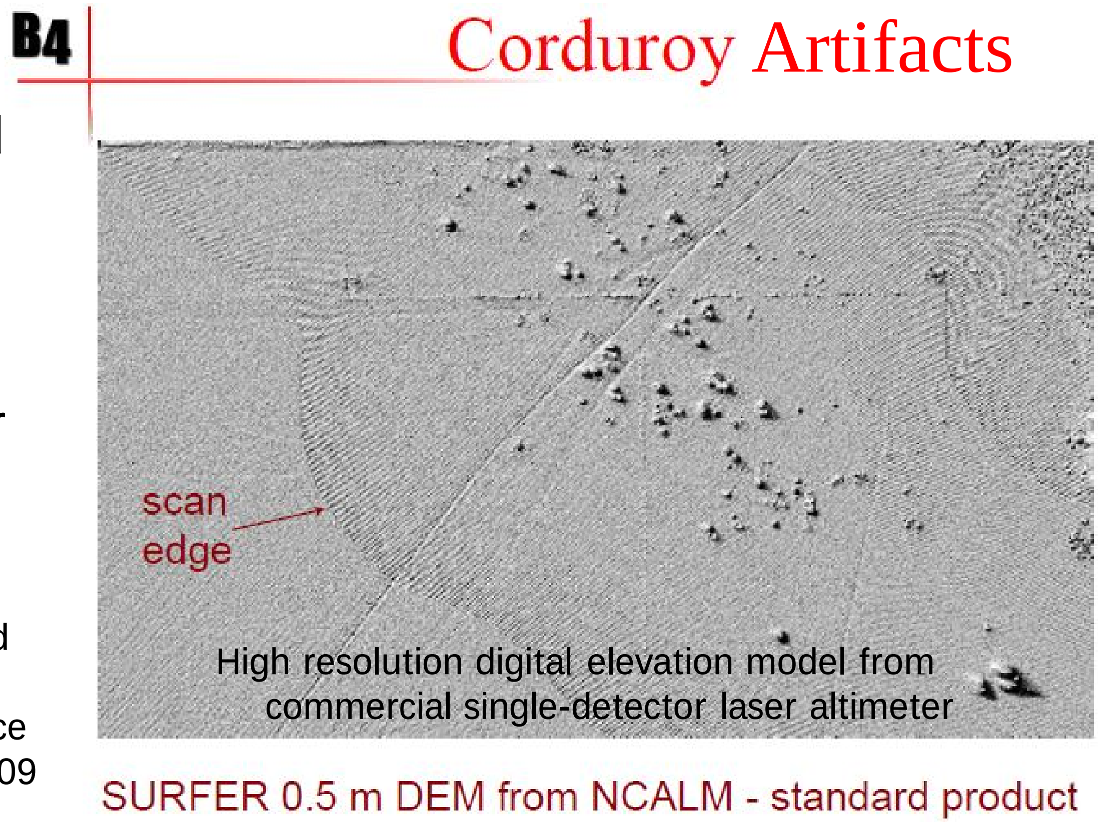
- Historically lidar (atmospheric measurements) has used relatively low pulse repetition frequencies (PRF), e.g., 10's to 100's Hz
  - Motivated by the need to overwhelm solar background and detector noise and stay within a laser's average power limit
  - One to at most a few analog photodetectors scanned over the interrogated atmospheric volume
  - Often specialized detectors ranging from the NUV to the LWIR
- More recently ladar, in particular commercial airborne altimeters, has moved to the MHz PRF region to increase area coverage rates
  - Still a single detector element rapidly scanned over a surface area
  - Eye-safety is driving this approach to 1.5 μm to take advantage of the higher single-pulse maximum permissible exposures (MPE)

Flying-Spot and Flash Airborne Ladar

- What is referred to as a "flying-spot ladar" has a single-photodetector that is rapid scanned transverse to the aircraft's flight path
- Whereas "flash ladar" uses focal plane array (FPA) and slower scan rate
- Motivations for flash lidar
  - Significantly increased area coverage rates
  - Reduced registration artifacts
  - Actual imaging; rather than point sampling

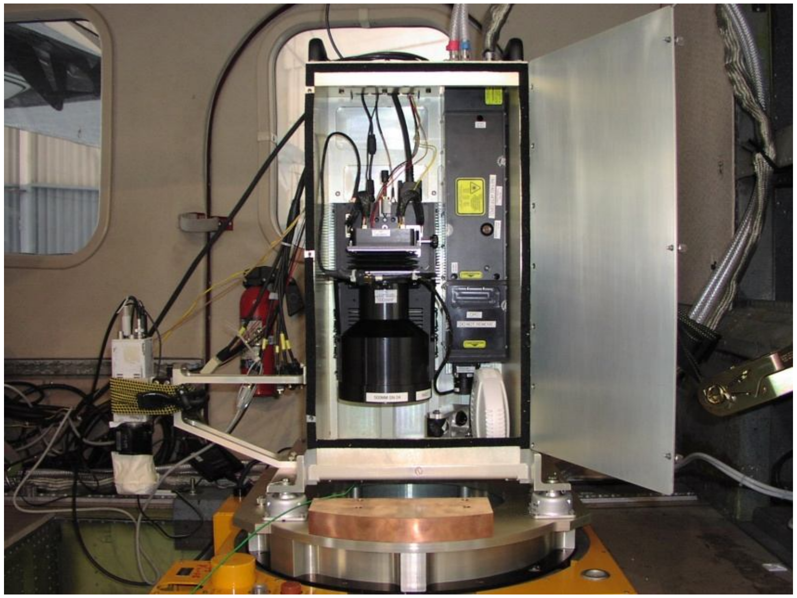


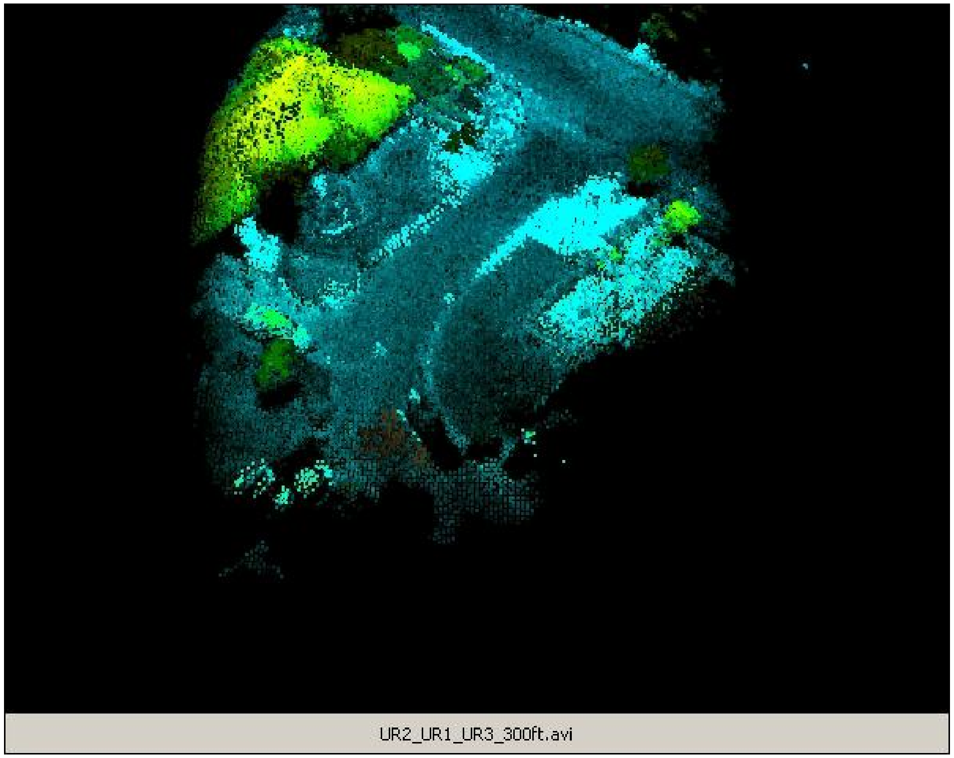
Slide taken from and with apologies to:

Ken Hudnut, *et al*., "Ladar sensor and system capabilities and issues", Keck Workshop on Monitoring Earth Surface Changes from Space, October, 29 2009

3D Imaging with “Flash Ladar”

- 3D image with a single laser pulse can be acquired with analog-mode APD at low altitudes and modest laser energy
- 128×128 InGaAs FPA at 1.5 μm
- Flights for model validation and data for image processing development completed in 2008





Exo-tropospheric Ladar Imaging

- Significant market for a ladar imaging missions if, among other things:
  - Spatial resolution and geolocation requirements met
  - High acquisition rates at long standoff ranges achieved
  - Platform size, weight, and power (SWaP) limits accommodated
- General assertions – without showing the detailed trades to justify them
  - FPA needed to meet area rate and low "data void" requirements
  - SWaP exceeded for applications of interest using 1.5-μm lasers
  - Eye-safety <u>not</u> achievable with low PRF ladar at 1 μm
  - Efficiency/reliability of high PRF 1-μm lasers is <u>currently</u> a necessity
  - Few-photon sensitivity needed to enable use of high PRF 1-μm lasers
- Viability of high-area-rate space-based imaging ladar just 6 years ago

  "If we had some ham we could have ham and eggs; if we had eggs."

  Quote from Laurel and Hardy depression era comedic film

High-Efficiency Laser Development at NGAS

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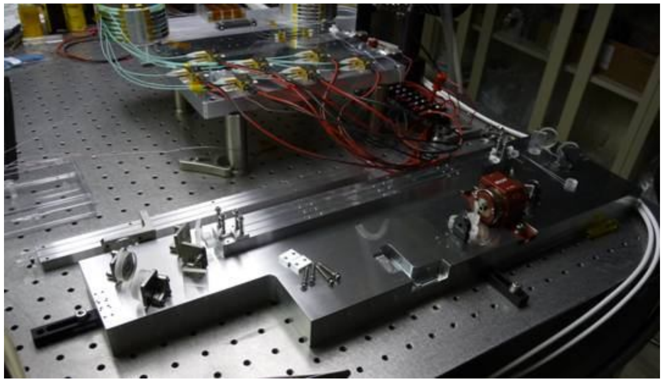
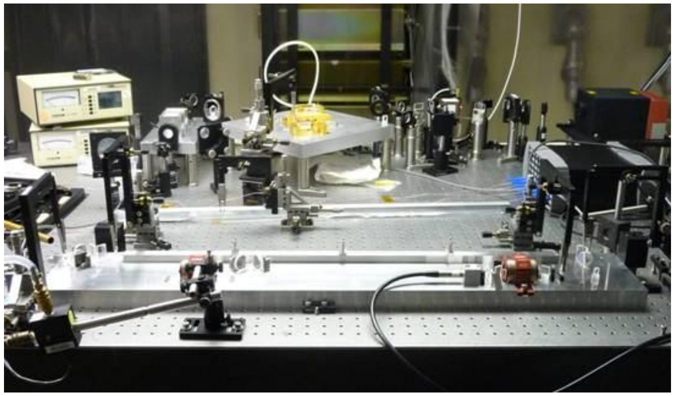
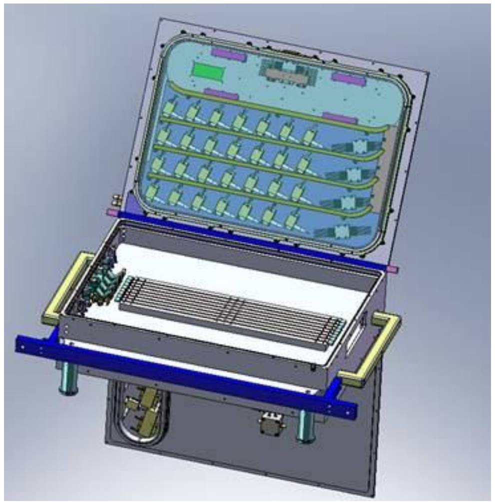


Compact Fiber Laser Demonstrator
Facilitates compact, ruggedized high energy, pulsed fiber opto-mechanical assemblies
Demonstrated operation at power with only a 2.5% loss (32.5% bus-plug)



High Efficiency Fiber Amplifier Testbed
Validated fiber laser efficiency advantage over conventional solid state laser systems
Demonstrated 33.5% bus-plug efficiency to date

High-Efficiency Fiber Laser

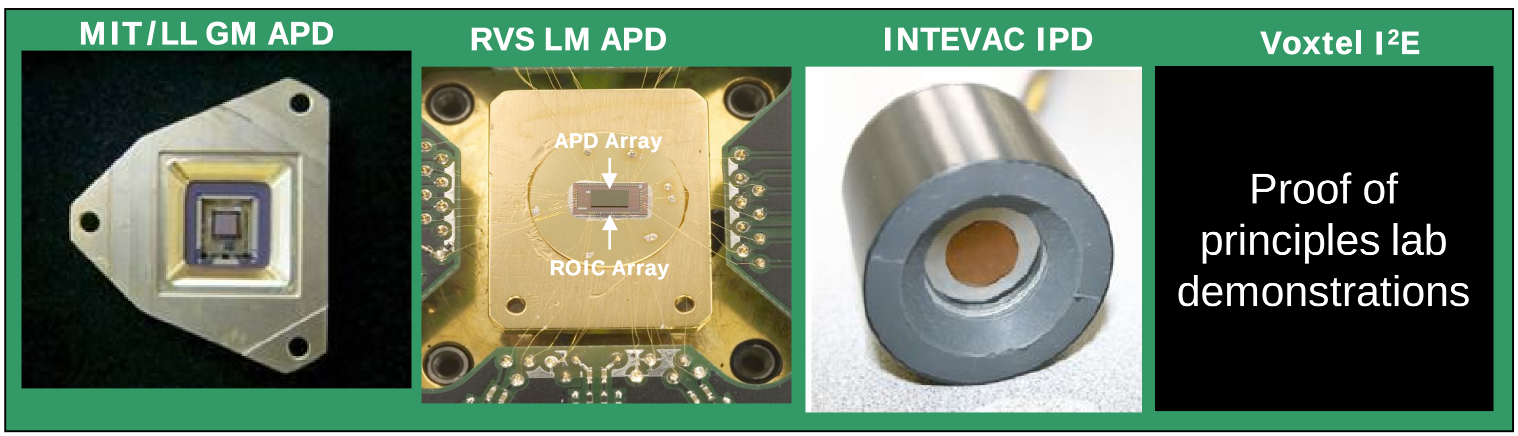


1-μm, 1-ns, high PRF pulsed laser
4 fiber amplifier, ~8 mJ/pulse
40-GHz wavelength separation
Spectrally combined beam
>160 W (20 KHz) average power
>300 W (50 KHz) average power
16”×19”×5.75” laser envelope
~50 lb. total weight
Scalable to higher energies
Design progressing, expected completion by Q1/2010

We have ham! – well almost

Single-Photon NIR Sensor Array Development

- Government sponsoring 1-μm Geiger-mode FPA/ROIC development at MIT LL
- Aggressive development of 1- to 2-μm low-noise, linear-mode FPA/ROIC at NGAS
  - Low ionization ratio homojunctions, e.g., k~0 for Hg_xCd_xTe
  - Impact ionization engineered, I^2E, III-V heterojunctions
- Moderate Q.E. IR intensified photodiode, IPD, complete and >2-yr. life testing
- Space qualification of single-photon sensitive lidar/ladar FPA's has been ongoing for several years



Eggs not all in one basket

MIT/LL NIR Geiger-Mode APDs

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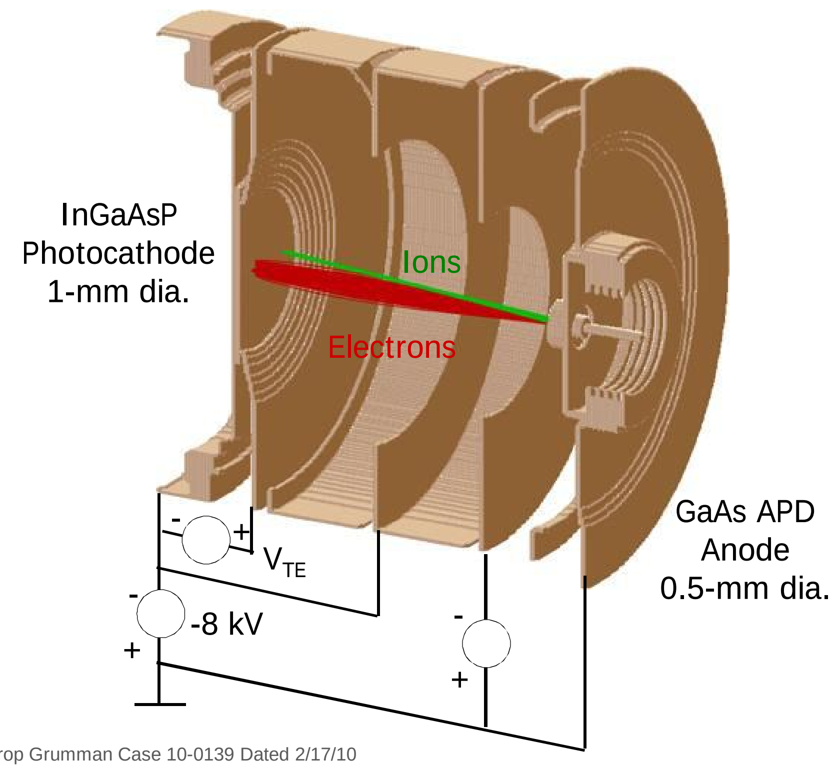
- Many variants of the InGaAsP FPAs and readout IC (ROIC) have been produced over recent years with formats of 32×32, 32×128, and larger
- Performance has been fluid as the design evolves to meet competing requirements, but top-level performance specs might be expected to be:
  - Probability of detection, i.e., Q.E. × probability of avalanche: ~30%
  - Dark counts: 10 to a few 100 kHz
  - Overall timing resolution: ~1 ns
  - Readout rate: ~20 kHz
- Early variant of the technology has been transferred to Spectrolab and Princeton Lightwave
- For space applications, radiation susceptibility requires management
- Contact for the InGaAs APDs: Simon Verghese, Lincoln Laboratories

Intevac Intensified Photodiode (IPD)

- A history of severe production, operational, and shelf life limitations
- During our collaboration, processes have been brought under control
- Photocathode materials processing still undergoing some refinement to improve reproducibility and yield
- Top-level performance
  - Wavelength: 0.93 to 1.3 μm
  - Q.E. 25% to 32% @ 1 μm
  - Dark current: <200 kHz @ 298°K (4x decrease for every -20°K)
  - Timing resolution: <1 ns
  - Dead time: 0 (linear mode)
- Finite operating life – not yet fully quantified but 100s of μC

Intevac Inc., Santa Clara, CA



Voxtel Impact Ionization Engineered APDs

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- Impact ionization engineering (I^2E) – heterojunctions designed to provide greater ionization localization than in spatially uniform structures
- I^2E tailors heterojunctions to produce carrier multiplication statistics that are more deterministic and/or favor electron over hole ionizations
- Allows use of III-V materials for APDs having otherwise unacceptable electron/hole ionization coefficient rations (k) for linear-mode APDs
- NGAS is working with Voxtel in a research effort that has produced such structures with exceptional high gain and low excess noise
- Next – focus on low noise, which was not part of the initial objective, in order to achieve single photon sensitivity in a linear-mode APD
- Single-pixel demonstrations intended as proof of principle, validation of theoretical models, and NGAS's ability to grow the complex structures

Contact: Andrew Huntington, Voxtel Inc., Beaverton, OR

RVS Single-Photon, Linear-Mode HgCdTe APD

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- NGAS funded linear-mode, HgCdTe APD development at Raytheon Vision Systems (RVS)
  - Goal: demonstrate photon counting, i.e., ≥95% P_d & ≤1% P_{FA}
  - 4x4 array – demonstration of scalability to large area FPAs
  - Rudimentary readout electronics, i.e., transimpedance amp
  - Provide devices for radiation exposure and post test
- Top-level performance at that time (2007) was encouraging
  - QE: 90% to 95% for detector optimized and AR coated for 1 μm
  - Gain: ~100 with dark currents and read noises low enough to show NEPs <1 photon at LN2 temperatures
  - Operability was an issue for the limited number of production runs
  - Radiation tolerance appears to be good to 10 krad
- For reasons unrelated to results, no NGAS internal funding for follow on

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MBE Based HgCdTe APDs and 3D LADAR Sensors

The 2009 U.S. Workshop on the Physics and Chemistry of II-VI Materials, October 6-8, 2009, Chicago, Illinois, USA

Dr. Michael D. Jack

Raytheon Vision Systems

805-562-2395

Excerpts 1-26-10

The following charts were provided by Raytheon Vision Systems and are cleared for public release by Raytheon and their sponsors

High Performance HgCdTe APDs Provide High Gain with No Excess Noise

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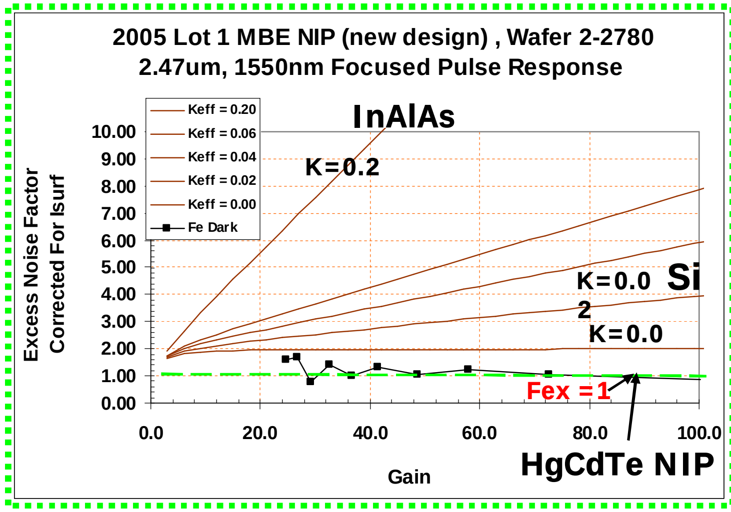
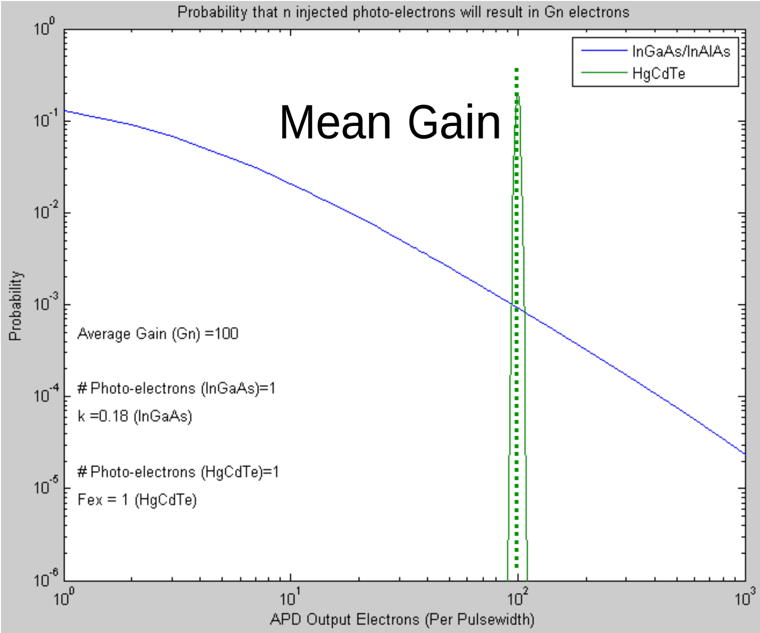
- Most APDs obey the Macintyre excess noise equation

$$F_e = k_{eff} M_e + (2 - 1/M_e)(1 - k_{eff})$$

- HgCdTe electron injection show gain and excess noise properties indicative of single ionization carrier gain
  - **Excess Noise is ~1 (Ideal Amplifier)**
- Significance: electron event to even gain probability is higher
  - Achieves a higher probability of detection

HgCdTe has a significant performance advantage over competing materials





2nd Gen MBE Engineered APDs Have Enabled Ultrahigh Performance at 300°K

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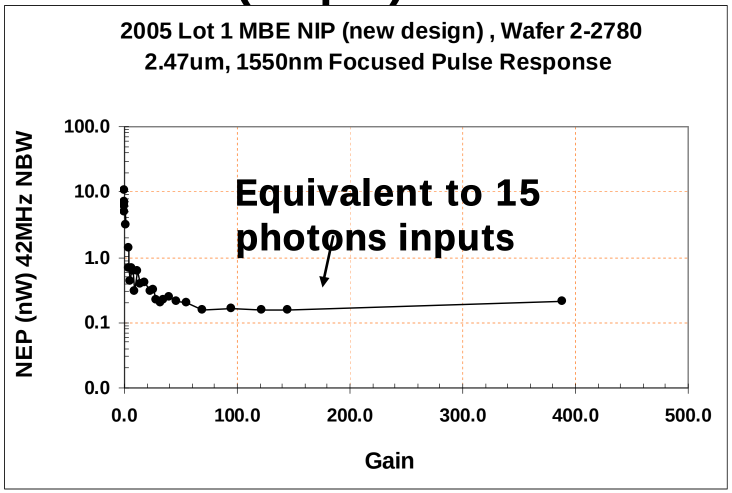
NEP is 0.15nW (15 ph.) to Gain of >300!!!



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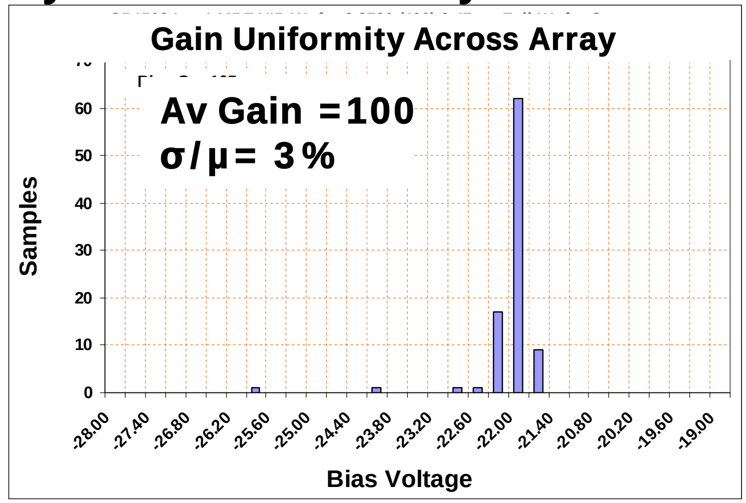
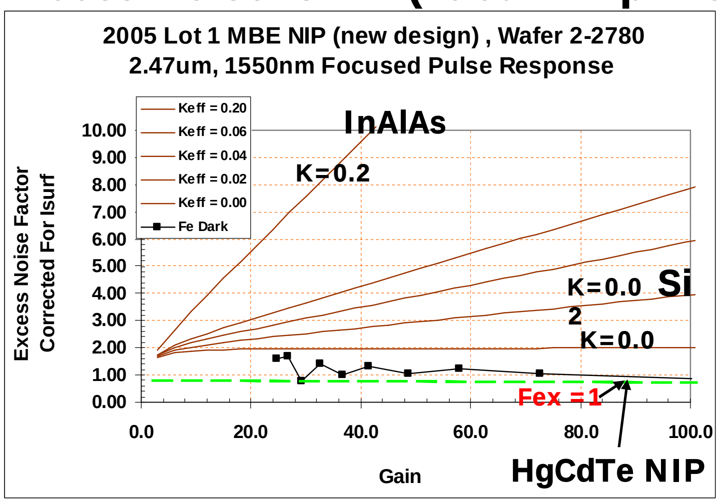
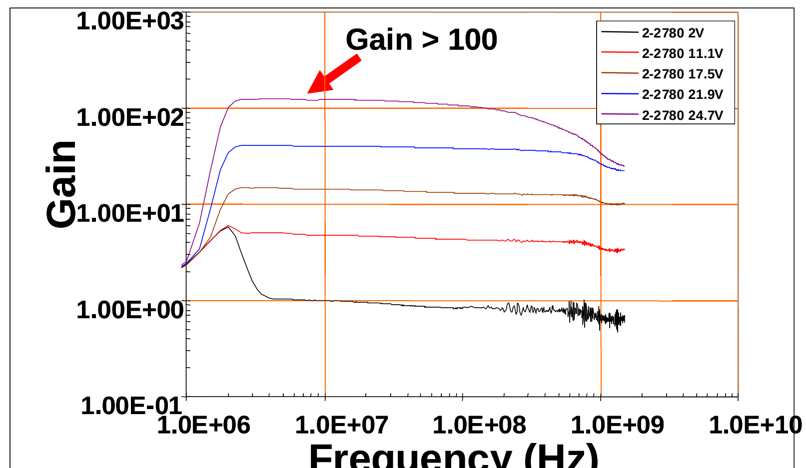
Only 3% Nonuniformity at Gain =100



Excess Noise is ~1 (Ideal Amplifier)



>1 GHz BW at Gain = 100



MBE HgCdTe APDs Provide M>100, Fex ~1 & GHz BW at 300K

Ultralow Dark Current and Photon Counting for Cryocooled APDs

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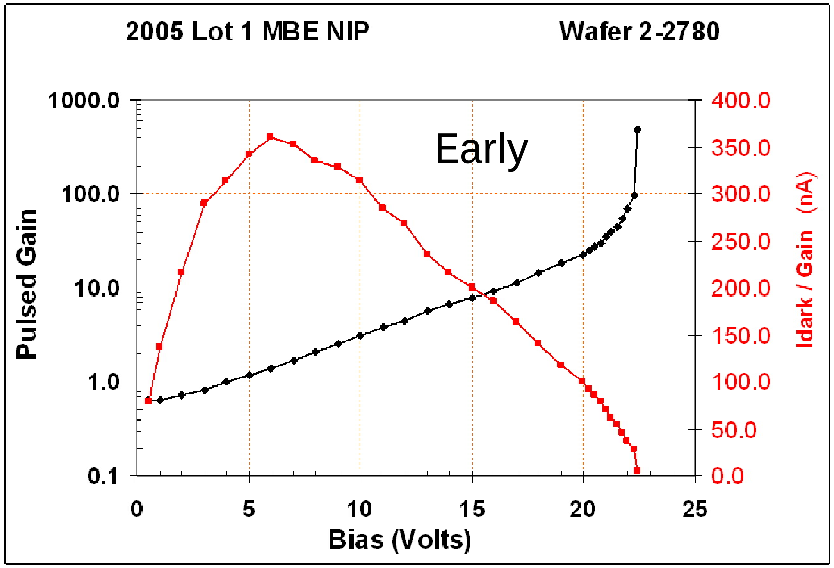
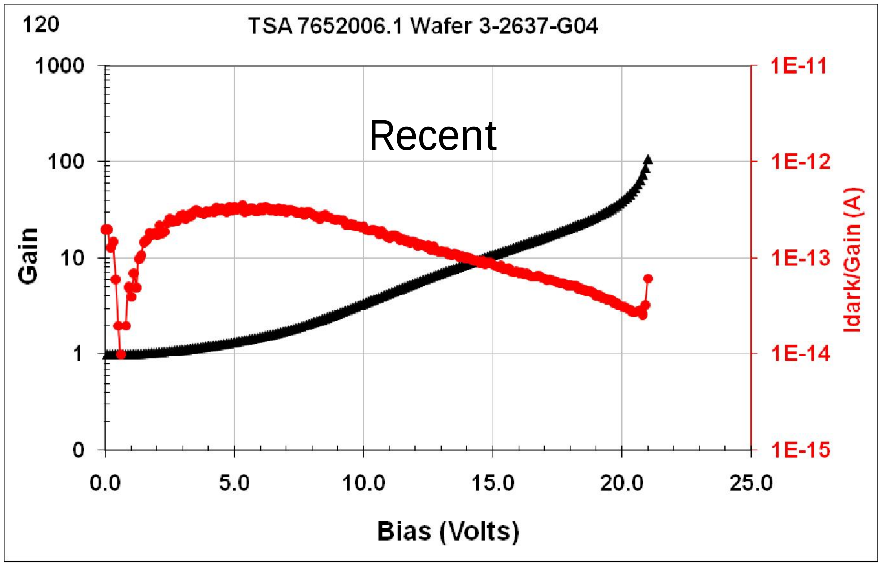
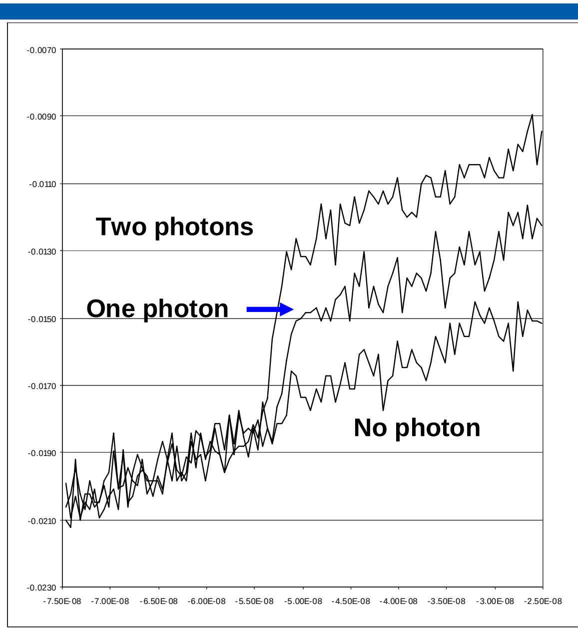
- Demonstrated devices for <u>photon counting application</u>
  - Idark/Gain < 5×10^{-14} A (bulk dark count lower)
  - Maintain Fex ~1
  - Cryogenic operation
- Surface leakage component greatly decreased in recent devices.

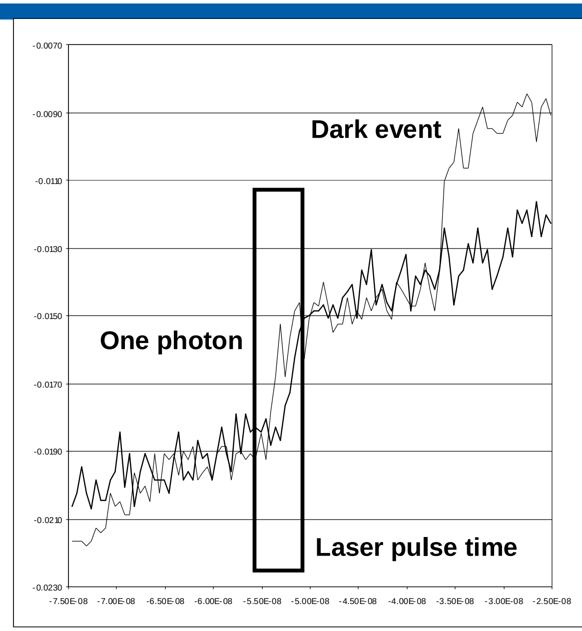




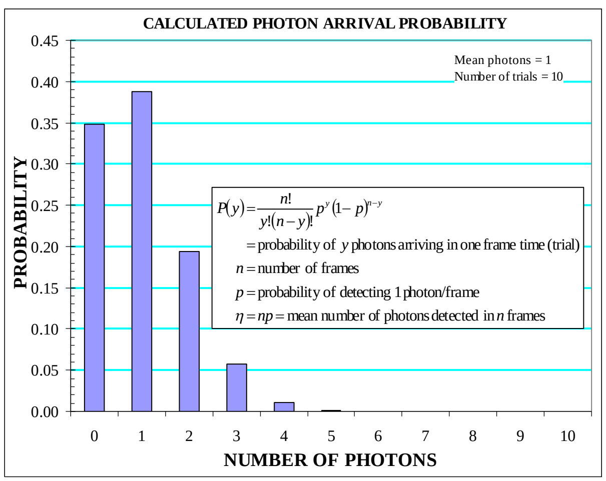
Photon Counting devices Demonstrated

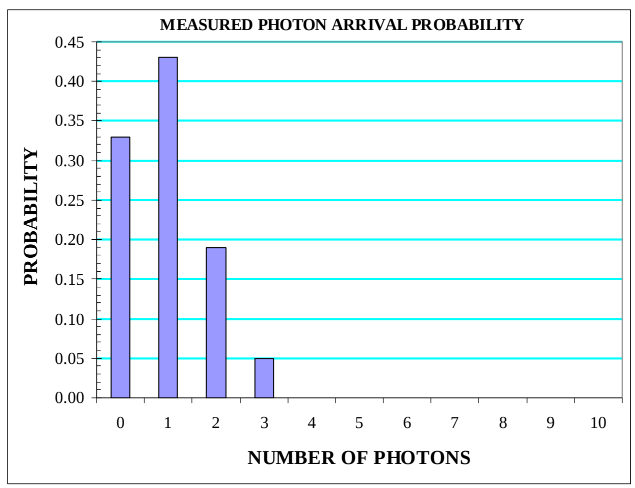
HgCdTe Single-Photon Detection Output Examples
Statistics Match Closely to Poisson Statistics





Measurements at 180°K





Probability	Calc	2V Pulse
0 photons	0.35	.33
1 photon	0.39	.43
2 photons	0.19	.19
3 photons	0.06	.05

Waveform Shows Two Single-Photon Pulses Spaced at 6 ns

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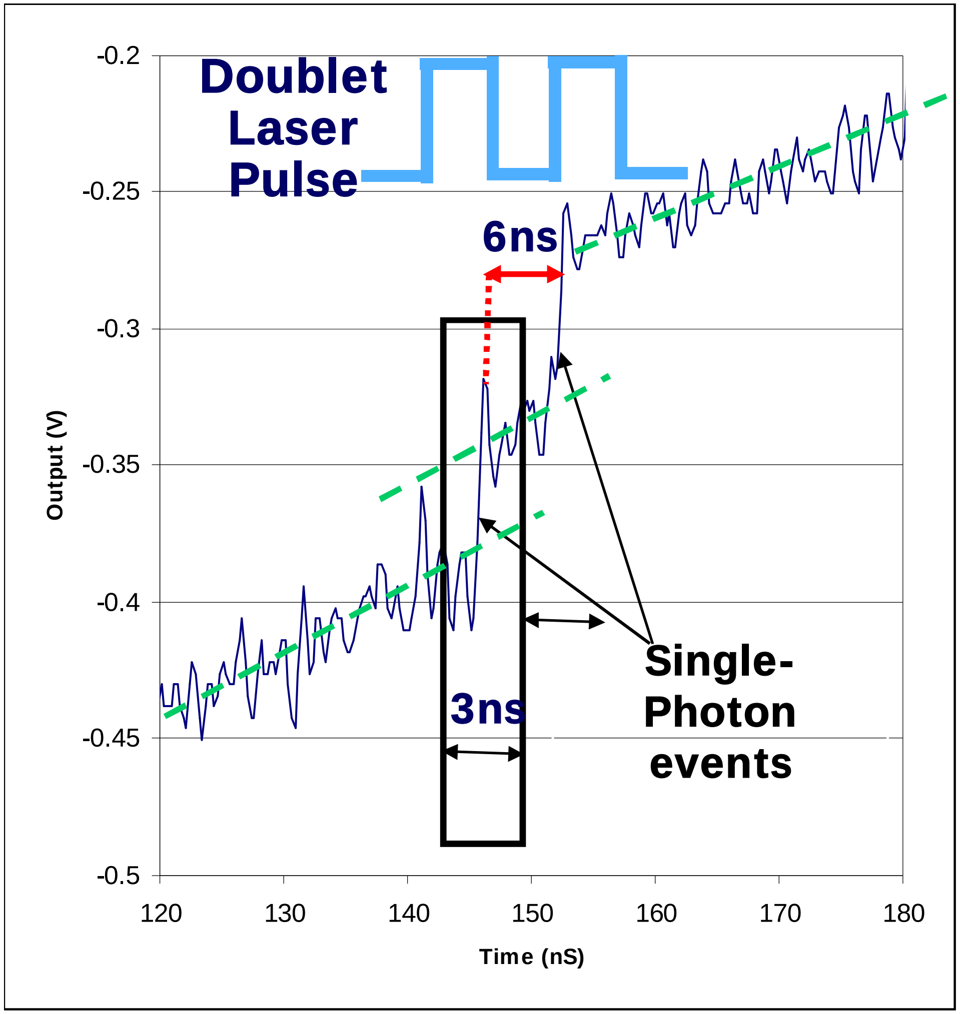

One single frame acquisition on one pixel from a 4×4 array

Doublet laser pulse with 6-ns spacing limited by minimum setting of pulse generator

4x4 assembly 7617614

HgCdTe Detector 2-2780-J22

Bias -18.1V at 180°K

100-ns integration time

Two 3-ns laser pulses

< 1> photon/pulse

Linear-mode detection makes discrimination of closely spaced targets possible