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1/f Noise QWIPs, nBn, and Superlattice Detectors

S. D. Gunapala, S. B. Rafol, D. Z. Ting, A. Soibel, C. J. Hill, A. Khoshakhlagh, J. Nguyen, L. Baker, A. Fisher, J. K. Liu, J. M. Mumolo, S. A. Keo, and B. Pepper

Center for Infrared Photodetectors

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, California

SPIE Infrared Remote Sensing and Instrumentation XXIV Conference (9973)
August 29, 2016, San Diego, California

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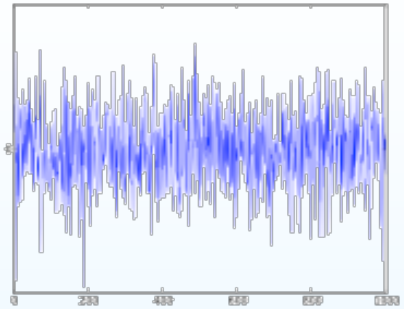
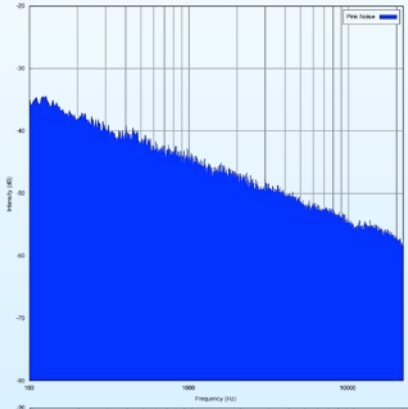
Colors (Types) of Noise

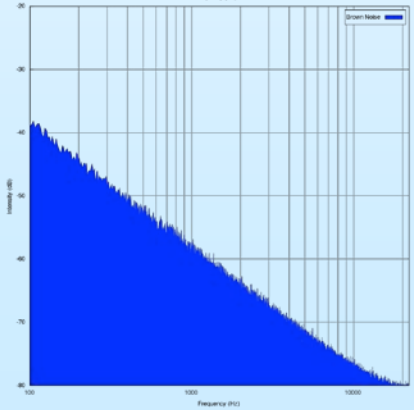
- White noise



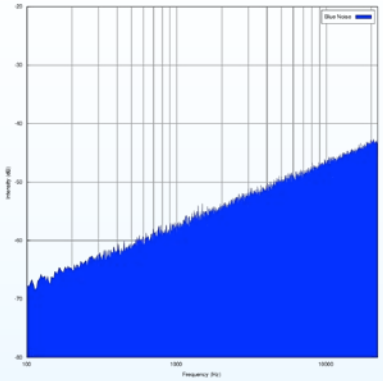
- Pink noise (1/f)



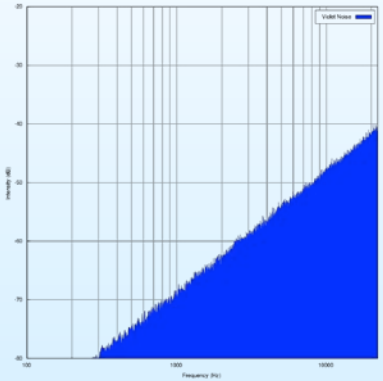
- Brown noise ($1/f^2$) (Red noise)



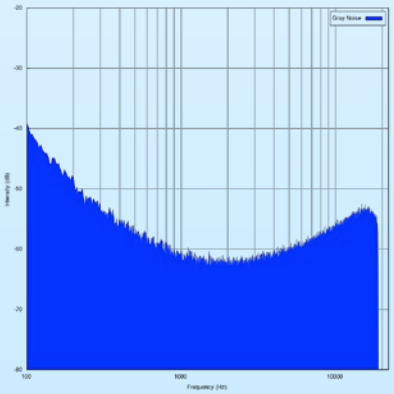
- Blue noise (f)



- Violet noise (f^2)



- Grey noise



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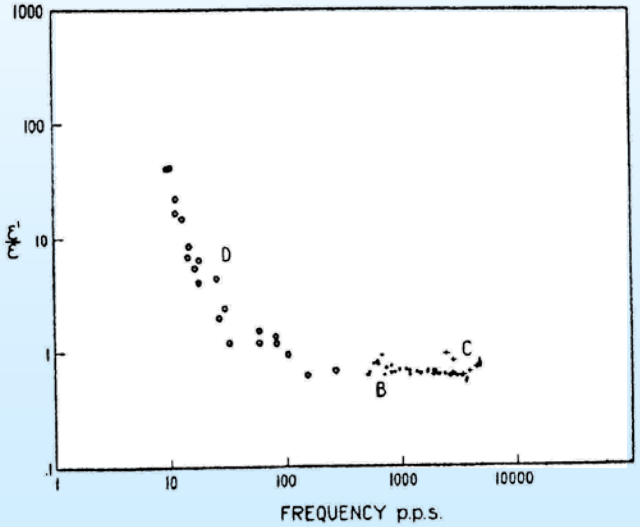
Noise in Electronic Devices

- 1918 W. Schottky reported that ideal vacuum tubes have two types of noises “Wärmeeffekt” and “Schroteffekt”. Ref. W. Schottky, Ann. Der Phys. **57**, 541 (1918)

- 1925 J. B. Johnson (Bell Telephone Laboratories) reported his experiment on Small-Shot Effect (Schroteffekt) now known as Shot noise

  - “The effect is much large in the lower range of frequencies than the theory predicts” – J. B. Johnson, Physical Review, Vol. 26 (1925) 71.
  - Now known as 1/f noise



- 1927 J. B. Johnson discovered the “Johnson Noise” – Nature **119**, 50 (1927). Also, he made the first working FET.

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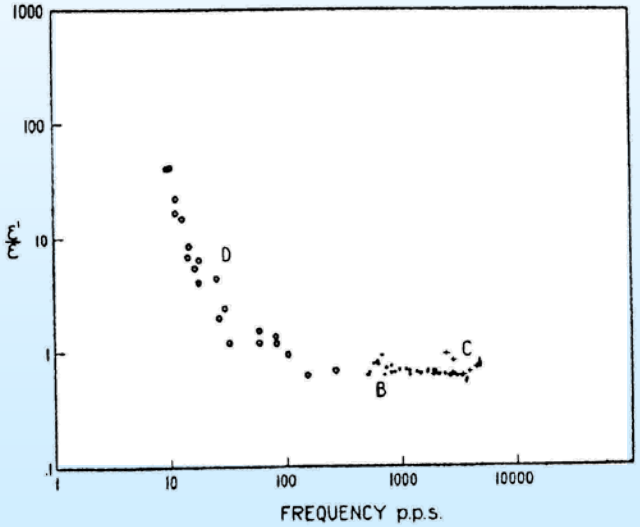

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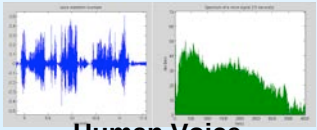
Historical & General Perspective of 1/f Noise

- 1/f noise of semiconductor devices (collision devices) generated by diffusion and recombination fluctuations - **Aldert van der Ziel**
- "1/f Noise is No Surface Effect" – **F. N. Hooge**; Mobility fluctuations due to lattice and impurity scattering gives 1/f noise in semiconductor devices
- "Quantum theory of 1/f noise" – **Peter Handel**
- 1/f noise of HgCdTe
  - HOT MWIR, 1/f knee is ~500Hz ->1KHz "Primary cause of 1/f noise in MCT diodes is charge tunneling from states in the passivation into the semiconductor volume" – M. A. Kinch, *et al.*, Proc. SPIE Vol. 7660, 76602V (2010)
  - LWIR, 1/f knee is few hundreds –> 1KHz – Infrared Detectors, Antoni Rogalski, CRC Press (2011)
  - VLWIR, 1/f knee is ~1KHz – A. I. D'Souza, *et al.*, J. Electro. Mat., Vol. 31, No. 7 (2002)
- 1/f noise was found in many systems
  - Electronics devices
  - Human voice, human heart



Human Voice

  - Human brain – 1/f noise knee is 10Hz due to random opening and closing of ion channels in cell membrane
  - Spatial frequency of "Natural Images"
  - Audio Power of Music, English Speech – J. Acoust. Soc. Am. Vol. 63, p. 258 (1978)
  - Dramas, Symphonies, and Operas
  - Hollywood Movies – Movie makers shape the movie structure to match the pulsatile, half-smooth, half-raggedy way humans attend to the world around us" – Prof. J. E. Cutting, Cornell University
  - Graphene layers – Appl. Phys. Lett., Guanxiong, *et al.*, **102**. 093111 (2013)
  - Rule of thumb is 1/f noise knee frequency < Nyquist frequency

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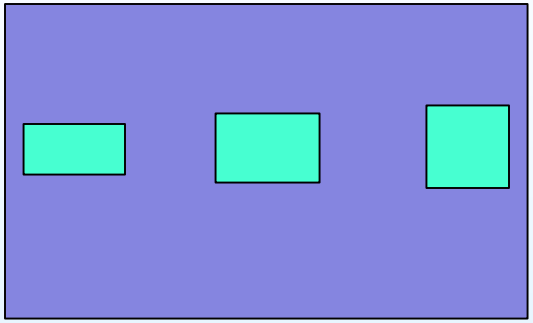
1/f Noise Measurement of QWIPs

- Detector – QWIP, λ_p- 6.2 μm, Operating temperature – 72K
- 640x512 pixel FPA, pixel pitch 25 μm, no passivation, 14 years old FPA
- FPA is part of a FLIR Phoenix camera



- Measurement technique
  - Let the camera run for a few hours until cooler get stabilized
  - Image integration time – 16 msec, Time interval (ΔT) – 40 sec
  - No flat field correction, since QWIP spatial noise has no 1/f noise
  - Selected three (Left, Middle, and Right) ROIs with 25x50, 40x50, and 60x50 pixels
  - Acquire a time series data – 2.5 days

- Time series data sets
  - Subtract the average of the first frame from other frames (evolution)
  - Subtract the mean value of noise distribution from each frame average (mean)
  - Select the center pixel, 4x4 pixels and 16x16 pixels (pixel)

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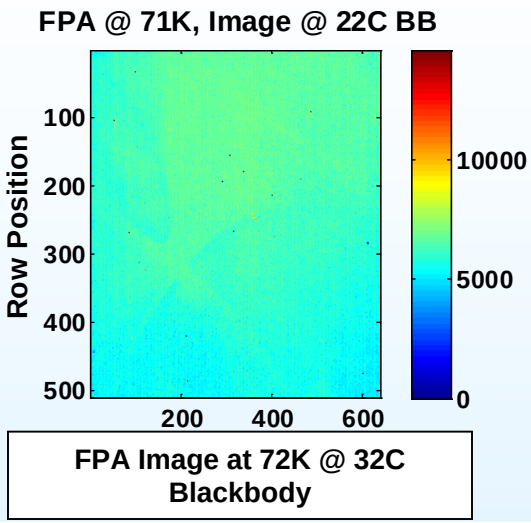
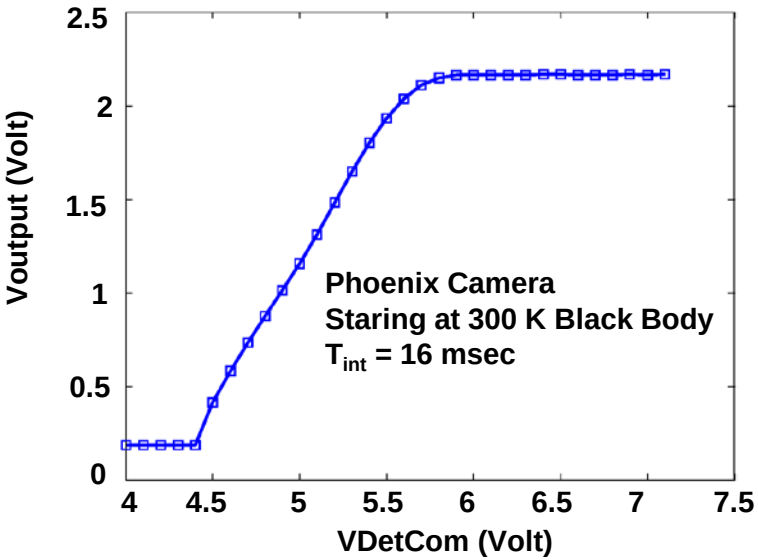
QWIP FPA Characteristics





Determine the Output Voltage as a Function of Bias

- Output Voltage versus V_{DetCom} at a constant blackbody temperature 305 K
- Non-zero bias above V_{DetCom} > 4.5 V
- Below 4.5 Volt the detector is not bias and expect zero noise generation.

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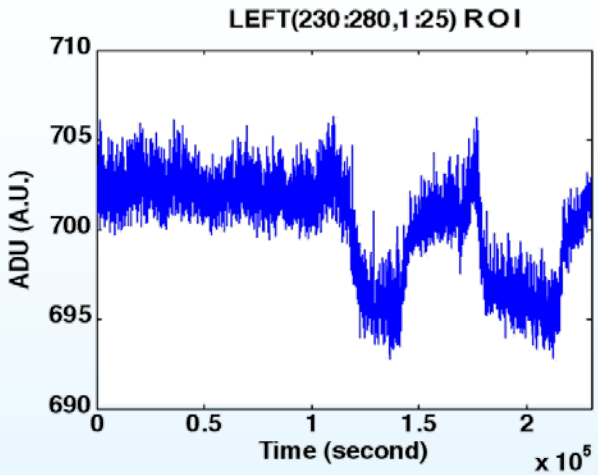
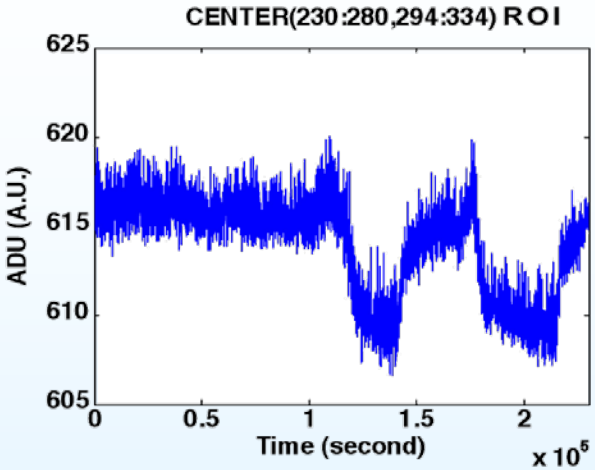
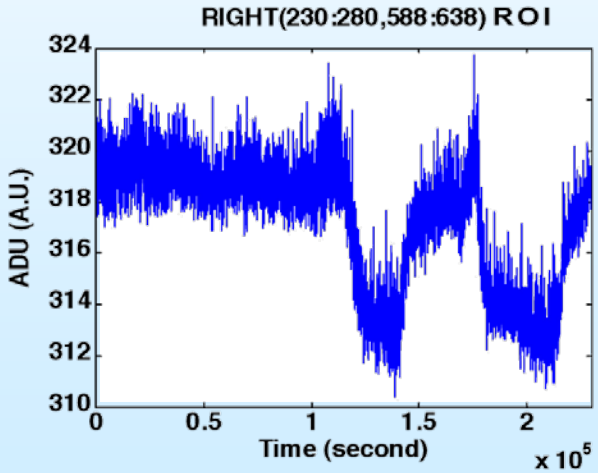
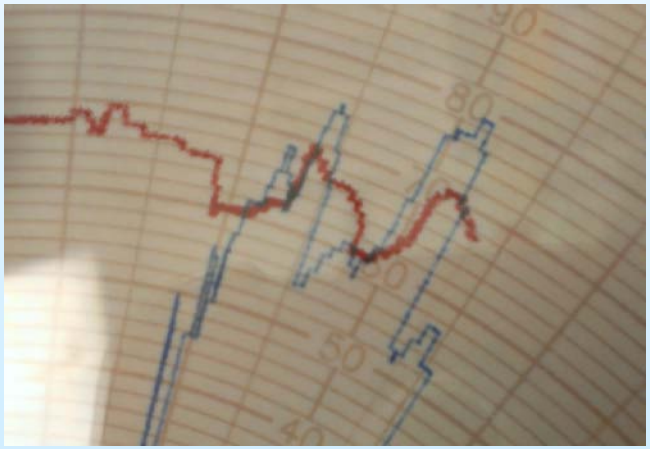
Time Series Data with Detector Off







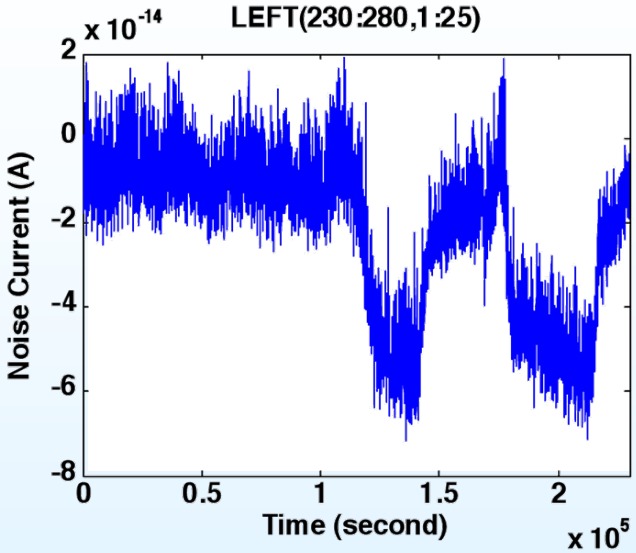


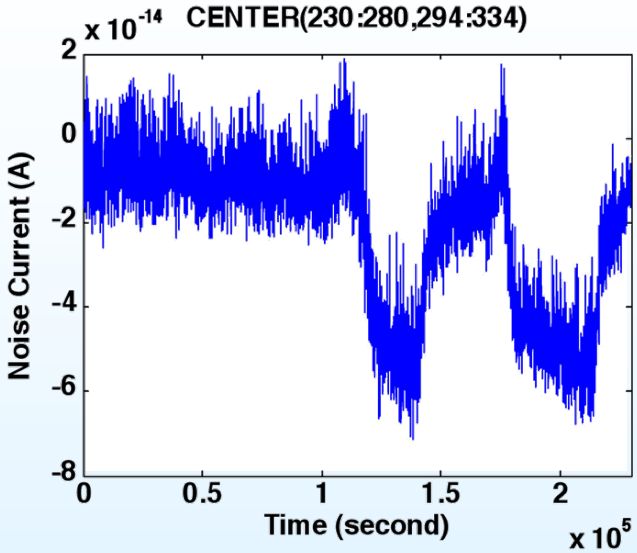
Laboratory Temperature Variation recorded on the Chart. Note this occurred over the weekend.

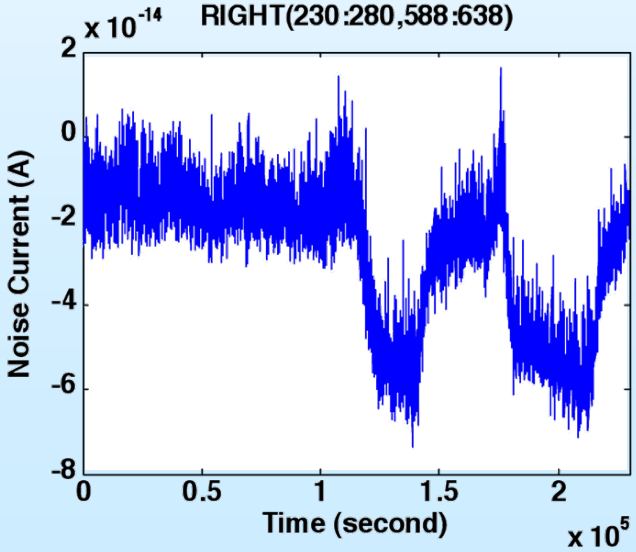
Time Direction

- V_{DetCom} – 4.0 V -> Bias – 0.0 V. This data for 63.8 hours duration.
- Note that the presence of two dips at 125000 seconds and 200000 seconds. This leads to low frequency noise.
- The Temperature dip occurred Saturday and Sunday

ADC Count Conversion to Current







Voltage Swing/2^{14} = V/ADC count

#ADC counts x V/ADC count = Voltage out

Voltage out x ROIC conversion = Voltage out x e/nV

Current = e/T_{int}

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Noise Current & Power Spectral Density (Left ROI)

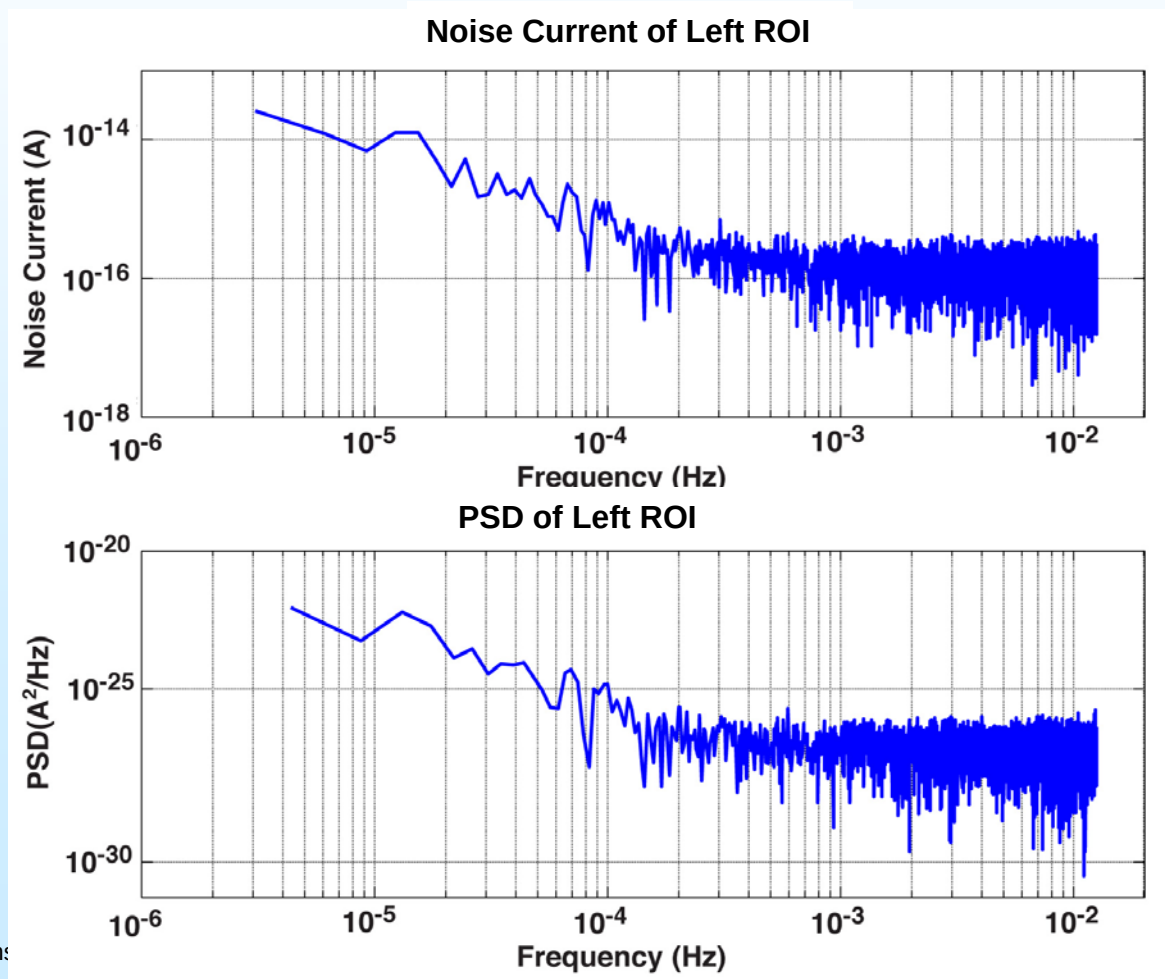
- *FFT to covert the time domain signal to frequency domain*
- *Single sided amplitude*
- $SingleSidedAmplitudeSpectrum(f) = 2\left|FFT(A_i)\right|$
- $PSD(f) = 2\dfrac{\left|FFT(A_i)\right|^2}{N(\Delta t)^{-1}} = 2\dfrac{\left|FFT(A_i)\right|^2}{NF_s}$

  A_i is time series data $i = 1,2,.....N$

  Δt is sampling time

  $F_s = \text{sampling frequency} = \dfrac{1}{40\,\text{second}} = 25\,\text{mHz}$

  N is total number of samples



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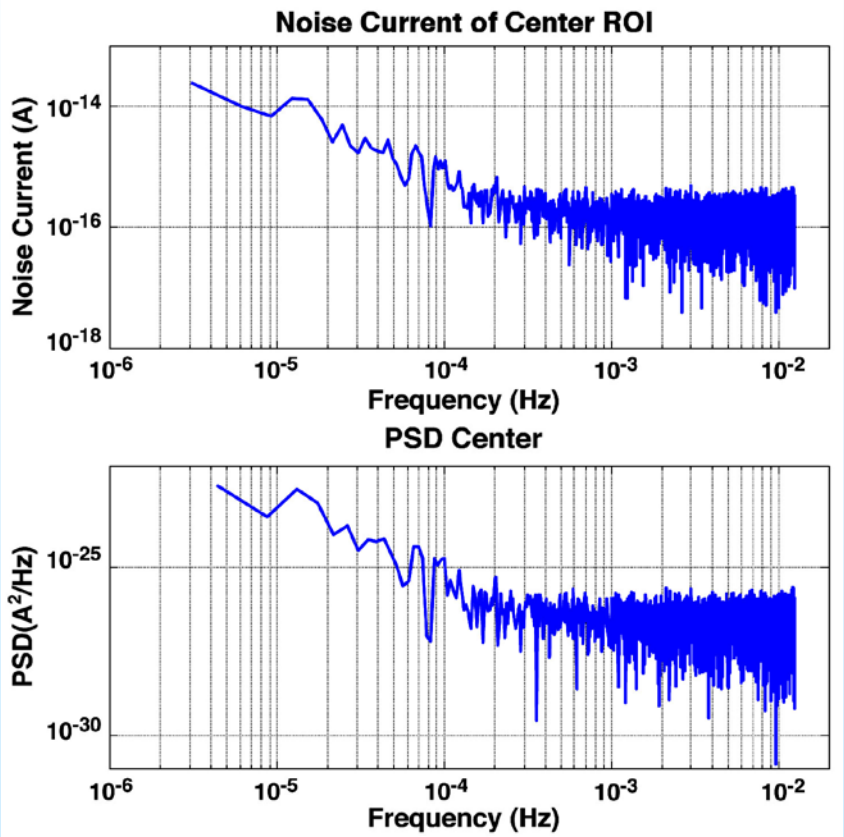
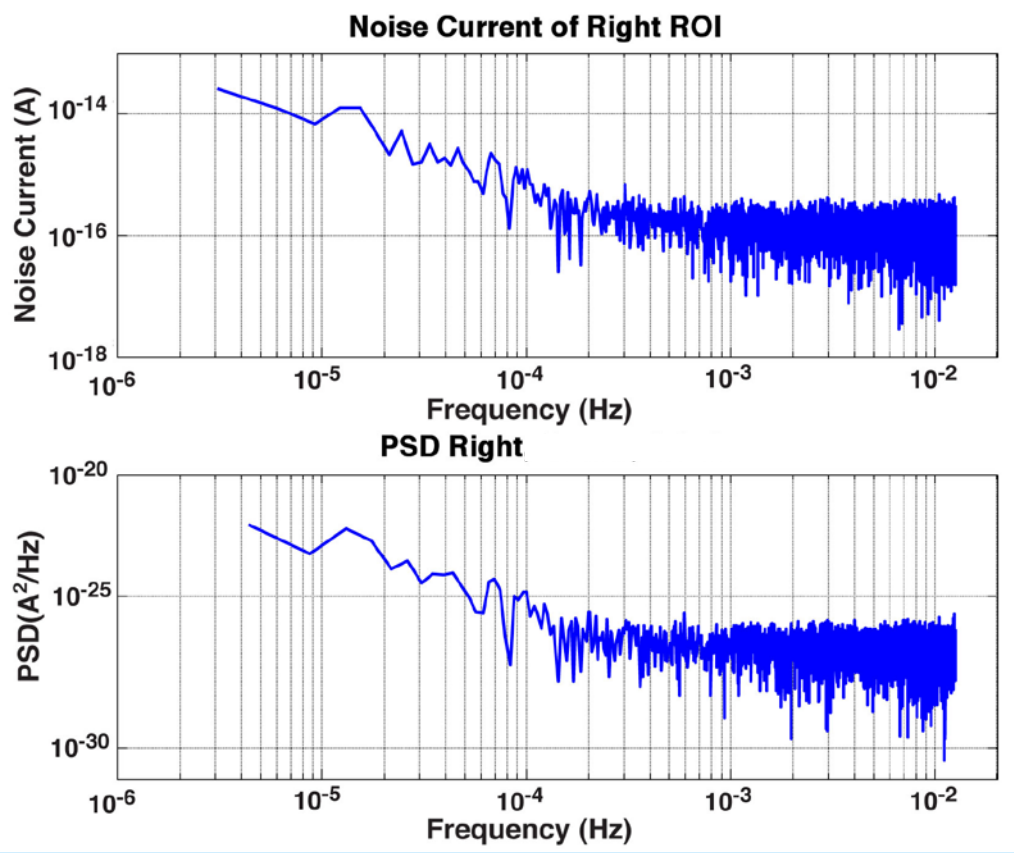
Power Spectral Density (Center & Right ROIs)





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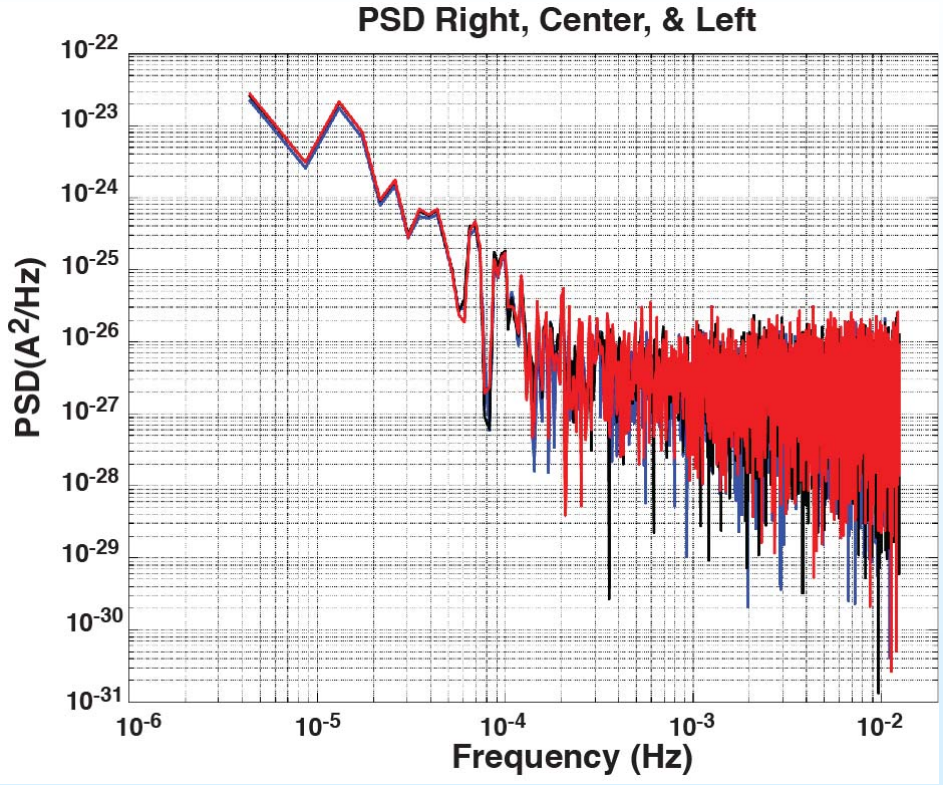
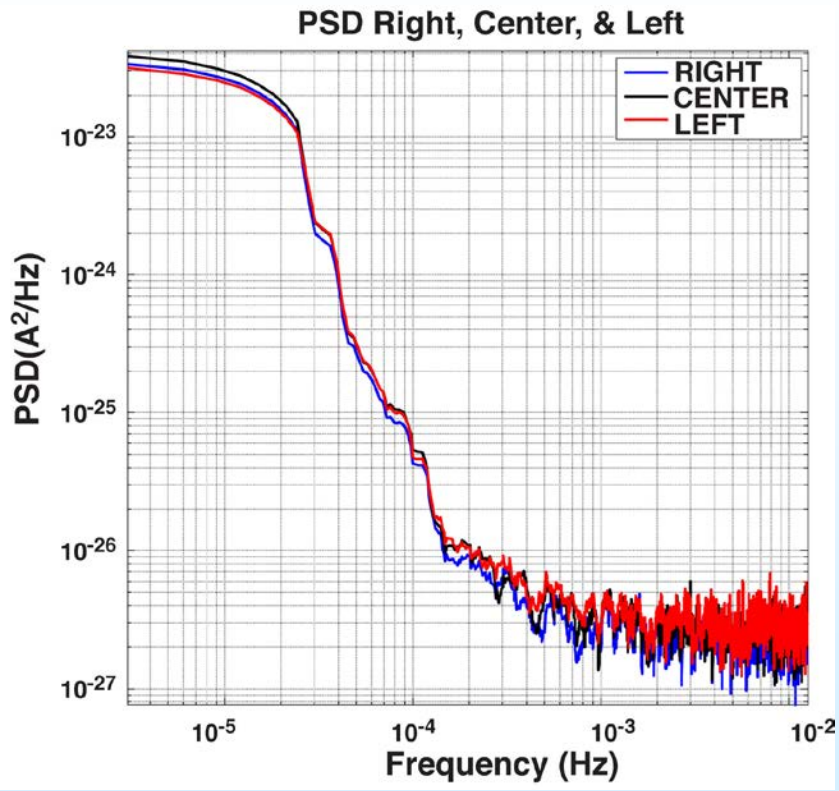
System Noise with Detector Array Off (Left, Center & Right ROIs)





- Low frequency values are very close (independent or region of interest)
- Laboratory temperature variation caused ~2 orders of magnitude increase in PSD

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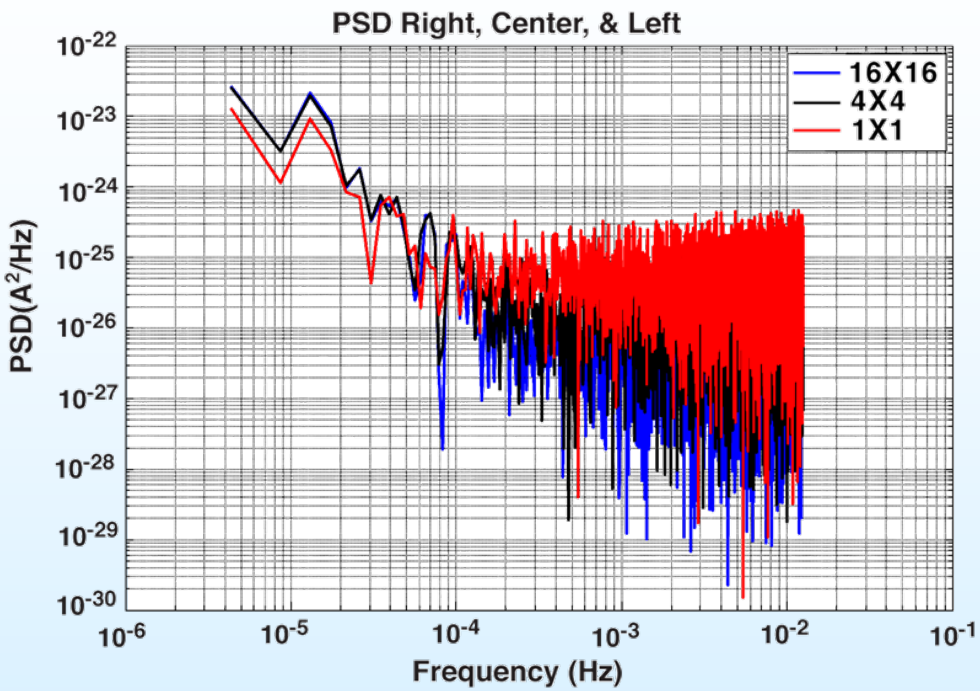
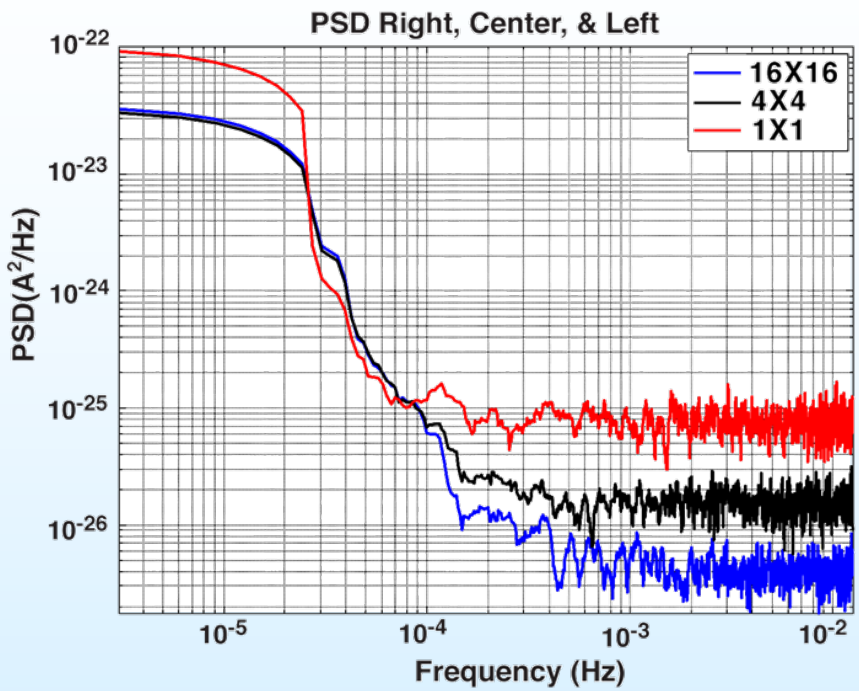
1/f Noise (Single Pixel, 4x4, & 16x16)





- Single Pixel has larger noise at high frequency, but converges at low frequency
- 3 orders of magnitude increase for single pixel
- 3.5 orders of magnitude increase wrt 4x4
- 4.5 orders of magnitude increase wrt 16x16

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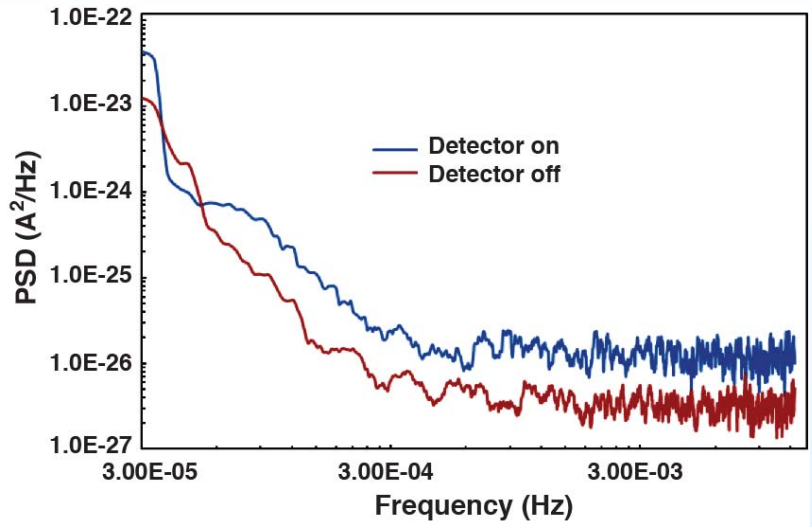
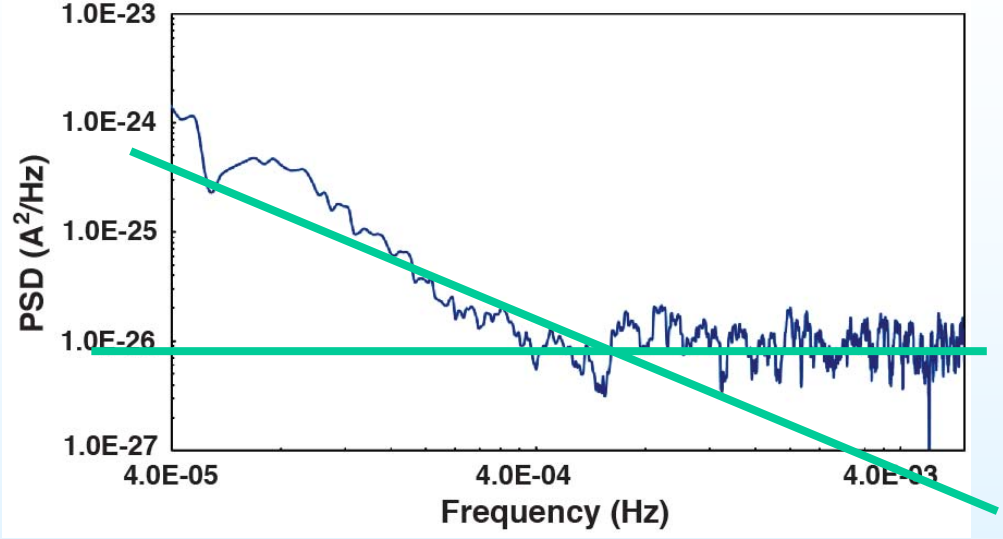
PSD of QWIP Detector Array



PSD with Detector Array On and Off



PSD of QWIP detector array

$$i^2_{n\ Total} = i^2_{n\ System} + i^2_{n\ Detector}$$

$$i^2_{n\ Detector} = i^2_{n\ System\ with\ detector\ on} - i^2_{n\ System\ with\ detector\ off}$$

$$PSD_{Detector} = PSD_{Detector\ on} - PSD_{Detector\ off}$$

1/f noise knee of 6.2 μm QWIPs < 0.5 mHz

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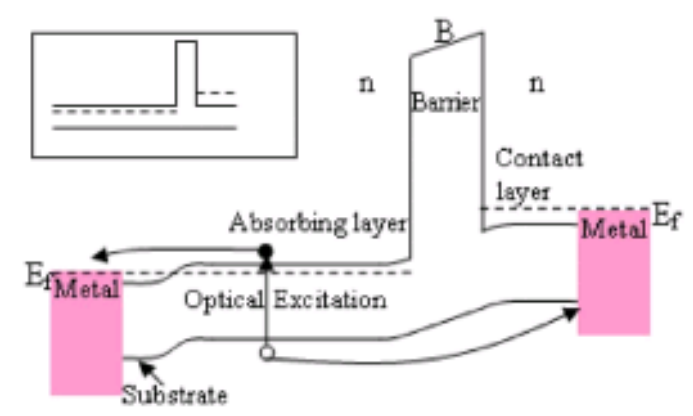
nBn Detectors and Focal Planes



Maimon & Wicks, APL, 2006

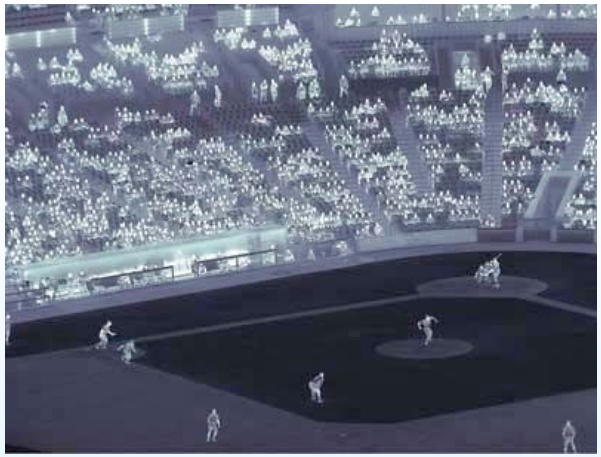
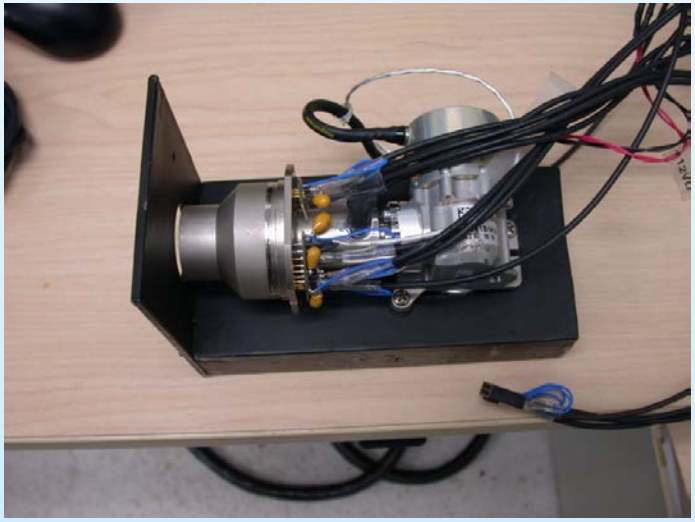


Image from 1280x1024, 12 μm pixel pitch nBn sensor running at 160 K (courtesy Santa Barbara Focalplane)[1,2]



Integrated Dewar Cooler Assembly with 640x512 pixel nBn FPA, Cutoff ~4.0 μm, Pixels fully delineated

NE∆T – 14mK @110K, QE – 67%

1. Mark Goodnough and Jeff Scott, “Capabilities of new Focal Array Demonstrated by Lockheed Martin at SPIE DSS”, Photonics Online, April 30, 2012.
2. Arnold Adams, “Infrared Imaging: New IR detector materials challenge existing technologies”, Vision Systems Design, Vol. 18, Issue 11, December 2013.

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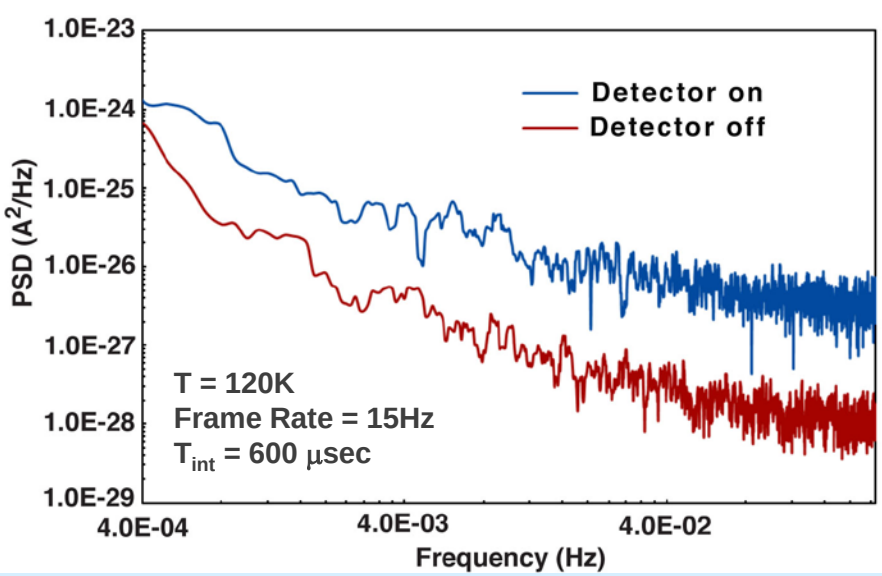
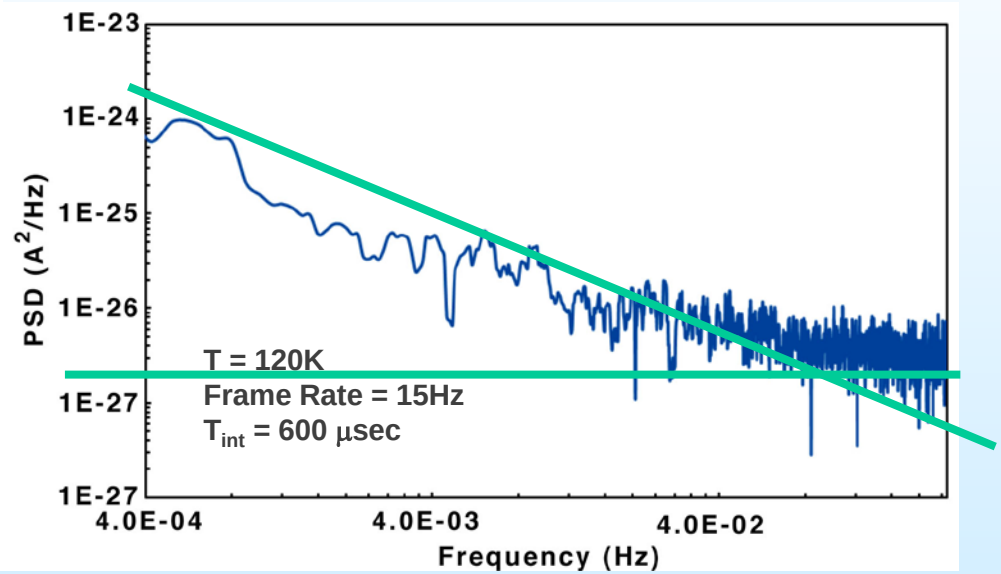
PSD of nBn Detector Array

PSD for Bias and No Bias



PSD Difference of Bias and No Bias Detector PSD



1/f noise knee of 4.1 μm nBn < 50 mHz

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1/f Noise Measurement of CBIRD FPA

- One hour cool down and electronic equipment warm up
- Collect data zero bias and 305 mV bias semi-simultaneously in 2-color mode
- Operate 0903 in two color mode
  - P-on-N zero bias
  - P-on-N negative bias at -305 mV
- Odd Columns and Rows
  - Temperature = 80 K, Integration time = 1.86 msec
  - Sampling time 10 seconds
- Total collected frames are 4261. Total time = 11 hours and 50 minutes
- Minimize number of LN2 transfer and stop data collection during transfer
  - Time domain data show no transient effect due to LN2 transfer

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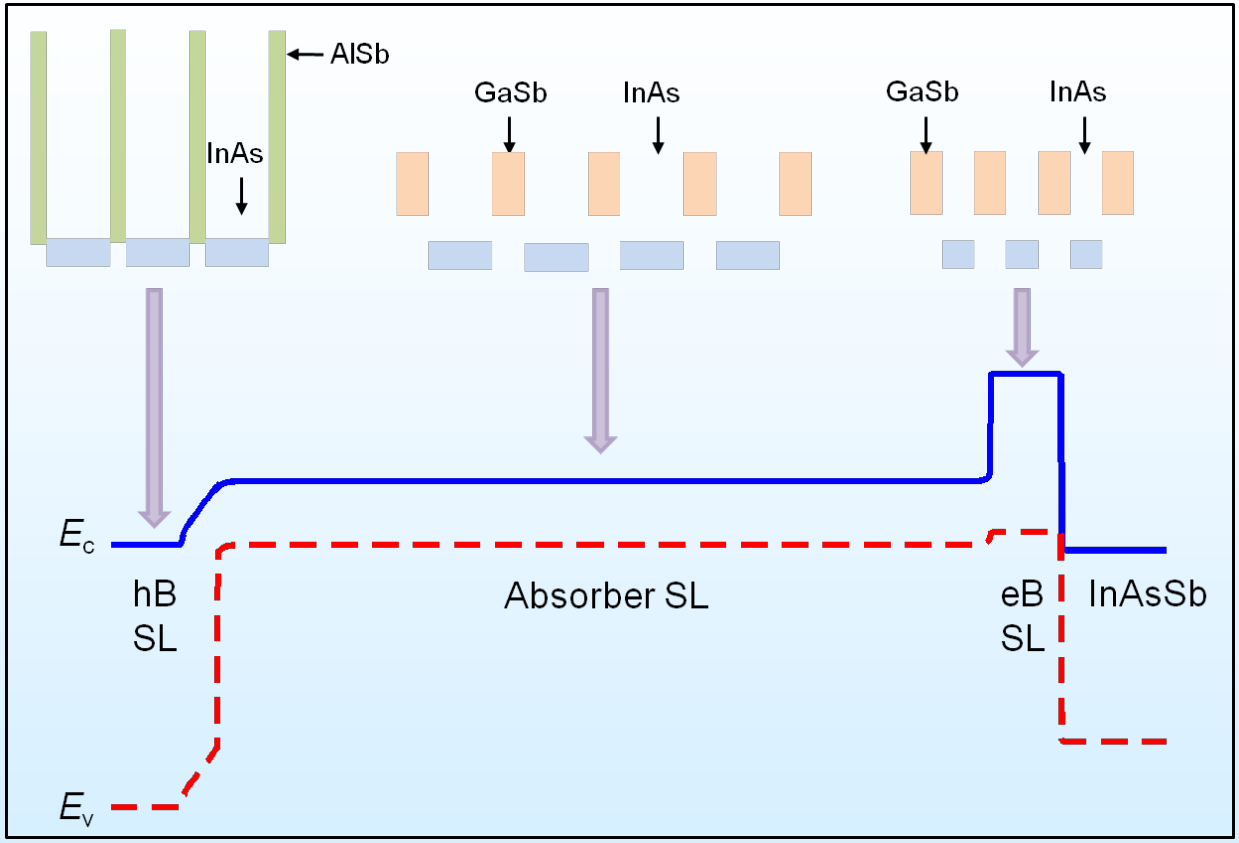
CBIRD Device Structure



- Complementary Barrier Infrared Detector (CBIRD)
- p-type LWIR superlattice absorber surrounded by
  - unipolar hole barrier (hB)
  - unipolar electron barrier (eB)

A high-performance long wavelength superlattice complementary barrier infrared detector, David Z.-Y. Ting *et al.*, *Appl. Phy. Lett.* **95**(2), 023508 (2009).

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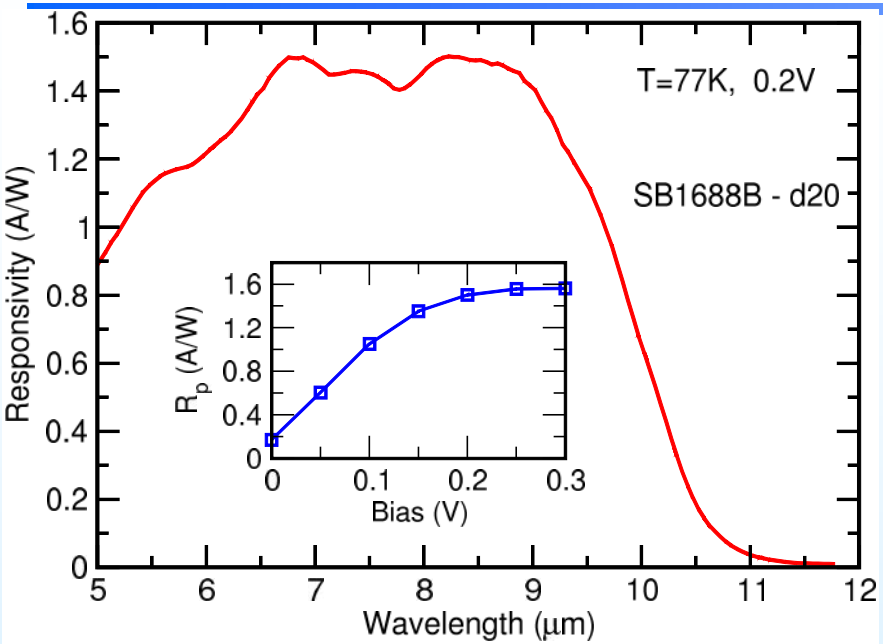
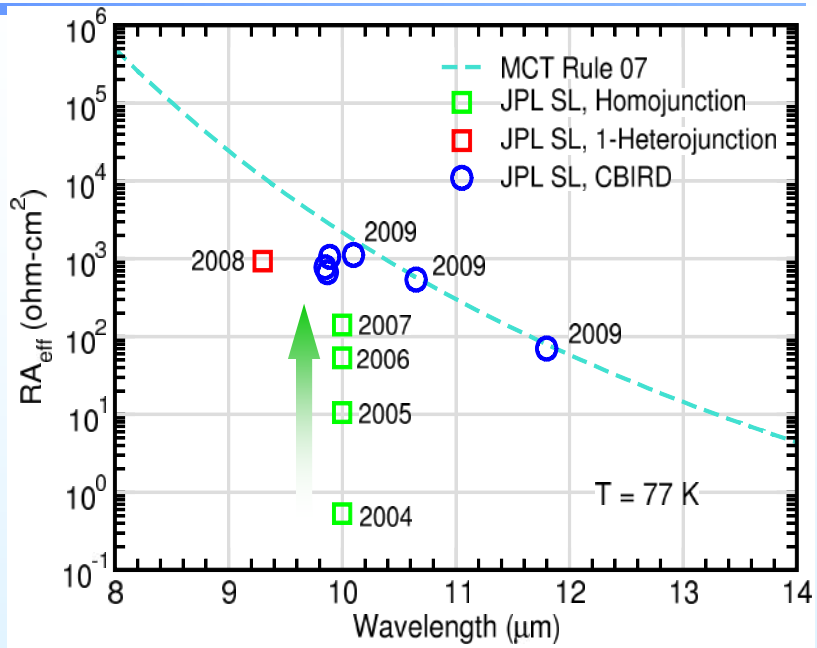
CBIRD Device Performance





- 10 μm cutoff (50% peak responsivity)
- R_{peak} increases with bias; plateaus for bias > 0.2 V
  - Operation in plateau region tolerates small pixel-to-pixel voltage variations
  - R_{peak} = 1.5 A/W at 0.2 V
  - Single pass; no anti-reflection coating

- R_0A =14,000 ohm-cm^2 at 77 K, 10 μm cutoff
  - Highest value reported to date for LWIR detector at 77 K
  - Shot noise limited operation at 0.2 V
  - Dark current density under operating condition: J_{dark} (0.2V)=0.989×10^{-5} A/cm^2 at 77K
  - Effective dynamic resistance – area product: $RA_{eff} = k_BT/qJ_d$

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Dry Etch Process Development

Sample	Type	Chemistry
A	Wet	$C_4H_6O_6$:H_3PO_4:H_2O_2:H_2O; citric clean
B	ICP Dry	BCl_3/Ar plasma; citric clean
C	ICP Dry	CH_4/H_2/Ar plasma
D	ICP Dry	CH_4/H_2/BCl_3/Cl_2/Ar plasma

Functions of the etch components

- Methane/hydrogen:
  - more effective indium removal allow lower etch temperature
  - promote the formation of a thin polymer pseudo-passivation layer
  - [A. Hood *et al.*, APL 2007]
- BCl_3:
  - effective in removing unwanted native oxides and re-deposited byproducts
  - [A. Gin *et al.*, Thin Solid Films (2004)]
- Cl_2 (slight amount):
  - increase the etch rate
  - reduce erosion of the SiN_x hard mask

"Low dark current long-wave infrared InAs/GaSb superlattice detectors", Jean Nguyen, Alexander Soibel, David Z.-Y. Ting, Cory J. Hill, Mike C. Lee, and Sarath D. Gunapala, *Appl. Phy. Lett*. **97**(5), 051108 (2010).

Etching Experiment: Dark Current Results

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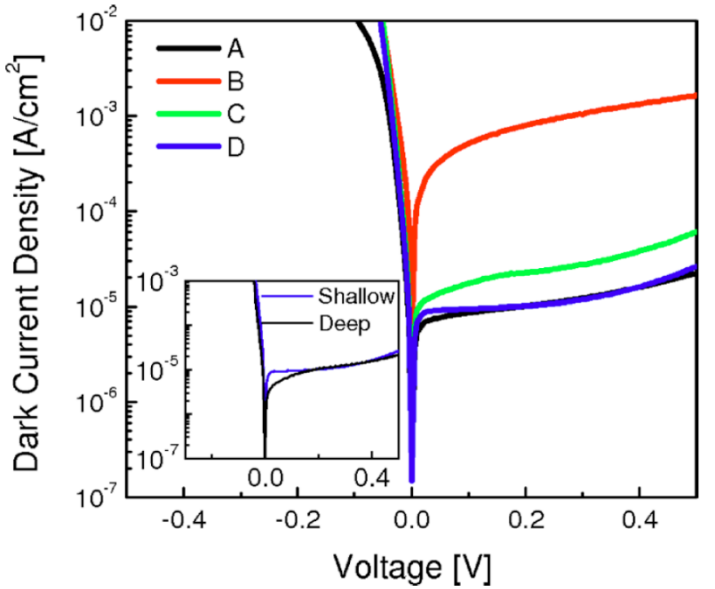

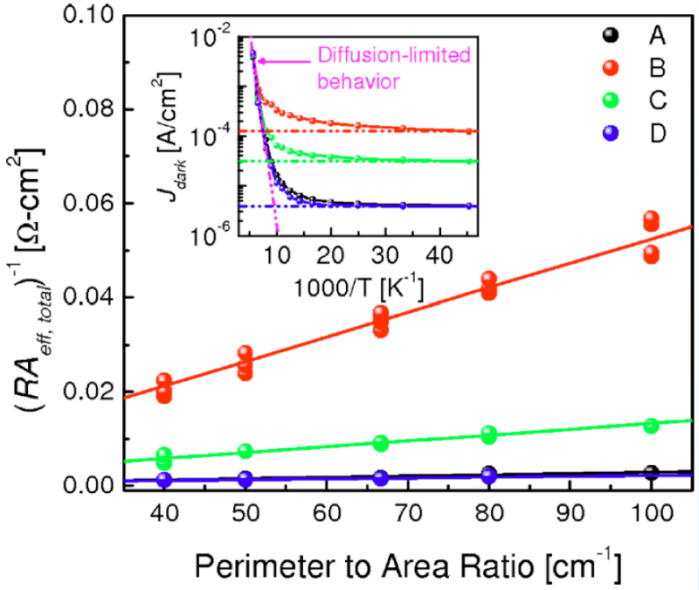

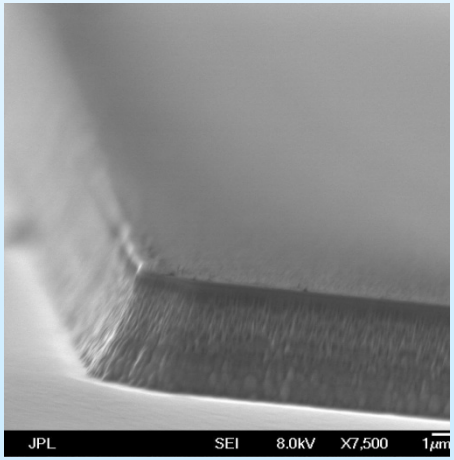

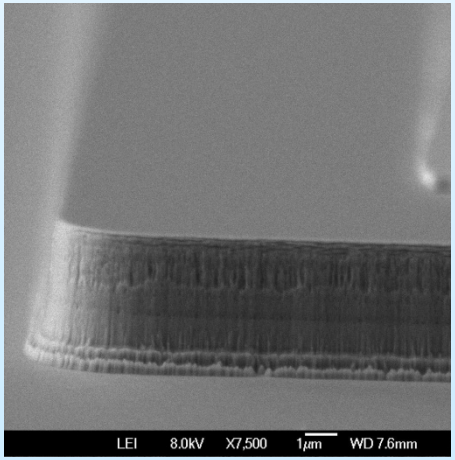

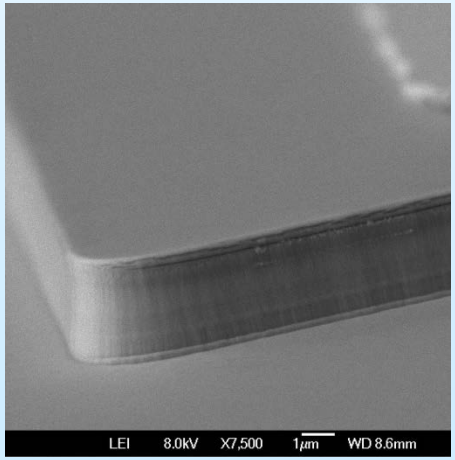

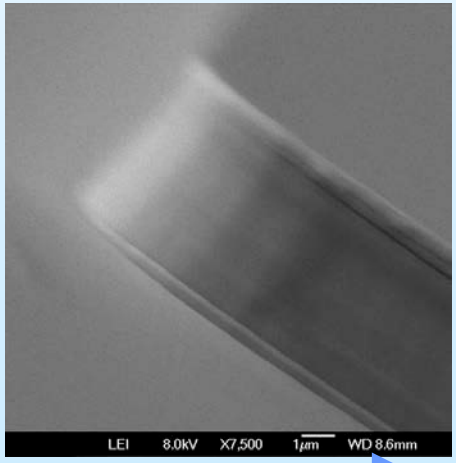

QWIP recipe

Optimization for p-i-n

Optimization for CBIRD

Remove the need for wet etch clean up

Tweak for 17.5 μm pitch FPAs

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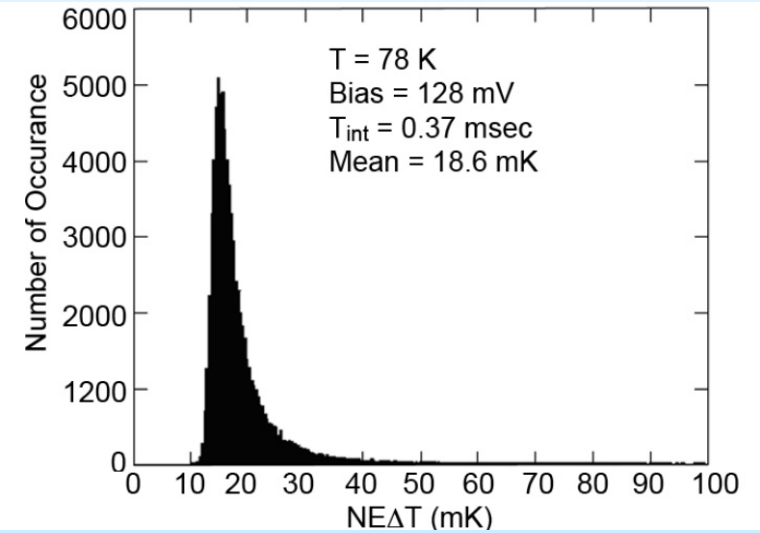
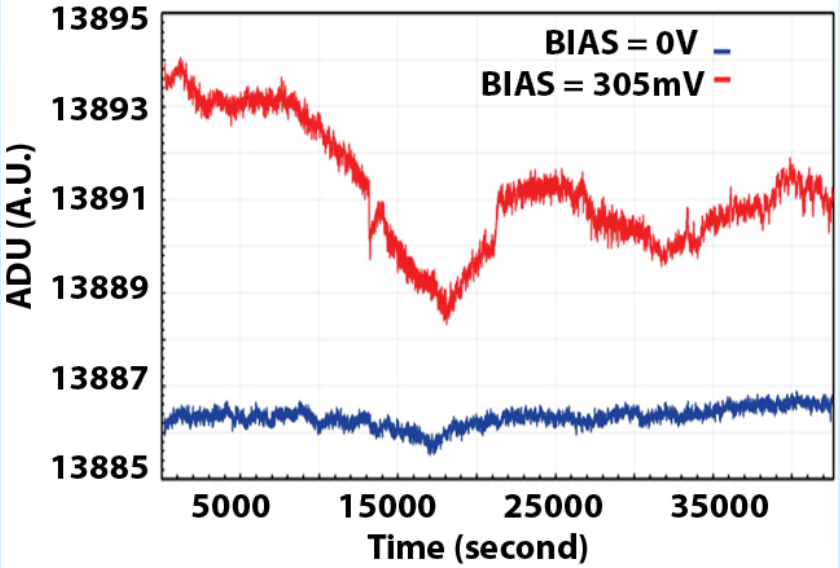
LWIR CBIRD FPA

Format	– 320x256
Pixel pitch	– 30 μm
ROIC	– ISC 0903 DI
Pixels	– Fully reticulated
Pixel Size	– 26x26 μm^2
Polarity	– N on P
Cutoff wave.	– 10 μm
Oper. temp.	– 78 K
QE (8-9.2 μm)	– 54% (without A/R)
NEΔT	– 18.6 mK with f/2 300K
Substrate	– Removed





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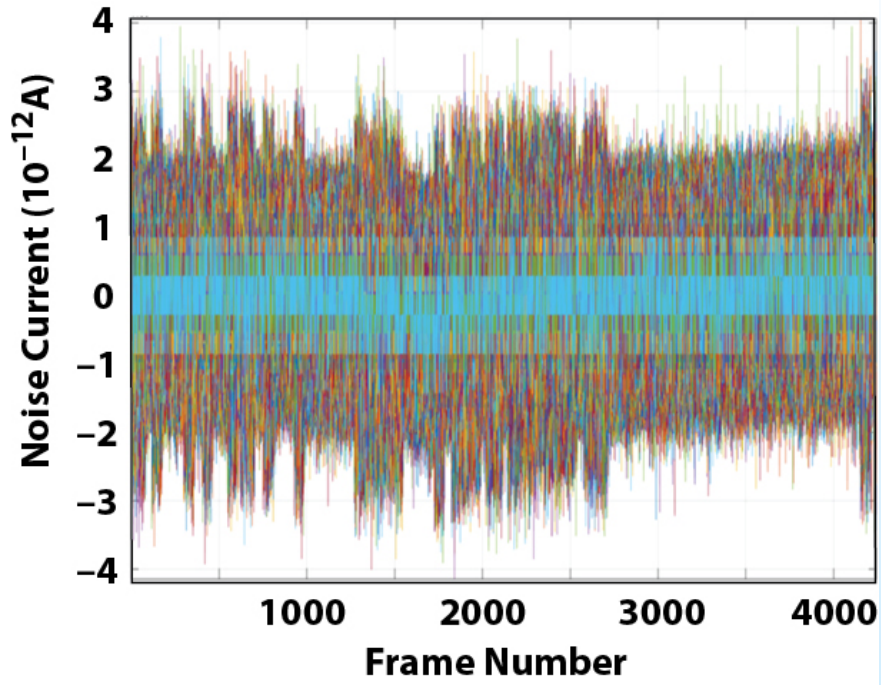
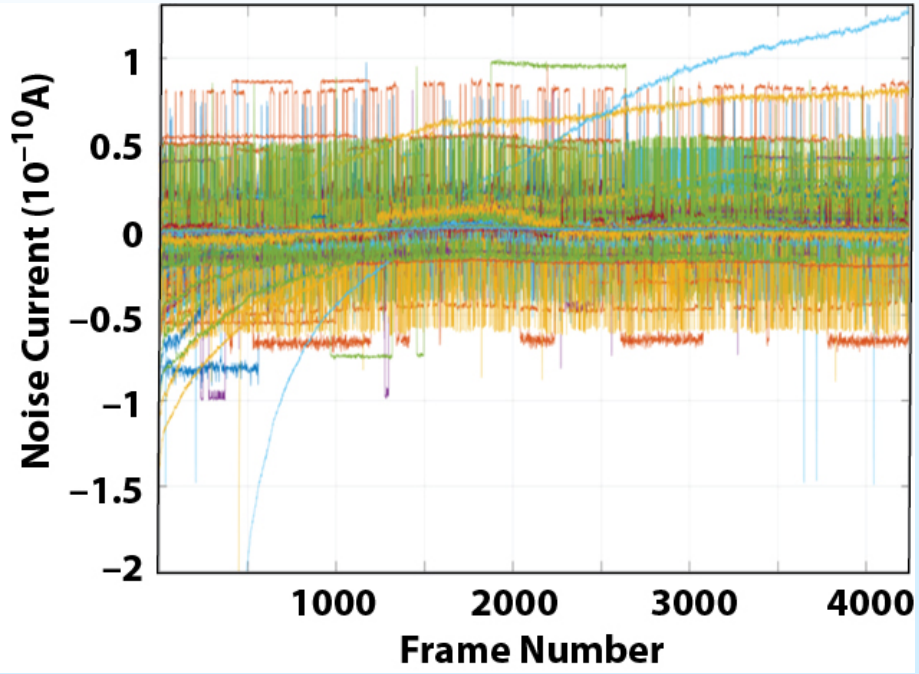
Noise Current vs Frames

Noise Current (V_b = 0 mV)



Noise Current (V_b = -305 mV)



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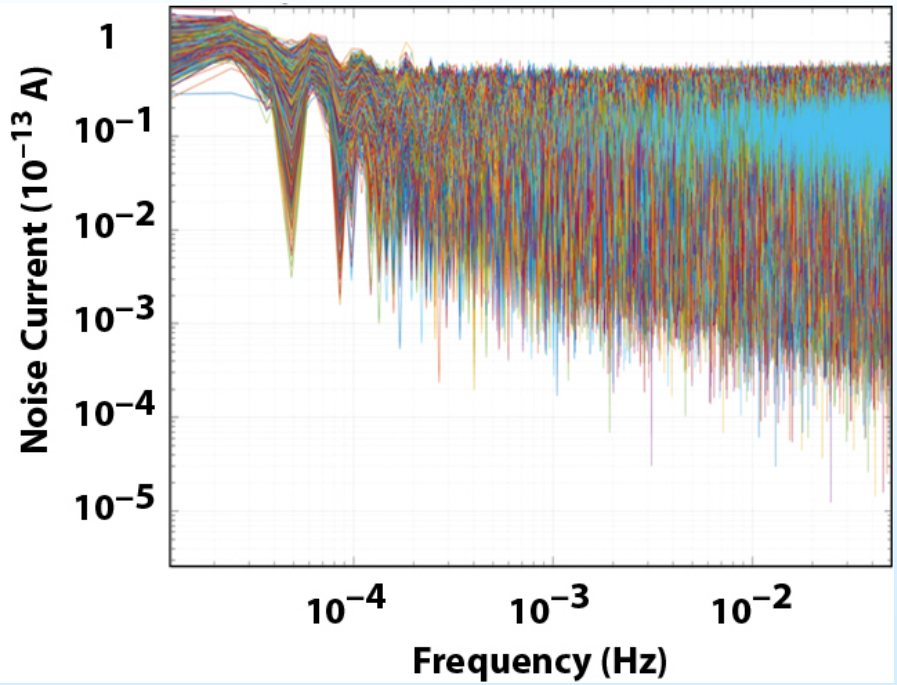
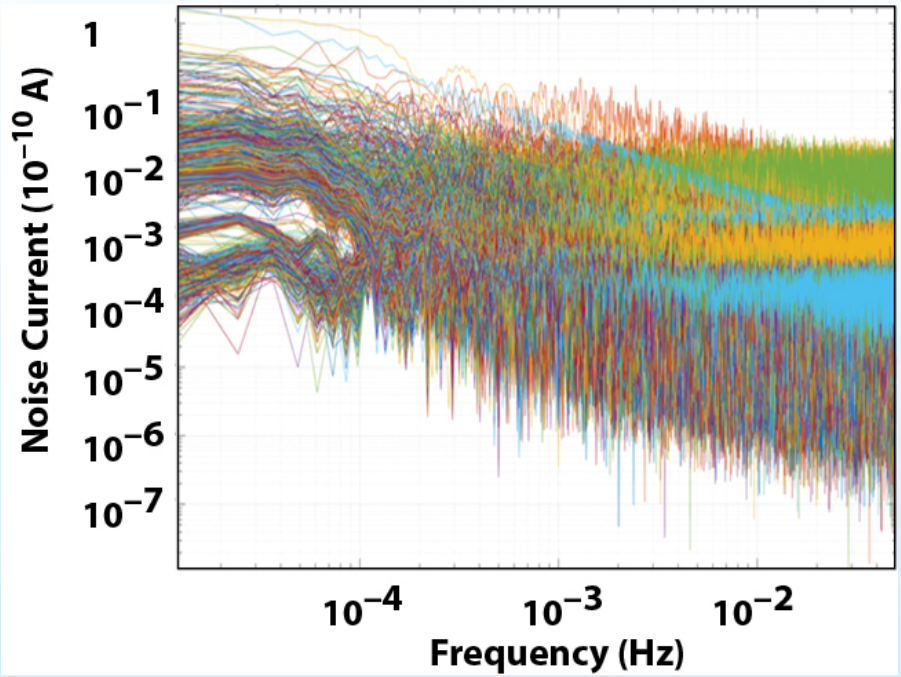
Noise Current vs Frequency

Noise Current (V_b = 0 mV)



Noise Current (V_b = -305 mV)



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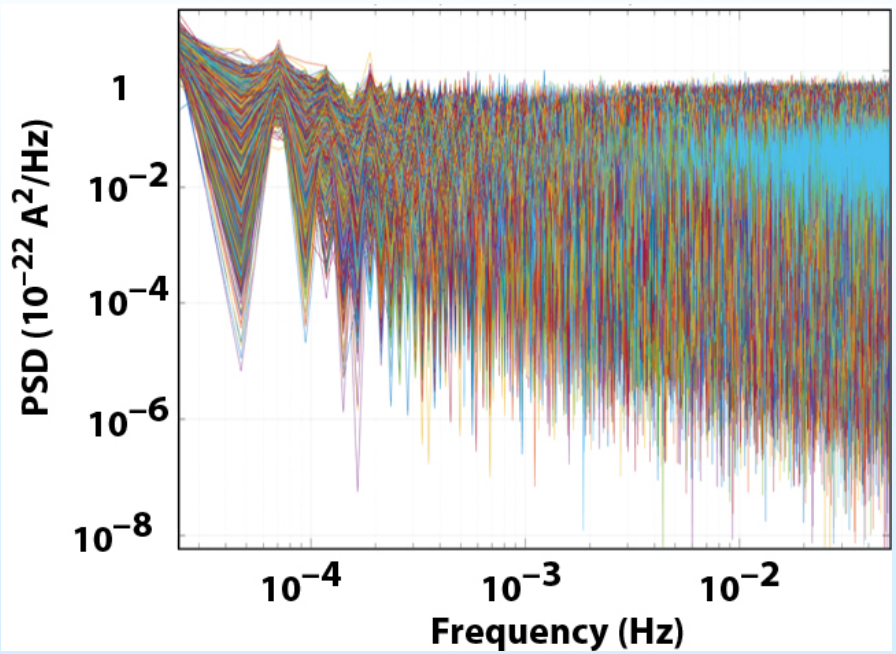
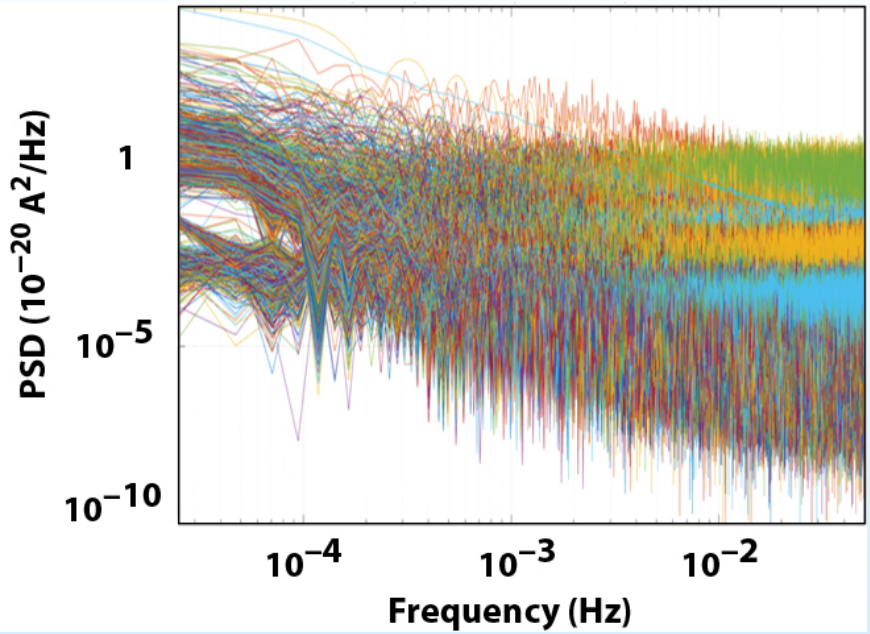
PSD of CBIRD Detector Array

Noise Current (V_b = 0 mV)



Noise Current (V_b = -305 mV)



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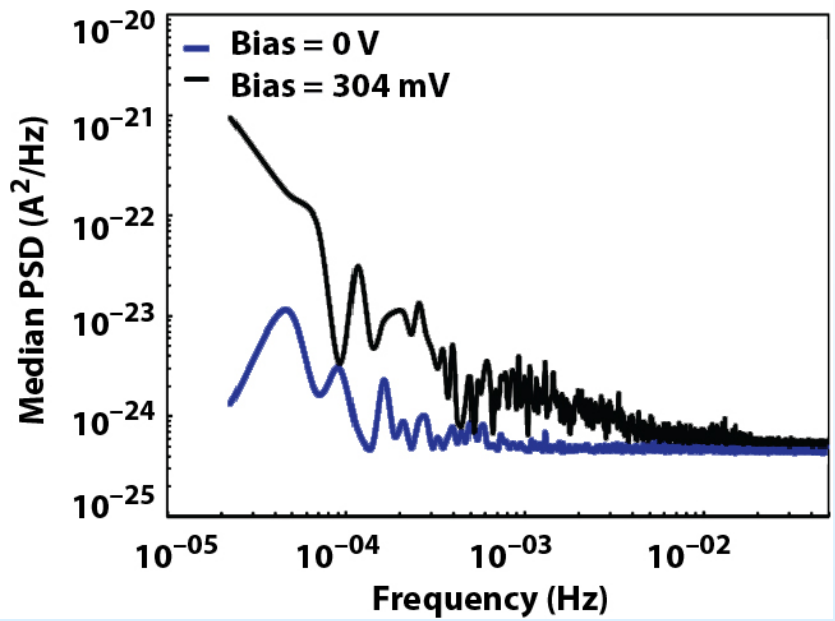
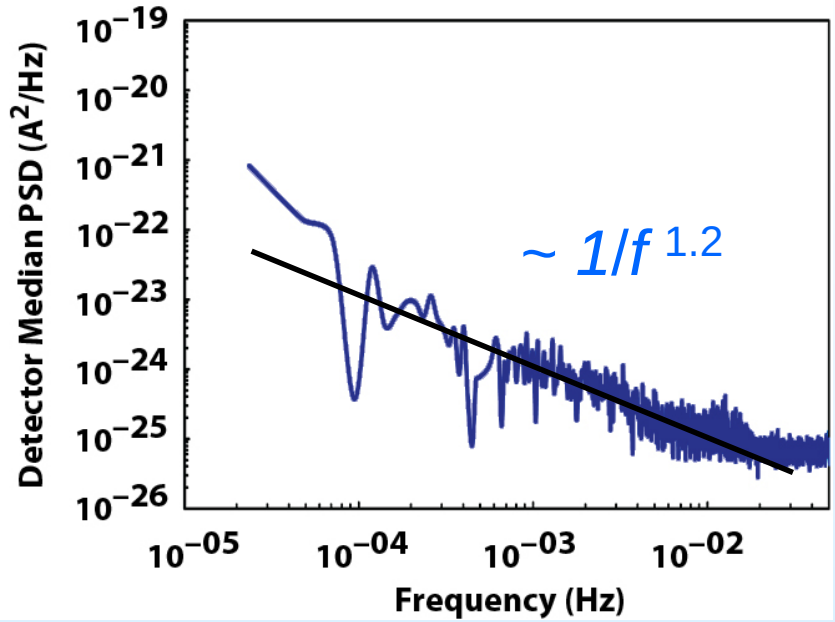
Median PSD of CBIRD Detector Array





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Summary

- 1/f noise was observed in many systems including electronics devices
- 1/f noise of electronic devices are due to large fluctuations in carrier density at low frequencies
  - *fluctuations in the source such a g-r of surface, bulk, etc.*
  - *fluctuations in the mobility of carriers*
  - *turbulence in carrier flow*
- 1/f noise knee of MWIR QWIPs ~ 0.5 mHz (LWIR QWIP ~ 10 mHz – M. E. Ressler *et al.*, 2000)
- 1/f noise knee of MWIR nBn (bulk InAsSb absorber) ~ 50 mHz
- 1/f noise knee of LWIR CBIRD (InAs/GaSb absorber; passivated; six years) ~ 30 mHz
- Measurements [Alexander Soibel, *et al.*, *Appl. Phy. Lett.* **96**(11), 111102 (2010)] clearly show that sidewall leakage current contributes to:
  - *increased shot noise (from higher dark current)*
  - *also additional frequency dependent noise*
- Surface leakage current can be a source of extraneous, frequency-dependent noise in InAs/GaSb superlattice devices
  - *Note: In MCT detectors, 1/f noise associated with surface charge tunneling into and out of the passivation interface*

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