# Indium Gallium Arsenide SWIR Detector Technology for Low Light Level and Eye-Safe Range-Gated Imaging

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# Topics

- What is Indium Gallium Arsenide?
- How is it used?
- InGaAs focal plane arrays for low light level imaging.
- InGaAs FPAs for eye-safe range-gated and 3D imaging.
- InGaAs avalanche photodiodes.
- The future...

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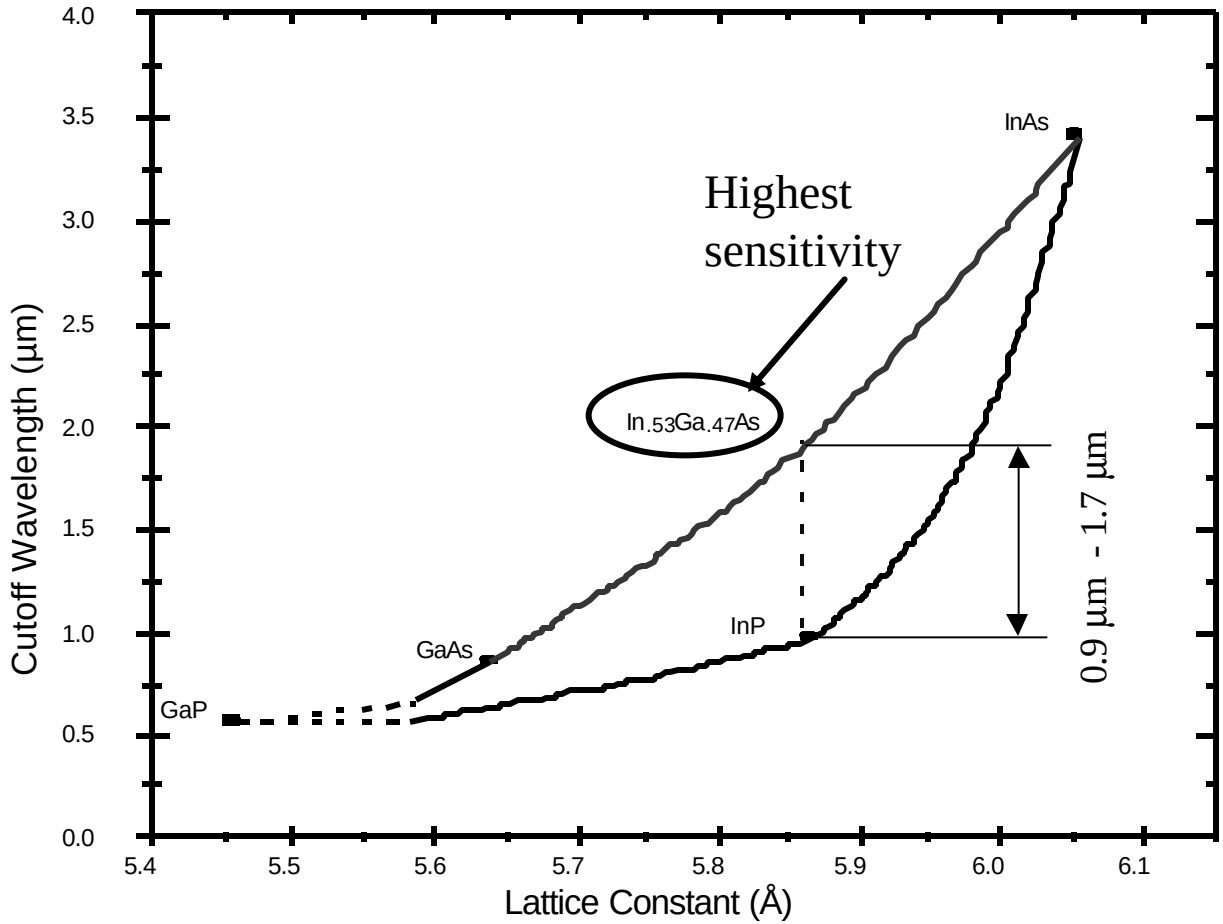
# Indium Gallium Arsenide is an alloy of GaAs and InAs

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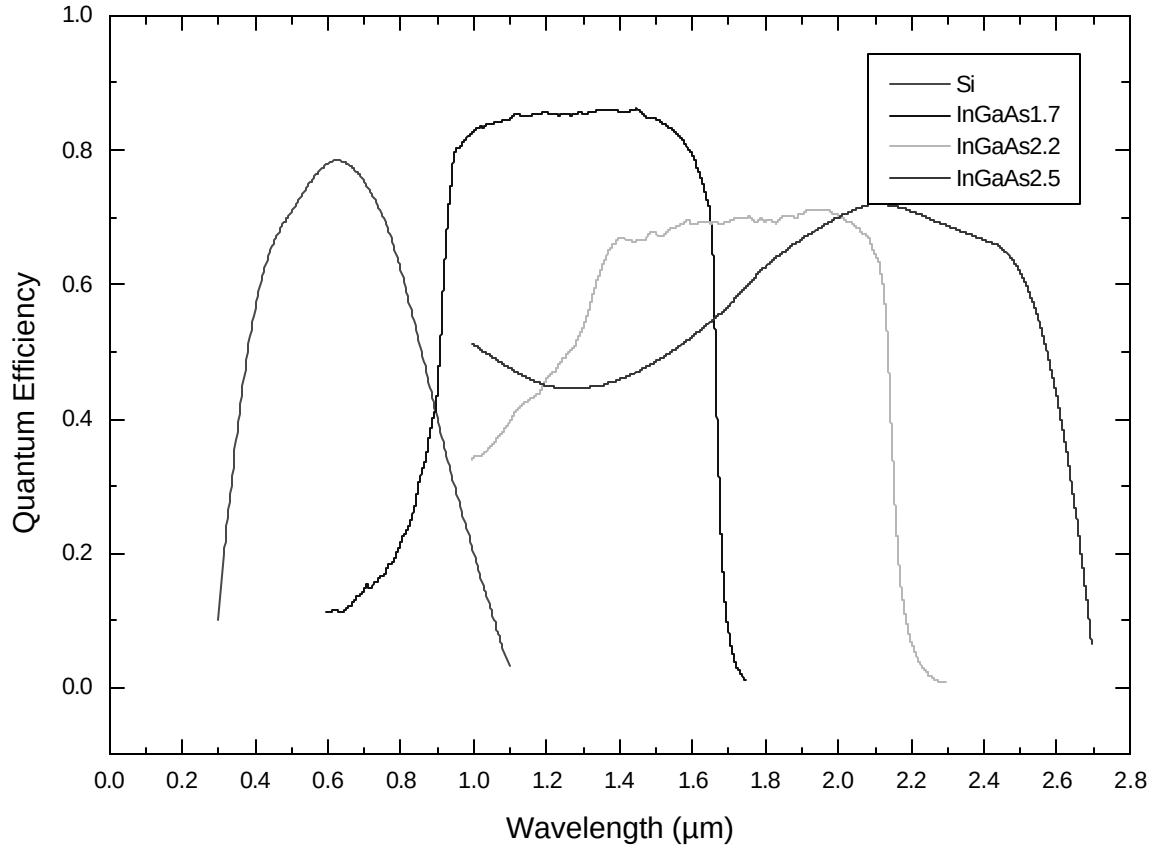
# Quantum Efficiency of $In_xGa_{1-x}As$

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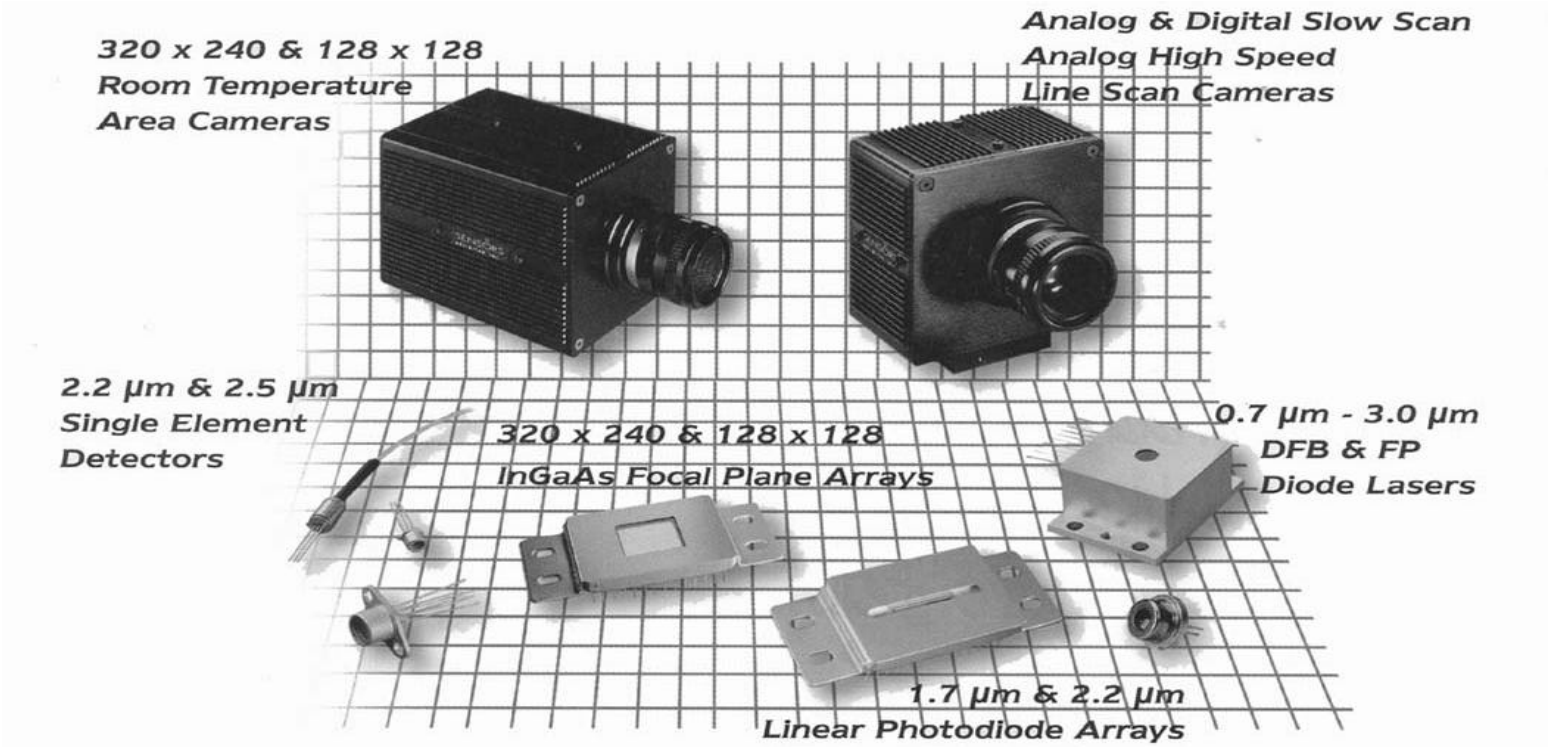
# The Products

We design, develop and manufacture imaging technologies used in the near infrared spectrum. These products include photodetector linear and focal plane arrays, area and line scan cameras, photodiodes and lasers.

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# Man-Portable InGaAs Room Temperature NIR Camera

LCPL Matt O'Grady, USMCR

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# Sensors Unlimited 320x240 Room Temperature SWIR MiniCamera

Developed under
DARPA sponsorship.

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# Applications of InGaAs Focal Plane Arrays
# A True "Dual Use Technology"

## Imaging

Night vision
Covert surveillance
Camouflage detection
Imaging through fog
Designation, illumination using eye-safe lasers
Range finding
Target acquisition and tracking
Aircraft de-icing
Semiconductor wafer inspection
Industrial thermal Imaging
Food processing
Inspection of fine art
Diode laser characterization

## Spectroscopy

Octane determination
Blood glucose concentration
Sorting of recyclables
Moisture content in food
Alcohol content of beverages
Fungus detection
Wavelength Division Multiplexing

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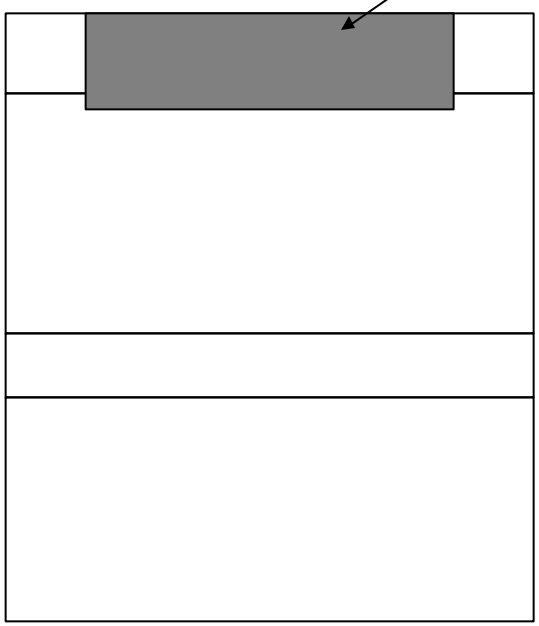
# InGaAs PIN Photodiodes



$p^+$-diffusion
through InP cap, 0.25 µm into InGaAs

InP “cap”: p-type, 1 µm

$In_{.53}Ga_{.47}As$ “active”: $n^-$-type, 3 µm

InP “buffer”: $n^+$-type, 1 µm

InP substrate: $n^+$-type

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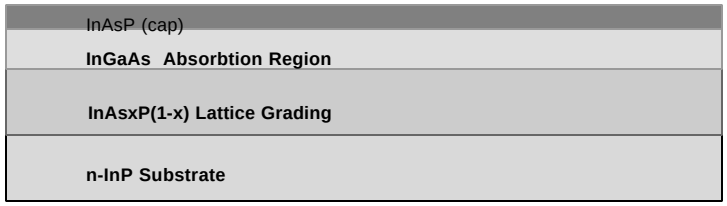
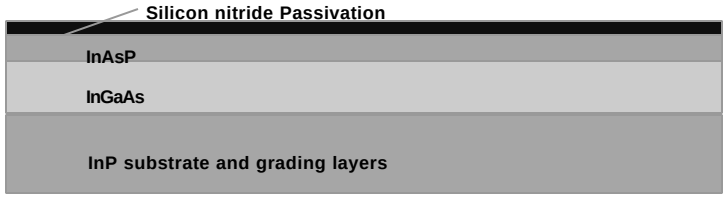
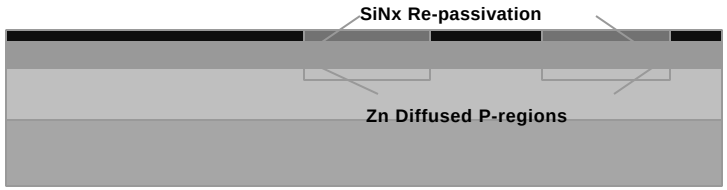
# InGaAs FPAs:
# A “Planar/Mesa” Technology



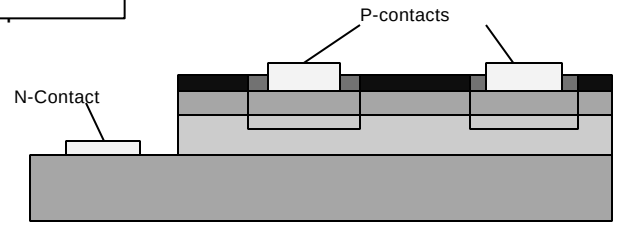

a) Unprocessed wafer



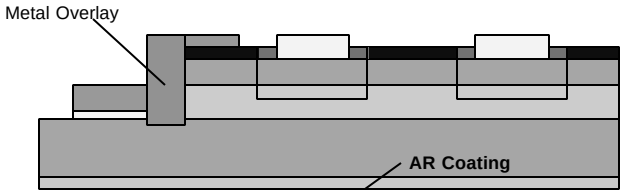

b) Wafer with silicon nitride passivation



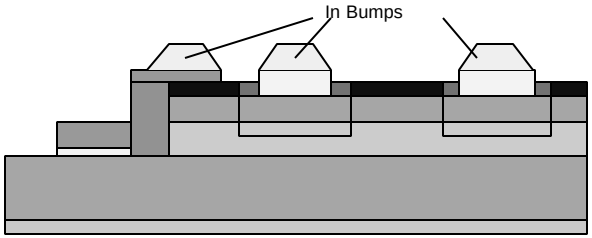

c) Wafer with diffused active areas and re-passivation




d) Wafer with P and N contact Metal




e) Wafer with metal overlay and AR




f) Completed Device with Indium Bumps

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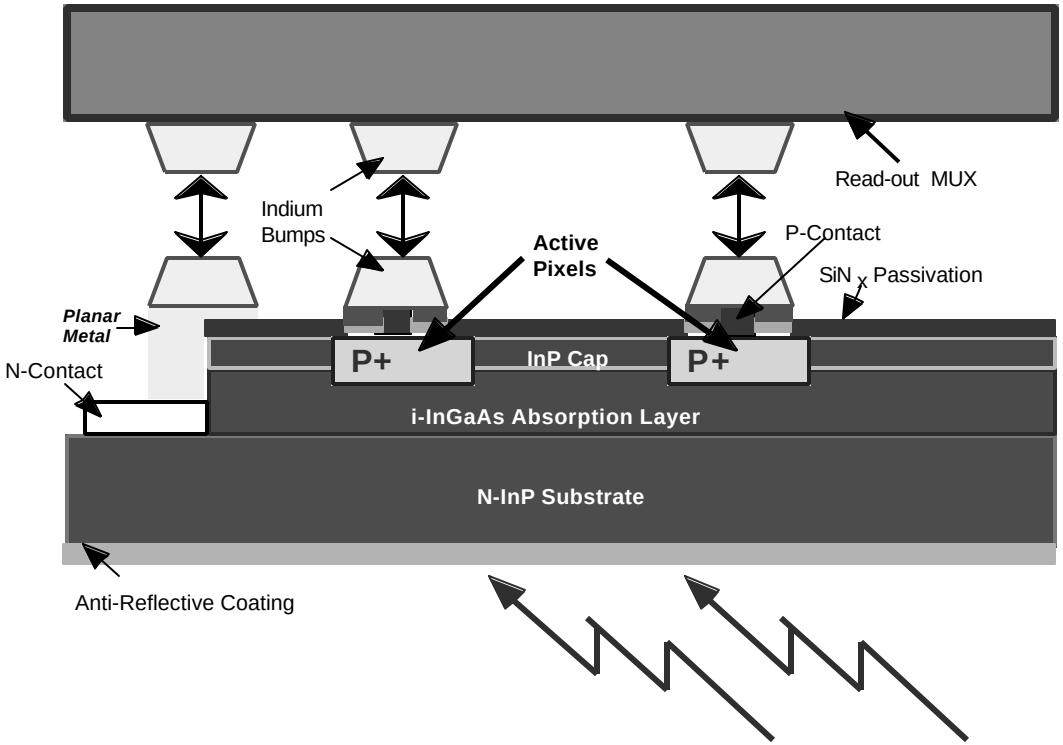
# Hybridization of Two-Dimensional InGaAs FPAs

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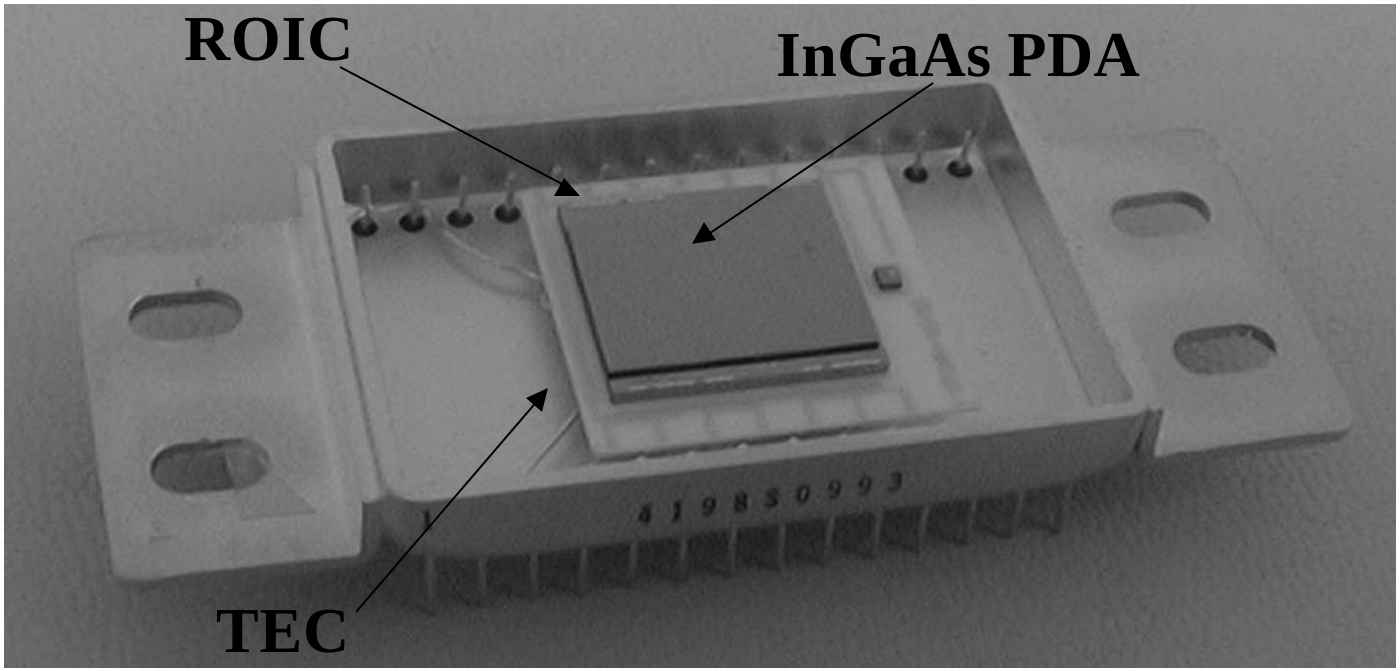
# Two-Dimensional InGaAs FPA

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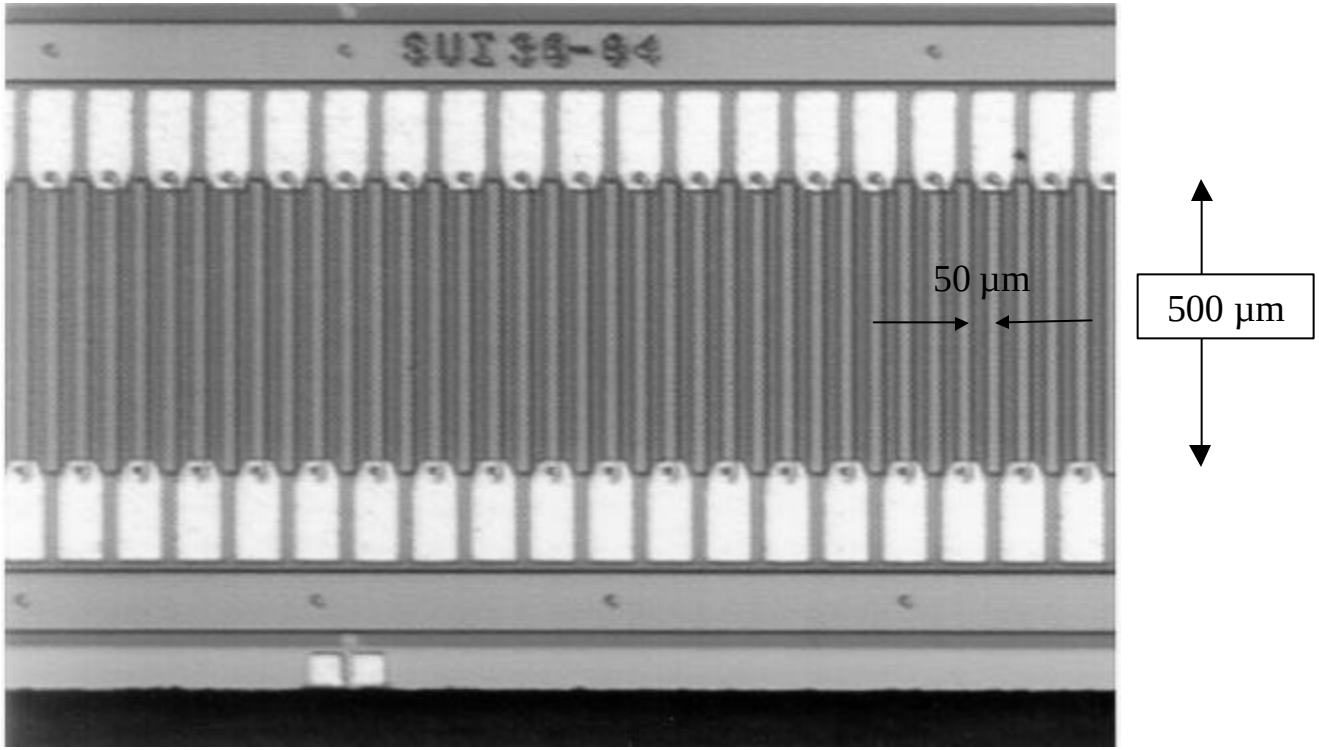
# One-Dimensional InGaAs Photodiode Array

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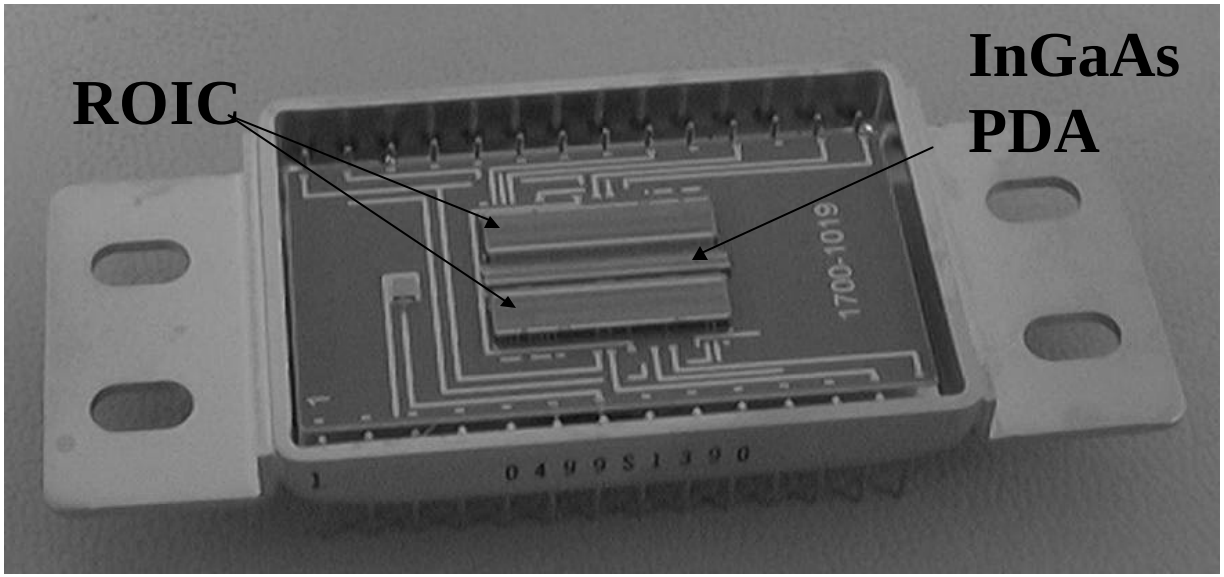
# One-Dimensional InGaAs FPA

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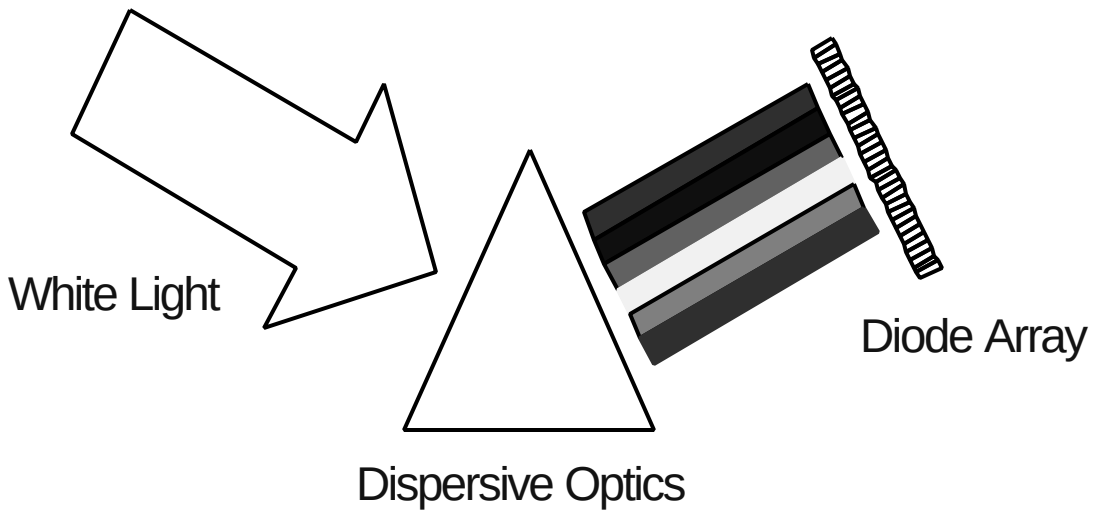
# Linear InGaAs FPAs for Near Infrared Spectroscopy

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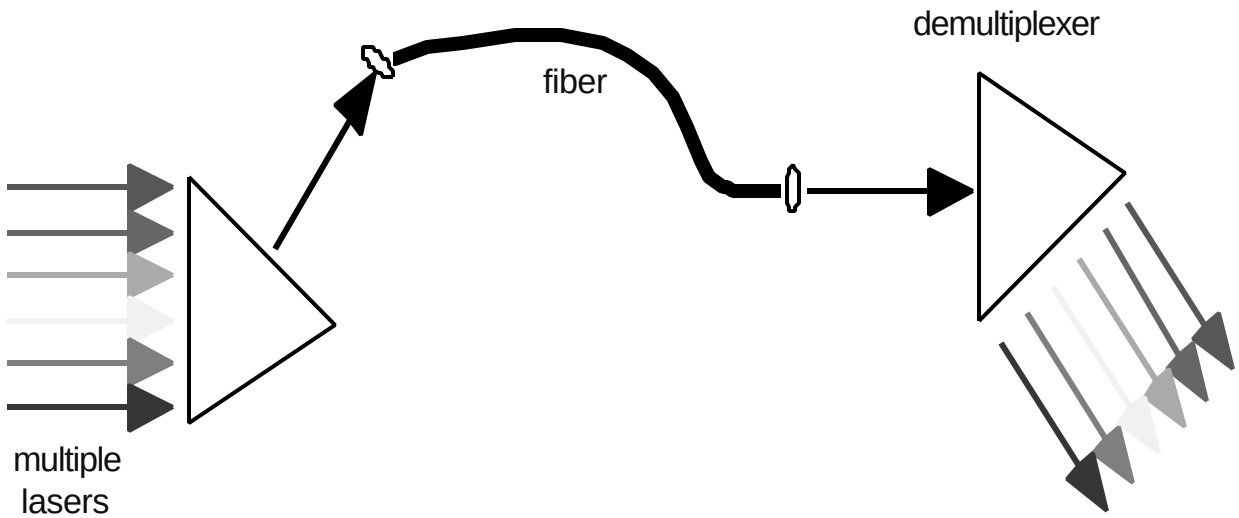
# Wavelength Division Multiplexing (WDM)

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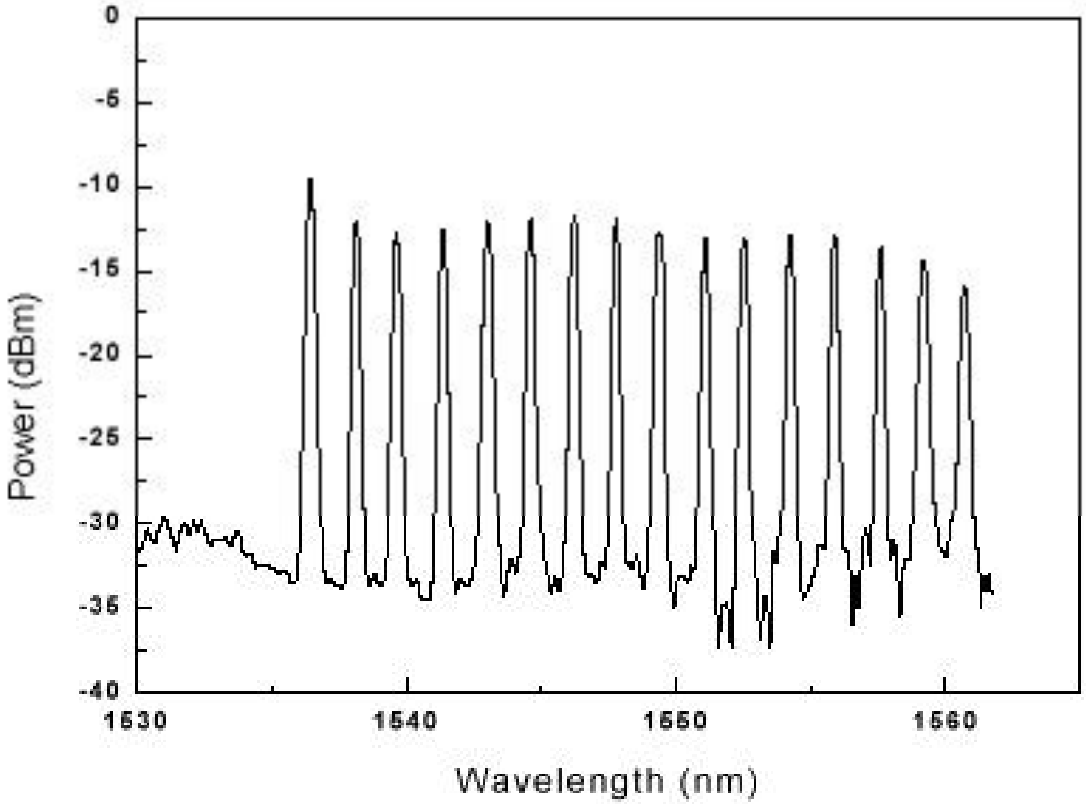
# WDM Source Monitoring




Koeppen, C., Wagener, J.L., Strasser, T.A., and DeMarco, J., "High Resolution Fiber Grating Optical Network Monitor", *Proc. National Fiber Optic Engineers Conference* (1998).

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# InGaAs FPAs for Low Light Level Imaging

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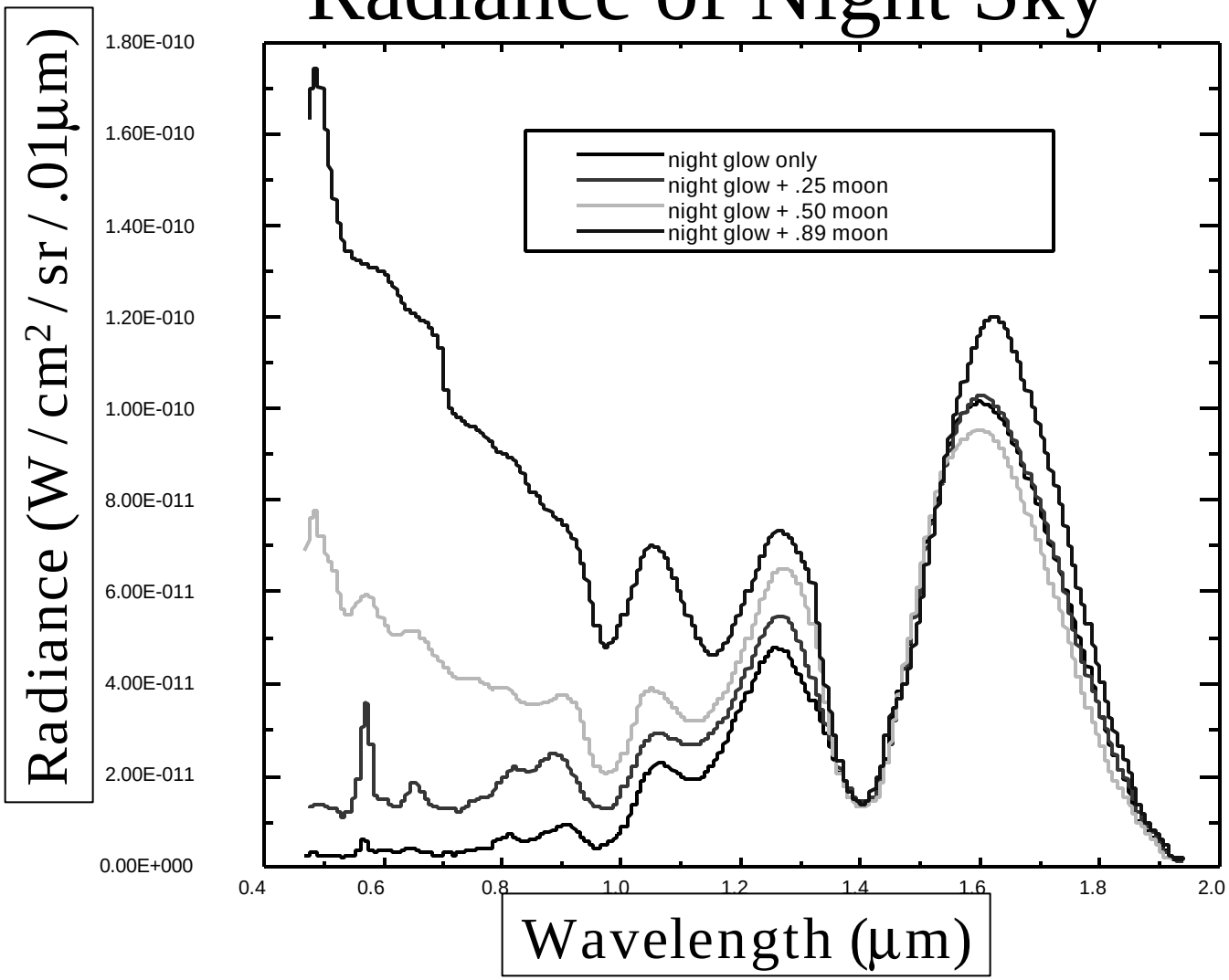
# Radiance of Night Sky




Vatsia, Mirshri, L. "Atmospheric Optical Environment", Research and Development Technical Report ECOM-7023, September (1972)

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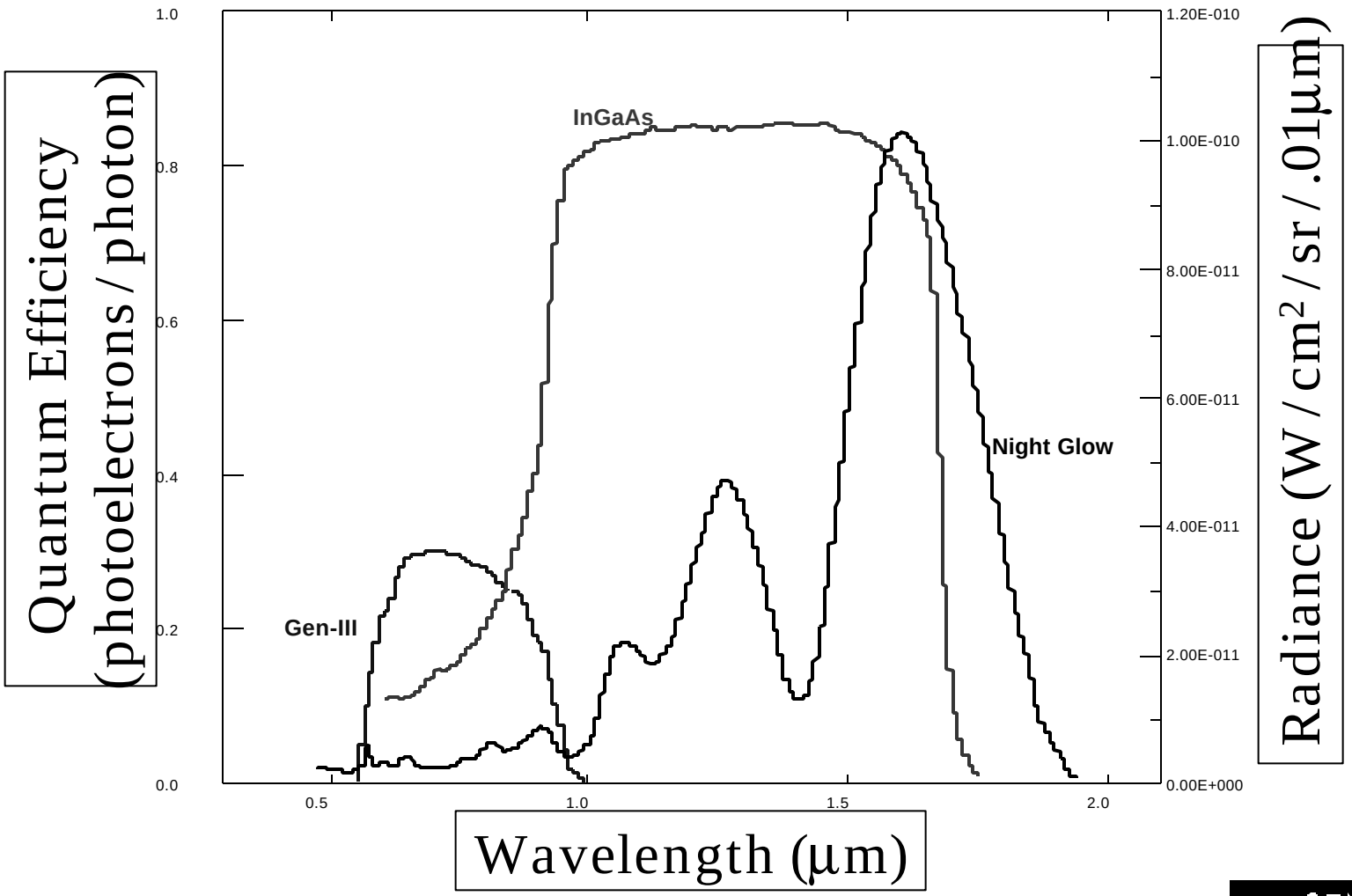
# Quantum Efficiency of InGaAs




Vatsia, Mirshri, L. "Atmospheric Optical Environment", Research and Development Technical Report ECOM-7023, September (1972)

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# Noise Sources and Detectivity

$$\left\langle I_{shot}^2 \right\rangle^{1/2} = \sqrt{2qBI_{dark}} = \sqrt{2qBJ_{dark}A}$$

$$\left\langle I_{Johnson}^2 \right\rangle^{1/2} = \sqrt{\frac{4k_BTB}{R_0}} = \sqrt{\frac{4k_BTBA}{R_0A}}$$

$$D^* = \frac{PR(l_{peak})}{\sqrt{2qJ_{dark}}} \quad \text{or} \quad D^* = PR(l_{peak})\sqrt{\frac{R_0A}{4k_BT}}$$

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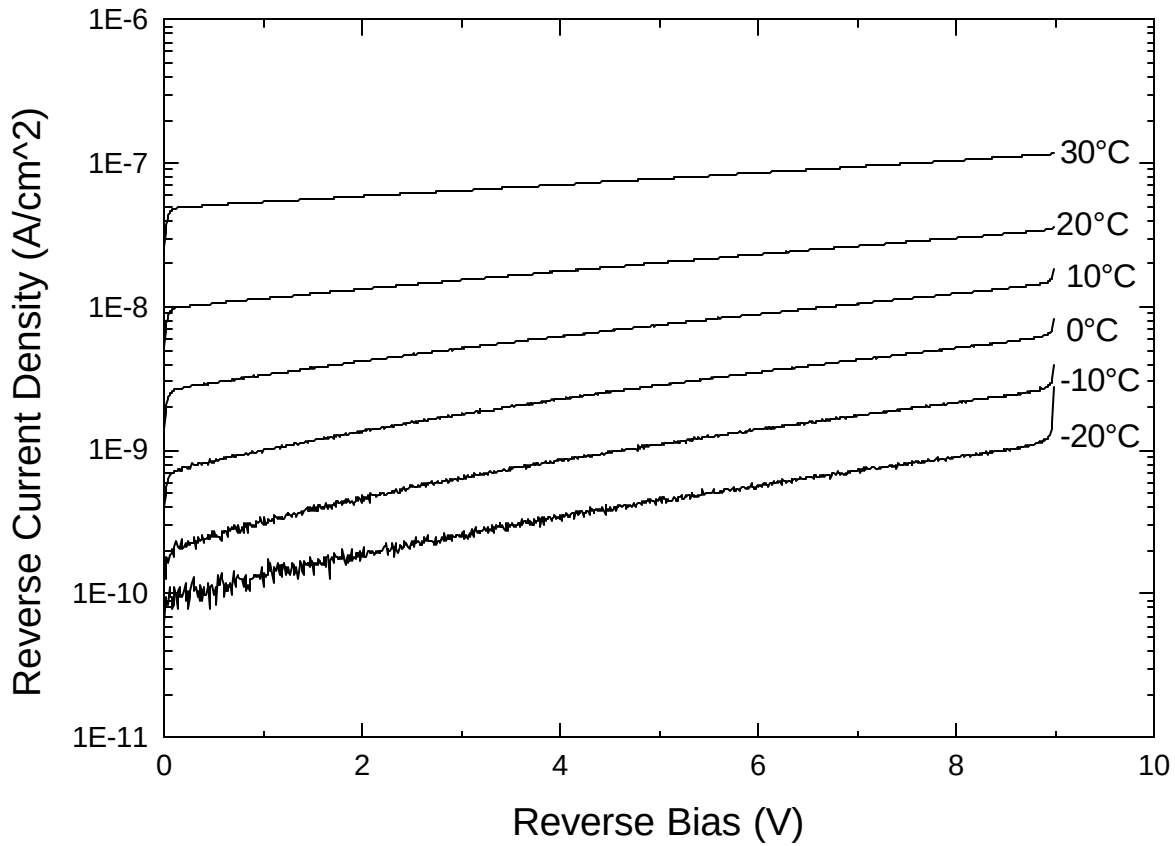
# Reverse Current-Voltage Characteristics of Lattice-Matched InGaAs

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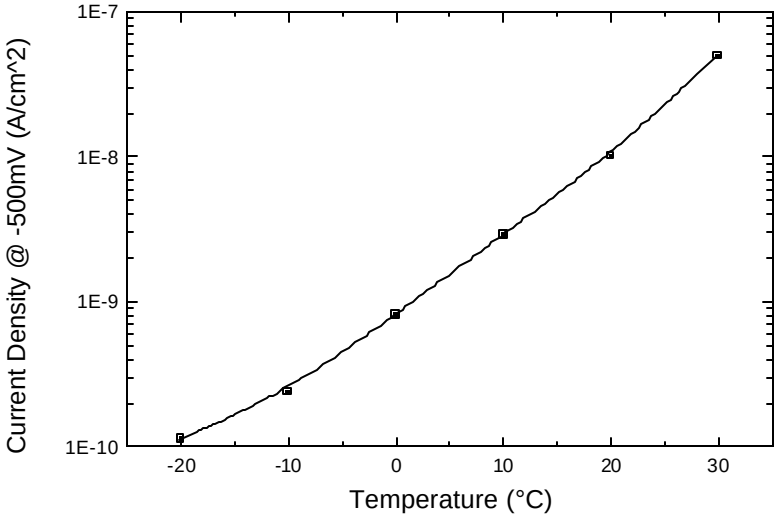
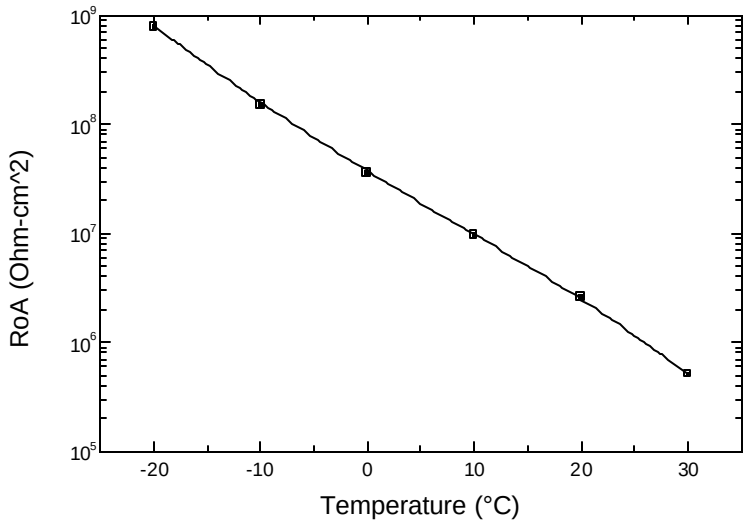
# Dark Performance of SUI's InGaAs PIN photodiodes




Dark Current Density




Shunt Resistivity

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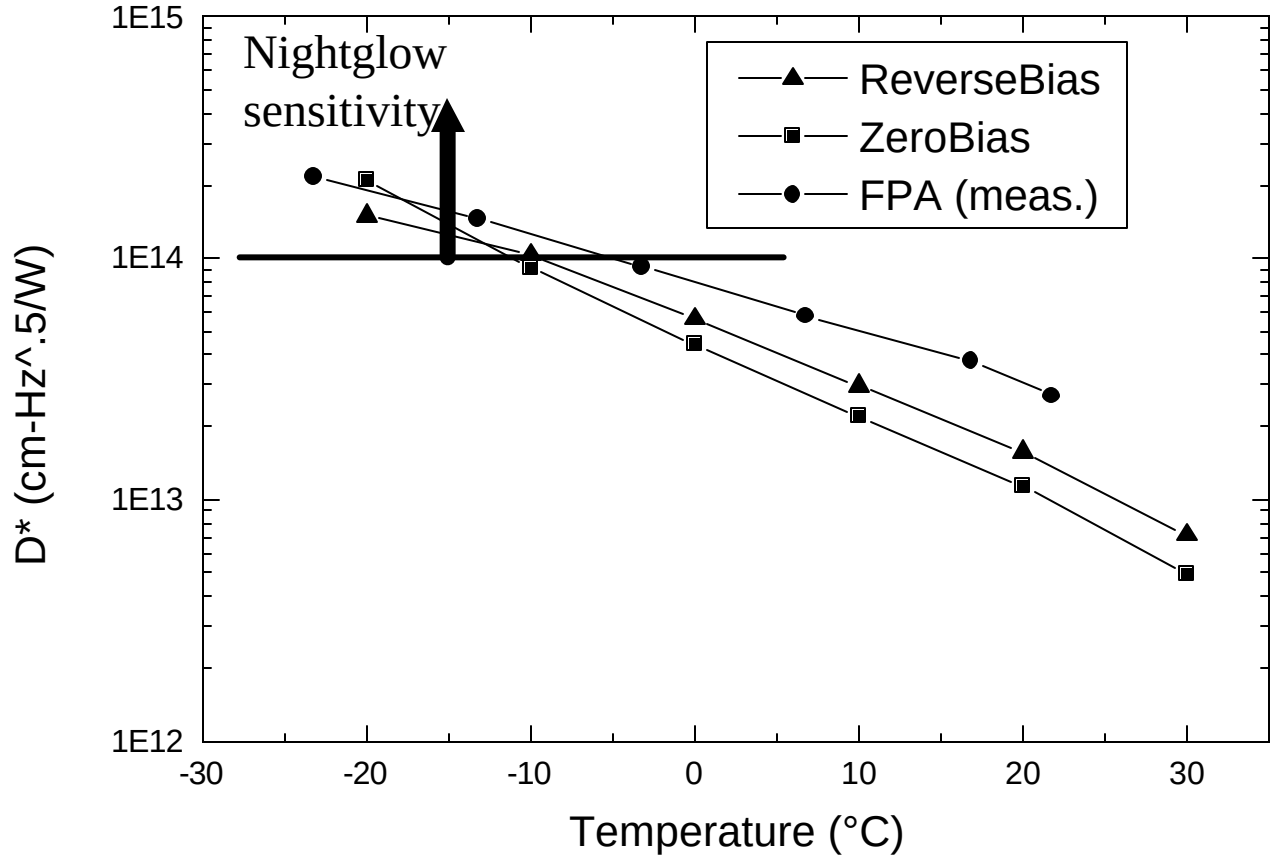
# Detectivity of SUI's InGaAs photodiodes and FPAs

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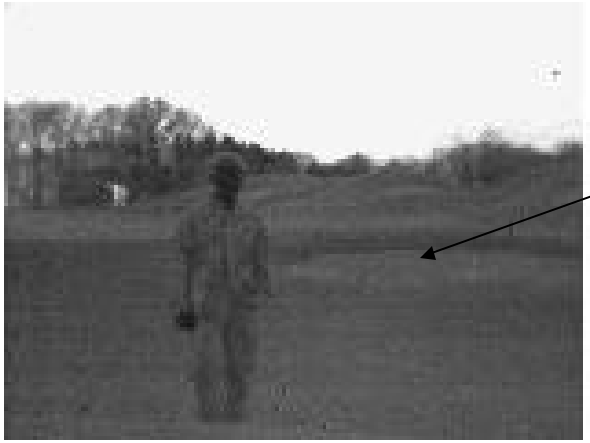
# Images at Night

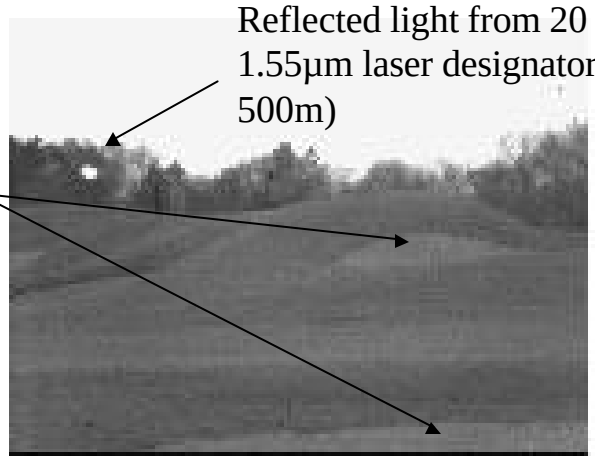
## 6th hole at Jasna Polana (Princeton, NJ)

**Background Illumination < 13 mlux**

**(FPA at 250K)**



25mm f/2.8, IFOV=18°




75mm f/2.8, IFOV=6°

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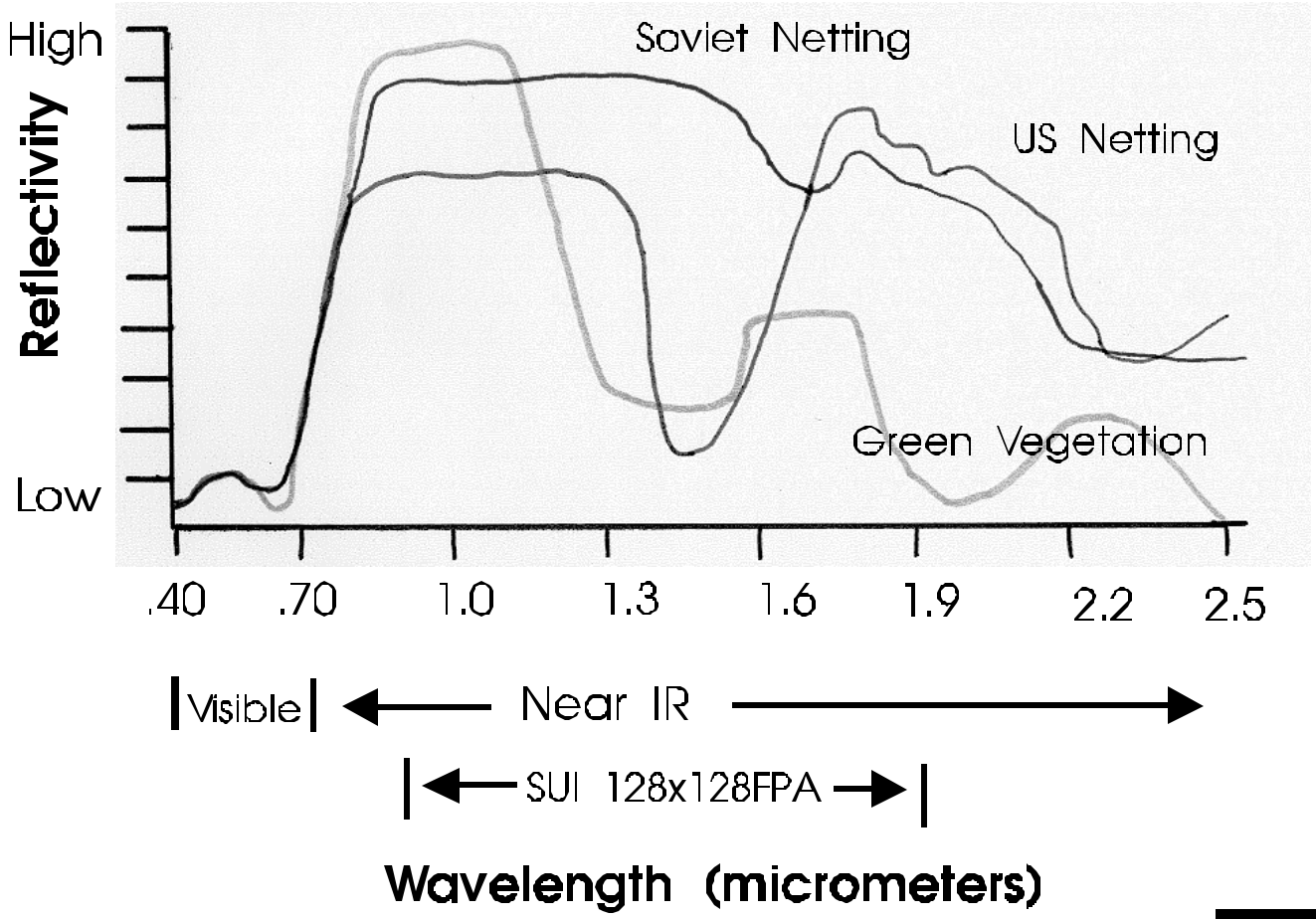
# Camouflage Detection

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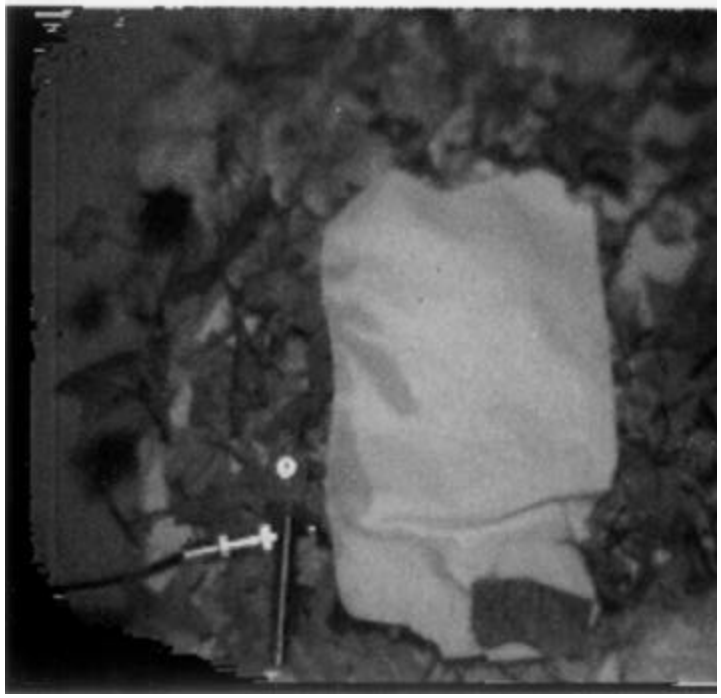
# Camouflage Detection



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# Snow in the SWIR

CCD Camera

SU320-1.7RT

SENSORS UNLIMITED, INC.

# Fog Penetration
# Gunston Cove

VISIBLE IMAGERY

SU320-1.7RT

SENSORS UNLIMITED, INC.

# Target Acquisition and Tracking

SUI InGaAs FPA

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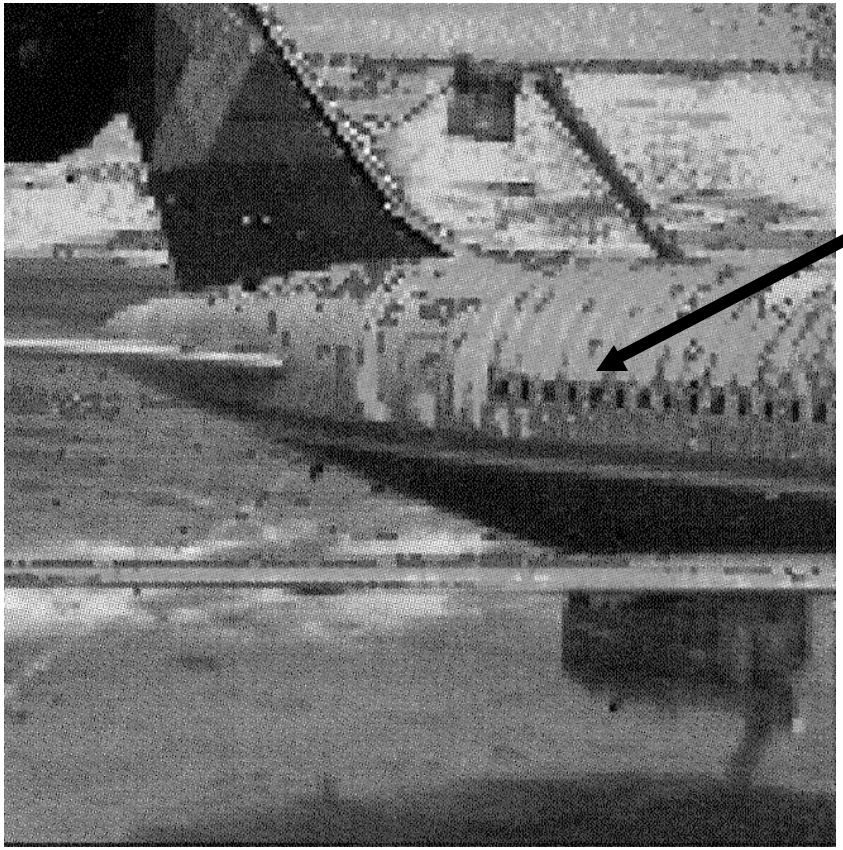
# Aircraft De-Icing



"clear" ice in SWIR

Photo courtesy of Cox and Company
New York, NY

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# InGaAs FPAs for Range-Gated And 3D Imaging using Eye-Safe Laser Illuminators

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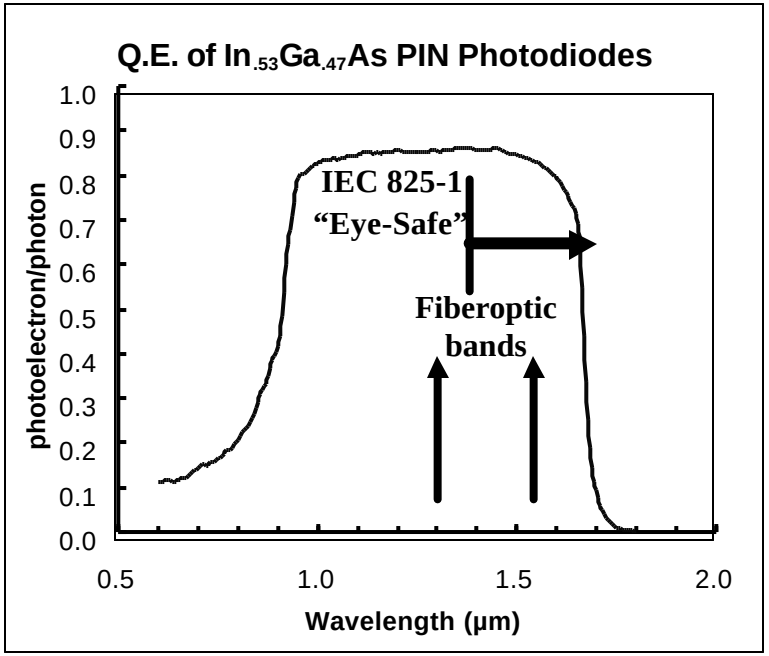
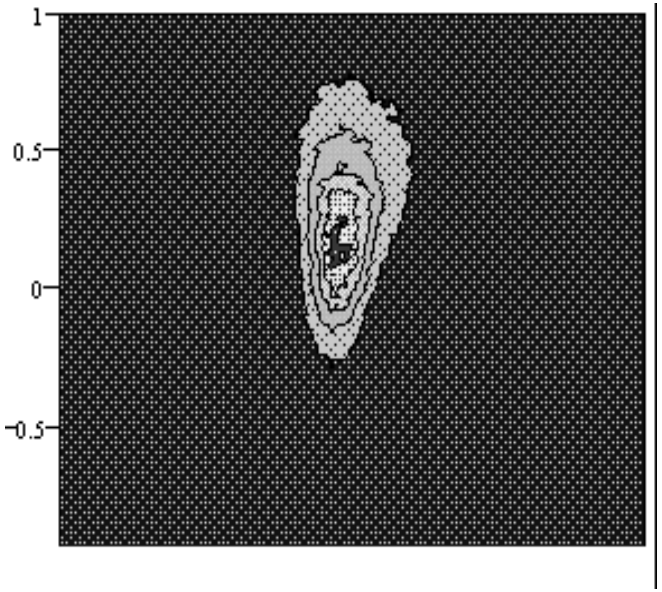
# InGaAs FPAs provide High Sensitivity to Eye-Safe Lasers




SU1393-DFB

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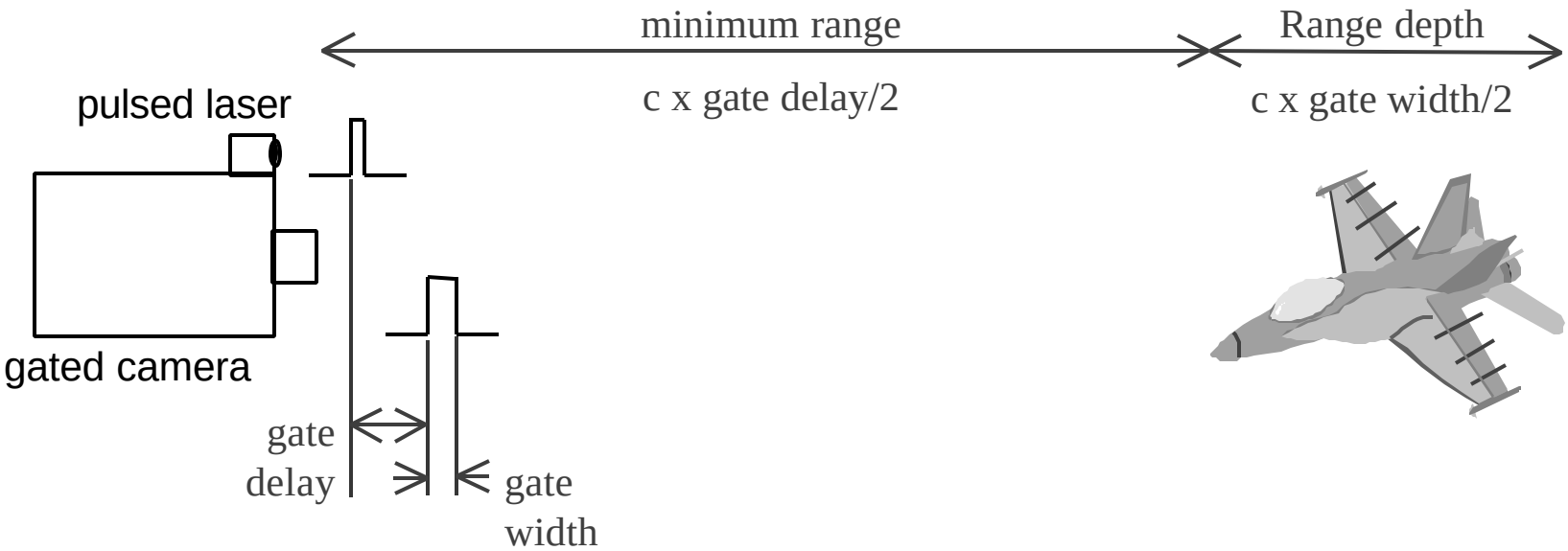
# Range-Gated Imaging at Eye-Safe Wavelengths

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# Nanosecond Gating for LADAR, Range-Gated,and 3D Imaging

- All solid state InGaAs gated FPA
  - high quantum efficiency (>75%)
  - low dark current (≈ pA)
  - ≤ 10 nsec gate width (CMOS ROIC)
  - ≤ 1 nsec gate width (GaAs ROIC)
- InGaAs EB-CCD
  - low quantum efficiency (< 20% - but gain)
  - high dark current (≈ μA)
  - ≥ 70 nsec gate width

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# InGaAs Avalanche Photodiodes for 3D Imaging

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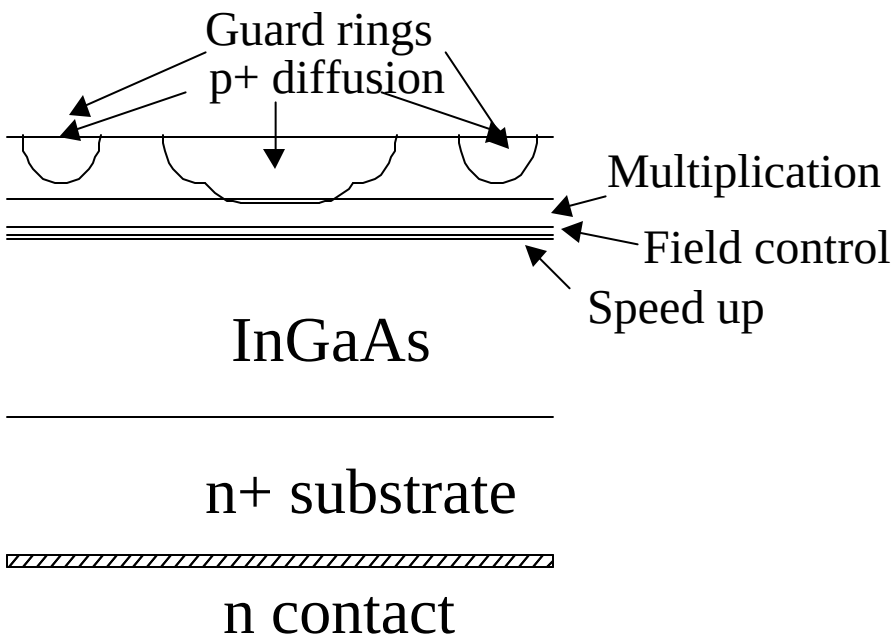
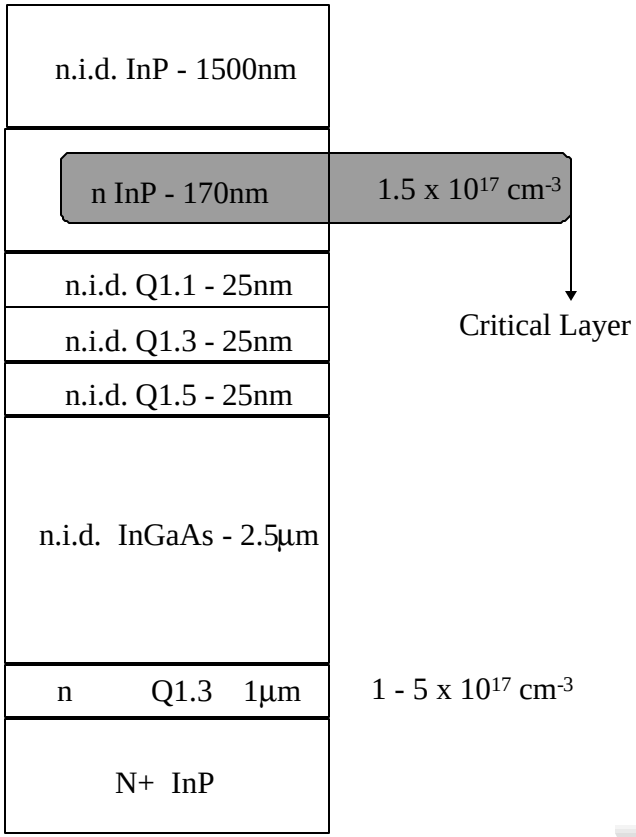
# InGaAs/InP SAM Avalanche Photodiode (Separate Absorption and Multiplication)

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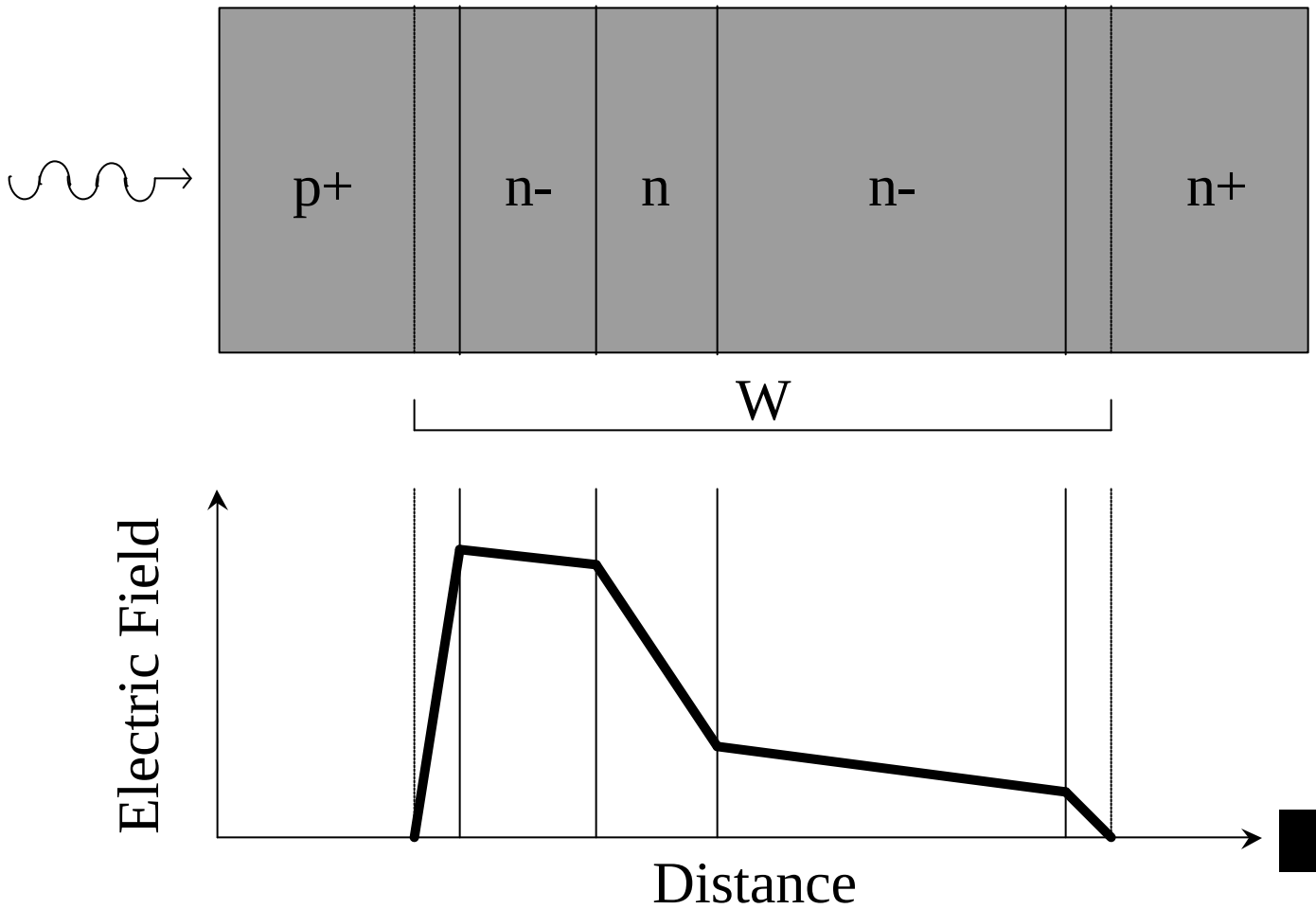
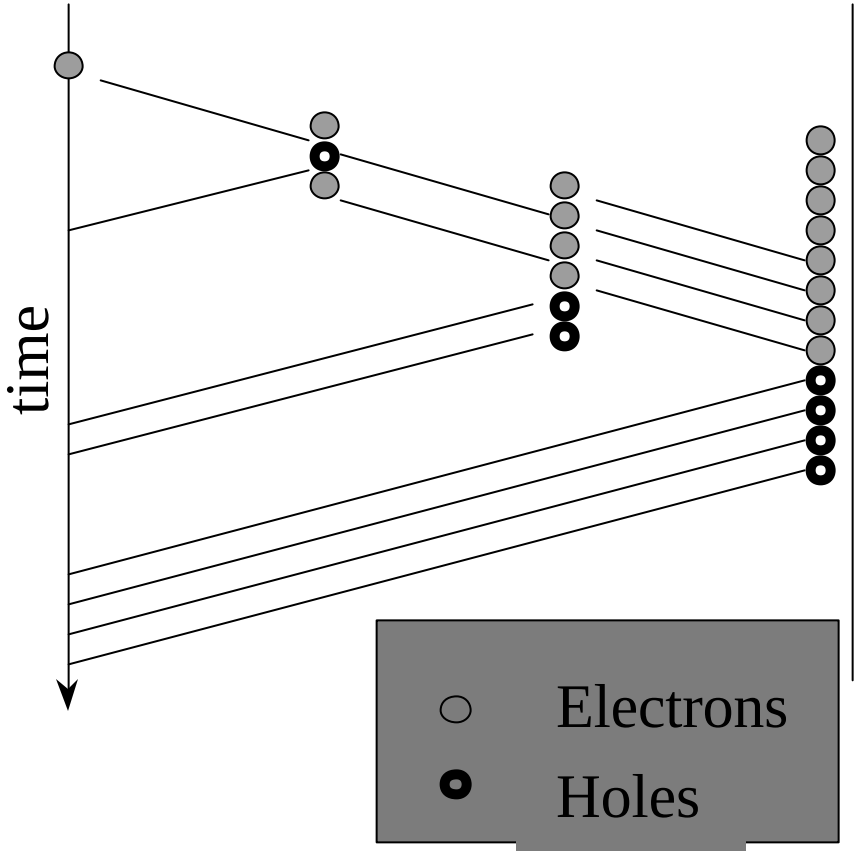
# Separate Absorption and Multiplication Layer APDs (SAM-APDs) Are Significantly More Complicated



# Avalanche Multiplication is the result of Impact Ionization




$$M_n = \frac{1}{1 - \int_0^W a \exp\left[-\int_0^x (a - b)\,dx'\right] dx}$$

$$M_p = \frac{1}{1 - \int_0^W b \exp\left[\int_x^W (a - b)\,dx'\right] dx}$$

This is a “k-0” device; electron ionization only.

However...

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# The APD Advantage is an Improved Signal-Noise Ratio

for a APD receiver, the SNR is given by:

$$SNR = \frac{I_p^2}{s_s^2 + s_T^2} = \frac{(MRP_{in})^2}{2qM^2F_A(RP_{in} + I_d)\Delta f + 4(k_BT/R_L)F_N\Delta f}$$

where

$F_n$ = Amplifier Noise Figure

$k$ = Ionization rate ratio

$\Delta f$ = Receiver Bandwidth

$I_p$ = Photocurrent

$I_d$ = Dark Current

$R$ = Dectector Responsivity

$P_{in}$ = Optical Input Power

$R_L$ = Load Resistance

$$F_A(M) = k \cdot M + (1-k)\cdot(2 - 1/M)$$

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# A Simpler View...

- APDs multiply both signal and noise so there is no SNR advantage.
- The excess noise from k>0 (both electron and hole ionization) makes this even worse. *But*...
- In high-speed applications, amplifier noise dominates.
- *There is a range of gains for which one takes advantage of signal multiplication but noise multiplication is not noticeable!*

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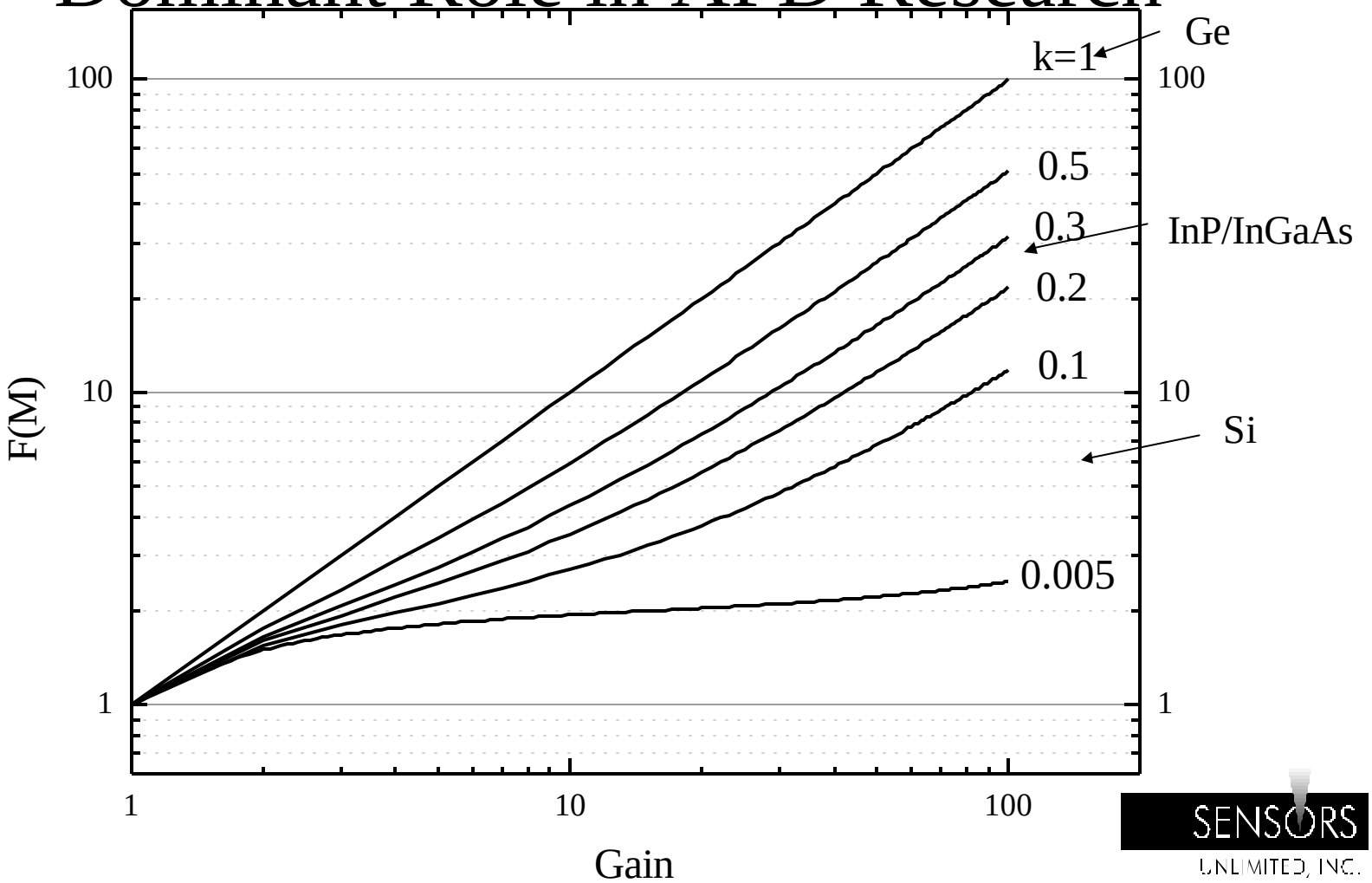
# Excess Noise Factor Has Played a Dominant Role in APD Research

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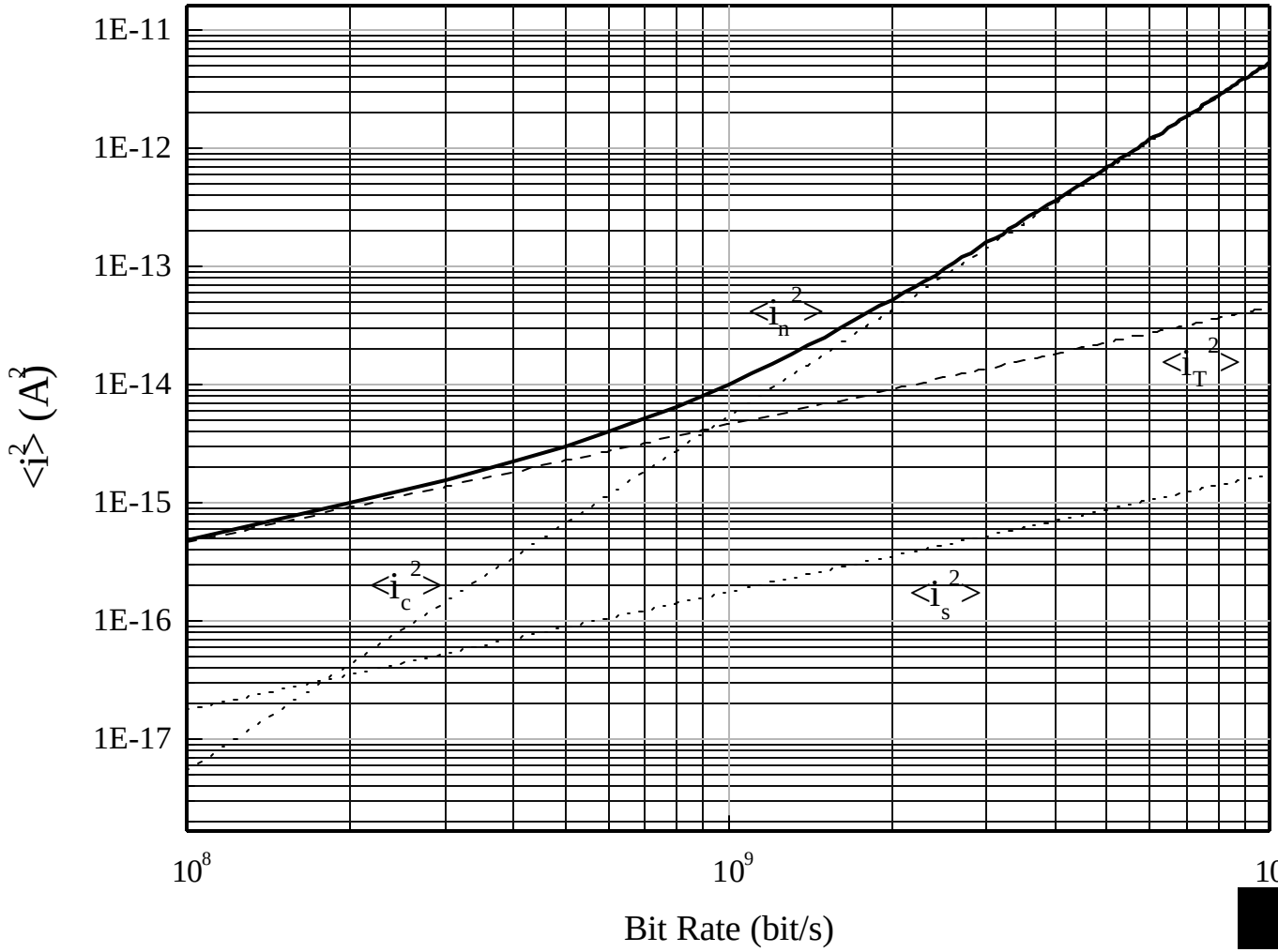
# Receiver Noise Dominates at High Bandwidths

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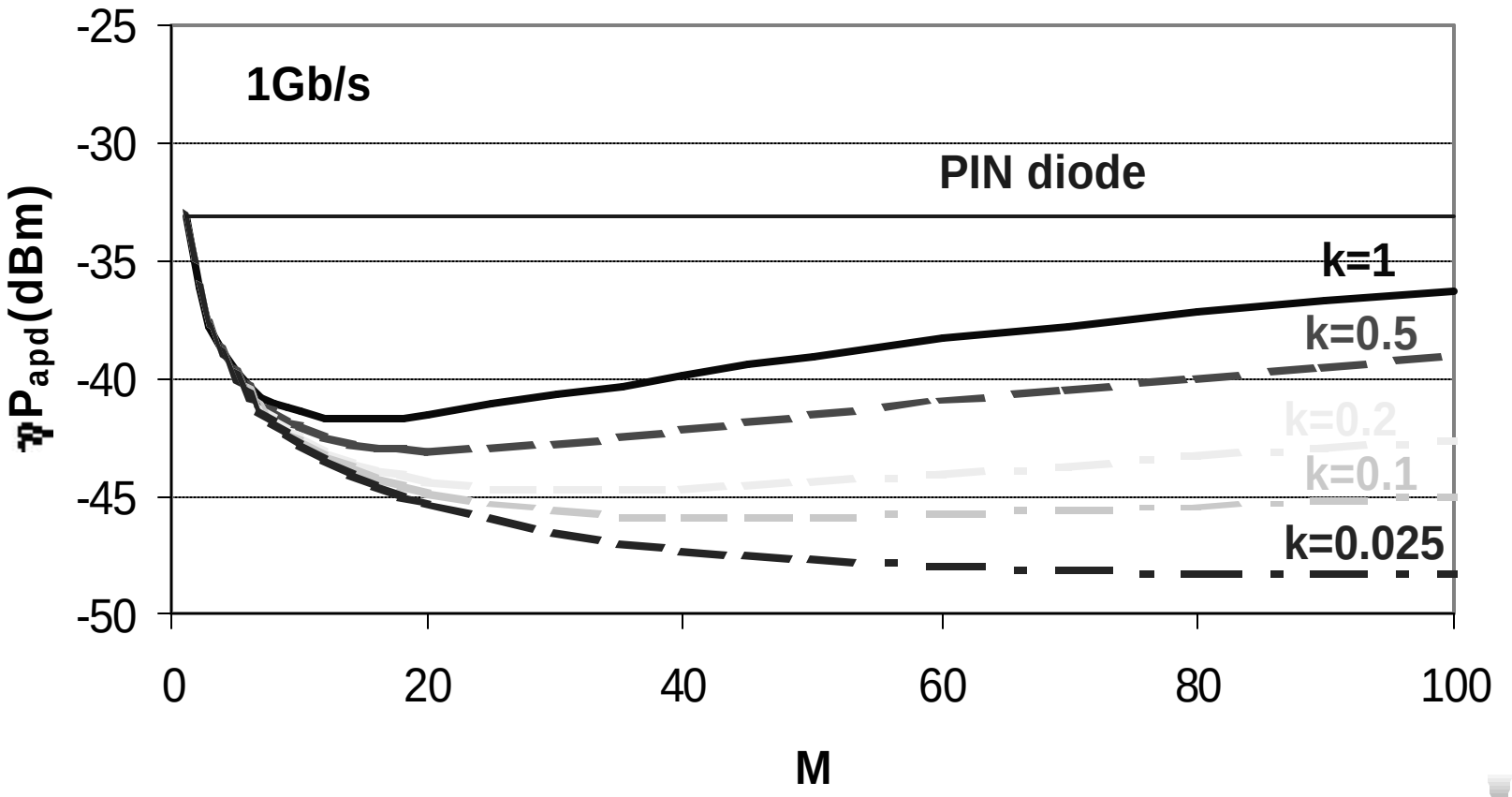
# APDs Have a HUGE sensitivity Advantage in High Bit-Rate Systems

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# The Future...

- For Low Light Level Imaging
  - Next generation CMOS readout integrated circuits with low noise *and* small image lag.
- For Range-Gated Imaging
  - CMOS and Si/Ge or GaAs readouts to support 1-10 ns gate widths.
- Monolithic integration
  - Photodiodes with amplifier and readout circuits.

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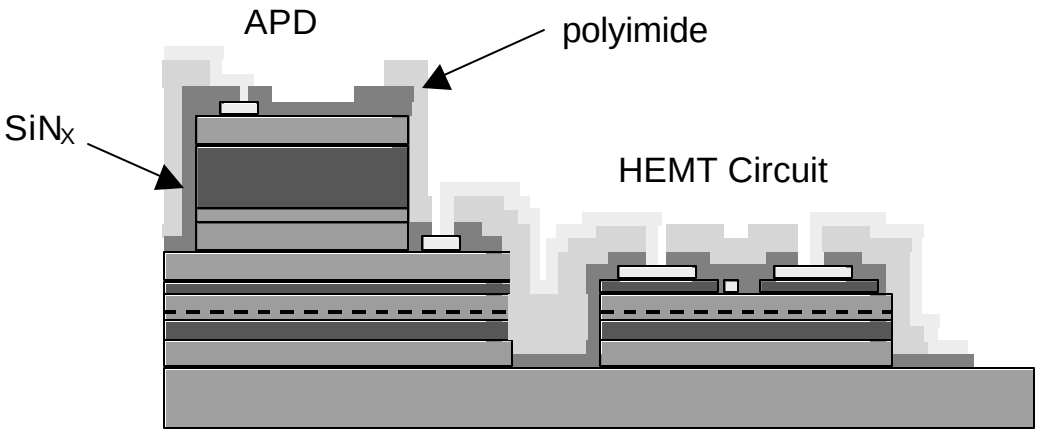
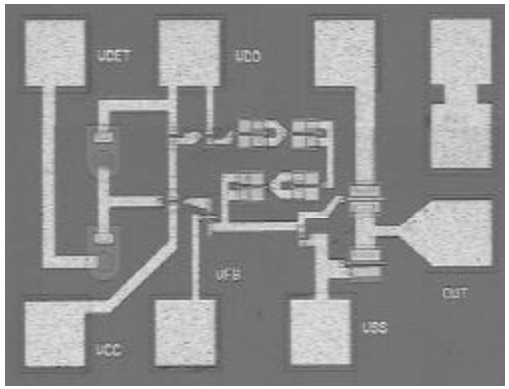
# Monolithic Eye-Safe Receiver Arrays

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# InGaAs versus HgCdTe APDs Quantitative

| **Parameter** | **$In_{0.52}Al_{0.48}As/InGaAs$** | **$Hg_{0.35}Cd_{0.65}Te$** |
|---|---|---|
| Breakdown Voltage | < 25 | 80 - 90 |
| Gain (Max) | 80 - 120 | < 2 |
| $\alpha/\beta$ | 5 - 8 | ? (~ 1) |
| Primary Dark Current @ $0.9V_B$ (nA) | < 10 | < 700 |
| Wavelength range (μm) | 0.95 - 1.65 | 1.1 - 1.6 |
| Quantum Efficiency | 0.8 | 0.5 |

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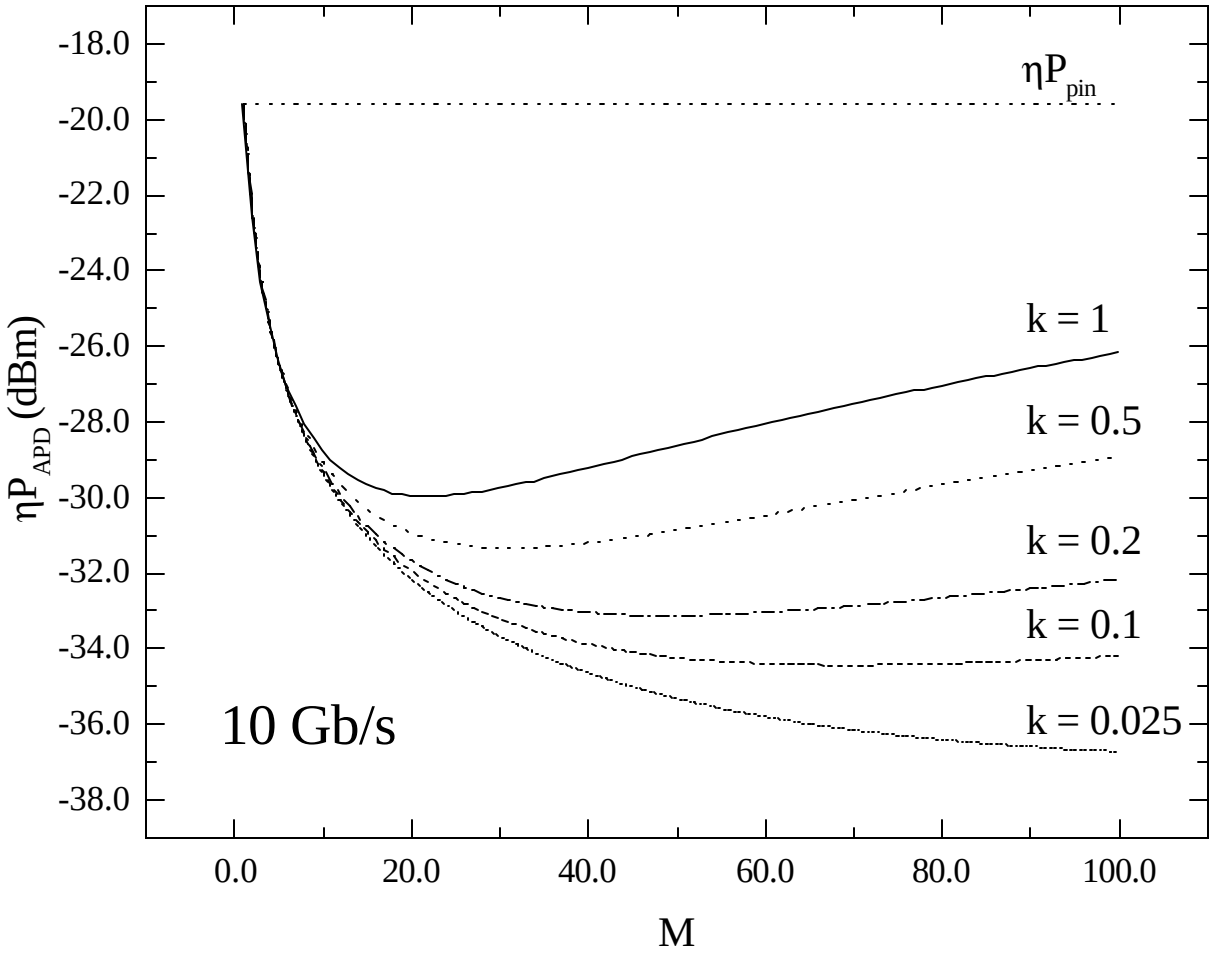
# APDs Have a HUGE sensitivity Advantage in High Bit-Rate Telecom Systems




SENSORS UNLIMITED, INC.

# SWIR MiniCamera Features

- The smallest and only room temperature 2-D SWIR camera available
  - 320x240x40 μm
  - 0.9 μm - 1.7 μm
  - RS-170 compatible
- Low Weight and Power
  - Less than 315g without a lens
  - Less than 1W at room temperature
    - special low power TEC
    - Xenon backfilled package for lower thermal conductivity

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