Optimization of corrugated-QWIPs for large format, high quantum efficiency, and multi-color FPAs

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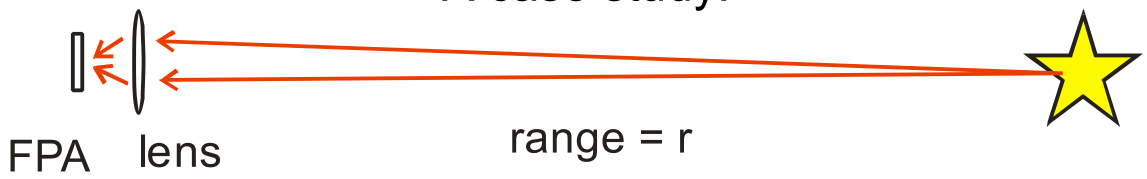
L3-Cincinnnati Electronics

Outline

- Detector requirements
- Detector coupling optimization
- Detector material optimization
- Voltage tunable two- and four-color detectors
- FPA results
- Conclusion

Detector Requirements

A case study:

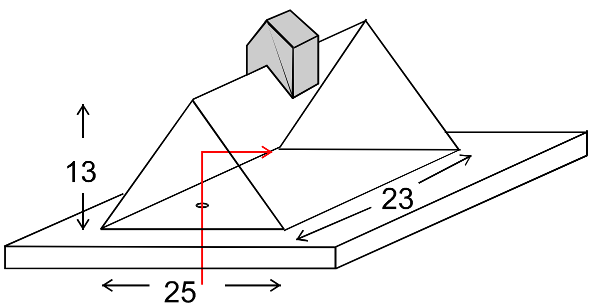


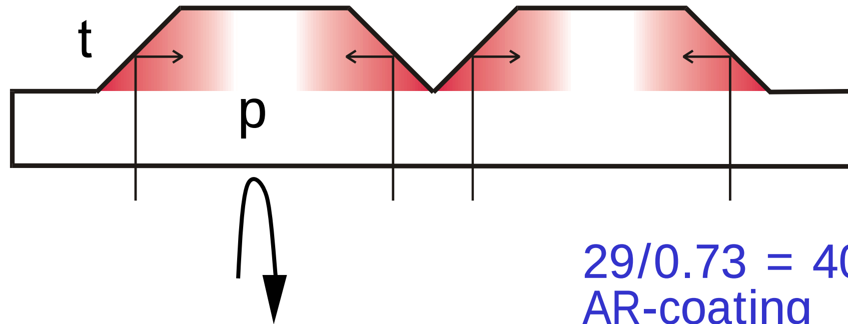
$$\frac{S}{N}=\frac{\eta g\kappa L_{tar}A_{tar}A_{opt}\cdot \mathrm{EoD}\cdot \tau_{\mathrm{int}}/r^2}{\sqrt{2g(N_b+N_d)+\sigma^2(N_b+N_d)^2+N_r^2}}\ .$$

$$\Rightarrow \qquad r^2=\frac{\eta g L_{tar}A_{tar}A_{opt}\cdot \mathrm{EoD}\cdot \tau_{\mathrm{int}}}{\left(\frac{S}{N}\right)\sqrt{2\eta g^2\frac{A_d\pi L_{opt}}{1+4(f/\#)^2}\tau_{\mathrm{int}}+\left(\sigma\eta g\frac{A_d\pi L_{opt}}{1+4(f/\#)^2}\tau_{\mathrm{int}}\right)^2+N_r^2}}\ ,$$

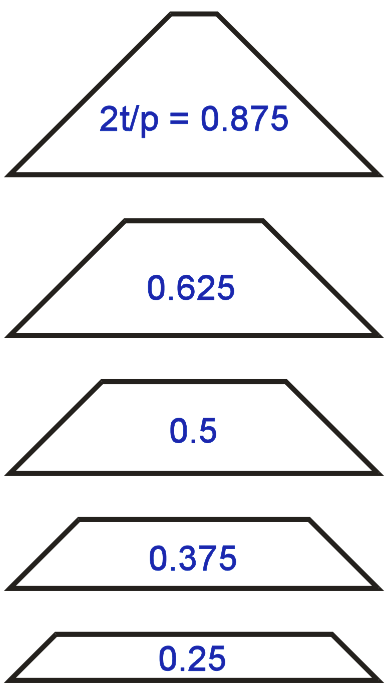
set #	η	g	σ (%)	N_r (e^-)	% of ideal range
1	1	1	0	0	100
2	1	0.4	0	0	100
3	1	0.4	0	200	99.9
4	1	0.4	0.02	200	86.9
5	0.5	0.4	0.02	200	77.6
6	0.4	0.4	0.02	200	74.4
7	0.1	0.2	0.05	1000	38.0

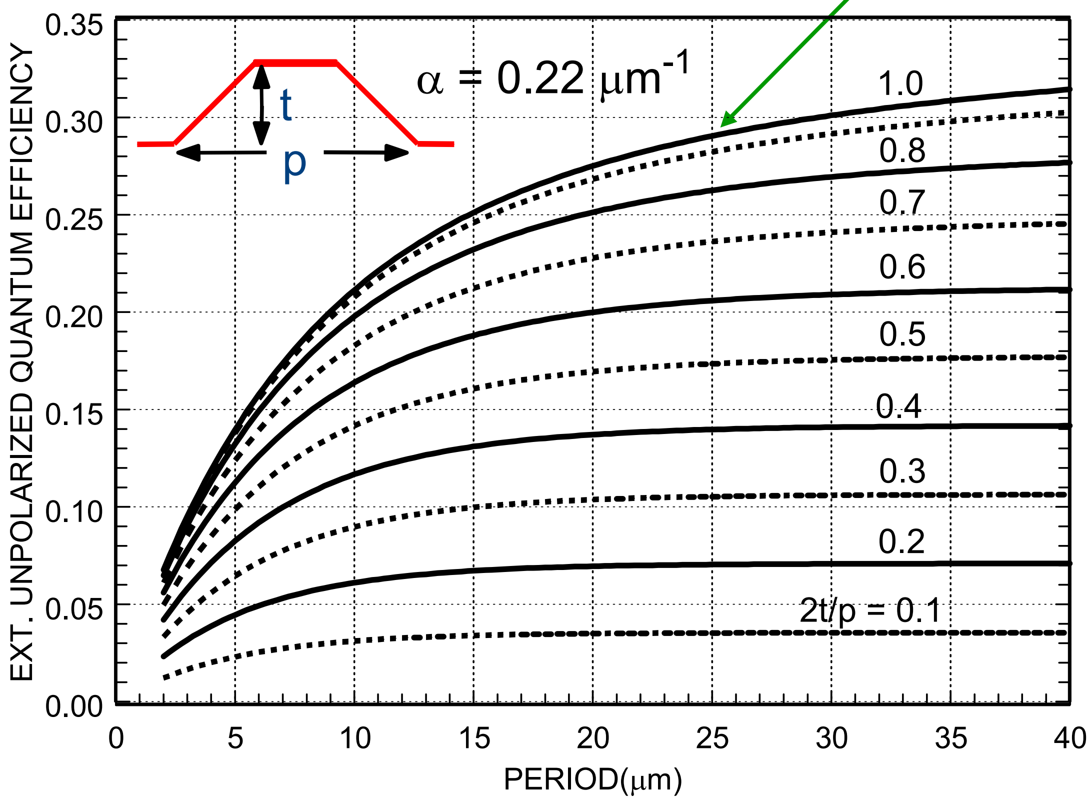
Corrugated-QWIP





29/0.73 = 40% with AR-coating





\+

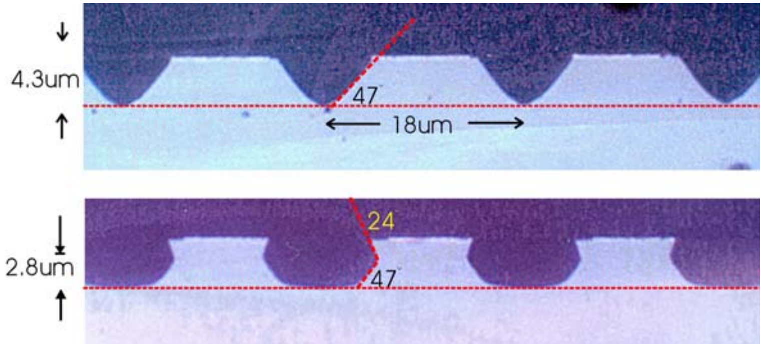
vertical sidewall diffraction (~ 7%)

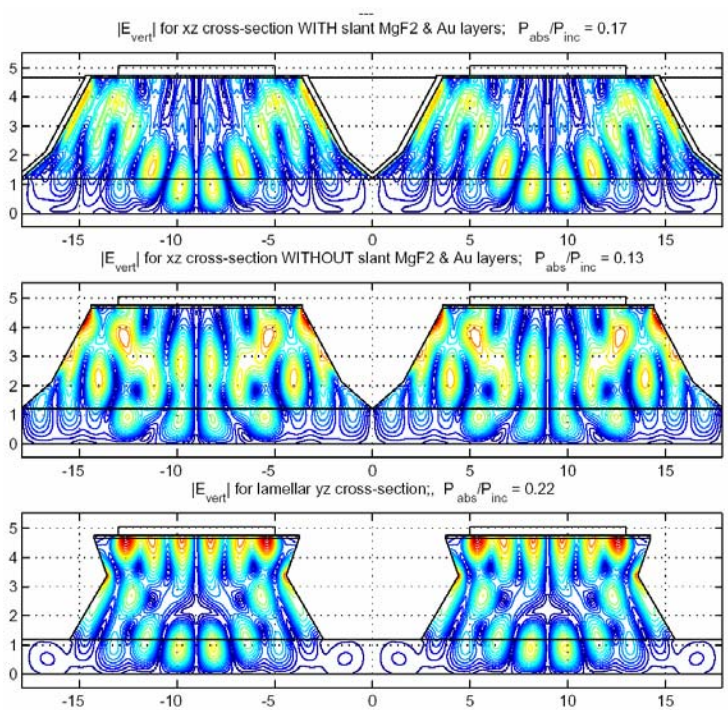
\+

free carrier absorption

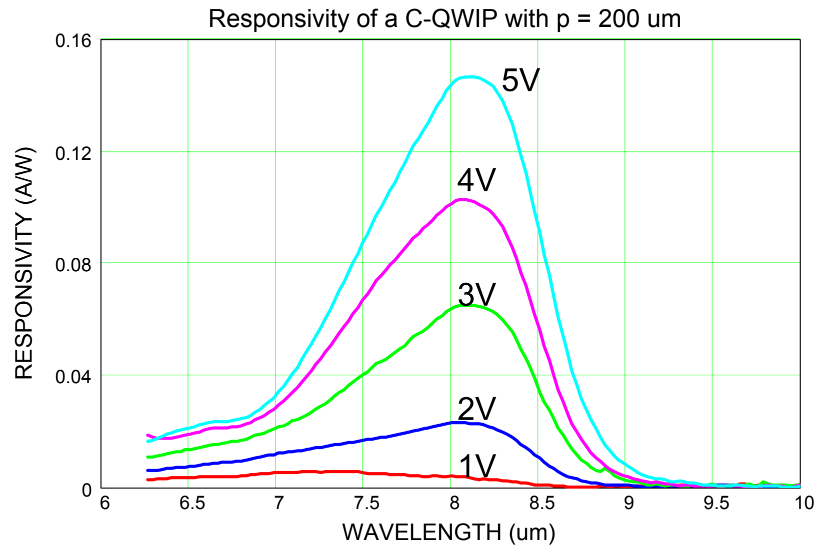
$\Rightarrow \eta \sim 50\%$

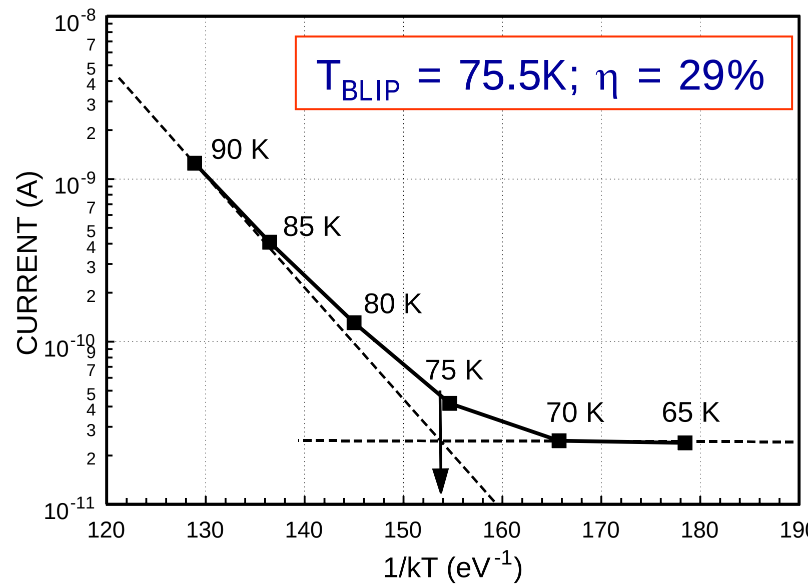
Previous Geometry



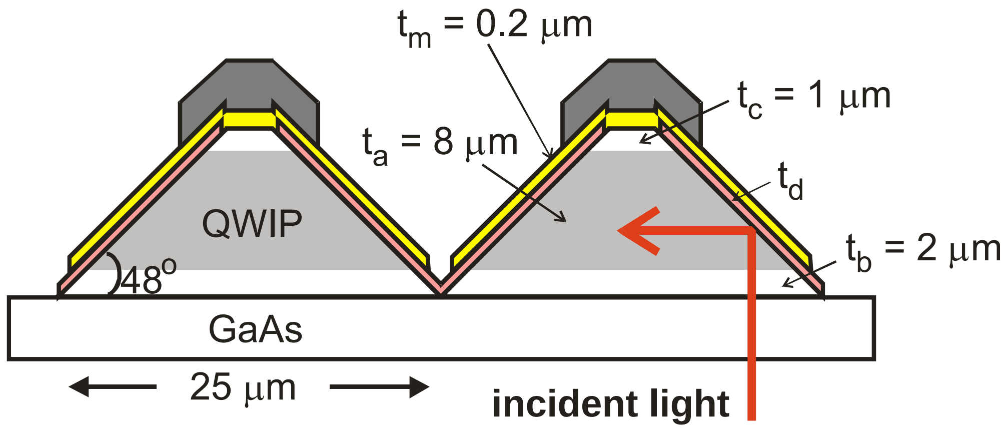


calculated η = 20%





Present Geometry

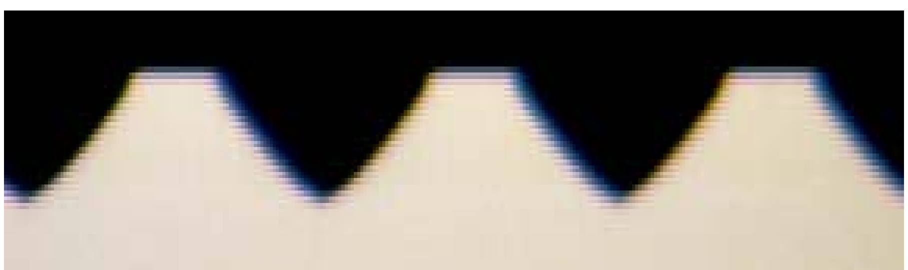


$S = 2t/p = 2 \times 11/25 = 0.88$,

For two sidewalls,

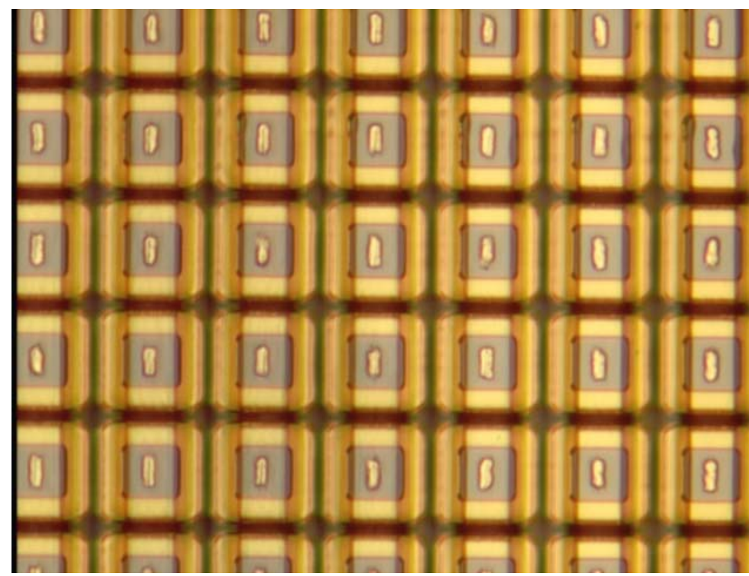
η = 27% w/o AR coating

η = 37% w AR-coating

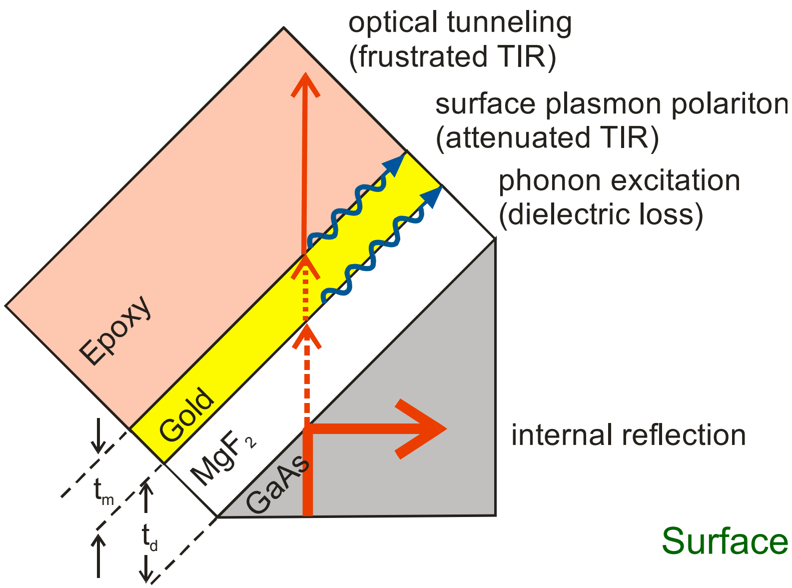


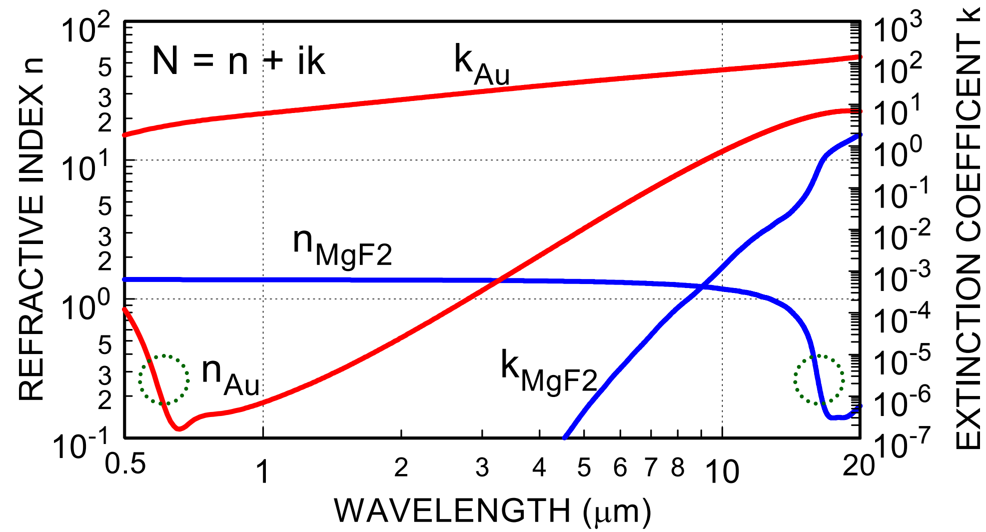
side view

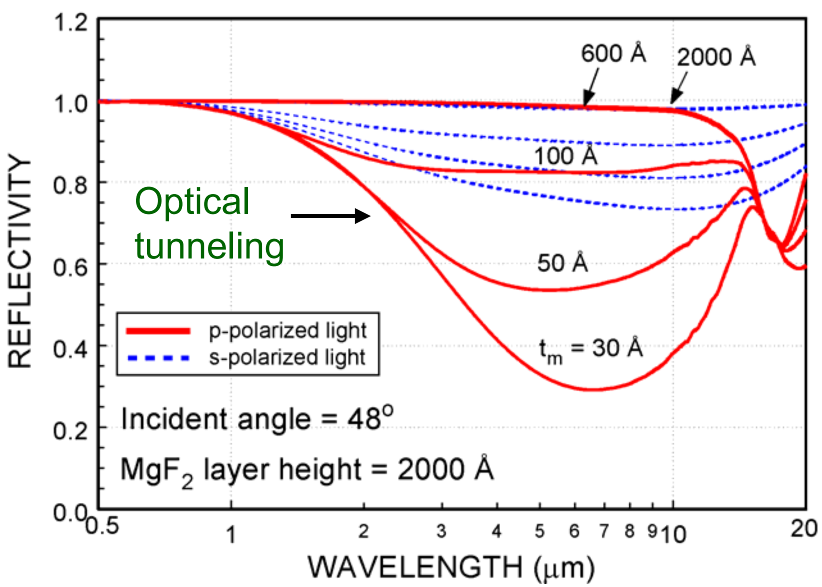
top view

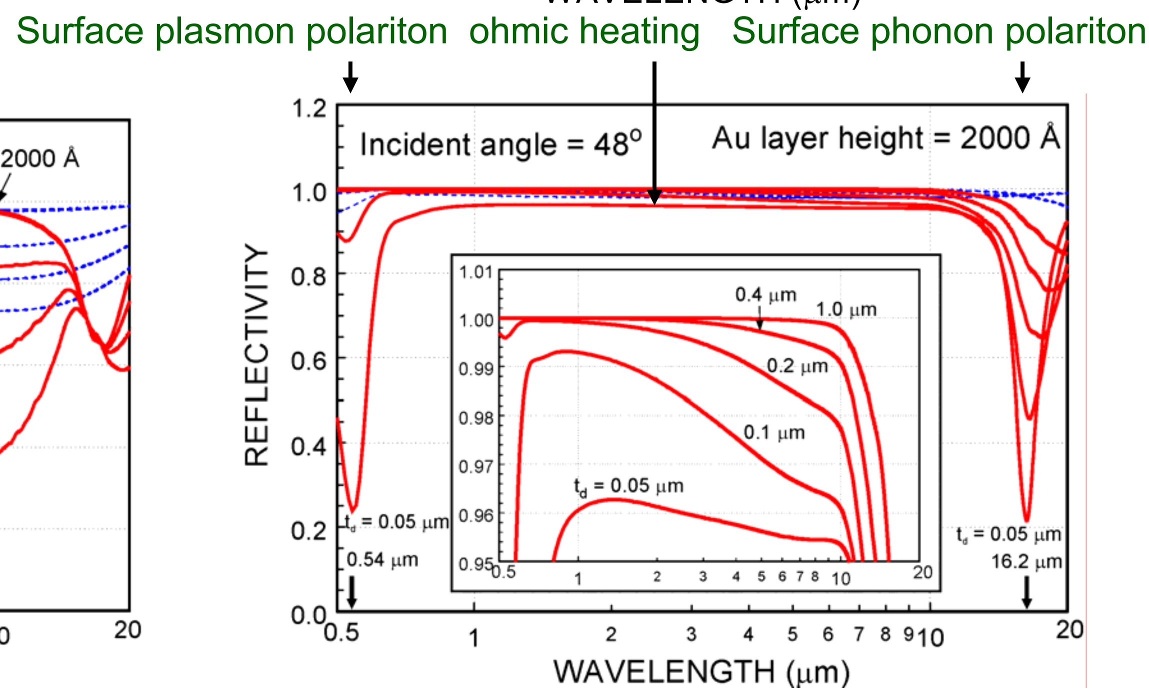


Reflecting Surface Optimization



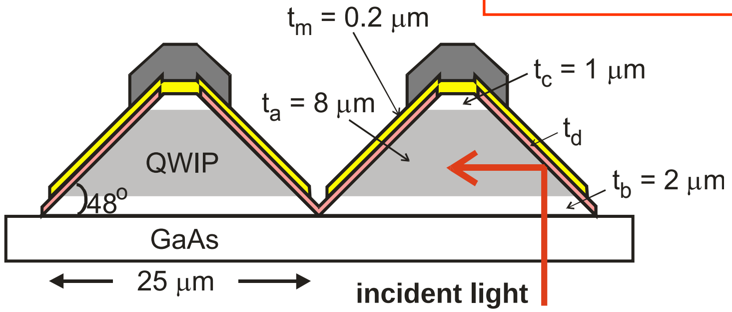


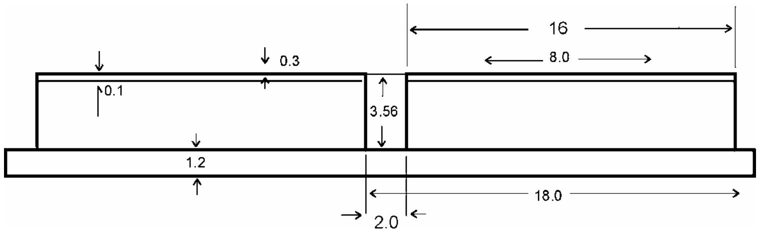


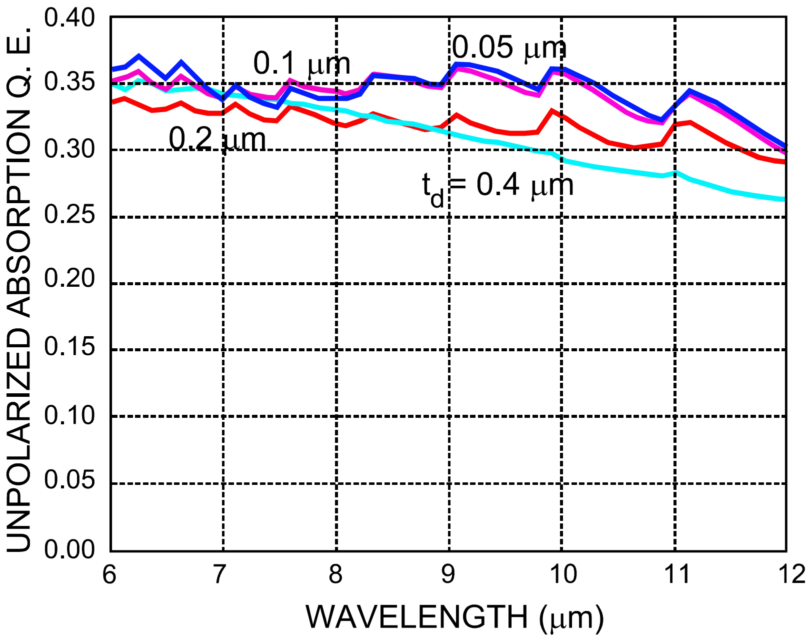


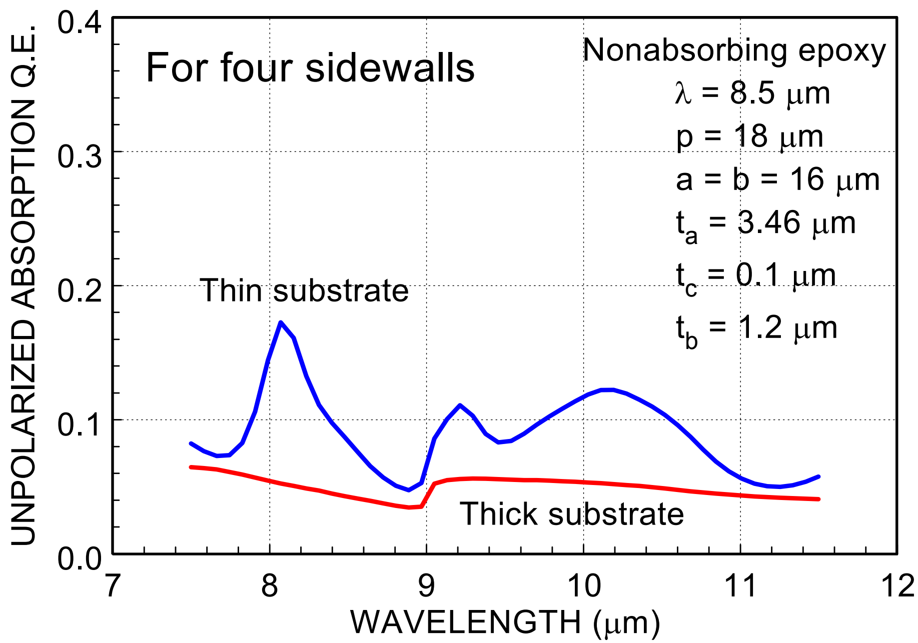
C-QWIPs with Thick Substrate

Modal Transmission-Line Theory





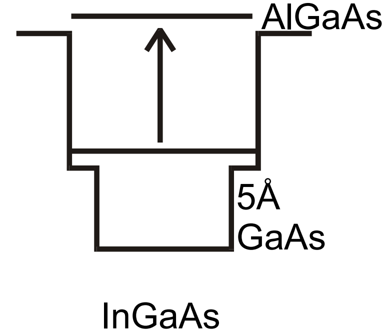




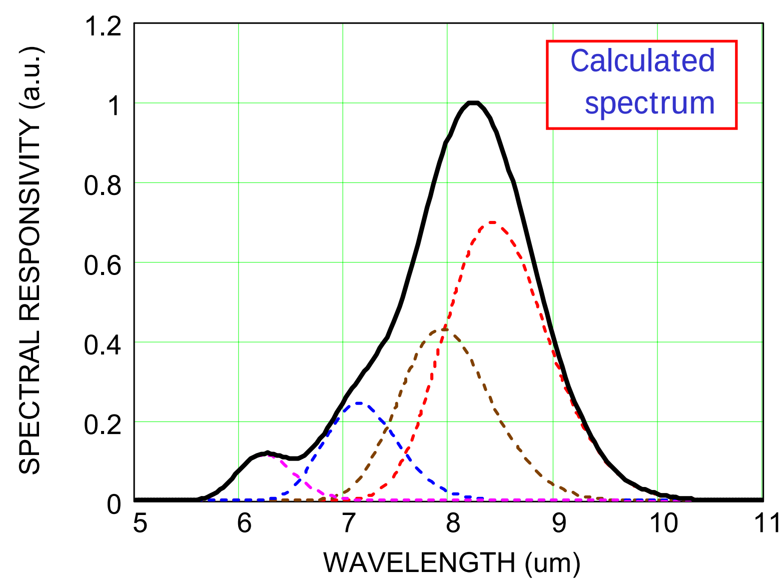
$(I_p/I_d)_{CQWIP} \approx 20\ (I_p/I_d)_{plain\ QWIP}$

Material Design (LC1)

15,000 Å	$n = 0.9\times10^{18}\ cm^{-3}$	GaAs	
50 Å	undoped	$Al_{0.21}Ga_{0.79}As$	
5 Å	$n = 0.9\times10^{18}\ cm^{-3}$	GaAs	x 106
40 Å	$n = 0.9\times10^{18}\ cm^{-3}$	$In_{0.1}Ga_{0.9}As$	x 106
5 Å	$n = 0.9\times10^{18}\ cm^{-3}$	GaAs	x 106
700 Å	undoped	$Al_{0.21}Ga_{0.79}As$	x 106
27000 Å	$n = 0.9\times10^{18}\ cm^{-3}$	GaAs	
500 Å	undoped	$Al_{0.3}Ga_{0.7}As$	(stop etch layer)
2500 Å	undoped	GaAs	
GaAs	semi-insulating substrate		

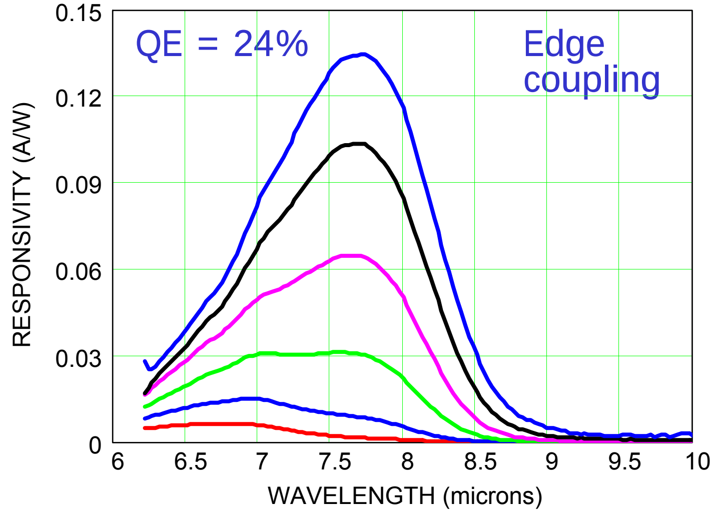


x = 0.21, y = 0.10, c = 0.67



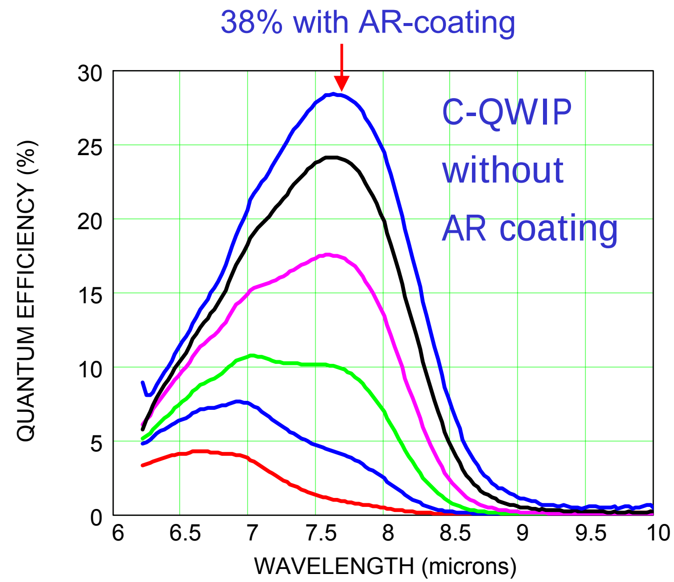
Bound-to-Bound Detector

Measured single detector data



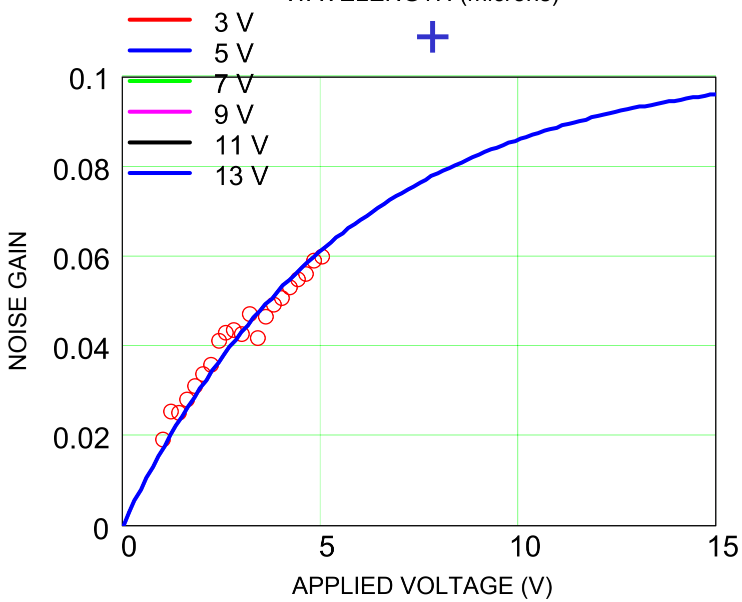
Projected

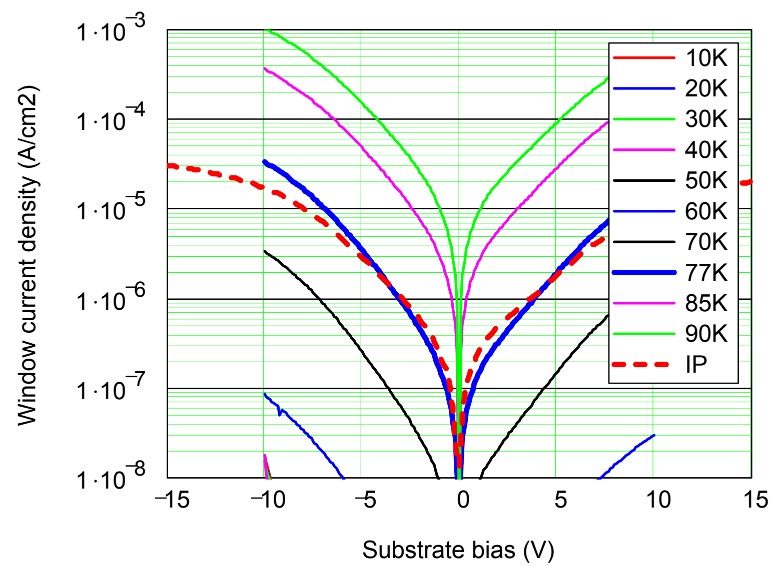
⟹



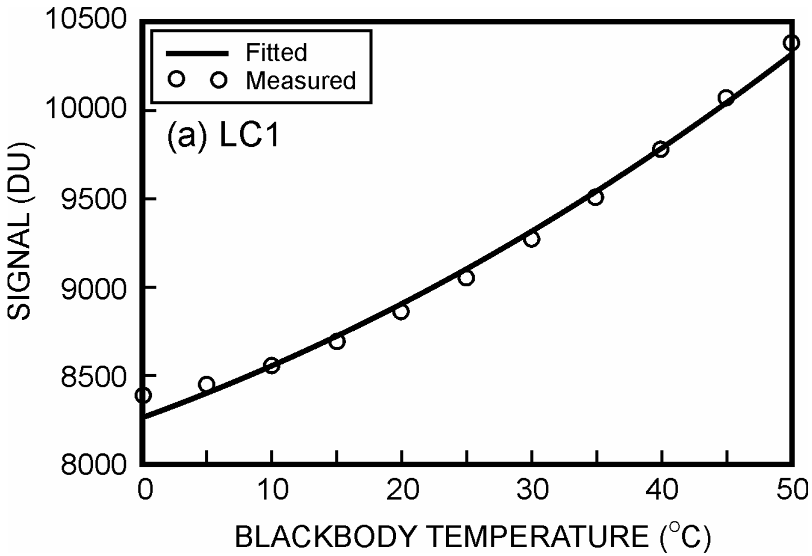
Q.E. = Absorption x tunneling probability

BLIP at 77 K





LC1 1K x 1K FPA Performance



Test Parameters:

- t_{int} = 16.383 msec
- V_{ig} = 0.85 V
- V_{detcom} = -3 V

Input Parameter:

- Photoconductive Gain = 0.048

Derived Parameters:

- Peak QE = 7.1%
- Dark Current = 8.7 μA/cm^2
- ROIC Noise = 1461 e

T = 80 K

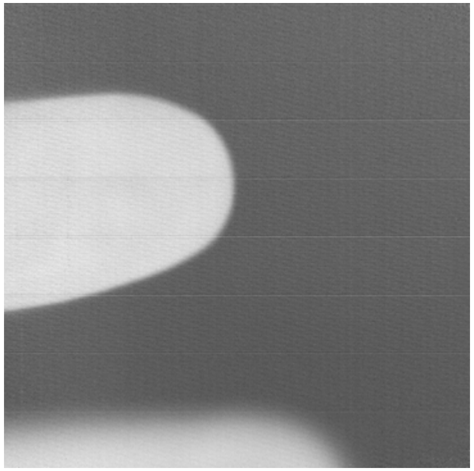
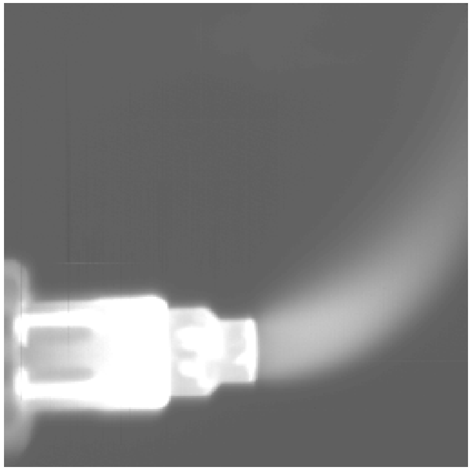


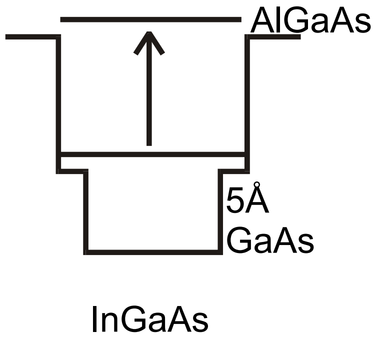
Image of fingers



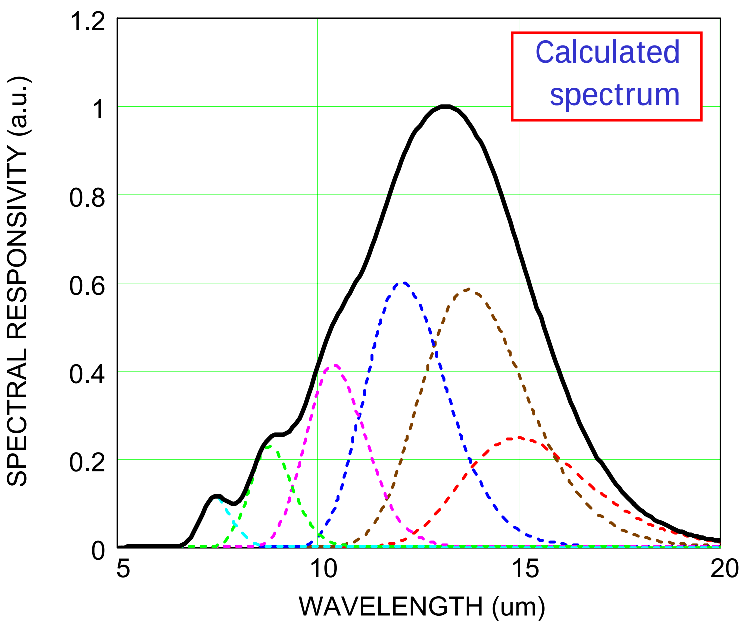
Torch flame

Material Design (LC2)

15,000 Å	$n = 0.9\times10^{18}$ cm^{-3}	GaAs	
50 Å	undoped	$Al_{0.12}Ga_{0.88}As$	
5 Å	$n = 0.9\times10^{18}$ cm^{-3}	GaAs	x 106
40 Å	$n = 0.9\times10^{18}$ cm^{-3}	$In_{0.1}Ga_{0.9}As$	x 106
5 Å	$n = 0.9\times10^{18}$ cm^{-3}	GaAs	x 106
700 Å	undoped	$Al_{0.12}Ga_{0.88}As$	x 106
27000 Å	$n = 0.9 \times10^{18}$ cm^{-3}	GaAs	
500 Å	undoped	$Al_{0.3}Ga_{0.7}As$	(stop etch layer)
2500 Å	undoped	GaAs	
GaAs	semi-insulating substrate		

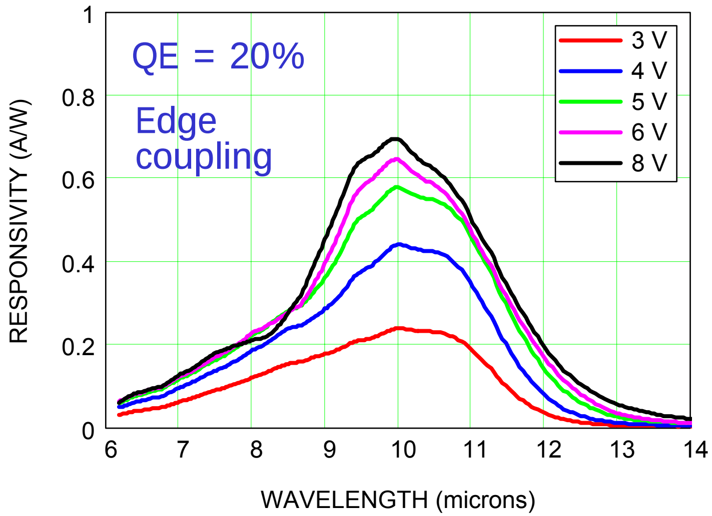


x = 0.12, y = 0.10, c = 0.67



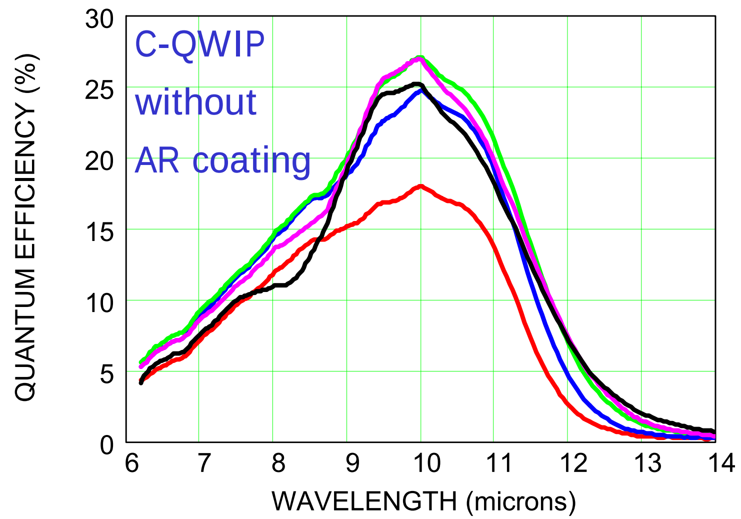
Bound-to-extended State Detector

Measured data

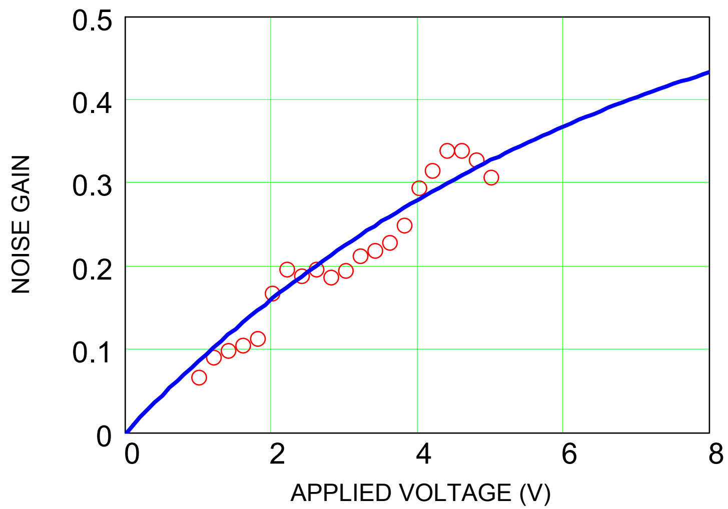


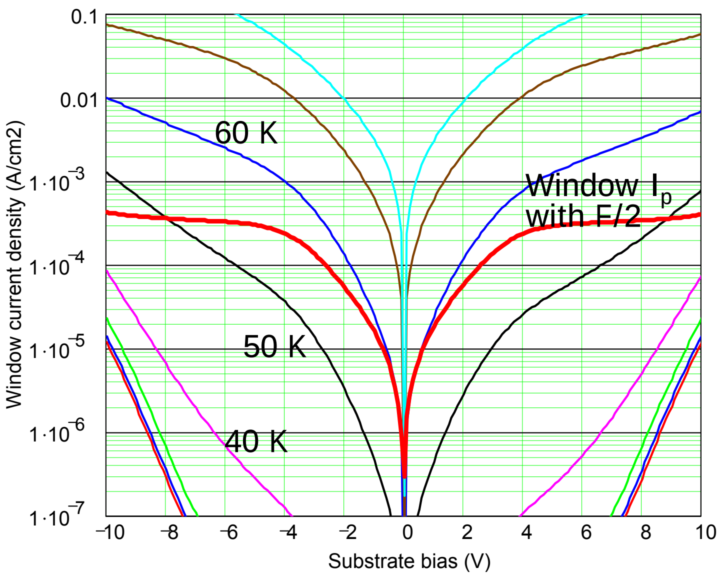
Projected

⇒

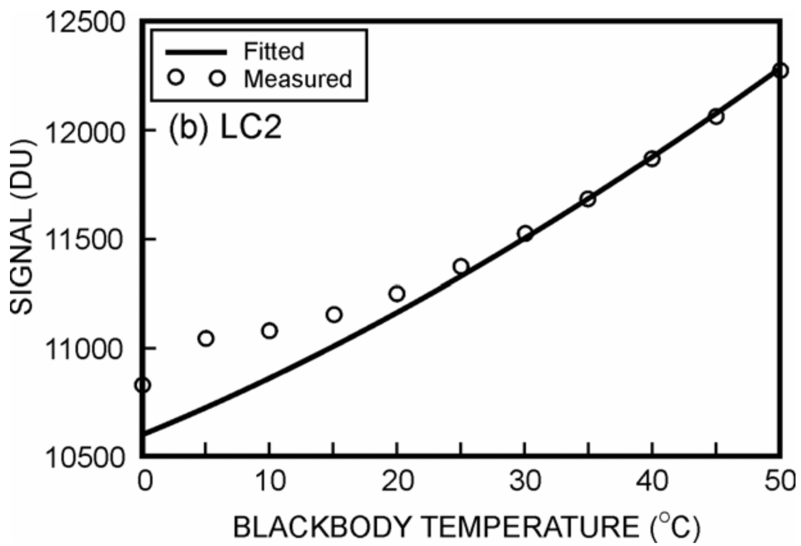


+





LC2 1K x 1K FPA Performance



Test Parameters:

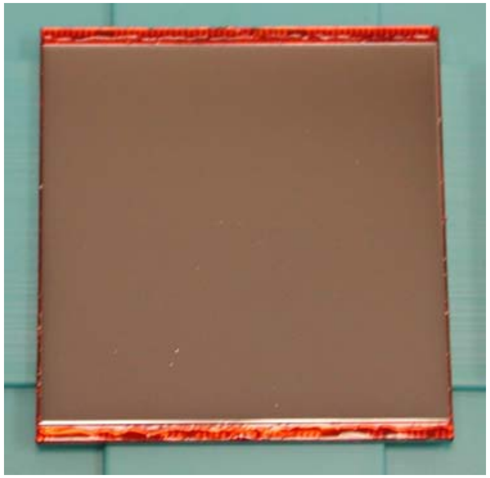
- t_{int} = 3.5 msec
- V_{ig} = 1.2 V
- V_{detcom} = -2 V

Input Parameter:

- Photoconductive Gain = 0.16

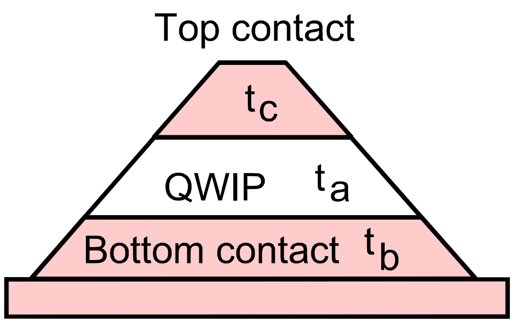
Derived Parameters:

- Peak QE = 14.24%
- Dark Current = 264.1 µA/cm^2
- ROIC Noise = 0 e



T = 68K, V_{ig} = 2V, Vdetcom = -2V, τ_{int} = 300 µsec.

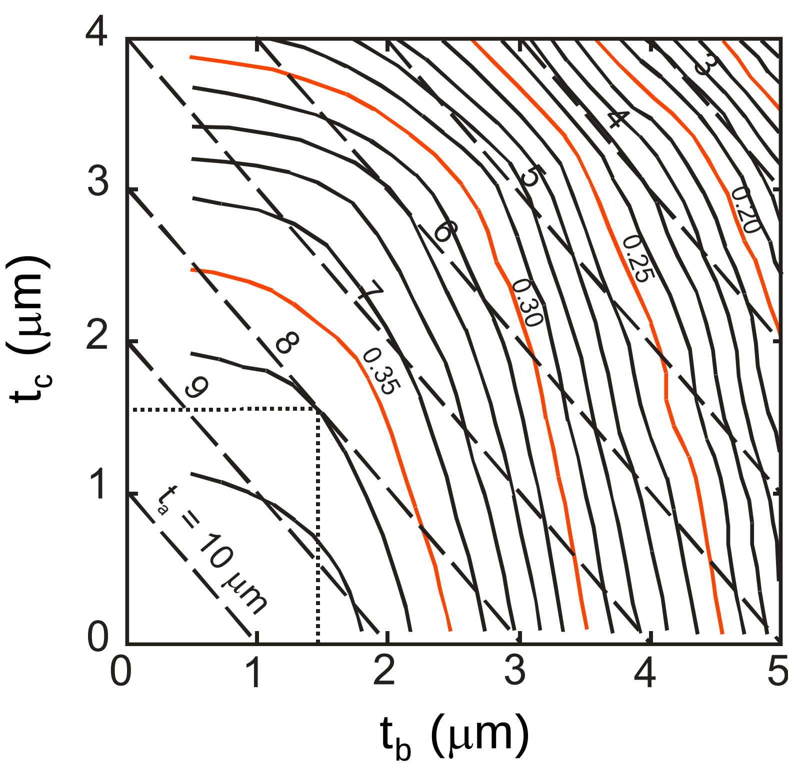
Q.E. Optimization for Lower Bias

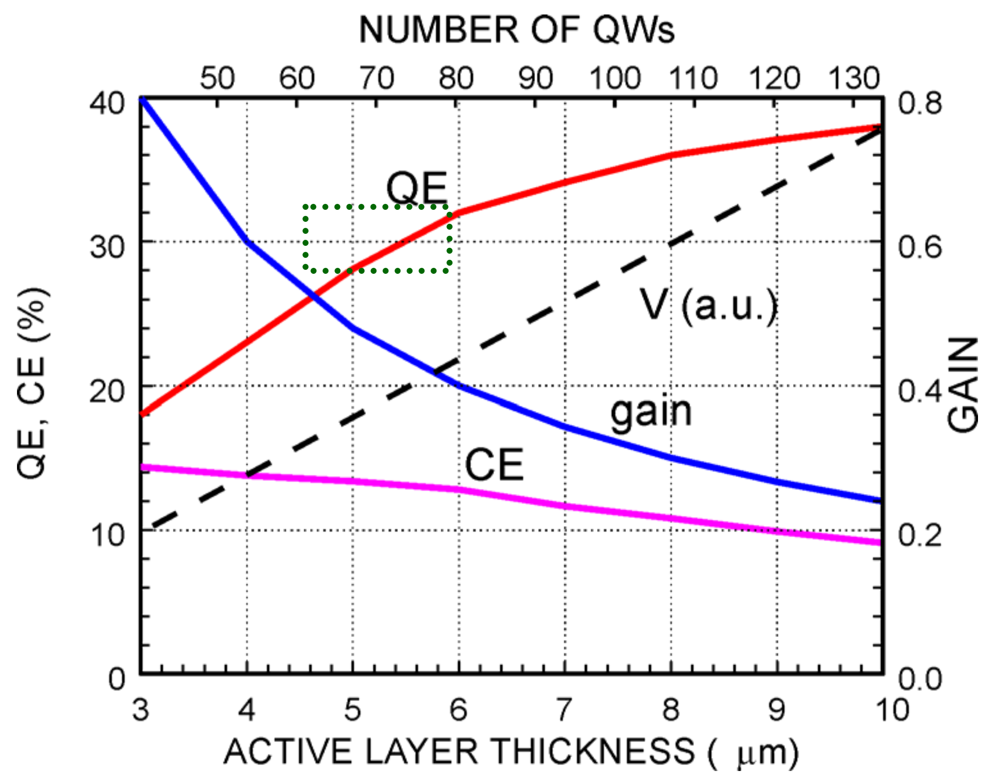


Two inclined sidewalls,

and, $t_c + t_a + t_b = 11\ \mu m$,

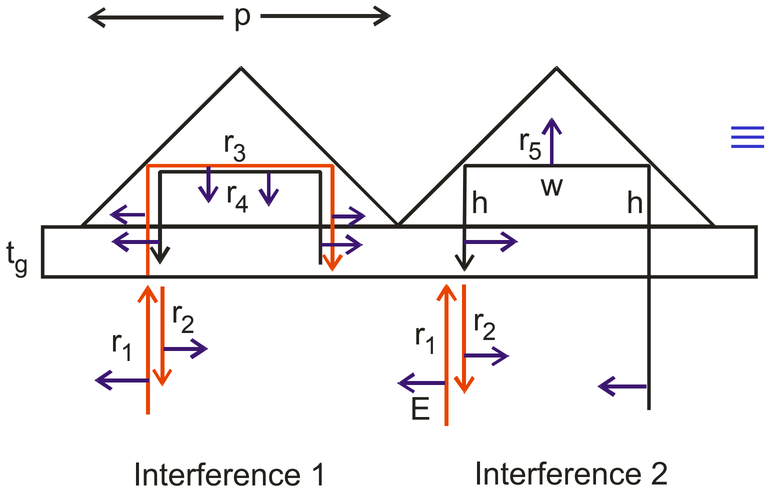
and, AR-coating is present.



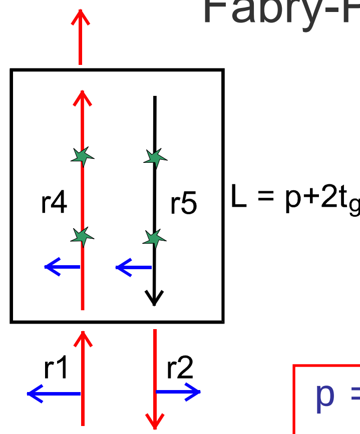


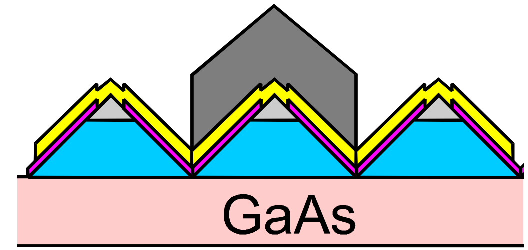
C-QWIPs with Thin Substrate

Thin substrate



Fabry-Perot Oscillations





p = 5.5 μm, t_g = 1.2 μm, t_a = 2.8 μm
t_d = 0.4 μm, QE_{max} = 50%

1:

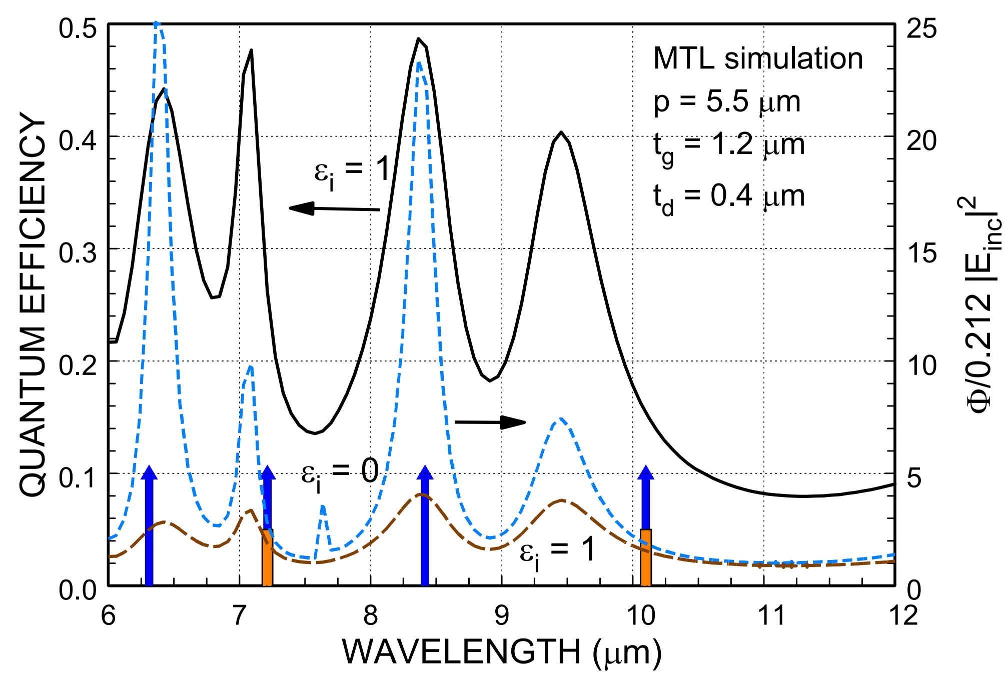
$$2\left(\frac{2\pi n_q p}{\lambda}+2\frac{2\pi n_s t_g}{\lambda}\right)=2N\pi\ ,$$

$$\Rightarrow \quad \lambda=\frac{2n_q p+4n_s t_g}{N}\ ,$$

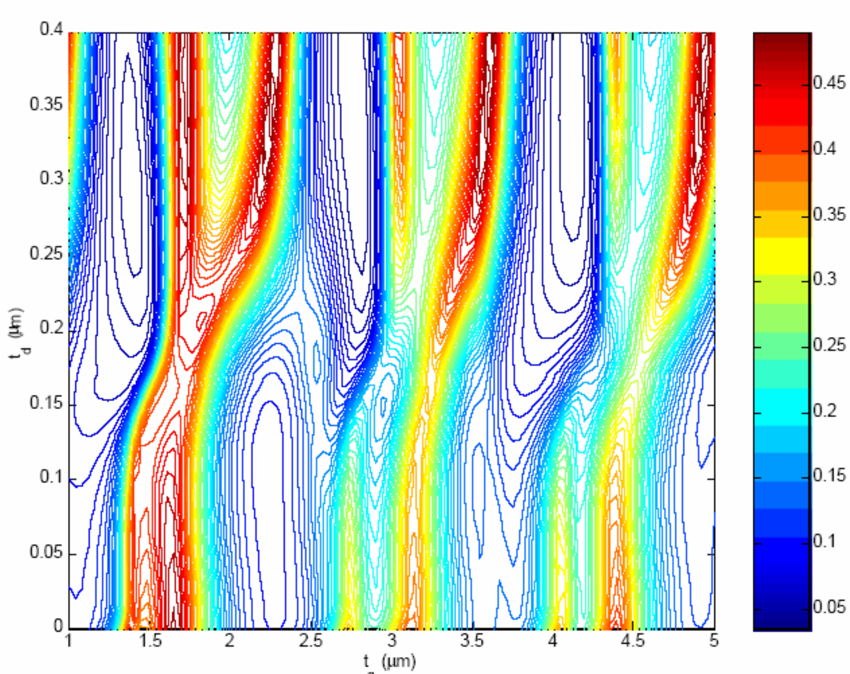
2:

$$\frac{2\pi n_q p}{\lambda}+2\frac{2\pi n_s t_g}{\lambda}=(2M+1)\pi\ ,$$

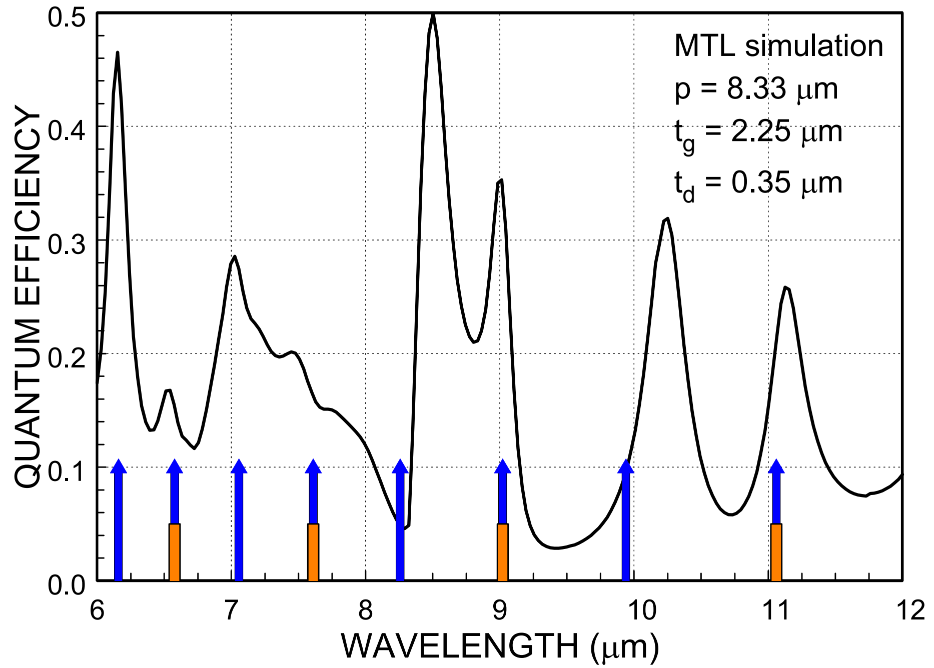
$$\Rightarrow \quad \lambda=\frac{2n_q p+4n_s t_g}{2M+1}\ ,$$



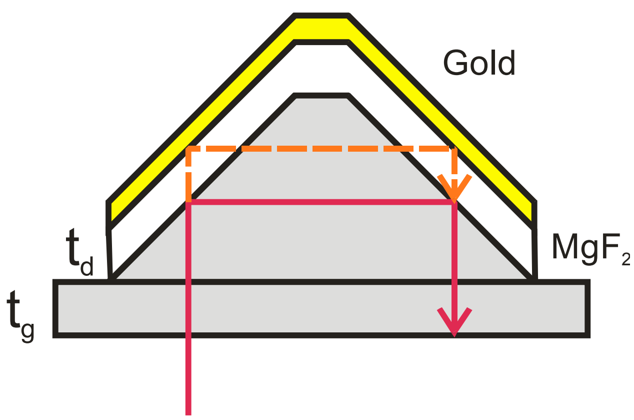
Reflector Layer Design



Q.E. for λ = 8.5 μm



With vertical sidewall coupling, QE ≥ 50%



For two-color detection at λ_1 and λ_2,

$$(n_q p + 2 n_s t_g)\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) = \text{integer}\,.$$

Next Material Design

Detector material design flow:

Operating voltage = 5 V

$\tau_{int} \approx 2$ msec

293 K, f/2 photocurrent = $3Me^-$/msec

$\Rightarrow$ 80 mV/QW $\Rightarrow$ 62 QWs

$\Rightarrow \eta = 30\%$

$\Rightarrow$ Conversion efficiency = 16%

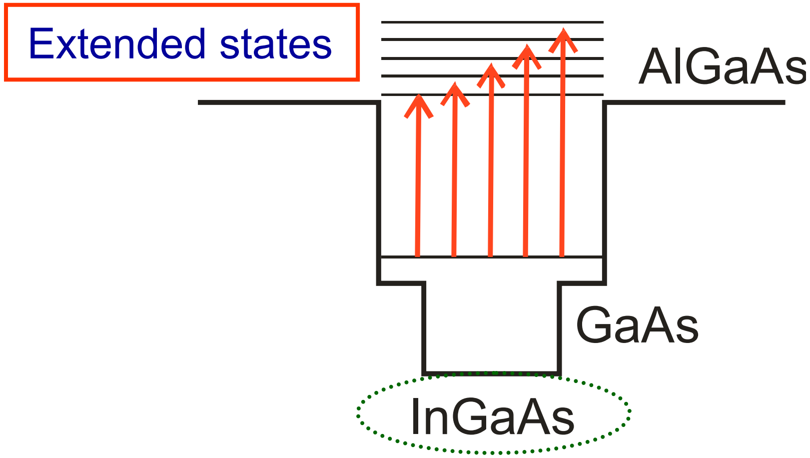
$\lambda_{peak} = 8.5\ \mu m$

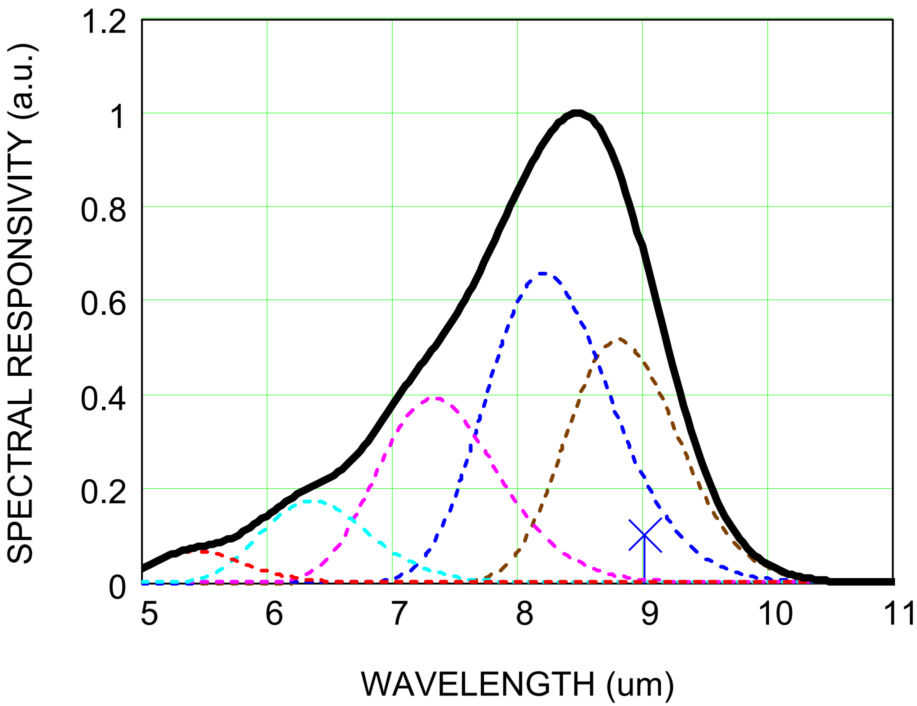
50% $\lambda_{cutoff} = 9.2\ \mu m$

$\Rightarrow$ BLIP temperature = 74 K

$\Rightarrow$ NEΔT = 30 mK @ 74 K, 2.2 ms

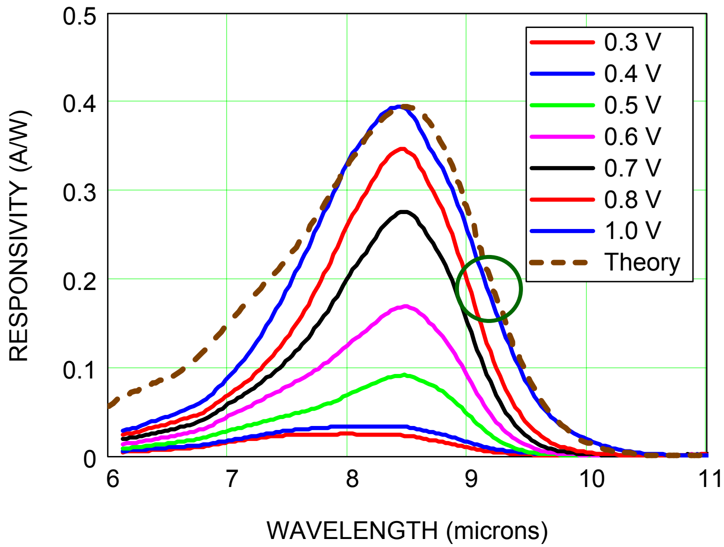
$\Rightarrow$ NEΔT = 19 mK @ 70 K, 3.5 ms





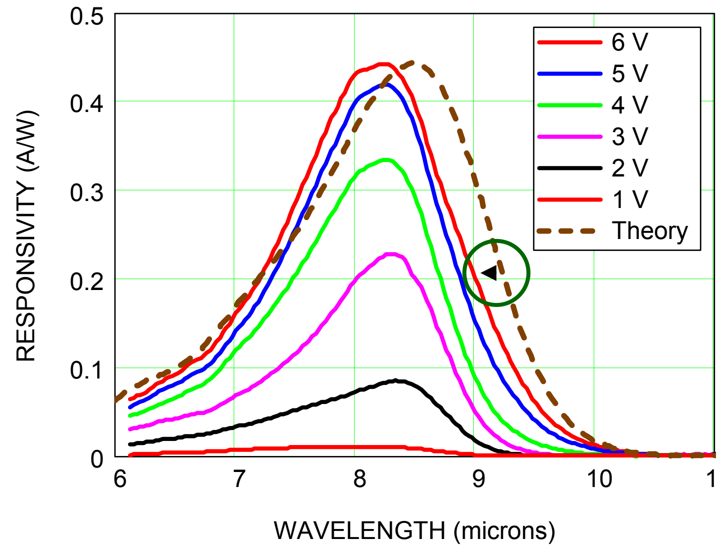
Optimized Detector Characteristics

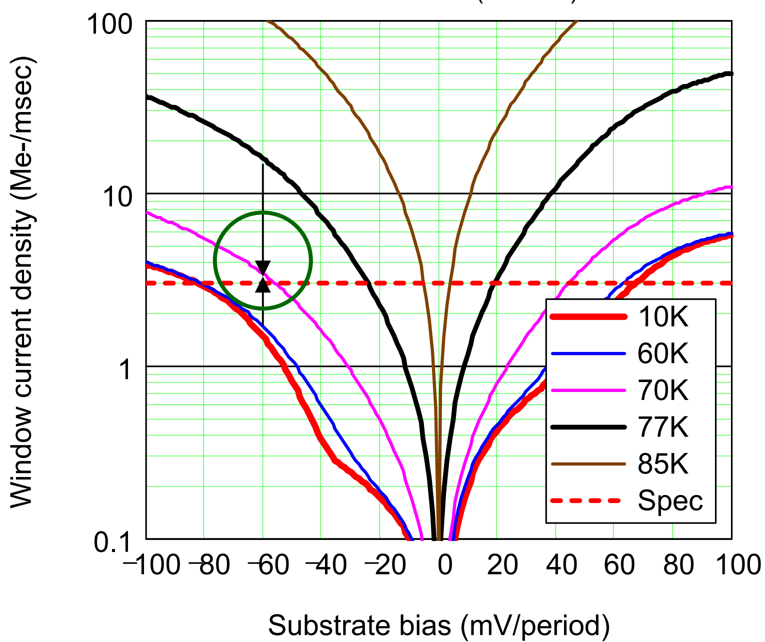
Test sample 40737

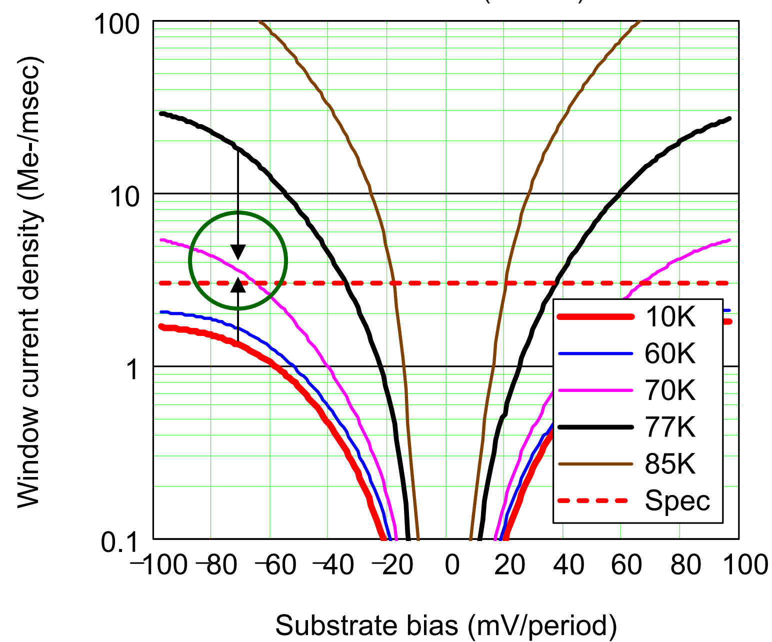


Full wafer 40787

Edge coupling



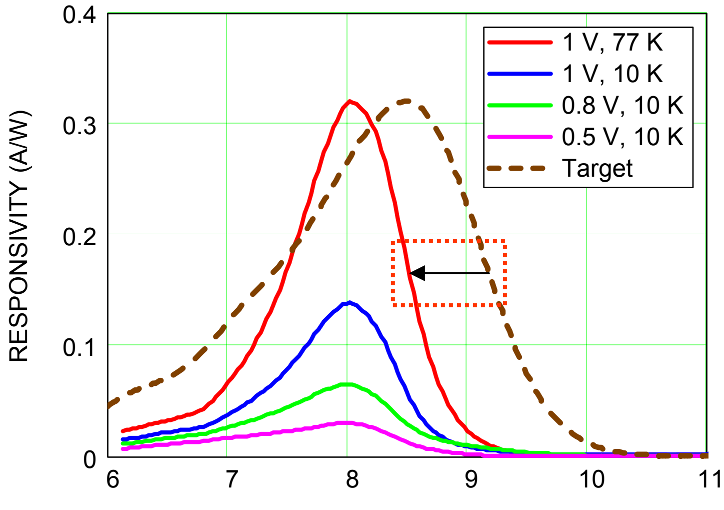


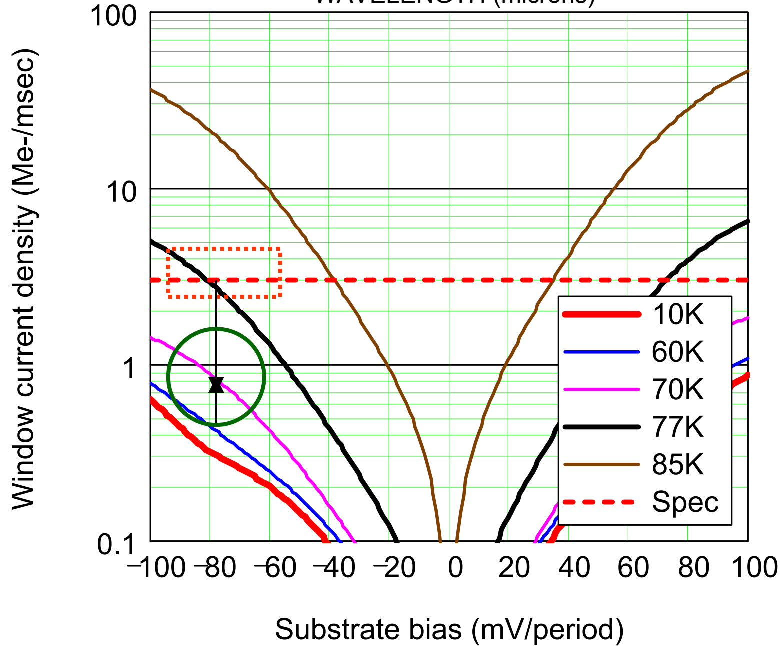


Finite threshold voltage

Other Detector Characteristics

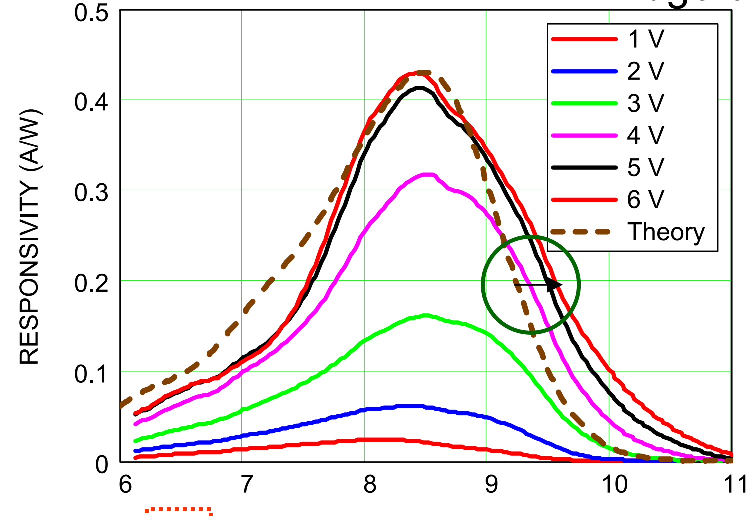
Test sample 40111, x = 0.21

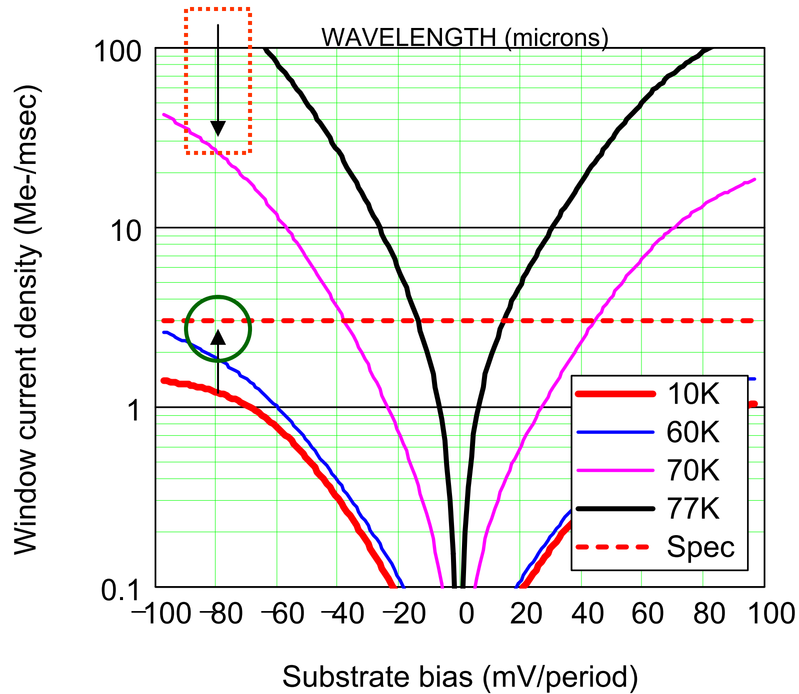




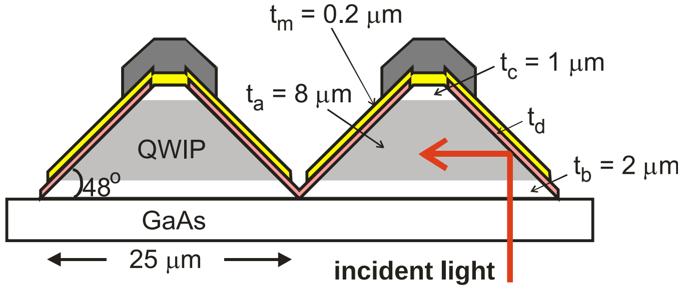
Full wafer 40145, x = 0.20

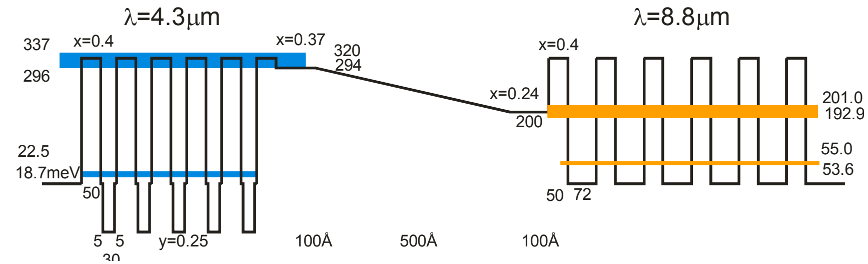
Edge coupling

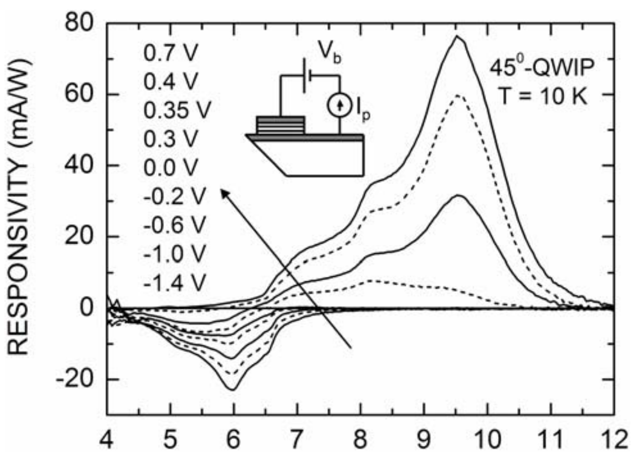


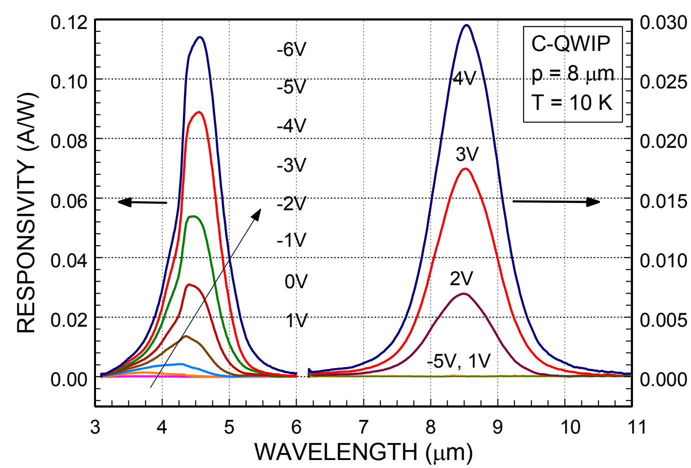


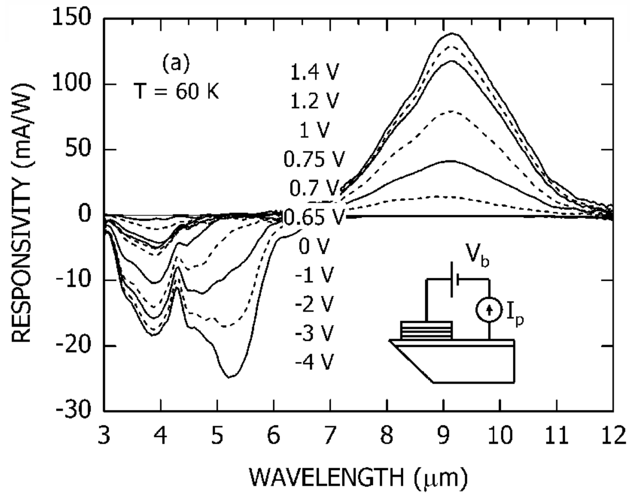
Voltage Tunable Two-Color QWIPs

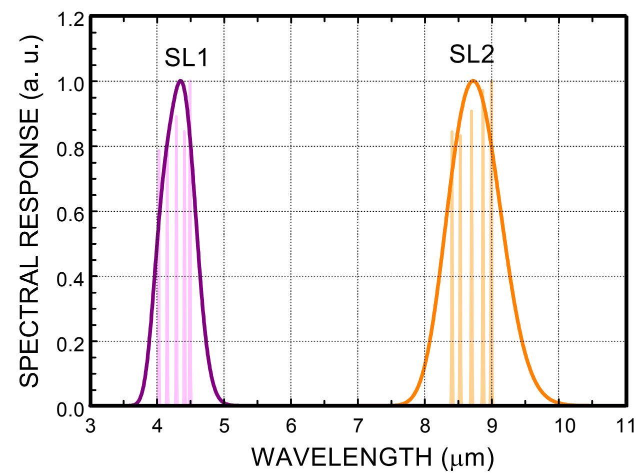




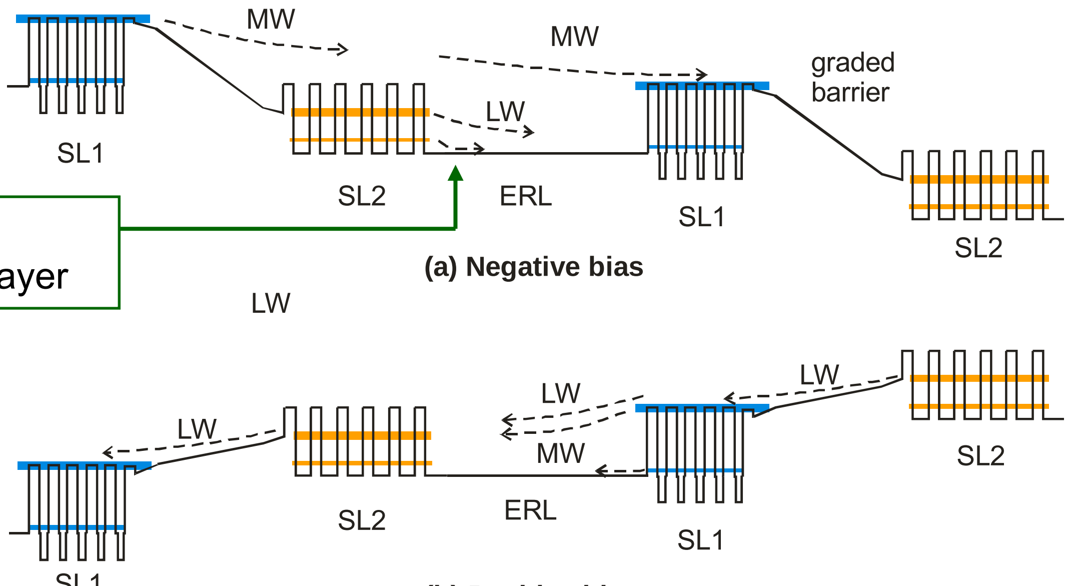








Detector Characteristics



Highly conducting, energy relaxation layer

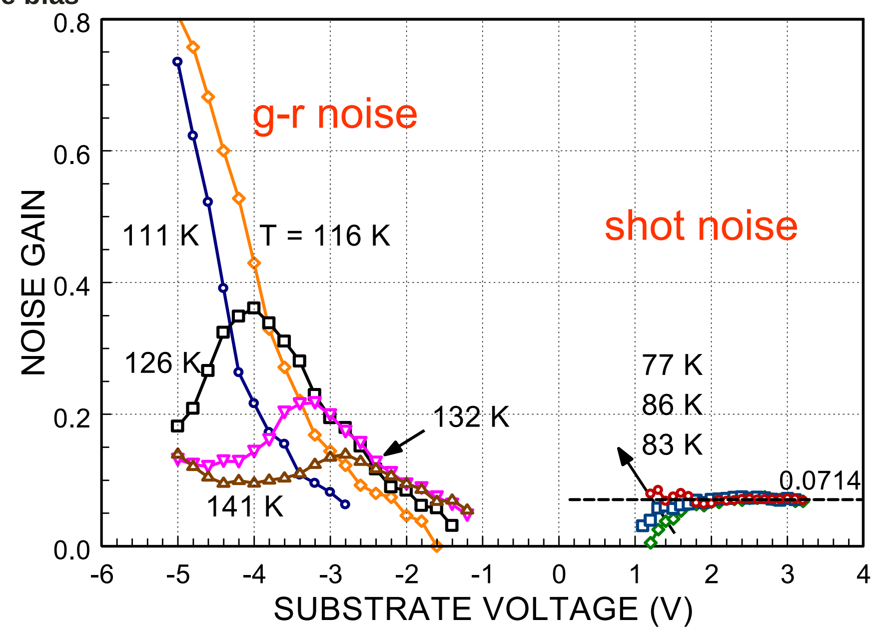
(a) Negative bias

(b) Positive bias

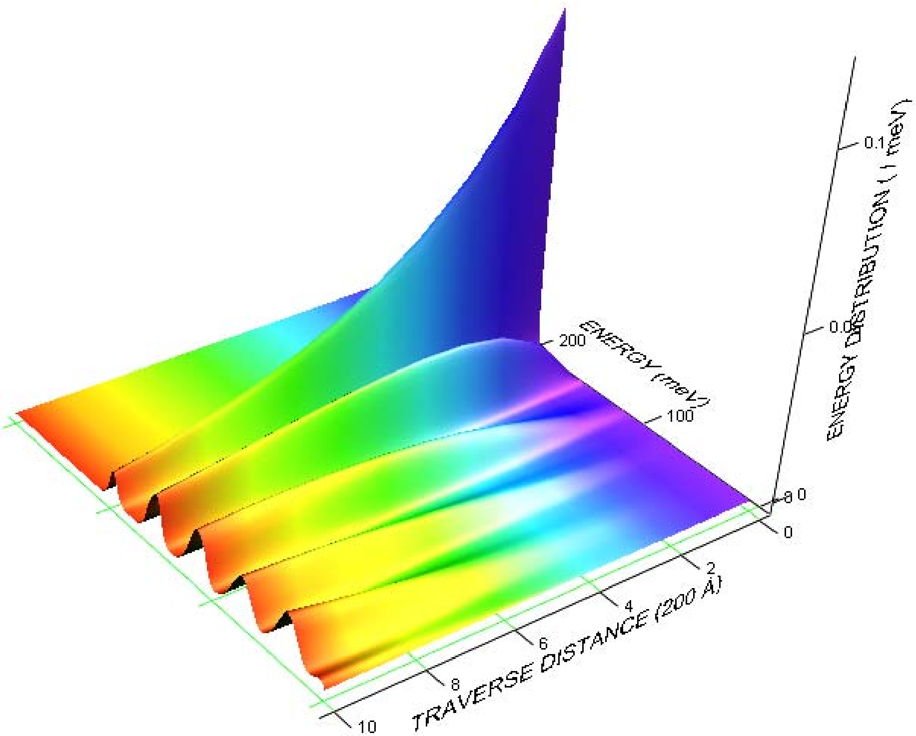
phonon plasmon

$$\frac{1}{\tau_T(E_k)} = \frac{m^* e^2}{2\pi^2\hbar^3}\frac{1}{k}\left[\gamma_{ph}\ln\left(\frac{k+k'_{ph}}{k-k'_{ph}}\right)+\gamma_{pl}\ln\left(\frac{k+k'_{pl}}{k-k'_{pl}}\right)\right],$$

Hot-electron lifetime ∝ momentum



Hot-Electron Energy Distribution

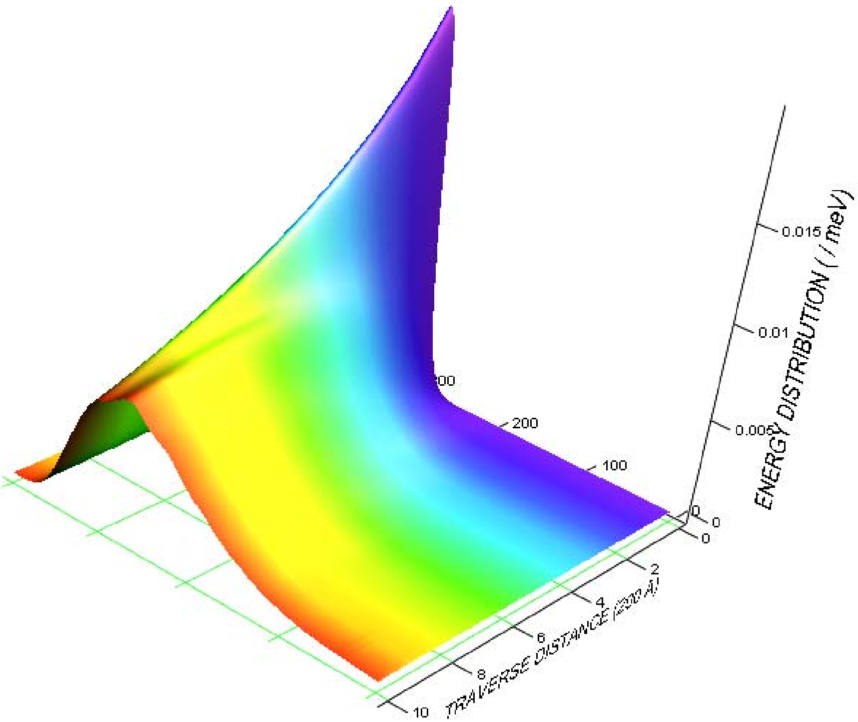


Injection energy = 197 meV

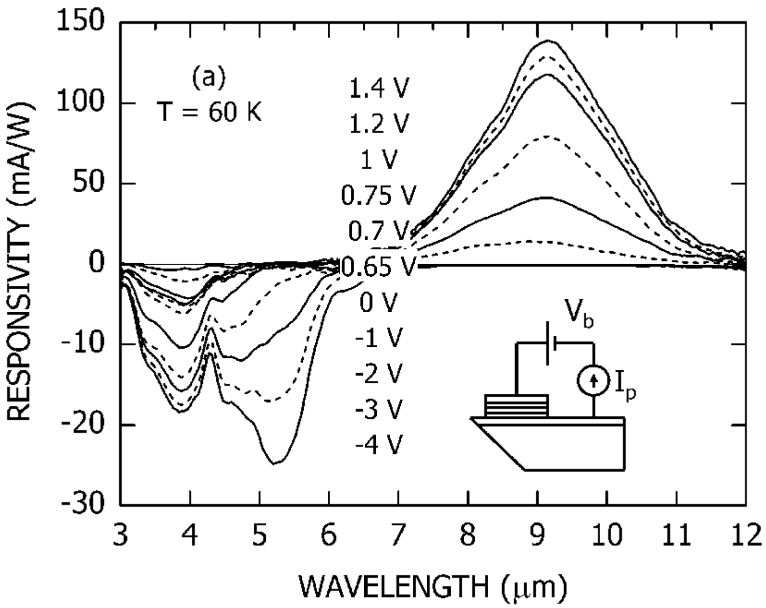
τ = 78 fs

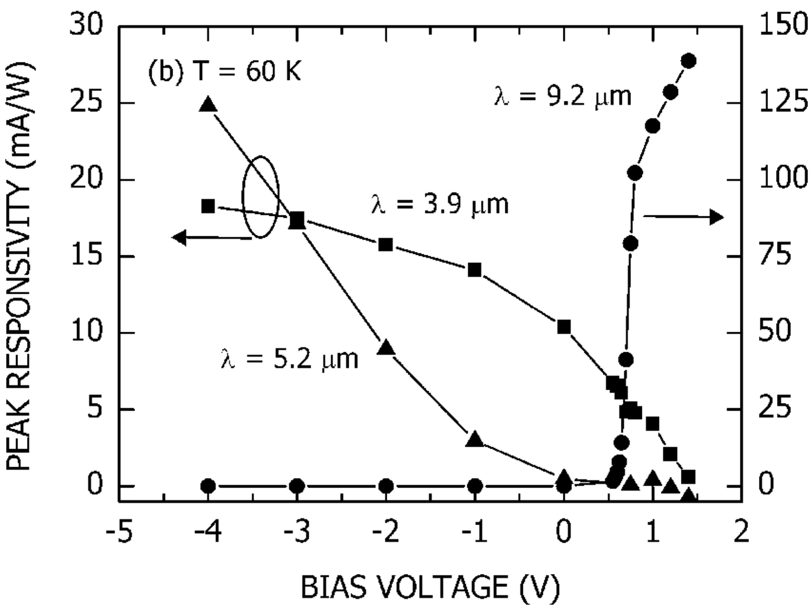
Injection energy = 317 meV

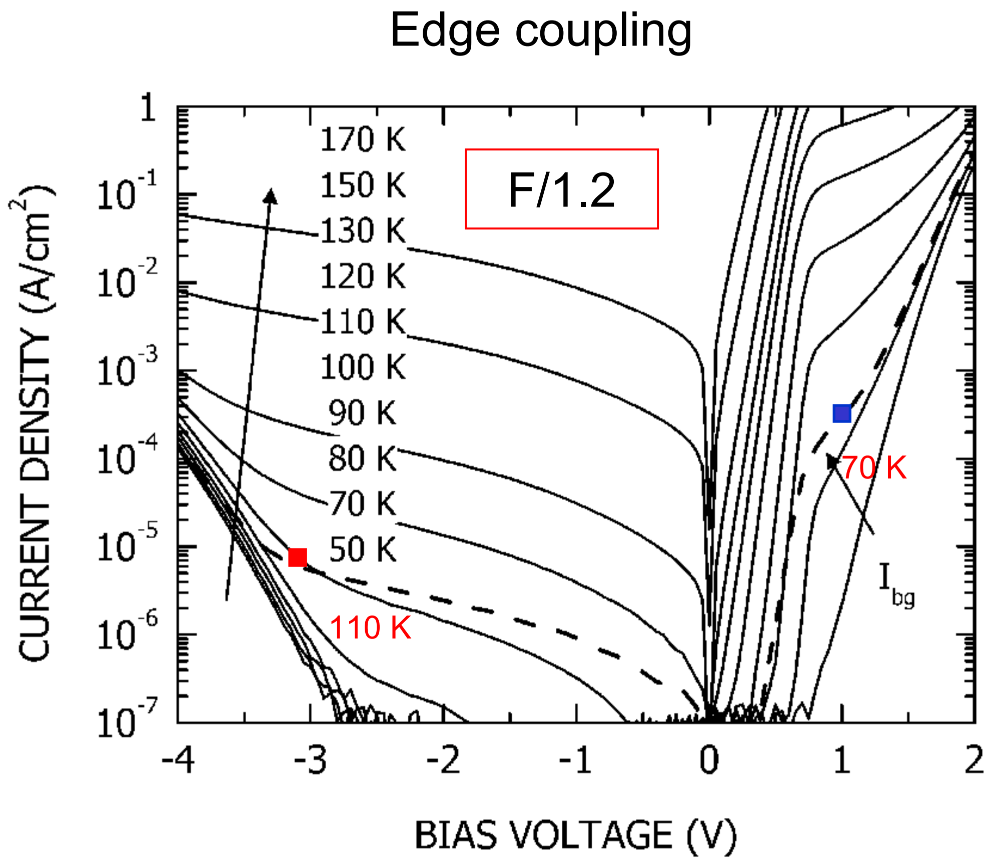
τ = 170 fs



3.9/9.2 μm Detection







For F/6, LW: NEΔT = 18 mK with τ = 10 ms

MW: NEΔT = 26 mK with τ = 23 ms

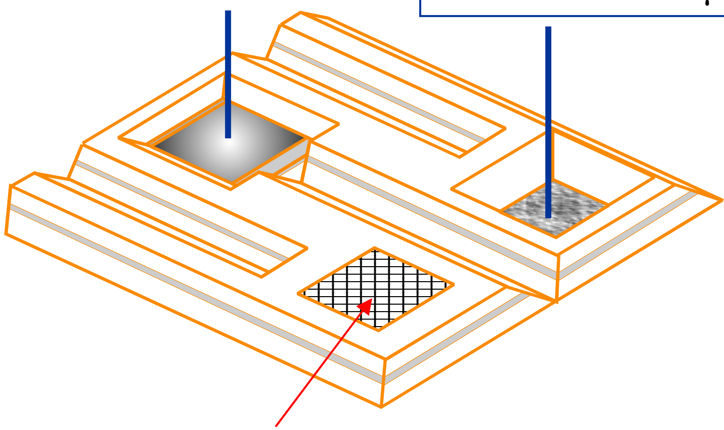
4-color Hybrid Approach

Voltage Tunable 4-color FPAs

middle contact, grounded

−3 V ⇒ 4.5 μm

+1.5 V ⇒ 8.3 μm

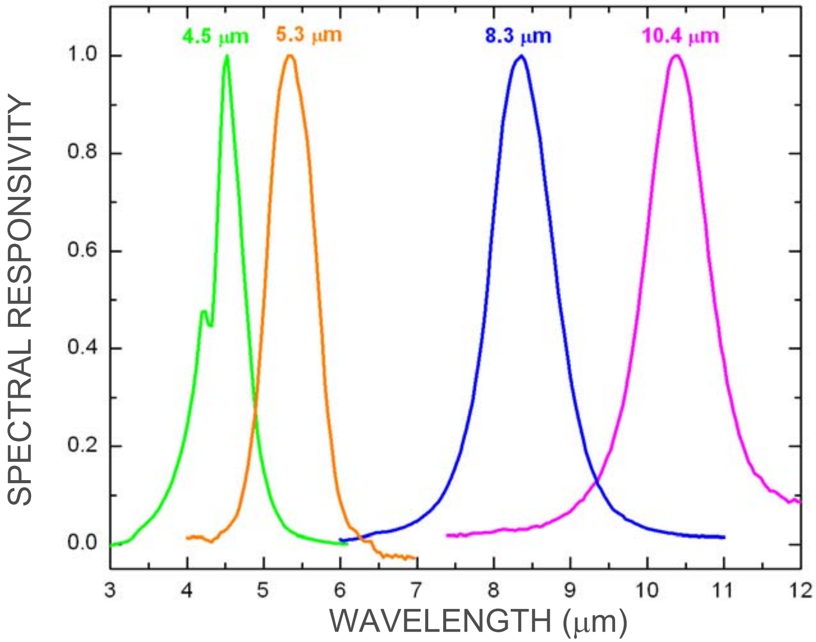


+3 V ⇒ 5.3 μm

-1.5 V ⇒ 10.4 μm

40 μm x 40 μm C-QWIP pixel

Experimental data



# of combinations of channels

= # of 2-color + # of 3-color + # of 4-color

= 6 + 4 + 1 = 11

e.g. 5.3/4.5 2-color, (5.3/10.4) 2-color

10.4 / (4.5/8.3) 3-color,

(5.3/10.4) / (4.5/8.3) 4-color.

Conclusion

We have investigated the basic elements in achieving large format, high quantum efficiency, and multi-color FPAs.

These elements include system requirements, broadband light coupling schemes, and voltage tunable detector materials.

The FPA results are consistent with the detector model.