N91-14392

Quantum Well Infrared Photodetectors (QWIP)

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There has been a lot of interest in III-V long wavelength detectors in the $\lambda = 8$ - 12 μm spectral range as alternatives to HgCdTe.[1-6] Recently high performance quantum well infrared photodetectors (QWIP) have been demonstrated. They have a responsivity of R = 1.2 A/W, and a detectivity $D_\lambda^* = 2\times10^{10}$ cm $Hz^{1/2}$ / W at 68 K for a QWIP with a cutoff wavelength of λ_c -= 10.7 μm and a R = 1.0 A/W, and $D_\lambda^* = 2\times10^{10}$ cm $Hz^{1/2}$ / W at T = 77 K for $\lambda_c = 8.4$ μm. These detectors consist of 50 periods of MBE grown layers doped $n = 1\times10^{18}$ cm^{-3} having GaAs quantum well widths of 40 Å and barrier widths of 500 Å of $Al_xGa_{1-x}As$.

Due to the well-established GaAs growth and processing techniques these detectors have the potential for large, highly uniform, low cost, high performance arrays as well as monolithic integration with GaAs electronics, high speed and radiation hardness.

Our latest results on the transport physics, device performance and arrays will be discussed.

1. J.S. Smith, L.C. Chiu, S. Margalit, A. Yariv, and A.Y. Cho, J. Vac. Sci. Technol. *B1*, 376 (1983).
2. D.D. Coon and R.P.G. Karunasini, Appl. Phys. Lett. *45*, 649 (1984).
3. K. W. Goossen, S. A. Lyon, and K. Aiavi, Appl. Phys. Lett. *52*, 1701 (1988).
4. A. Kastalsky, T. Duffield, S. J. Allen, and J. Harbison, Appl. Phys. Lett. *52*, 1320 (1988).
5. S. R. Kurtz, L. R. Dawson, T. E. Zipperian, and R. D. Whaley, Jr., IEEE Electron. Dev. Lett. *11*, 54 (1989).
6. B. F. Levine, C. G. Bethea, G. Hasnain, V. O. Shen, E. Pelve, R. R. Abbott, and S. J. Hsieh, Appl. Phys. Lett. *56*, 851 (1990).

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Quantum Well Infrared Photodetectors

QWIP

Research

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R. M. Braun

LWIR GaAs Quantum Well Detectors

Esaki, Sakaki

Smith, Chiu, Margalit, Yariv, Cho

Coon, Karunasiri

Goosen, Lyon

Capasso, Mohammed, Cho

Kastalsky, Duffield, Allen, Harbison

Janousek, Daugherty, Bloss, Rosenbluth, O'Loughlin, Kauter, DeLuccia, Perry

Woodall

Wu, Sato, Wen

Maserjian

Döhler

Mii, Karunasiri, Wang, Bai

Abstreiter et al.

MATERIAL FOR 10 μm DETECTORS

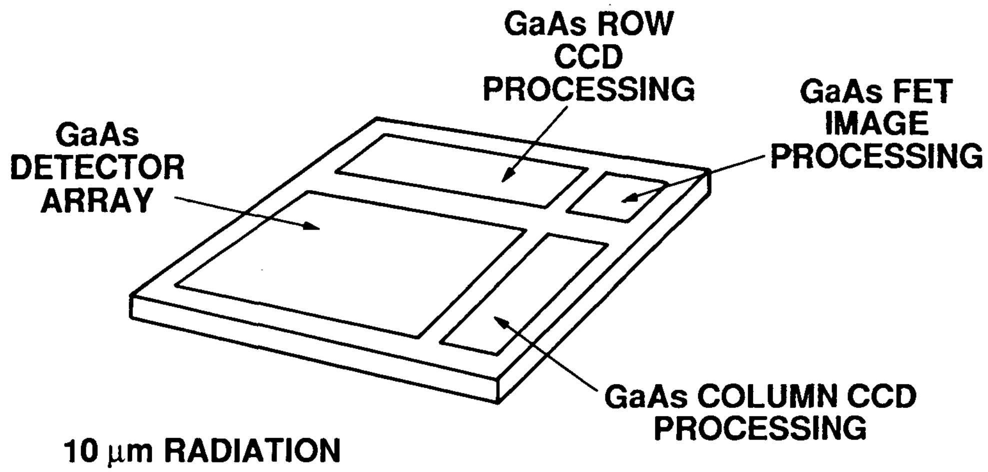
HgCdTe DETECTORS

- DIFFICULT GROWTH AND PROCESSING TECHNOLOGY
- POOR UNIFORMITY OF ARRAYS
- LOW QUALITY CdTe SUBSTRATES

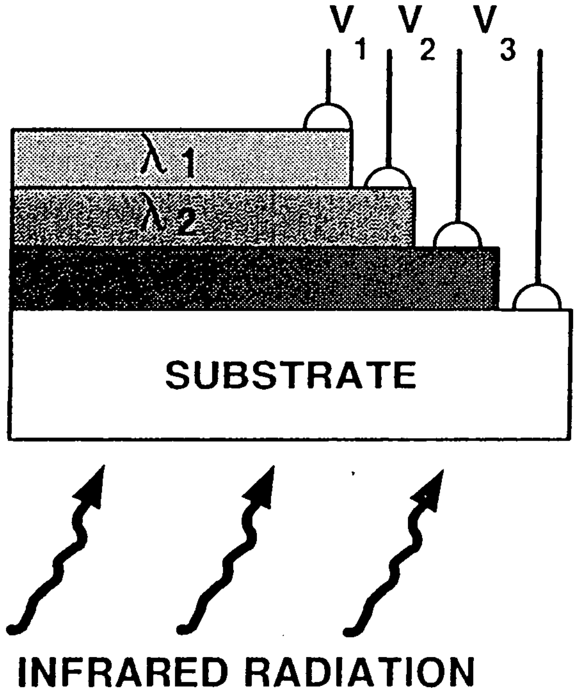
GaAs DOPED QUANTUM WELL DETECTORS

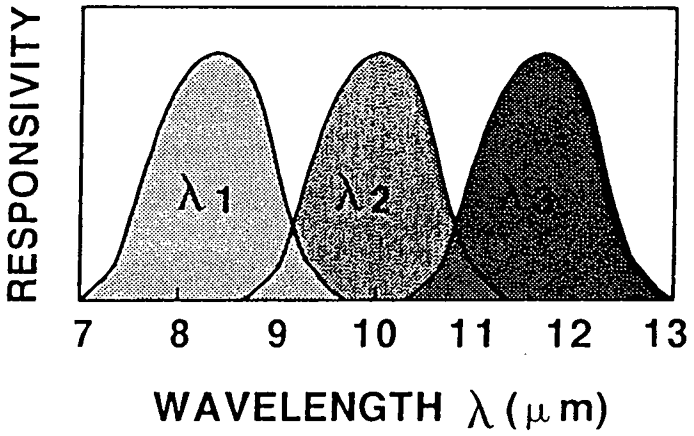
- PERFORMANCE COMPARABLE TO HgCdTe
- MATURE GROWTH AND PROCESSING TECHNOLOGY
- EXCELLENT 3" GaAs SUBSTRATES
- MONOLITHIC INTEGRATION WITH GaAs ELECTRONICS

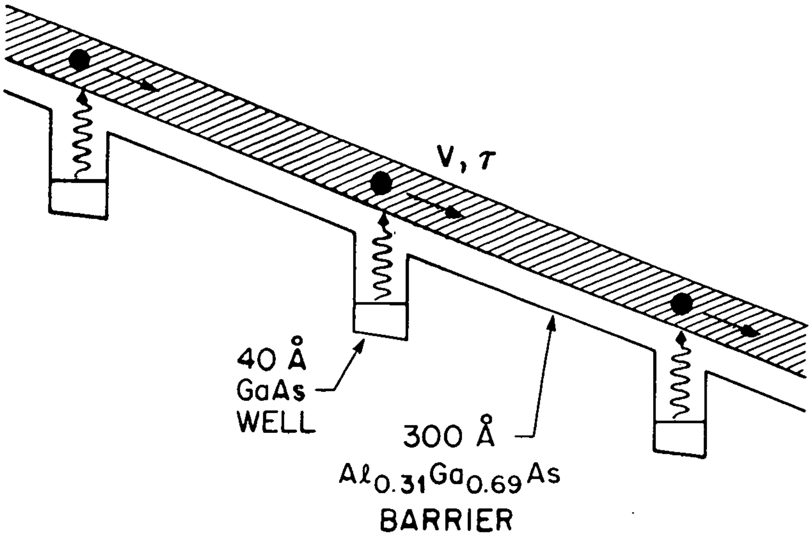
MONOLITHICALLY INTEGRATED GaAs QUANTUM WELL DETECTOR ARRAY AND IMAGE PROCESSING ELECTRONICS

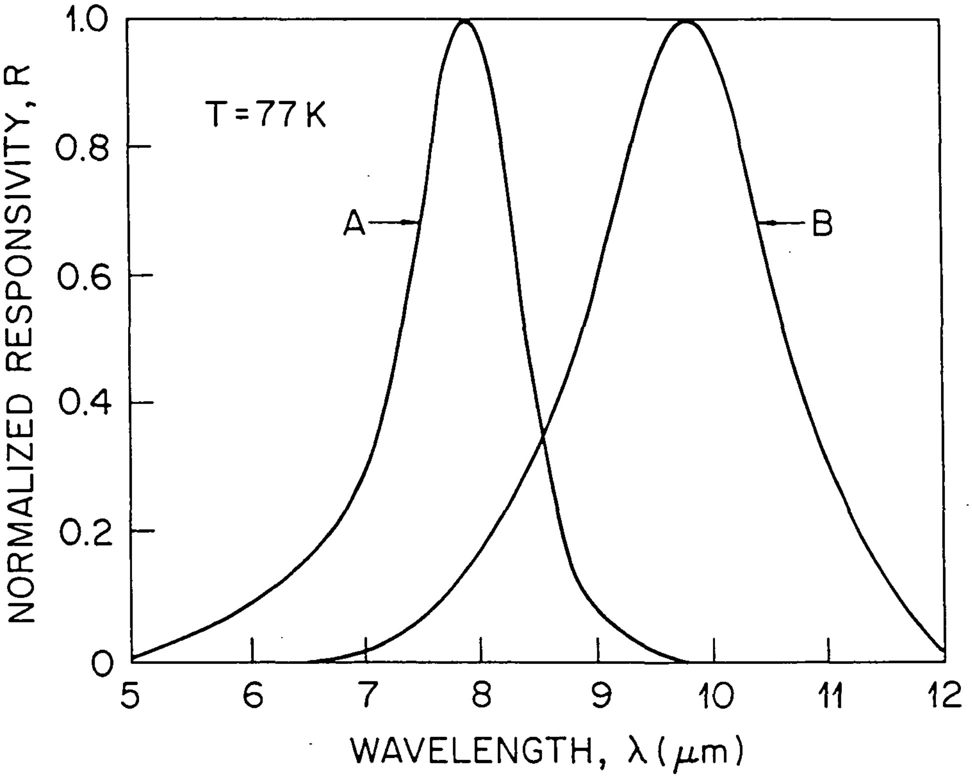


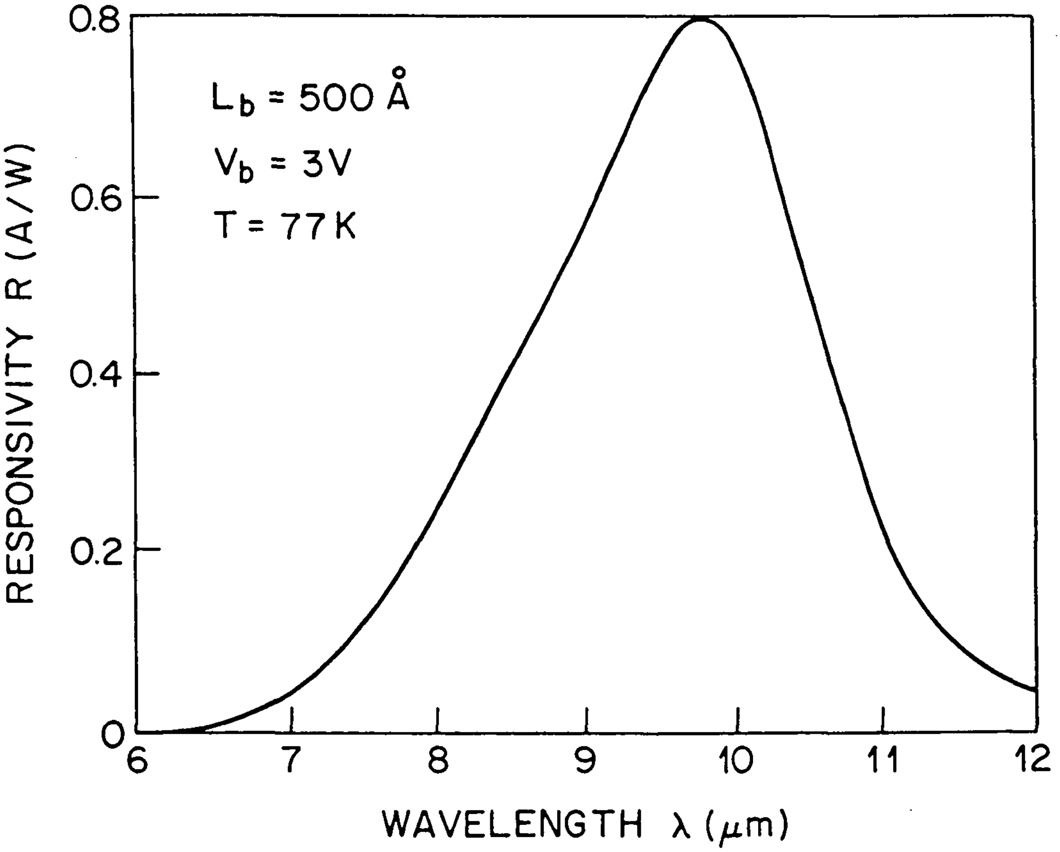
VERTICALLY INTEGRATED GaAs QUANTUM WELL INFRARED SPECTROMETER

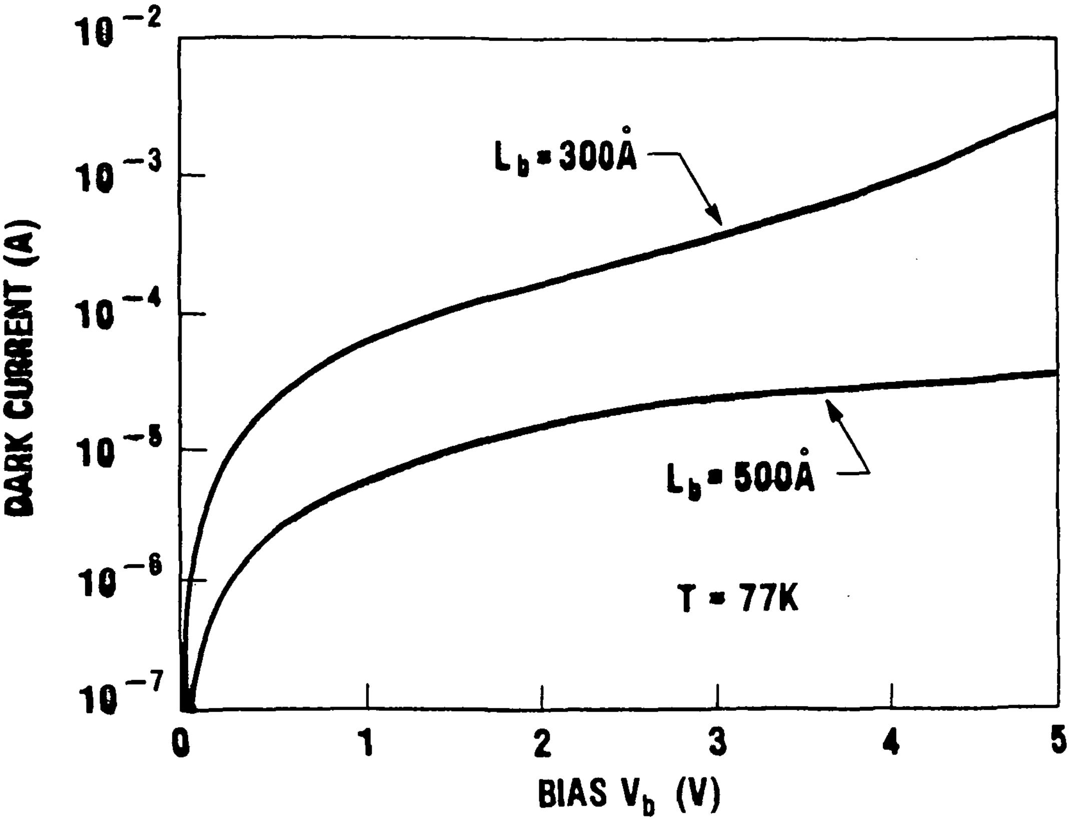







1.0
0.8
0.6
0.4
0.2
0
NORMALIZED RESPONSIVITY, R
T=77K
A
B
5
6
7
8
9
10
11
12
WAVELENGTH, λ (μm)


0.8
0.6
0.4
0.2
0
RESPONSIVITY R (A/W)
L_b = 500 Å
V_b = 3V
T = 77K
6
7
8
9
10
11
12
WAVELENGTH λ (μm)



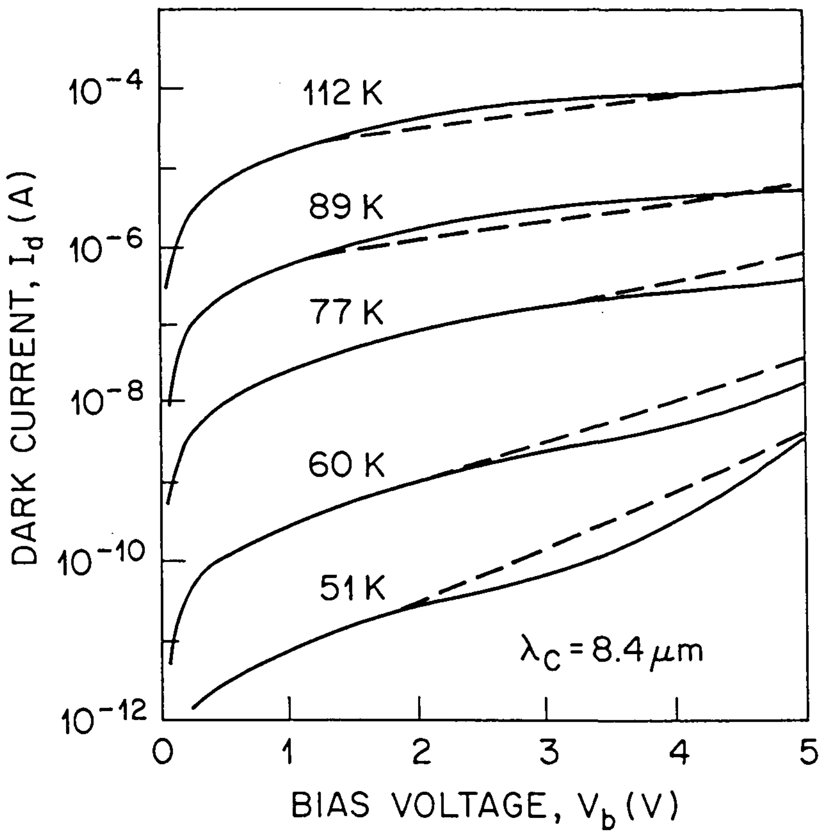
DARK CURRENT CALCULATION

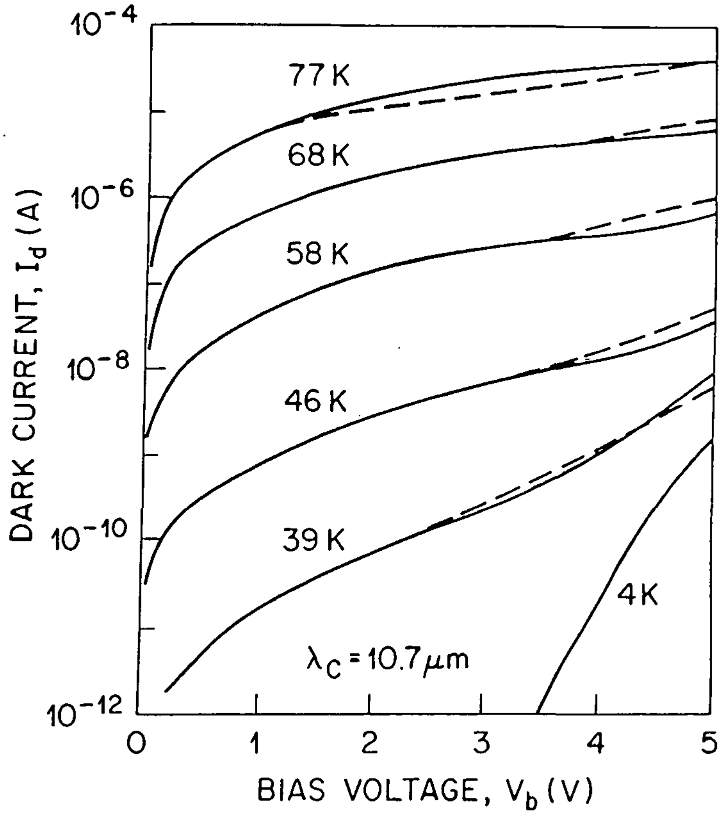
$$n(V) = \frac{m^*}{\pi \hbar^2 Lp} \int_{E_0}^{\infty} f(E)T(E)dE$$

$E > E_b$ Thermionic

$E < E_b$ Tunneling

$$I_D = nevA$$


DARK CURRENT, I_d (A)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
112 K
89 K
77 K
60 K
51 K
$\lambda_C = 8.4\,\mu m$
0
1
2
3
4
5
BIAS VOLTAGE, V_b (V)


DARK CURRENT, I_d (A)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
77 K
68 K
58 K
46 K
39 K
4 K
$\lambda_C = 10.7\,\mu m$
0
1
2
3
4
5
BIAS VOLTAGE, V_b (V)

$$\lambda_c = 10.7\ \mu\text{m}$$

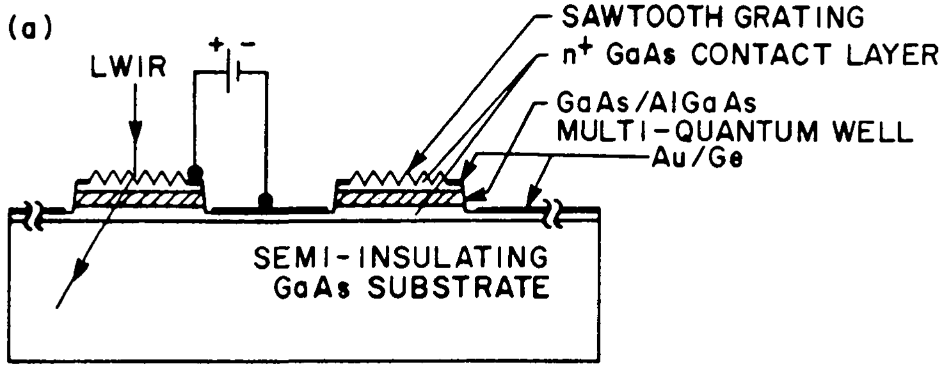
$$D^* = 1\times 10^{10}\ \text{cm}\sqrt{\text{Hz}}/\text{W}$$

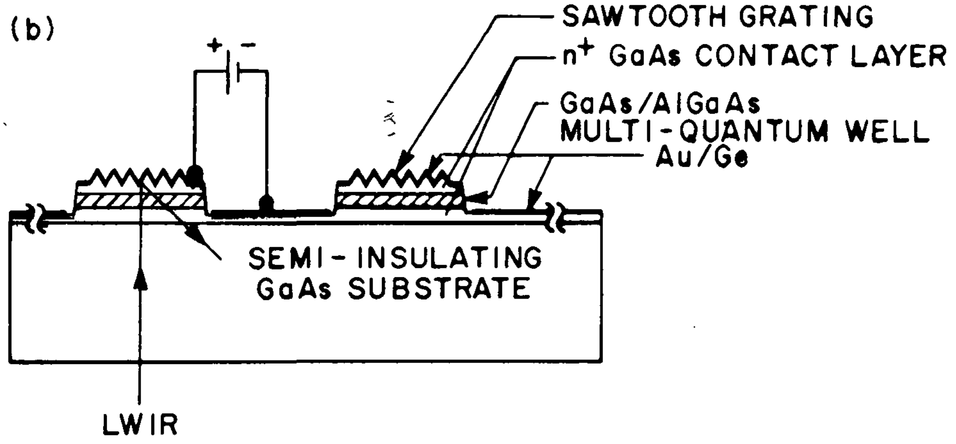
$$T = 68\ \text{K}$$

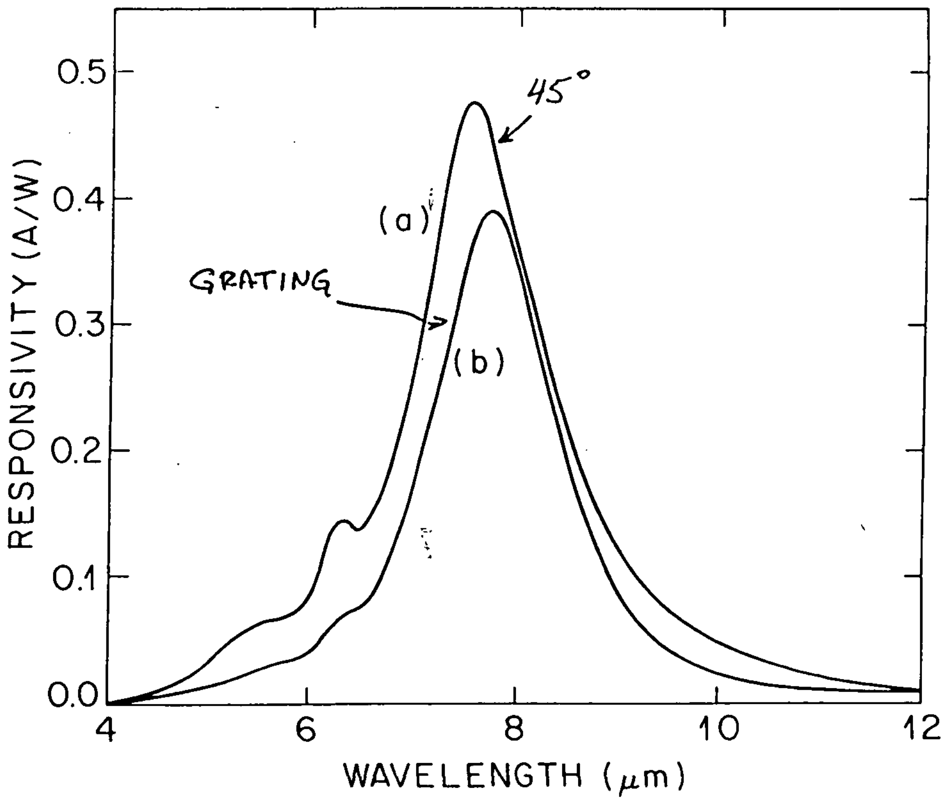
$$\lambda_c = 10\ \mu\text{m}$$

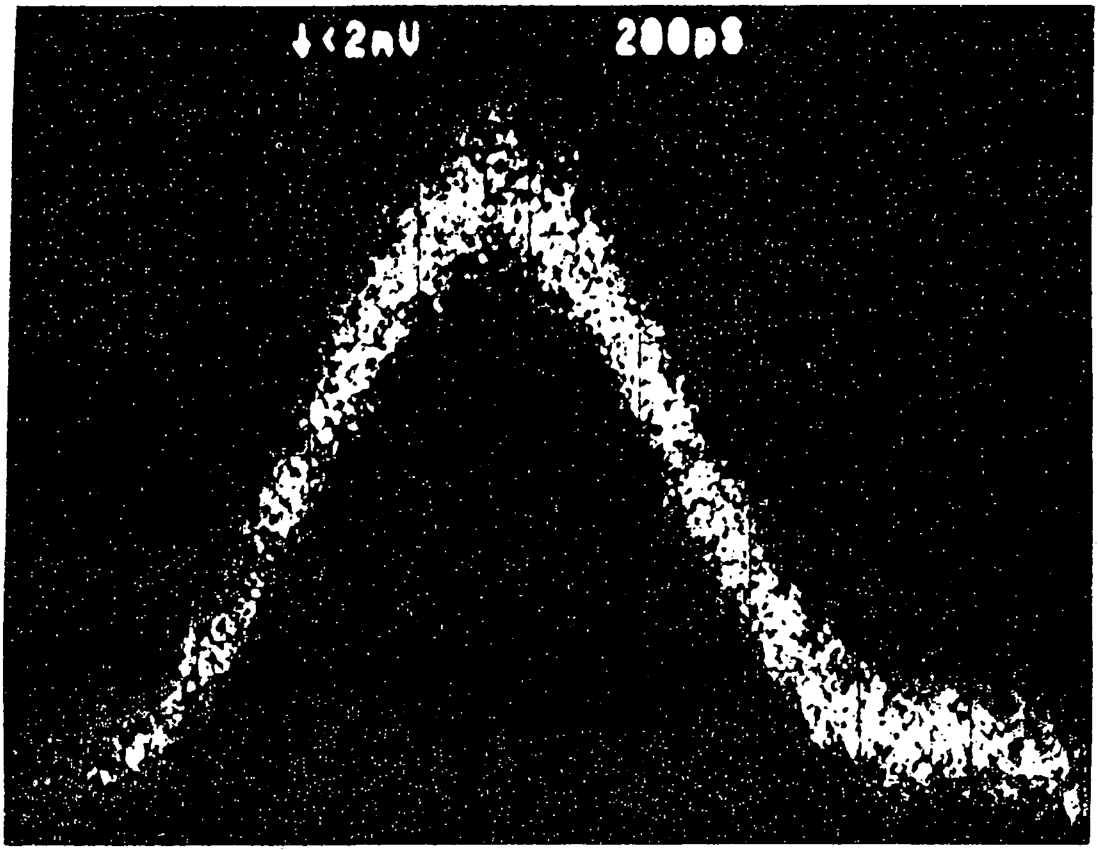
$$D^*(\text{theory}) > 10^{10}\ \text{cm}\sqrt{\text{Hz}}/\text{W}$$

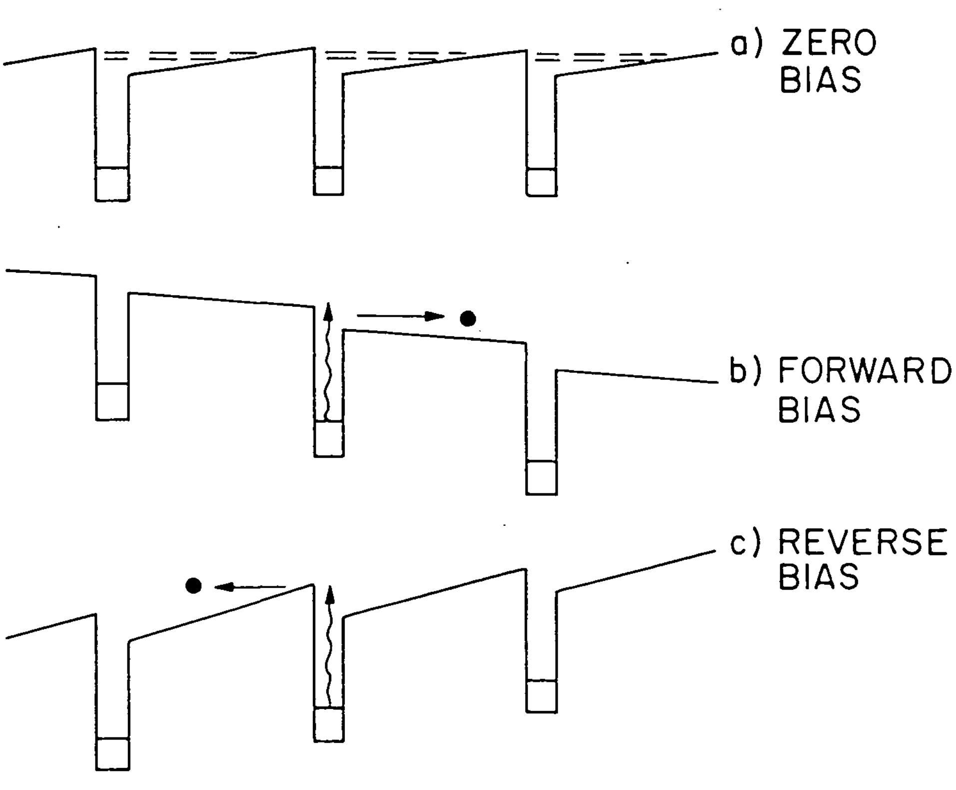
$$T = 77\ \text{K}$$

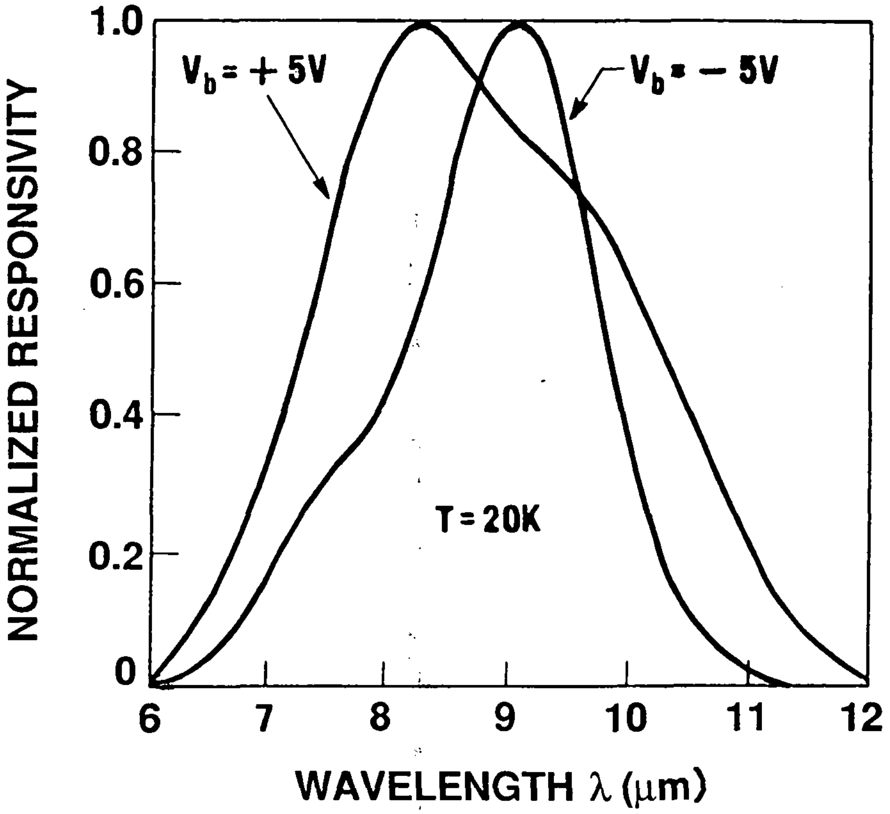

(a)
LWIR
+ −
SAWTOOTH GRATING
n+ GaAs CONTACT LAYER
GaAs/AlGaAs
MULTI-QUANTUM WELL
Au/Ge
SEMI-INSULATING
GaAs SUBSTRATE

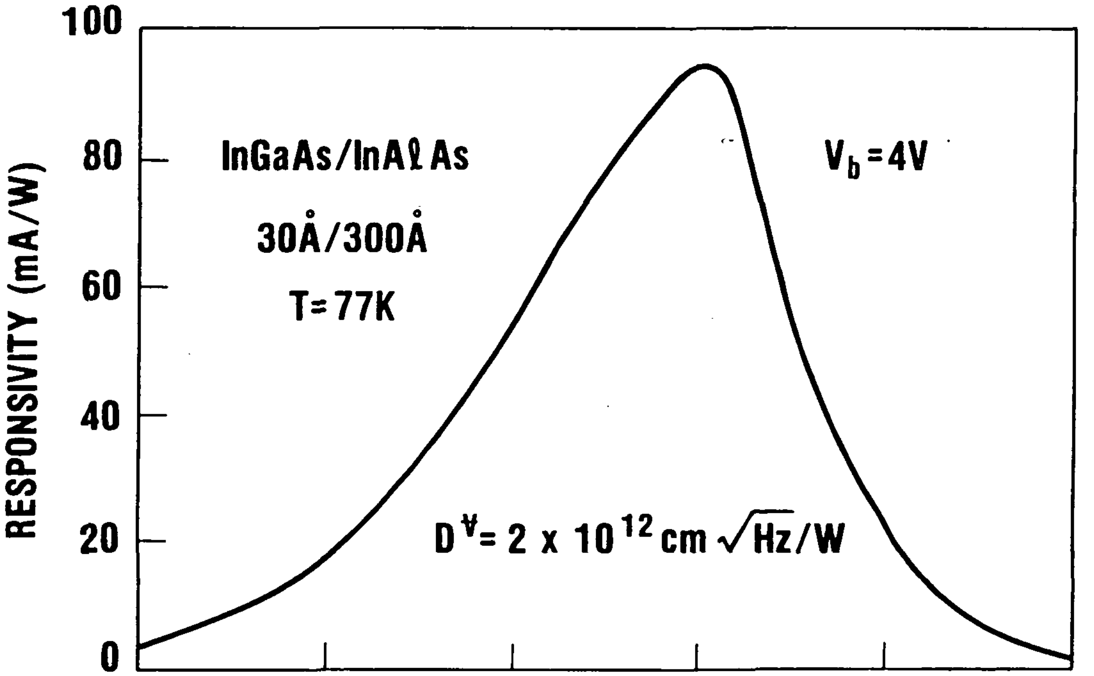

(b)
+ −
SAWTOOTH GRATING
n+ GaAs CONTACT LAYER
GaAs/AlGaAs
MULTI-QUANTUM WELL
Au/Ge
SEMI-INSULATING
GaAs SUBSTRATE
LWIR

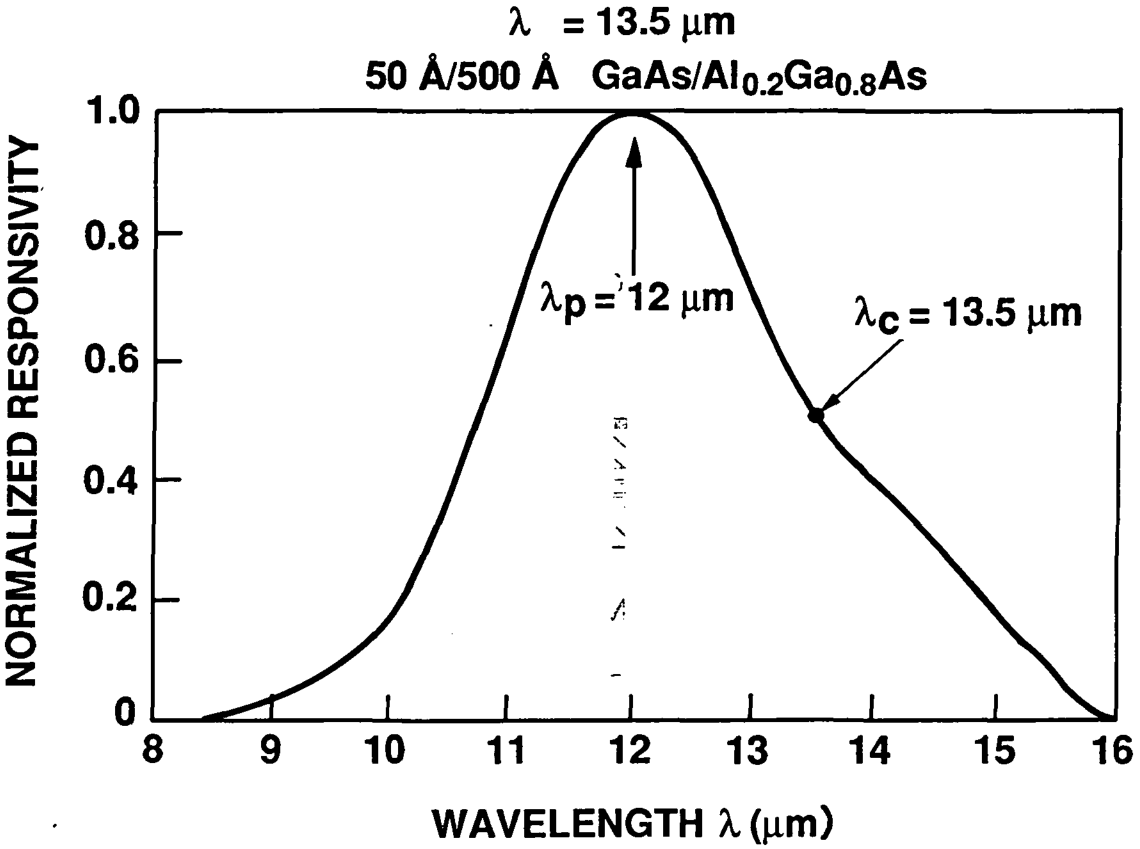

45°
(a)
GRATING
(b)
RESPONSIVITY (A/W)
0.0
0.1
0.2
0.3
0.4
0.5
4
6
8
10
12
WAVELENGTH (μm)


↓<2mV
200pS


a) ZERO BIAS
b) FORWARD BIAS
c) REVERSE BIAS

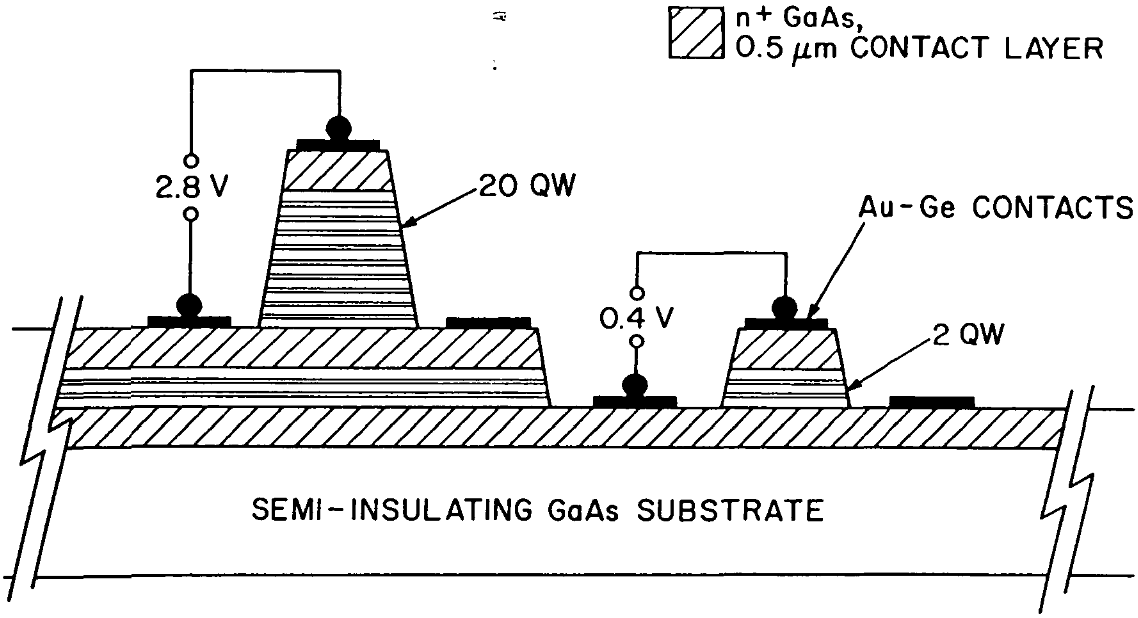

1.0
0.8
0.6
0.4
0.2
0
NORMALIZED RESPONSIVITY
$V_b = +5V$
$V_b = -5V$
T = 20K
6
7
8
9
10
11
12
WAVELENGTH λ (μm)

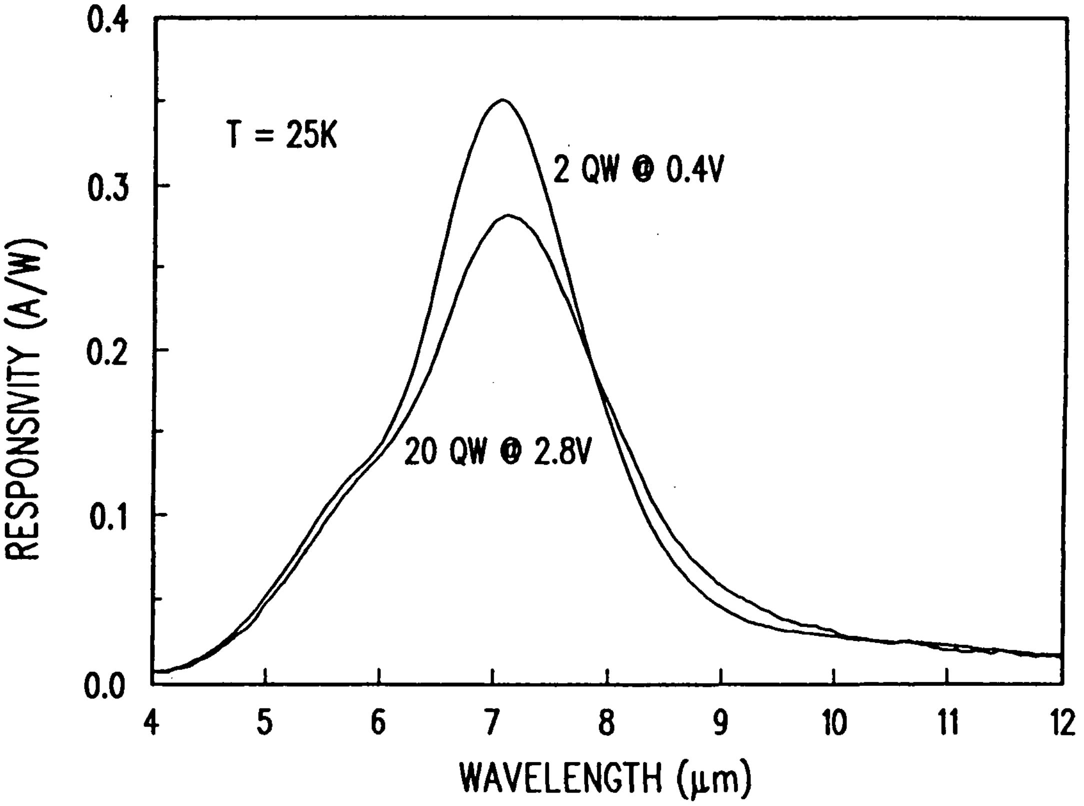

100
80
60
40
20
0
RESPONSIVITY (mA/W)
InGaAs/InAlAs
30Å/300Å
T=77K
$V_b = 4V$
$D^* = 2 \times 10^{12} cm\sqrt{Hz}/W$
2.5
3.0
3.5
4.0
4.5
5.0
WAVELENGTH λ (μm)

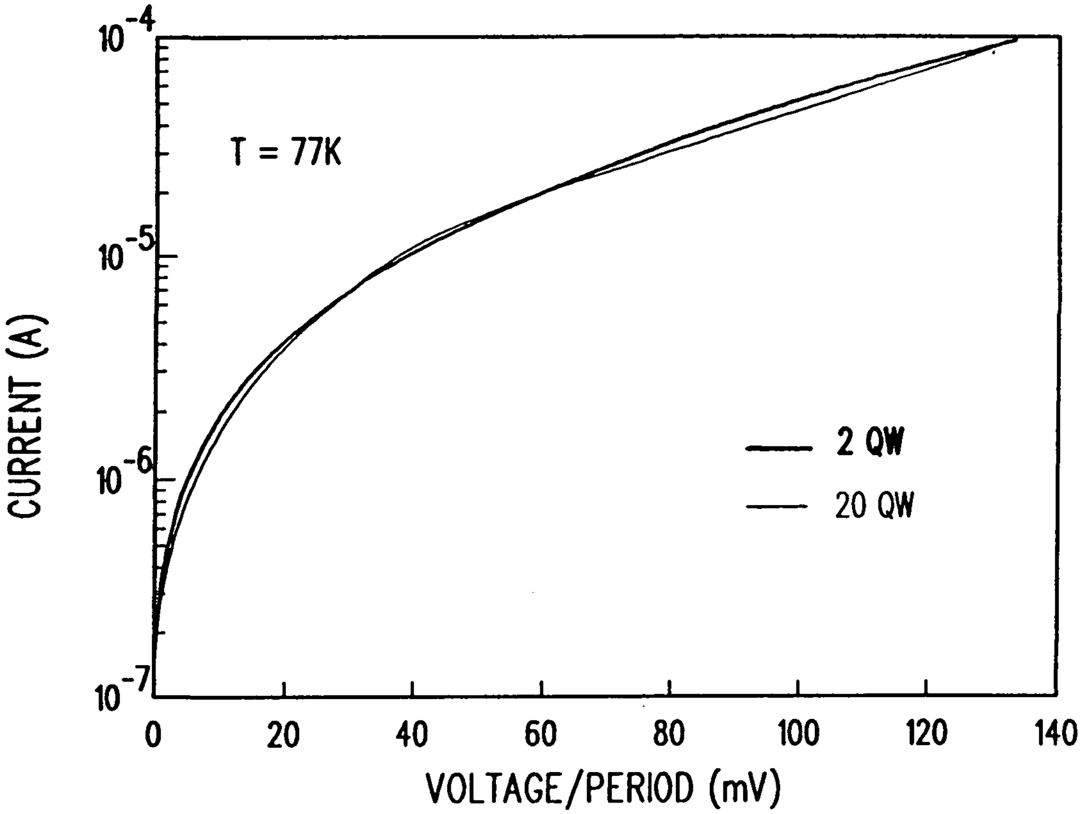


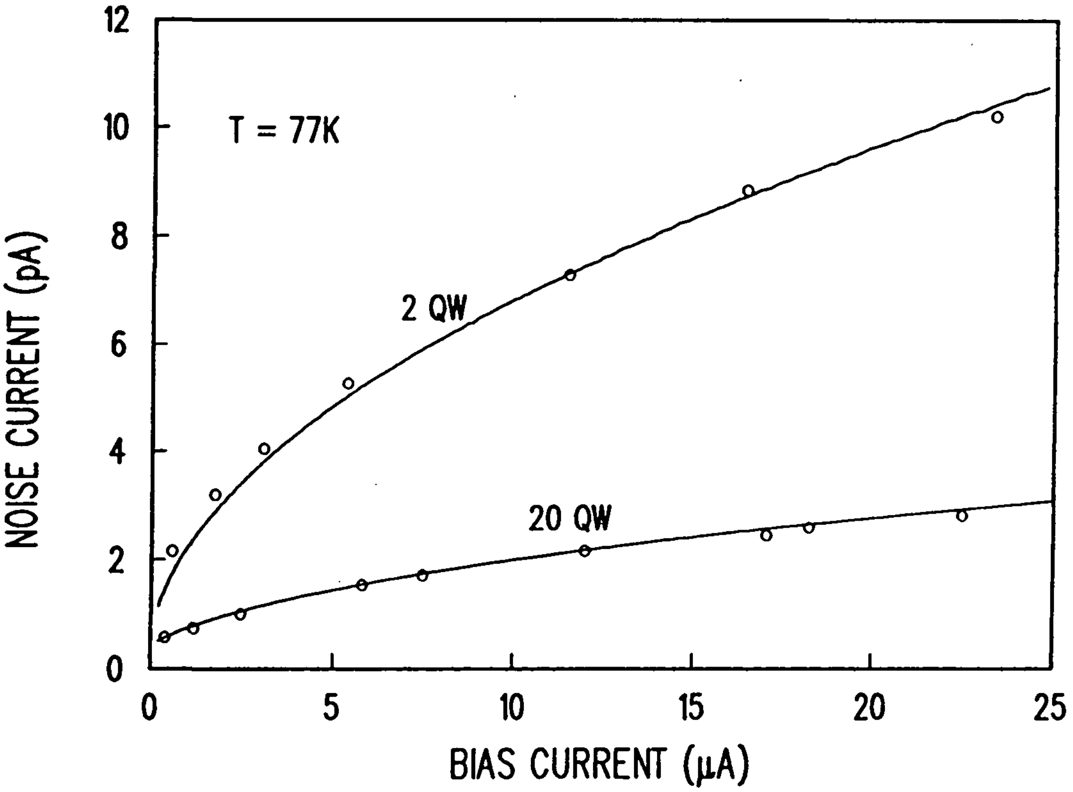
Optical Gain

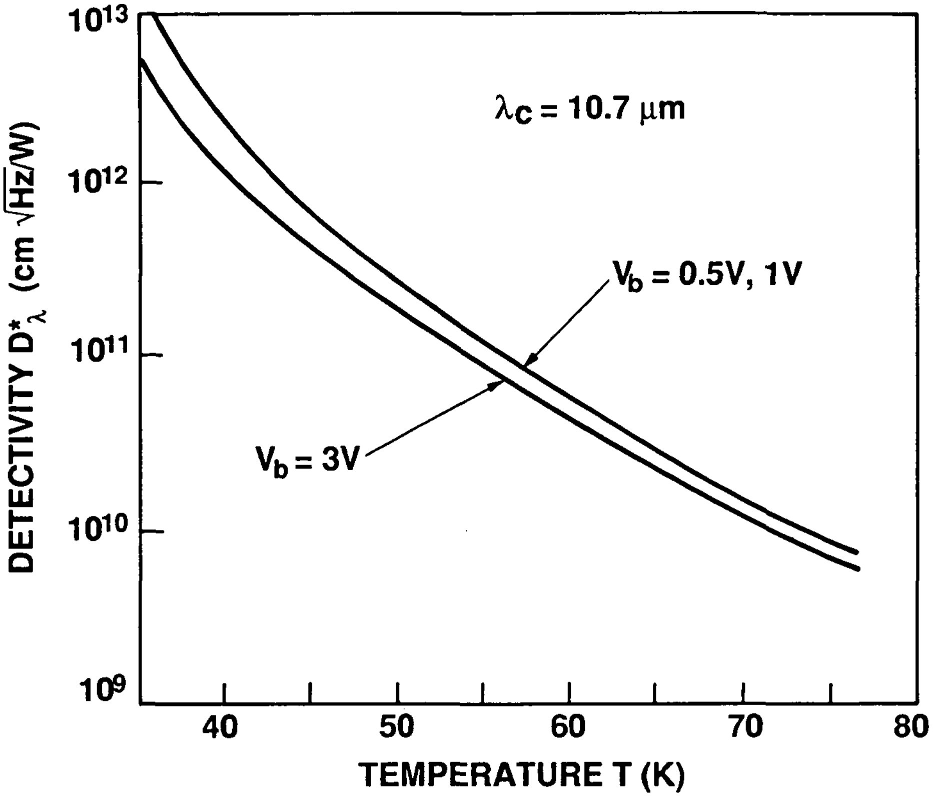
$$g = \frac{\tau_L}{\tau_T} = \frac{L}{\ell}$$


n+ GaAs,
0.5 μm CONTACT LAYER
2.8 V
20 QW
Au-Ge CONTACTS
0.4 V
2 QW
SEMI-INSULATING GaAs SUBSTRATE


T = 25K
2 QW @ 0.4V
20 QW @ 2.8V
RESPONSIVITY (A/W)
0.0
0.1
0.2
0.3
0.4
WAVELENGTH (μm)
4
5
6
7
8
9
10
11
12


T = 77K
CURRENT (A)
VOLTAGE/PERIOD (mV)
2 QW
20 QW
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
20
40
60
80
100
120
140


T = 77K
NOISE CURRENT (pA)
BIAS CURRENT (μA)
2 QW
20 QW
0
2
4
6
8
10
12
0
5
10
15
20
25



NOISE EQUIVALENT TEMPERATURE CHANGE

$$NE\Delta T = \frac{(A\Delta f)^{1/2}}{D^*_B (dP_B/dT)\sin^2(\theta/2)}$$

$$A = (50\ \mu m)^2$$

$$\Delta f = 60\ Hz$$

$$f/2 \text{ optics } (\theta/2 = 14^\circ)$$

$$D^* = 1 \times 10^{10} cm\sqrt{Hz}/W$$

$$NE\Delta T = 0.01\ K$$

ARRAY NONUNIFORMITY

To Obtain Background Limited Array Performance

$$U < \frac{1}{\sqrt{N}}$$

$U =$ uniformity

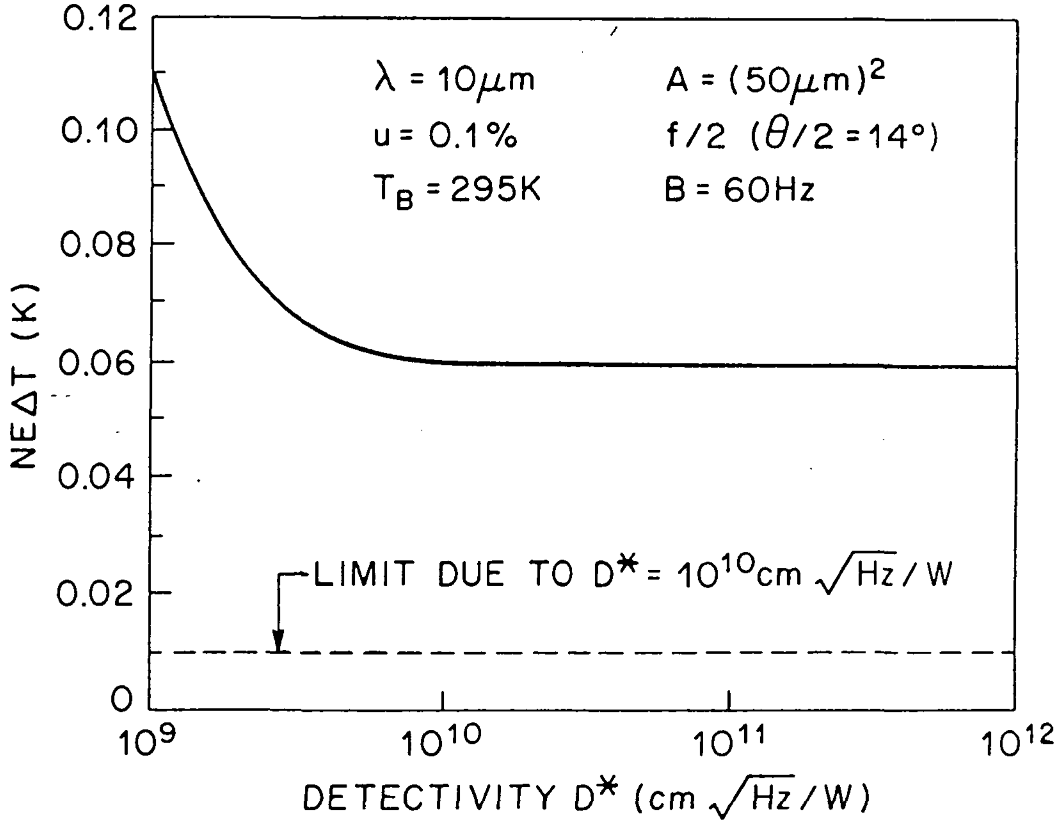
$N =$ number of photoelectrons

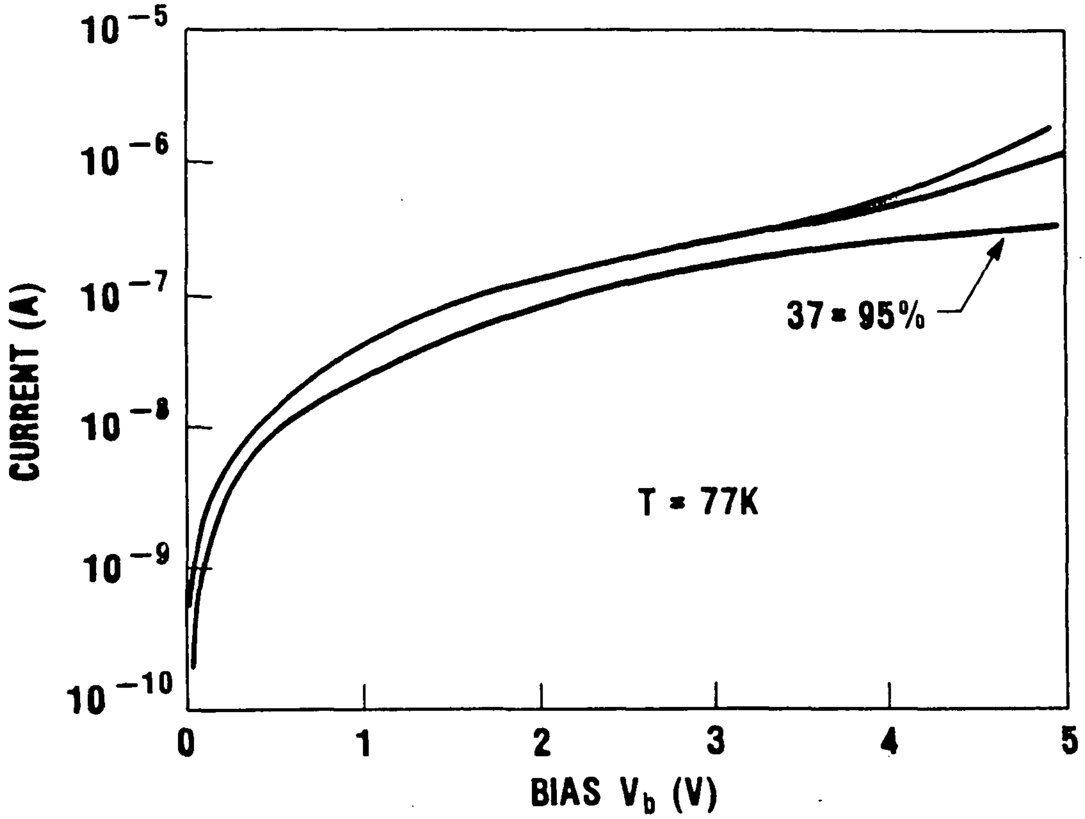
$N = 10^6 \Longrightarrow U < 0.1\%$

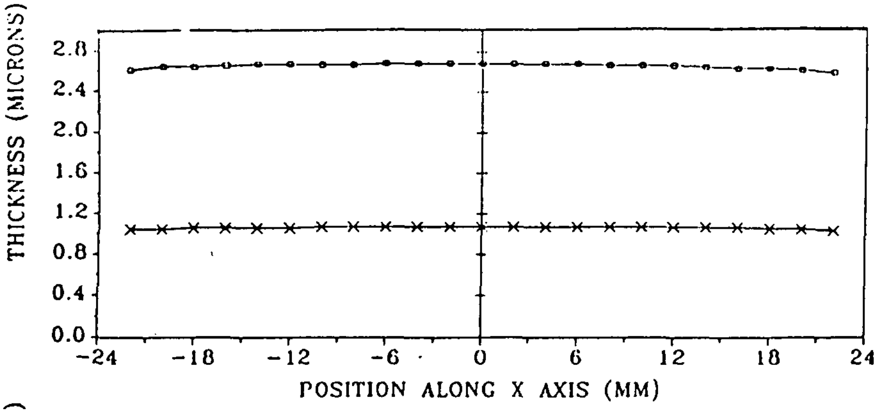
$$(NE\Delta T)_U = \frac{T_B^2 \lambda U}{1.44}$$

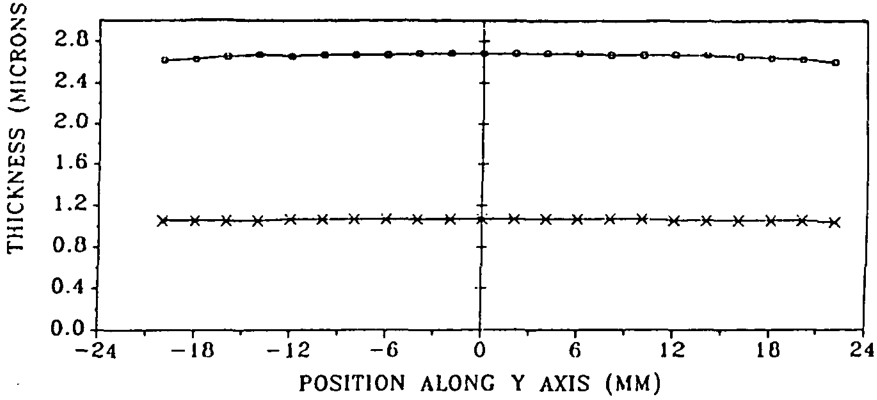
$T_B = 295$ K, $\lambda = 10\ \mu$m, $U = 0.1\%$

$(NE\Delta T)_U = 0.06$ K

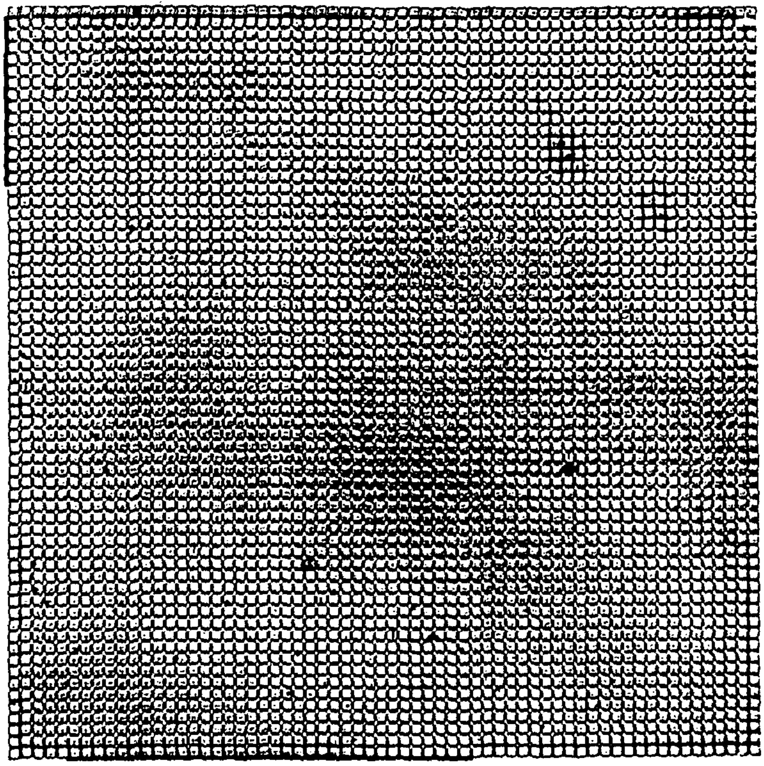


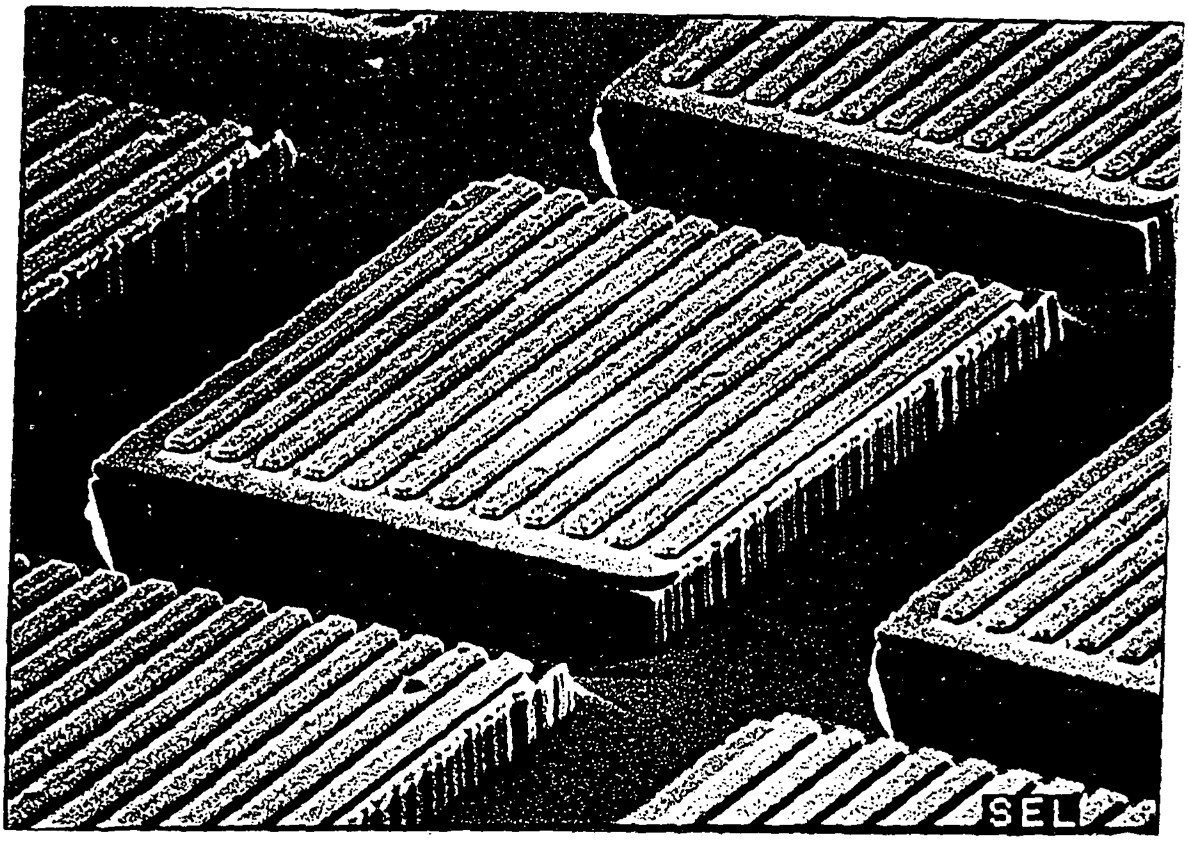

CURRENT (A)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
37 = 95%
T = 77K
0
1
2
3
4
5
BIAS V_b (V)


THICKNESS (MICRONS)
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
−24
−18
−12
−6
0
6
12
18
24
POSITION ALONG X AXIS (MM)


THICKNESS (MICRONS)
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
−24
−18
−12
−6
0
6
12
18
24
POSITION ALONG Y AXIS (MM)

64 X 64 ARRAY 50 μm PIXELS





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Conclusions

- Demonstrated detectors having $\lambda_c = 4-13.5\ \mu m$
- Spectral width $\Delta\nu/\nu = 13\% - 36\%$
- $D^*_{BB} = 1\times10^{10} cm\sqrt{Hz}/W \quad T = 68\ K \quad \lambda_c = 10.7\ \mu m$
- $D^*_{BB} = 3\times10^{10} cm\sqrt{Hz}/W \quad T = 77\ K \quad \lambda_c = 8.4\ \mu m$
- $D^*_{BB} = 1\times10^{13} cm\sqrt{Hz}/W \quad T < 40\ K \quad \lambda_c = 10.7\ \mu m$
- D^* sufficiently large (arrays uniformity limited)
- Calculated dark current (thermionic, tunneling)
- Hot electron continuum transport resonances
- High speed $\tau < 200$ psec
- Optical gain
- Graded barrier tunable spectral response
- Demonstrated grating detectors
- High uniformity
- Large arrays
- Camera demonstration