Quantum Well Infrared Photodetectors (QWIP)

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There has been a lot of interest in III-V long wavelength detectors in the $\lambda = 8 - 12 \ \mu m$ spectral range as alternatives to HgCdTe.\textsuperscript{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 $D^* = 2 \times 10^{10} \ cm \ Hz^{1/2} / W$ at $68 \ K$ for a QWIP with a cutoff wavelength of $\lambda_c = 10.7 \ \mu m$ and a $R = 1.0 \ A/W$, and $D^* = 2 \times 10^{10} \ cm \ Hz^{1/2} / W$ at $T = 77 \ K$ for $\lambda_c = 8.4 \ \mu m$. These detectors consist of 50 periods of MBE grown layers doped $n = 1 \times 10^{18} \ cm^{-3}$ 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.

Quantum Well Infrared Photodetectors
QWIP

Research
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Development
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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

GaAs ROW
CCD
PROCESSING

GaAs COLUMN CCD
PROCESSING

GaAs DETECTOR
ARRAY

GaAs FET
IMAGE
PROCESSING

10 μm RADIATION
VERTICALLY INTEGRATED GaAs QUANTUM WELL INFRARED SPECTROMETER

INFRARED RADIATION

SUBSTRATE

WAVELENGTH \( \lambda \) (\( \mu \)m)

RESPONSIVITY

GaAs WELL

\( \lambda_1 \)

\( \lambda_2 \)

\( \lambda_3 \)

V, \( \tau \)

40 Å GaAs WELL

300 Å \( \text{Al}_{0.31}\text{Ga}_{0.69}\text{As} \) BARRIER
DARK CURRENT CALCULATION

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

\[ \begin{align*} 
E > E_b & \text{ Thermionic} \\
E < E_b & \text{ Tunneling} 
\end{align*} \]

\[ I_D = nevA \]
\[ \lambda_c = 10.7 \, \mu m \]
\[ D^* = 1 \times 10^{10} \, \text{cm} \sqrt{\text{Hz}} / \text{W} \]
\[ T = 68 \, \text{K} \]

\[ \lambda_c = 10 \, \mu m \]
\[ D^*(\text{theory}) > 10^{10} \, \text{cm} \sqrt{\text{Hz}} / \text{W} \]
\[ T = 77 \, \text{K} \]
LWIR

SAWTOOTH GRATING
n⁺ GaAs CONTACT LAYER
GaAs/AlGaAs
MULTI-QUANTUM WELL
Au/Ge

SEMII-INSULATING
GaAs SUBSTRATE

(a)

(b)

SAWTOOTH GRATING
n⁺ GaAs CONTACT LAYER
GaAs/AlGaAs
MULTI-QUANTUM WELL
Au/Ge

SEMII-INSULATING
GaAs SUBSTRATE

LWIR

RESPONSIVITY (A/W)

45°

GRATING

(a)

(b)

WAVELENGTH (μm)

0.0

0.1

0.2

0.3

0.4

0.5

4

6

8

10

12

219
a) ZERO BIAS

b) FORWARD BIAS

c) REVERSE BIAS
Optical Gain

\[ g = \frac{\tau_L}{\tau_T} = \frac{L}{\ell} \]
As,

0.5 μm CONTACT LAYER

2.8V

Au-Ge CONTACTS

SEMI-INSULATING GaAs SUBSTRATE

WAVELENGTH (μm)

RESPONSIVITY (A/W)

T = 25K

2 QW @ 0.4V

20 QW @ 2.8V

WAVELENGTH (μm)
$T = 77K$

**Top Graph:**
- X-axis: Voltage/Period (mV)
- Y-axis: Current (A)
- Two curves labeled 2 QW and 20 QW

**Bottom Graph:**
- X-axis: Bias Current (μA)
- Y-axis: Noise Current (pA)
- Two curves labeled 2 QW and 20 QW
NOISE EQUIVALENT TEMPERATURE CHANGE

\[ \text{NEAT} = \frac{(A\Delta f)^{1/2}}{D^* (dP_B/dT) \sin^2(\theta/2)} \]

\[ A = (50 \ \mu\text{m})^2 \]

\[ \Delta f = 60 \ \text{Hz} \]

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

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

\[ \text{NEAT} = 0.01 \ \text{K} \]
ARRAY NONUNIFORMITY

To Obtain Background Limited Array Performance

\[ U < \frac{1}{\sqrt{N}} \]

\( U \) = uniformity

\( N \) = number of photoelectrons

\( N = 10^6 \Rightarrow U < 0.1\% \)

\[ (\text{NEAT})_U = \frac{T_B^2 \lambda U}{1.44} \]

\( T_B = 295 \text{ K}, \lambda = 10 \mu\text{m}, U = 0.1\% \)

\( (\text{NEAT})_U = 0.06 \text{ K} \)

\[ \lambda = 10\mu\text{m} \quad A = (50\mu\text{m})^2 \]

\( u = 0.1\% \quad f/2 \quad (\theta/2 = 14^\circ) \)

\( T_B = 295\text{K} \quad B = 60\text{Hz} \)
64 X 64 ARRAY 50 μm PIXELS
Conclusions

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