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New Heterojunction LWIR Detector Options*

J. Maserjian
Center for Space Microelectronics Technology
Jet Propulsion Laboratory

We investigate a heterojunction internal photoemission (HIP) approach that potentially offers LWIR photovoltaic detector performance (single pixel) that is competitive with the best of other approaches being considered. Most significantly, our approach offers a relatively simple device technology that promises producible and uniform FPA's. We emphasize an exciting process based on intervalence band absorption. We investigate both III-V and Si-based heterojunctions grown by molecular beam epitaxy (MBE) in which the barrier can be tailored to the desired cutoff wavelength. In addition, MBE allows one to optimize the device structure with precise control of doping profiles and layer thicknesses, and perform band structure engineering by control of composition and heterojunction strain.

We also consider free carrier absorption in heterojunctions. Acceptable absorption coefficients can be achieved in very heavily n^+ doped semiconductor layers ($\approx 10^{20}$ cm^{-3}). However, in this case the appreciable filling of conduction band states leads to a Schottky-like photoresponse with a gradual (quadratic) turn-on above threshold. A more satisfactory approach would be to use p^+ doping so that with the higher density of states in the heavy hole valence band there would be a narrow band of occupied states. This gives the desirable effect of a more rapid (linear) turn-on above threshold. Unfortunately, the higher hole effective mass also reduces (inversely) the free carrier absorption. For this and other reasons, the intervalence band absorption process looks much more promising.

The valence band structure of GaAs (and closely related alloys) is particularly attractive for achieving an optimum effect. The light and heavy hole bands become parallel at values of wave vector **k** away from the zone center, separated by a constant energy of about 80 meV along the <100> directions. The parallel E-**k** behavior leads to a large joint density of states and correspondingly, a large absorption coefficient α for photon energy $h\nu$ equal to this separation (corresponding to wavelengths $\approx$15 μm). This effect requires heavy doping ($>10^{19}$ cm^{-3}) so that states are occupied to sufficient values of **k**. Extrapolation of theoretical work of E.O.Kane and published absorption data suggest $\alpha > 10^4$ cm^{-1} for our case of interest. Theoretical calculations are in progress to extend Kane's early work.

Some interesting features are immediately evident. The selection rules for these transitions *prefer normal incidence of light* (giving a $\sin^2\theta$ distribution of **k**-directions, where θ is the angle from the field vector in the plane of the layer). Furthermore, photoexcitations between the <100> E-**k** bands generate the dominant **k**-directions normal to the heterojunction interface of (100) oriented

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material. We have the opportunity of tailoring the interband separation to the desired value of hν and matching with an optimum (slightly smaller) heterojunction barrier ϕ. In this case the conservation of transverse momentum at the interface is satisfied for most **k**-directions of photoexcited holes. Holes excited in the reverse direction can be redirected in the forward direction by reflection from a higher barrier (e.g., AlGaAs/GaAs). Therefore, inelastic scattering losses can be minimized with an optimum layer thickness to achieve a maximum quantum efficiency η.

In the case of Si-based structures, we can still utilize transitions to the split-off valence band. In this case we lose some of the above advantages, but still retain strong absorption (large matrix element) and favorable selection rules. We can also use band structure engineering through control of composition and interface strain to optimize the intervalence band transition energies relative to the heterojunction barrier (i.e., the cutoff wavelength).

Preliminary results on $Si_{1-x}Ge_x/Si$ heterojunctions are encouraging (see T-L. Lin, next session) and work on $In_xGa_{1-x}As/\ Al_xGa_{1-x}As$ heterojunctions is just getting under way. The opportunity exists for fabricating photovoltaic detector structures designed to achieve maximum η and the limiting thermionic emission dark current at the heterojunction. To minimize inelastic scattering loss of photoexcited holes while still obtaining adequate absorption per layer (e.g.,>1%), the p^+ layers must be of some optimum thickness (e.g.,≈40 nm). The total absorption can be enhanced by multiple passes; for example, two passes with a single reflector or 2N passes in an optical cavity structure (as commonly done with SB detectors). The HIP structures can also be configured as two stacked diodes connected in parallel (straightforwardly with planar technology) to gain another factor of two.

Based on the above considerations, we project $\eta \approx 0.20$ in optimized detector structures. The thermionic emission limited detectivity [$D^* \rightarrow (\eta/h\nu)(2J_o/e)^{-1/2}$, where $J_o=120(m^*/m)T^2\exp(-\phi/kT)$ A/cm^2] becomes $D^* \cong 10^9$ cm-Hz$^{1/2}$/W, for 15μm peak response (hν=82 meV), with ϕ=0.9hν and T=65K. This gives a noise equivalent differential temperature NEDT≅0.04K for a background temperature of 300K (assuming f/2 optics, 50μm square pixels and 30Hz bandwidth). Therefore, even with relatively low η, the thermionic emission dark current of HIP detectors provides excellent pixel performance. Most important, the simplicity of the HIP structure offers real promise for producibility and uniformity which often are the limiting factors for FPA performance.

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Joseph Maserjian
Center for Space Microelectronics Technology
Jet Propulsion Laboratory

Contributors

Theory:	Mark Huberman
	Robert Terhune
Si MBE:	Robert Fathauer
	True-Lon Lin
III-V MBE:	Frank Grunthaner
	Anders Larsson
Readouts:	Eric Fossum

Outline

- Motivation
- Heterojunction Approach
- Theoretical Considerations
- Detector Structure
- Predicted Performance

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Technology Considerations

Detector Performance
Detectivity (D*)
Quantum Efficiency (QE)
Noise Equiv. Diff. Temperature (NEDT)
Operating Temperature
Thermal Generation Noise
Excess Detector Noise (eg, 1/f)

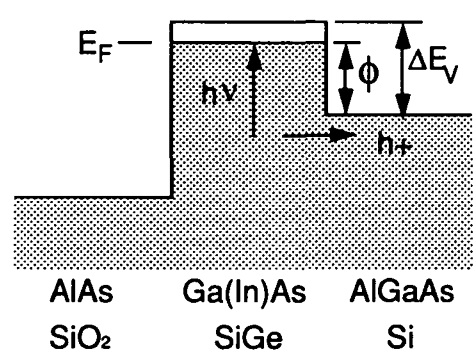
Array Compatibility
Hybrid or monolithic readout circuits
Zero or reverse bias resistance
Dark current / power dissipation
Detector capacitance
Fill factor (front vs. backside illum.)
Detector linearity and stability
Frame rate and dynamic range
Array uniformity

Producibility & Robustness
Material manufacturability
Material quality and uniformity
Material stability / surface passivation
Production yield / cost
Radiation hardness

Approach

Heterojunction Internal Photoemission (HIP)

- Simple structure / normal incidence radiation
- Emphasis on intervalence band absorption
- Optimized HIP structure using MBE:
  - valence band engineering with control of composition and strain
  - optimize doping and layer thickness for maximum quantum efficiency
  - match heterojunction barrier to cutoff wavelength for minimum dark current
- Configure into high performance PV detector arrays:
  - stacked planar detector structures
  - optical cavities



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Free Carrier Absorption
Classical Theory

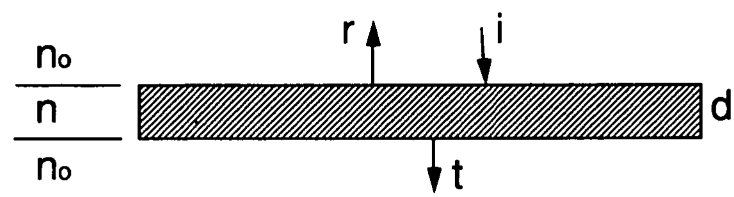
$\varepsilon = \varepsilon_o + 4\pi i\, \sigma/\omega$, $\qquad n = \sqrt{\varepsilon}$

$\sigma = \sigma_o /(1 - i\,\omega\tau)$, $\qquad \sigma_o = Ne^2\tau/m$

$\mathbf{E} = \hat{\mathbf{x}}\, E \exp\{i(nkz-\omega t)\}$

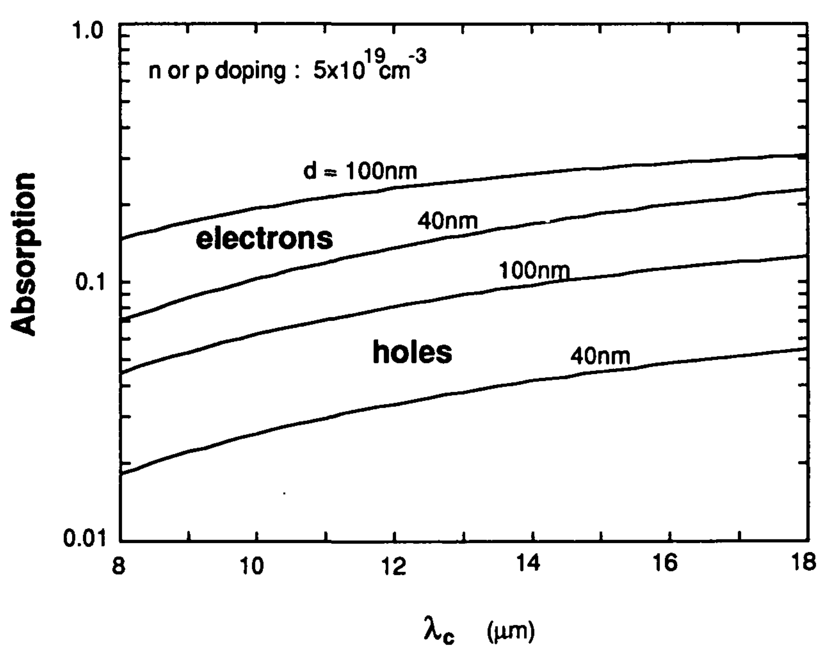
$\mathbf{H} = \hat{\mathbf{y}}\, nE \exp\{i(nkz-\omega t)\}$

Match **E** and **B** at boundries of thin layer:



Free Carrier Absorption

(classical theory for finite GaAs layer of thickness d)



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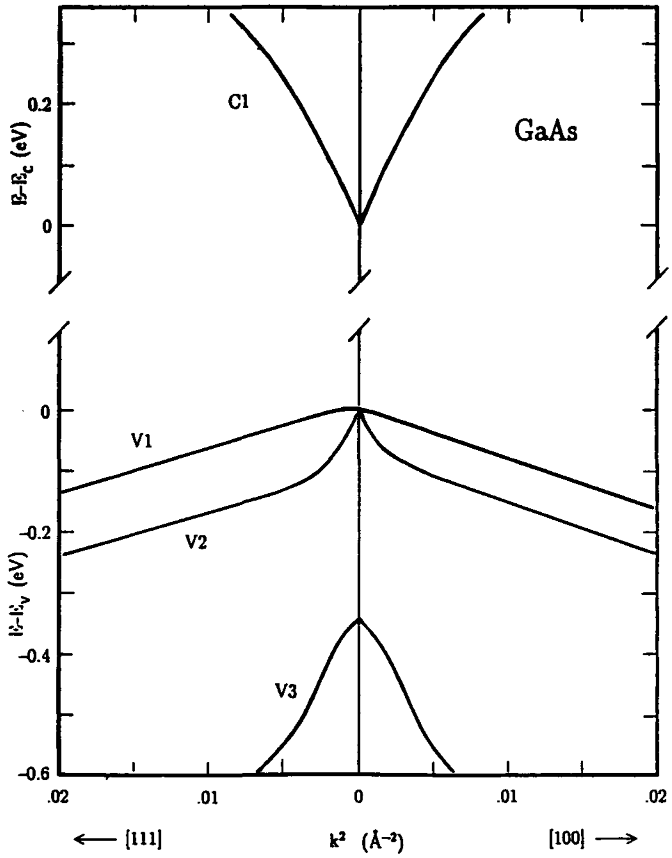
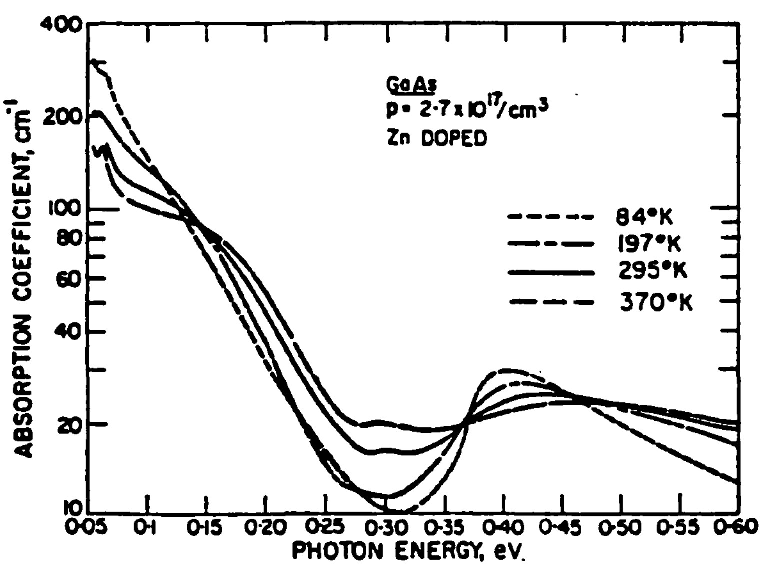
GaAs Band Structure



GaAs Absorption Data

R.Braunstein and E.O.Kane (1956)



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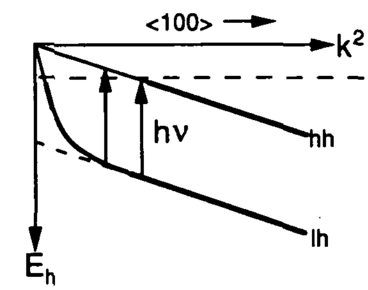
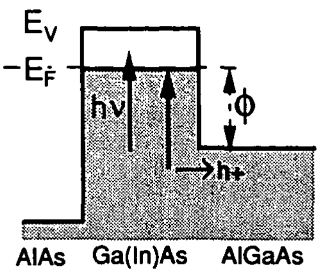
Intervalence Band Absorption



Valence Band E - k^2 Diagram



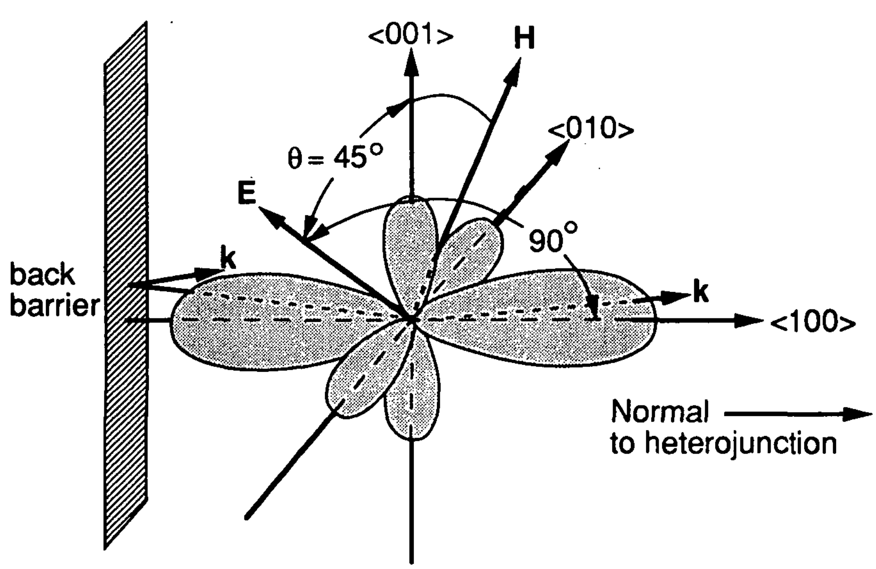
Heterojunction Internal Photoemission

$$\alpha = \frac{4\pi^2 e^2 \hbar^2}{n c \omega m^2} \sum_{\mathbf{k}} |M(\mathbf{k})|^2 \, \delta\{E_{lh}(\mathbf{k}) - E_{hh}(\mathbf{k}) - h\nu\}$$

$$|M(\mathbf{k})|^2 = \langle \psi_{lh} | \hat{\mathbf{e}} \cdot \nabla | \psi_{hh} \rangle^2$$

$$\sim \sin^2\theta$$

Selection Rules for k-Directions



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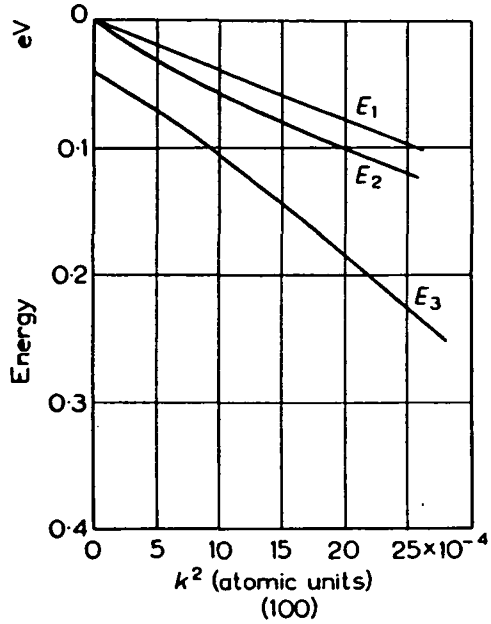
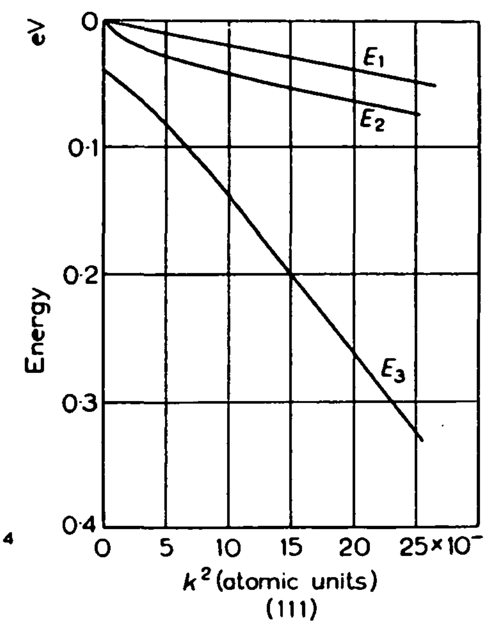
Si Valence Band Structure

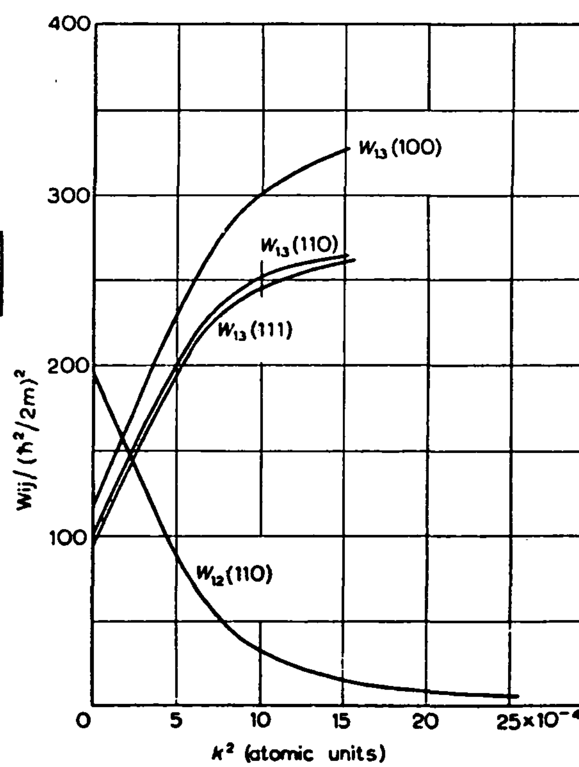




Intervalence Band Absorption Matrixes for Ge

(E.O. Kane, 1962)

$$\boxed{W_{ij} = M_{ij}^2 / k^2}$$



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Quantum Efficiency (η)

$$\eta = (1 - e^{-2N\alpha d})\, e^{-d/L_z}$$
$$\cong 2N\alpha d \cdot e^{-d/L_z}$$

Maximum η when: $d = L_z$

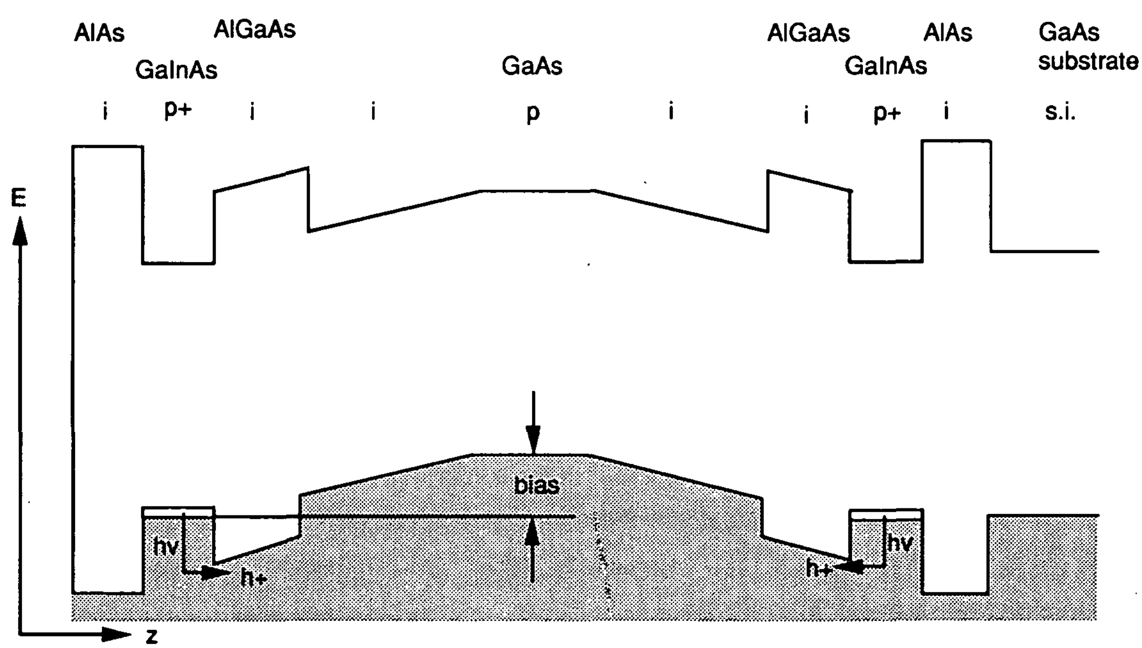
$$\boxed{\eta_{max} = 2N\alpha L_z e^{-1}}$$

Assume: $\langle v_z \rangle \approx 2 \cdot 10^7$ cm/s
$\tau \approx 3 \cdot 10^{-13}$ s
$\alpha \approx 2 \cdot 10^4$ cm^{-1}

Then: $L_z = \langle v_z \rangle \tau$
≈ 60nm
$\eta_{max} \approx .09\,N$

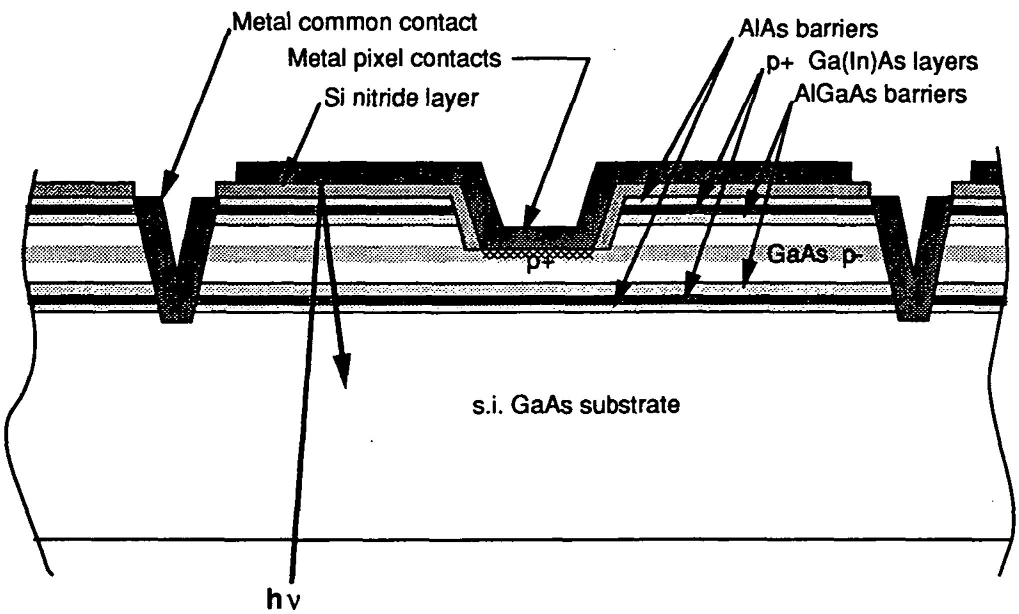
Stacked HIP Diode

Band Diagram



Stacked HIP Diode

Planar Structure



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Detector Relations

(HIP Photovoltaic Diode)

$D^* \equiv (A\Delta f)^{1/2} / NEP$

$= (\eta/\sqrt{2}\, h\nu)\,(r_B + r_T + r_{ex})^{-1/2}$

Background: $r_B = \int_{\nu 1}^{\nu 2} \eta(\nu)\,[S(\nu,T_B)/h\nu]\,d\nu$, $S = 2\pi h\nu^3/c^2 \,/\, (e^{h\nu/kT_B} - 1)$

Thermal: $r_T = [A^{**}T^2/e]\,\exp(-\phi/kT)$, $\phi \cong .9\,h\nu$

$D^*(\nu,T) \longrightarrow (\eta(\nu)/h\nu)\,(2r_T)^{-1/2}$

$NEDT \equiv NEP / dP/dT_B = (A\Delta f)^{1/2} / D^* dP/dT_B$

where for f-number F:

$P = A\int_{\nu 1}^{\nu 2} S(\nu,T_B)\,d\nu \,/\, 4F^2$

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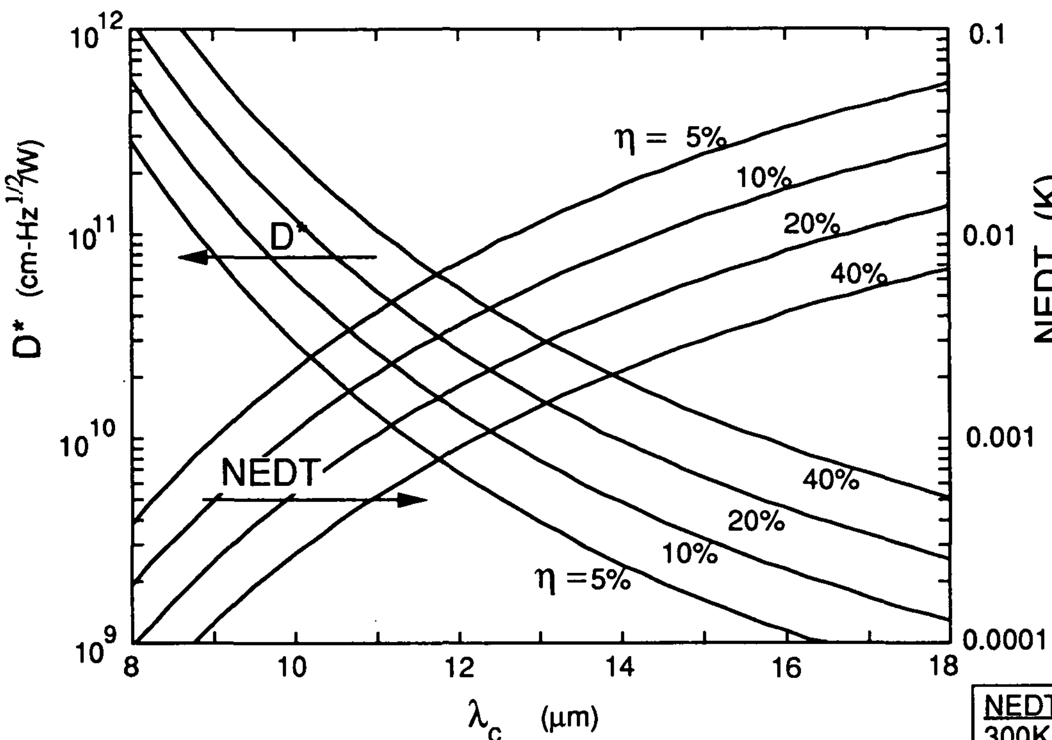
Predicted Performance of HIP Detector at 65K



NEDT assumes:
300K Background
f / 2 optics
50μm sq. pixels
Δf = 30 Hz

Summary

- HIP detector uses normal incidence radiation
- Intervalence band absorption offers high η
- Band structure / barrier tailoring for optimum response
- Thermionic current gives good performance at 65K
- Simple device structure -- easy to configure into stacked PV diode arrays
- Compatible with monolithic readout circuits
- Potential for low cost uniform arrays