

Grein - cover
PBR

Institute of Fundamental Studies (IFS), Kandy

Workshop on

Current Status and Future Trends in

Thin Film Solar PV Technology

28-29 June 2012

Christoph H. Grein, Ph.D.

**Chief Scientific Officer, Sivananthan Laboratories,
Bollingbrook, Illinois, USA**

6-1

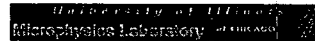


Introduction to Infrared Photovoltaics and Parallels With Solar Cells

C.H. Grein

Outline

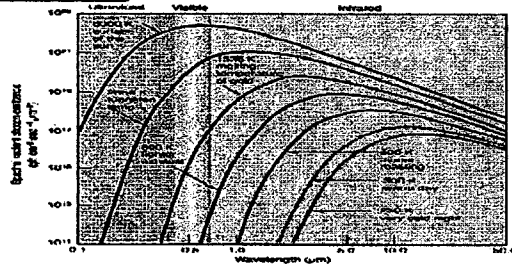
- Introduction to infrared detectors
- Applications of infrared detectors
- Types of infrared detectors and materials-parallels with solar cells
- HgCdTe as a detector material
- CdTe/Si: dual use in infrared and solar photovoltaics
- Multicolor infrared detectors and multijunction solar cells
- Nanostructures for infrared and solar photovoltaics
- Summary



Infrared Spectral Bands



- LWIR:**
- near 100% transmission 9-12 μm
 - excellent for most terrestrial objects
- MWIR:**
- near 100% transmission 3.3-5.0 μm
 - lower background noise
- SWIR:**
- contains peak solar illumination
 - need moonlight or other illumination

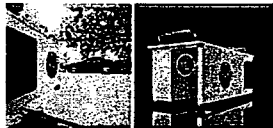


A Brief History of Infrared Detectors

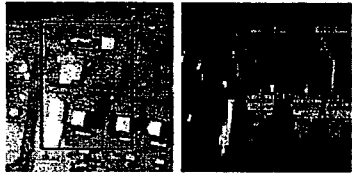
- 1800: Herschel-employed prism and thermometer to first observe infrared
- 1821: Seebeck-demonstrated first thermocouple
- 1829: Nobili-constructed first thermopile
- 1833: Melloni-modified Nobili's thermopile to permit measurements by radiation; could detect the heat from a man at a distance of 25 to 30 ft.
- 1880: Langley-developed bolometer
- 1901: Langley's bolometer detects cow at a distance of 1/4 mile
- 1917: Case-first photon detector (thallous sulfide)
- 1940's-1950's: many new materials-PbS, PbSe, PbTe, InSb, HgCdTe, extrinsic Ge
- 1960's: photolithography permits array production, HgCdTe becomes workhorse

Applications

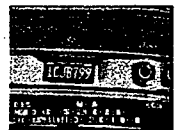
Remote Sensing



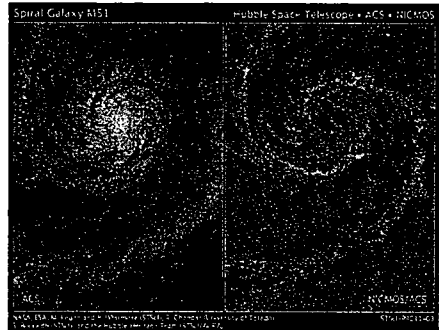
Smog Dog-CO, NO detection



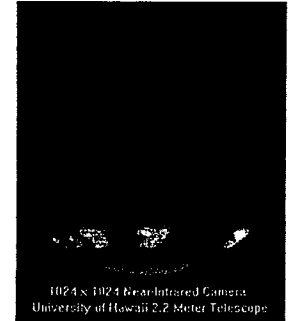
Coal fired power plant-SO₂ emissions



Astronomy



M51, Whirlpool Galaxy: visible (left) and infrared (right) images



Shoemaker Levy impact on Jupiter-3.41 μm

Other Applications

Manufacturing: Thermal Process Control

- Large area temperature uniformity
- Preventative maintenance

Night and Day Driving Aids

Medical

- Non-invasive measure of temperature (blood flow, tumors, etc.)
- Early diagnosis

Security

- 24 hr/day monitor

Aircraft Landing

- TV-quality all weather take-off/landing

Thermophotovoltaics

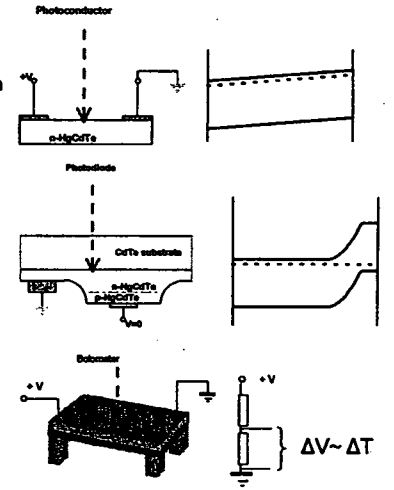
Military



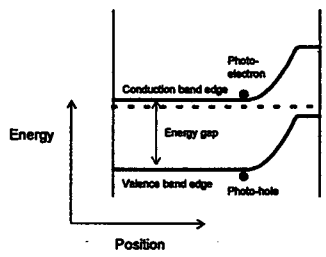
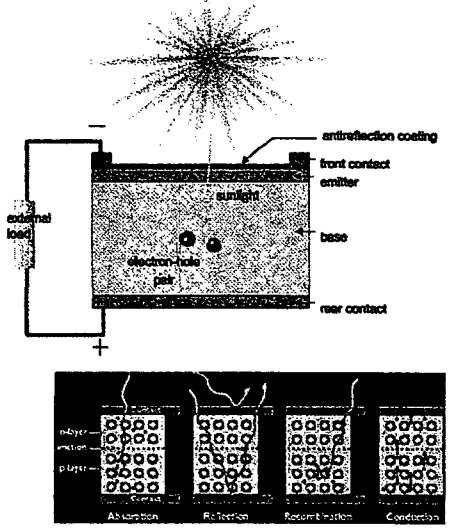
Thermoelectrically-cooled HgCdTe focal plane array

Some Types of Infrared Detectors

- Photon Detectors
 - Photoconductor
 - IR photons create excess charge, which changes conductivity => change in voltage (current)
 - ΔV (or ΔI) ~ # of photons
 - Photovoltaic
 - IR photons create excess electron-hole pairs in a p-n diode => diffuse to edge of depletion region => separate in depletion region => diffuse towards respective contacts
 - Metal-Semiconductor
 - Low quantum efficiencies: uncommon
- Thermal Detectors; e.g. Bolometers
 - Incoming infrared radiation heats material, raising lattice temperature; temperature change detected



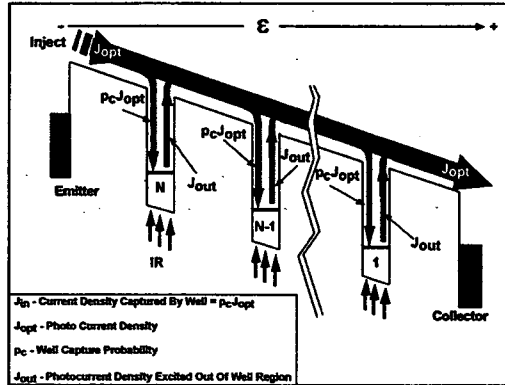
Photovoltaic Infrared Detectors and Photovoltaic Solar Cells are Both Photodiodes



- Solar cell:**
- Energy gap ~1.1-1.5 eV
 - Photon-rich
- Infrared detector:**
- Energy gap: ~0.01-1.1 eV
 - Photon-starved

Quantum Well Infrared Photodetectors (QWIPs)

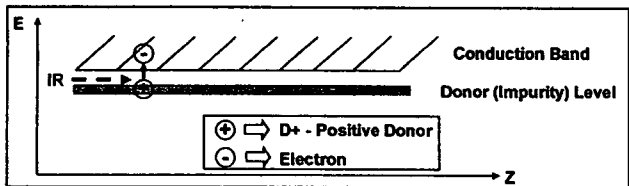
Type I multiple quantum wells such as GaAs/AlGaAs QWIPs (majority carrier transport)



- Easily fabricated due to large commercial foundation
- GaAs/AlGaAs has low absorption, hence low quantum efficiency
- Very narrow (~ 1 to 2 μm) absorption band width
- Low operating temperature needed (majority carrier device)
- High dark current – large thermal noise and low sensitivity
- Background-dependent responsivity

Extrinsic Semiconductors

Extrinsic semiconductors such as Si:Ga or Ge:Hg (majority carrier transport)



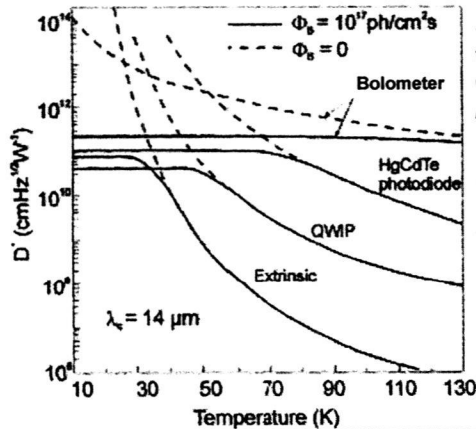
- Impurities form a narrow donor-like band
- Infrared photons excite carriers from impurity band to conduction band
- Very high (~10¹⁸ cm⁻³) doping density needed to yield sufficient optical absorption, hence responsivity
- When doping density is high, the thermal generation rate is also high and thermal noise will dominate the background g-r noise except at very low temperatures

Background-limited performance (BLIP) is very difficult to achieve

Advantages and Disadvantages of Various Types of Infrared Detectors

	Advantages	Disadvantages
Photoconductive	• Highest sensitivity at room temperature • Cheap	• Slow response • Not readily used for multicolor imaging
Photovoltaic	• Negligible power dissipation due to minimal biasing (0 to 20 mV) • 10-100 Hz noise • 10 ⁻¹⁰ to 10 ⁻¹² W/cm ² (10 ⁻¹⁰ to 10 ⁻¹² W/cm ²) • Radiation hard • Multicolor arrays	• Minority carrier recombination rates are high at high temperatures
Quantum Well Infrared Photodetector (QWIP)	• Uniform responsivity	• Low quantum efficiency • Short carrier lifetimes due to phonon-assisted recombination

Fundamental Sensitivity Limits of Various Types of Infrared Detectors



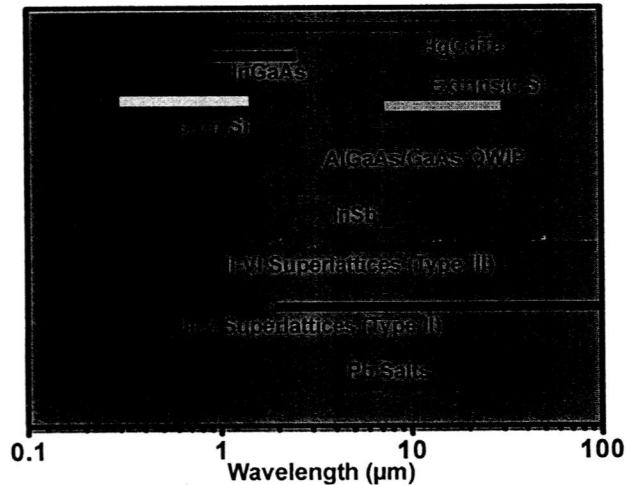
• Ratio of absorption coefficient to the thermal generation rate, α/G determines the detectivity limits of **photon detectors**.

• Sensitivity limit of **bolometers** is set by temperature-fluctuation noise, i.e., random fluctuations in the temperature of the detector element due to fluctuations in the radiant power exchange between the detector and its surrounding

Ultimate performance of direct gap semiconductor photodiodes is higher than that of other types of infrared detectors

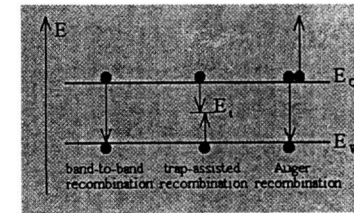
A. Rogalski, Proceedings of SPIE Vol. 4650 (2002) Photodetector Materials and Devices VII

Photovoltaic Detector Materials



Direct Gap Semiconductors

- Direct bandgap semiconductors (minority carrier transport)
 - Ternary II-VI alloys (tunable bandgap HgCdTe)
 - Binary III-V alloys such as (tunable bandgap InAsSb)
 - II-VI tunable bandgap Type I (HgCdTe/CdTe) and III (HgTe/CdTe) SLs
 - III-V tunable bandgap Type II SLs such as InAs/GaInSb
- Very high absorption coefficients, give good responsivities
- Limited by minority carrier recombination
 - Band-to-band radiative (fundamental, material system and device dependent)
 - Trap-assisted Shockley-Read-Hall (not fundamental, fabrication method-dependent)
 - Auger (fundamental, material system and device dependent)

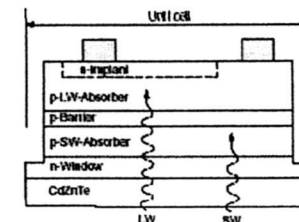


Why HgCdTe?

HgCdTe is needed for high performance...

- Bolometers
 - Low cost, room temperature infrared imagers
 - Bolometers slower than HgCdTe and not readily used for multicolor imaging
- Other technologies
 - HgCdTe has performance superior to quantum well infrared photodetectors (QWIPs) and strained layer superlattices (SLSs)
 - HgCdTe can do multicolor imaging, unlike InSb
- HgCdTe is tunable through SW, MW, LW, VLWIR infrared absorption
- Multicolor, large area enabling technology for HgCdTe growth is molecular beam epitaxy (MBE)

Two-color SWIR/LWIR HgCdTe structure

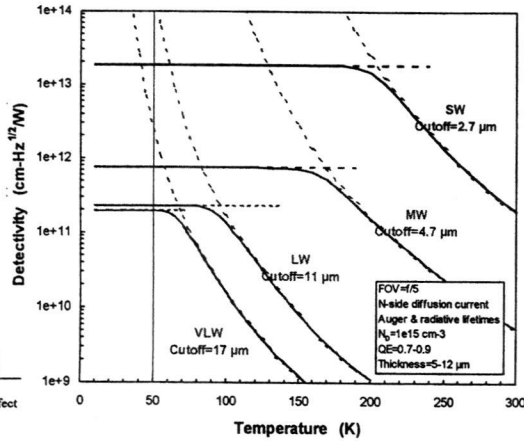


Control alloy composition of $Hg_{1-x}Cd_xTe$, layer thickness and doping levels

Operating Temperature of HgCdTe

HgCdTe has highest photon detector operating temperatures because it has longest carrier recombination lifetimes.

Maximum operating temperature decreases with increasing wavelength to be detected (decreasing target temperature)



Lifetime:

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{Auger-1}}} + \frac{1}{\tau_{\text{Radiative}}} + \frac{1}{\tau_{\text{Defect}}}$$

- Defect recombination is negligible in many cases for n-type HgCdTe: LW, VLV

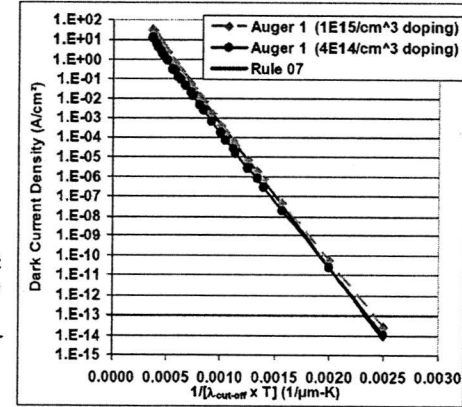
See: M. A. Kinch, "Fundamental Physics of Infrared Detector Materials," J. Electronic Materials 29 (2000)

From: M. B. Reine, "HgCdTe Photodiodes for IR Detection: A Review," Proc. SPIE 4288, 266-277 (2001).

HgCdTe Photodiodes Operate at the Theoretical Limit

Beyond $\lambda_{\text{threshold}}$ Rule 07 Follows Extrinsic Auger-1

- Plot for $\lambda_{\text{cutoff}} \cdot T$ product ($\lambda_{\text{cutoff}} \geq 4.635 \mu\text{m}$)
- λ_{cutoff} 50% QE point, assuming
 - 100% QE at short wavelengths
 - Reflecting contact
 - Layer thickness = λ_{cutoff}
- Doping ranges selected are realizable for MBE HgCdTe
- At higher temperatures must assume intrinsic carriers are not present
 - To be expected for reverse-biased diodes and arrays

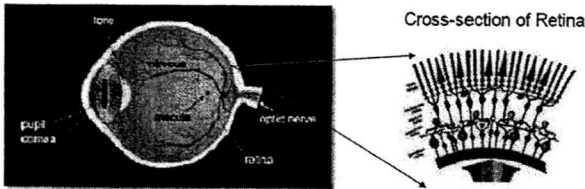


TELEDYNE IMAGING SENSORS
A Molecular Beam Epitaxy Company

W. E. Tennant, II-VI Workshop, 2009

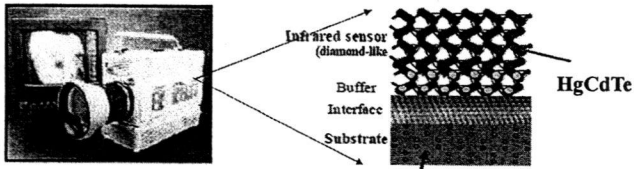
Infrared Camera-Human Eye Analogy

Human eye senses visible light



Next generation infrared camera will offer multi-color imaging

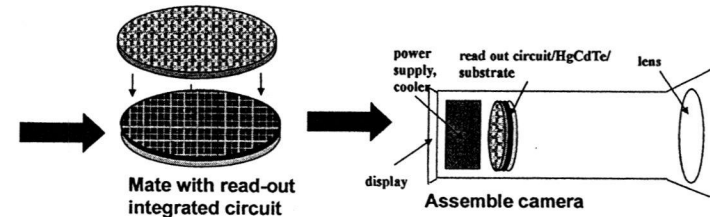
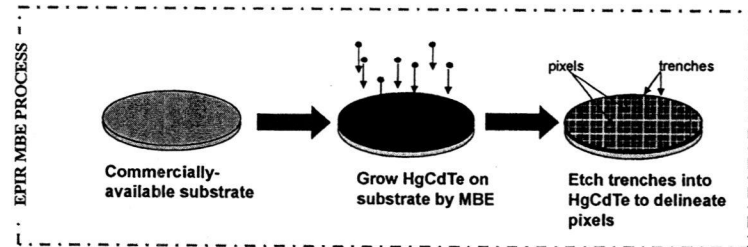
Infrared camera senses infrared light



Substrate is template for growth of infrared sensor material

Molecular beam epitaxy (MBE) technique allows atom-by-atom deposition of mercury cadmium telluride sensor materials

Fabrication of an Infrared Camera

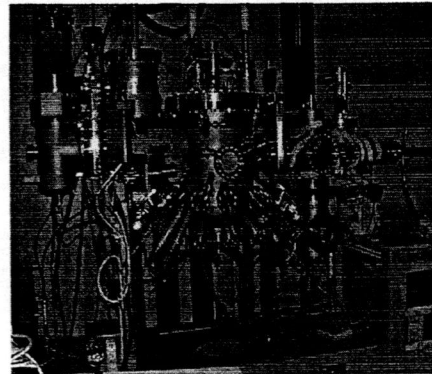


MBE Thin Film Growth of HgCdTe

II-VI Thin Film Growth – Key Technology

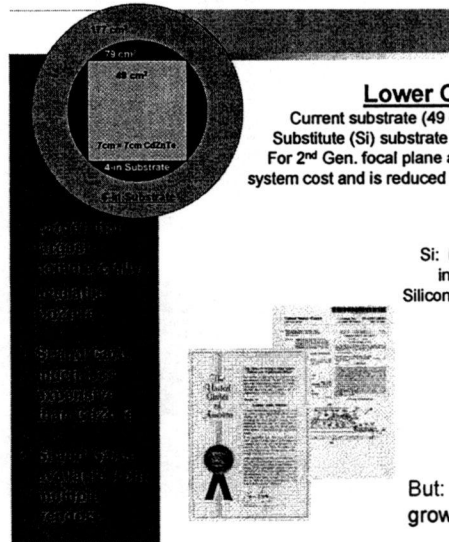
Molecular Beam Epitaxy (MBE): Mature Manufacturing Technology

- Bandgap engineering
- In situ doping control
- Precise film thickness
- Low maintenance cost
 - II-VI specific
 - Non-volatile sources
 - Low vapor pressures
 - Non-flammable
- Low downtime
- High throughput
- Scalable for low cost



One of EPIR's MBE chambers

Need for Alternative Substrates for HgCdTe



Lower Cost

Current substrate (49 cm²) ≥ \$ 10,000
 Substitute (Si) substrate (79 cm²) ≤ \$ 1000
 For 2nd Gen. focal plane array: cost ~ 20% of system cost and is reduced by a factor of 10 to 20

More Reliable

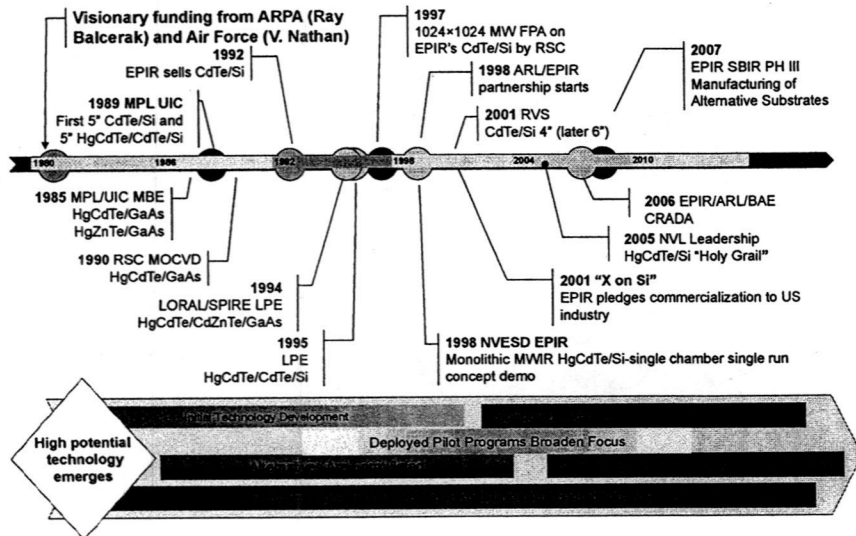
Si: No thermal mismatch between read out integrated circuit and focal plane array
 Silicon and GaAs are more rugged than CdZnTe

Higher Performance

Si and GaAs: Champions of microelectronics
 Monolithic integration reduces noise and increases end-of-life operability
 Multisensor integration available at chip level

But: high quality HgCdTe cannot be directly grown on Si (or GaAs)
 -need buffer layer

CdTe/Si Technology Development – Some Highlights

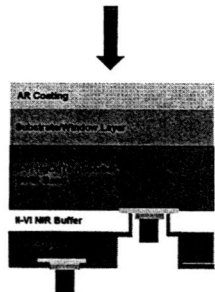


Impact of CdTe/Si Development

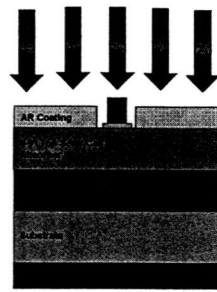
- Large format infrared focal plane arrays
- Robust substrates for high-yield, low cost fabrication
- Increased availability of high-performance, low-cost night vision imagers
- Large area CdZnTe/CdTe/Si thin-film photovoltaics as renewable source of energy



Two Color Infrared and Multijunction Solar



Two-color infrared detectors absorb photons in the two different infrared portions of the spectrum in different homojunction layers and convert them to electrical signals – weak signal, extremely noise-sensitive.



Multijunction solar cells absorb photons in the UV, visible and near infrared portion of the spectrum in different homojunction layers and convert them to electrical power – noise insensitive, less sensitive to material defects.

MBE-based II-VI technology developed for infrared is ideally suited for high efficiency multijunction solar cells.

Proposed Technology: II-VI/Silicon Concentrated Photovoltaic (CPV) Solar Cells



Cost Reduction Path (NREL CPV Roadmap)	III-V	II-VI/Si	Advantage
Lower Epitaxy Cost	III-V MOCVD	II-VI MBE	II-VI
Lower Substrate Cost	Ge: \$1 - \$2/cm ²	Si: < 20 ¢/cm ²	II-VI
Increased Automation	Compatible	Compatible	Equal
Larger Substrate Size	Ge: 4" - 6"	Si: up to 12"	II-VI
Improved Yield	Less Control Less Robust ~10 ns τ	More Control Robust Substrate >100 ns τ	II-VI

- ❖ Proposed II-VI/silicon multijunction solar cells have the potential to reach efficiencies comparable to or greater than III-V solar cells with similar configurations at a fraction of the manufacturing cost.
- ❖ Technology will reduce the cost of traditional CPV systems and enable the use of medium concentration CPV systems which will even further reduce installed costs.
- ❖ Consistent doping of CdZnTe and forming low-resistance tunnel junctions are challenges.

Calculated Theoretical Solar Cell Efficiencies

Calculated Multijunction Cell Efficiencies (with $\beta = 3 \text{ mA/cm}^2\text{-K}^3$)					
II-VI Multijunction Solar Cell Efficiencies			III-V Multijunction Solar Cell Efficiencies (III-V junction $E_g \leq 1.9 \text{ eV}$ *)		
Cell (with Si optical path length and junction energies)	One-sun efficiency (%)	500-suns efficiency (%)	Cell (with Ge optical path length and junction energies)	One-sun efficiency (%)	500-suns efficiency (%)
II-V/VI (500 μm) 1.8/1.12 eV	39	44	III-V/Ge (500 μm) 1.5-1.6/0.67 eV	34	40
			Inverted two-junction 1.9/1.4 eV	37	41
II-VII-VI/VI (500 μm) 2.1/1.5/1.12 eV	45	52	III-V/II-V/Ge (500 μm) 1.9/1.4/0.67 eV	36	46
Inverted 3-junction 2.0/1.4/1.0 eV	46	54	Inverted 3-junction 1.9/1.4/0.9 eV	44	51

* Upper limit imposed on calculated multijunction cell efficiencies assuming approximate lattice-matching constraint

D. Xu et al., Appl. Phys. Lett. 96, 073508 (2010).

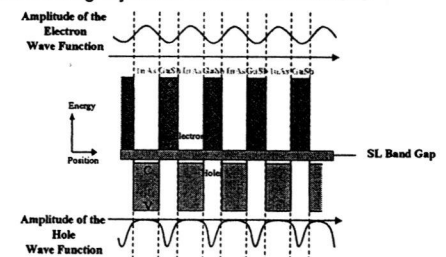
Nanostructures for Infrared and Solar Photovoltaics Why Superlattices (SLs) for IR Detectors?

SL is a material with thin, periodically alternating layers of several substances

Most common: two types of substances, but three, four, ... also possible and employed

Multiple design degrees of freedom:

- choice of substances
- alloy compositions
- thicknesses of layers



For absorber layers of IR detectors:

-one degree of freedom constrained to produce desired cutoff

-remaining degrees of freedom can be exploited to obtain desirable electronic/phonon/structural properties

SLs can be active layers in IR devices/arrays as direct replacements for bulk materials:

- PV or PC
- multicolor detectors
- HOT detectors
- avalanche photodiodes

Anticipated Advantages of SLs for IR Detection

Relative to HgCdTe alloys, SLs are predicted to possess:

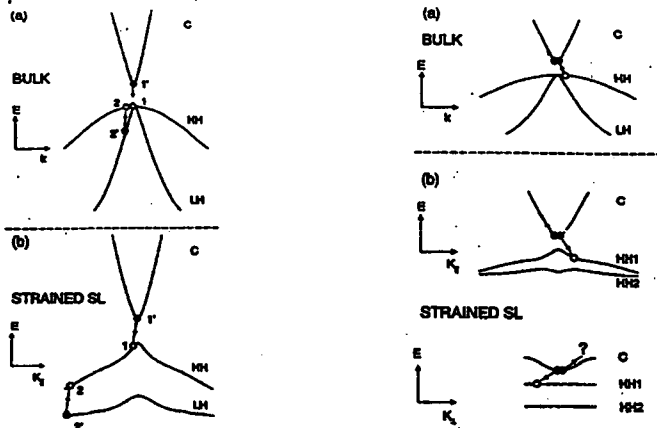
- longer Auger lifetimes via electronic band structure engineering
- lower tunneling currents due to greater effective masses in the growth-axis direction
- comparable MW to LWIR optical absorption
- more uniform cutoffs due to weak sensitivity of cutoff on layer thicknesses



Type I Type II Type III

Example: HgCdTe/CdTe InAs/GaInSb HgTe/CdZnTe

Type II and III SLs can be Designed to Suppress Hole-Hole Auger (Auger-7-like) or Electron-Electron Auger (Auger-1-like)



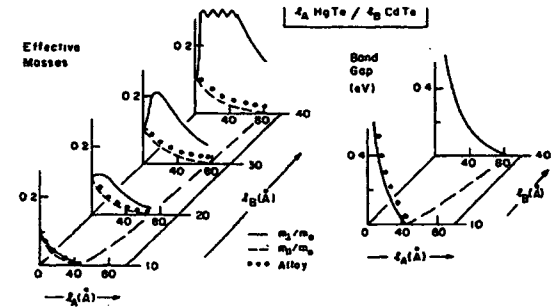
Splitting between HH and LH requires one of the hole states to be deep in the HH band where there are few holes (Fermi distribution tail), thereby decreasing hole-hole Auger

In-plane: final hole state is in a region of low occupation probability
Growth direction: no available final states for one electron

SL Effective Masses and Impact on Tunneling Currents

HgTe/CdTe SLs:

-growth axis (\perp) effective mass increases with increasing barrier (CdTe) thickness



Johnson et al., Phys. Rev. B, vol. 41, No. 6, February 15, 1990, pp. 3655-3669

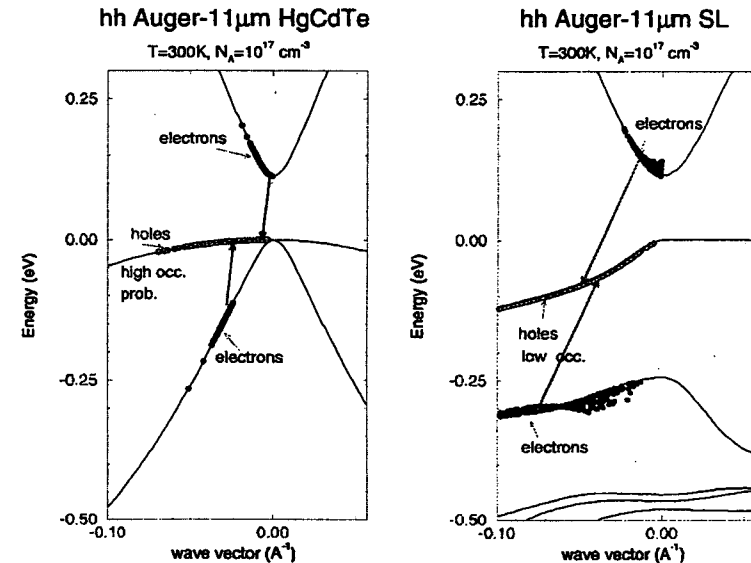
Tunneling currents:

$$\text{Zener } J_T = \frac{e^3 F(V) V}{4\pi^2 \hbar^2} \sqrt{\frac{2m_T}{E_R}} \exp\left(-\frac{4\sqrt{2m_T} E_R^2}{3e\hbar F(V)}\right)$$

$$\text{trap-assisted } J_{\text{trap}} = \frac{e^2 m_T V M^2 N_i}{8\pi \hbar^2} \exp\left(-\frac{4\sqrt{2m_T} (E_R - E_i)^2}{3e\hbar F(V)}\right)$$

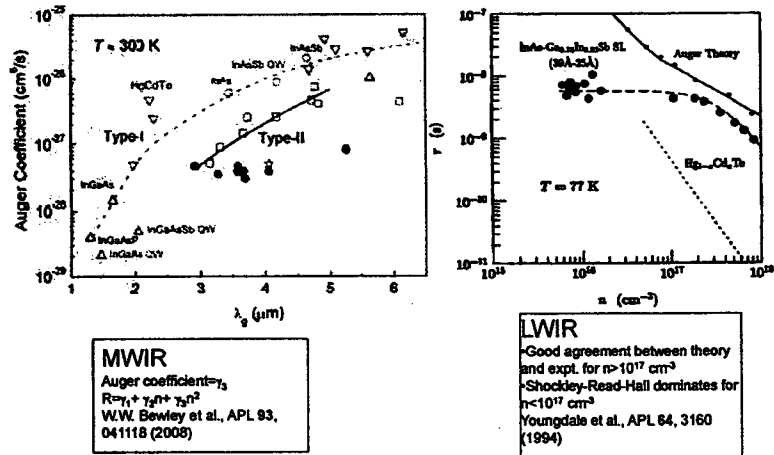
- larger effective masses in the SLs results in exponentially weaker tunneling currents
- also varies with the field F
- orders of magnitude reductions possible

Hole-Hole Auger Transitions in Bulk Alloy and Superlattice Materials



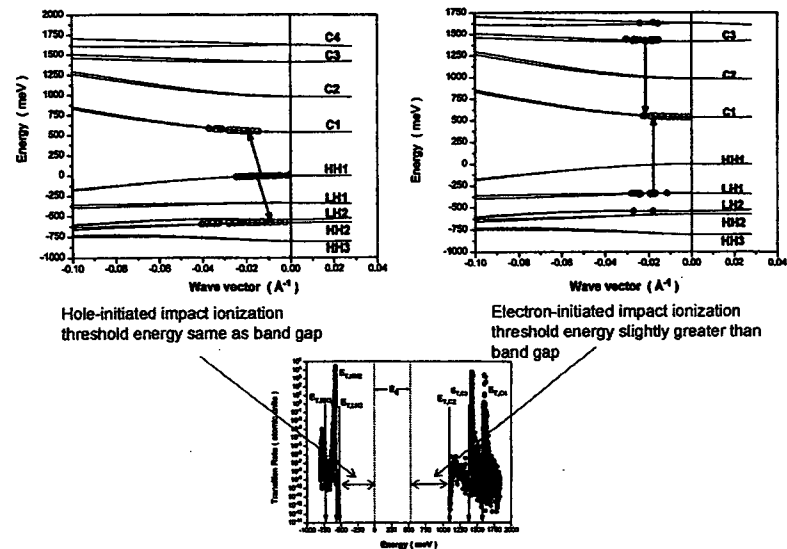
Experimental Evidence of Auger Suppression in Type II SLs

- Responsible for order of magnitude or greater *reductions* of Auger rates



Band Structure Engineering SLs to Promote Impact Ionization

- Important for infrared avalanche photodiodes and solar cells



Summary

- Decades of II-VI semiconductor development for infrared detector applications has resulted in HgCdTe photovoltaic detectors grown by MBE performing at theoretical limits
- Among many infrared detector technologies, HgCdTe photodiodes operate with the highest sensitivity
- High quality CdTe/Si developed to reduce cost of HgCdTe substrates and increase array formats
- Photon-starved infrared detectors require higher quality materials that photon-rich solar cells
- Major opportunity: transfer infrared II-VI semiconductor technology to solar photovoltaics
- II-VI-based multijunction solar cells promise approx. same efficiencies as present-day ultra-high efficiency cells but at fraction of cost
- Nanostructures hold promise for next generation infrared and solar photovoltaics