The Infrared Retina: Ushering in the Fourth Generation of IR Detectors

Sanjay Krishna

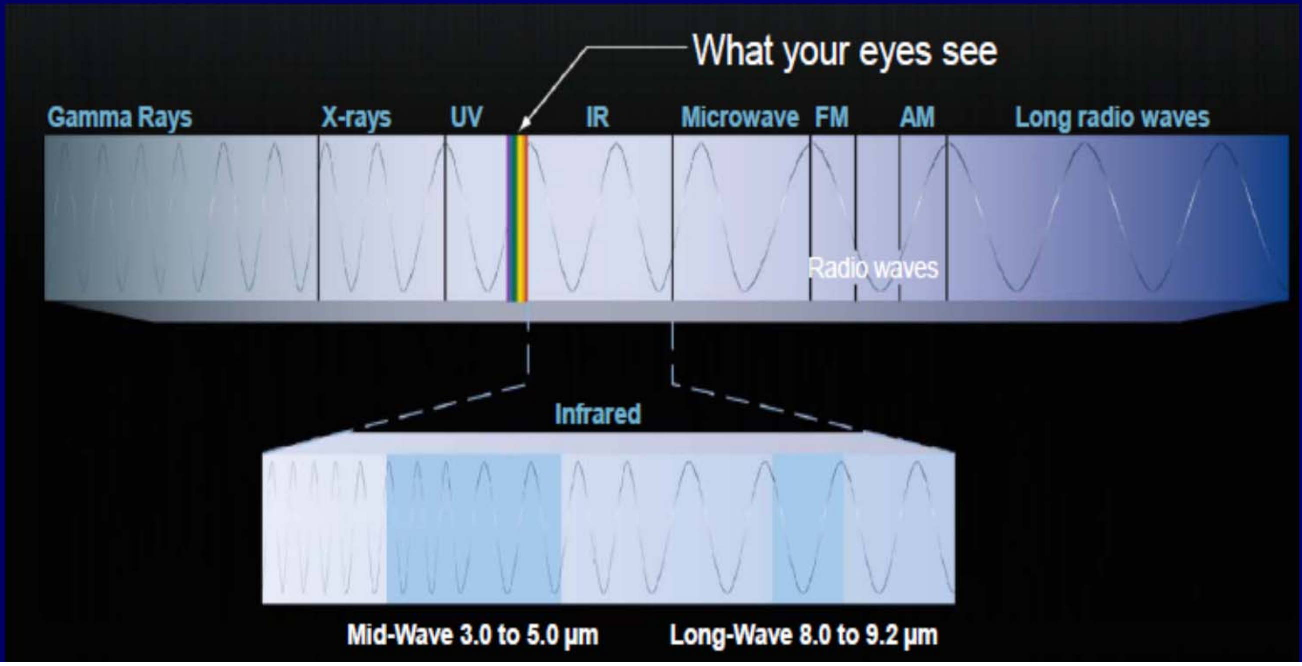
Professor
Department of Electrical and Computer Engineering
University of New Mexico, Albuquerque, USA

Email: skrishna@chtm.unm.edu

Krishna INfrared Detector (KIND) Laboratory (www.chtm.unm.edu/kind)

Outline

- *Background and Motivation*
- *Type II Strain Layer Superlattices*
- *Quantum Dots in a Well Detectors*
- *4th Gen Imagers: The Infrared Retina*



Krishna Infrared Nanostructure Detector (KIND) Laboratory

UNM

Senior Researchers

- Dr. Tom Rotter
- Dr. Elena Plis
- Dr. Y.D. Sharma
- Dr. Z.B. Tian
- Dr. J.O. Kim
- Dr. D. A. Ramirez

Graduate Students

- Stephen Myers
- John Montoya
- Eric Jang
- Freddie Santiago
- Maya Kutty
- Nutan Gautam
- Brianna Klein
- Ted Schuler Sandy
- Glauco Fiorante
- Vince Cowan
- Marziyeh Zamiri
- Ali Shirazi
- Nathan Henry (UG)

Collaborators

- *Brueck, Hayat, Ha (UNM)*
- *Javey Group (Berkeley)*
- *Noh/Lee (KRISS)*
- *Cardimona (AFRL/VSSS)*
- *Gunapala Group (JPL)*
- *Painter Group (Caltech)*
- *QmagiQ LLC*
- *Raytheon Vision Systems*
- *Lin Group (RPI)*
- *Vandervelde (Tufts)*
- *SK Infrared LLC*
- *CINT /SNL (Brenner/Peters)*

Past Group Members

- *POSTDOCs: Dr. A.Amout (Emcore), Dr. P. Dowd (ASU), Dr. J. Brown (Micron), Dr. J.B. Rodriguez (Montpellier), Dr. T. Vandervelde, (Tufts); Dr. M. Naydenkov Lightspin*
- *PhDs: Dr.Winckel, Uni. Graz; Dr. Zhu, Law Firm; Dr.Plis, UNM; Dr.Attaluri, Lehigh Univ.; Dr. Newmann, Emcore; Dr. Andrews, NRL; Dr. Wilcox NRL, Dr. Khoshakhlagh (JPL), Dr. Hasul Kim (UCB), Dr. Rajeev Shenoi (RPI), Dr. David Ramirez (UNM), Dr. Jiayi Shao (Purdue); Dr. Ajit Barve (UCSB)*
- *M.S. : N. W. Bernstein, LANL, J. Shelton, SNL, G. Bishop, SNL, E. Varley, D. Jepson, AFRL; M. Lenz, SNL, K. Posani, Qualcomm, C. Wilcox, NRL, S. Annamalai, Triquint, M. Serna, Oxford; S.Raghavan*

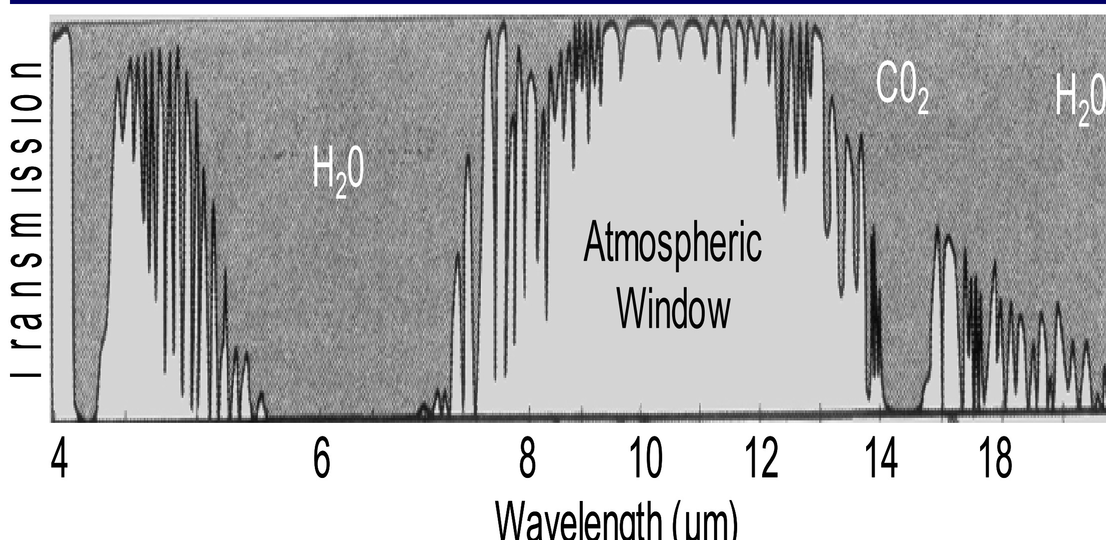
Funding Agencies

AFOSR, AFRL, NSF, IC, DIA, DARPA, KRISS-GRL

Infrared Imaging: Background and Applications

Applications

- **Defense and Security**
- **Medical Diagnostics**
- **Surveillance**
- **Astronomy**
- **Home inspections**
- **Fire fighting**
- **Entertainment**



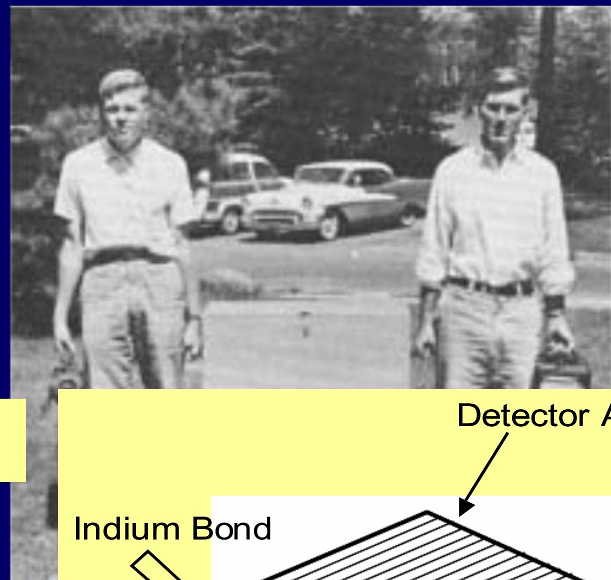
The Infrared Imaging Market

- Low Volume, High Performance, High Cost ($300K-500K)
  - Requirements: High quantum efficiency, extremely low dark current, no cost or operating temperature limit
  - Applications: low background applications, such as Astronomy
  - MWIR-InSb, LWIR-MCT, VLWIR- Si:IBC
  - **Type II SLS**
- Large Volume, Uncooled Operation, Low Cost ($5K-20K)
  - Low cost, slower speeds, room temperature operation, no spectral information
  - Bolometers
- Intermediate Volume, Performance and Cost ($70K-100K)
  - Desired Features: Low dark current, moderate quantum efficiency, high operating temperature, large format, multicolor, intermediate cost
  - Current players: MWIR-InSb, LWIR-QWIP
  - **QD Detectors**

Historical Perspective

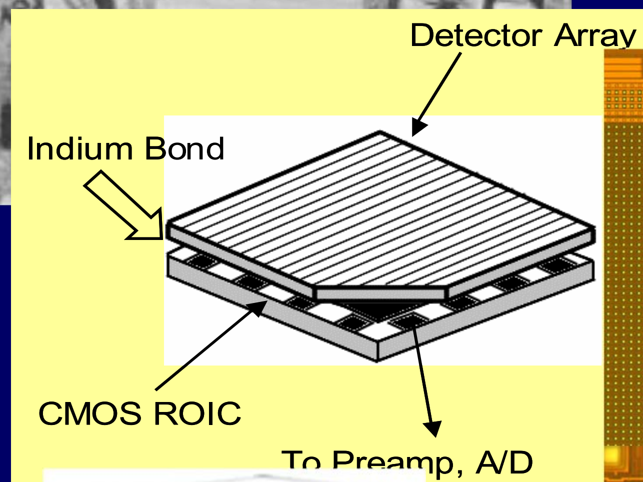
First Gen Systems

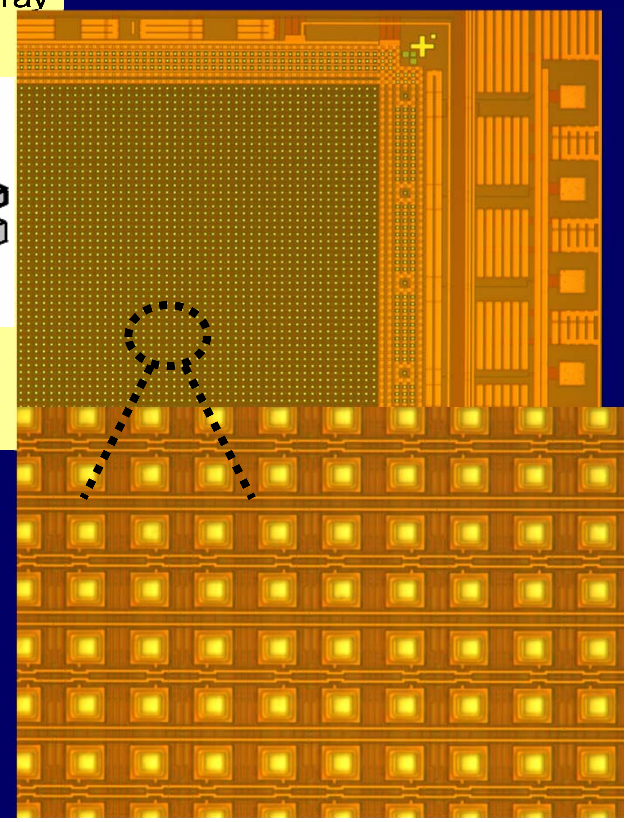
- Single Pixel
- Linear Arrays



Second Gen Systems

- 2D Staring Arrays
- Mostly Single Color





Third Generation Systems

- Higher Operating Temperature (HOT)
- Multicolor Capability
- Large Format Arrays

Skin Cancer in the US

Skin Cancer Facts

- Most common type of cancer in US
- More cases of skin cancer than those of breast cancer, prostate cancer, lung cancer and colon cancer combined.
- One in every five Americans develops skin cancer in their lifetime.
- Melanoma is the deadliest form of cancer and is responsible for 75% of Skin Cancer related deaths (~70,000 deaths in 2009)

Current Technology

Subjective Visual Test

OR

Invasive Biospy

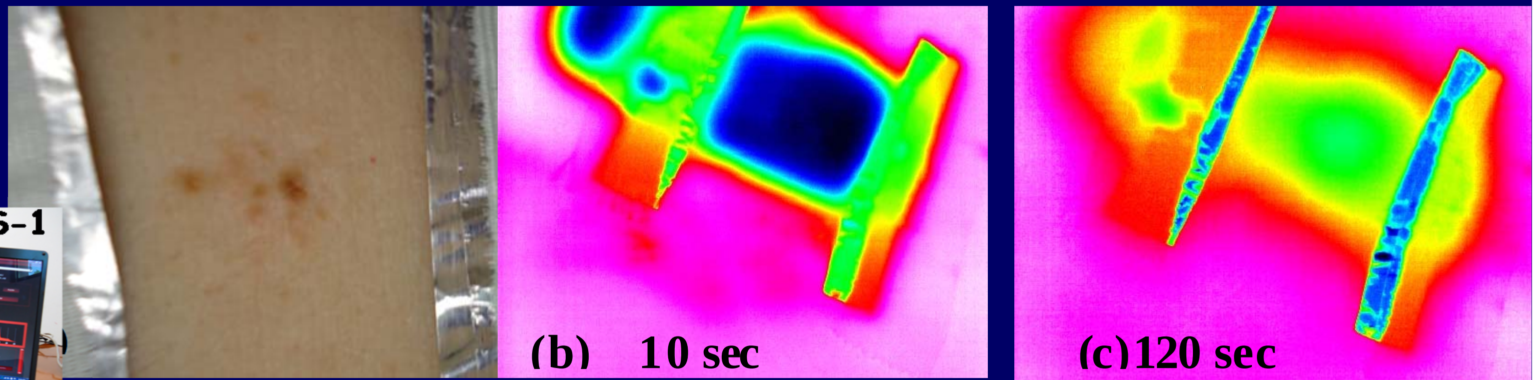
Early diagnosis is key in preventing the occurrence of skin cancer

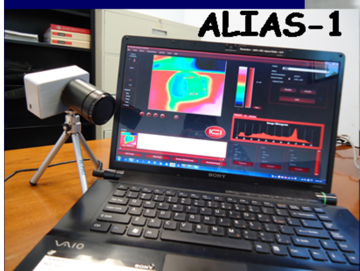
*Rates are per 100,000 and are age-adjusted to the 2000 U.S. standard population.

†Source: U.S. Cancer Statistics Working Group. *United States Cancer Statistics: 1999–2006 Incidence and Mortality Web-based Report.*

Early Detection of Skin Cancer with IR Imaging

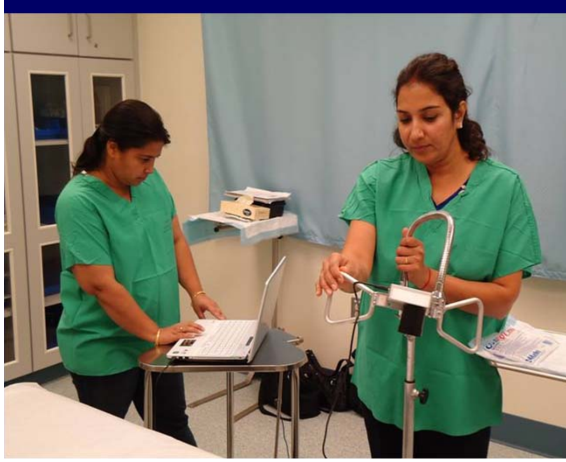
(a)Visible image of a benign dysplastic nevi and infrared images at (b) 10 seconds and (c) 120 seconds after cooling using ALIAS-1 developed by SK Infrared LLC

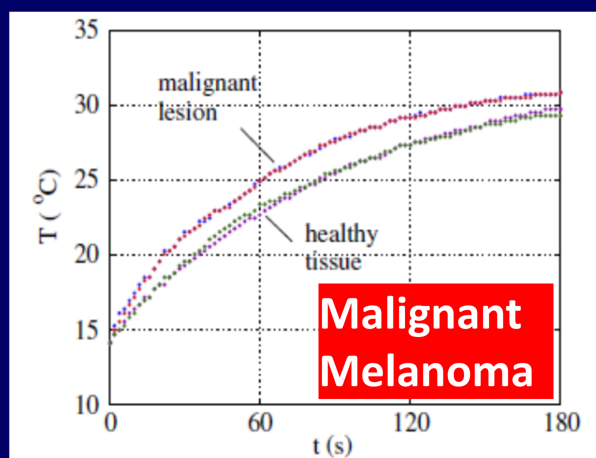


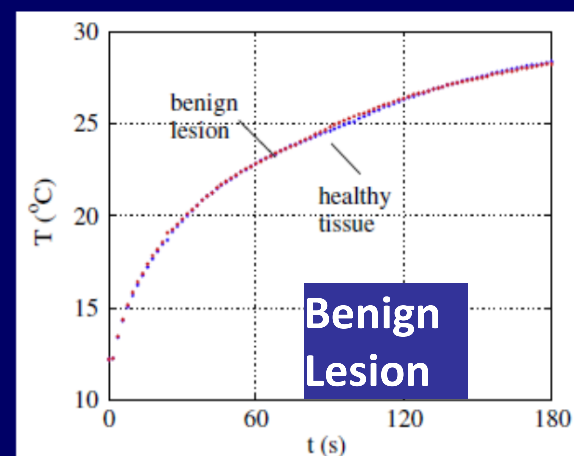


No significant difference was observed in the response of the nevi and the surrounding skin, indicating a benign lesion

Advanced Longwave infrared Imaging Analysis System (ALIAS)

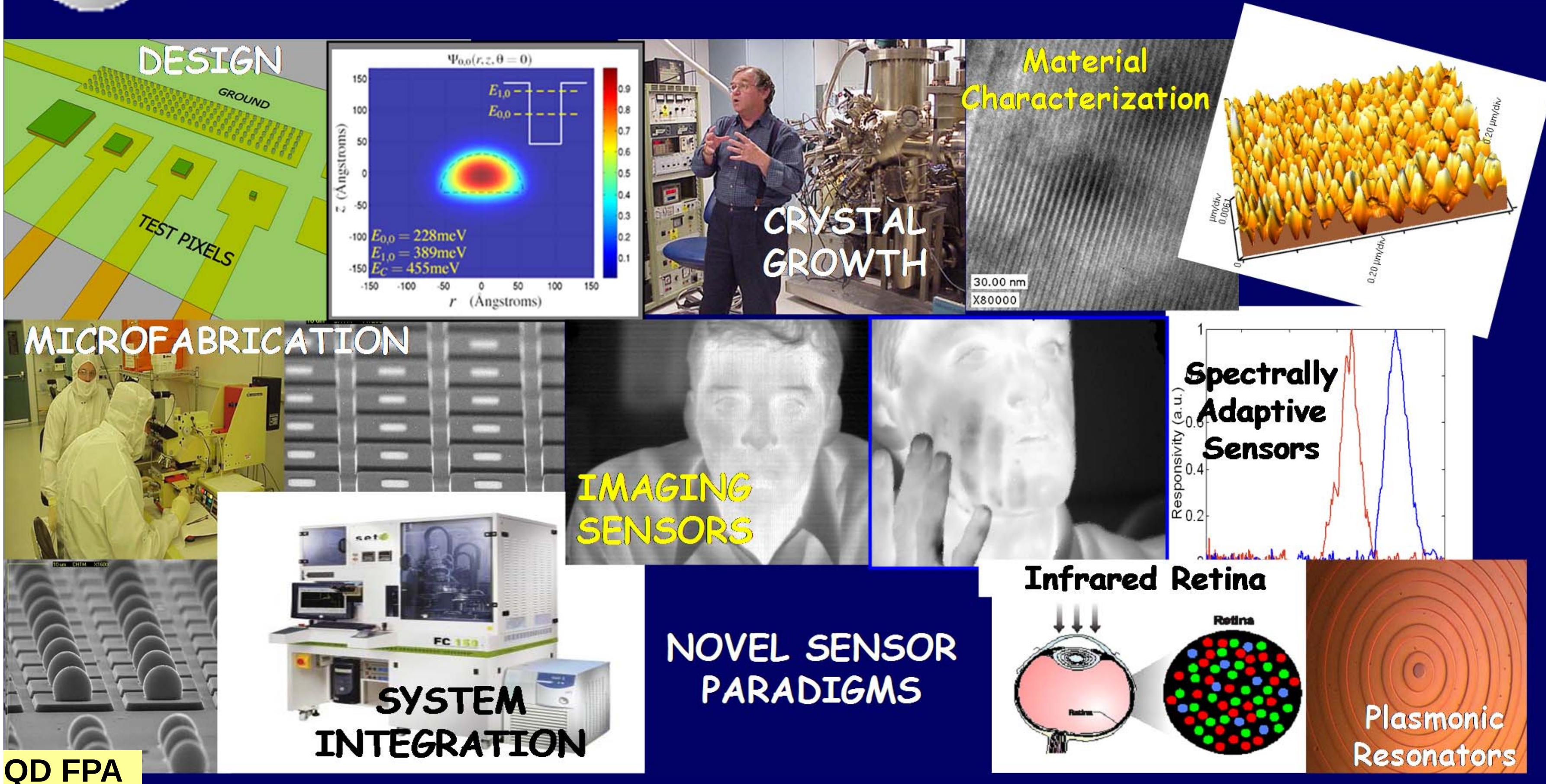




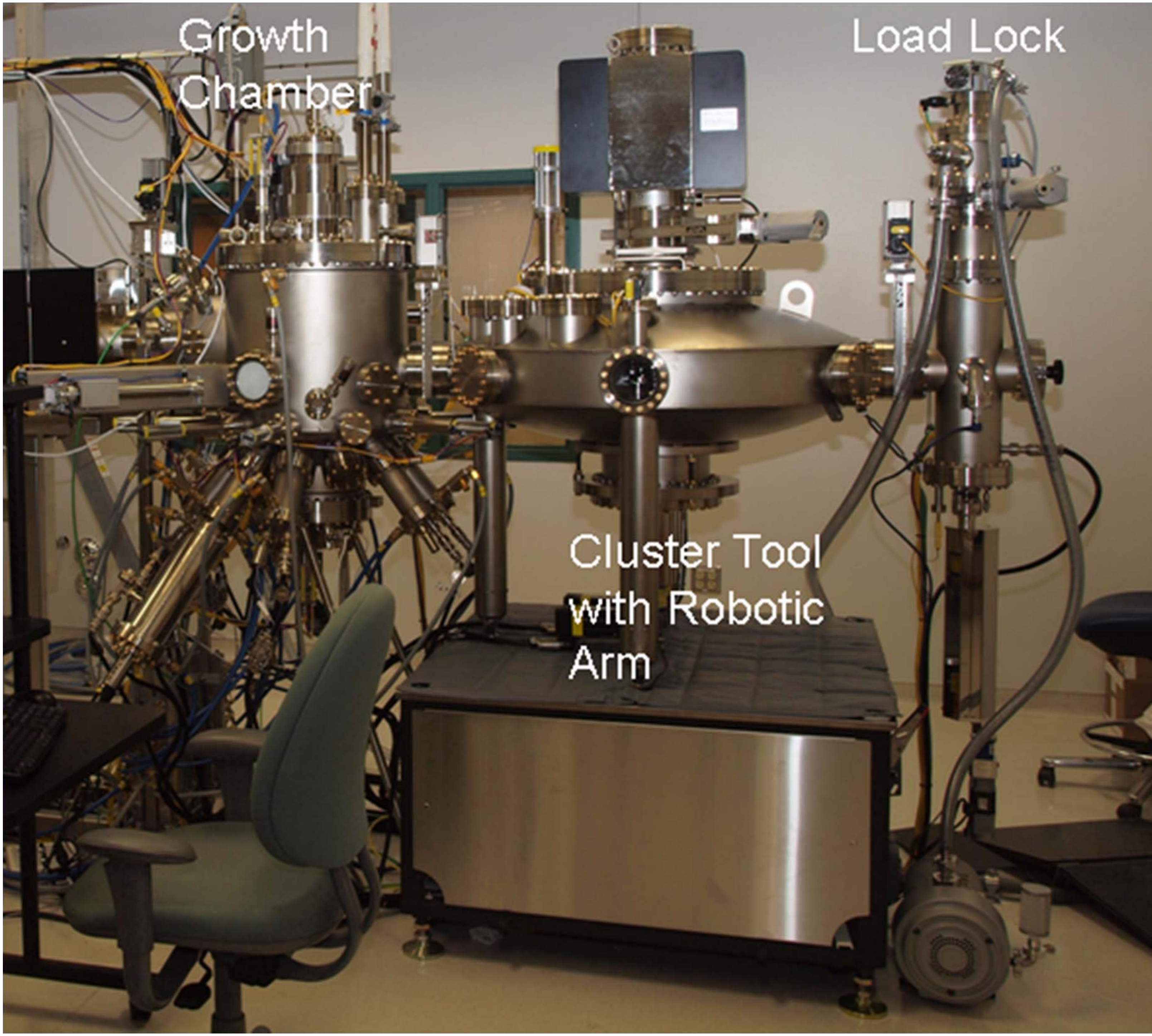


Pritini et al, International Journal of Thermal Sciences, 2010

Epi to Camera Research



KIND Lab: One of two university laboratories in the country that can undertake “Epi to Camera” research



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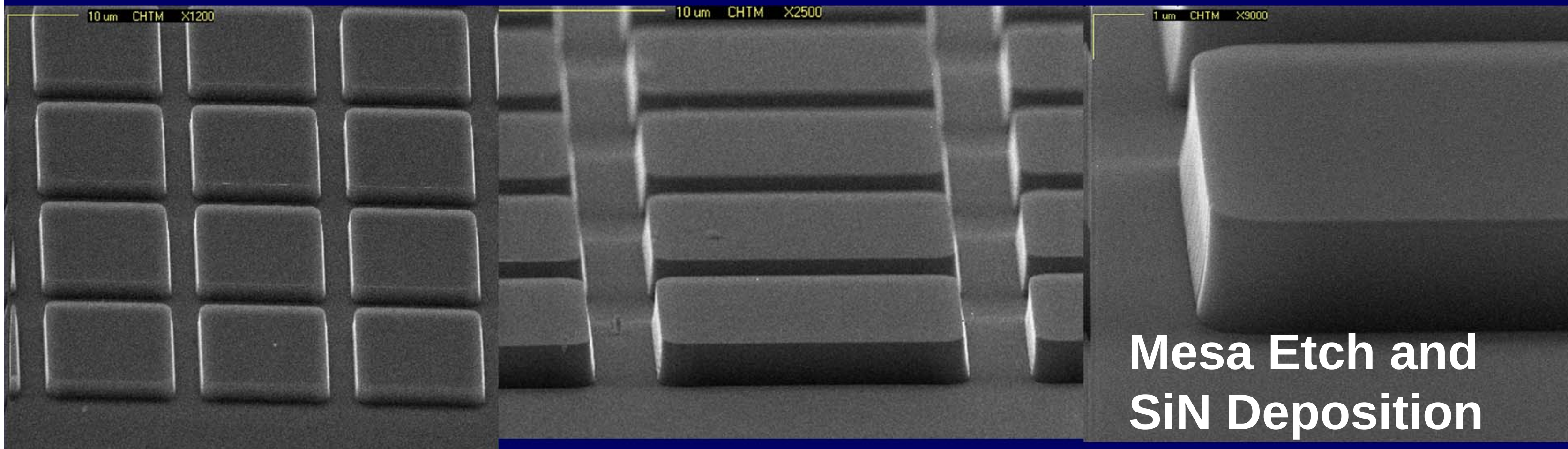
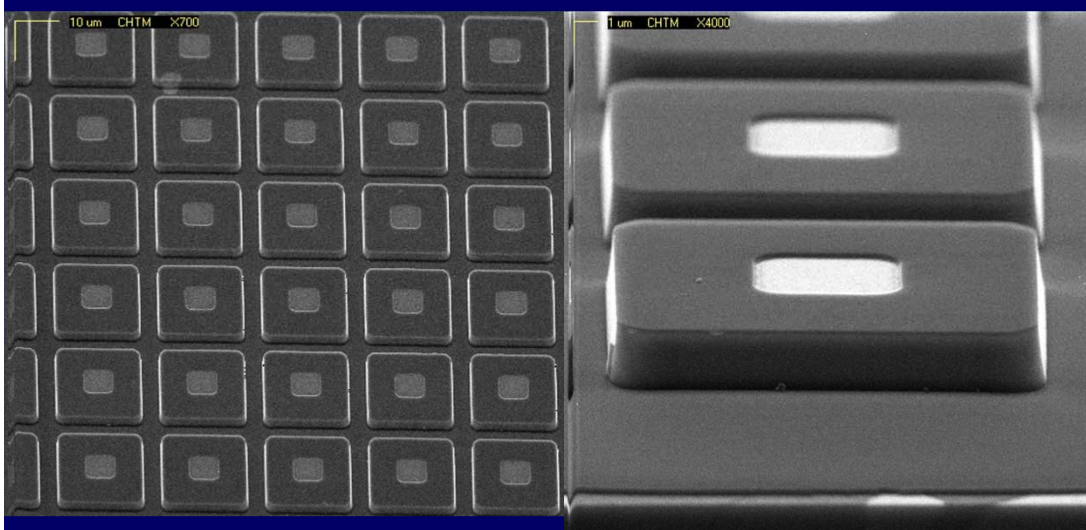
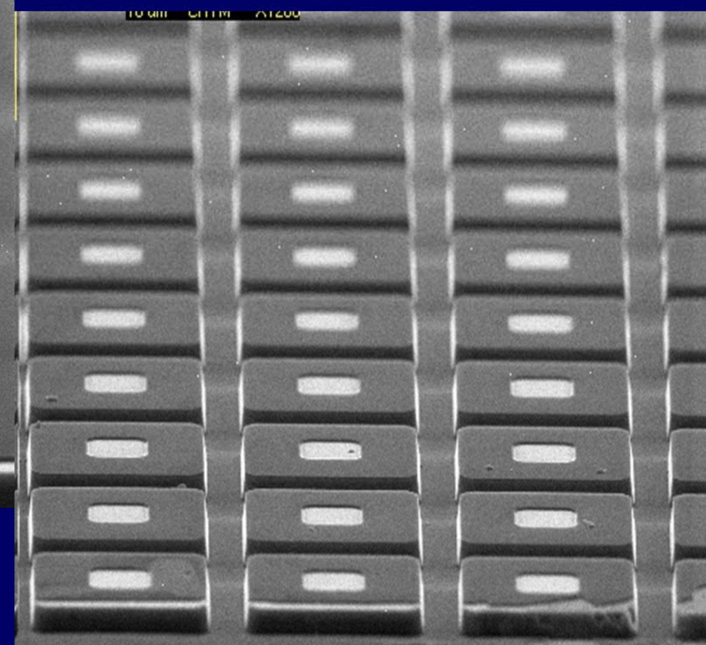
Processing: Material to FPA



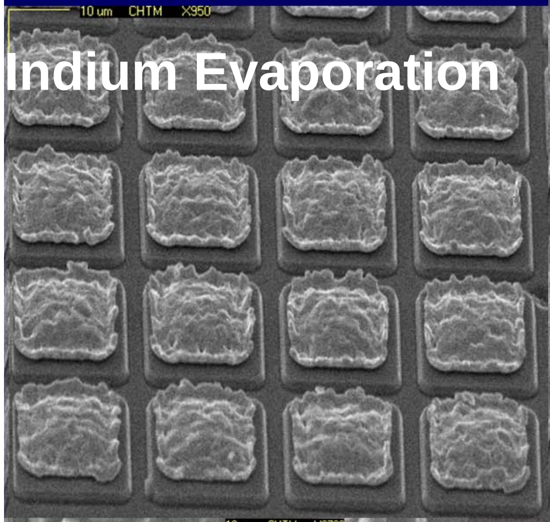
Mesa Etch and SiN Deposition



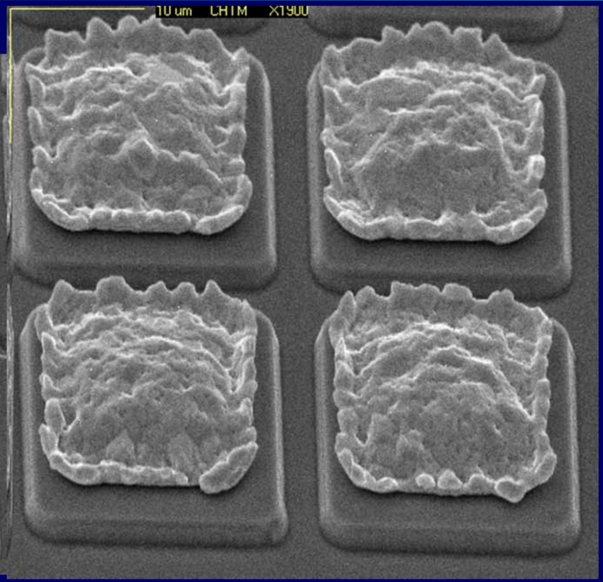


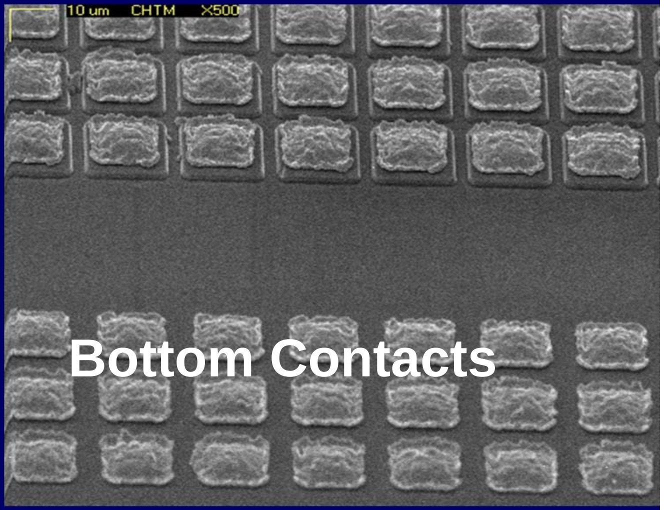
Contact Metal Deposition

Processing: Material to FPA

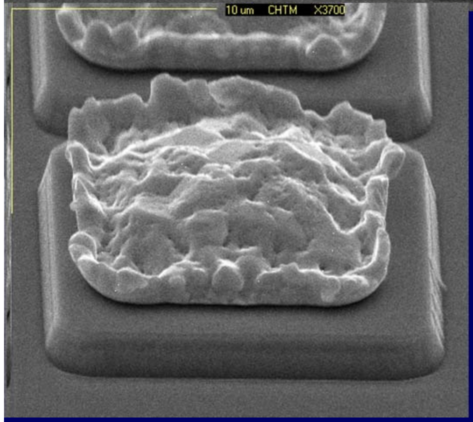


Indium Evaporation

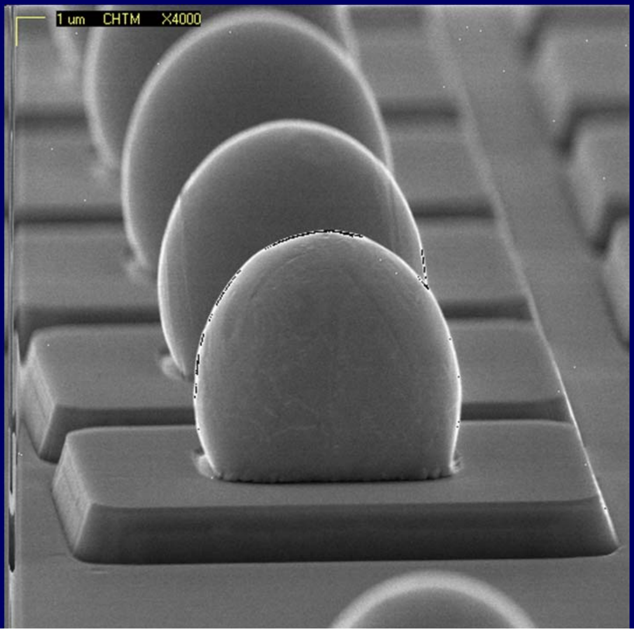


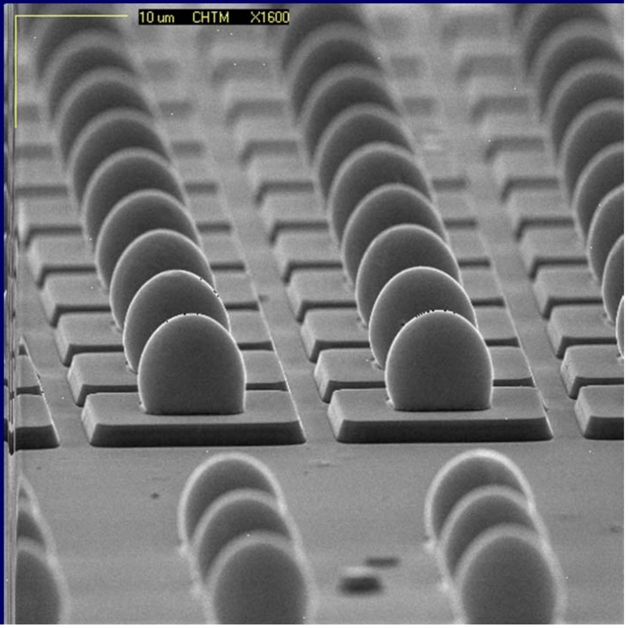


Bottom Contacts

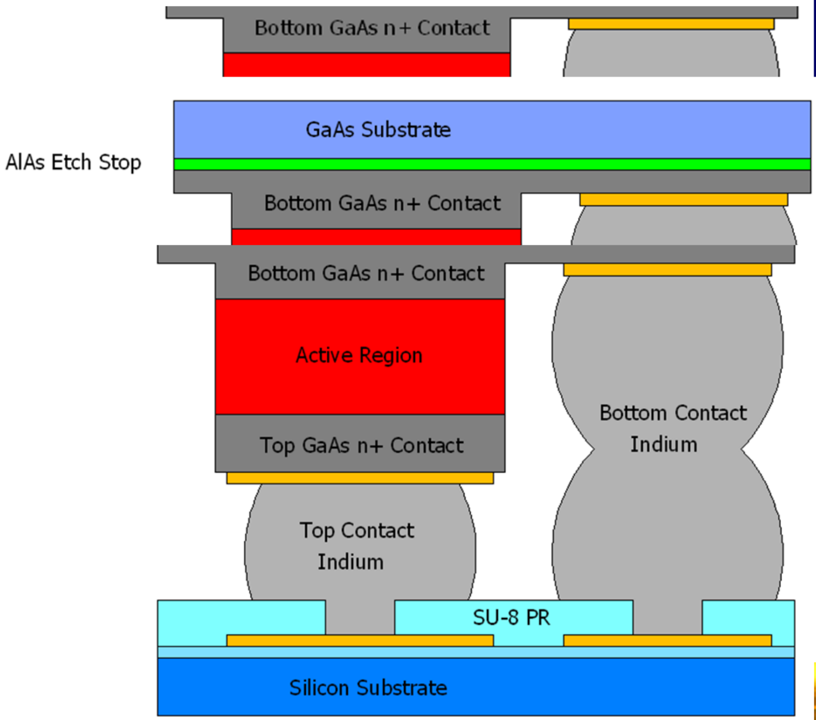


After Indium Reflow





Processing: Material to FPA



STEP 4: Indium Bump Metallization/Dicing

- Establish a process for indium bump metallization and dicing of wafers

STEP 5: Hybridization to Fanout/ROIC

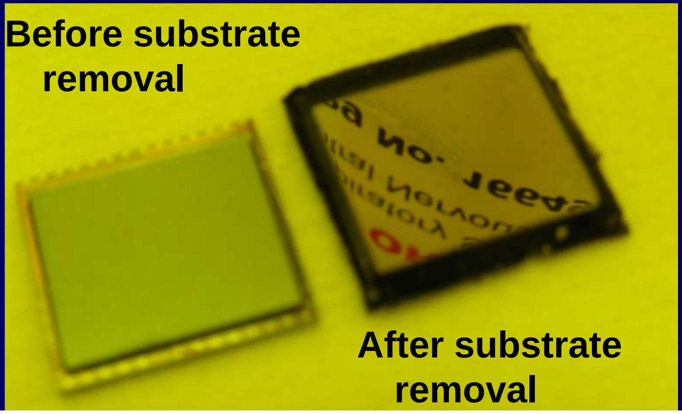
- Test structures are hybridized to Fanout
- After initial characterization, the actual ROICs are hybridized

STEP 6: Substrate Removal

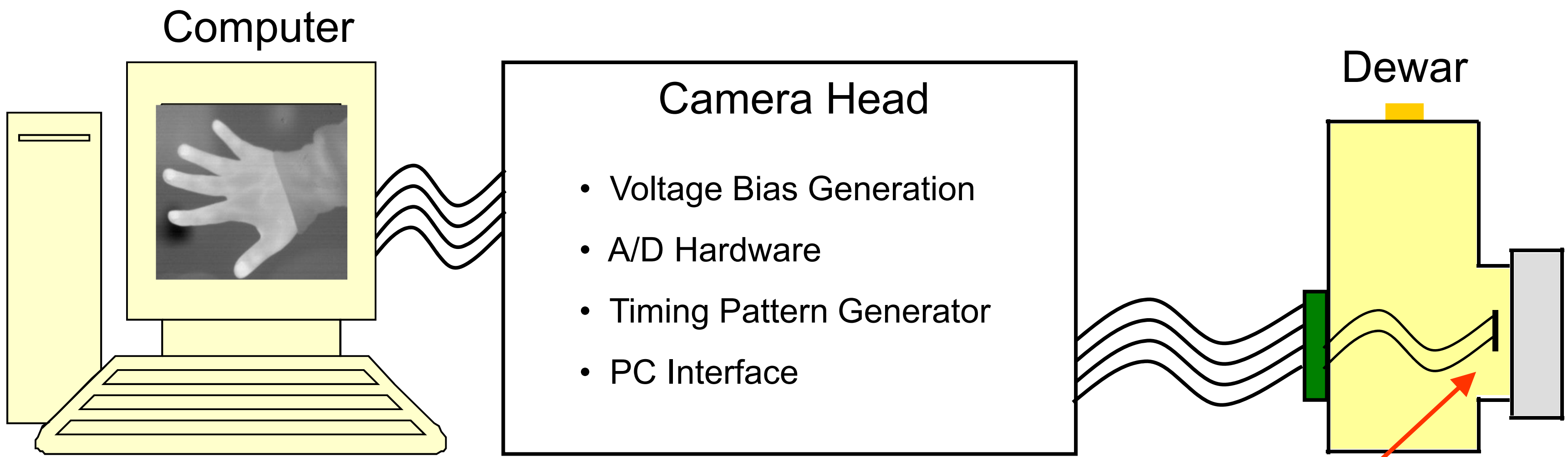
- Substrate will be removed by a combination of chemical and mechanical polishing

STEP 7: Characterization and Evaluation

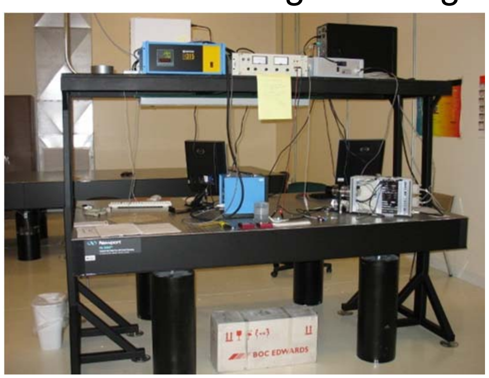
- Performance of devices will be evaluated
- FPA characterization will be undertaken

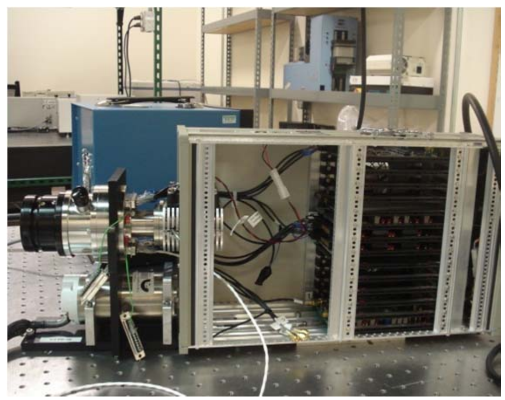


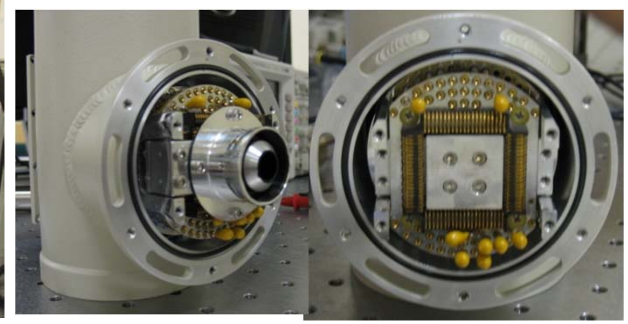
Mid-infrared Imaging Characterization and Applications (MICA) Lab



■ Data Processing & Storage







■ **Commercially available SE-IR CamIRa™ demonstration system:**

☐ Janos Technology Ninox 3 ~12 μm lens

☐ SE-IR CamIRa software, Closed cycle dewar, Camera Head electronics

☐ Extended (plate) Blackbody source

Images from 320x256 FPAs

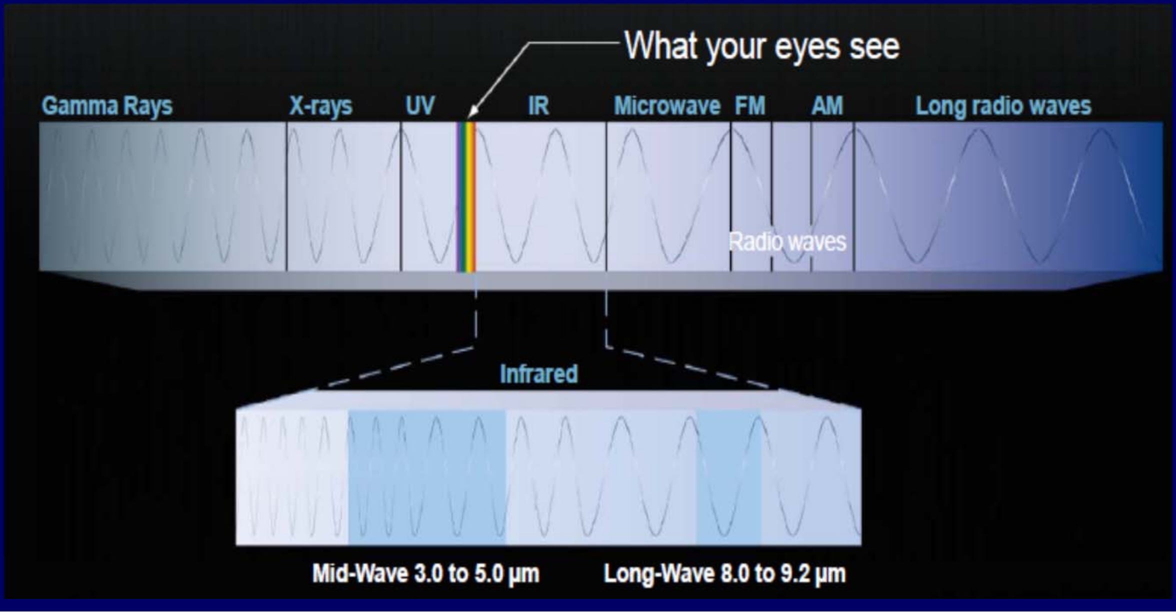

Superlattice FPAs

Quantum Dot FPAs



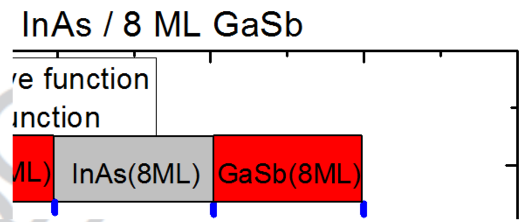
Outline

➢ ***Type II Strain Layer Superlattices***



Band-gap Engineering of Type-II Semiconductor Active Layers

45, 1987.



0.17 InAs/(In)GaSb Type II Strain Layer Superlattice Detectors

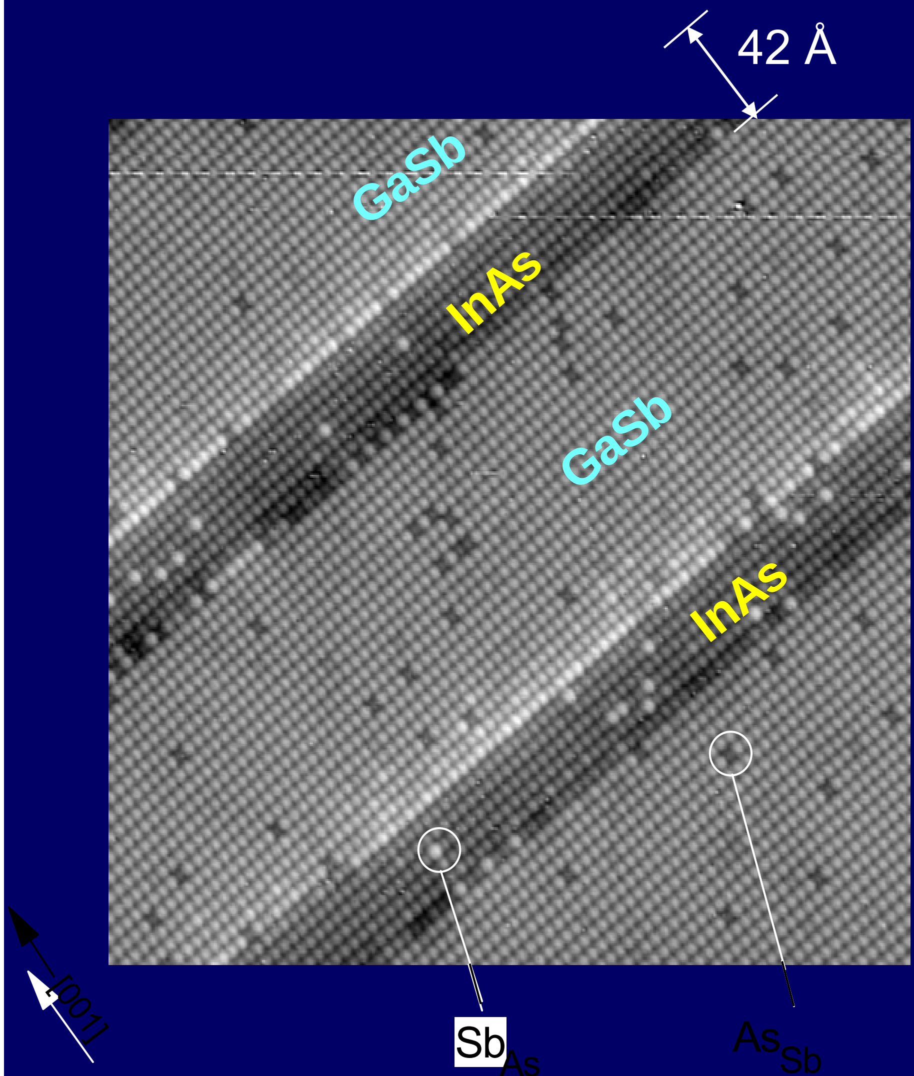
E Plis, University of New Mexico, Albuquerque, NM, USA

J B Rodriguez, Université Montpellier 2, Montpellier, France

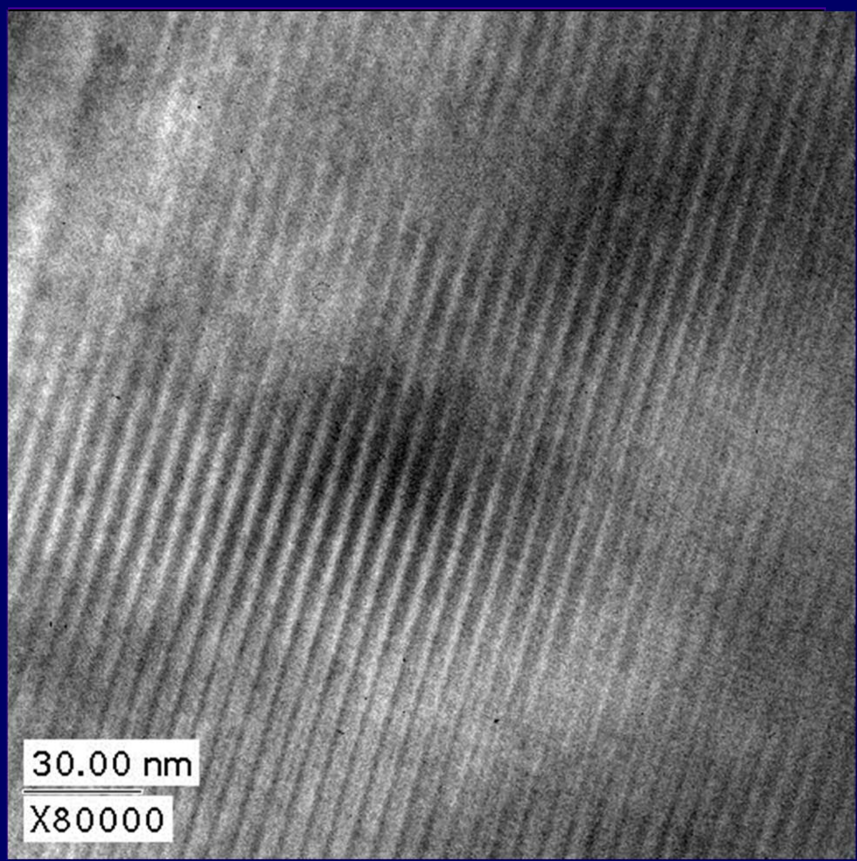
S Krishna, University of New Mexico, Albuquerque, NM, USA

Epitaxial Growth of Type-II Strain Layer Superlattices

Growth by Solid Source MBE System at CHTM by Kaspi

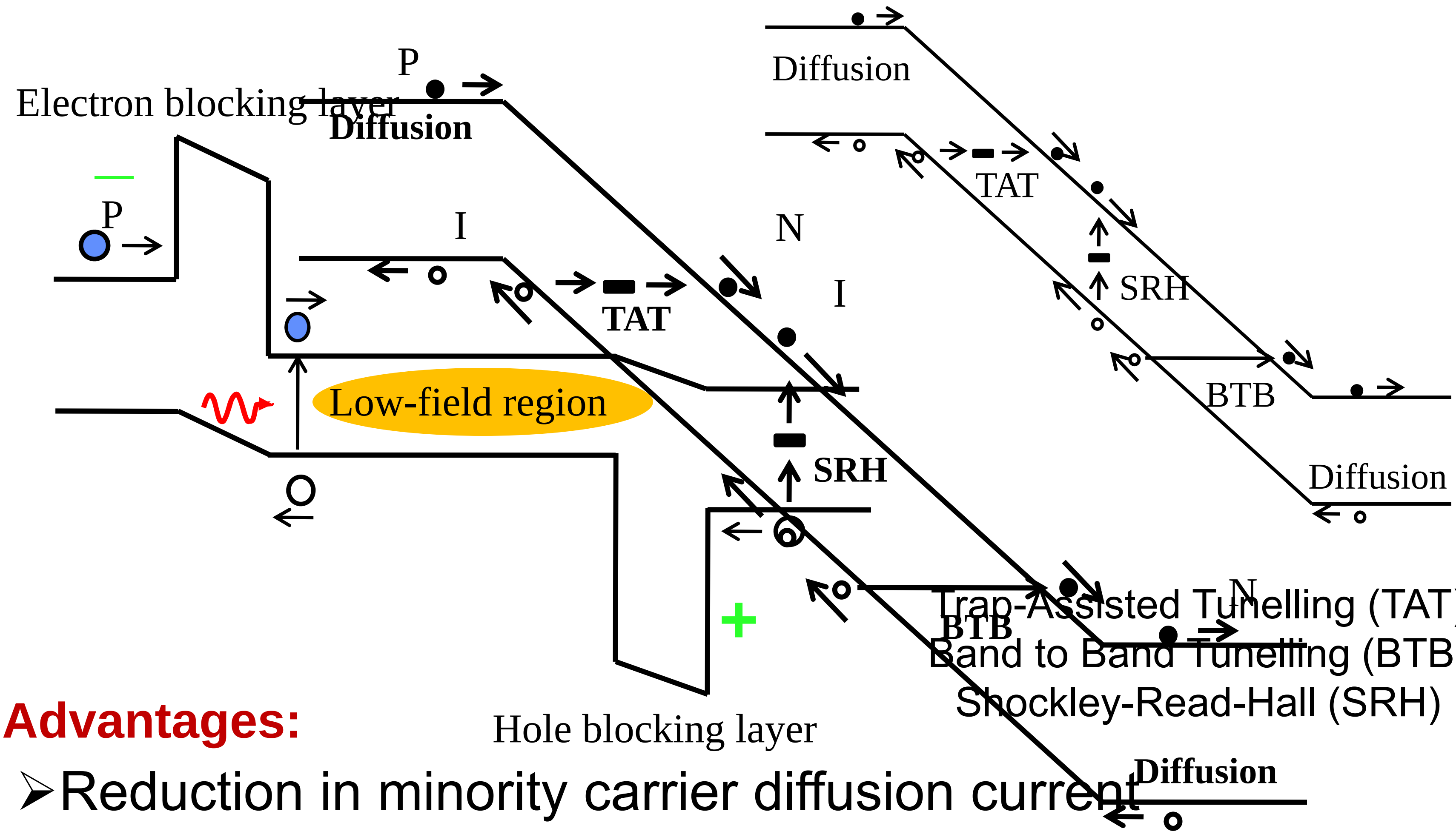


STM by Michael Weimer (Texas A & M)



TEM by Paul Rotella (UNM)

Unipolar Barrier Diode (PbIbN)

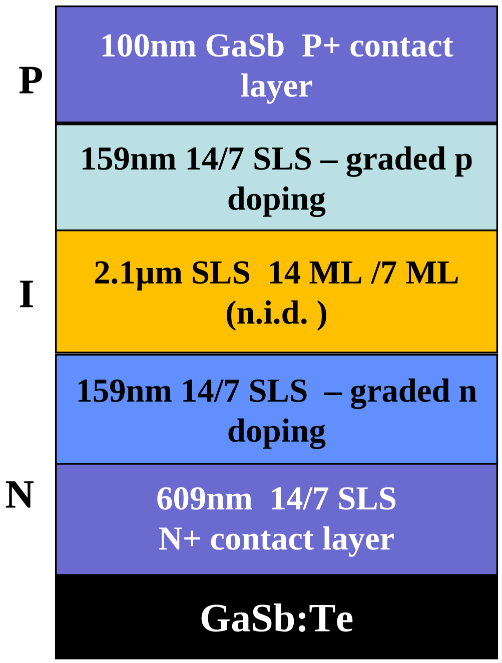


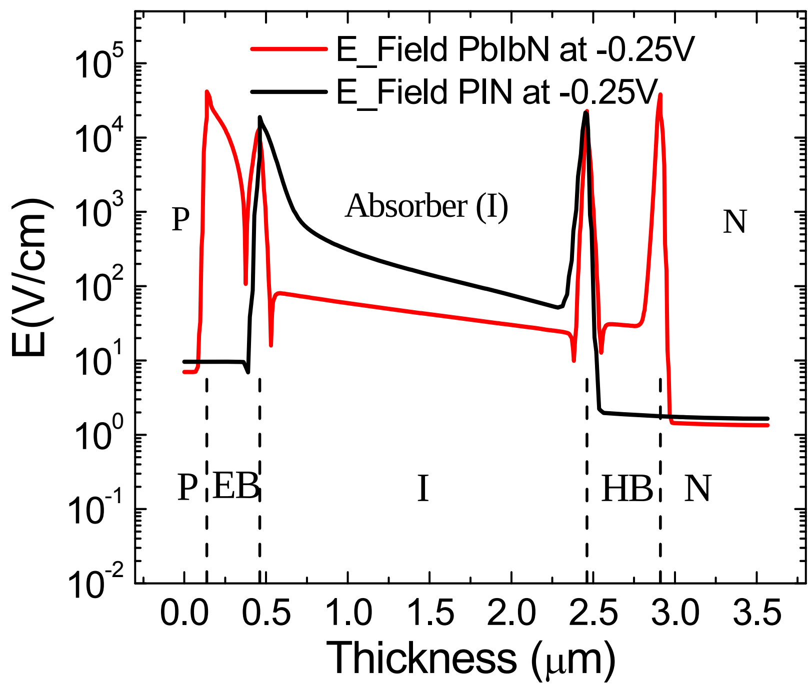
PIN diode under reverse bias operation

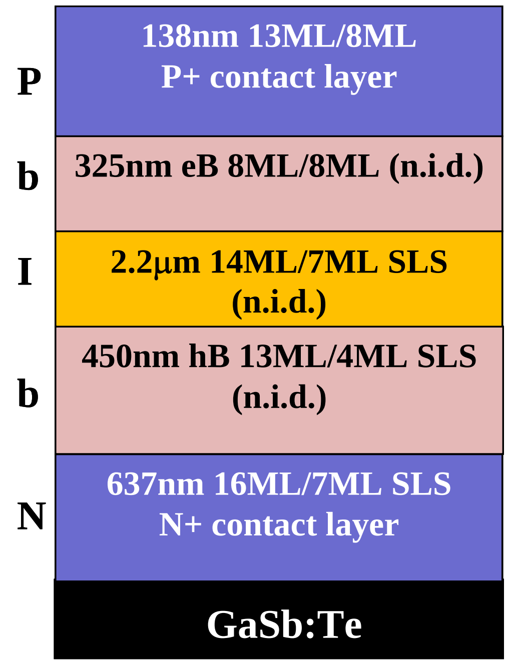
Advantages:

- Reduction in minority carrier diffusion current
- Reduction in tunneling
- Reduction in SRH currents

Unipolar Detector Design







Band offsets and bandgaps obtained from Semi-Empirical Pseudopotential Method and fed to Sentaurus T-CAD for further calculations

Significant reduction in field drop across absorber region

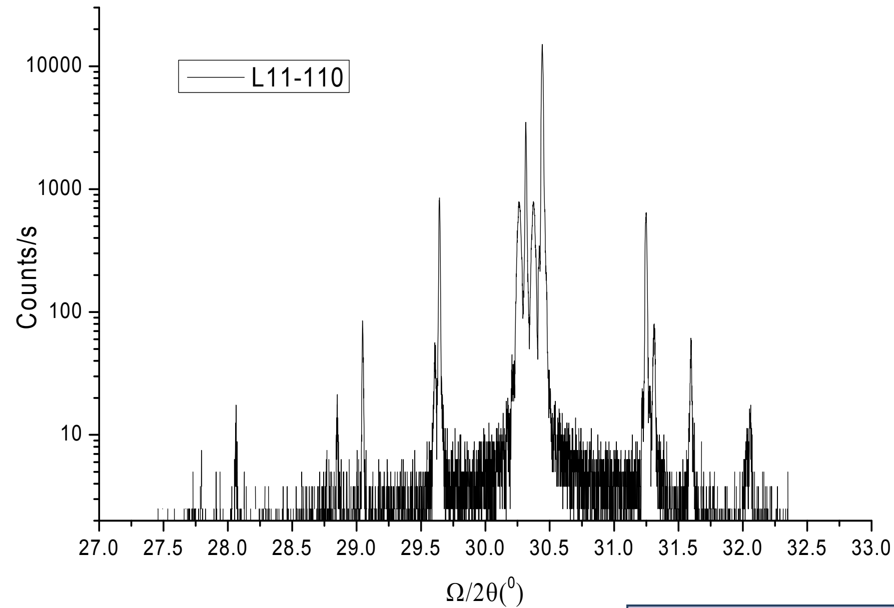
[1]Gregory C. Dente and Michael L. Tilton, J. Appl. Phys. 86, 1420 (1999)
[2]http://www.synopsys.com/Tools/TCAD/Pages/default.aspx

Improved PbIbN Design

5/8 SLS P+ contact Layer (38 P) 130nm
EB 7ML GaSb/4ML AlSb SLS (45 Periods) (149nm)
14ML InAs/7ML GaSb SLS (1.94μm thickness) (p1e16) (300 P) (both layers dopes p-type)
45P (16ML InAs/4ML AlSb) (n.i.d) (275nm)
N+ Contact Layer 9/4 SLS (200 Periods)(800nm)
GaSb:Te 2” wafer

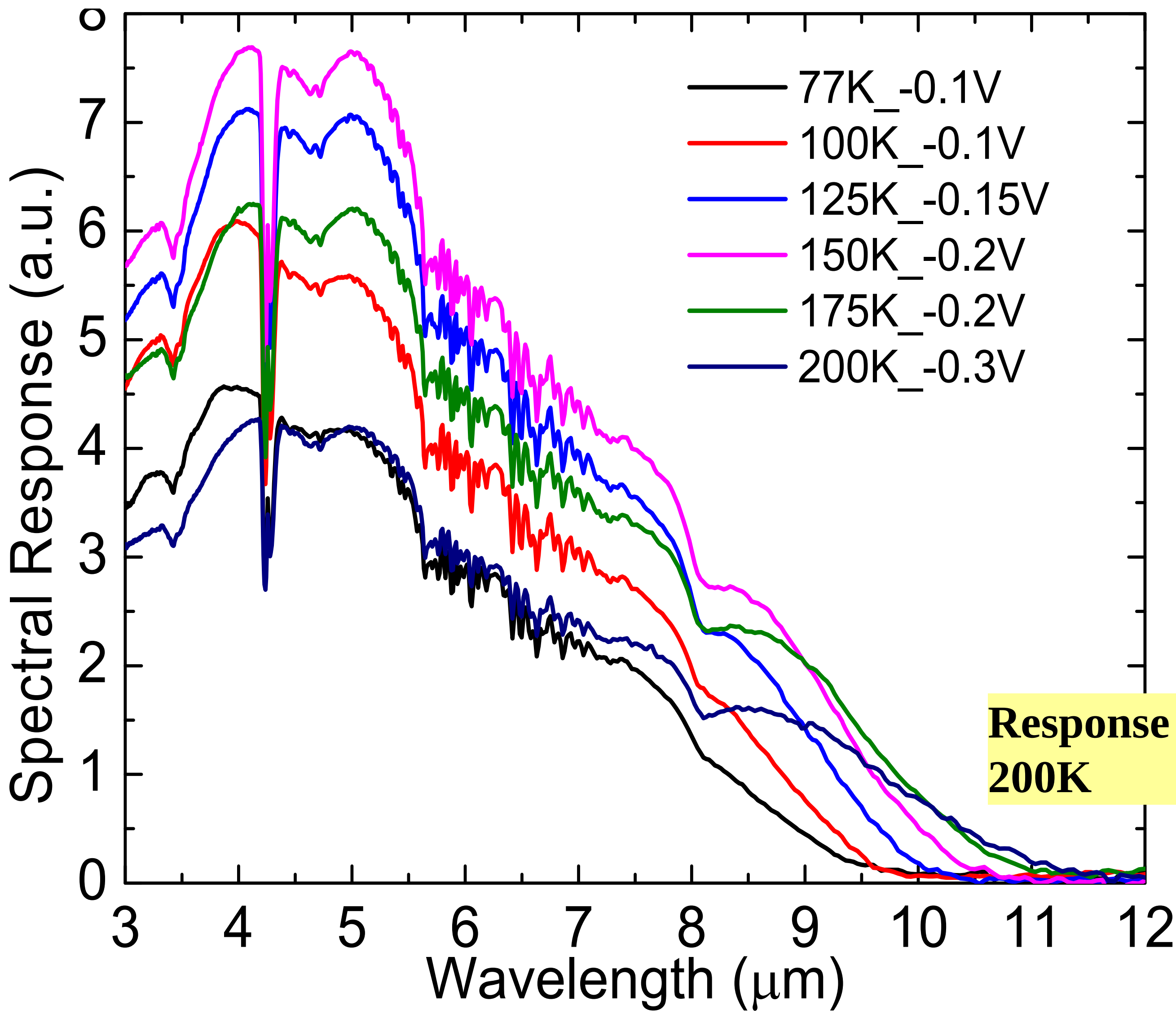
Not previously reported

- Optimized barrier height to reduce operating bias
- Increased barrier height using AlSb



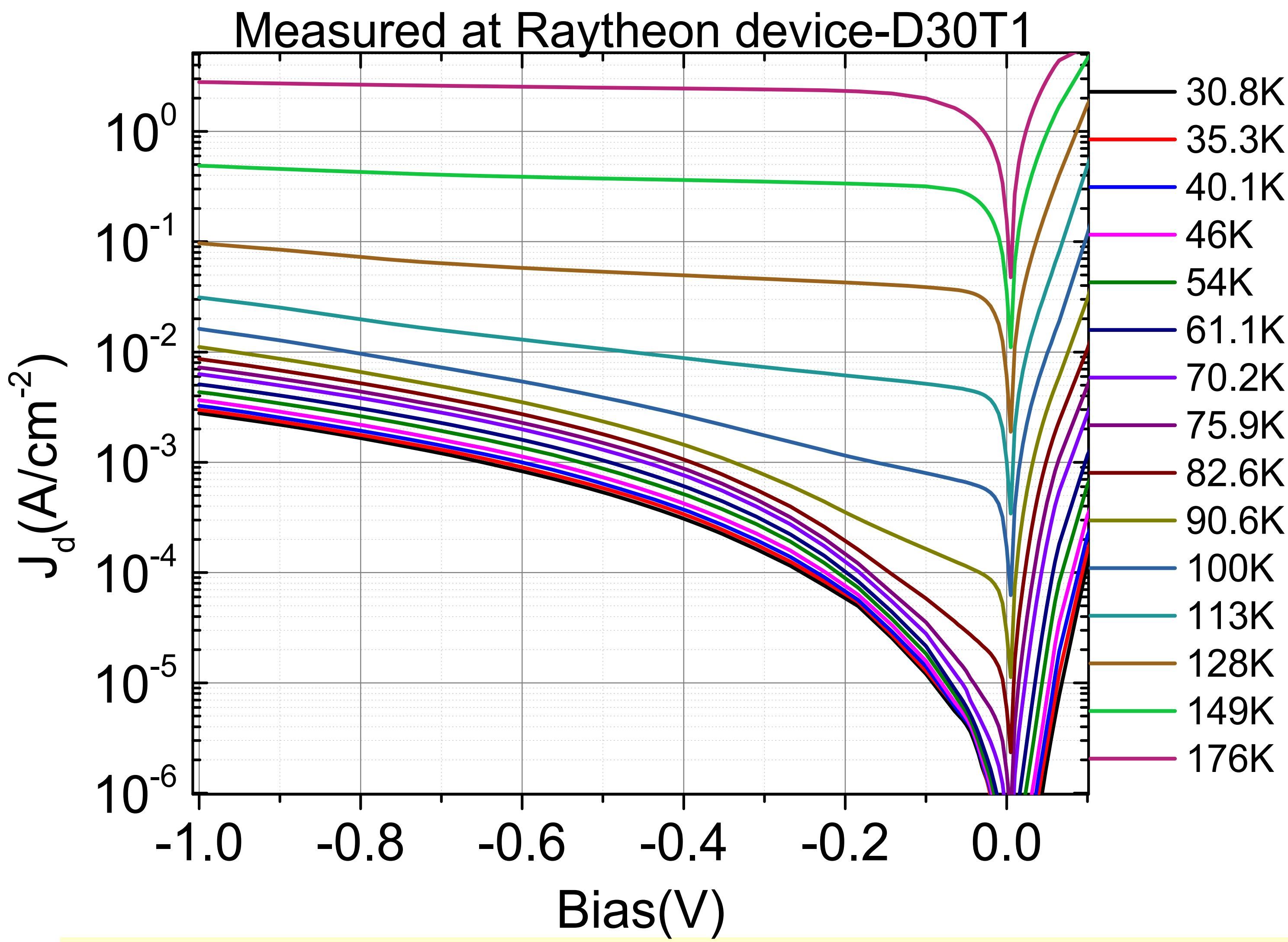
L11-110

Spectral Response



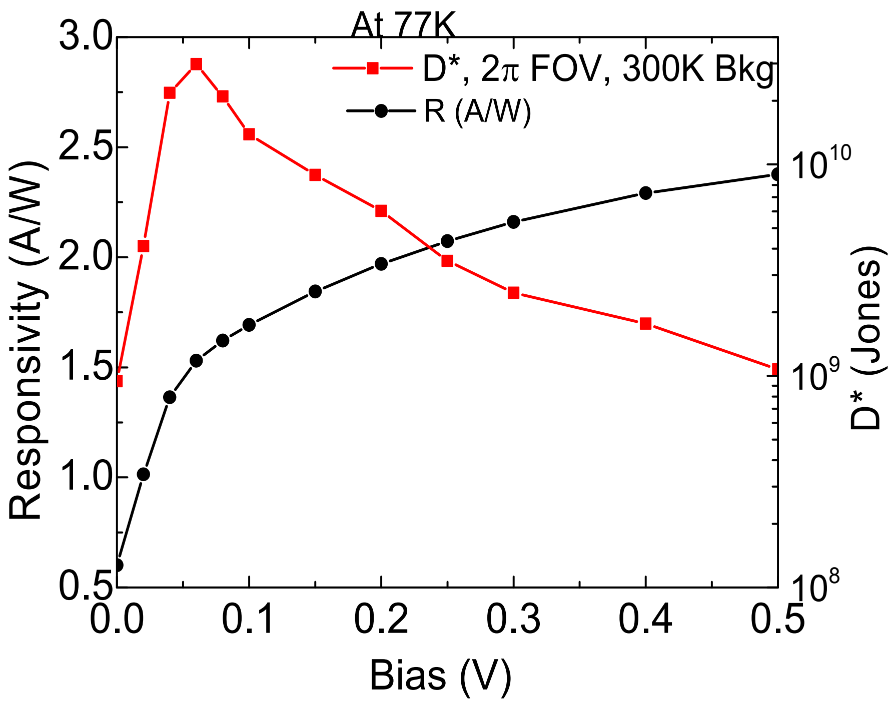
Response observed till 200K

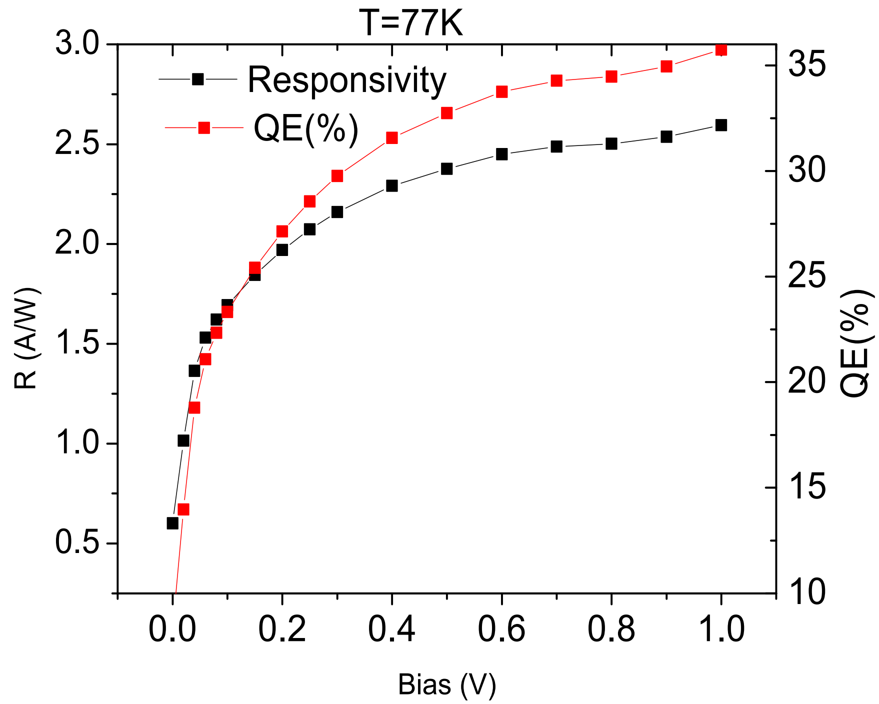
Dark Current Measurements at RVS



J_d=1.6e-5 A/cm^2 at 76K at -60mV (bias for highest SNR)

Quantum Efficiency

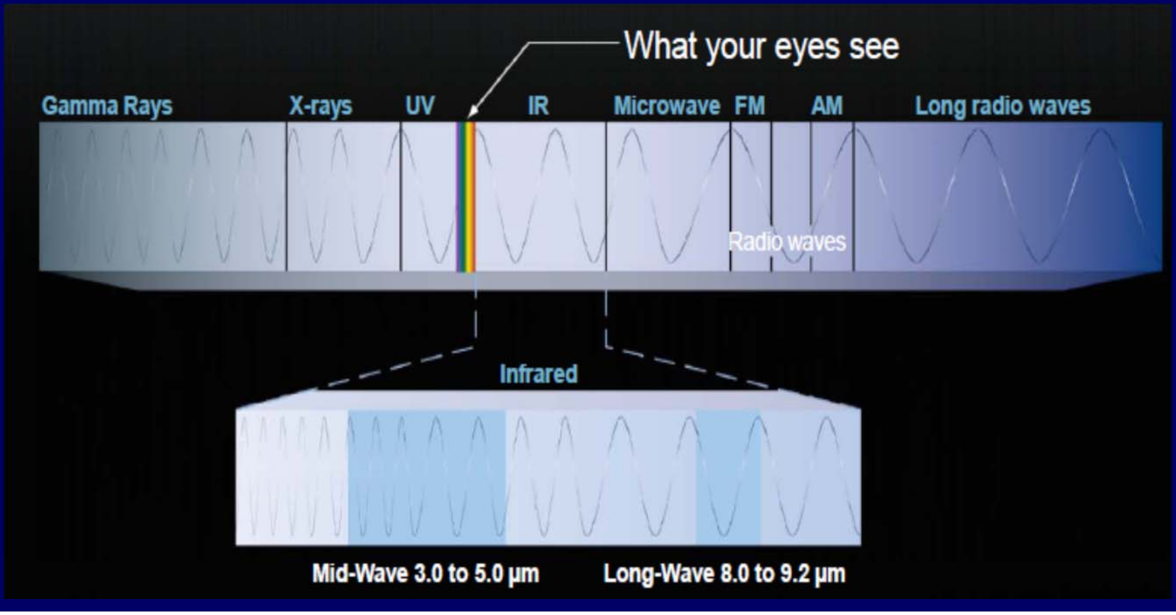




- Single pass QE=23% at 60 mV without AR coating
- Detectivity calculated with noise measurements and NOT from dark current data
- Signal measured using 8.4 μm long pass filter
- Devices are at RVS for independent evaluation

Outline

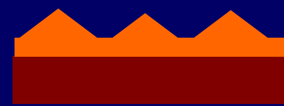
- ***Quantum Dots in a Well Detectors***



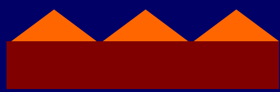
Self-Assembled Growth of Quantum Dots

Frank-van der Merwe
2d layer by layer

Stranski-Krastanow
Initial 2d growth,
Later 3d island growth

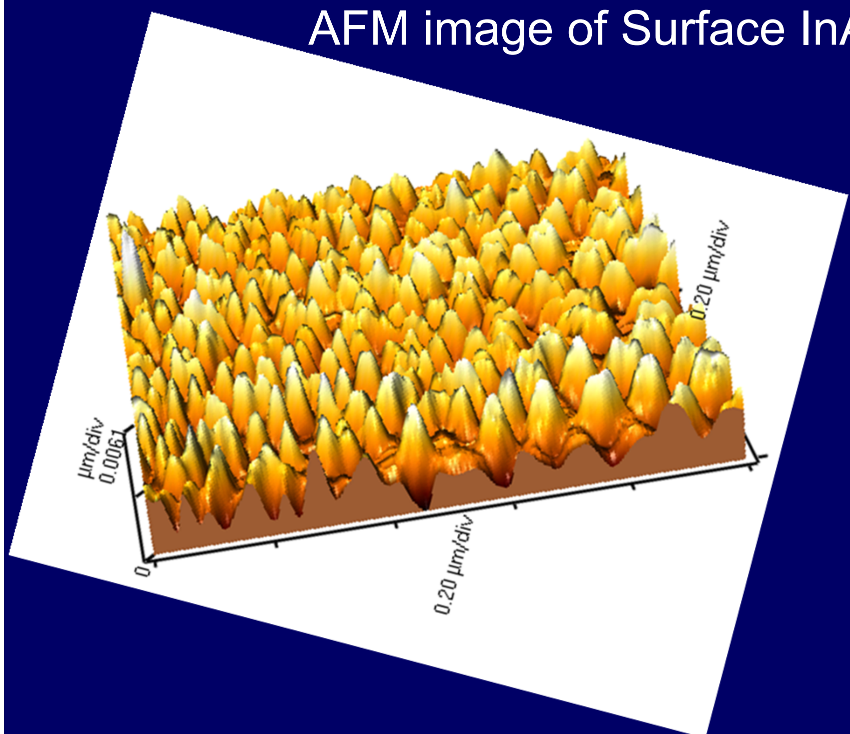


Vollmer-Weber 3d
island growth

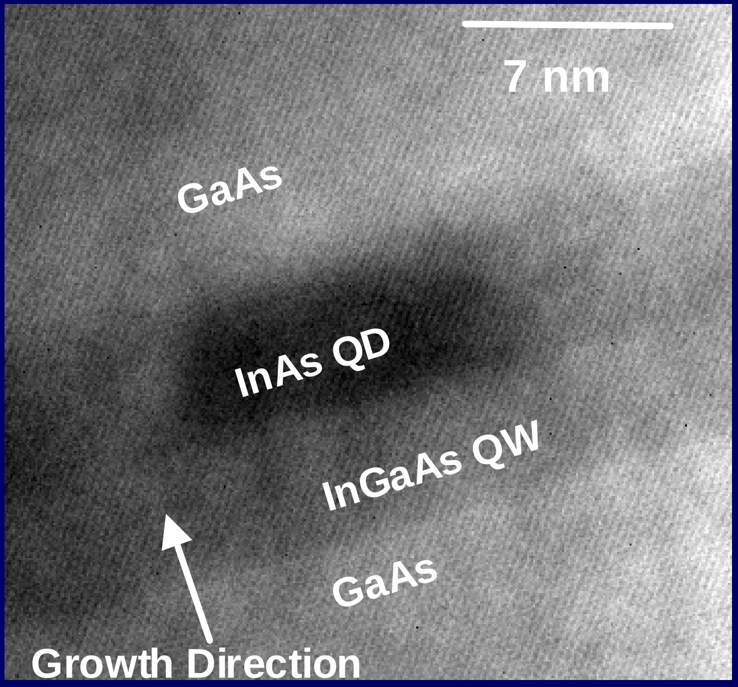


Increasing Strain

AFM image of Surface InAs QDs



TEM by P. Rotella

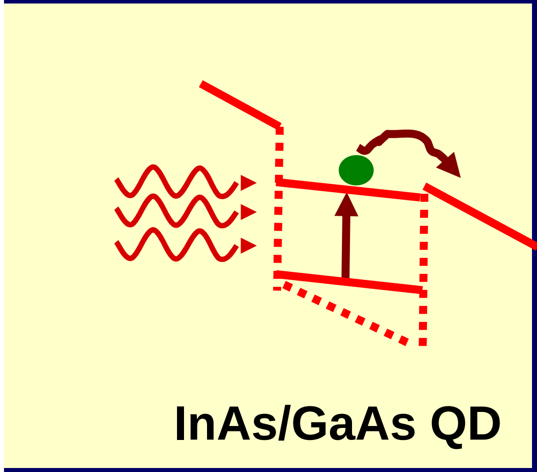


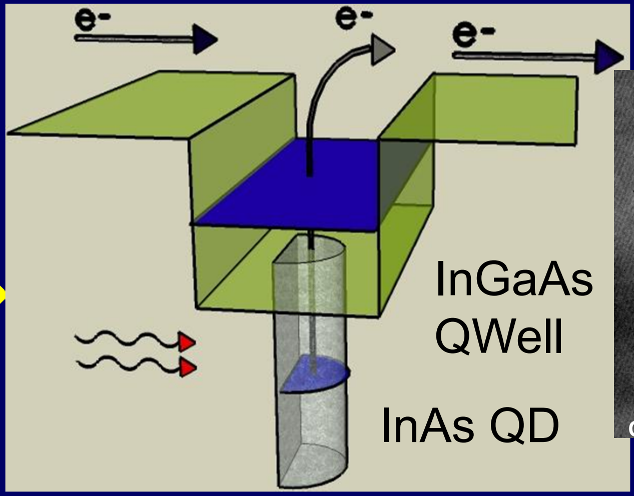
XTEM image of an InAs/InGaAs QD

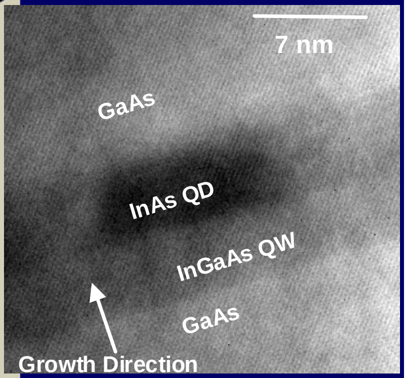
InAs/InGaAs Dots in a Well Detectors

Band-structure Engineering of QD Detectors

- Placing the dots in an InGaAs well (DWELL) is expected to lead to reduced thermionic emission → lower dark current→ higher operating temperature
- The operating wavelength and nature of transition can be tailored by varying the width and the composition of the InGaAs QW
- Tailoring asymmetry in bandstructure for exploiting QCSE
- Novel Physics: transitions between carriers with different degrees of confinement







Krishna et al, *Appl. Phys. Lett.*, 80, 3898, 2002

Raghavan et al, *Appl. Phys. Lett.*, 81, 1369, 2002

* Krishna et al, *IEEE Circuits and Devices,* p.14, Jan. 2002; *Appl. Phys. Lett.*,**79**, 21, 2001.

InAs/InGaAs Dots in a Well Detectors

- **Various Research Groups are now using DWELLs**
  - IR Nova/Linkoping University (Sweden)
  - Wilson/David Group (Sheffield University)
  - Jagadish Group (Australian National University)
  - J.Deen Group (McMaster University)
  - Razeghi Group (Northwestern University)
  - Wang Group (Taiwan)
  - Gunapala Group (NASA JPL)
  - Lu Group (UMass)

Bias and temperature dependence of t... dots-in-a-well infrared photodetectors

L. Höglund,[1,a)] P. O. Holtz,[2] H. Pettersson,[3] C. As... S. Smuk,[4] E. Petrini,[1] and J. Y. Andersson[1]
[1]Acreo AB, Electrum 236, S-16440 Kista, Sweden
[2]Department of Physics, Chemistry and Biology (IFM), Lin...
[3]Center for Applied Mathematics and Physics, Halmstad Un... Sweden and Solid State Physics and the Nanometer Structu... S-22100 Lund, Sweden
[4]IRnova, Electrum 236, S-16440 Kista, Sweden

(Received 11 July 2008; accepted 10 August 2008; pu...

Spectral function of InAs/InGaAs qu... using Green's function

M. A. Naser, M. J. Deen,[a)] and D. A. Thompso...
Department of Electrical and Computer Engineering, M... West, Hamilton, Ontario L8S 4K1, Canada

(Received 11 July 2006; accepted 22 August 2006;...

Energy level structure and electron relaxation times in $InAs/In_xGa_{1-x}As$ quantum dot-in-a-well structures

P. Aivaliotis,[a)] S. Menzel, E. A. Zibik, J. W. Cockburn, and L. R. Wilson[b)]
Department of Physics and Astronomy, The University of Sheffield, Sheffield S3 7RH, United Kingdom

M. Hopkinson
EPSRC National Centre for III-V Technology, The University of Sheffield, Sheffield S1 3JD, United Kingdom

(Received 5 October 2007; accepted 1 November 2007; published online 17 December 2007)

640 x 512 Pixels Long-Wavelength Infrared (LWIR) Quantum-Dot Infrared Photodetector (QDIP) Imaging Focal Plane Array

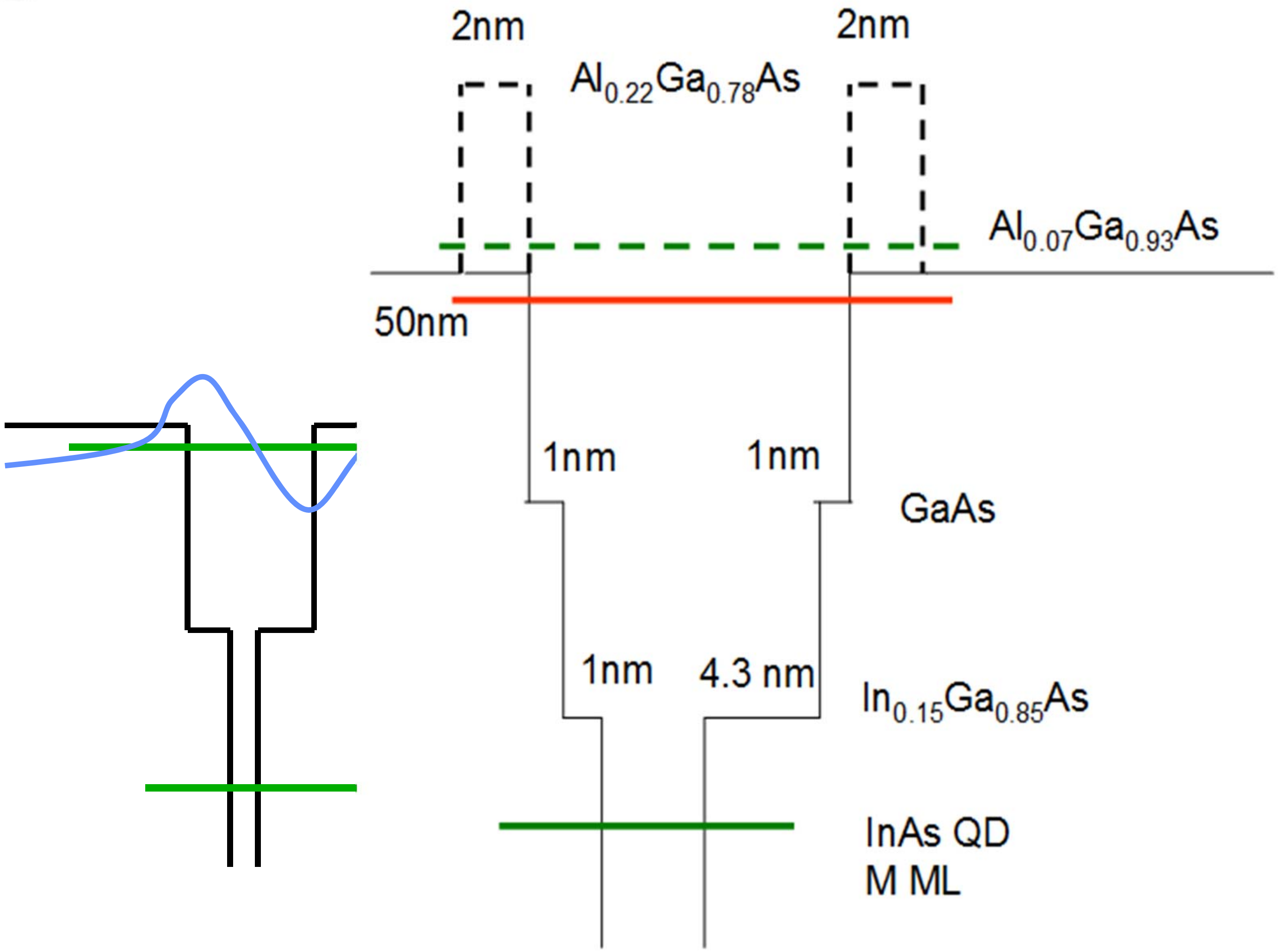
Sarath D. Gunapala, Sumith V. Bandara, Cory J. Hill, David Z. Ting, John K. Liu, Sir B. Rafol, Edward R. Blazejewski, Jason M. Mumolo, Sam A. Keo, Sanjay Krishna, Y.-C. Chang, and Craig A. Shott

PHYSICAL REVIEW B 78, 115320 (2008)

Gain and recombination dynamics in photodetectors made with quantum nanostructures: The quantum dot in a well and the quantum well

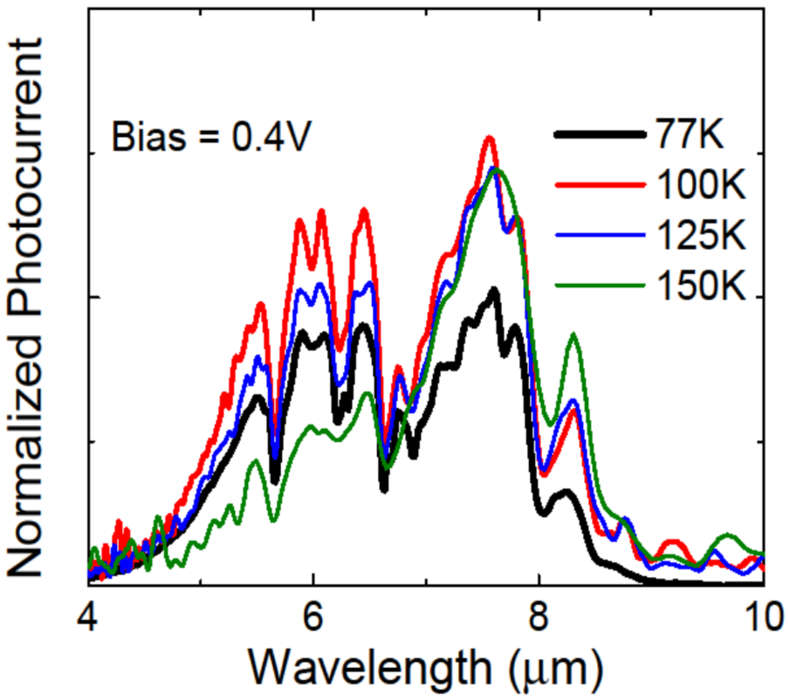
B. Movaghar, S. Tsao, S. Abdollahi Pour, T. Yamanaka, and M. Razeghi
Center for Quantum Devices, Electrical Engineering, and Computer Science, Northwestern University, Evanston, Illinois 60208, USA
(Received 1 May 2008; revised manuscript received 30 July 2008; published 23 September 2008)

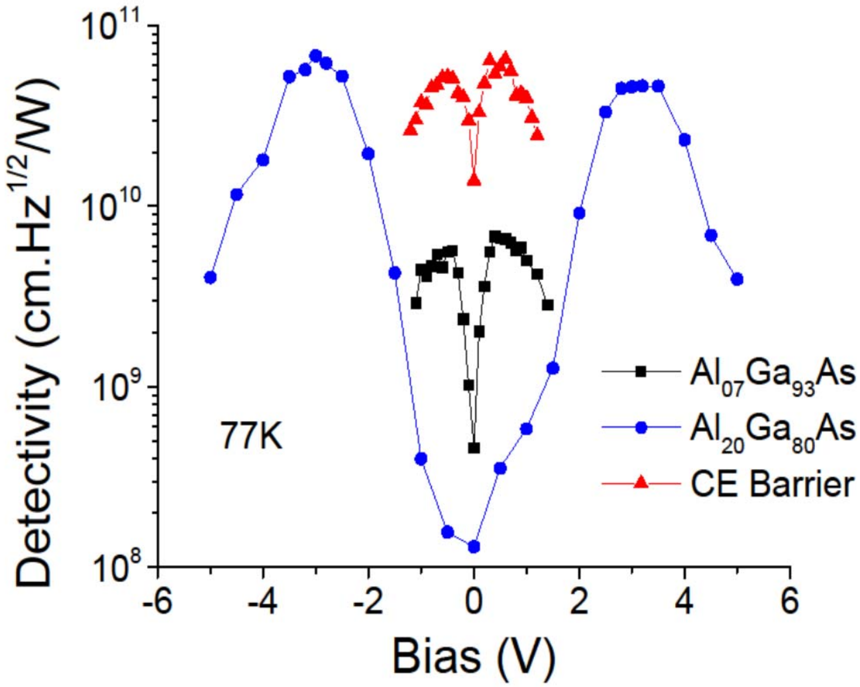
Confinement Enhancing DWELL Design



Barve et al, APL, 2011

Spectral Response and Radiometric Characterization



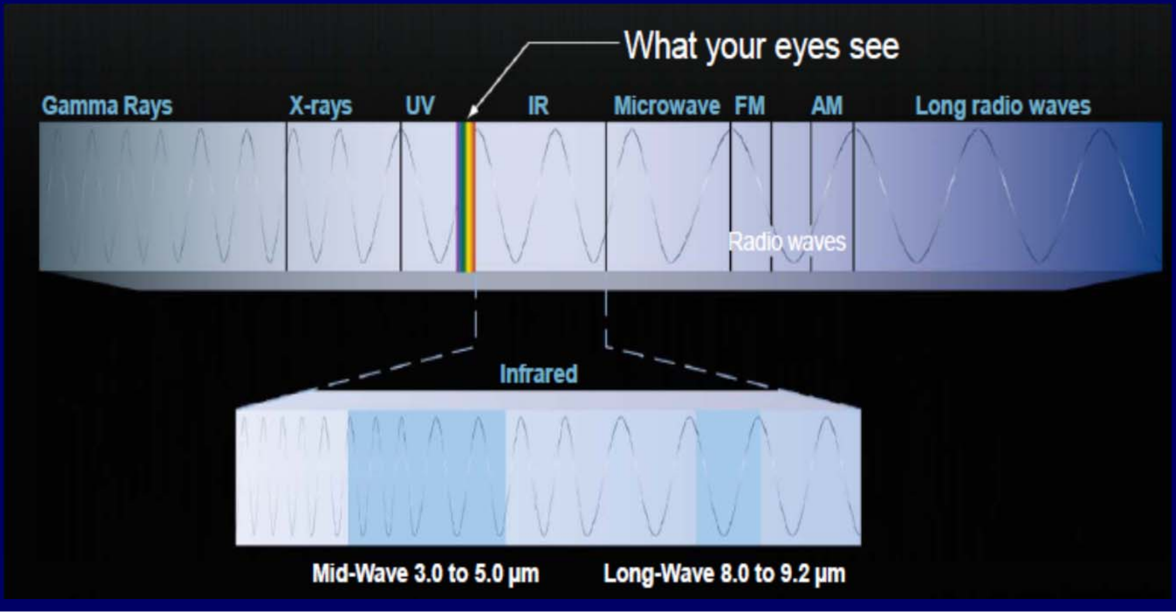


- Response observed till 150K
- Detectivity of 6e11 cm $Hz^{1/2}$/W at 0.4V (77K)
- High detectivity at low bias

Barve et al, APL, 2011

Outline

➢ ***4^{th} Gen Imagers: The Infrared Retina***

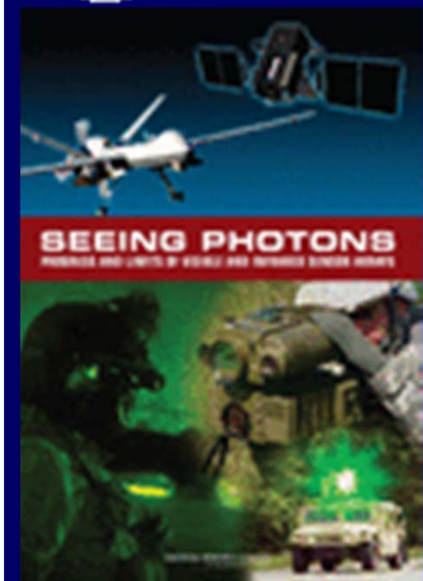


Looking Ahead: Vision for 4th Gen

Figer Questions !

1. What are the problems with the current generation of IR detectors?
2. What are the most interesting developments that you would like to see for your topic over the next ten years?
3. What are the biggest challenges for developing relevant technology over the next ten years?
4. What science breakthroughs could be enabled by this technology over the next ten years?

“Too Much Data” Problem



SEEING PHOTONS

PROGRESS AND LIMITS OF VISIBLE AND INFRARED SENSOR ARRAYS

Committee on Developments in Detector Technologies

Standing Committee on Technology Insight —Gauge, Evaluate, and Review

Division on Engineering and Physical Sciences

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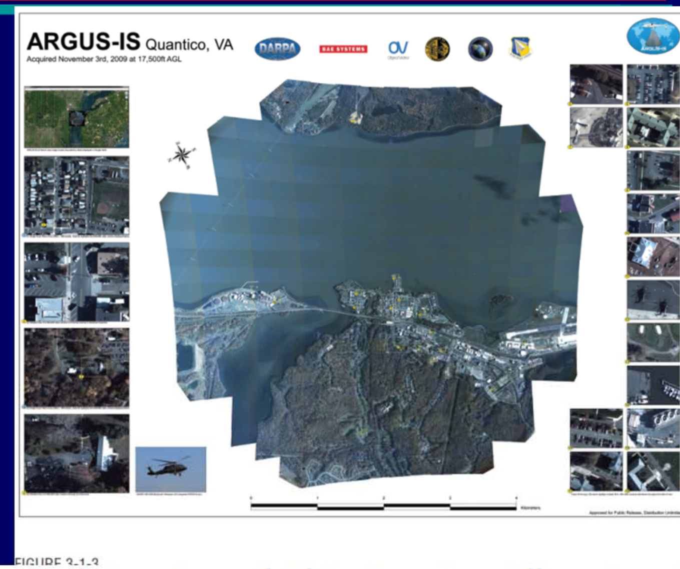


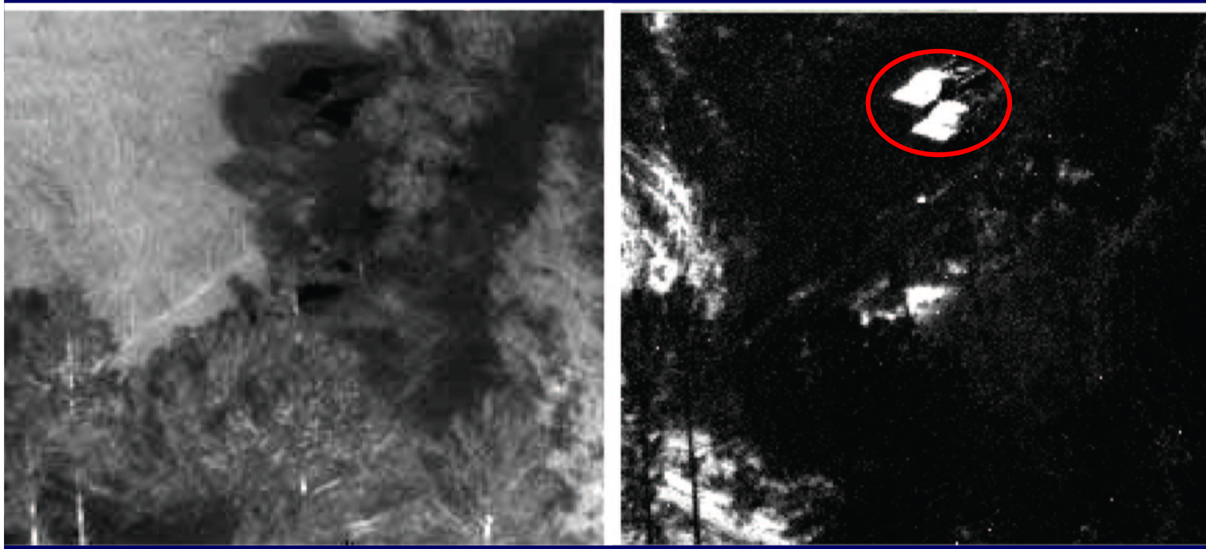
Autonomous Real-time Ground Ubiquitous Surveillance Imaging System

a modest degree of compression. For example, an ARGUS-IS-like system can produce up to 770 gigabits per second. The use of a Common Data Link (CDL) operating at 274 megabits per second would require compression ratios on the order of 2,800, far beyond the capabilities of lossless compression techniques.

The bottleneck to decision making is the user in the loop

Multimodal Sensing

- *Present Day Infrared FPAs*
  - *Mostly Single Color (Monitor Emissivity)*
  - *Multispectral FPAs use either multiple FPAs or spinning filter wheel*
  - *Cost Increases Dramatically*



[2] Rehm et. al Electronic Letters, *42, 577 (2006)*

[3] J. S. Tyo et.. al Applied Optics, 45 (2006)

Looking Ahead: Vision for 4th Gen

All Pixels look the same in present day systems

The Fourth Generation Infrared Imaging Systems should have the following information encoded at the **pixel level**

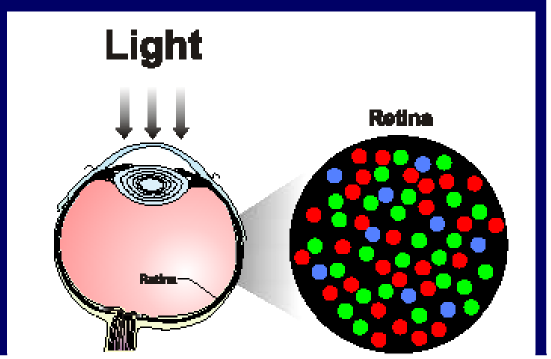
Spectral Content

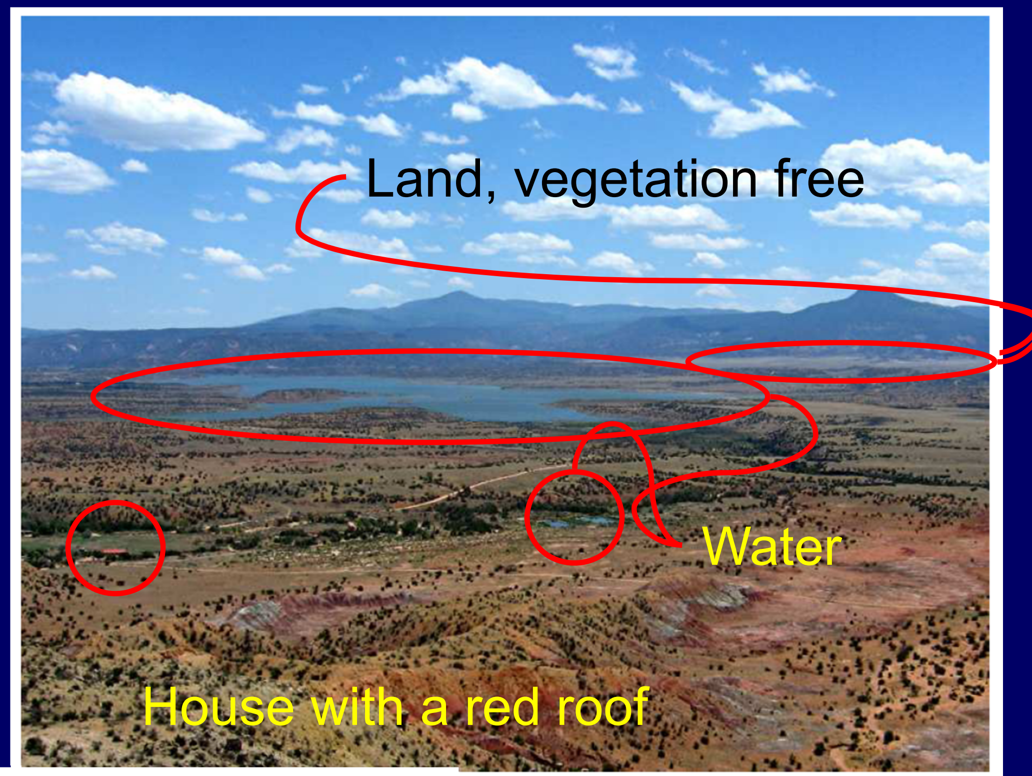
Polarization Information

Dynamic Range (or gain)

Phase Sensitive Detection

Reduced Data Bandwidth





(12) **United States Patent**
Krishna et al.

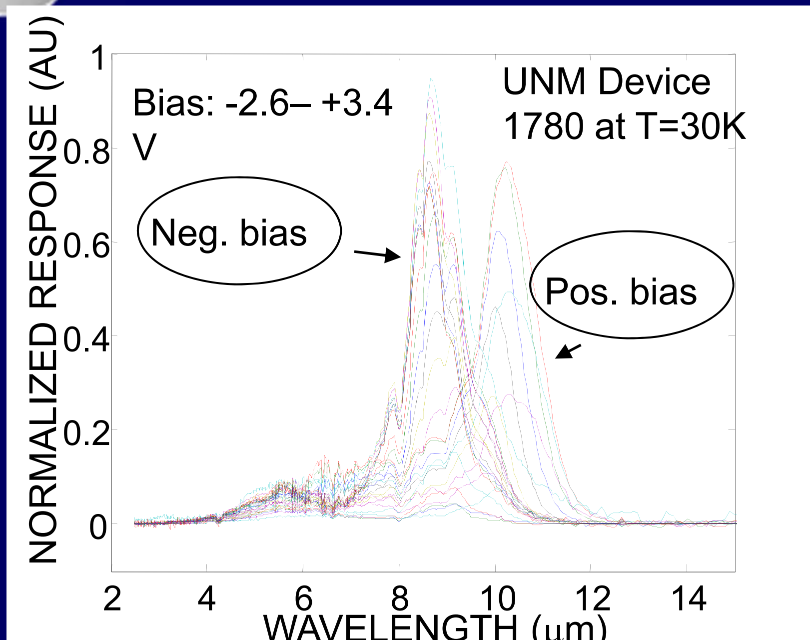
(10) **Patent No.:** **US 8,071,945 B2**
(45) **Date of Patent:** **Dec. 6, 2011**

(54) **INFRARED RETINA**

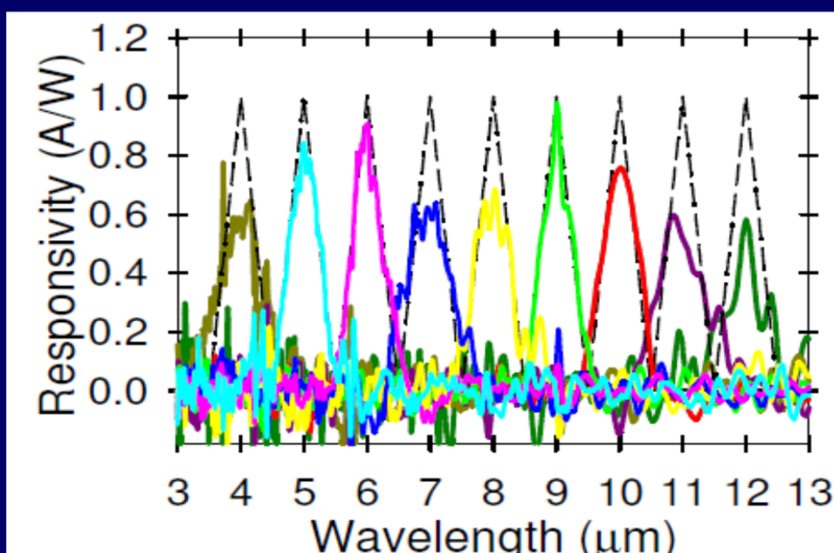
(56) **References Cited**

Images by N. W. Bernstein, LANL

Spectrally Tunable Smart Sensors



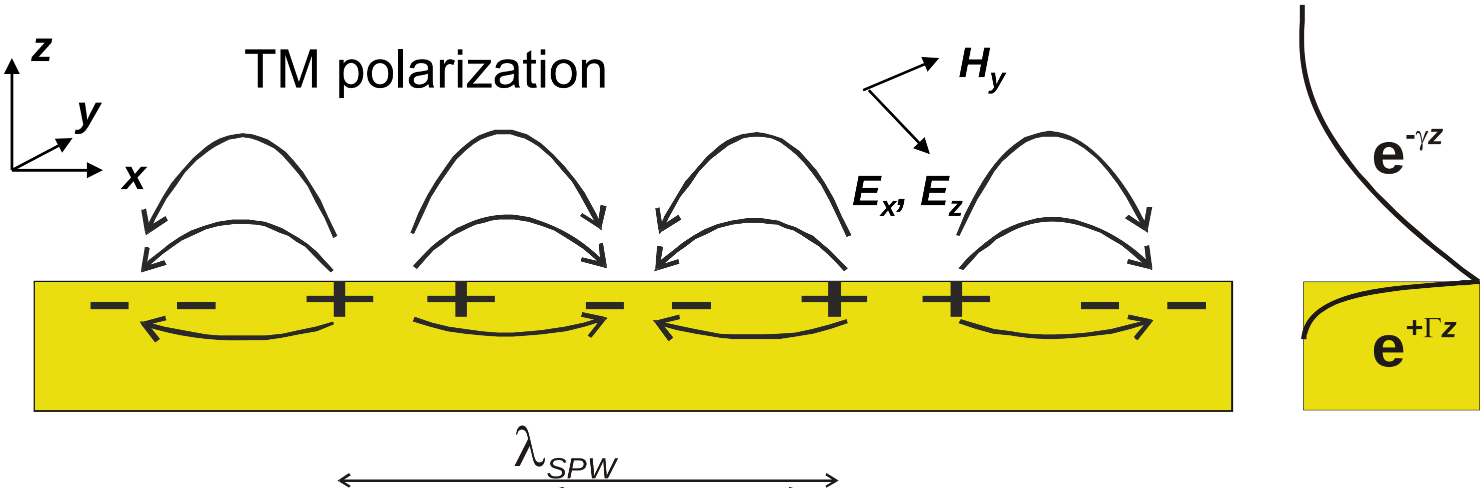
- **Our idea is based on a *bias-tunable* Quantum Dot Infrared Photodetector (QDIP)**
- In an asymmetric well allow the spectral response to vary as the bias voltage is changed
- The spectral diversity is then passed through a post-processing algorithm to achieve (~) arbitrary spectral response
- A single FPA can be used for several different spectral imagery missions ***software reconfigurable!***



Multicolor Response using different bias combinations

University of Sheffield/UNM Collaboration

SURFACE PLASMA: WAVES BOUND TO METAL/DIELECTRIC INTERFACE



Dielectric: $\vec{E}_a = E_0 \left\{ \hat{e}_x - \frac{ik_x}{\gamma} \hat{e}_z \right\} e^{-ik_x x} e^{-\gamma z}$ $\qquad \gamma = \sqrt{k_x^2 - \varepsilon_d}$

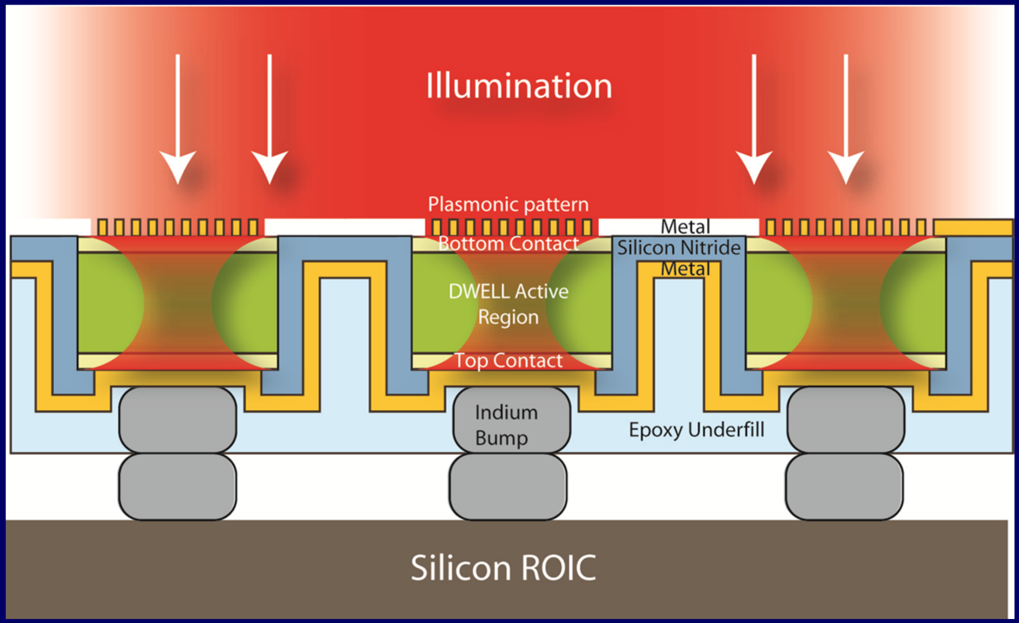
Metal: $\vec{E}_m = E_0 \left\{ \hat{e}_x + \frac{ik_x}{\Gamma} \hat{e}_z \right\} e^{-ik_x x} e^{+\Gamma z}$ $\qquad \Gamma = \sqrt{k_x^2 - \varepsilon_m}$

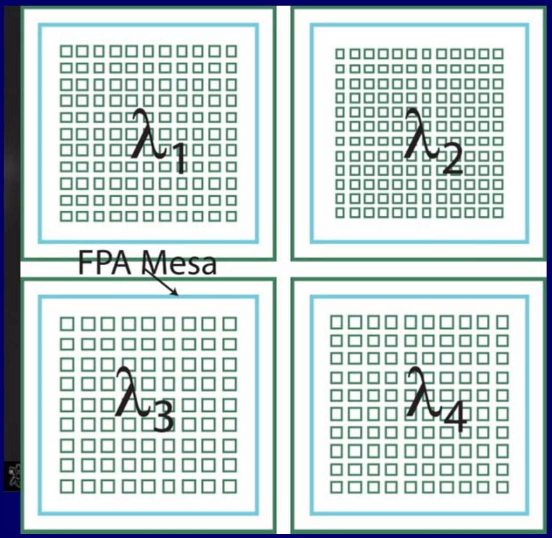
Dispersionrelation:

$$\frac{\varepsilon_d}{\gamma} + \frac{\varepsilon_m}{\Gamma} = 0 \qquad \gamma, \Gamma, \varepsilon_d > 0 \Rightarrow \varepsilon_m < 0$$

Plasmonic Focal Plane Arrays

- Multispectral FPA
  - Integration of subwavelength patterns with illumination side of FPA.
  - Each pixel can detect different wavelength.
  - A thin semiconductor region between metals.





Plasmonic QD Focal Plane Array

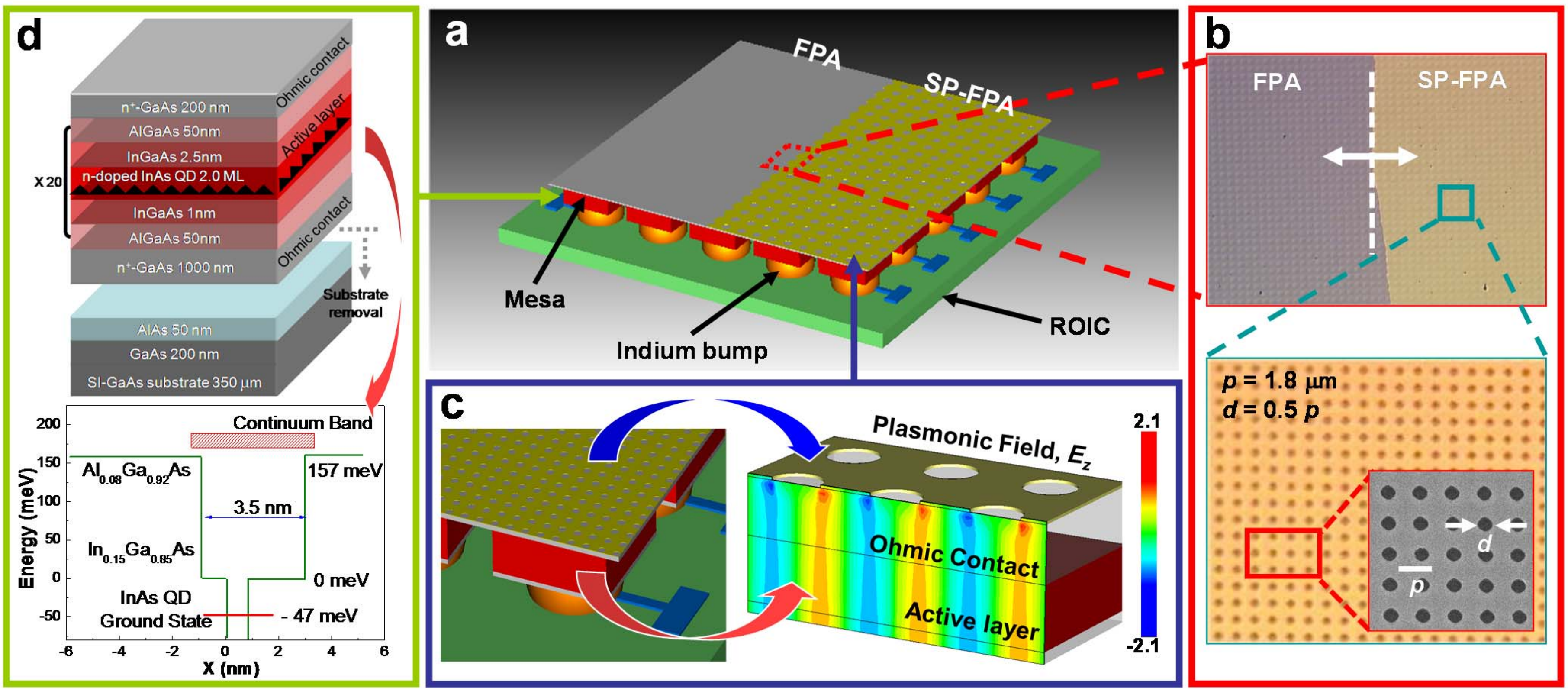
ARTICLE

Received 5 Jan 2011 | Accepted 17 Mar 2011 | Published xx xxx 2011

DOI: 10.1038/ncomms1283

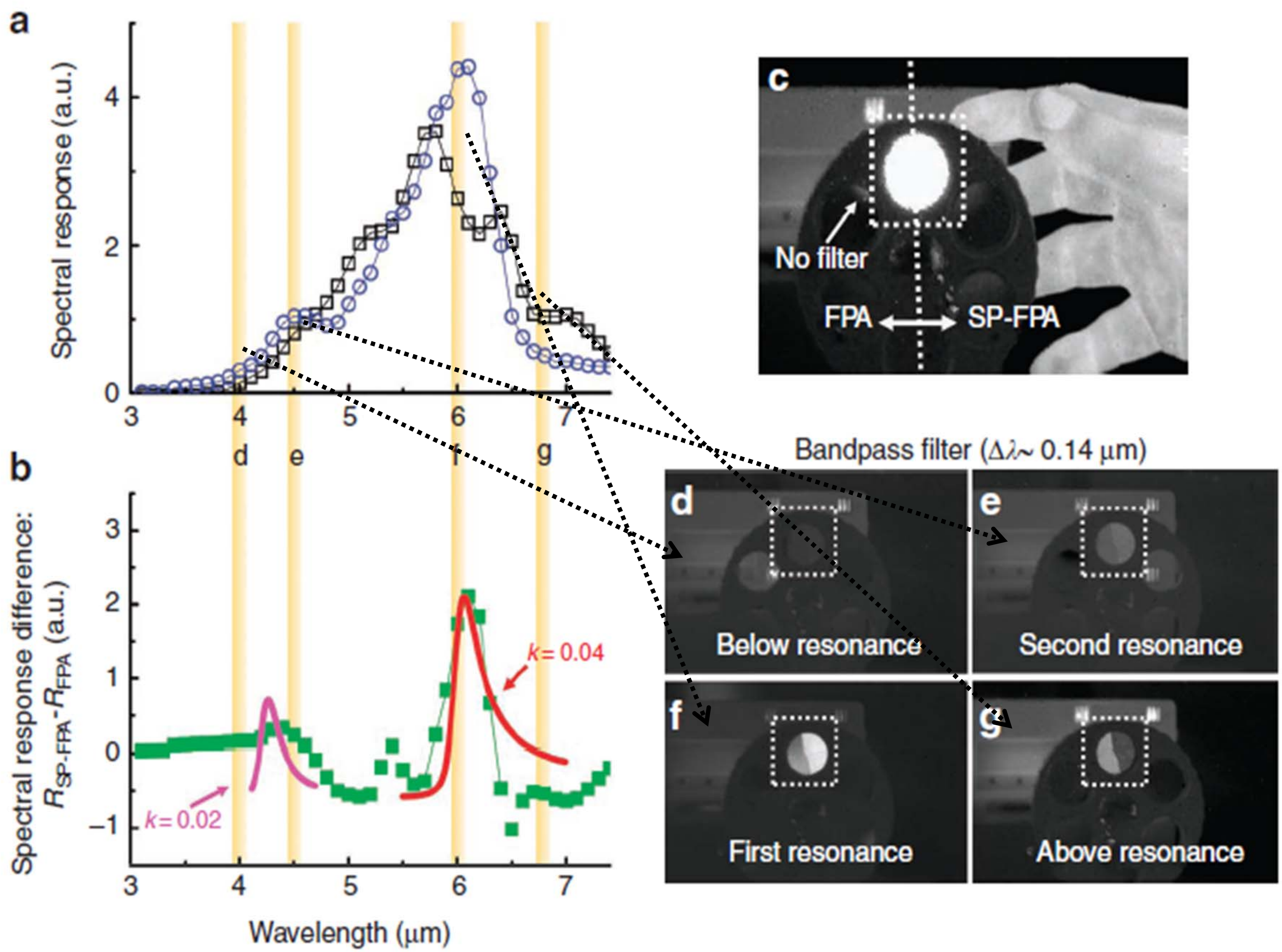
A monolithically integrated plasmonic infrared quantum dot camera

Sang Jun Lee[1,*], Zahyun Ku[2,*,†], Ajit Barve[2], John Montoya[2], Woo-Yong Jang[2], S. R. J. Brueck[2], Mani Sundaram[3], Axel Reisinger[3], Sanjay Krishna[2] & Sam Kyu Noh[1]

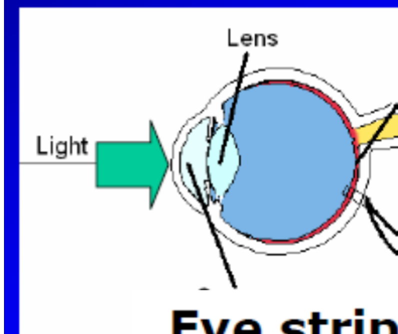


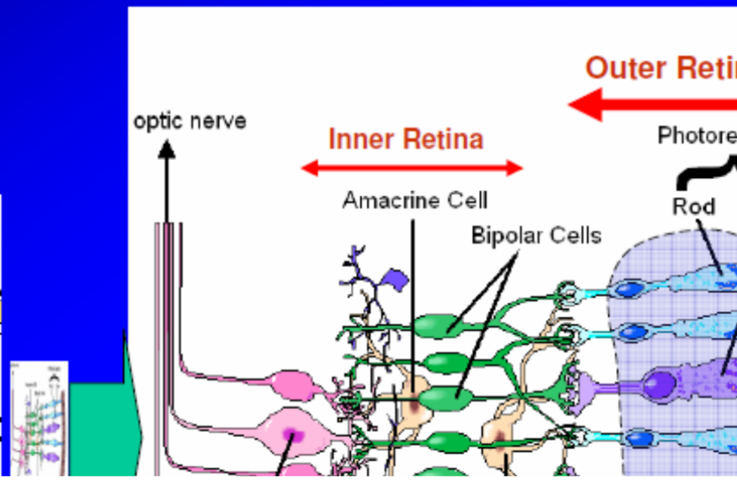
Collaboration with Prof. Brueck's group at UNM

Spectral results Show ~ 2X Enhancement at SPW Resonance



The Eye as an Imaging System





Vertical interactions across ten parallel, stacked representations in the mammalian retina

Botond Roska & Frank Werblin

Department of Molecular and Cell Biology, University of California at Berkeley, 145 LSA, Berkeley, California 94720, USA

letters to nature

Eye strips images of all but bare essentials before sending visual information to brain, UC Berkeley research shows

The eye as a camera has been a powerful metaphor for poets and scientists alike, implying that the eye provides the brain with detailed snapshots that form the basis for our rich experience of the world.

Recent studies at the University of California, Berkeley, however, show that the metaphor is more poetic than real. What the eye sends to the brain are mere outlines of the visual world, sketchy impressions that make our vivid visual experience all the more amazing.

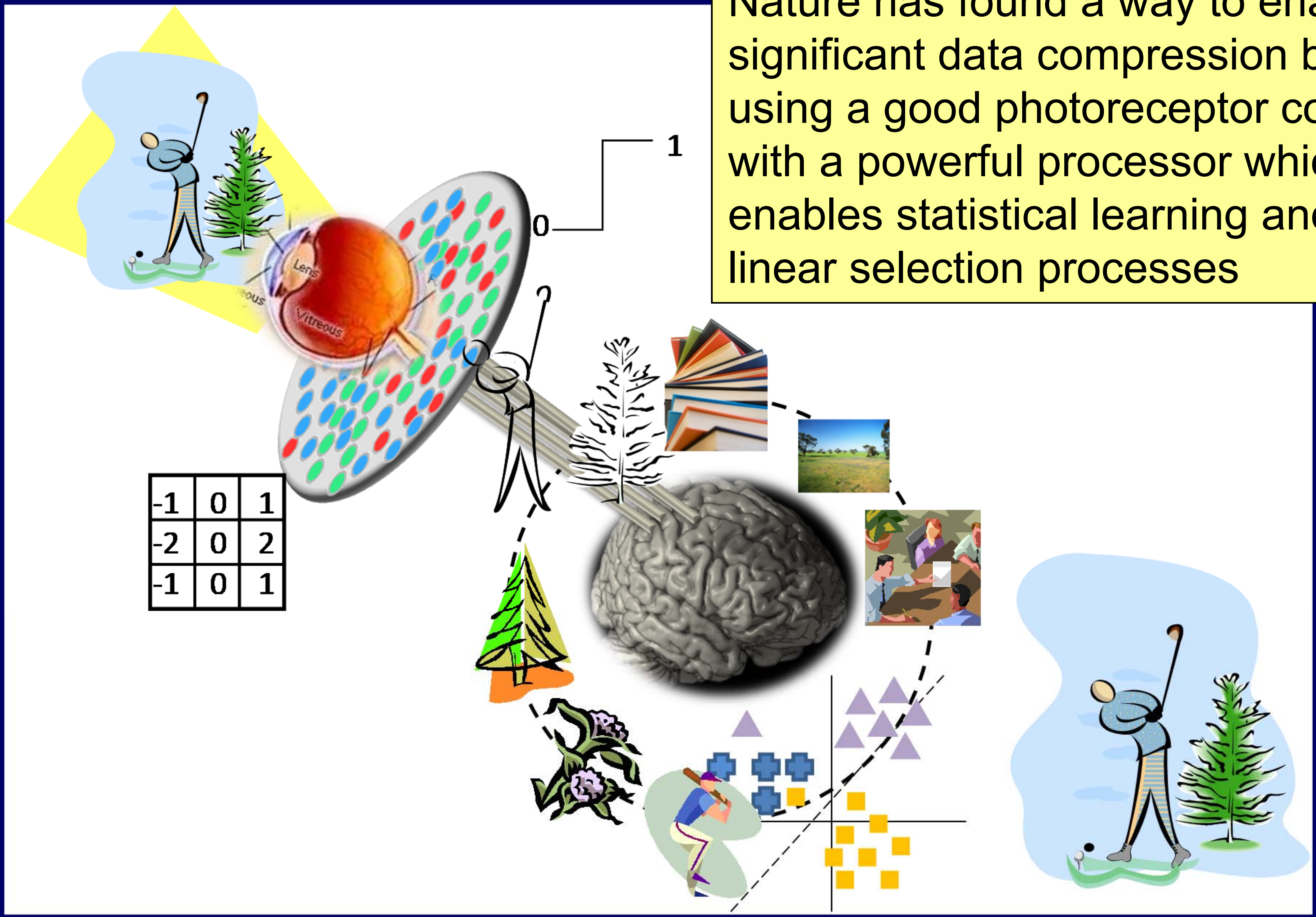
"Even though we think we see the world so fully, what we are receiving is really just hints, edges in space and time," said Frank S. Werblin, professor of molecular and cell biology in the College of Letters & Science at UC Berkeley. Werblin is part of UC Berkeley's Health Sciences Initiative, a collaboration among researchers throughout the campus to tackle some of today's major health problems.

The brain interprets this sparse information, probably merging it with images from memory, to create the world we know, he said.

Roska e

Bioinspired Infrared Retina

Nature has found a way to enable significant data compression by using a good photoreceptor coupled with a powerful processor which enables statistical learning and non-linear selection processes

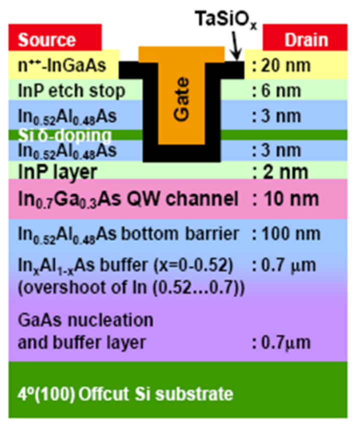


Paskaleva, Jang, Hayat, Sharma and Krishna (Manuscript in prep)

New Functionality in Read Out Circuitry

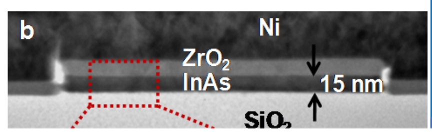
Process Innovation

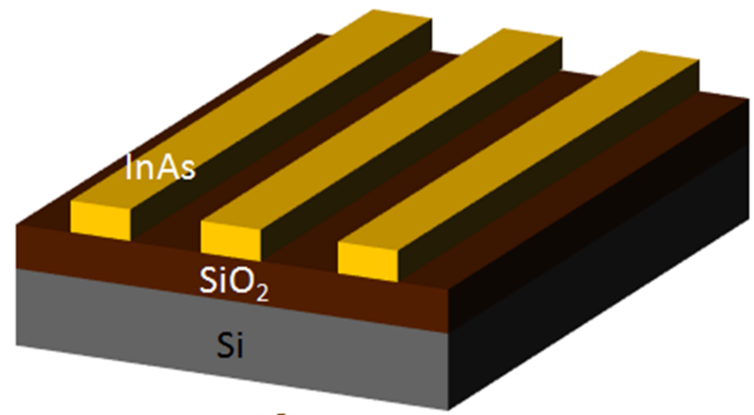
Current – III-V QWFETs require ***complex heteroepitaxial growth processes***

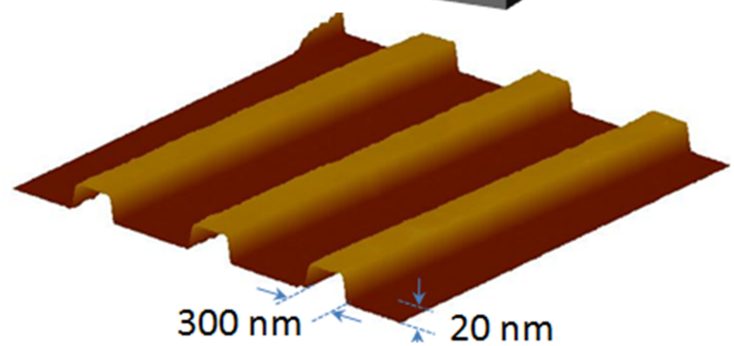


InGaAs QWFET on Si
Intel (*IEDM*, 2009)
J. del Alamo (*TED*, 2010)

XOI platform – integration of ***ultra-thin*** III-V materials ***on Si/SiO$_2$ by*** an ***epitaxial transfer process***, similar to wafer-bonding







LETTER

doi:10.1038/nature09541

Ultrathin compound semiconductor on insulator layers for high-performance nanoscale transistors

Hyunhyub Ko[1,2,3]*†, Kuniharu Takei[1,2,3]*, Rehan Kapadia[1,2,3]*, Steven Chuang[1,2,3], Hui Fang[1,2,3], Paul W. Leu[1,2,3], Kartik Ganapathi[1], Elena Plis[5], Ha Sul Kim[5], Szu-Ying Chen[4], Morten Madsen[1,2,3], Alexandra C. Ford[1,2,3], Yu-Lun Chueh[4], Sanjay Krishna[5], Sayeef Salahuddin[1] & Ali Javey[1,2,3]

Summary and Conclusions

- Type II Superlattice and Quantum Dots as emerging IR technologies
- Plasmonic Detectors and Focal Plane Arrays
- Bioinspired Infrared Retina

Superlattice FPAs

Quantum Dot FPAs

Future Outlook

1. What are the problems with the current generation of IR detectors?

Data Overload

2. What are the most interesting developments that you would like to see for your topic over the next ten years?

Bio-inspired Sensing

3. What are the biggest challenges for developing relevant technology over the next ten years?

Integration of powerful hardware with intelligent algorithms

4. What science breakthroughs could be enabled by this technology over the next ten years?

Intelligent Imaging for Biomedical Applications

Krishna Infrared Nanostructure Detector (KIND) Laboratory

Summer 2011 ~$14M in external funding since 2001

Senior Researchers
- Dr. Ralph Dawson
- Dr. Tom Rotter
- Dr. Elena Plis
- Dr. Y.D. Sharma
- Dr. M. Naydenkov
- Dr. J.O. Kim

Graduate Students
- Stephen Myers
- John Montoya
- Eric Jang
- Freddie Santiago
- Maya Kutty
- Nutan Gautam
- Brianna Klein
- Ted Schuler Sandy
- Glauco Fiorante
- Vince Cowan
- Marziyeh Zamiri
- Ali Shirazi
- Nathan Henry (UG)

Collaborators
- *Brueck, Hayat, Ha (UNM)*
- *Javey Group (Berkeley)*
- *Noh/Lee (KRISS)*
- *Cardimona (AFRL/VSSS)*
- *Gunapala Group (JPL)*
- *Painter Group (Caltech)*
- *QmagiQ LLC*
- *Raytheon Vision Systems*
- *Lin Group (RPI)*
- *Vandervelde (Tufts)*
- *SK Infrared LLC*
- *CINT*

Past Group Members
- *POSTDOCs: Dr. A.Amout (Emcore), Dr. P. Dowd (ASU), Dr. J. Brown (Micron), Dr. J.B. Rodriguez (Montpellier), Dr. T. Vandervelde, (Tufts)*
- *PhDs: Dr.Winckel, Uni. Graz; Dr. Zhu, Law Firm; Dr.Plis, UNM; Dr.Attaluri, Lehigh Univ.; Dr. Newmann, Emcore; Dr. Andrews, NRL; Dr. Wilcox NRL, Dr Arezou Khoshakhlagh (JPL), Dr. Hasul Kim (UCB), Dr. Rajeev Shenoi (RPI), Dr. David Ramirez (UNM), Dr. Jiayi Shao (Purdue); Dr. Ajit Barve (UCSB)*
- *M.S. : N. W. Bernstein, LANL, J. Shelton, SNL, G. Bishop, SNL, E. Varley, D. Jepson, AFRL; M. Lenz, SNL, K. Posani, Qualcomm, C. Wilcox, NRL, S. Annamalai, Triquint, M. Serna, Oxford; S.Raghavan*

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