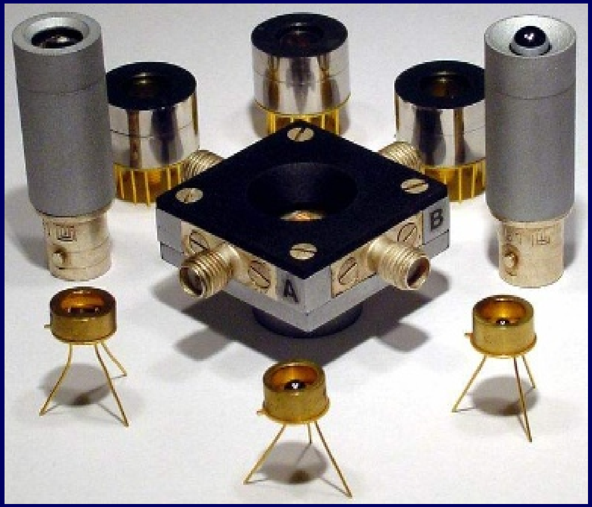
Fast and sensitive photodetection of long wavelength IR radiation without cryocooling

2-16 µm, 190-300 K



Jozef Piotrowski
VIGO System S.A.
129/133 Poznanska St
05-850 OZARÓW MAZ., PL
www.vigo.com.pl
jpiotr@vigo.com.pl
jpiotr@skype.com

INFN SEMINAR
FRASCATI 21.09.2010

VIGO SYSTEM S.A.

-a *SME for research, development and commercialization of optoelectronics*

- **Team: ~60 workers: 9 PhD, 15 engineers**
- ***Dpts: Detector, MOCVD Lab, Electronics,Optical Coating, Sales***
- **2 facilities**

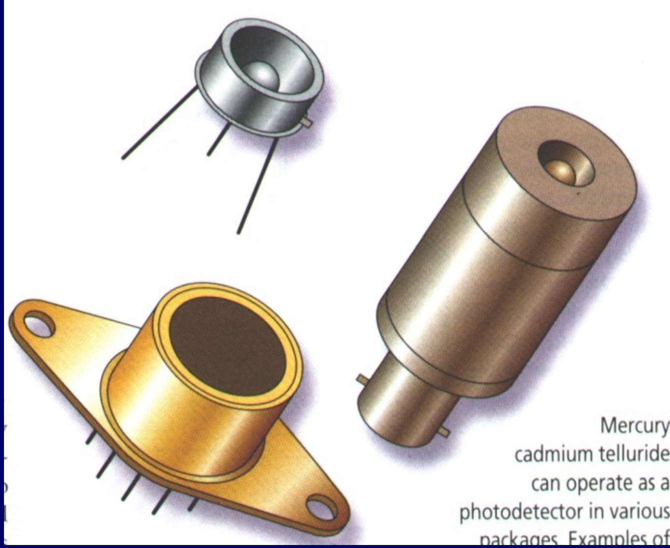
labs and offices

production facility

labs under construction

VIGO SYSTEM MISSION:

Perfect, fast and convenient IR sensing at MWIR and LWIR


Mercury
cadmium telluride
can operate as a
photodetector in various
packages. Examples of

THE GOAL: „**HOT” photodetectors**

- fundamental limits of D*
- wide bandwidth (GHz)
- any wavelength (2-16um)

KNOWLEDGE-BASED HIGH TECH PRODUCTS for GLOBAL MARKET

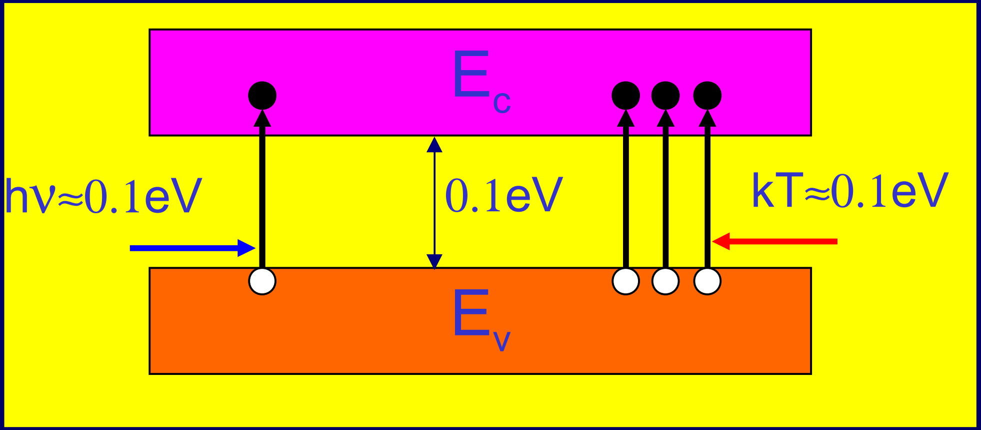
- **Versatile manufacturing- small /volume**
- **Short time-to-market**
- **Niche strategy- unique products**

Why IR detectors cooled?

-thermal generation

T=300 K

λ= 10 µm



- hν ≈ kT
- huge (≈10^{25} $cm^{-3}s^{-1}$) thermal G-R (Auger, radiative, SHR)!
- noise due to statistical nature of G-R
- D* limited by G-R noise
- cooling

> **„The need for cooling is a major limitation of infrared photodetectors that prevents more widespread use of infrared technology”**
>
> *C. T. Elliott*

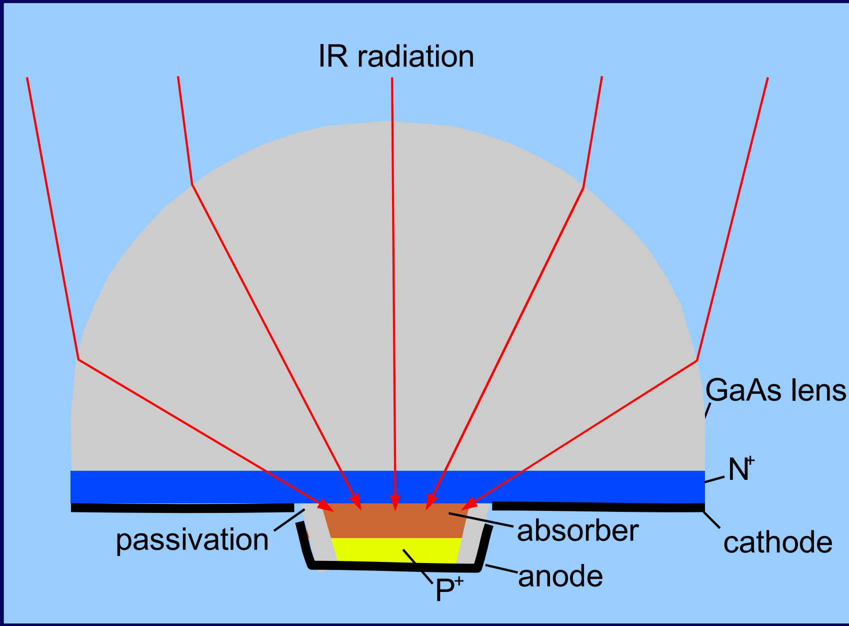
But thermal generation can be prevented!

Vigo Concept of IR Photodetector

-integration of optical, detection and electric functions in one chip

Functions:

- concentration of radiation
- enhanced absorption
- efficient/fast collection of charge carriers
- suppression of thermal generation with design of active element
- shielding agains unwanted radiation
- minimized parasitic impedances
- gain
- and other…



Optimization: max I_{ph}/I_n for a given λ and f

The concept used in uncooled PC, PV, Dember and magnetoconcentration devices

- high performance
- fast response
- convenient operation

HOT Detectors at VIGO Systems

- Pre-Vigo era:
  - importance of HOT recognized in early 60-ties
  - uncooled 10.6um PC and PEM demonstrated in 1970
- Vigo Systems S.A. since 1984
  - 1984- open tube ISOVPE- a success story
  - 1985- commercial PC, PEM and PV devices
  - monolithic immersion 3D architecture concept of IR devices
  - multiple heterojunction devices
- MOCVD era:
  - advanced heterostructures
  - GaAs µ-optics
  - improved sensitivity and response speed
  - shaped spectral response & multicolor devices
  - 2008- Vigo facilities in Ozarow

HgCdTe- THE MATERIAL of CHOICE for MWIR/LWIR PHOTODETECTORS

Advantages:

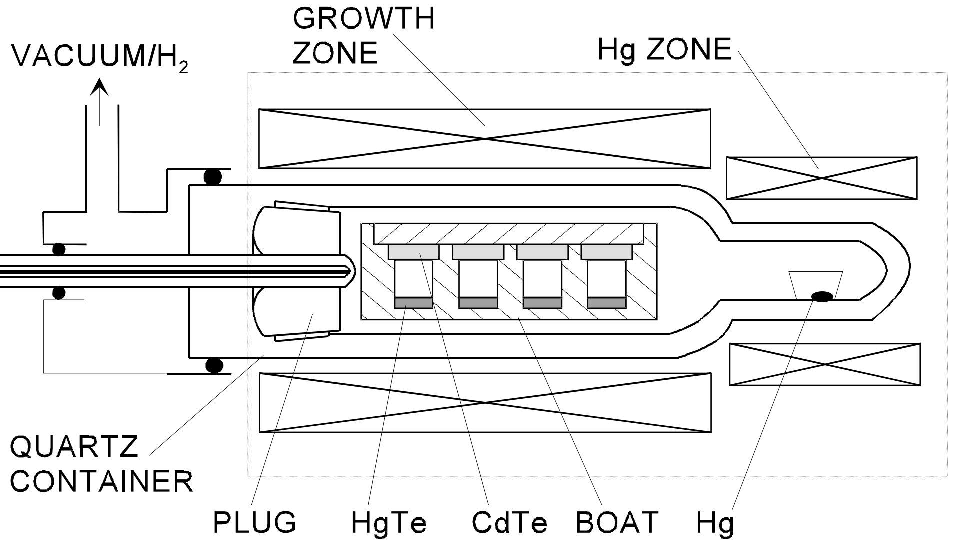
- band gap tunability 0-1.4 eV → X, UV, V, SWIR, MWIR, LWIR
- large α/g_{th} → high performance
- lattice constant vs. x → any complex 3D heterostructures

Problems:

- Uniformity issues → arrays problems
- Weak Hg-Te bond → native defects, stability
- Difficult technology → costly

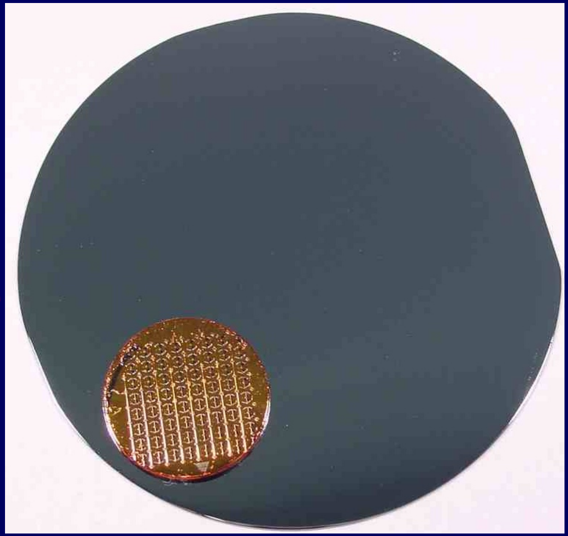
Two techniques of HgCdTe growth

ISOVPE (500°C)



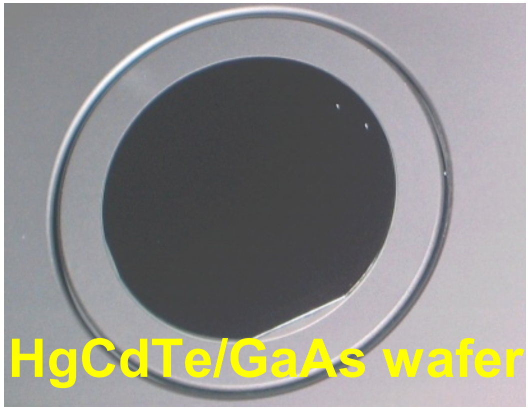
MOCVD (350°C)

- versatile technique
- low consumption of Hg, Cd, Te
- low cost equipment
- convenient anneal *in situ*
- efficient As doping
- higher growth temperature
- soft interfaces
- limited wafer area



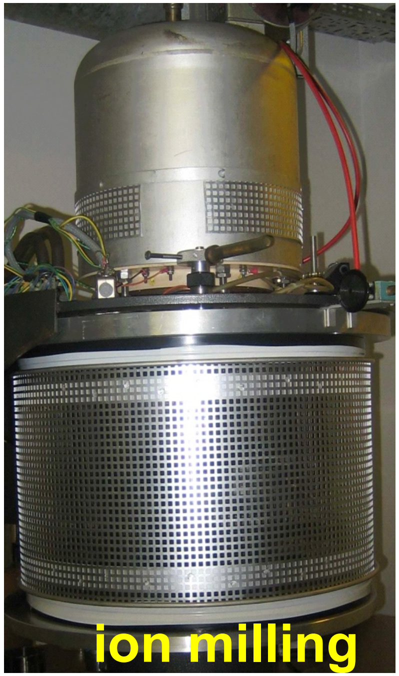
- MOCVD IMP mode
- complex band gap/doping profile
- more sharp interfaces
- easy I and As dopants activation
- large wafers
- more difficult anneal *in situ*
- costly growth system

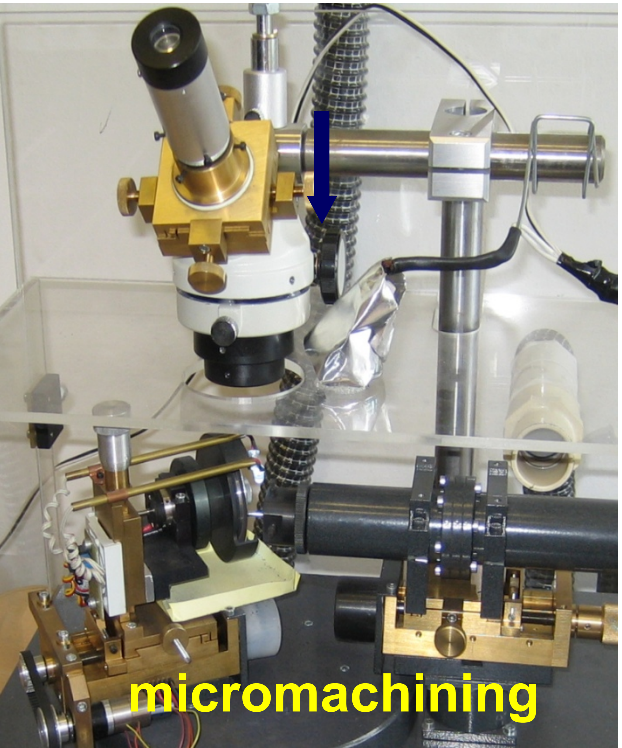
Procesing of HgCdTe devices


HgCdTe/GaAs wafer


epilayer mapping


photolithography

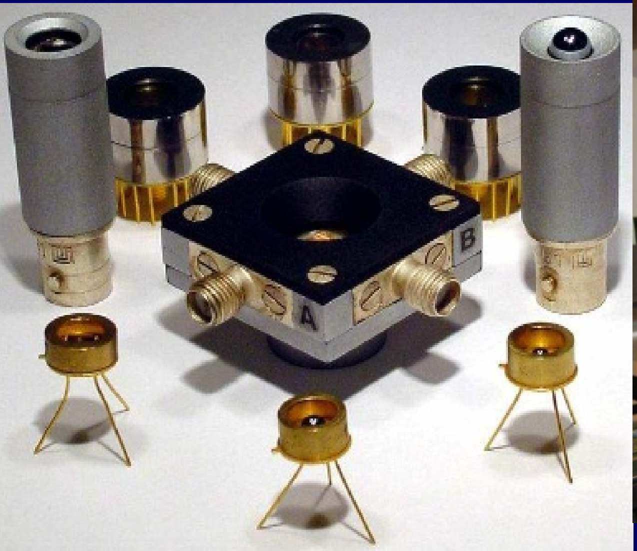

ion milling


micromachining

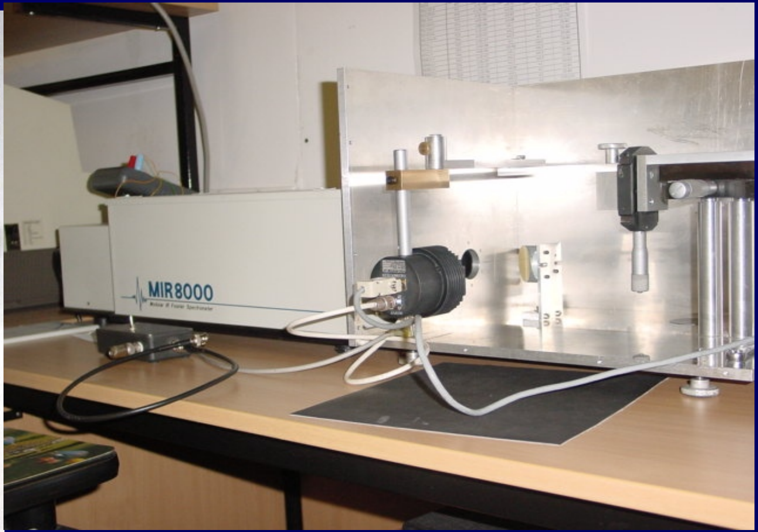

flip chip bonding


hi-resolution optical profiler

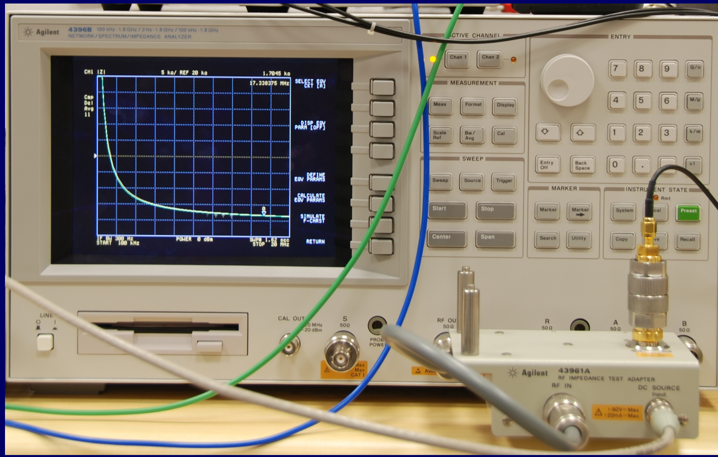
Packaging and Quality Control



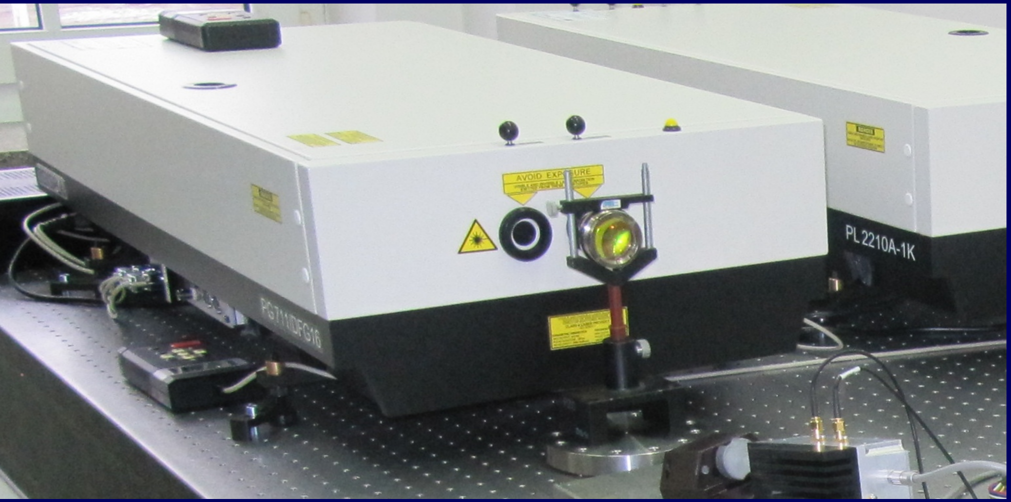
detector packages



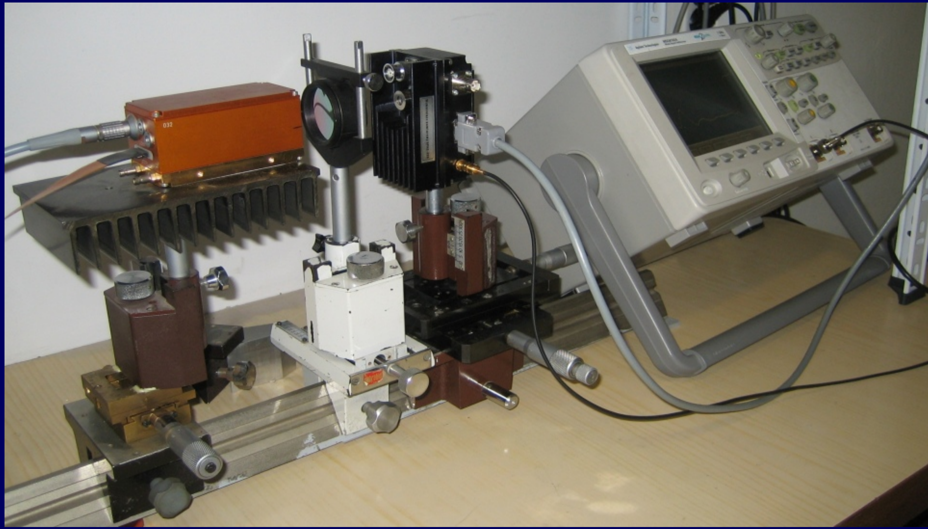
spectral response with FTIR



I-V, C-V, noise v.s. bias using signal/impedance analyzers



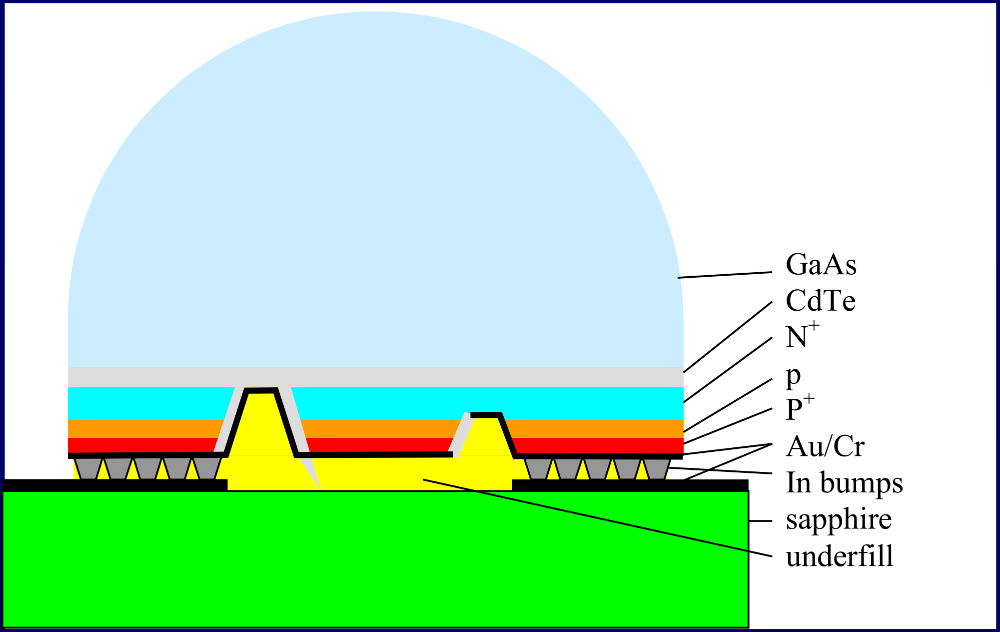
response time with OPO pulses
UV to 16 um, 25 ps pulses, 2 MW

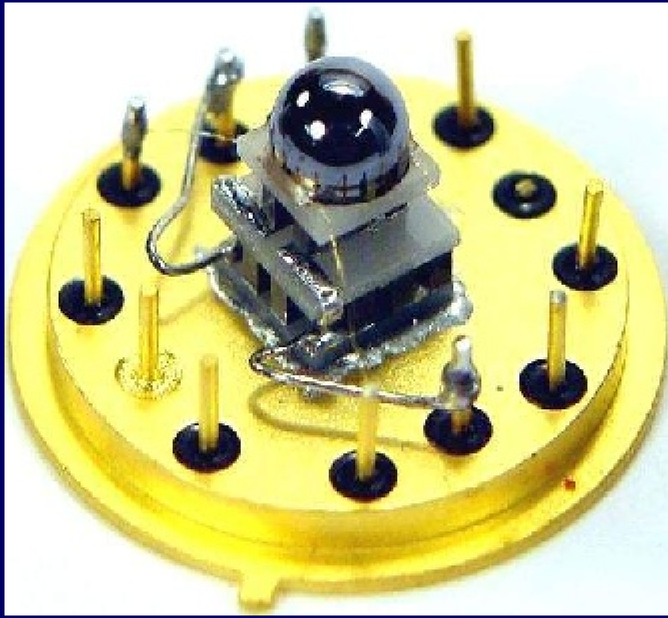


response time with QC lasers

MONOLITHIC OPTICAL IMMERSION

-Vigo approach to IR concentrator





backside illuminated immersed photodiode

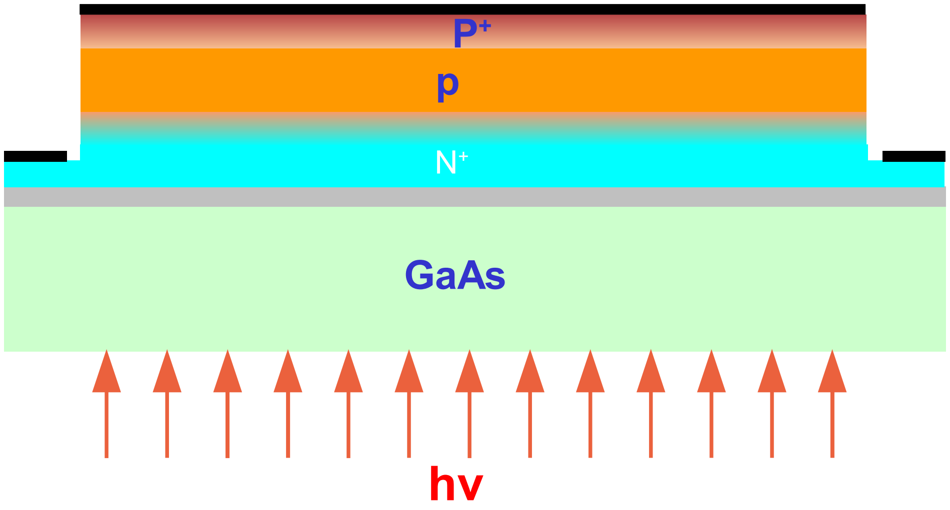
μ-lenses formed in GaAs, CdZnTe or Si

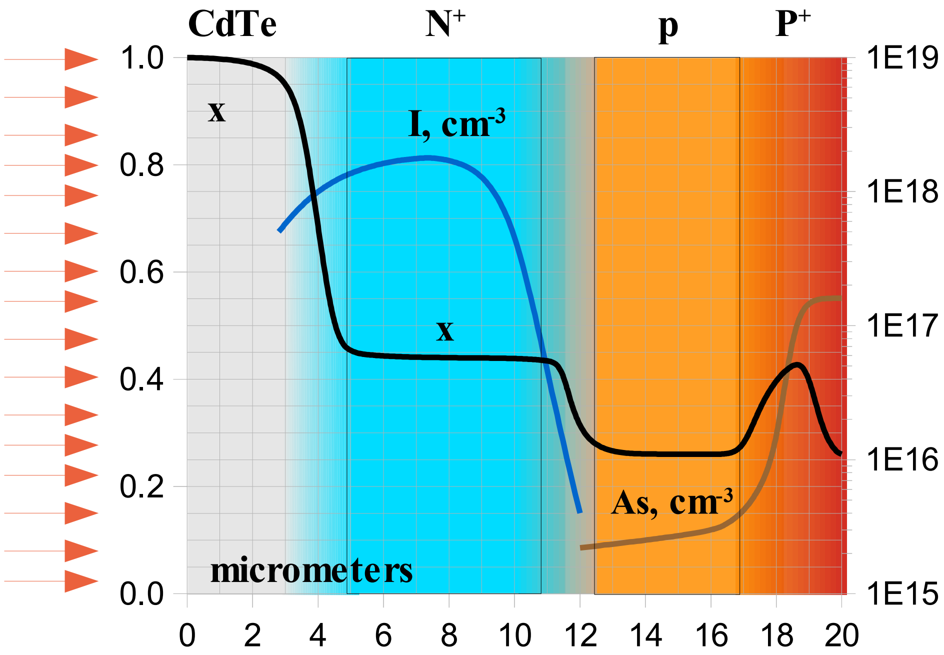
- no glue → no reflection/absorption losses
- backside reflection
- 3D heat dissipation
- shield against thermal radiation

huge gains:

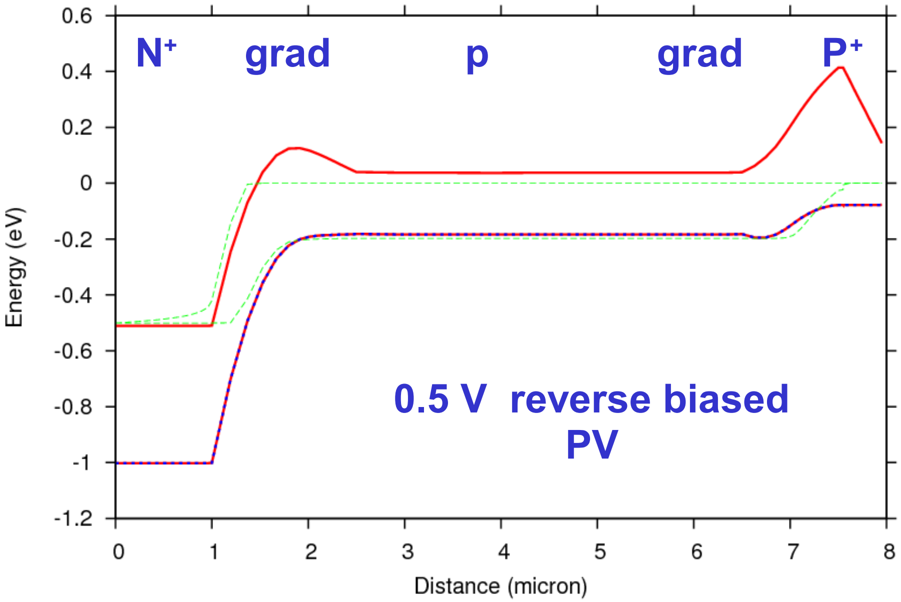
- n^2=10 in D*
- n^4=100 in τ_{RC}, P

Band gap engineered graded gap HgCdTe photodiodes



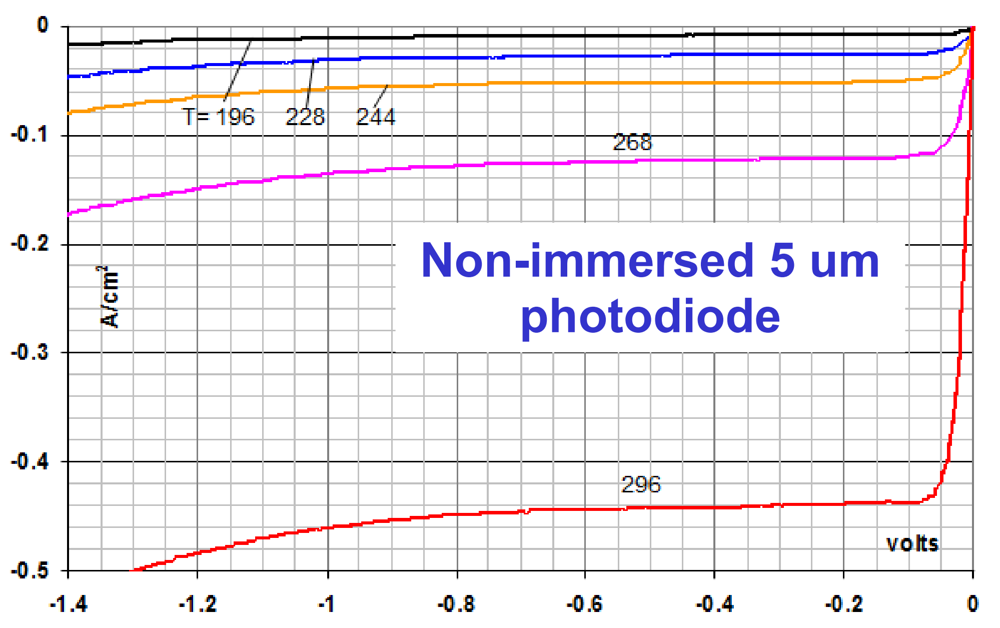


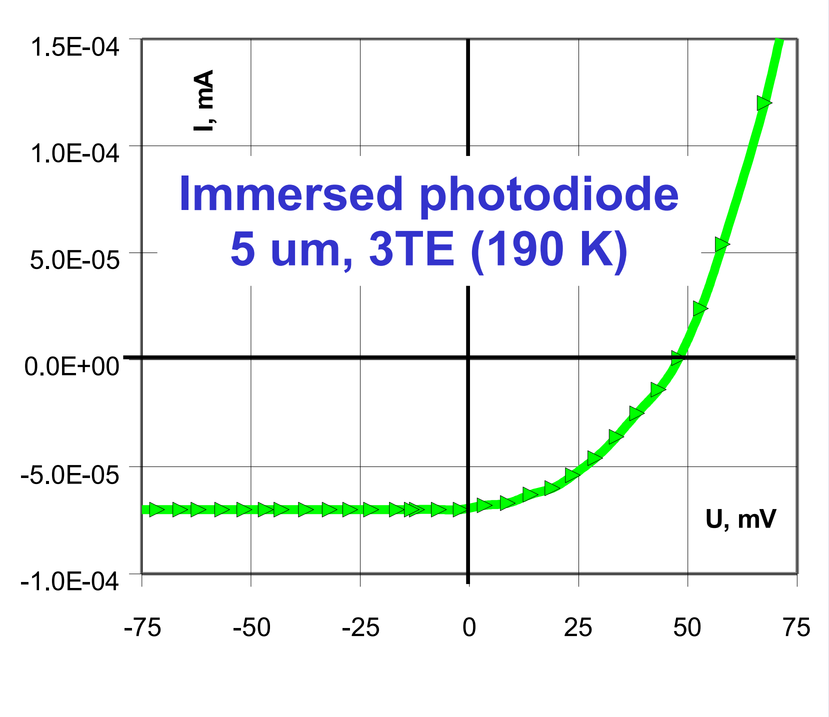
- Computer designed
  - N^+: mesa base, electron contact and IR window
  - p: absorber
  - P^+: hole contact
- Graded gap interfaces
- Programed MOCVD growth



MWIR Photodiodes

-uncooled and Peltier cooled 3-8 um photodiodes



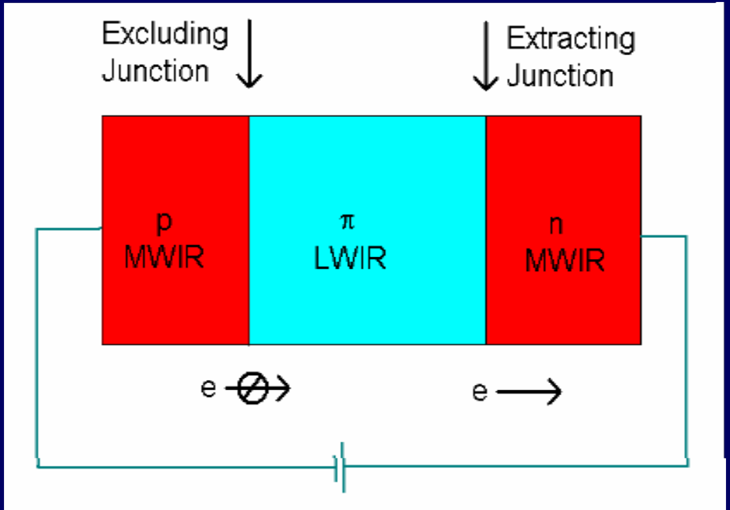


- good saturation of dark current
- J_{sat} generated in absorber
- dark current larger than BLIP current
- but with hyperhemispherical immersion 180° BLIP limit achieved at~270 K

- current mostly due to background radiation
- ~36° D^*_{BLIP} at 230 K

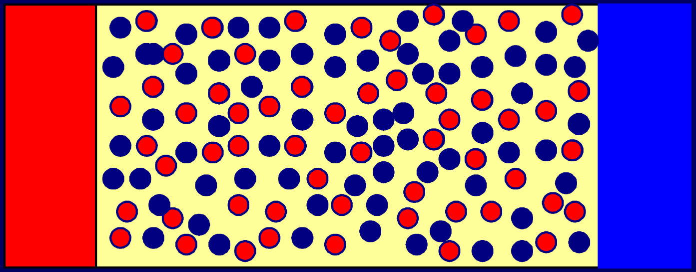
LWIR (8-16um) photodiodes

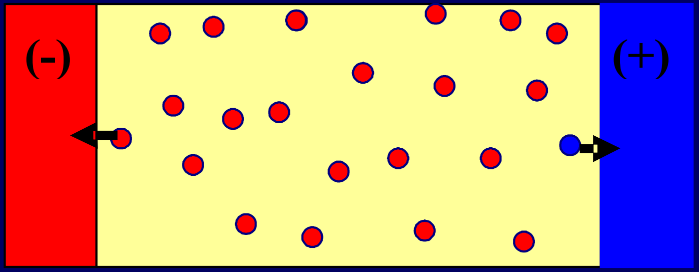
-*AUGER generation suppression*



$N_a \approx 1E15 cm^{-3}$, $n_i \approx 6E16 cm^{-3}$ (300 K)

$$G_A = \frac{n}{2\tau^1_{A1}} + \frac{p}{2\tau^1_{A7}} = \frac{1}{2\tau^1_{A1}}\left(n + \frac{p}{\gamma}\right)$$





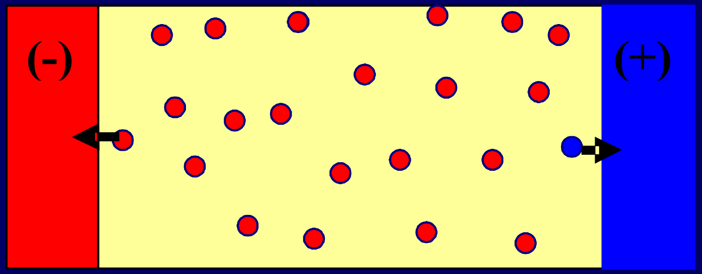
$V=0$ $n \approx p \approx n_i$

$V=-0.3V$ $n \approx 0$ $p= N_a$

$$G_A = \frac{n_i(\gamma + 1)}{2\tau^1_{A1}\gamma}$$

$$G_A = \frac{N_A}{2\tau^1_{A1}\gamma} \qquad D^* = \frac{\lambda}{hc}\frac{\eta}{t^{1/2}}\left(\frac{\tau^i_{A1}}{N_a/\gamma}\right)^{1/2}$$

Dramatic consequences!



Material

- Deep depletion:
  - no electrons
  - much less holes
- Large ambipolar mobility (=electron mobility)
- Reduced thermal generation/recombination

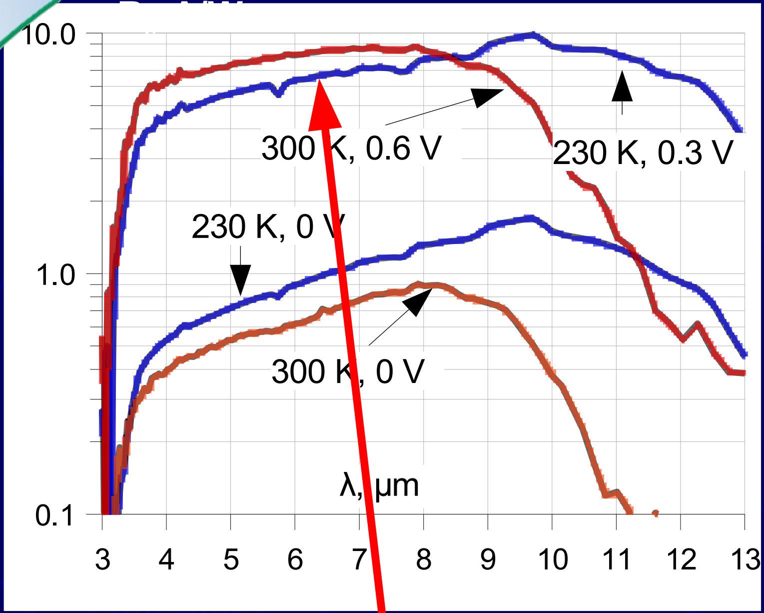
Detectors

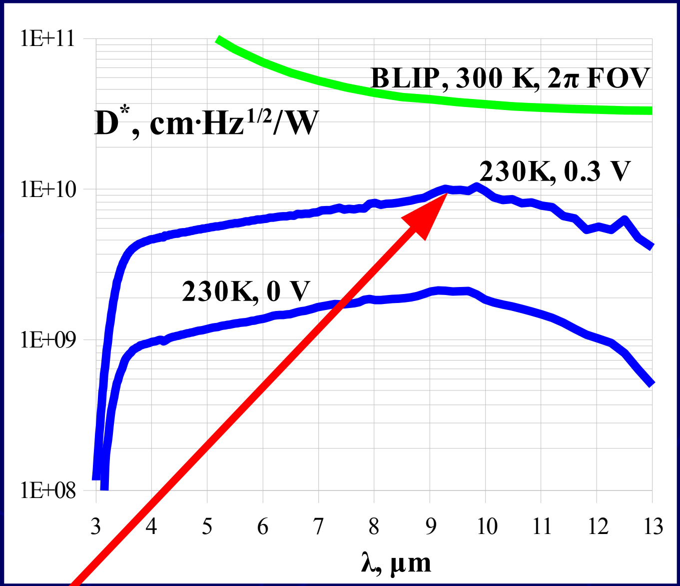
- Reduced dark current and shot noise
- Large Rd
- Elimination of Burstein-Moss
- Improved D*

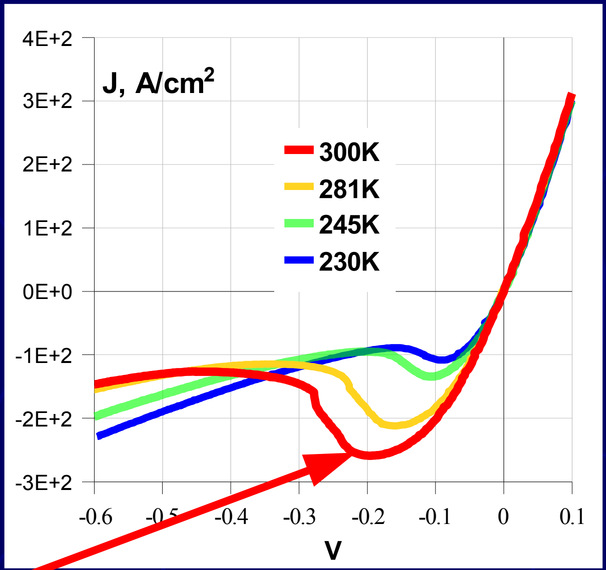
Other devices

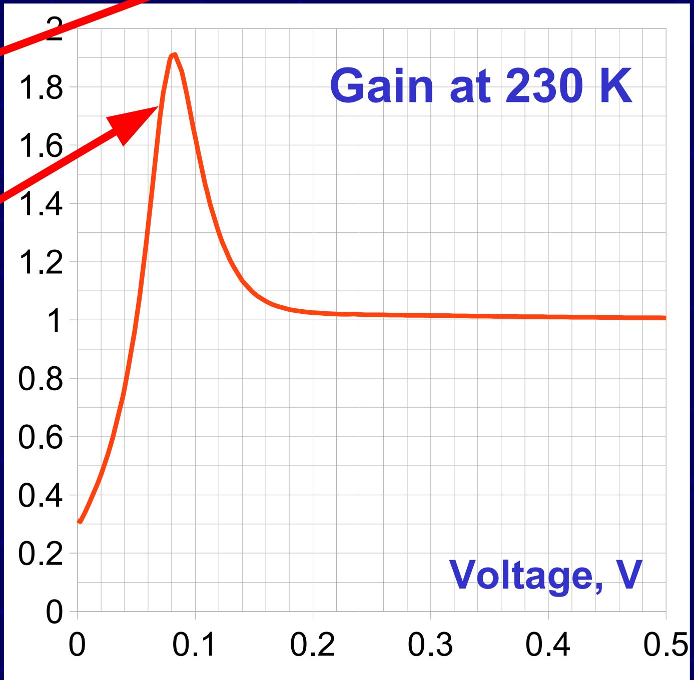
- Low voltage high frequency electronics for computers

Spectral response and I-V plots in LWIR HgCdTe photodiodes









- R_i and D* improved with bias and cooling
- Respectable performance at ~10 µm, 2TE
- Auger suppression observed
- Significant photoelectric gain, up to ~10x
- -reduced EMI, less critical electronics
- -nature: negative resistance, positive feedback

- Useful spectral range extended to >16 µm

RESPONSE TIME

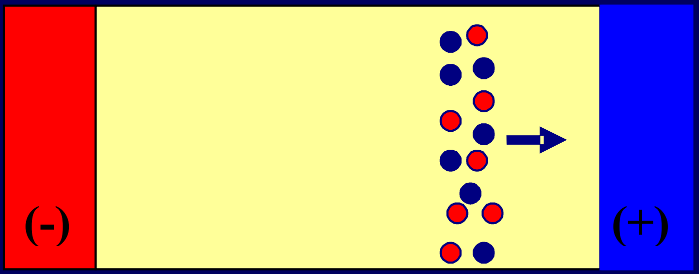
HOT detectors generally fast due to:

- rapid recombination of photogenerated charge carriers
- high mobility
- How to make them more fast?
- increase recombination rate
  - Very short response time possible by band gap narrowing or/and increase doping
  - Poor S/N performance due to large generation-recombination
- rapid removal of photogenerated carriers by transport to contacts

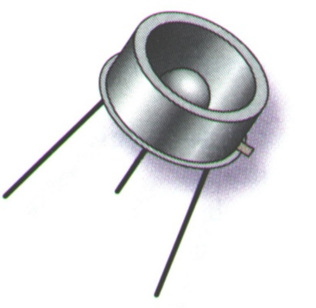
difusion $\tau = t^2/2D_a$

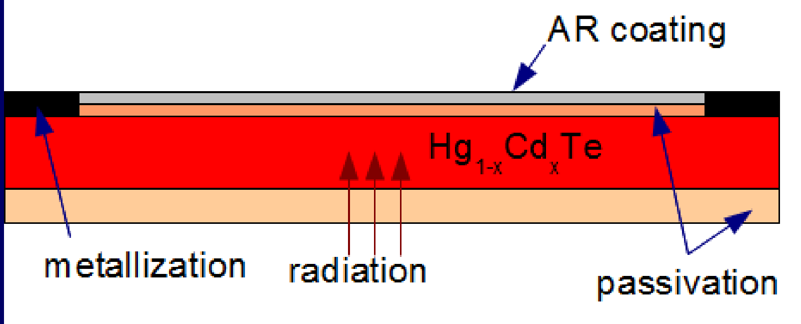
drift $\tau = t^2/V\mu_a$

good: large ambipolar μ_a and D_a



Fast photoconductors





Advantages

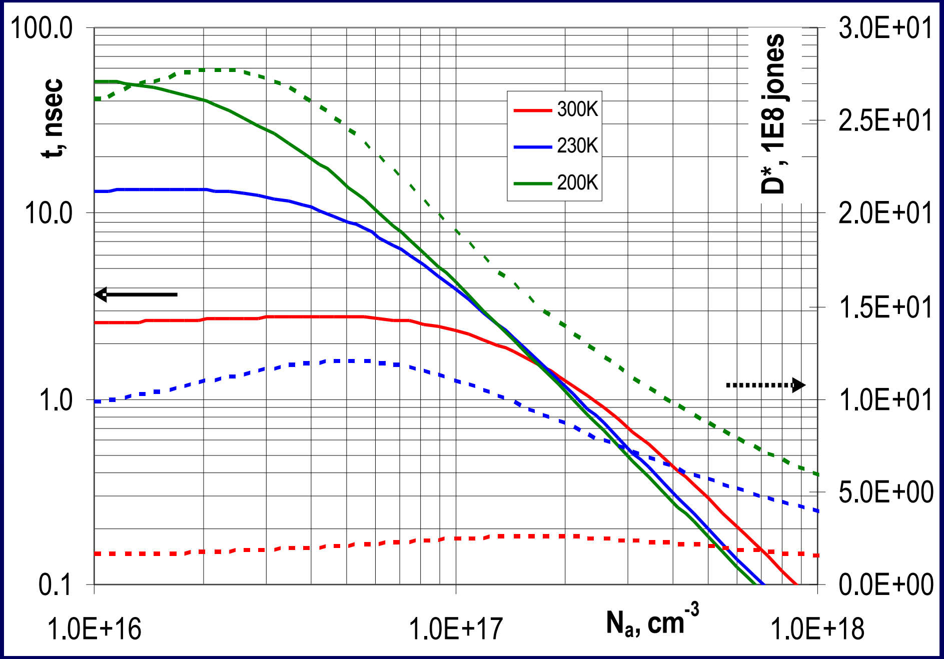
- simple device
- low capacitance

Disadvantages

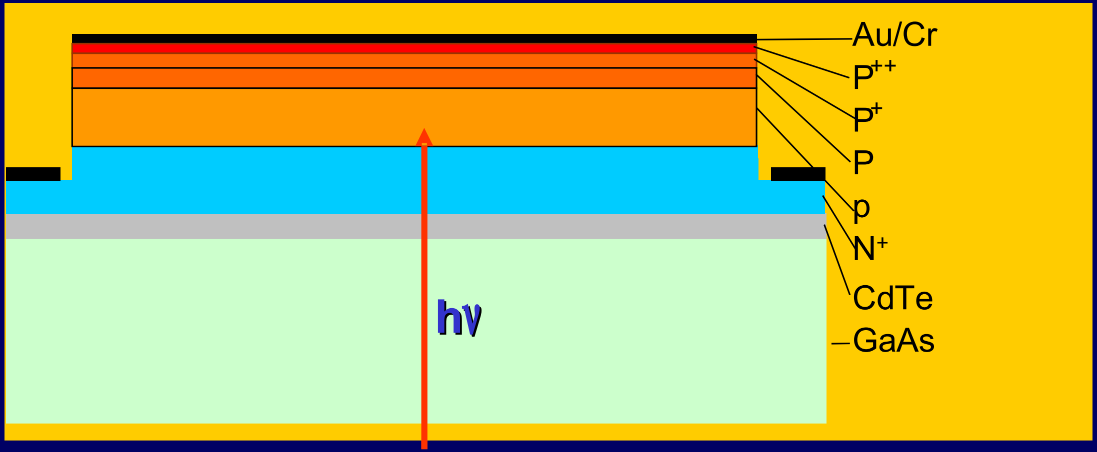
- low D*
- large reverse dark current
- low resistance

Design Principles

- heavy p-type doping
- narrow gap absorber
- optimized bias
- preamplifier optimized for low Rd
- optical immersion for D*
- electronics: current readout



Fast photodiodes



Design Principles:

- N+ base: low R_s
- lightly p-doped absorber
- reduced absorber thickness
- optimized reverse voltage
- low parasitic impedances at interfaces
- optical immersion: reduce physical size for small RC
- electronics: current readout

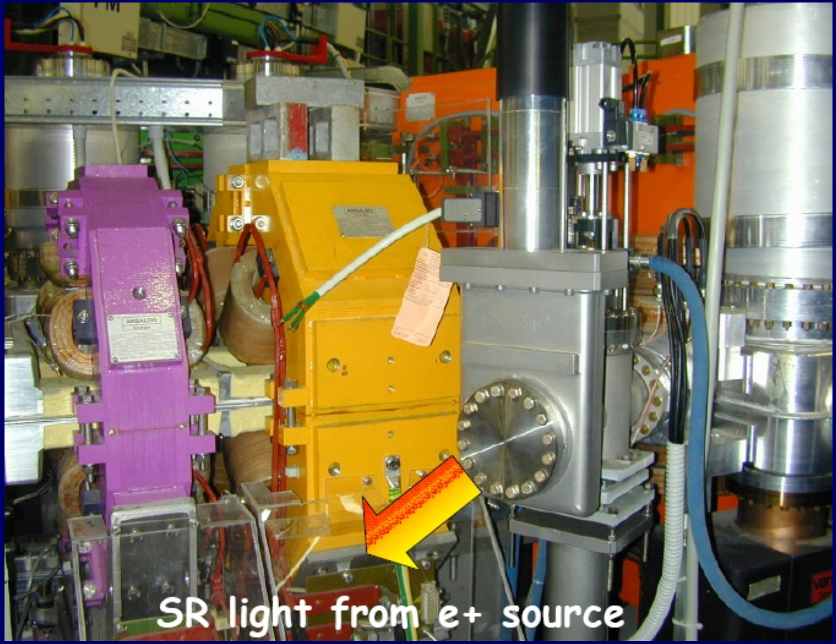
Measurements of time response at INFN and VIGO

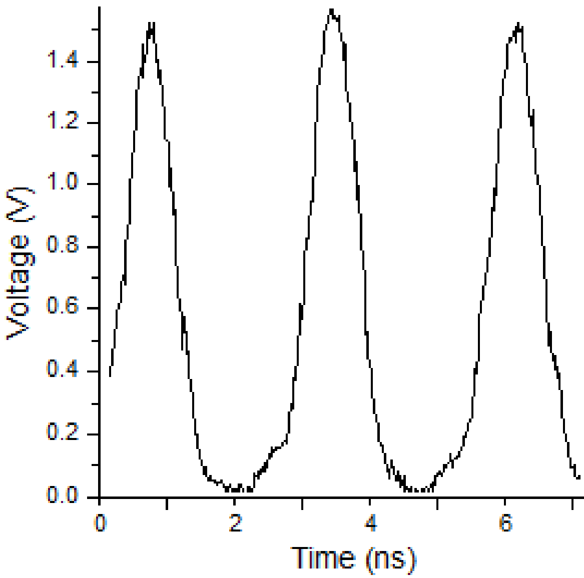
Prefered conditions

- constant voltage bias
- current readout

Electronics

- DC-coupled TI PA
- fast oscilloscope

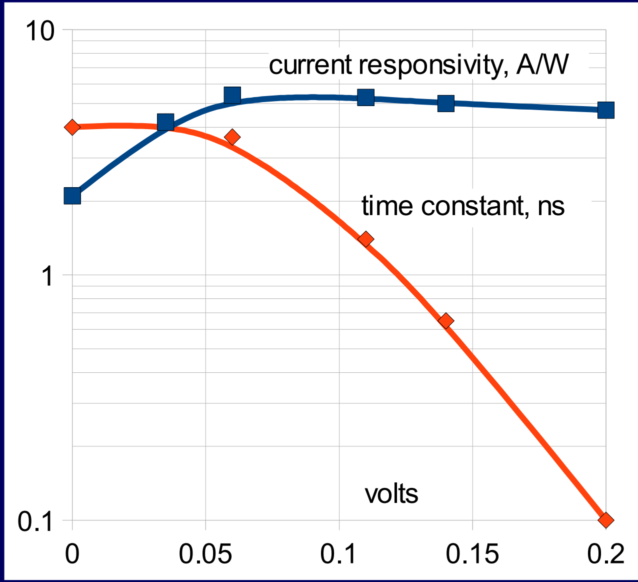




waveforms observed with synchrotron source

Results:

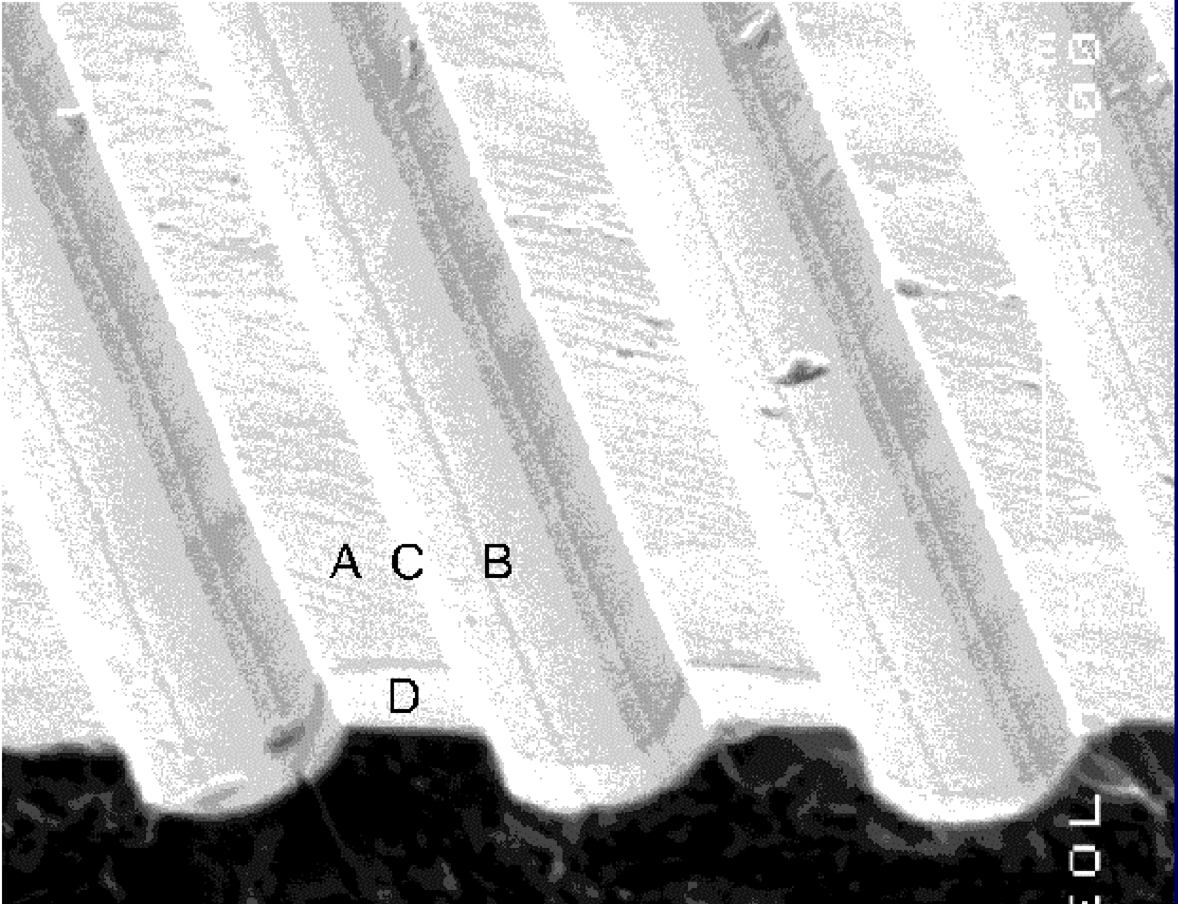
- subnanosecond time constants measured
- in PC, PEM and PV HOT detectors
- with SR, QCL and OPO sources
- agreement with simultaions



time constants vs bias in PVI-2TE-11 um device

MULTIPLE HETEROJUNCTIONS PV

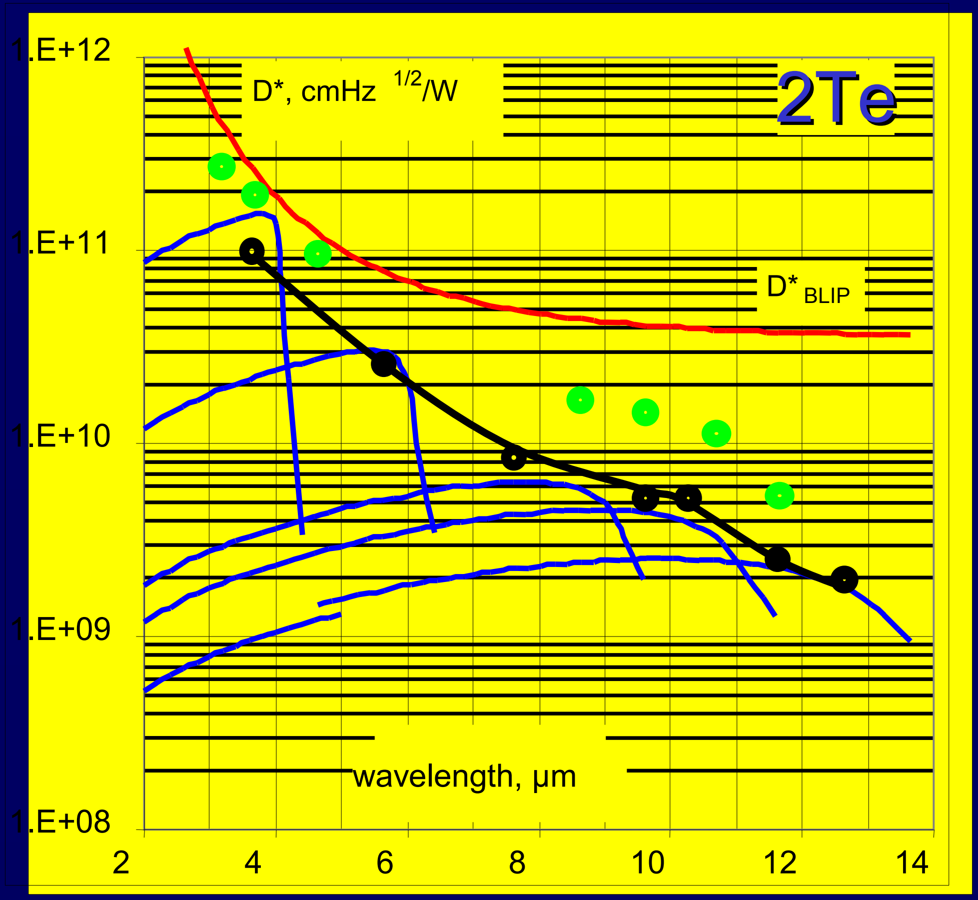
- First uncooled LWIR PV devices on market (1996-)
- Photonics Spectra Award (1996)
- Micromachined using ion milling and wet eching
- Multiple heterojunction cells with ~10 μm period



- good responsivity
- large voltage output

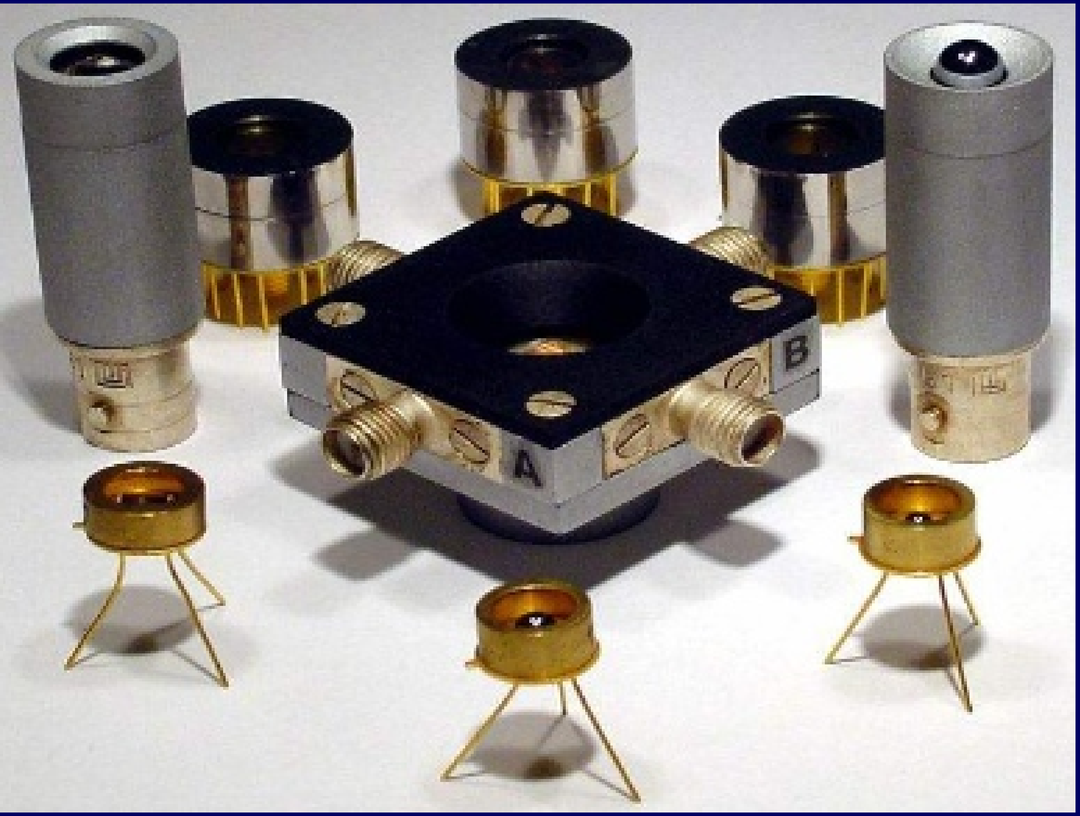
- D* far from limits
- long response time
- dead regions
- polarization sensitive

WHERE WE ARE NOW…



- near-BLIP detection in 3-5 µm range
- <1 order of magnitude to BLIP for λ>7µm

PRACTICAL „HOT” DEVICES...



Standard devices

2<λ<16 µm

o PC, PCI
o PC-2TE, PCI-2TE
o PEM, PEMI
o PV, PVI
o PV-2TE, PVI-2TE 3 and TE)
o PVM (I, 2TE)
o 3TE and 4TE versions

Custom devices:

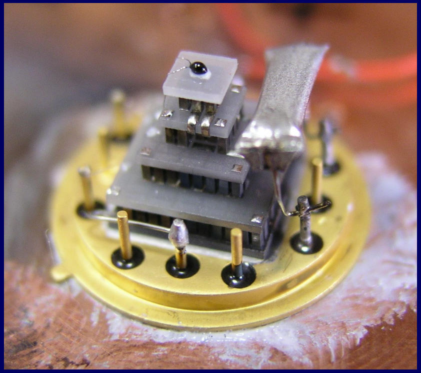
o LN cooling
o shaped spectral response and multicolor
o linear arrays up to 120 el.
o small 2D arrays e.g. quads
o sizes: from few µm to a few mm
o no large 1- and 2D arrays!

Improving Peltier cooling

Cooling depends on thermal losses and can be improved with better insulation

Recent improvements

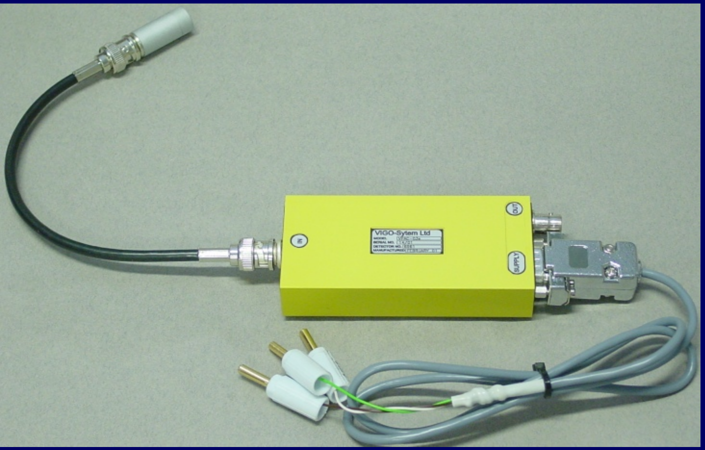
- anti-convection shields for gas filled packages
- vacuum thermal insulation
- new getters for xenon (Ba) and vacuum (Zr)
- indium sealing of detector package
- reduced power consumption
- miniaturized TO-8 packages for 3TE and 4TE



Achievable temperatures (T_{sink}=300 K)

2 TE	220 K	Xe mixture
3 TE	190 K	vacuum
4 TE	180 K	vacuum

DETECTION MODULES- design and fabrication



Low noise PA (+ detector bias):

voltage and current, DC to GHz

Integrated Packages and OEM Modules

- Detector
- TE cooler
- electronics: PA, bias, TE controler, A/D
- optics

Advantages

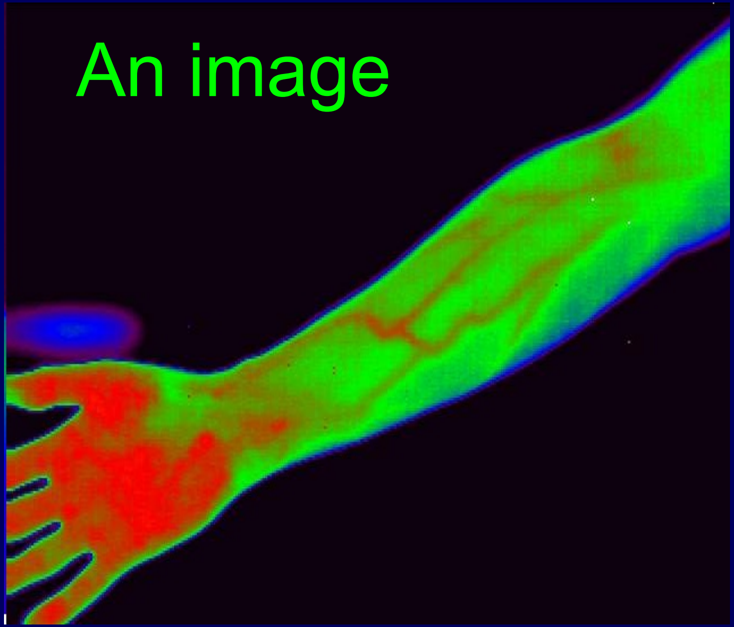
- Rugged,
- Miniaturized
- Less vulnerable to EMI
- Fast (GHz)- reduction of parasitic impedances

IR SYSTEMS at Vigo

- Solutions for measurements of temperature, pressure, flow etc.
- Software for advanced data processing

Fast pyrometer

V-20 imager

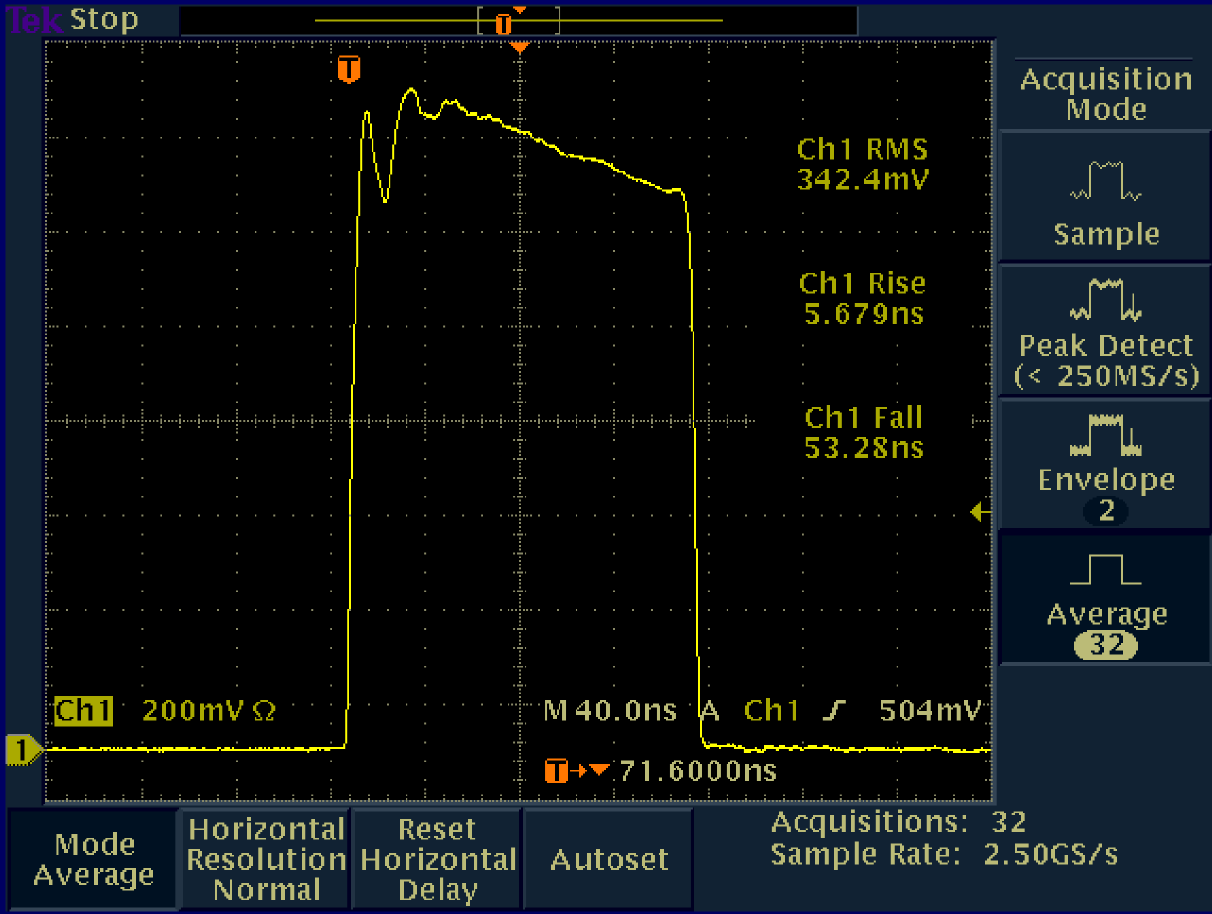


An image

High resolution
384x288 and 480x640
μ-bolometer cameras

APPLICATIONS of HOT DEVICES

NDT
spectroscopy
gas analyzers
plasma physics
smart munition
laser metrology
laser technology
laser microfusion
ultrafast pyrometry
optical communications
laser rangefinders/alerters
CO_2 and quantum cascade laser systems
lidars.... and many others



Tek Stop

Ch1 RMS 342.4mV

Ch1 Rise 5.679ns

Ch1 Fall 53.28ns

Ch1 200mV Ω M 40.0ns A Ch1 ∫ 504mV

T→▼ 71.6000ns

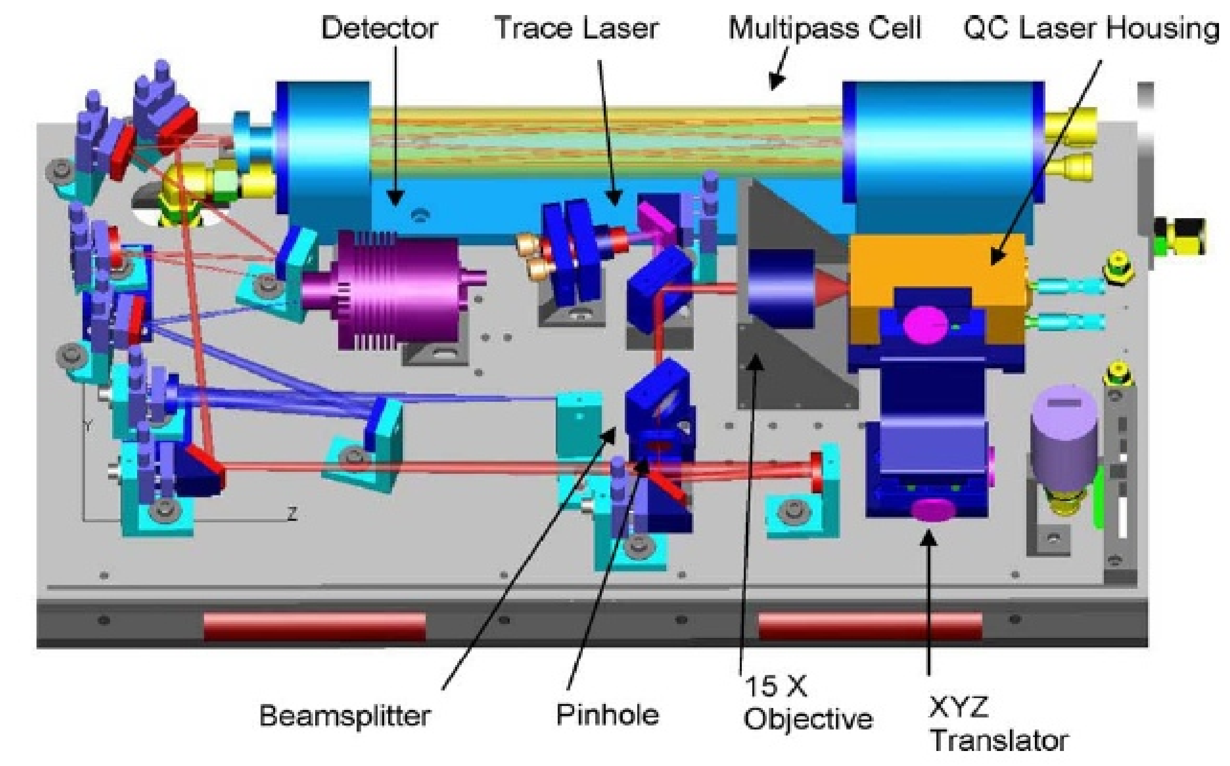
Acquisitions: 32
Sample Rate: 2.50GS/s

Users of HOT photodetectors manufactured at VIGO Systems S.A.

QC LASER-BASED SENSORS
-high end ppb/ppt chemical sensing

Aerodyne Research

„A precision of 0.3 ppb Hz$^{-1/2}$ is obtained using a Vigo thermoelectrically cooled detector which allows continuous unattended operation over extended time periods with a totally cryogen-free instrument"



D. D. Nelson et al, „Sub part-per-billion detection of nitric oxide in air using a thermoelectrically cooled mid-infrared quantum cascade laser spectrometer", Appl. Phys. (B), 2002

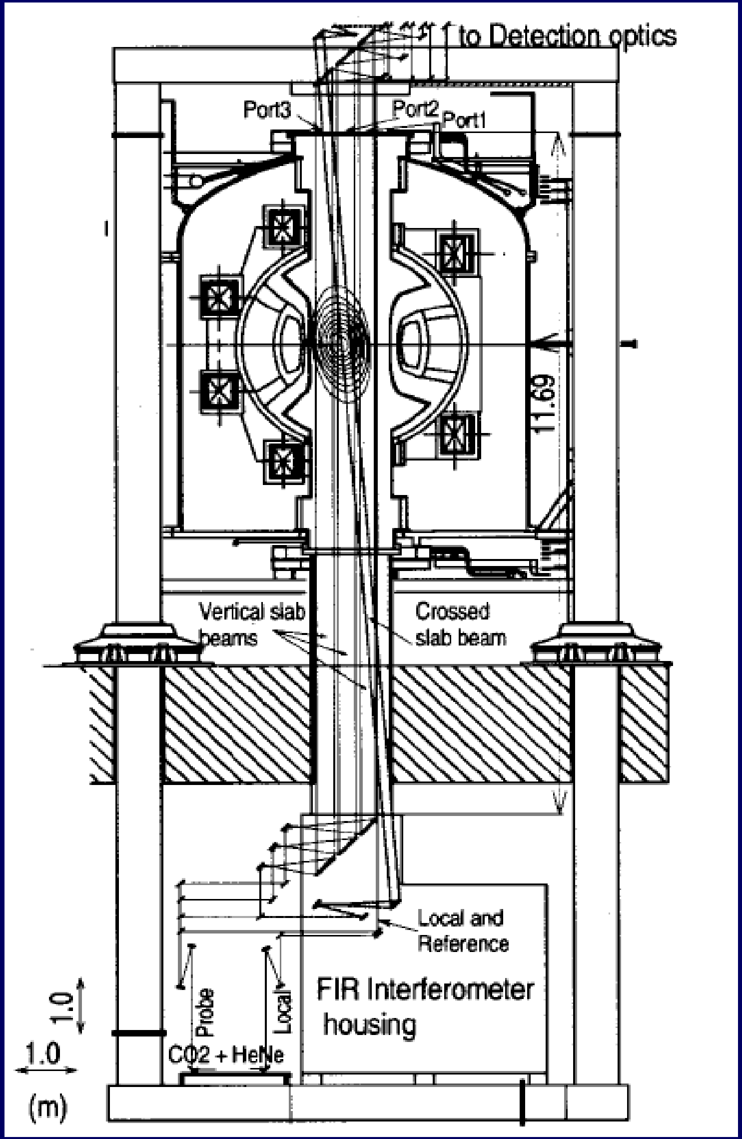
- non-invasive medical diagnostics: pre-cancer and other illness detection
- narcotics and explosives detection
- air and water quality monitoring
- industrial and science applications

Laser Technology

- monitoring of laser welding, cutting, scribing, drilling and marking
- monitoring of laser surgery
- NDT systems

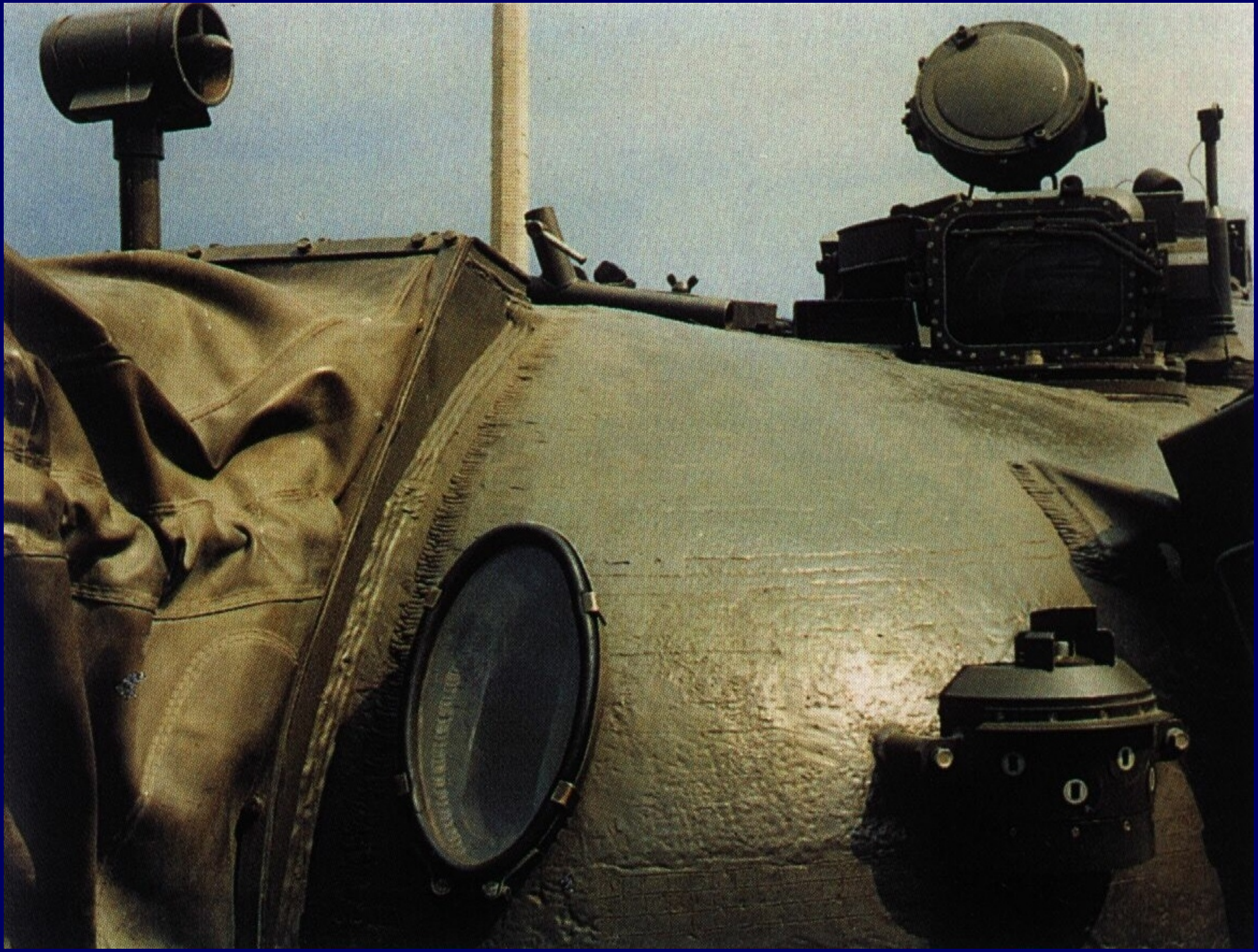
Plasma Research

- various systems in EU, US, Japan



K. Tanaka *et al*, „CO$_2$ laser imaging interferometer on LHD” Rev. Sci. Instr. 72 1081 (2001)

LASER THREAT WARNING SYSTEMS



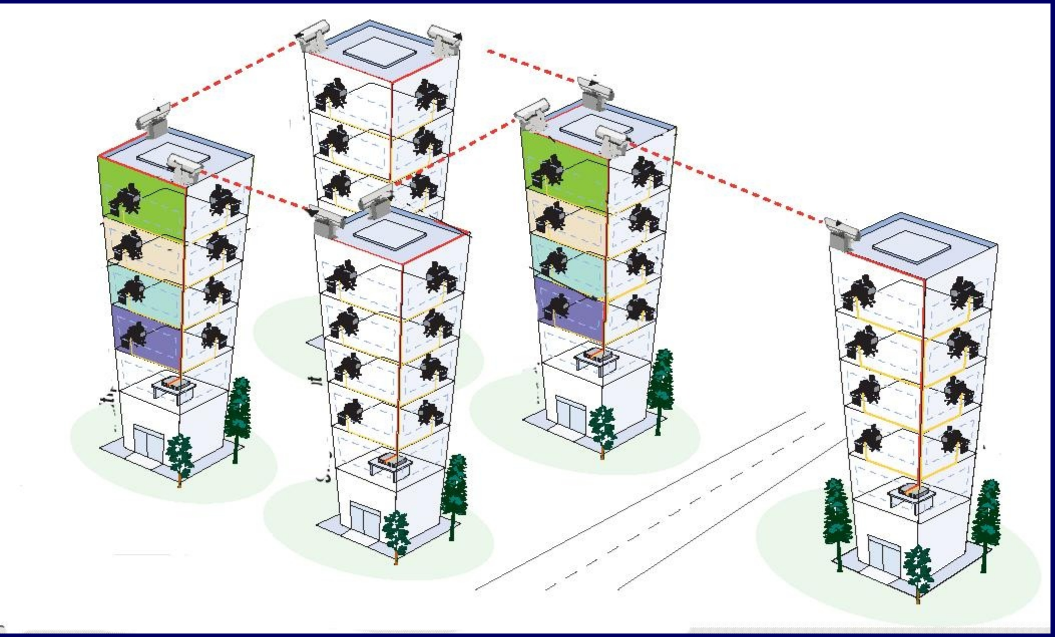
POLISH “OBRA” TANK LASER WARNING SYSTEM

- uncooled VIGO detectors

•spectral range	0.5-11 µm (all laser rangefinders)
•detection range	9 km

FREE SPACE OPTICAL COMMUNICATION

-second generation



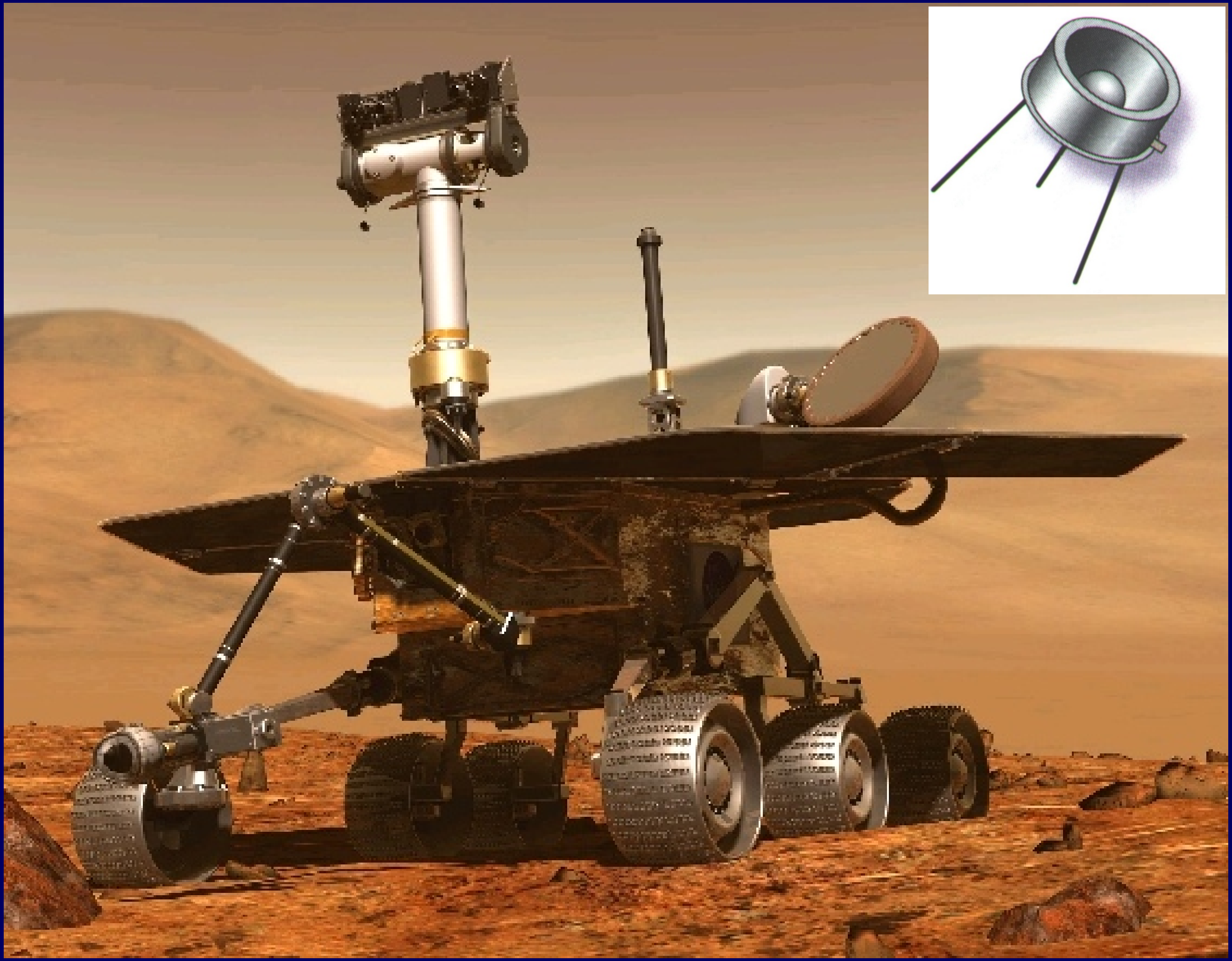
Features:

-large transfer rates (GB/s)

-all-weather operation with $\lambda = 10$ µm devices

-licence-free solution for last mile problem (internet, cellular)

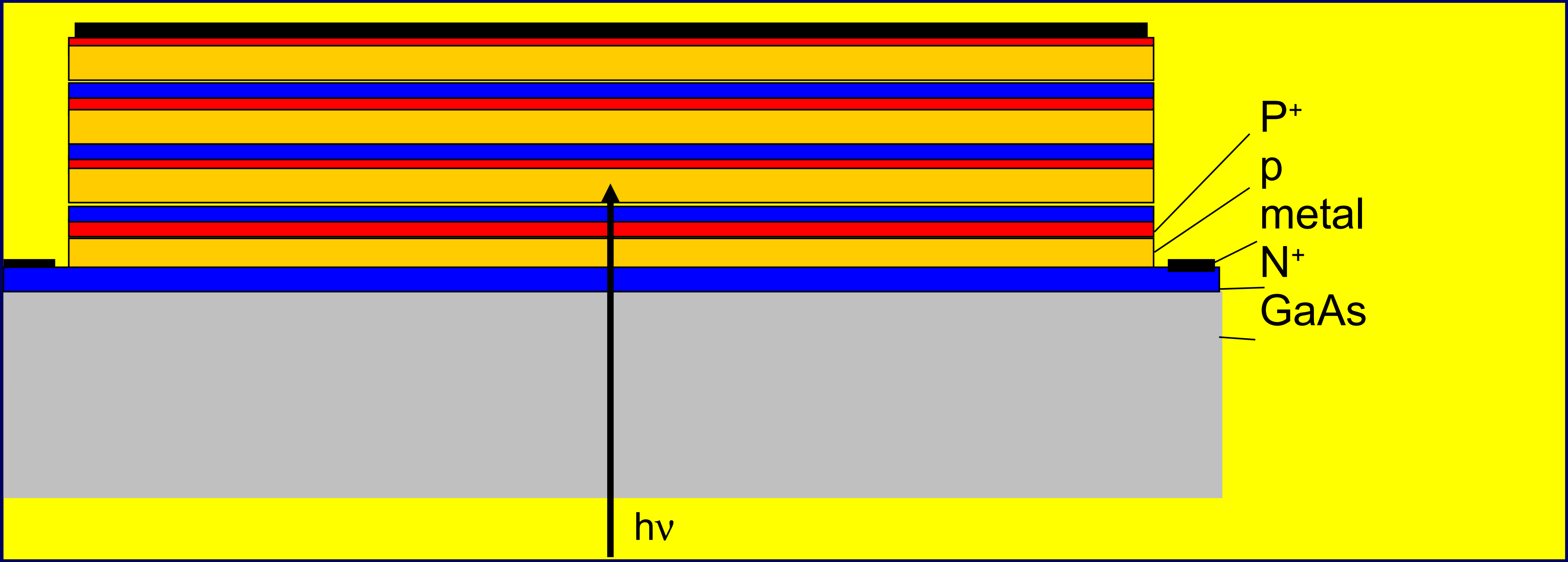
SPACE APPLICATIONS of VIGO DEVICES



2011 NASA Mars Science Laboratory Mission

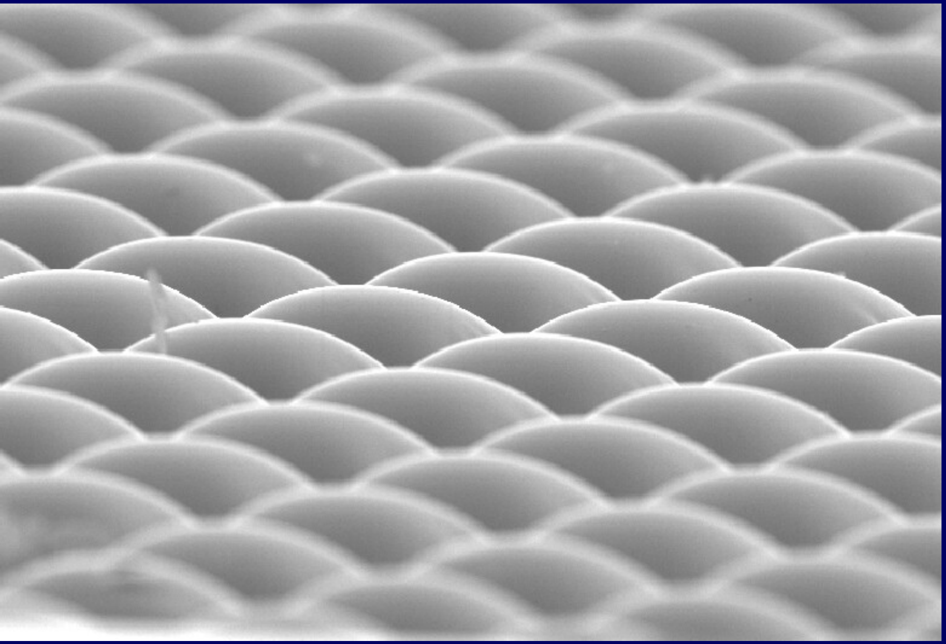
- uncooled PVI-4 and PVI-8.2 for extreme requirements
- remote chemical analysis in search of life traces

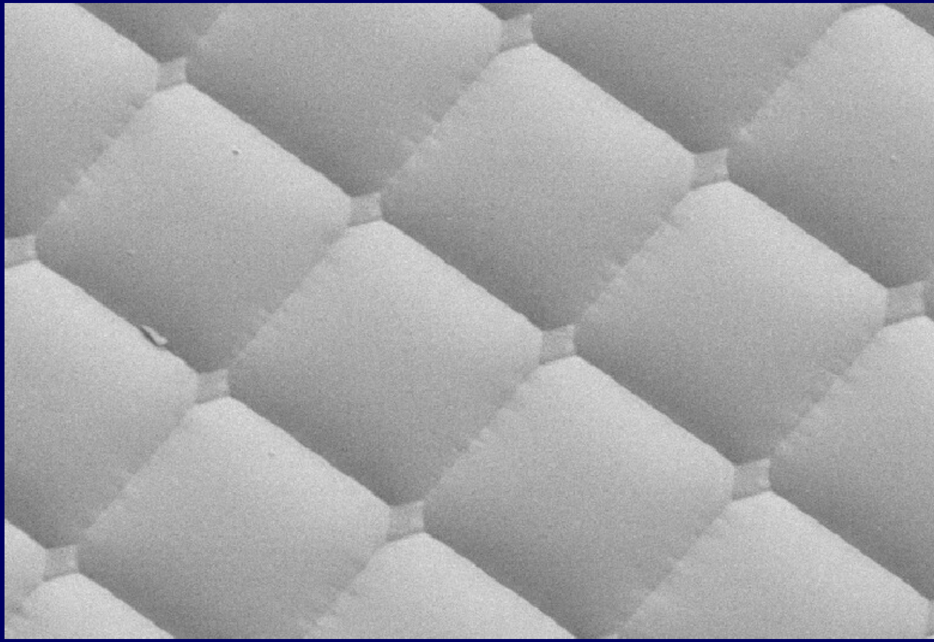
STACKED MULTIPLE HETEROJUNCTIONS



- multiple N^+pP^+ cells
- $d_{abs} < L_d$, $d_{tot} \approx 1/\alpha$
- high QE and efficient collection
- very short response time
- problems: interdiffusion, N^+P^+

Arrays of μ-lenses





- ≈50 μm pitch CdZnTe, GaAs or Si
- combination of ion milling and wet etching
- photolithography assisted

not commercialized yet: run-to-run reproducibility problems

„HOT” PHOTODECTORS REVIEWS

- J. Piotrowski, W. Galus and M. Grudzien
  "Near Room-Temperature IR Photo-detectors”
  Infrared Phys. 31, 1,1-48. (1991)

- J. Piotrowski, “$Hg_{1-x}Cd_xTe$ Infrared Photodetectors” in: I*nfrared Photodetectors*, 391-494, SPIE, Bellingham (1995)-ed. A. Rogalski

- J. Piotrowski and A. Rogalski,
  „High-Operating Temperature Infrared Photodetectors”,
  SPIE, Bellingham (2007)

- J. Piotrowski and A. Piotrowski
  „Uncooled photodetectors”
  Willey (2010- to be published)