Fast and sensitive photodetection of long wavelength IR radiation without cryocooling

2-16 µm, 190-300 K

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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
VIGO SYSTEM MISSION:

Perfect, fast and convenient IR sensing at MWIR and LWIR

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

- thermal generation

► $h\nu \approx kT$

► huge ($\approx 10^{25} \text{cm}^{-3}\text{s}^{-1}$) 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 against unwanted radiation
► minimized parasitic impedances
► gain
► and other…

The concept used in uncooled PC, PV, Dember and magnetoconcentration devices
► high performance
► fast response
► convenient operation

Optimization: max $I_{ph}/I_n$ for a given $\lambda$ and $f$
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 $\alpha/g_{th}$ → 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)
- 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 (350°C)
- 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
Processing of HgCdTe devices

- 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 $\tau_{RC}$, $P$
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

![Diagram of HgCdTe photodiode structure]

- $N^+$ grad
- $p$ grad
- $P^+$

- $0.5 \text{ V reverse biased PV}$
MWIR Photodiodes
-uncooled and Peltier cooled 3-8 um photodiodes

- good saturation of dark current
- \( J_{\text{sat}} \) 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
- \(~36° D^*_{\text{BLIP}}\) at 230 K
LWIR (8-16um) photodiodes

- AUGER generation suppression

\[ N_a \approx 1 \times 10^{15} \text{cm}^{-3}, \quad n_i \approx 6 \times 10^{16} \text{cm}^{-3} \] (300 K)

\[ G_A = \frac{n}{2} \frac{1}{\tau_{A1}} + \frac{p}{2} \frac{1}{\tau_{A7}} = \frac{1}{2} \frac{1}{\tau_{A1}} \left( n + \frac{p}{\gamma} \right) \]

\[ V = 0 \quad n \approx p \approx n_i \]

\[ V = -0.3 \text{V} \quad n \approx 0 \quad p = N_a \]

\[ G_A = \frac{n_i(\gamma + 1)}{2\tau_{A1}/\gamma} \]

\[ G_A = \frac{N_A}{2\tau_{A1}/\gamma} \quad D^* = \frac{\lambda}{hc} \frac{\eta}{t^{1/2}} \left( \frac{\tau_{A1}^i}{N_a/\gamma} \right)^{1/2} \]
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 \(~10 \ \mu\text{m}, 2\text{TE}\)
- Auger suppression observed
- Significant photoelectric gain, up to \(~10\times\)
  - reduced EMI, less critical electronics
  - nature: negative resistance, positive feedback
- Useful spectral range extended to \(>16 \ \mu\text{m}\)
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

  \[ \tau = \frac{t^2}{2D_a} \]
  \[ \tau = \frac{t^2}{V \mu_a} \]

  good: large ambipolar $\mu_a$ 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 $R_d$
► 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

Preferred conditions
- Constant voltage bias
- Current readout

Electronics
- DC-coupled TI PA
- Fast oscilloscope

Results:
- Subnanosecond time constants measured in PC, PEM and PV HOT detectors
- With SR, QCL and OPO sources
- Agreement with simulations

Waveforms observed with synchrotron source

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 etching
- Multiple heterojunction cells with ~10 µm period

- good responsivity
- large voltage output
- D* far from limits
- long response time
- dead regions
- polarization sensitive
• near-BLIP detection in 3-5 µm range
• <1 order of magnitude to BLIP for λ>7µm
PRACTICAL „HOT” DEVICES...

Standard devices

- $2 < \lambda < 16 \, \mu m$
- PC, PCI
- PC-2TE, PCI-2TE
- PEM, PEMI
- PV, PVI
- PV-2TE, PVI-2TE 3 and TE)
- PVM (I, 2TE)
- 3TE and 4TE versions

Custom devices:

- LN cooling
- shaped spectral response and multicolor
- linear arrays up to 120 el.
- small 2D arrays e.g. quads
- sizes: from few $\mu m$ to a few mm
- 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 \( (T_{\text{sink}} = 300 \text{ K}) \)

- 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 controller, 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

V-20 imager

Fast pyrometer

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
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”


• 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

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 $\lambda=10 \ \mu m$ 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
- multiple $N^+pP^+$ cells
- $d_{\text{abs}} < L_d$, $d_{\text{tot}} \approx 1/\alpha$
- 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”


► 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)