Les filières de photodétecteurs pour les prochaines applications de l'imagerie infrarouge

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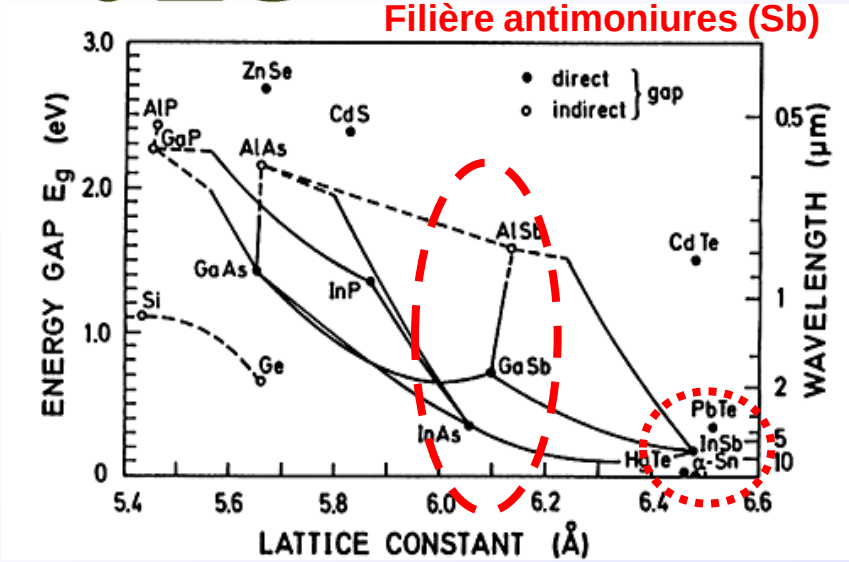
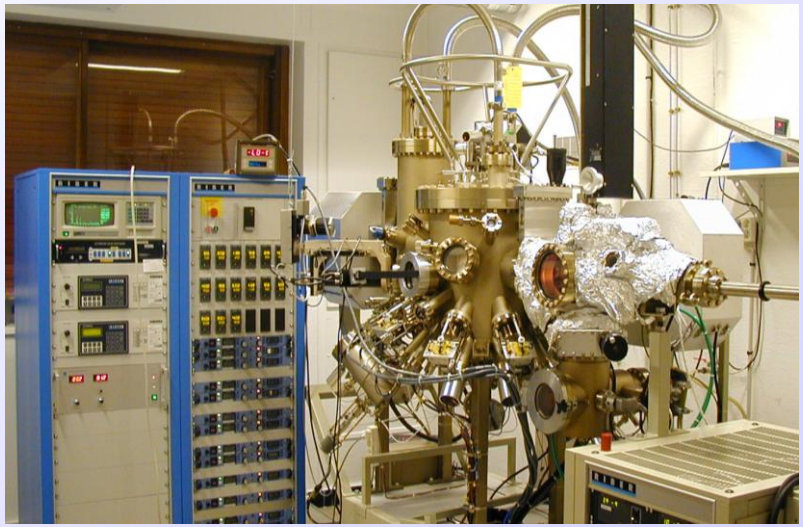
Groupe de recherche **nanoMIR** de l'IES

*Composants à **nano**structures pour **M**oyen **I**nfra**R**ouge*

Filière antimoniures (Sb)



GaSb, InAs, AlSb, InSb



Croissance par Epitaxie par Jets Moléculaires (EJM)

Fabrication de composants photoniques pour applications Moyen IR

➔ Diodes Lasers EELs et VCSELs

- Lasers à Multipuits Quantiques InGaAsSb/GaAlAsSb
- Lasers à superréseaux InAs/GaSb
- Lasers à cascade quantique (QCL) InAs/AlSb

➔ Photodétecteurs pour imagerie

- Photodiodes In(As)Sb et Photodetecteurs à **SR InAs/GaSb** pour imagerie IR
- Photocathodes pour imagerie IL

Les filières de photodétecteurs pour les prochaines applications de l'imagerie infrarouge

Plan de l'exposé

- Historique : 1ère, 2ème, 3ème génération de détecteurs IR
- Les critères pour les besoins actuels et futurs de la photodétection IR
- Les performances des filières leaders :

  HgCdTe (MCT)

  Quantum Well IR Photodetector (QWIP) GaAs
- Les filières en émergence

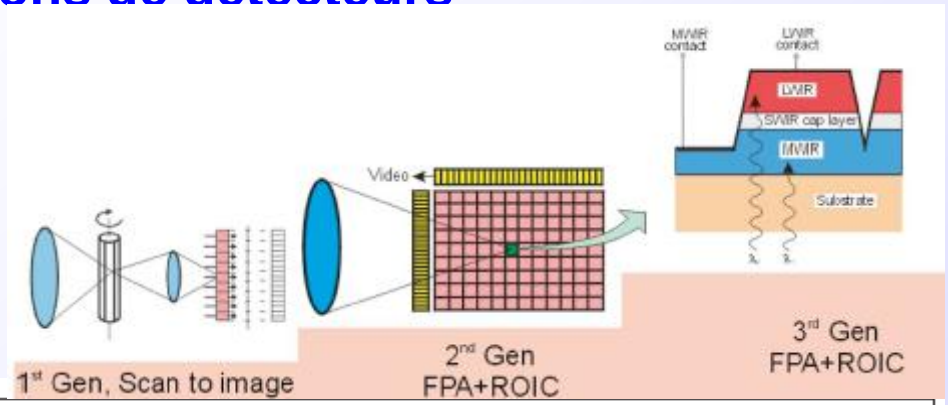
  Quantum Dot IR Photodetector (QDIP)

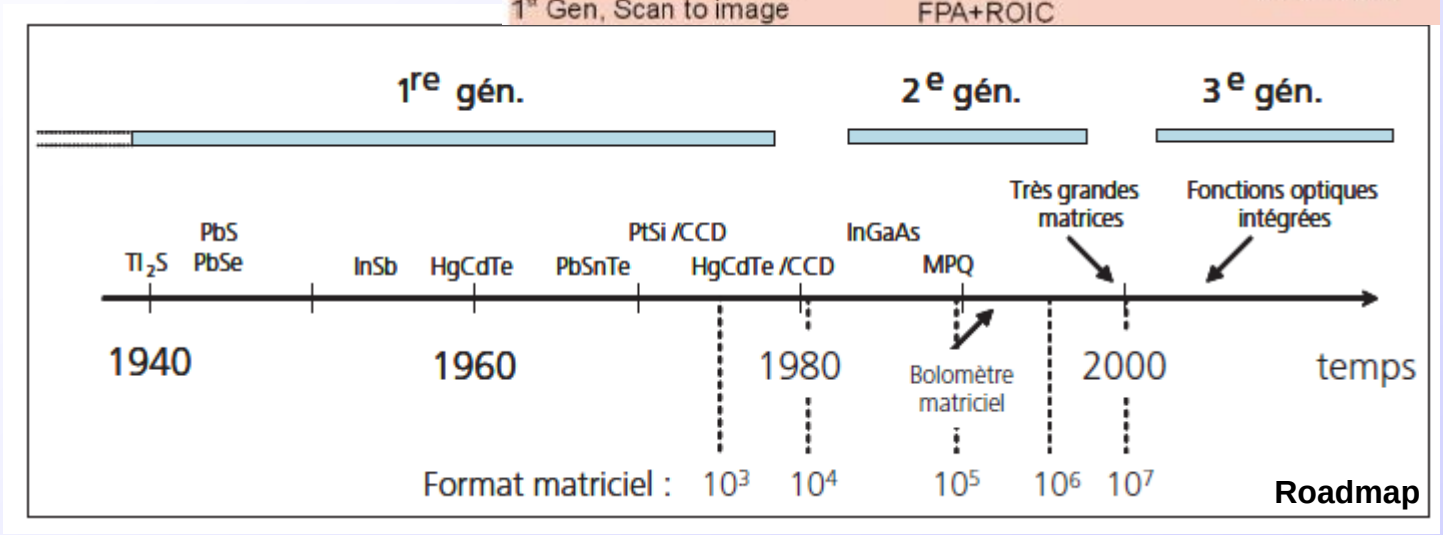
  Superréseaux (SR) InAs/GaSb
- Conclusion

Les filières et les générations de détecteurs

Historique

Revue Photoniques n°42 (2009)



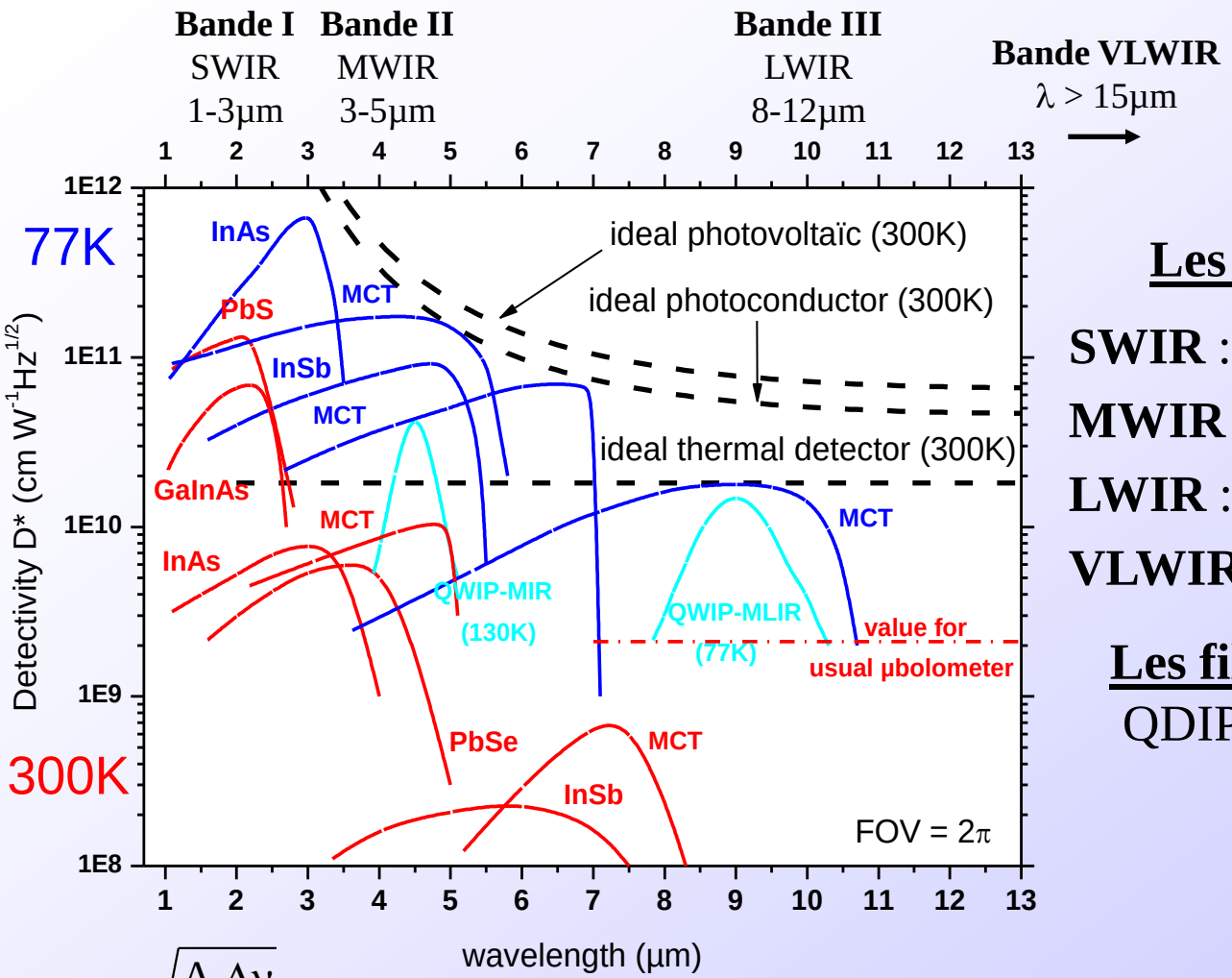


➔**Les Filières de matériaux** : Sels de Plombs puis InSb et HgCdTe (MCT)
puis InGaAs et MPQ GaAs (QWIP) et µbolomètres (Vox, a-Si)

➔**Les Générations de détecteurs** :

1ère Gén : monoélément
2ème Gen : matrice 2D (FPA) + ROIC jusqu'au format TV (640x480)
3ème Gen (début 2000) : matrice Mégapixel
+ multifonctions intégrées (multispectral, polarisation, amplification …)

Les filières de détecteurs



$$D^* = \frac{\sqrt{A\,\Delta\nu}}{NEP}$$

Les filières leaders

SWIR : InGaAs, MCT (HgCdTe)

MWIR : InSb, MCT, QWIP (MPQ)

LWIR : MCT, QWIP, µbolo

VLWIR : BIB (Si:As, Si:Sb, Ge:Sb)

Les filières en émergence

QDIP, QCD, SR (SuperRéseaux)

Avantages/Inconvénients

☞ Perfs (D*, NETD, FPA, $t_{resp,}$ uniformité), fabrication, $T°_{fonc}$, coût

Les formats de matrices présents sur le marché

Technologie MCT (HgCdTe) : SOFRADIR.

- **MARS** SW, MW, LW : 320x256, pixel 30µmx30µm.
  - SWIR : λ < 2µm (2.5µm), T_{op} =250K (200K)
  - MWIR : up to 110K, NETD ≤10mK (f/2)
  - LWIR : 77K, NETD ≤ 25mK
- **SCORPIO** MW, LW **:** 640x512 (format TV), 15µm pitch.
- **JUPITER** MW **:** 1280x1024 (Mégapixel), 15µm pitch
- **ALTAIR** MW/MW **:** bispectral (3-4µm) / (4-5µm)
- d'autres formats matriciels, barettes (480x6, 288x4 …)

☞ **P. TRIBOLET (Sofradir)**

"défis et applications des détecteurs infrarouge refroidis"

Technologie InSb : SAGEM

MWIR 77K**,** 320x240 & 256x256,

NETD ~ 20mK

Technologie QWIPs GaAs :THALES

LW : 768x576, NETD≤ 20mK $T°_{Op}$ ≤77K

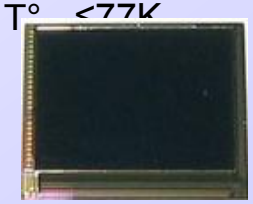
Mégapixel LW : 1280x1024, NETD≤ 25mK

cameras Catherine XP & MP

- **SIRIUS** LW 640x512 (20µm pitch)

λ_{peak}= 8.5 µm, NETD~31mK (f/2,7ms)

T°$_{Op}$ <77K



GaAs QWIP FPA THALES

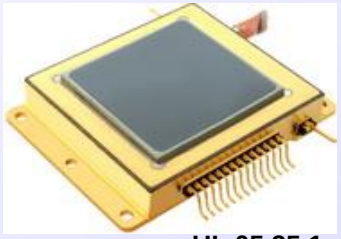
Intégration Sofradir

- **Catherine XP bi-spectral MWIR/LWIR**
  384x288 (pitch 25µm)
  QWIP FPA (Thales) + VEGA IDCA (Sofradir)

Technologie µbolomètre : ULIS (aSi)

LWIR non refroidi, formats VGA/16, VGA/4, VGA, XGA

-



UL 05 25 1

XGA 1024x768, 17µm pitch

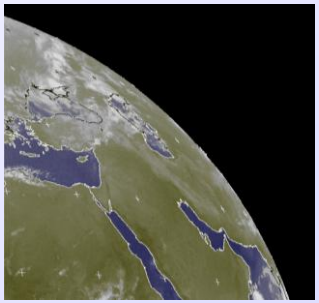
VGA 640x480, 25µm pitch

☞ **J-L. TISSOT (ULIS)**

"la détection infrarouge avec les détecteurs non refroidis"

Les applications de la détection IR très haute performance

- Applications militaires (vision nocturne, détecter-reconnaître-identifier)
- Applications spatiales (spectroscopie, cartographie de l'Univers)
- Aide au diagnostic médical (dépistage préventif)
- Maintenance/surveillance industrielle, contrôle de la pollution
- Météorologie (3ème Gén Météosat), Climatologie, Agronomie
- Détection de personnes en situation difficile (fumée, tempête)
- Aide à la conduite en conditions extrêmes (nuit, brouillard, pluie)

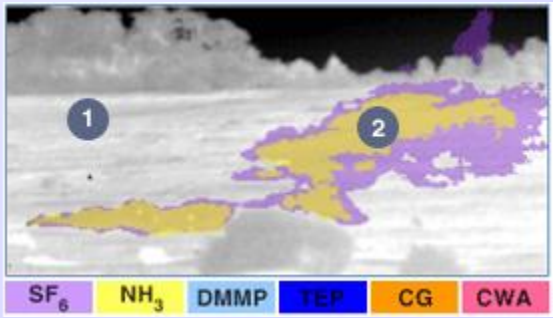


Surveillance Climatique

Vision IR d'une scène

Aide à la détection de personnes

Aide à la conduite en conditions extrêmes



Détection de fuites de gaz

Les applications de la détection IR très haute performance

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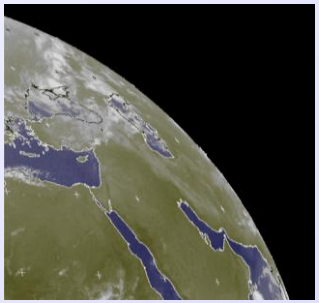

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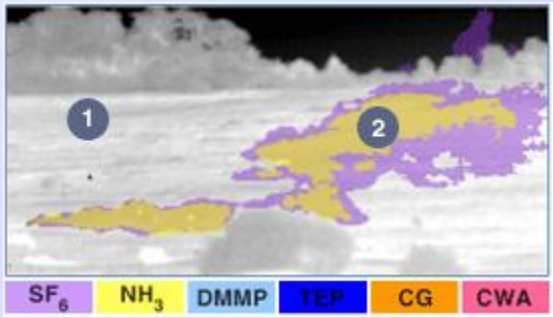


Détection de fuites de gaz

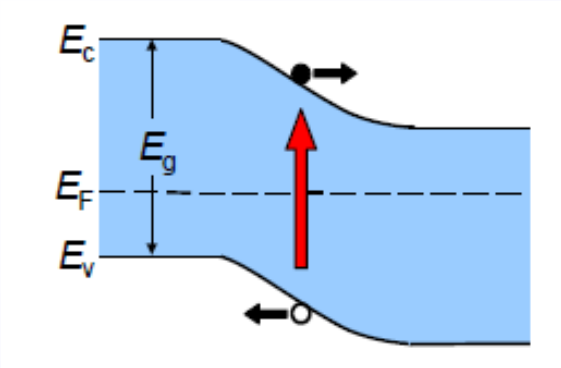
Les critères pour les prochaines applications de la photodétection IR

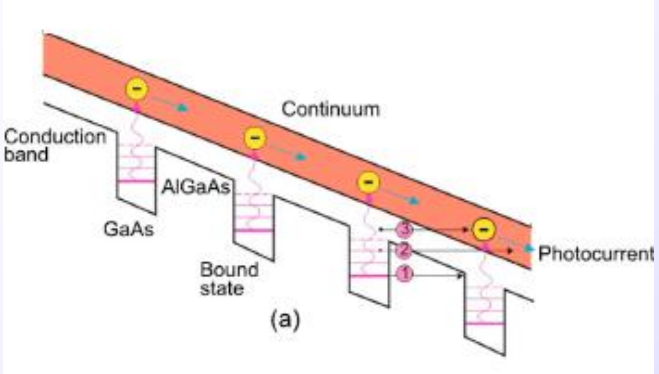
- multispectralité/ hyperspectralité
- large matrice de plans focaux (FPAs) (> 10^6 pixels)
- détection grandes longueur d'onde (λ>15µm)
- fonctions optiques intégrées (polarisation, amplification)
- détectivité D* élevée / NETD ~ 10mK
- fonctionnement non-cryogénique (T>110K)

☞ haute définition
☞ haute résolution
☞ nouvelles applications
☞ compacité/nouvelles applications
☞ haute performance
☞ allumage/coût/maintenance

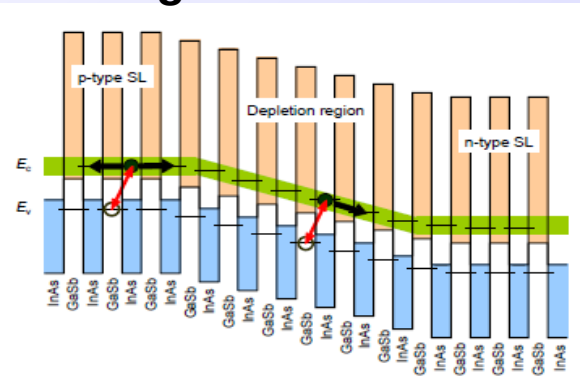
Quelle(s) Technologie(s) pour atteindre ces nouveaux critères ?

Filières établies





Filières émergentes



HgCdTe (MCT)

Photodiode (porteurs minoritaires)

-Filière historique (50 ans)
-Communauté scientifique
-Technologie mature
-Multispectralité possible (SW-MW-LW …)
-Broad-band absorption
-HOT detector (PV),
-High QE, APD

<u>Désavantages</u>
-substrat Cd(Zn)Te (211)
-Hg pour grande λ

QWIP GaAs → QDIP

Photoconducteur (porteurs majoritaires)

-Filière reconnue (25 ans)
-Communauté scientifique
-Technologie GaAs
-Substrats 4", 6"
-Homogénéité/Uniformité
-Multispectralité (MW→VLW)
-Spectral shape, NETD

<u>Désavantages</u>
- T° fonct (PC)
- QE, spectral shape
- Pas d'incidence normale
  ➔Gratings (mais …)

SuperRéseaux InAs/GaSb

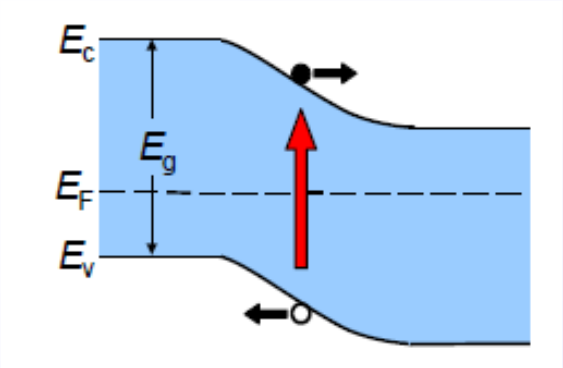
Photodiode (porteurs minoritaires)

-Technologie III-V
-Multispectralité aisée (3-30µm)
-Filière GaSb (flexibilité)
-Broad-band absorption
-HOT detector (PV), high QE

<u>Désavantages</u>
-Filière en émergence (< 15 ans)
-Technologie non mature
-Petite communauté scientifique
-Connaissance du matériau
-Taille des substrats (4" à venir ?)

Quelle(s) Technologie(s) pour atteindre ces nouveaux critères ?

Filières établies



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-Hg pour grande λ

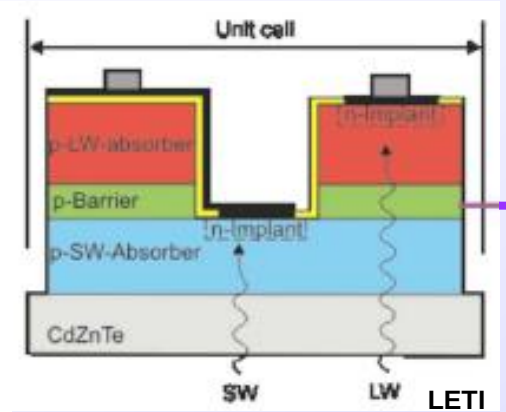
Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

HgCdTe (MCT)

Photodiode n/p (absorption couche p)

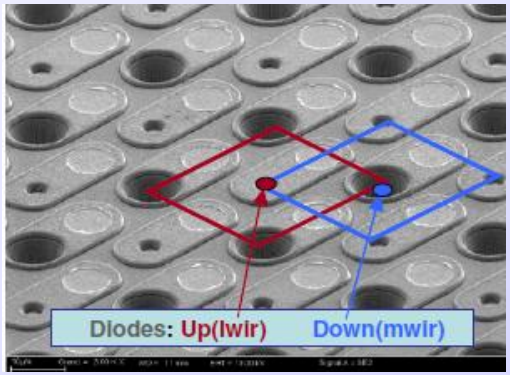
Dual-band detectors

MW/MW, MW/LW, LW/LW

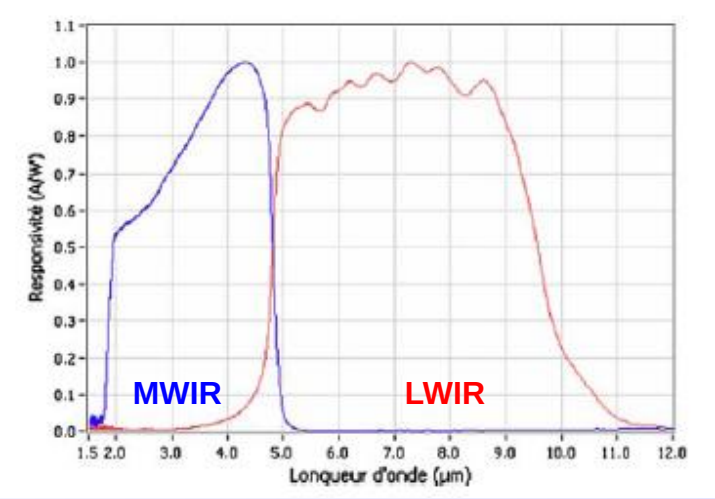


LETI

Bispectral MW/LW 30 µm pixel pitch

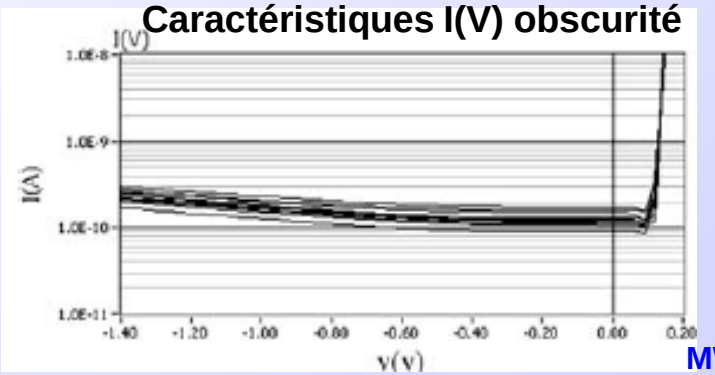


G. Destefanis *et al*
J. Electron. Mater 36 (2007)



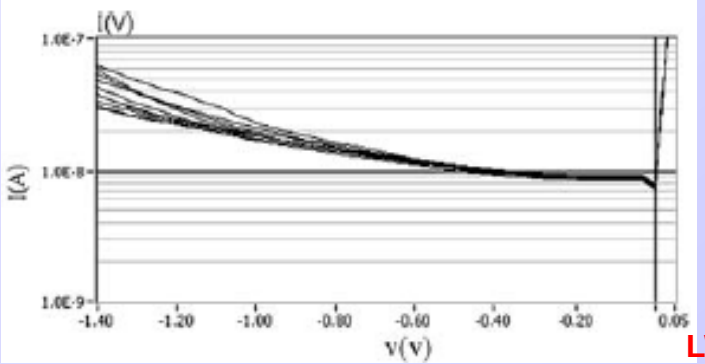
Réponse spectrale $\Re_\lambda$

Caractéristiques I(V) obscurité



I_{obs}

MWIR (λ_C=5µm)



I_{obs}

LWIR (λ_C=9.5µm)

Pour une photodiode

$$D^* = \Re_\lambda \sqrt{\frac{R_0 A}{4kT}}$$

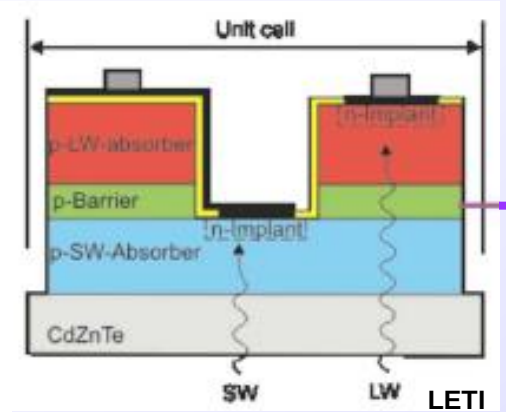
Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

HgCdTe (MCT)

Photodiode n/p (absorption couche p)

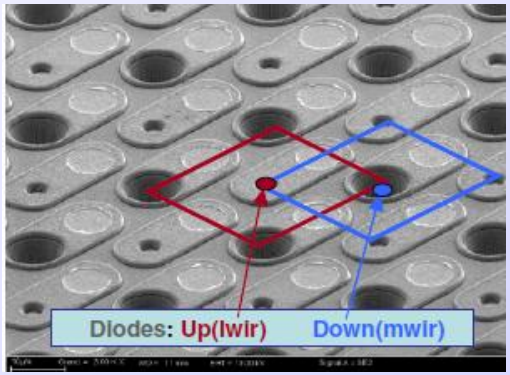
Dual-band detectors

MW/MW, MW/LW, LW/LW



LETI

Bispectral MW/LW 30 µm pixel pitch



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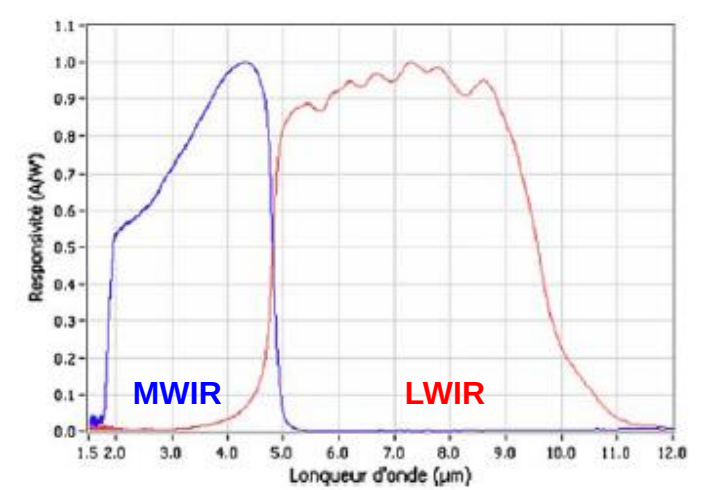
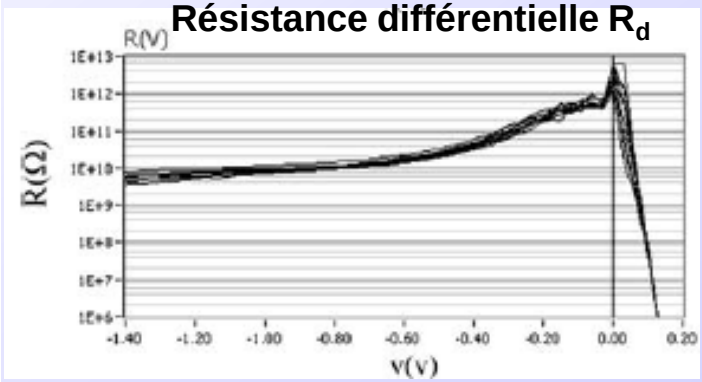


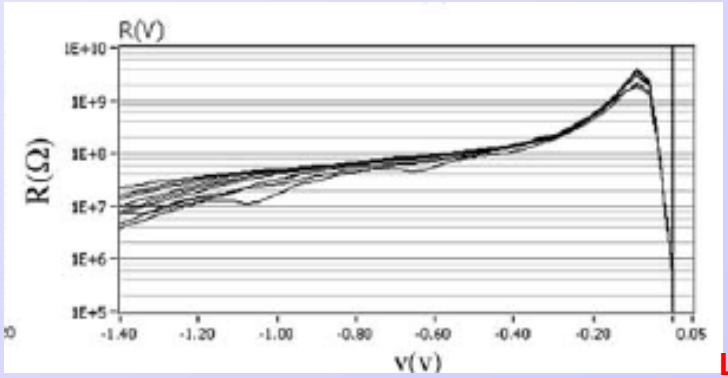
Réponse spectrale $\Re_\lambda$

Résistance différentielle R_d



R_0A~9M Ω.cm²

MWIR (λ_c=5µm)



R_0A~9 Ω.cm²

LWIR (λ_c=9.5µm)

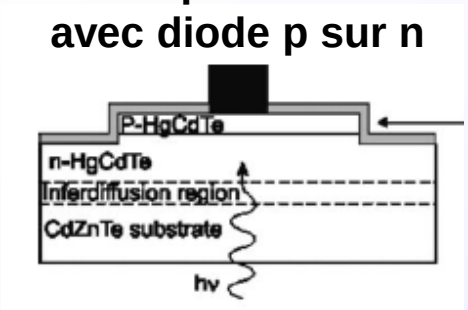
Pour une photodiode

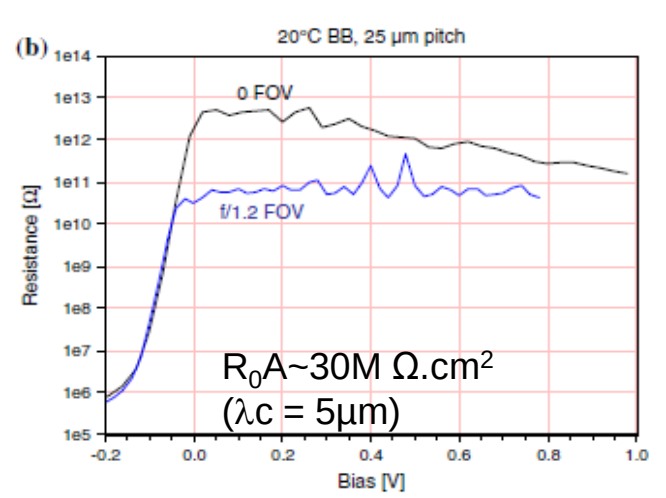
$$D^* = \Re_\lambda \sqrt{\frac{R_0 A}{4kT}}$$

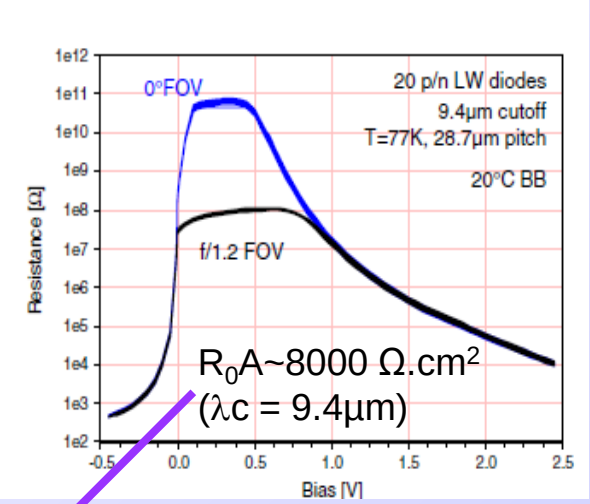
Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

HgCdTe (MCT)

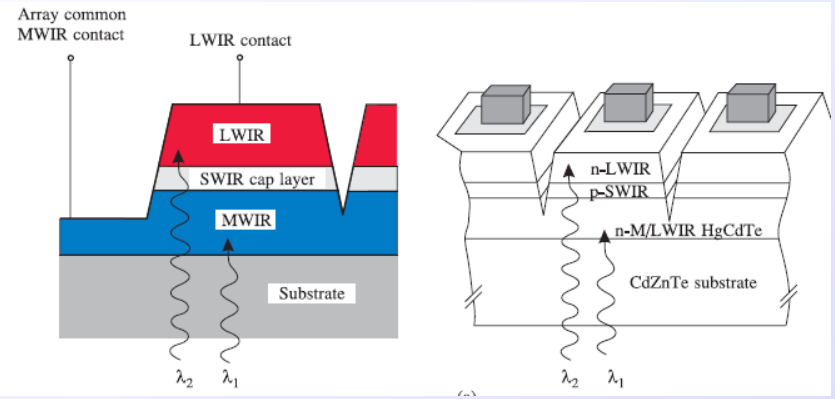
Haute performance avec diode p sur n

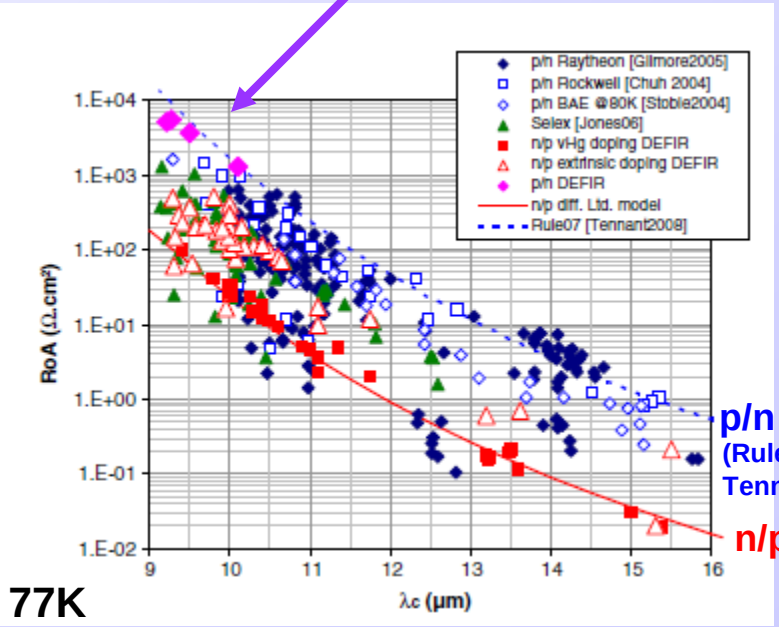






O. Gravrand *et al*
J. Electron. Mater 38 (2009)





☞ dual-color MW/LW FPA 1280x720 (20µm pitch)
Op 99.9% NETD 20mK MW,
Op 98% NETD 25mK LW

Raytheon Vision Systems (2006)

➔ **Three-color, T° operation, VLWIR …**

Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

HgCdTe (MCT)

☞ **VLWIR**

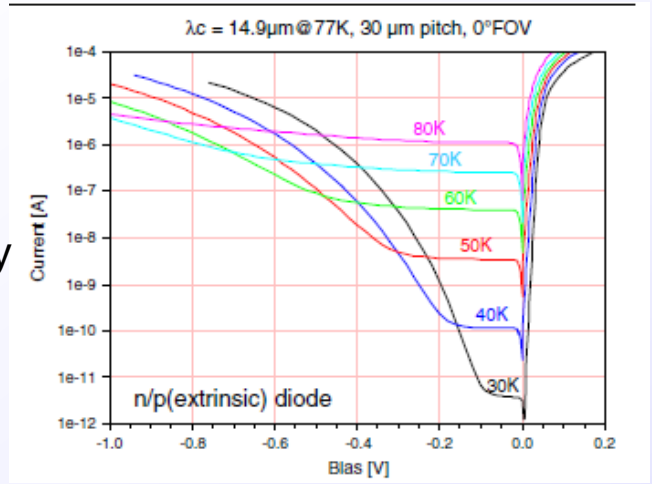
n/p diode

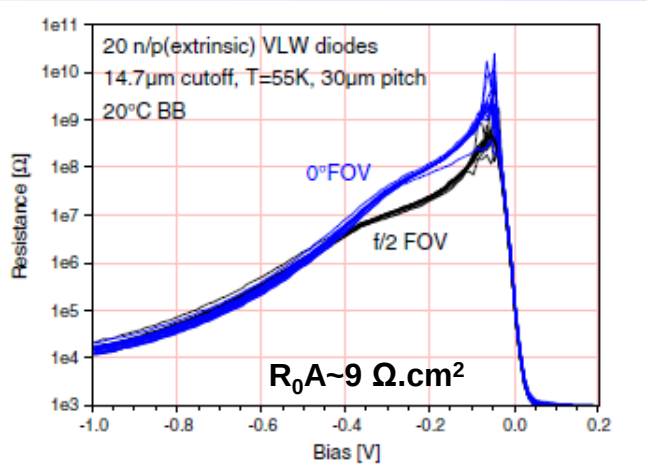
FPA :320x256 array

(30µm pitch)

λ_C= 14.7µm (55K)

Opérabilité 99.5%



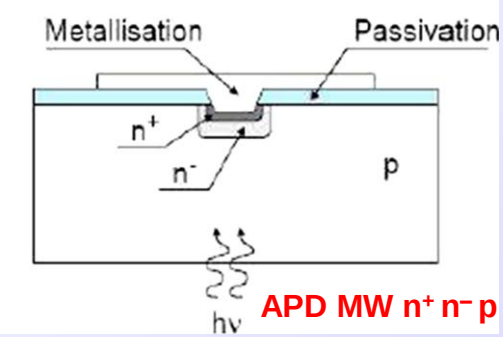


➔ **p/n diode …**

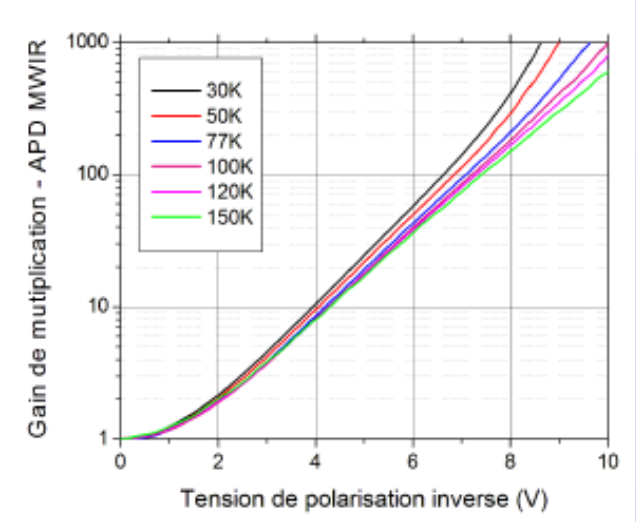
O. Gravrand *et al*
J. Electron. Mater 38 (2009)

☞ **APD**

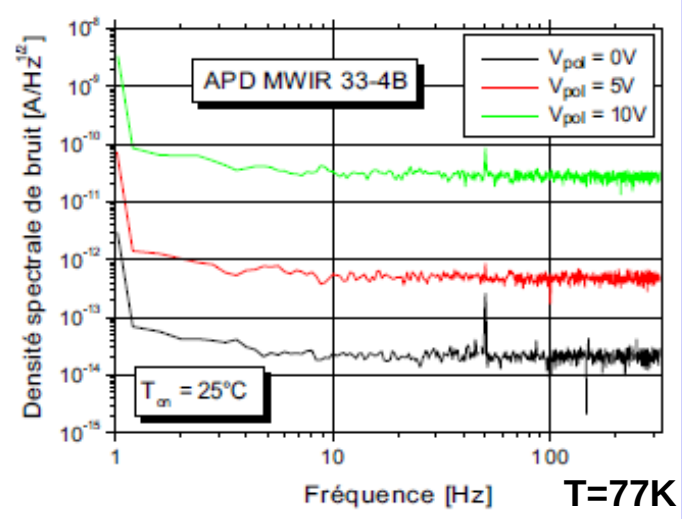
Imagerie IR active
Détection très faible flux
(astrophysique, biomedical)



APD MW $n^+ n^- p$



Thèse S. Derelle (ONERA-LETI) Déc 2009

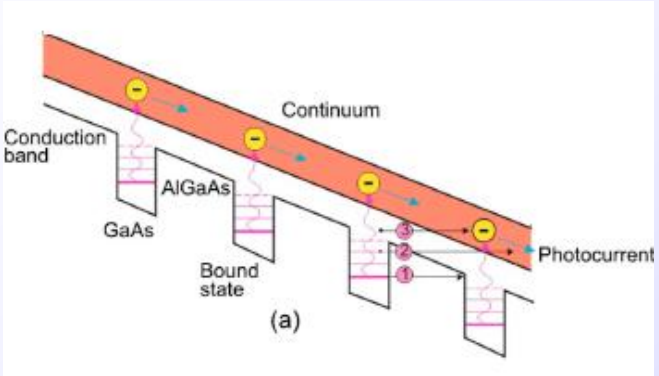


Pas de bruit en 1/f

➔ **APD LW, HOT eAPD …**

Quelle(s) Technologie(s) pour atteindre ces nouveaux critères ?

Filières établies **Filières émergentes**



QWIP GaAs → QDIP

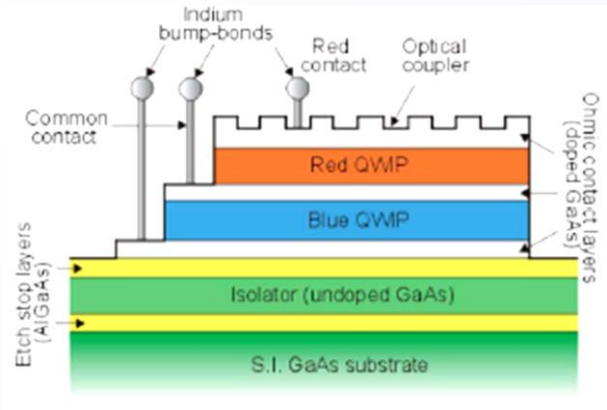
Photoconducteur (porteurs majoritaires)

-Filière reconnue (25 ans)
-Communauté scientifique
-Technologie GaAs
-Substrats 4", 6"
-Homogénéité/Uniformité
-Multispectralité (MW→VLW)
-Spectral shape, NETD

<u>Désavantages</u>
- T° fonct (PC)
- QE, spectral shape
- Pas d'incidence normale
  ➔Gratings (mais …)

Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

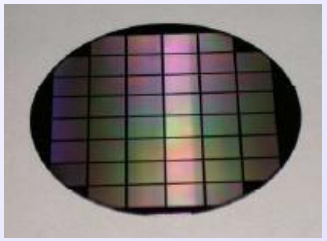
QWIP GaAs



architecture empilée (JPL, THALES, IAF …)

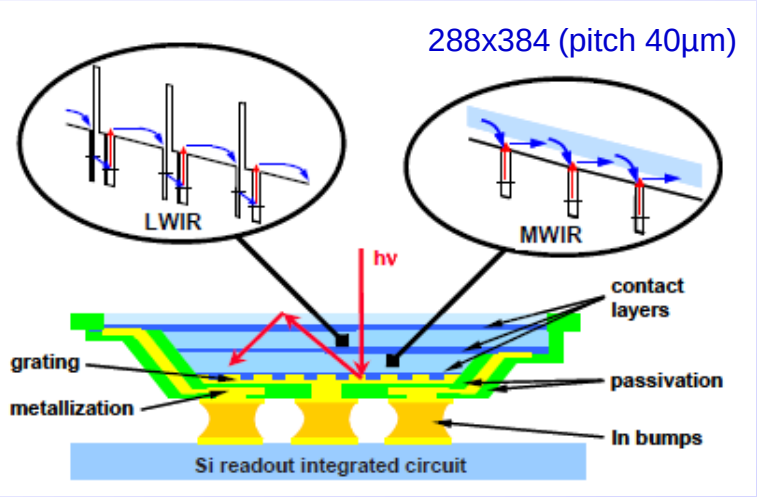
JPL: dual-band (320 x 256)
(NETD : 22mK MW, 24mK LW f/2, 65K)

Pixel MWIR/LWIR

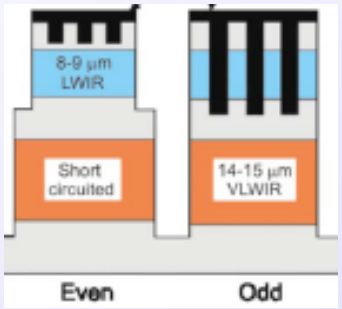


FPA on 4" GaAs wafer

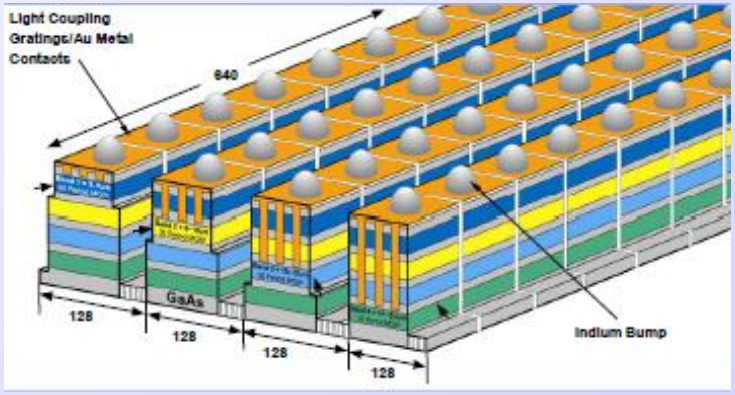
Dual band QWIP (Fraunhofer IAF-2006)



IAF : dual-band λ_{p1} =4.8µm, λ_{p2} =7.8µm, T= 70K
NETD (f/2, 6.8ms) MW 27mK LW 21mK, Op> 99.5%

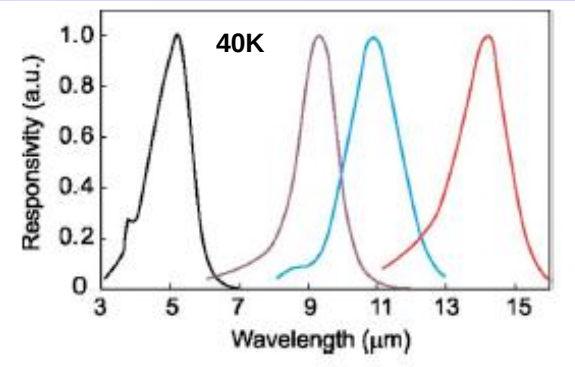


architecture décalée



Four-band QWIP (640x128) : JPL+ARL (2006)

λ = 4-6, 8.5-10, 10-12, 13-15µm
NETD : 21 45 14 44mK

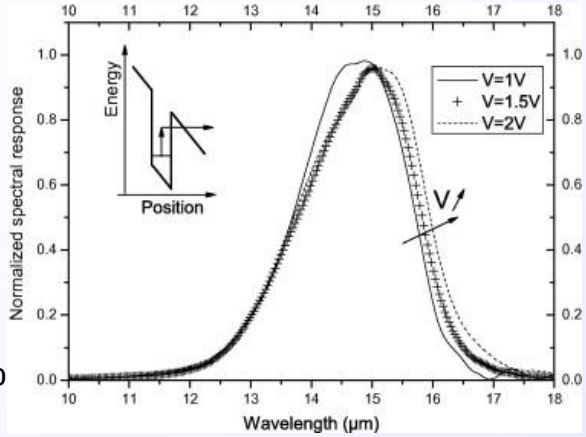


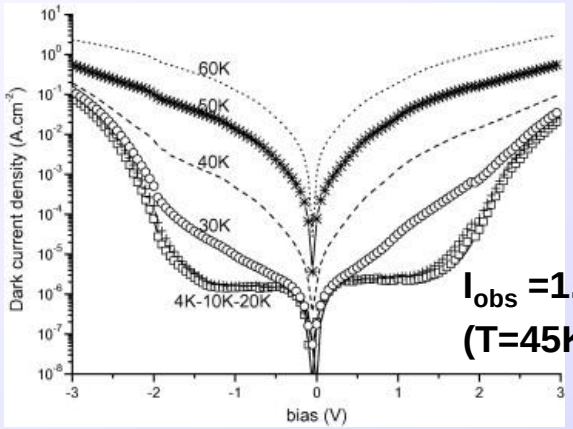
Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

QWIP GaAs

☞ **VLWIR**

384x288 array
(25µm pitch)
λ_C= 15.5µm (45K)
Opérabilité 99.96%



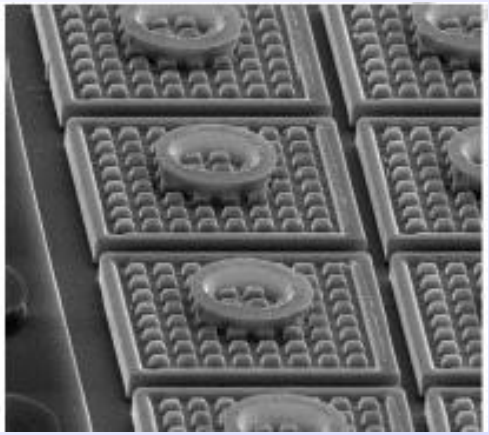


I_{obs} =1.5x10^{-4}A/cm^2
(T=45K, V=-0.8V)

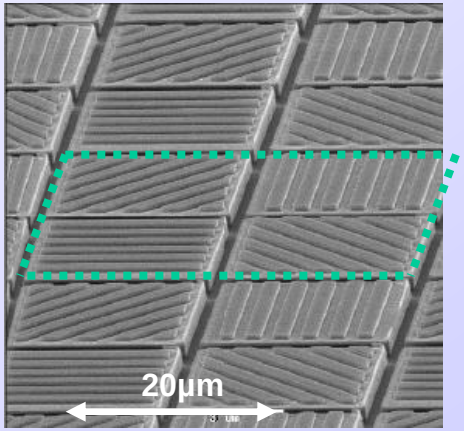
Thèse E. Lhuillier (ONERA-Paris 7-Thales), Oct 2010

☞ **Polarisation**

Pas d'absorption en incidence normale
➔Réseaux de diffraction en surface
pour couplage lumière/matière



Conventional QWIP array (THALES)



Array sensitive to
4 directions of polarisation

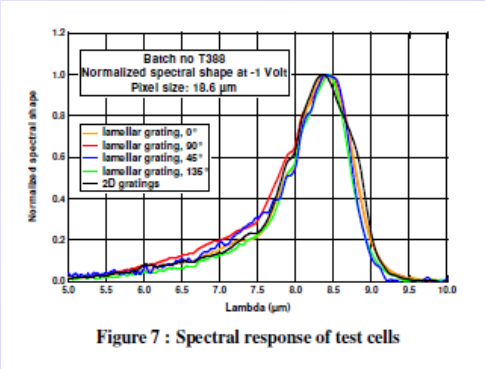
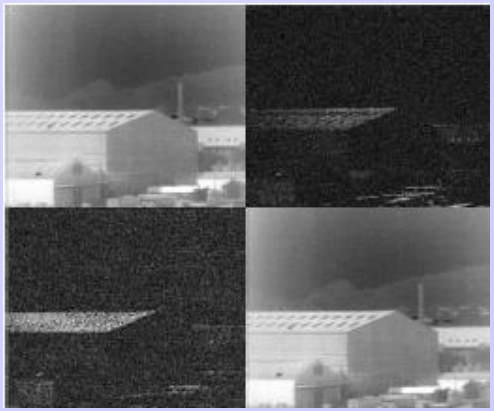


Figure 7 : Spectral response of test cells



Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

QWIP GaAs

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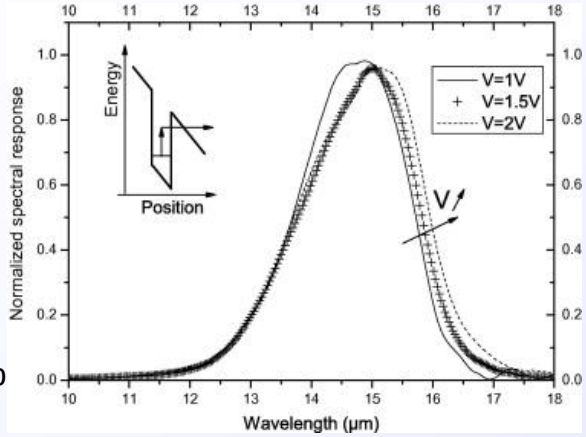

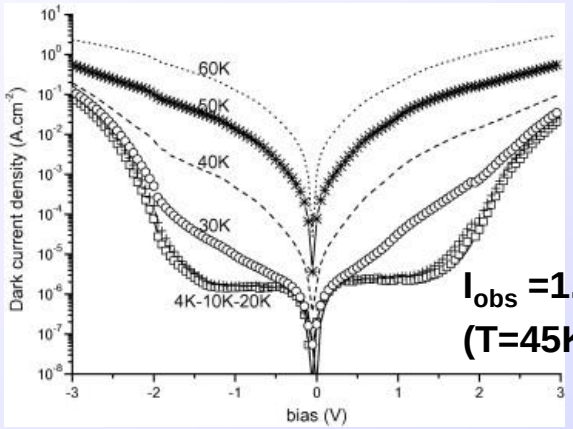

I_{obs} =1.5x10^{-4}A/cm^2
(T=45K, V=-0.8V)

Thèse E. Lhuillier (ONERA-Paris 7-Thales), Oct 2010

☞ **Polarisation**

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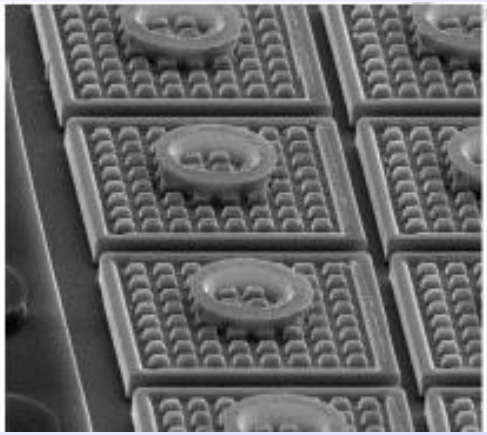
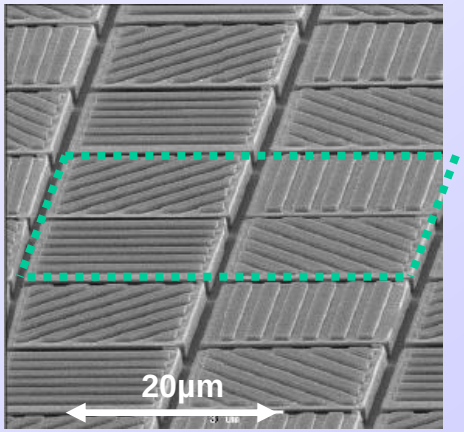


Conventional QWIP array (THALES)



Array sensitive to
4 directions of polarisation

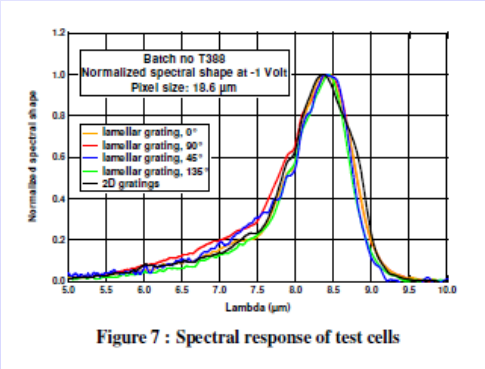


Figure 7 : Spectral response of test cells

E. Costard *et al*
"QWIP Status at THALES"
Infra. Phys. Technol. 52 (2009)

Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

Alternative au QWIP GaAs : QDIP (Quantum Dot IR detector)

QDIP vs QWIP

- **absorption incidence normale (QE↑)**
- **confinement 3D (QE↑)**
- **durée de vie des porteurs (QE↑)**
- **MWIR-LWIR-VLWIR**
- **Uniformité des dots (Perfs ↓)**

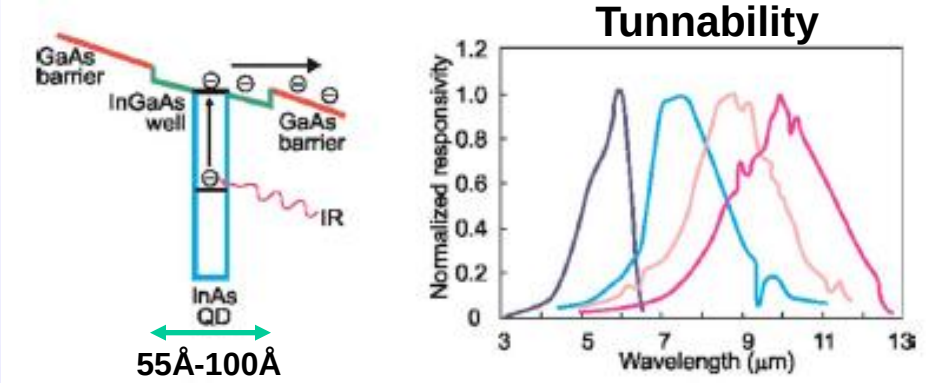
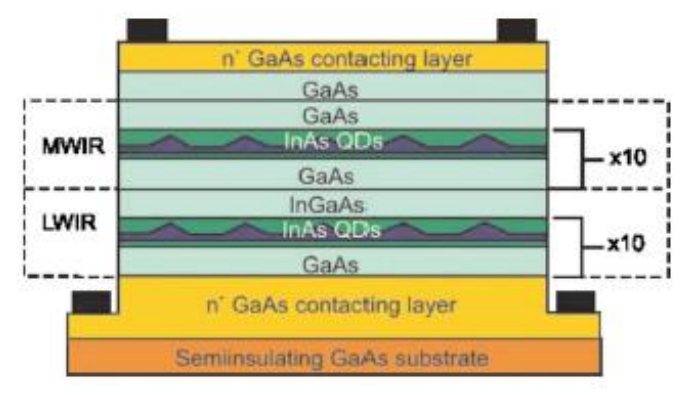


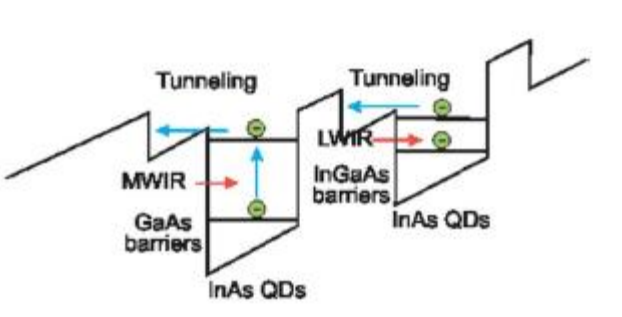
Image LWIR avec FPA QDIP

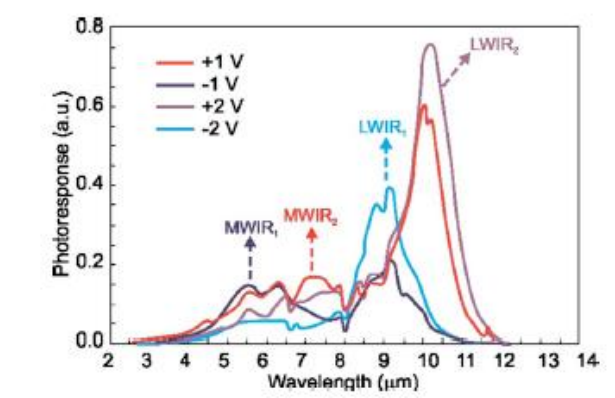
JPL (2009) : 1ère matrice Mégapixel QDIP

1024x1024 FPA
(80K, f/2 optics)
QE =20%, NETD 31mK
Opérability 99.8%

Inf. Phys.Technol. **52**, 395 (2009)







Multiband MW/LW QDIP

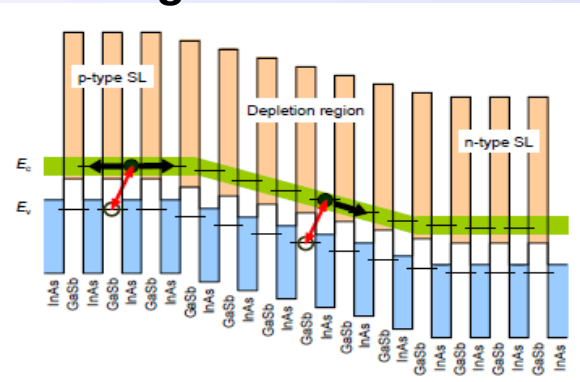
CHTM : S. Krishna *et al* , IEEE proc 95 (2007)

☞**Midwave infrared quantum dot avalanche photodiode**

*APL **97**, 221106 (2010)*

Quelle(s) Technologie(s) pour atteindre ces nouveaux critères ?

Filières émergentes



SuperRéseaux InAs/GaSb

Photodiode
(porteurs minoritaires)

-Technologie III-V
-Multispectralité aisée (3-30µm)
-Filière GaSb (flexibilité)
-Broad-band absorption
-HOT detector (PV), high QE

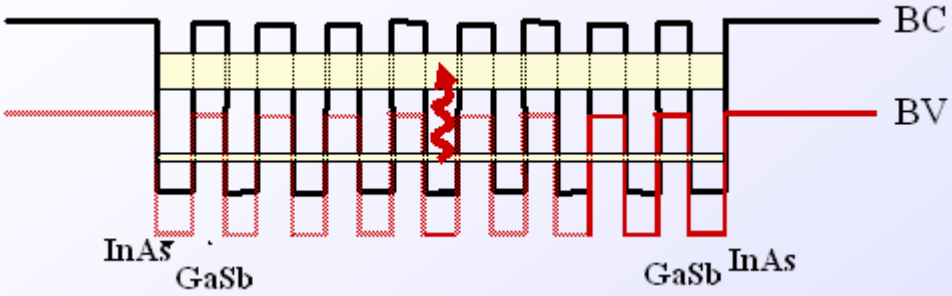
<u>Désavantages</u>

-Filière en émergence (< 15 ans)
-Technologie non mature
-Petite communauté scientifique
-Connaissance du matériau
-Taille des substrats (4" à venir ?)

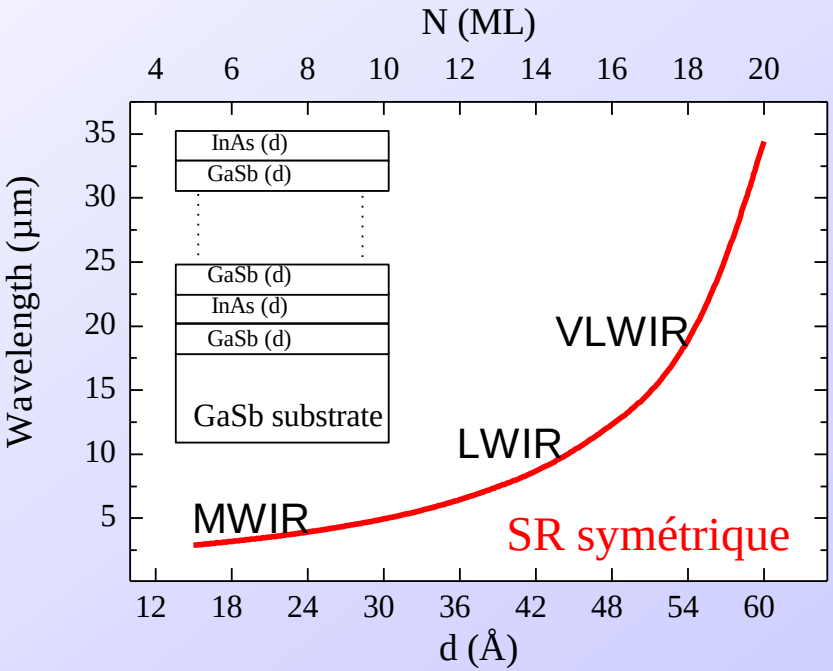
Alternative aux filières établies : Le Photodétecteur à Superréseau (SR) InAs/GaSb

SR : Empilement de couches de quelques nanomètres d'InAs et GaSb
la longueur d'onde de coupure λ_c est ajustée en jouant sur l'épaisseur des couches (2.5 µm < λ_c < 25 µm)

SR : MQW couplé $\Rightarrow$ Minibandes d'énergies



*Structure de bande d'un superréseau InAs/GaSb (**Type-II**) et transition inter-bande correspondant à l'absorption d'un photon infrarouge.*



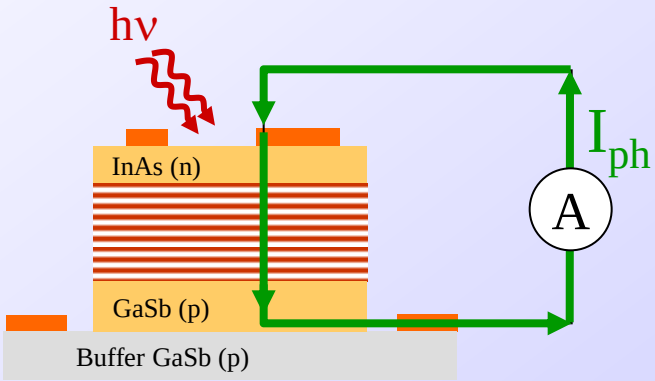
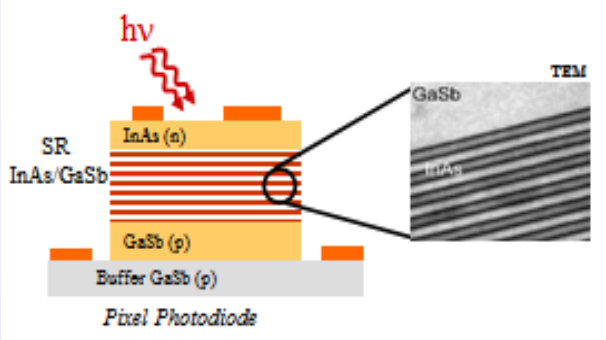


Schéma d'un pixel à superréseaux InAs/GaSb

SR : zone absorbante d'une jonction pin
$\Rightarrow$ détecteur photovoltaïque

Alternative aux filières établies : Le Photodétecteur à Superréseau (SR) InAs/GaSb



- ✓ Epitaxie III/V
- ✓ Technologie GaSb
- ✓ SL JDOS ⇒ absorption importante
- ✓ absorption incidence normale
- ✓ jonction pin ⇒ détecteur PV
- ✓ transition optique ajustable de 2.5µm à 25µm ⇒ multispectralité
- ✓ Alignement de bande de Type-II ⇒ gestion des recombinaisons Auger
- ✓ masse effective ($me^* \sim 0.03m_0$) ⇒ réduction du courant tunnel

USA

CQD (1997) : 1ère matrice LWIR 320x256 (2008), 1ère matrice LWIR Mégapixel (2010)

AFRL (2002), NRL (2002), CHTM (2005), ARL (2005), Univ Illinois (2006), SFA. Inc (2006), BAE Systems (2006), Raytheon (2006), Rockwell (2006), SVT systems (2008), …

JPL (2005) : 1ère matrice Mégapixel MWIR (2009)

Agence de moyen depuis 2005 : MDA (Missile Defence Agency)

Allemagne

Fraunhofer IAF (1995)
1ère matrice bicolore MW/MW 288x384 (2006)

France

IES (2003)
1ère photodiode MWIR non refroidie (2005)

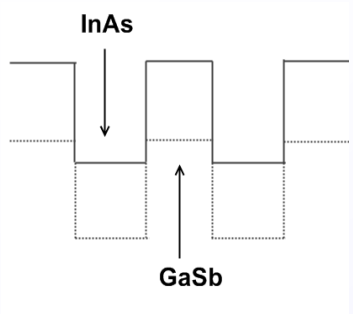
Israel

SCD (2006)

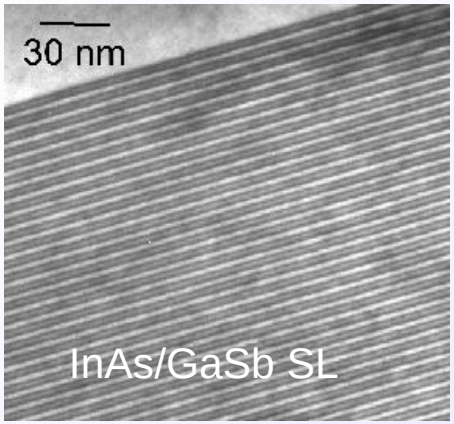
Chine

Nombreux labos depuis 2006/2007

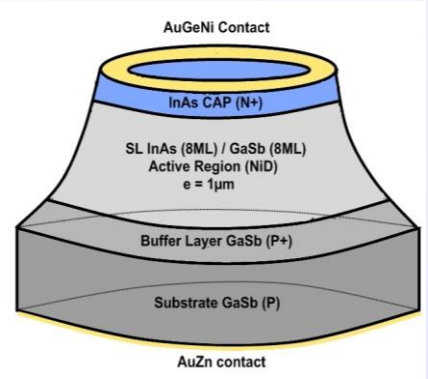
La photodiode à SR MWIR (à l'IES)



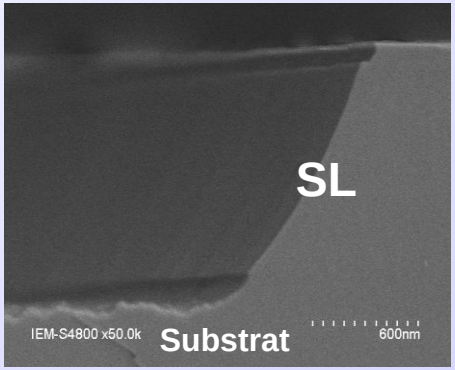
période symétrique de type II



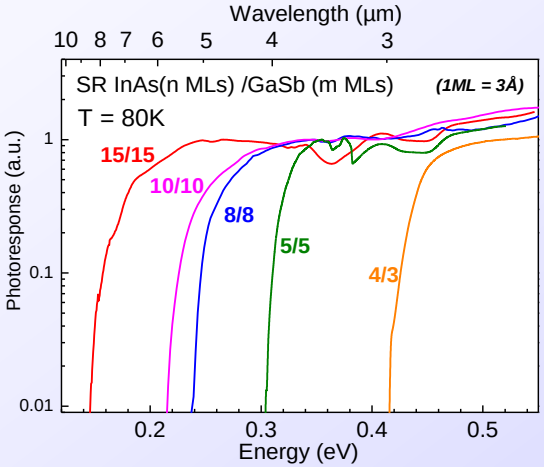
Fabrication par EJM



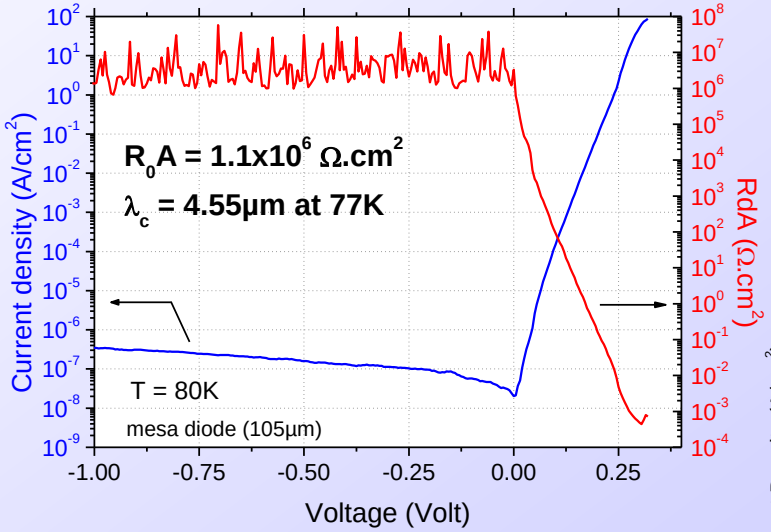
monopixel



Fabrication Photodiode

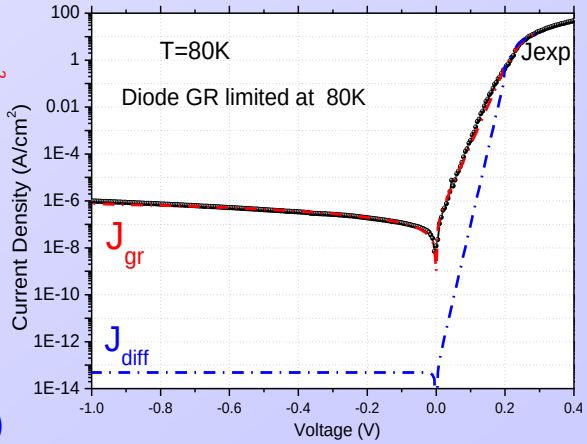


Cut-off Tuning



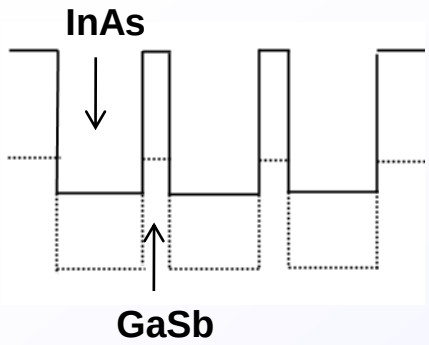
InAs (8Mc) / GaSb (8Mc)

C. Cervera *et al.* JAP **106**, 024501 (2009)



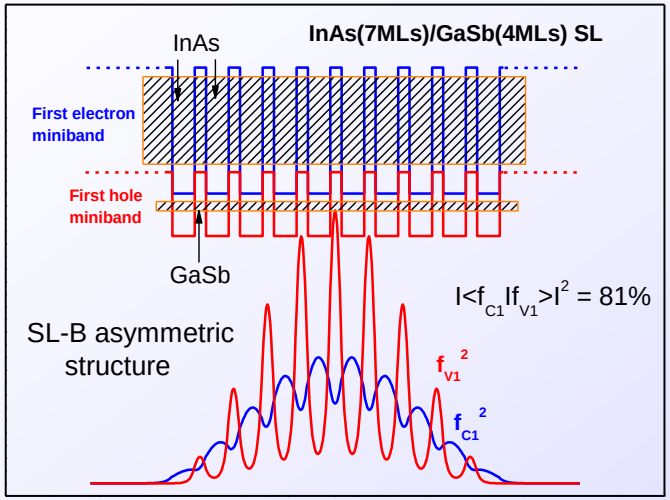
Analyse des courants

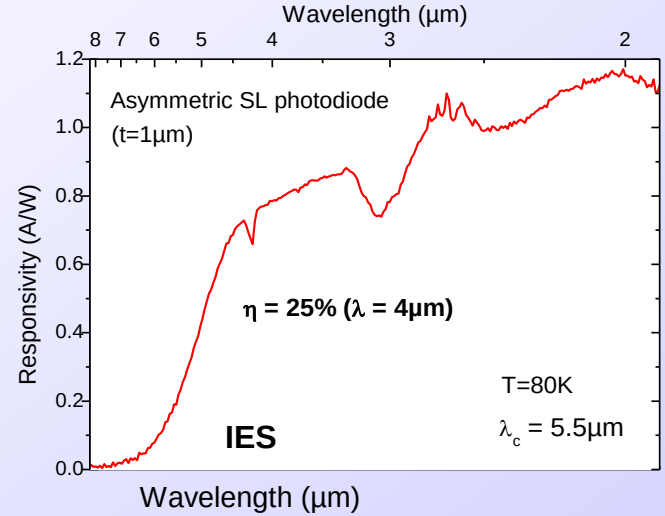
La photodiode à SR MWIR (à l'IES) : Amélioration des performances

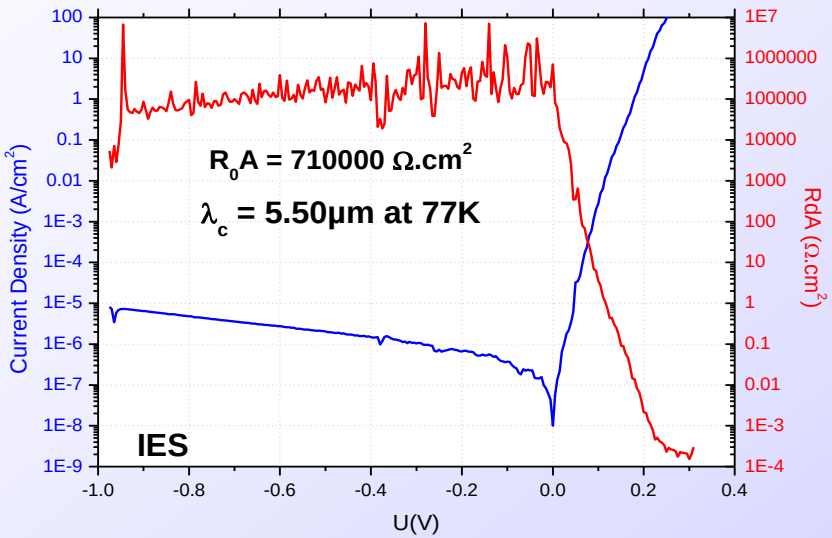


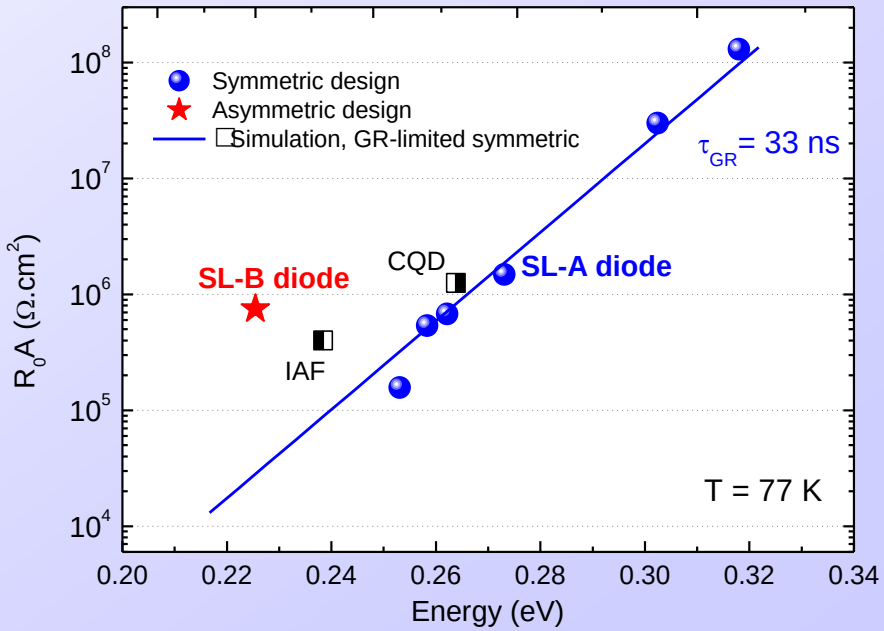
période asymétrique

InAs (7Mc) / GaSb (4Mc)









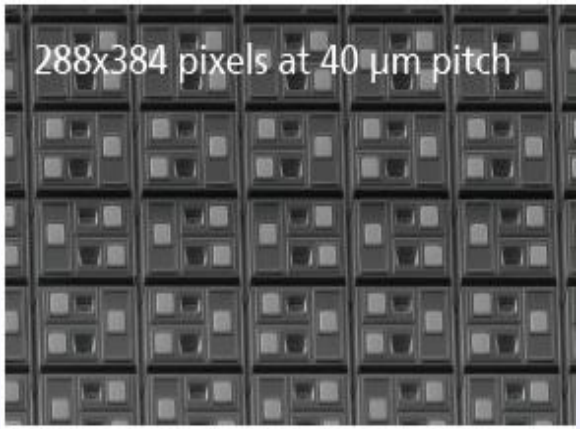
$$R_0A(\lambda) = \tau_{GR}.V_{bi}/(q.n_i.W)$$

GaSb↓ ⇒ m* ↓ ⇒ ni ↓ ⇒ **R_0A↑ à 77K ou T_{fonc}↑**

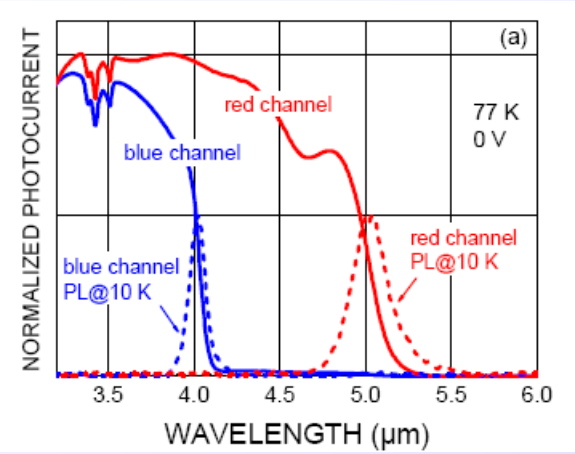
☞ **à paraître dans APL**

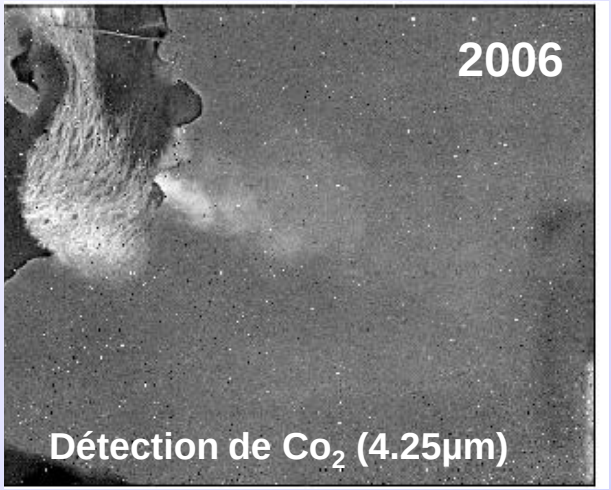
La photodiode à SR MWIR (autres résultats) : Imageur Bi-colore MWIR (288 x384)

☞ **Fraunhofer IAF (fabrication FPA) + AIM Infrarot-Module (hybridation, camera)**



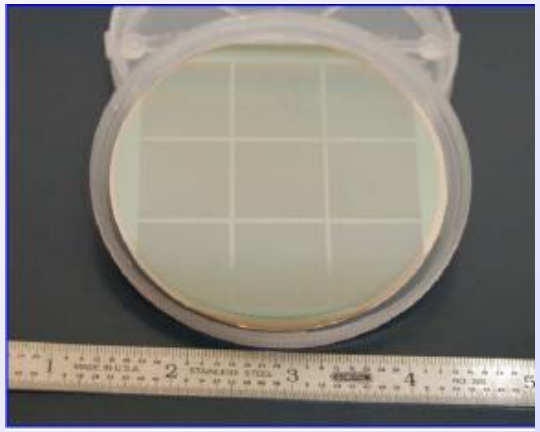
NETD = 22 mK, 12mK (f/2, 2.8ms)



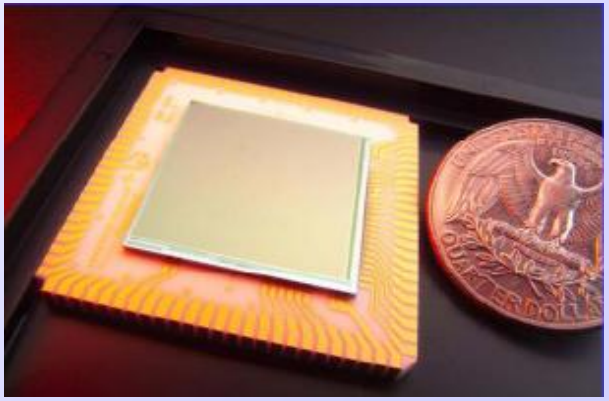


La photodiode à SR MWIR (autres résultats) : Imageur Mégapixel MWIR (1k x1k)

☞ **JPL (NASA) + Raytheon**

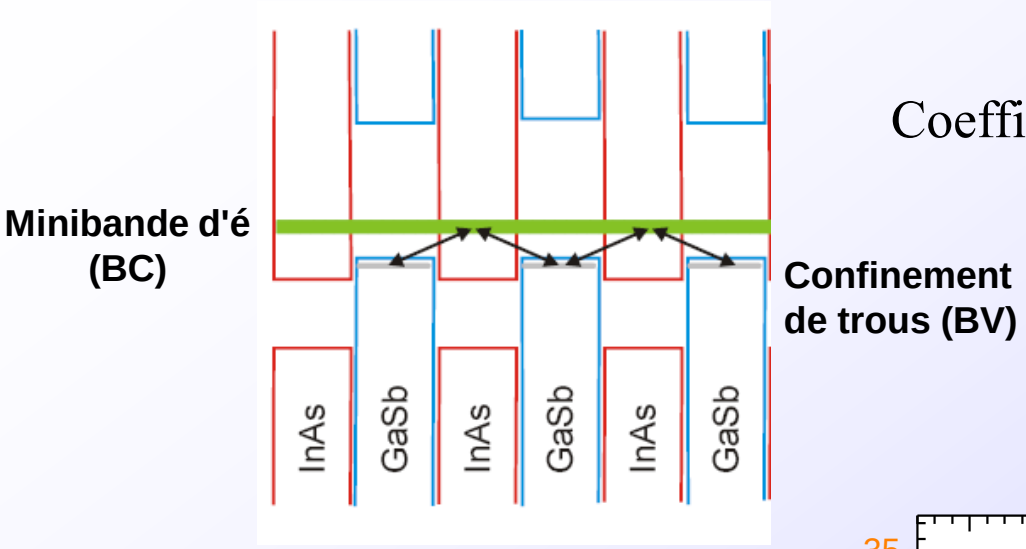


Five 19µm pitch megapixel MWIR Arrays on commercial 3" GaSb wafer



Megapixel MWIR image

La photodiode à SR pour les grandes longueurs d'ondes : LWIR et VLWIR

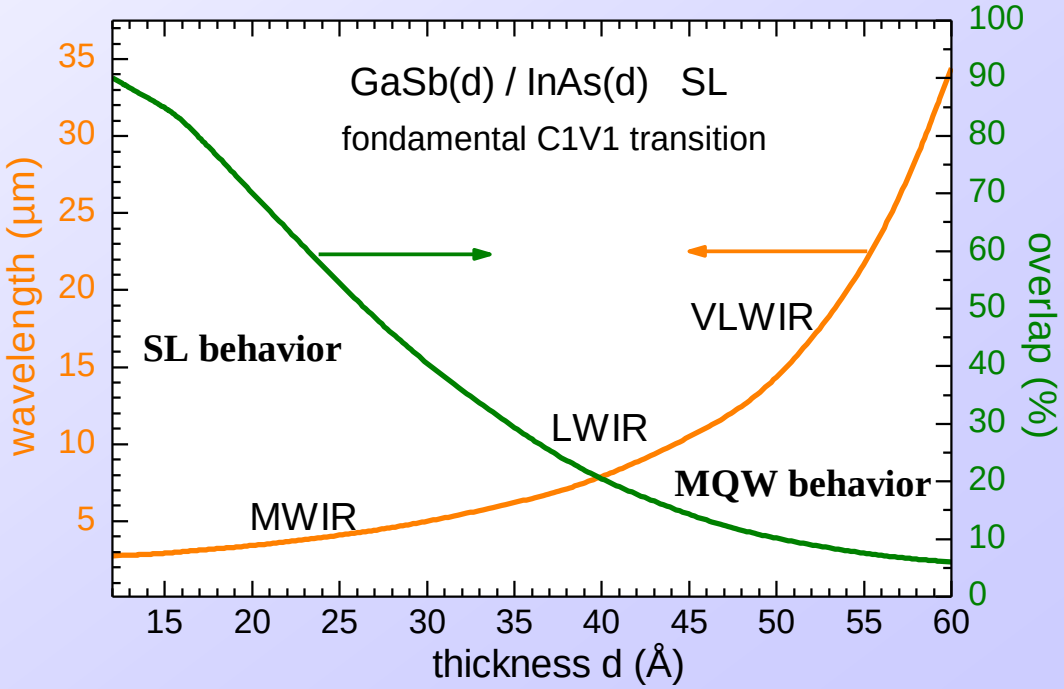


Coefficient d'absorption

$$\alpha(\omega) = \frac{e^2\pi}{n_{op} c m_0^2 \omega \varepsilon_0 V_{mat}} |d_{cv}|^2 D_{cv}(\omega)$$

overlap $|\langle f_e | f_h \rangle|^2$.

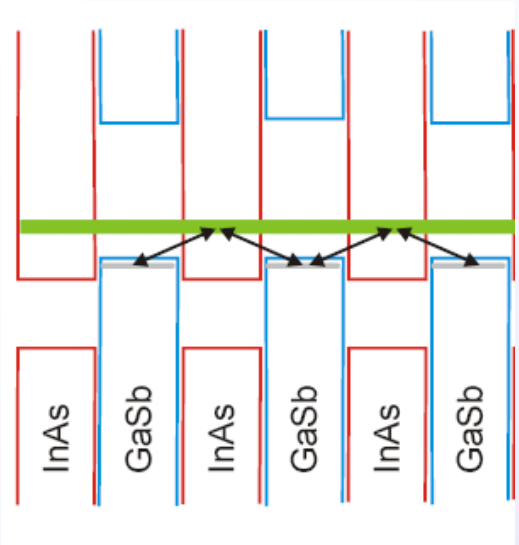
SR symétrique



Overlap = 80-40% | **Overlap $|\langle f_e | f_h \rangle|^2 \sim 0$**

La photodiode à SR pour les grandes longueurs d'ondes : LWIR et VLWIR

Minibande d'é (BC)



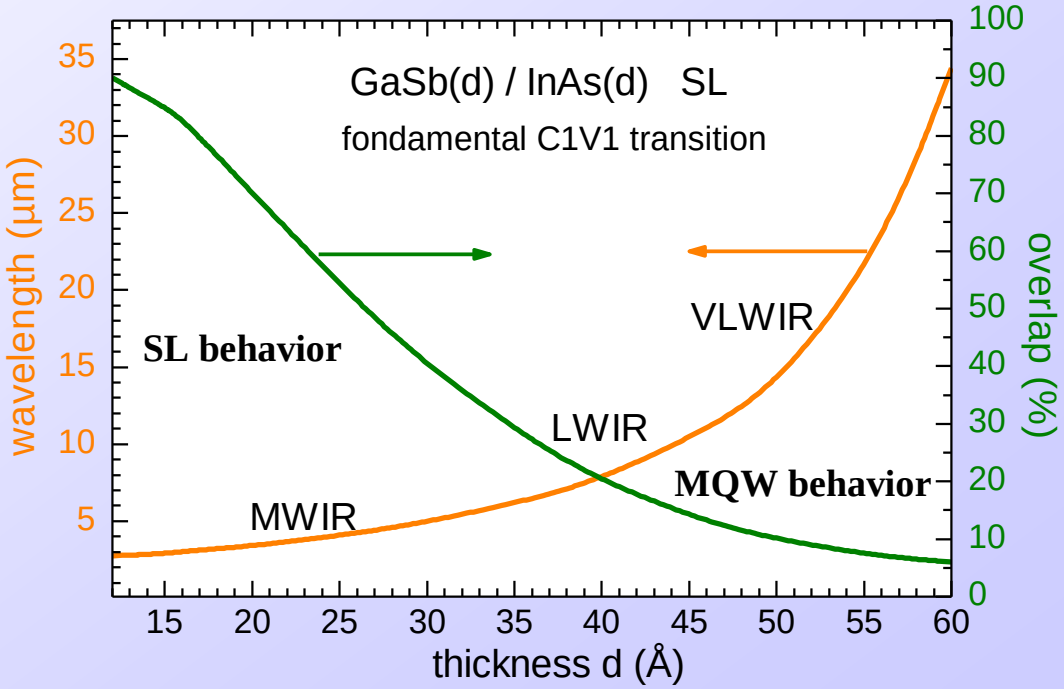
Confinement de trous (BV)

Coefficient d'absorption

$$\alpha(\omega) = \frac{e^2\pi}{n_{op} c m_0^2 \omega \varepsilon_0 V_{mat}} |d_{cv}|^2 D_{cv}(\omega)$$

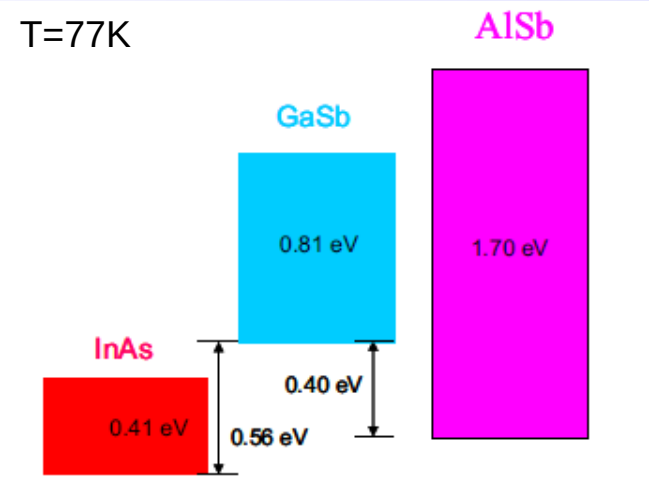
overlap $|\langle f_e | f_h \rangle|^2$.

SR symétrique



Overlap = 80-40% | Overlap $|\langle f_e | f_h \rangle|^2 \sim 0$

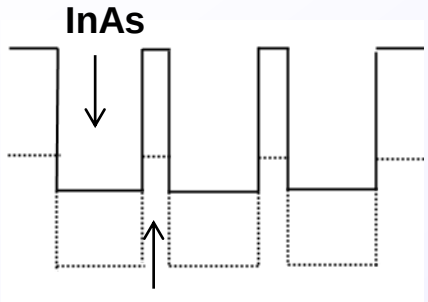
☞ **Maximiser l'absorption et les courants par ingénierie de la structure de bande**



La photodiode à SR pour les grandes longueurs d'ondes : LWIR et VLWIR

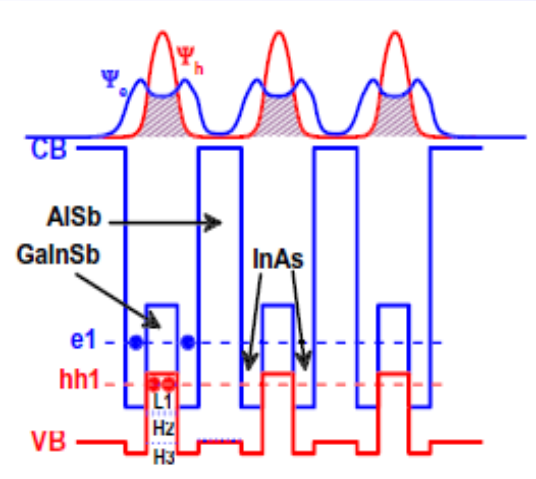
☞ New Designs

"Asymetric" structures

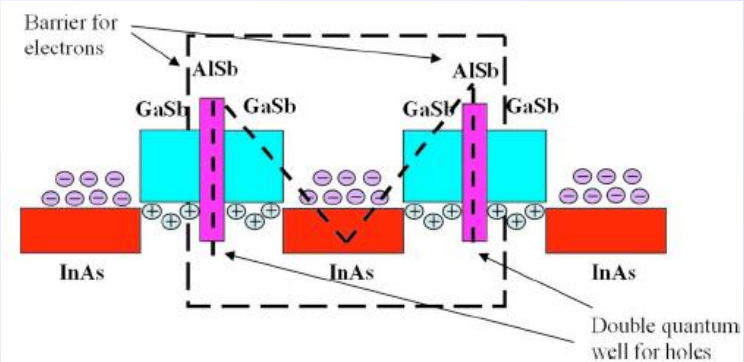


IAF : structure "InAs/GaInSb"
SPIE Vol. 5783 (2005)

"Overlap" structures

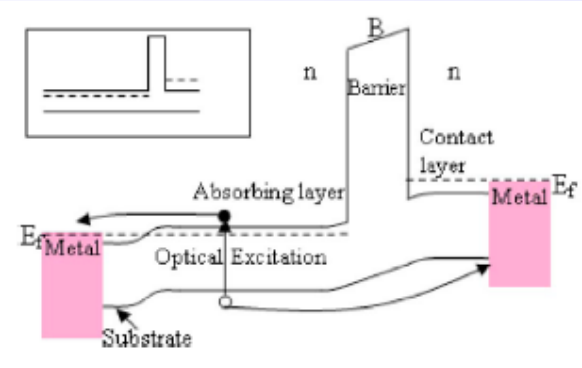


NRL : structure "W"
SPIE Vol. 5732 (2005)



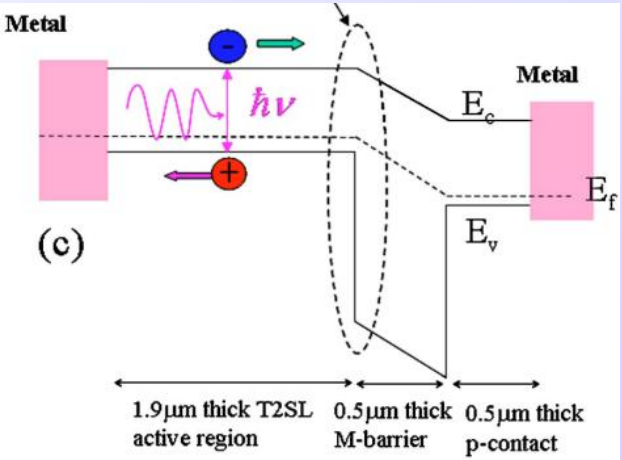
CQD : structure "M"
*APL **93**, 163502 (2008)*

"BIRD" structures

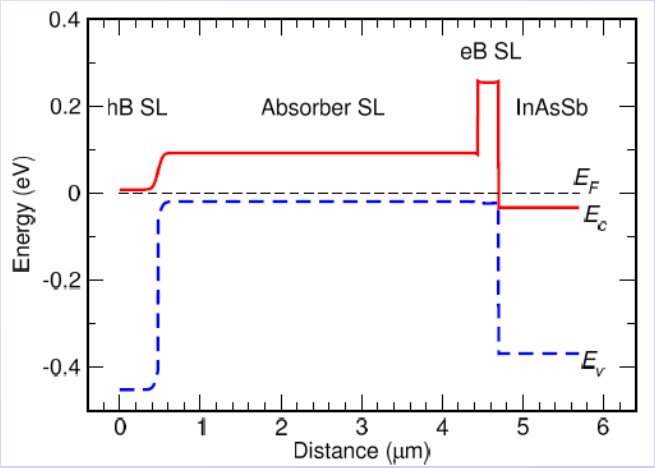


S. Maimon, G.W. Wicks :"nBn detector"
*APL **89**, 151109 (2006),*
US patent 2007/0215900

CHTM : structure "nBn"
*IEEE JQE **46**, 959 (2010)*



CQD : structure "pBp"
*APL **95**, 183502 (2009)*



JPL : structure "pBn"
*APL **96**, 111102 (2010)*

La photodiode à SR LWIR : Imageur Mégapixel LWIR (1k x1k)

☞ Center for Quantum Device ("M" structure)

APPLIED PHYSICS LETTERS **97**, 193505 (2010)

High performance long wavelength infrared mega-pixel focal plane array based on type-II superlattices

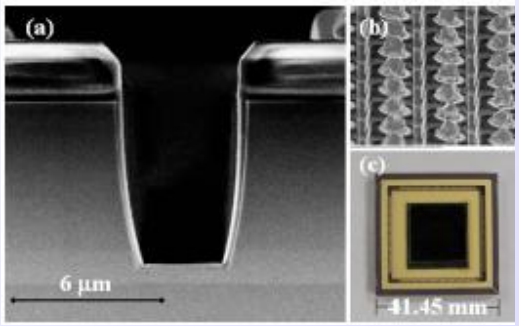
Paritosh Manurkar,[1] Shaban Ramezani-Darvish,[1] Binh-Minh Nguyen,[1] Manijeh Razeghi,[1,a)] and John Hubbs[2]

[1]*Department of Electrical Engineering and Computer Science, Center for Quantum Devices, Northwestern University, Evanston, Illinois, 60208, USA*

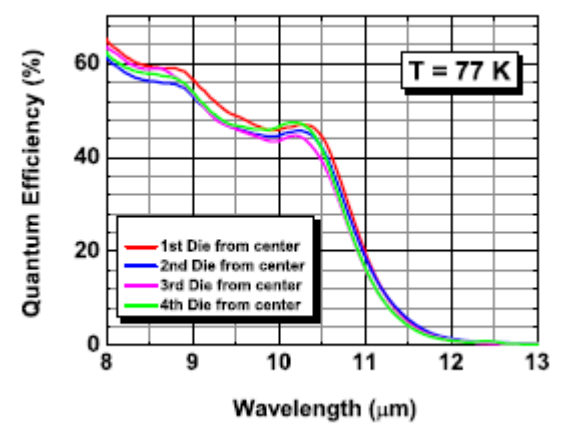
[2]*U.S. Air Force Research Laboratory/RVSS, Kirtland Air Force Base, New Mexico 87117, USA*

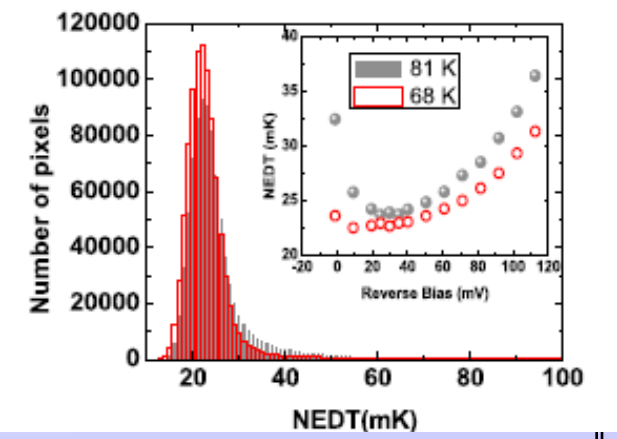
(Received 22 September 2010; accepted 20 October 2010; published online 8 November 2010)

A large format 1k × 1k focal plane array (FPA) is realized using type-II superlattice photodiodes for long wavelength infrared detection. Material growth on a 3 in. GaSb substrate exhibits a 50% cutoff wavelength of 11 μm across the entire wafer. The FPA shows excellent imaging. Noise equivalent temperature differences of 23.6 mK at 81 K and 22.5 mK at 68 K are achieved with an integration time of 0.13 ms, a 300 K background and f/4 optics. We report a dark current density of 3.3×10^{-4} A cm^{-2} and differential resistance-area product at zero bias R_0A of 166 Ω cm^2 at 81 K, and 5.1×10^{-5} A cm^{-2} and 1286 Ω cm^2, respectively, at 68 K. The quantum efficiency obtained is 78%. © *2010 American Institute of Physics*. [doi:10.1063/1.3514244]



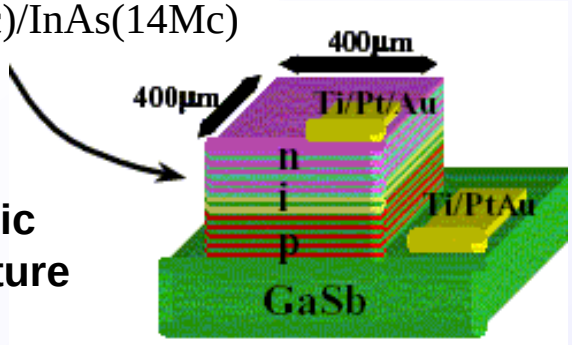
1024 x 1024 array (18µm pitch)





La photodiode à SR VLWIR :

GaSb(5Mc)/InAs(14Mc)



Asymetric pin structure

CQD+NRL+AFRL

Hood et al. APL **87** (2005)

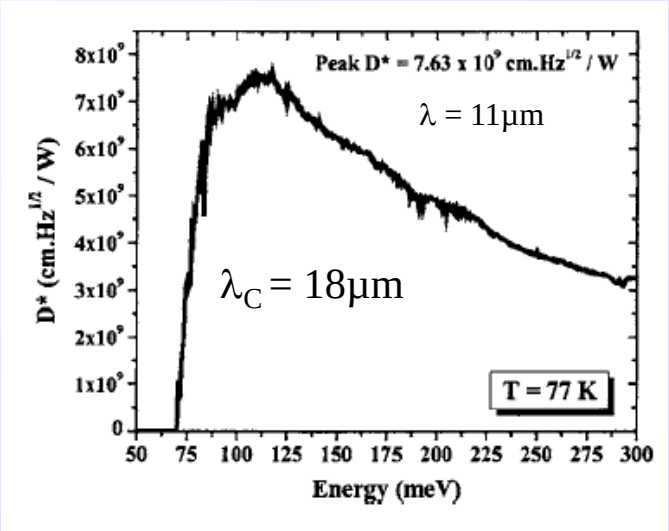
Diode passivée S_iO_2

R_0A =0.04 Ω.cm²

η=30% à 77K

D* 7.6 10^9 Jones

(*D*BLIP ~ 5 10^{10} Jones pour λ> 15µm*)



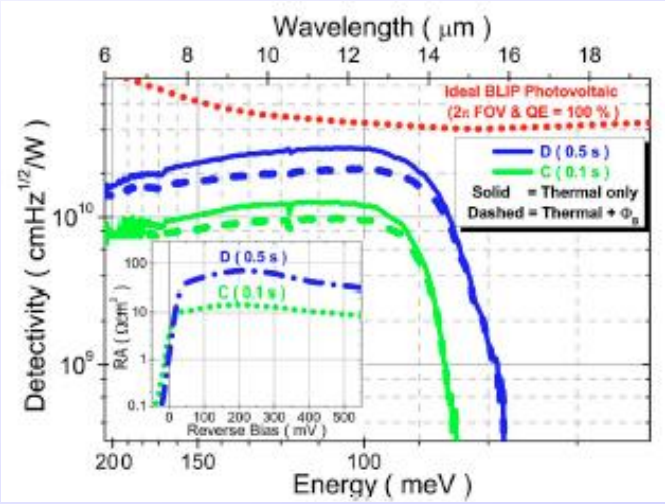
☞ CQD

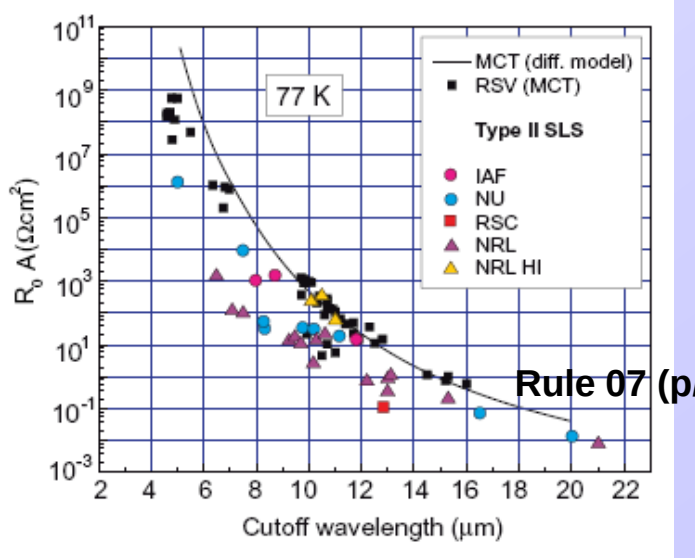
structure "M"

*APL **93**, 031107 (2008)*

R_0A =3.5 Ω.cm²

λ_C = 14µm (77K)





Rule 07 (p/n)

➔ Photodiode SR VLWIR …

Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

Pour la filière à SR ?

Ce qui est fait

- MWIR haute performance
- HOT detector
- Bispectral MWIR/MWIR FPA
- Mégapixel MWIR
- Megapixel LWIR

Ce qui doit être fait

- LWIR haute performance
- VLWIR
- Bispectral MWIR/LWIR FPA
- GaSb 4"
- Connaissance matériau
(durée de vie, dopage, mobilité, noise, Techno)

Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

Pour la filière à SR ?

Ce qui est fait

- MWIR haute performance
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- Mégapixel MWIR
- Megapixel LWIR

Ce qui doit être fait

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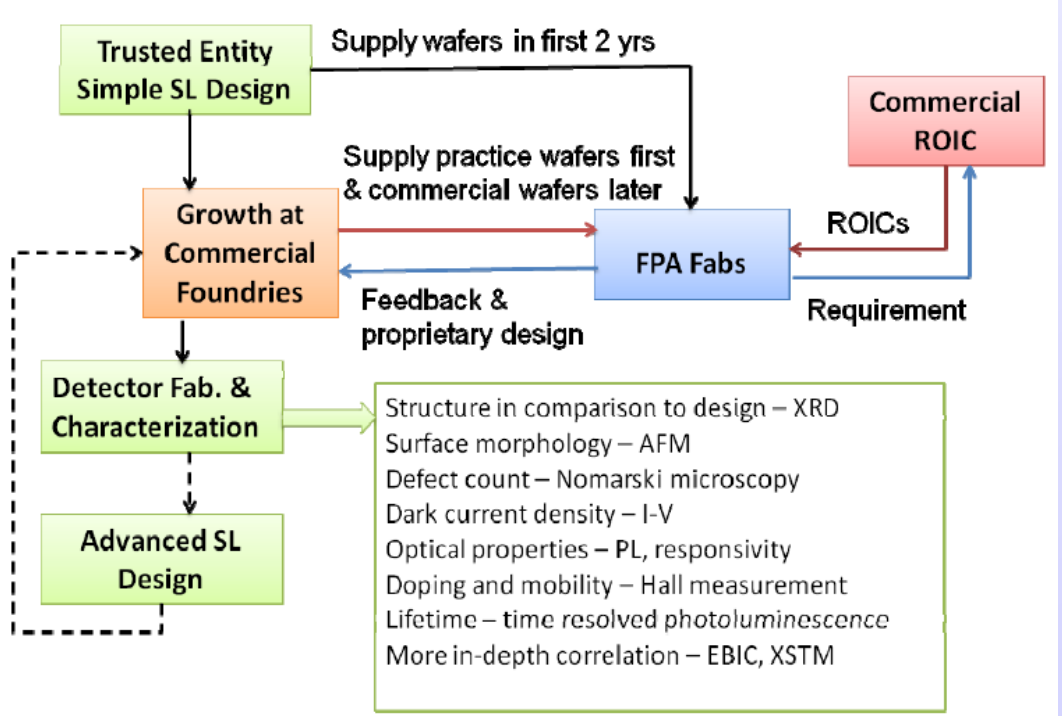


Figure 3: FastFPA program execution model.

SPIE DSS Orlando April 2010

FastFPA program (4 ans)
"Fabrication of superlattice infrared FPA"

☞ stratégie de développement (US government)

Developing High Performance III-V Superlattice IRFPAs for Defense : Challenges and Solutions

- Institute for Defense Analyses
- US Army Night Vision Dpt
- Cobham Analytic Solution (Defense Pentagon)
- Space Dynamics Laboratory

La photodiode à SR : Nouvelles fonctionnalités ??

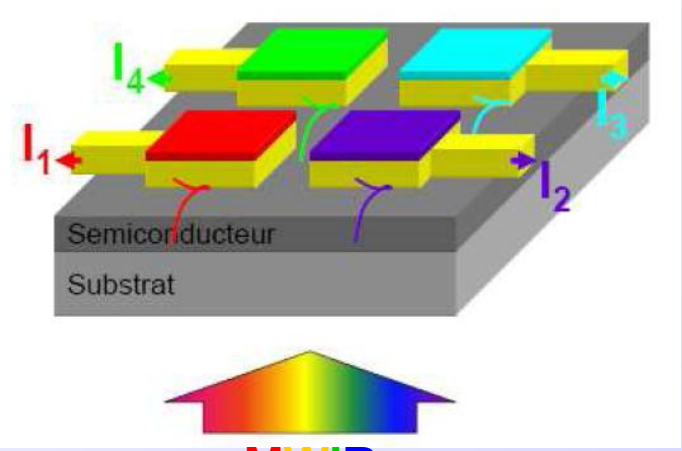
☞ **Le SR et les plasmons de surface (microstructures ou réseaux métalliques)**

- Effet antenne : confinement électromagnétique spatial

  ➔ Augmentation de l'absorption ou T° fonctionnement

- Sélection spectrale : confinement électromagnétique spectral

  ➔ Réalisation d'un détecteur IR quadrichromique



Super-pixel quadrispectral

➔ **ANR INTREPID (1er Déc 2010)**
"INTégration de REsonateurs pour la Photodétection Infrarouge quaDrichromique"

LETI – IES – LPN – ONERA - SOFRADIR

☞ Démonstration sur matrice MWIR MCT (pitch 30µm)

☞ Démonstration sur mini-matrice MWIR à SR

Conclusion : Les filières de photodétecteurs pour les prochaines applications de l'imagerie infrarouge

Prochaines applications

⇓

Perfs = I_{obs}, R_0A, D*, NETD, FPA, $T°_{fonc}$, multi/hyper, gde λ, n^{elle} fonctions (pola, ampl …)

Filières établies	Filières émergentes
MCT, QWIP	QDIP, SR

Filières complémentaires pour applications spécifiques

☞ **Des progrès à faire : $T°_{fonct}$, multicolor, λ >15µm, fonctionnalités, intégration …**

Bibliographie

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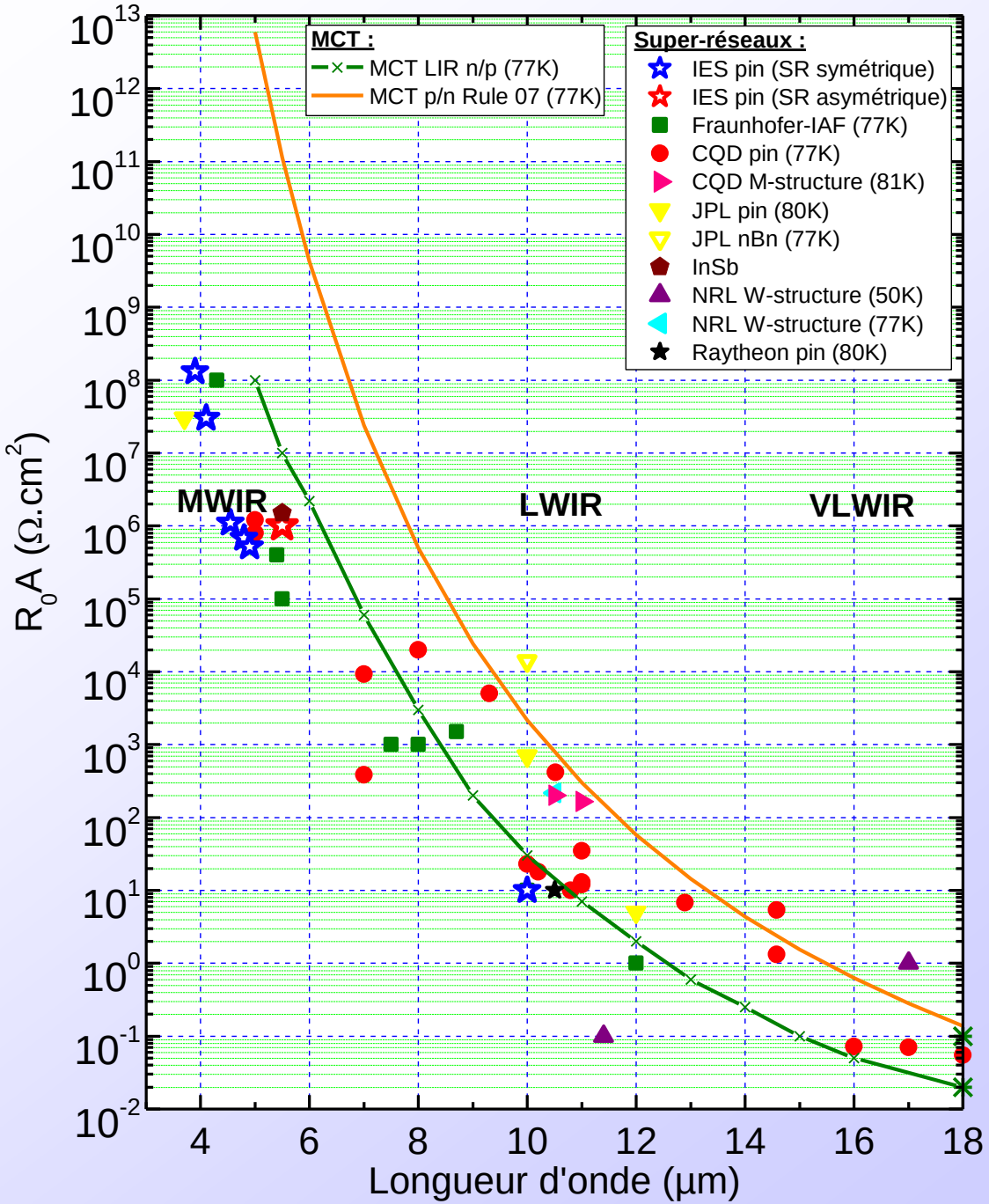
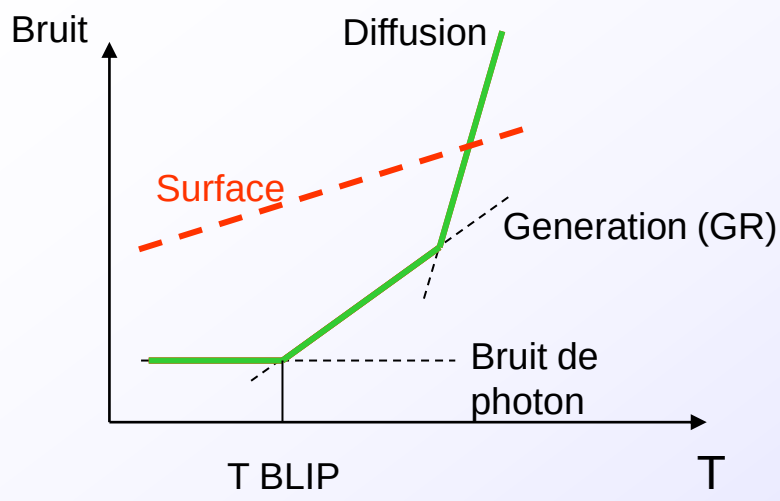
- **M.Z. Tidrow** "Type-II strained layer superlattice : a potential future IR solution" Infr. Phys. Technol. **52**, 322 (2009)
- **L. Zheng & M. Tidrow** "Analyses of infrared focal plane array figure of merit and its impact on sensor system trades" Infr. Phys. Technol.**52**, 408 (2009)
- **A. Rogalski** "Third-generation infrared photodetector arrays" J. Appl. Phys. **105**, 091101 (2009)


MCT :
MCT LIR n/p (77K)
MCT p/n Rule 07 (77K)
Super-réseaux :
IES pin (SR symétrique)
IES pin (SR asymétrique)
Fraunhofer-IAF (77K)
CQD pin (77K)
CQD M-structure (81K)
JPL pin (80K)
JPL nBn (77K)
InSb
NRL W-structure (50K)
NRL W-structure (77K)
Raytheon pin (80K)
MWIR
LWIR
VLWIR
R_0A ($\Omega.cm^2$)
Longueur d'onde (µm)

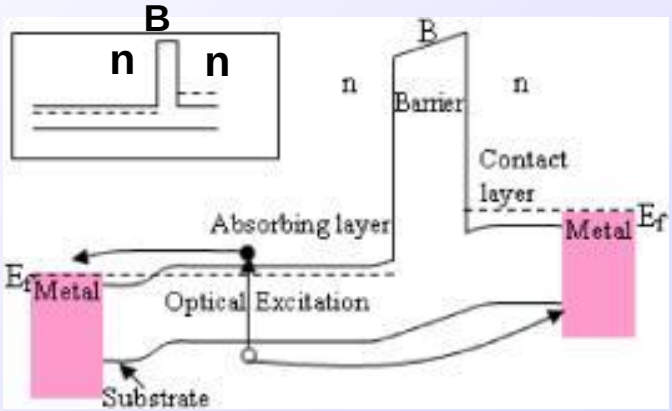
La photodiode à SR MWIR (autres résultats)

Analyse des courants



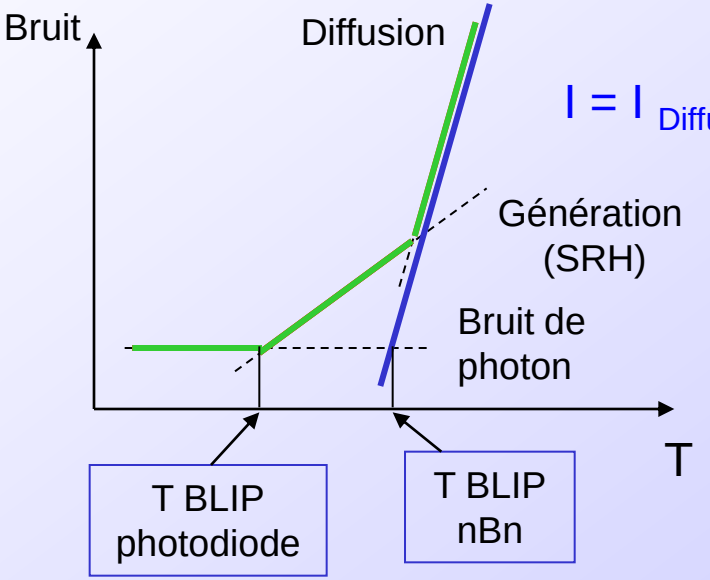
$I_{Tot} = I_{Diffusion} + I_{GR} + I_{Surface} + \ldots$

☞ **Améliorer les perfs** : nouveau design : **Structure nBn**



S. Maimon and G.W. Wicks, APL **89** (2006)

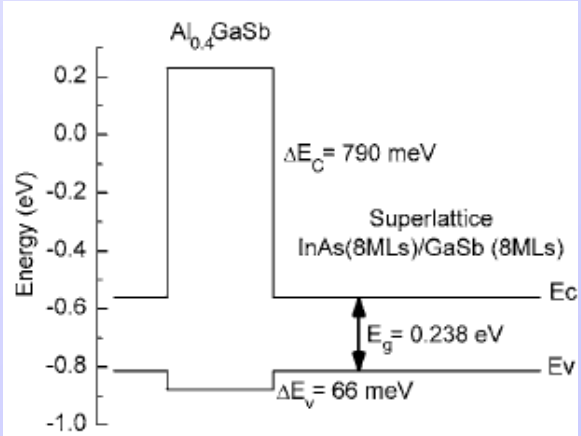
- Pas de zone de charge d'espace
- Pas de surfaces latérales



$I = I_{Diffusion} + \cancel{I_{GR}} + \cancel{I_{Surface}} + \ldots$

$\Downarrow$

$T_{Fonc} \uparrow$



CHTM : J.B. Rodriguez et al, APL **91** (2007)