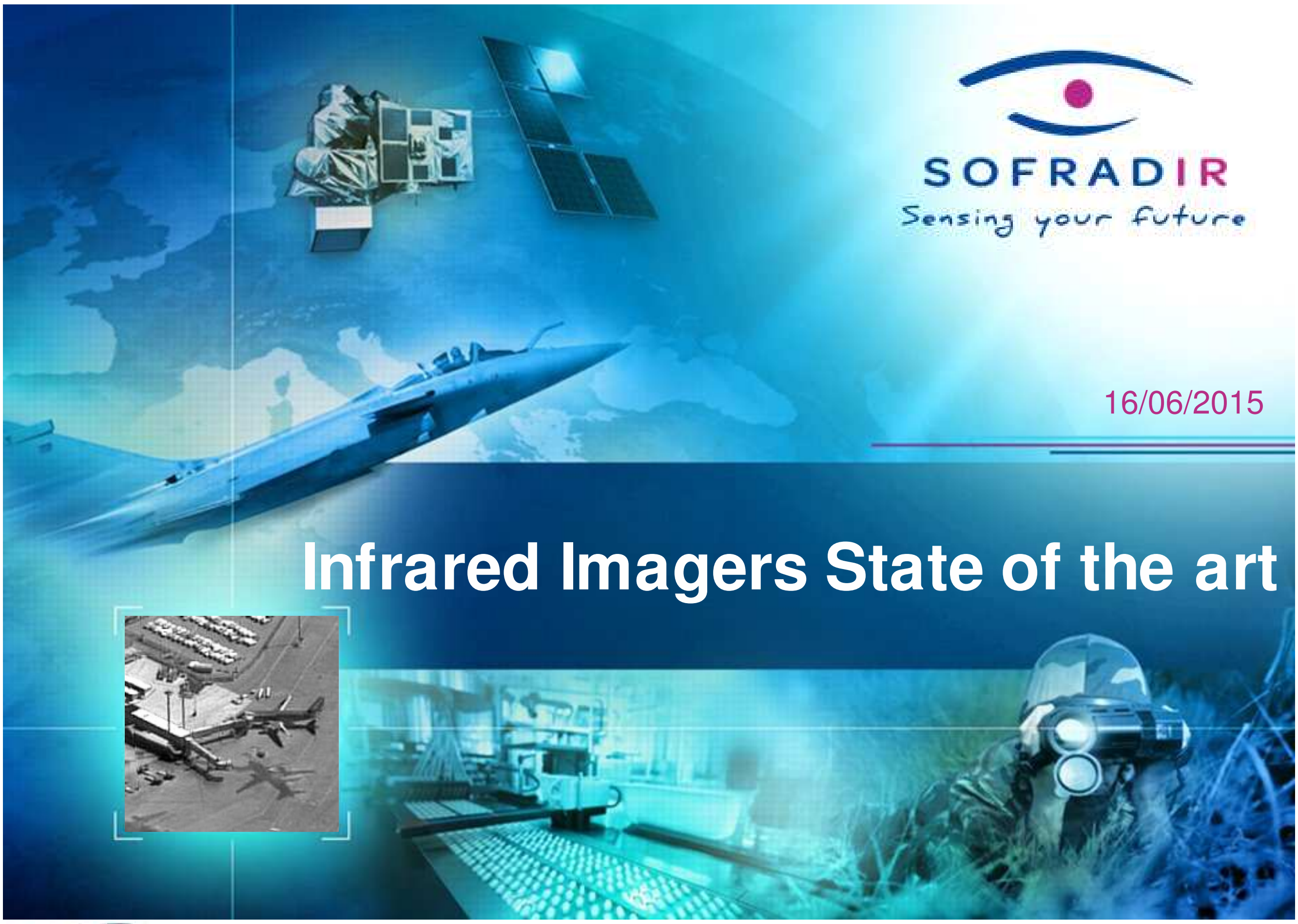
16/06/2015

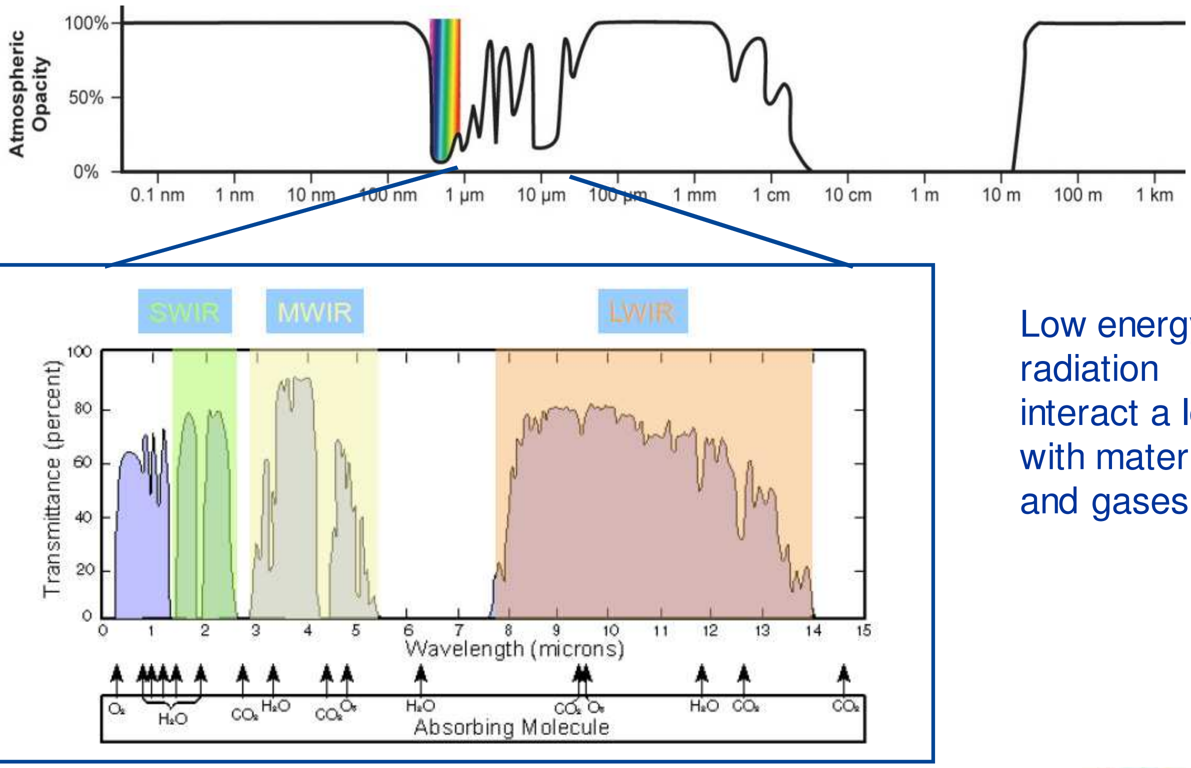
Infrared Imagers State of the art



IISW 2015. Eric Mazaleyrat. June 10th 2015

Groupe SOFRADIR

Infrared spectrum



Low energy radiation interact a lot with mater and gases

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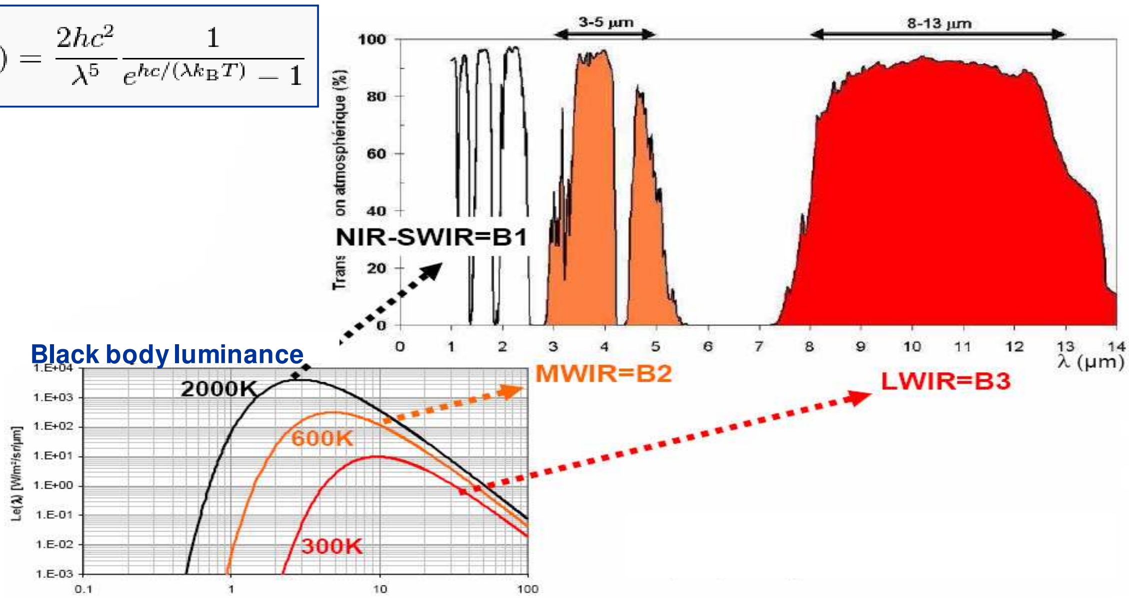
Planck law and black body

- Every physical body continuously emits electromagnetic radiation.
- Near thermodynamic equilibrium, the emitted radiation is described by Planck's law:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_B T)} - 1}$$



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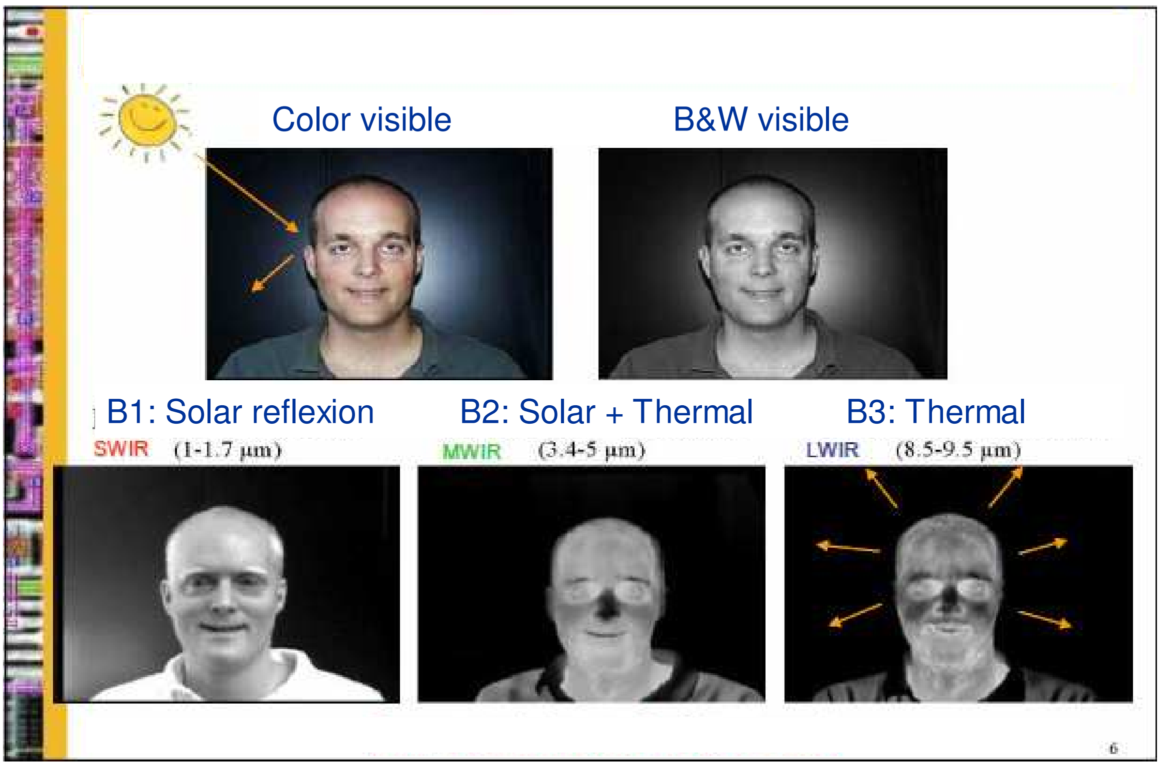
Examples of images



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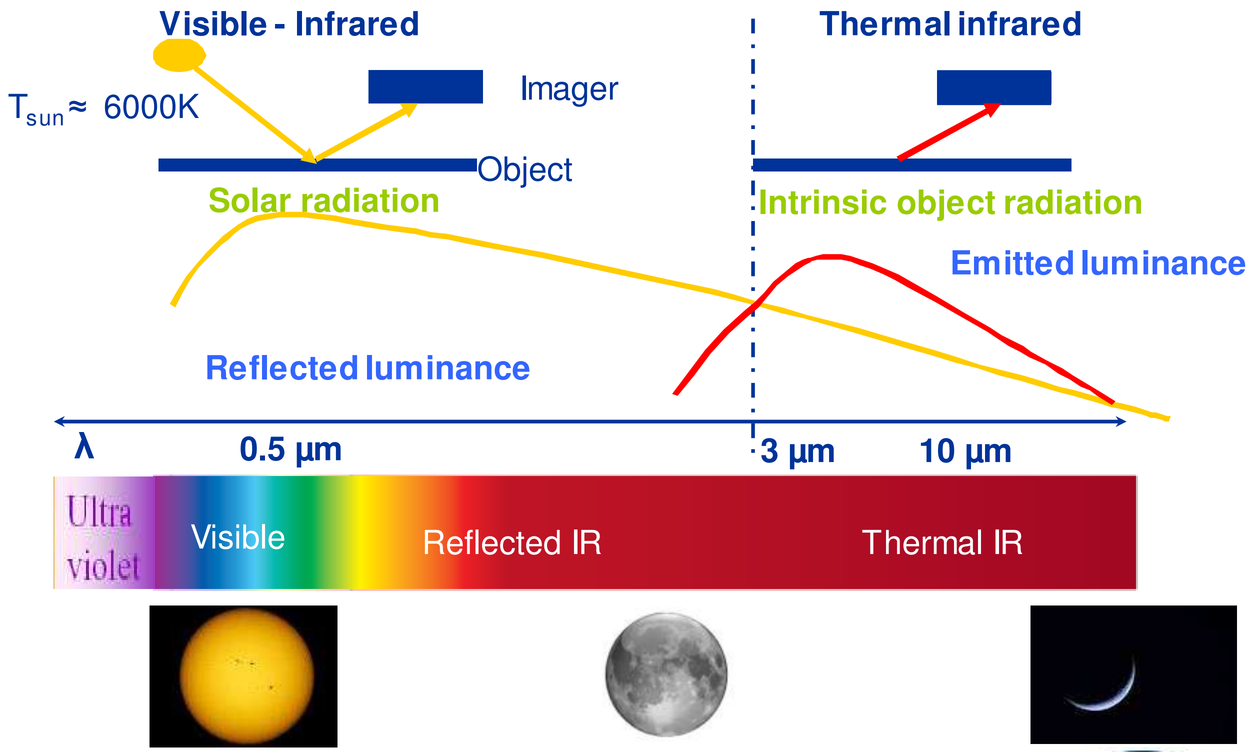
Infrared light nature

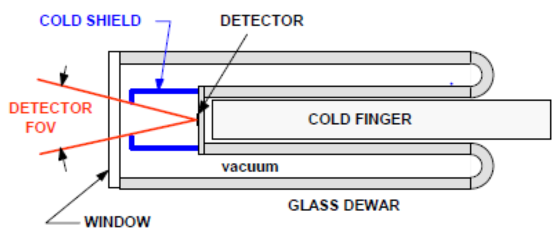


Some InfraRed specific concepts

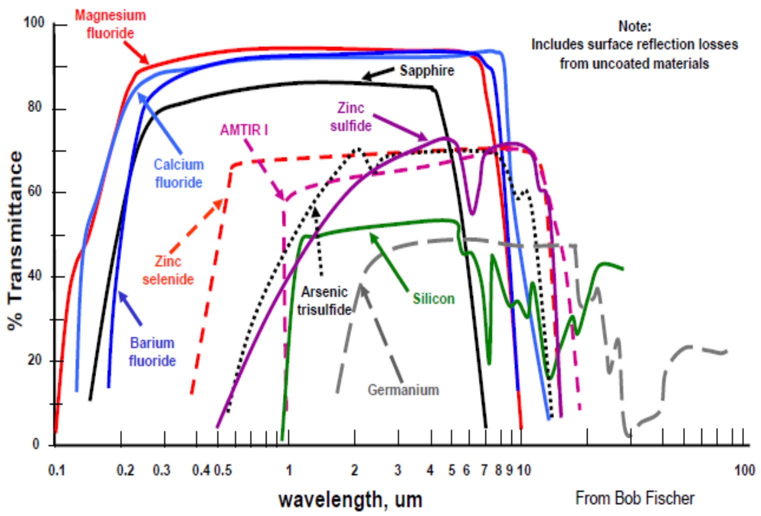
- **Noise Equivalent Temperature Difference**
  - ~ Smallest measurable temperature difference

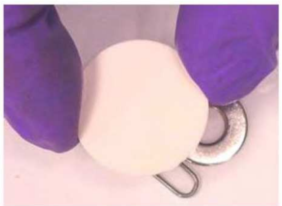
$$\textbf{NETD (T)} = \frac{\textbf{RMS noise (V)}}{\textbf{Responsitivity (V/K)}}$$

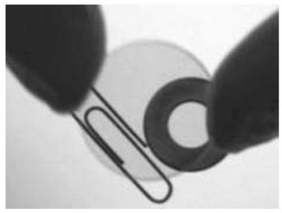
- **Image Sensor are sealed under vacuum into a dewar.**
  - To minimize the thermal exchanges with the outside world
  - To avoid frosting up of the sensor.



Optics for Infrared







Typical IR optics material

- *ZnS*
- *ZnSe*
- *Si*
- *Ge*
- *GASIR (Chalcogenides glass)*
- *…*

Overview of Cooled IR photodetectors

Why infrared Imaging?

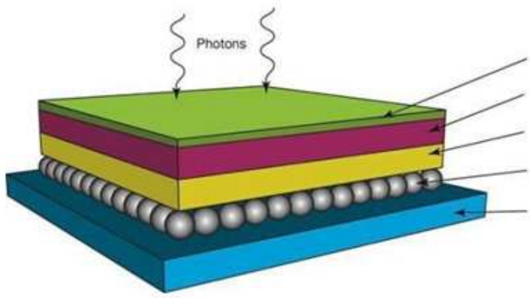
Visible vs SWIR

Visible vs MWIR

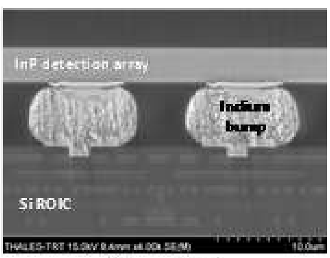
MWIR vs LWIR

Anatomy of a cooled IR detector

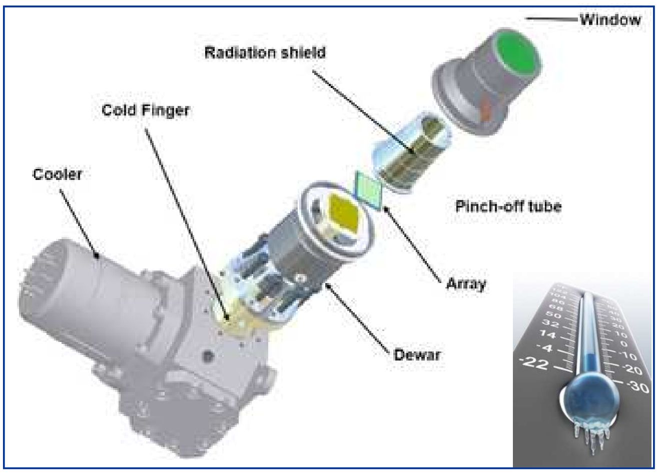
- Integrated Detector Dewar Cooler Assembly (IDDCA)



Anti-reflective Coating
Thinned initial substrate
Sensitive material (pixels)
Bumps, flip-chip
ROIC. CMOS device



15µm pixel pitch

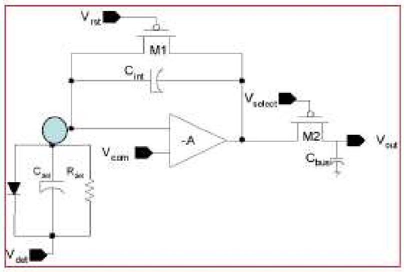


Why cooling an IR photodetector?

- For photodiodes detectors, photons to detect have an energy comparable to thermal energy in the material at room temp.
- → To obtain a good image you need:
  - I IR scene >> I dark
  - I IR scene >> I parasitic flux

Typical temperatures are between 70 K et 200 K depending the bandwith

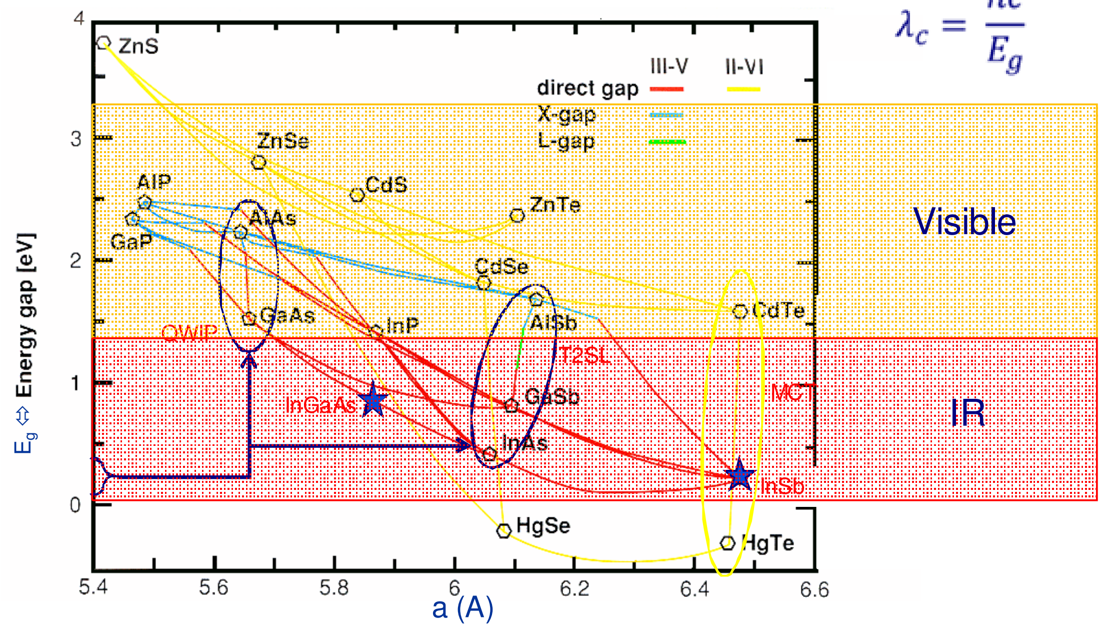
CMOS ROIC



- **Some important needs:**
  - Radiometry requires >14bit converters.
  - Applications requires snapshot (~global shutter).
- **Main functions of ROIC:**
  - Polarisation of the detector and current integration
  - Multiplex each signal to output.
  - Adaptation for outside data processing.
- **Four main architectures (depending on flux conduction and Cint):**
  - DI: Direct Injection
  - BDI: Buffered Direct injection
  - SFD: Source Follower per Detector
  - CTIA: Capacitive TransImpedance Amplifier.
- **Design specificity: must work at cryogenic temperature**
- **Compared to visible imagers today's situation:**
  - CMOS technology: 0.18µm (15µm pitch), 0.13µm (10µm pitch), 90nm (5µm)
  - Progressive switch to digital output (on board DC converter)
  - Internal CDS being considered…

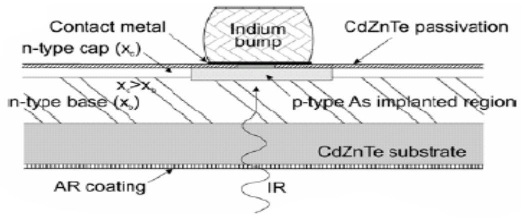
Energy Gap vs lattice

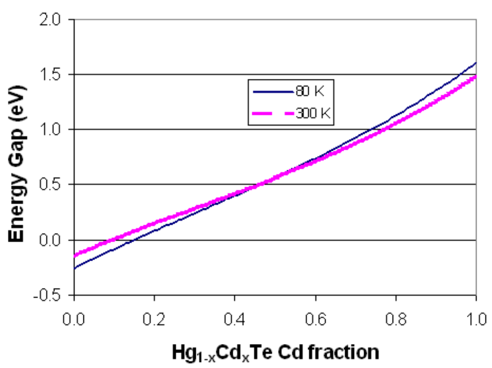
II-VI: HgCdTe, CdZnTe
III-V: InSb, InGaAs, InAsSb



$$\lambda_c = \frac{hc}{E_g}$$

The magic of MCT (HgCdTe) II-VI





By controling the respective fraction of Hg and Cd,
→ fine tune the energy gap

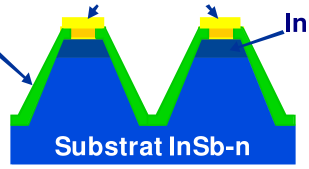
- **MCT pros:**
  - QE ~ 60-70%
  - Moderated Idark.
  - Temp FPA~ 110-150K
  - Tunable Spectrum
  - Fine pitch 10µm then 5µm.

- **MCT Cons:**
  - Image stability (blinking pixels).
  - Substrates size.

InSb IR detectors

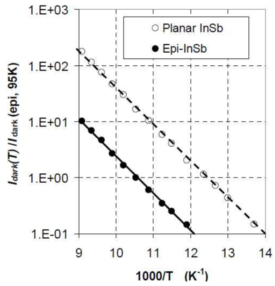
> Pros

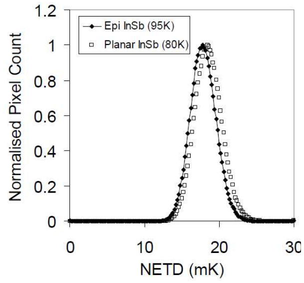
* Cost/wafer size
* Material stability
* 10µm pitch demonstrated



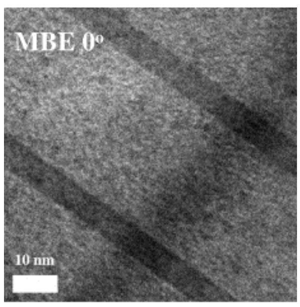
> Cons

* Limited cutoff frequency (4.2µm)
* Difficult to passivate
* J_{dark}~ 10^{-6}A.cm^{-2} @ 77K

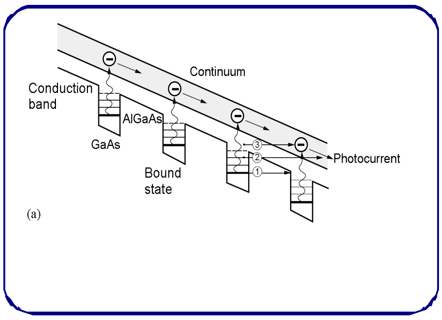




Quantum Well Infrared Photodetector

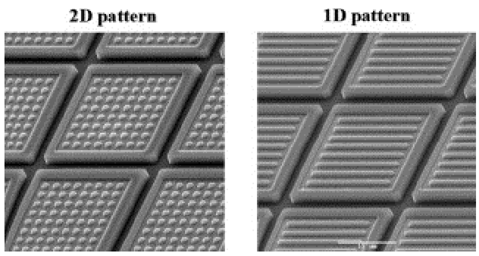


MBE or MOVPE epitaxy



Exemples :

- A : GaAs, InGaAs
- B : AlGaAs, InAlAs



Requires diffraction pattern

QWIP Pros

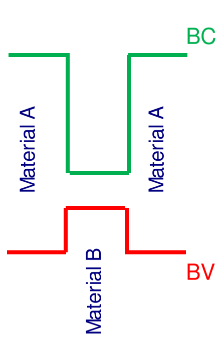
Image stability (NUC, opérability, BPR)
III-V substrate. (GaAs 4 then 6'')
Spectral selectivity

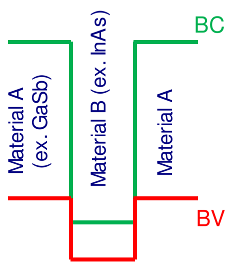
QWIP Cons:

QE below 10%
High Idark → Temp FPA 65-70K

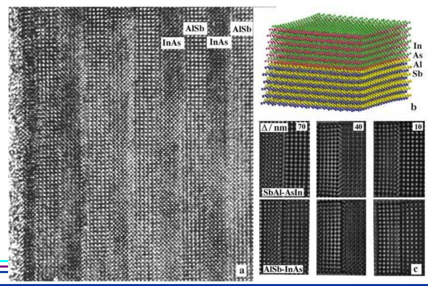
Other type of structure

Type II Super Lattice (LWIR)

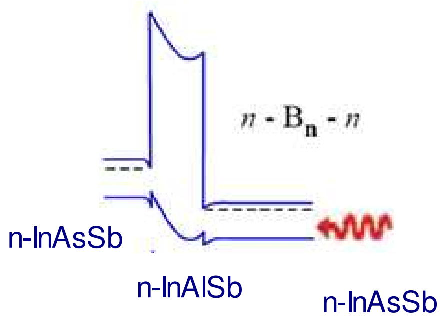




Substrate GaSb (alternative GaAs)



XBn (MWIR)

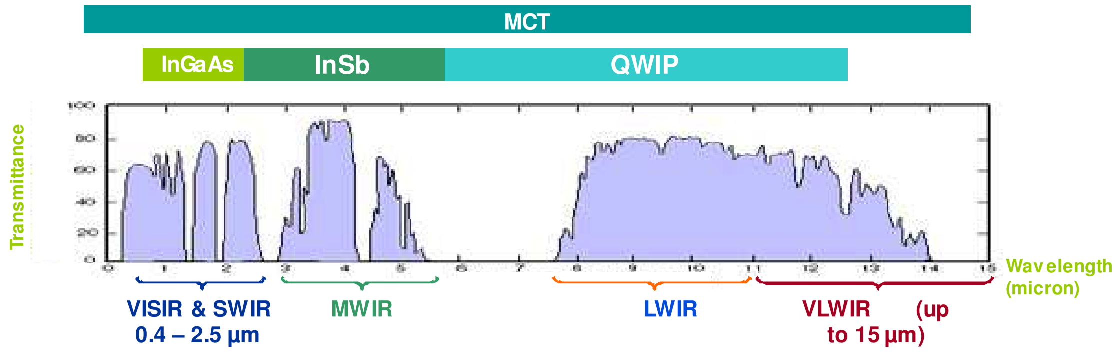


Substrate GaSb

$InAs_{0.91}Sb_{0.09}$ λc = 4,2 µm

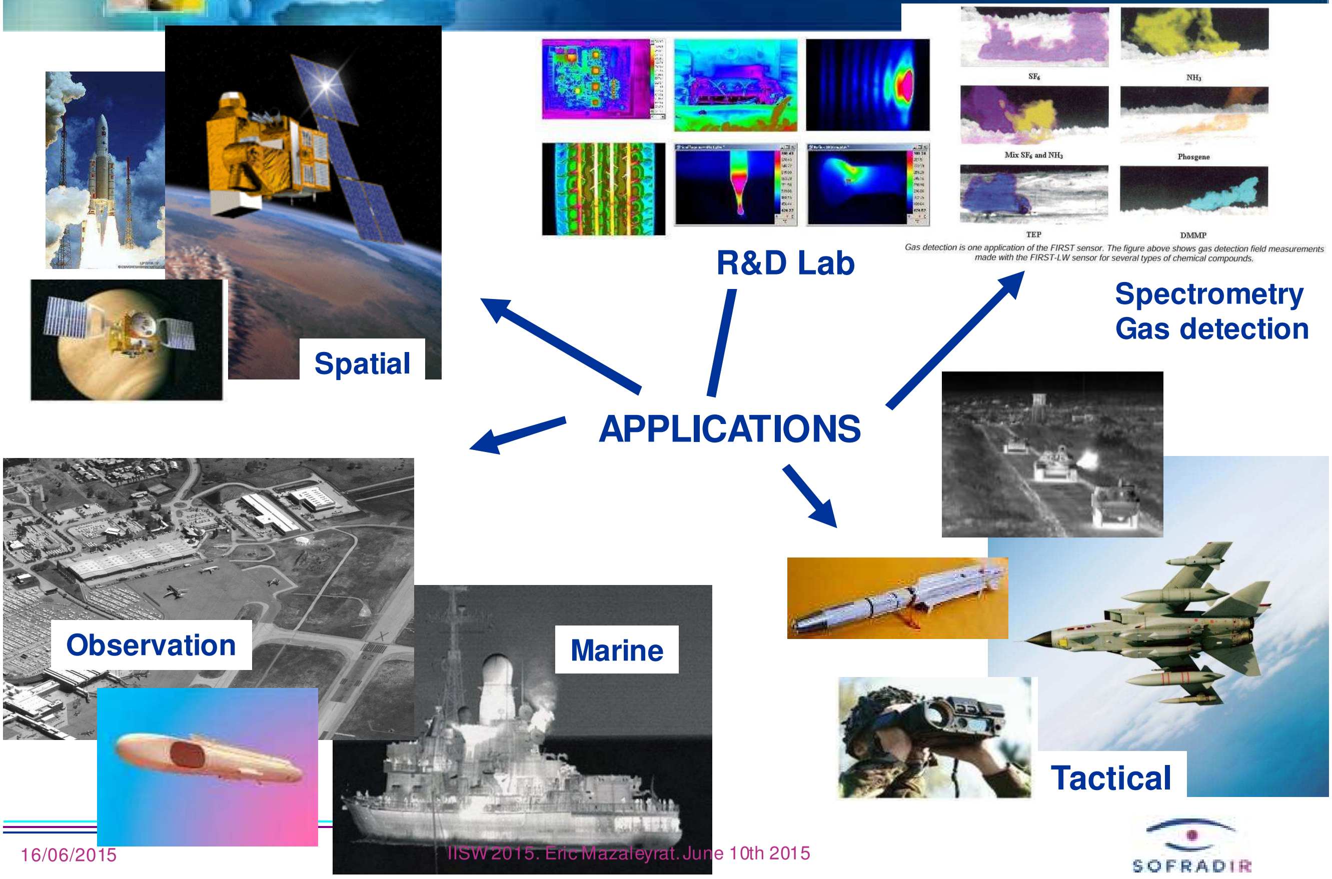
640 X 512@15µm
Works at 150K
λc = 4,2 µm
NETD < 30mK

Tradeoffs technology-applications



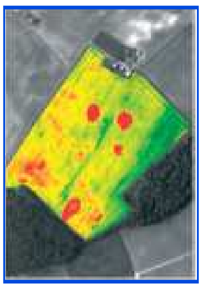
	MCT	InSb	InGaAs	QWIP
FPA temp (typ)	110K	77K	TEC regulated	<77K
FPA temp (under dev)	150-180K	150K(XbN)	TEC less	<77K
Image stability				
Large format				
Small pixel pitch				

Overview of cooled IR applications



Commercial applications

- A broader range of applications to enhance the safety of transportations and to secure sensitive sites (nuclear and electric plants, jails…)
- Demand for higher level of surveillance.

Spectrometry and hyperspectral imaging

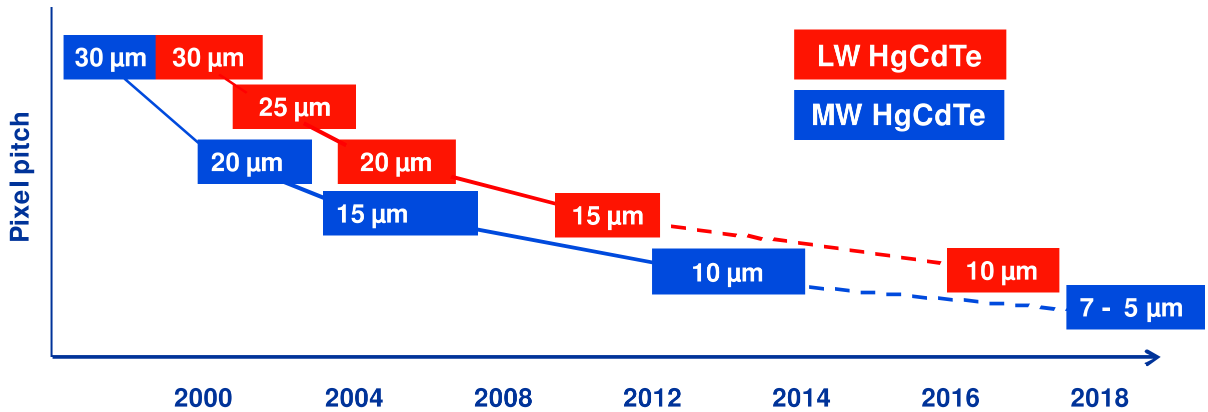
Coastal surveillance



Homeland security and border surveillance

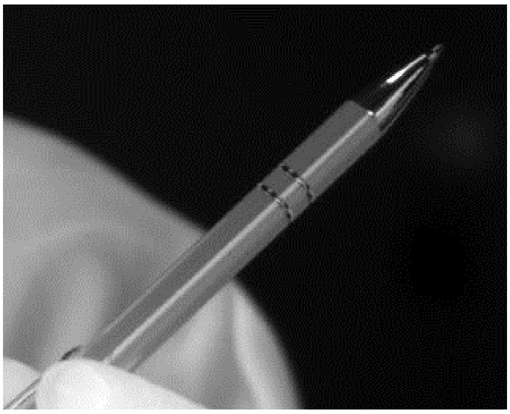
Competitive landscape

Coolde IR detectors: Pixel Pitch reduction:

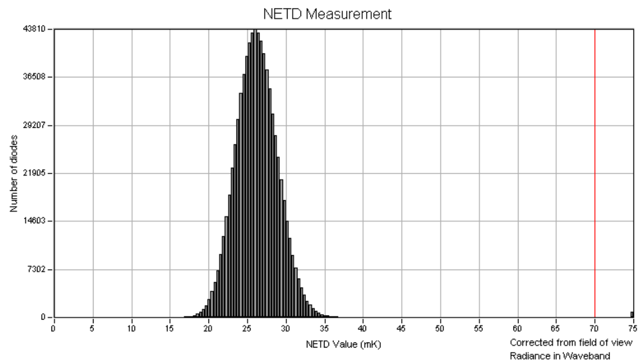


- **Pixel pitch: a key parameter for the system**
  - Decrease FPA size for more system compactness
  - Increase FPA resolution for more performance

SOFRADIR 1280x720 MCT 10µm @110K



- Nice Gaussian NETD
- Mean NETD 26.3 mK (f/2)
- 99.9% operability



Type / Name of the component :	CH278B/175956
Black body temperature :	20.00 °C
Mean value corrected 80 % :	2.63E+01
Standard deviation corrected 80 % :	2.71E+00 (10.33%)
Number of diodes > +/- 100 % :	994 (0.13%)
Number of diodes > 70 , < 0 :	805 (0.10%)

DAPHNIS-HD
1280×720 16:9 image format

SELEX: SuperHawk MCT 1280x720 8µm @ 110K

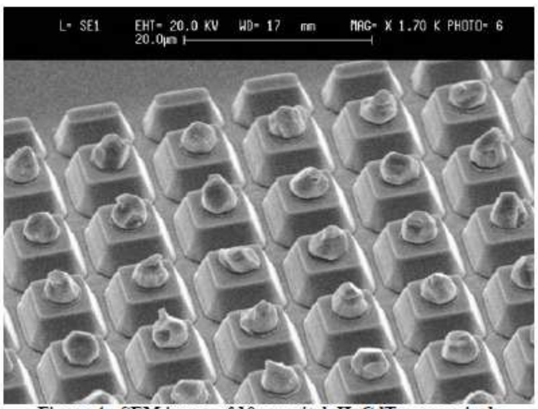
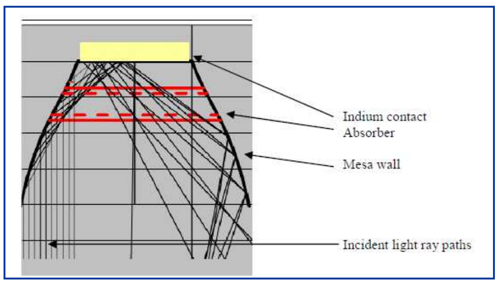


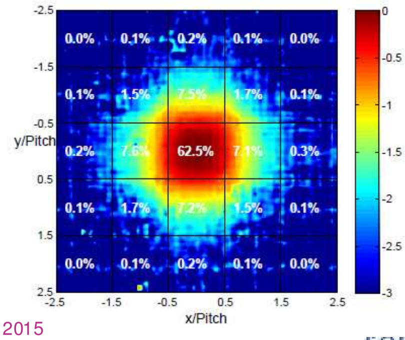
Figure 4 - SEM image of 10 µm pitch HgCdTe mesa pixels



SCD: 1280x1024, 15µm pitch @ 150K

- 1280x1024, 15µm pitch

	Hercules InSb	Hercules XBN
Cooler	K548	K508N
Temp FPA	77K	150K
Power	15W	5.5W
MTTF	>5000h	20000h
Cooldown time	8min	10min



DRS: 1280x 720 LWIR 5 µm pitch MCT

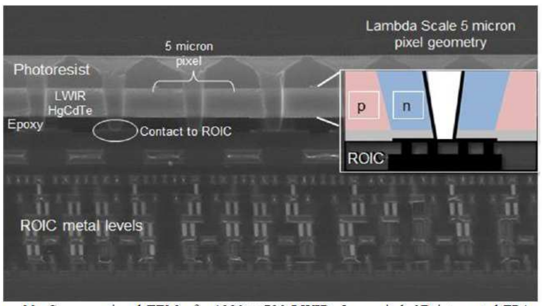


Figure 20: Cross-sectional TEM of a 1280 × 720 LWIR, 5 µm pitch 3D integrated FPA using HDVIP technology with specific components labeled with white lettering. The inset is an illustration depicting the HDVIP pixel geometry used for the FPA.

DRS Technologies
A Finmeccanica Company

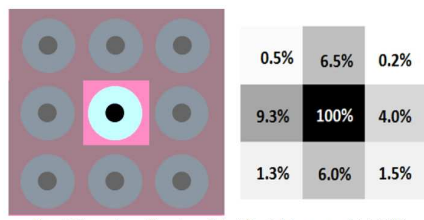


Figure 7 Diagram of cross-talk aperture on diodes (left) and relative response of pixels (right).

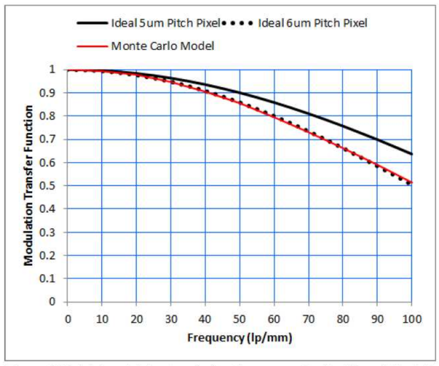


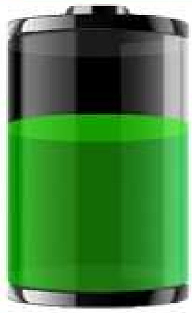
Figure 6 Modeled modulation transfer function compared to ideal 5µm pitch pixel.

Towards “HOT” detectors

- High Operating Temperature (> 120K)
- Allows smaller cooler, less power consumption
- Evolution toward SWaP: Size, Weight, And Power

WEIGHT REDUCTION

AUTONOMY INCREASE

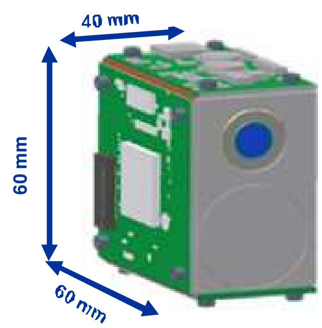


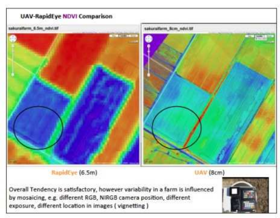
COST REDUCTION

RELIABLILITY IMPROVEMENT

HOT/SWAP (140K) GALATEA 640x512 MW

- HOT VGA for portable Low Power MWIR systems



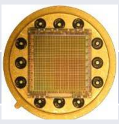


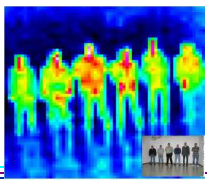
- Mean NETD < 23 mK
- Pixel pitch 15 µm x 15 µm
- Detector spectral response 3.4 µm – 4.2 µm
- Cooler regulated input power < 2 WDC @20°C
- Weight < 280 g (0.61 lb) IDCA

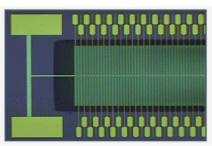
Uncooled IR Thermal Imagers overview

Main uncooled IR technologies

	ThermoPile	Pyroelectric	µbolometer
Principle	Seebeck: V = q.dT	DT ->DQ	Thermistance: DT -> DR
Max Array	64 x 62	510 pixels	1024x1024
Min Pixel size	220µm	10µm x 768µm	12µm
Time constant	40ms	500ms	7-12ms
Pro	Simple and robust	Low sensitivity to ambiant temp	MEMS like technology
Cons	Requires cold reference	Requires chopper (128Hz)	Requires TEC (TEC-less solution available)
Material	Metal/ semiconductor	LiTaO3, DLaTGS, PZT	Vox, a-Si
IR Spectrum	Broad spectrum	Broad spectrum	LWIR
NETD	0.1K	< 1K	60mK (f/1)







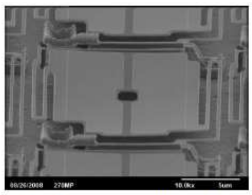
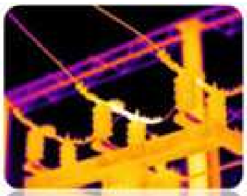


Fig. 1. 17µm high fill factor α-Si/α-SiGe pixel design.

Uncooled IR applications

Civilian

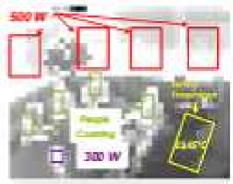


Thermography
Predictive maintenance
Building inspection
Gas detection

Medical
Health checks
Veterinary

Firefighting
Safety & Rescue

Transportation
Automotive / AEB
EVS / Taxi
Engine monitoring



Smart buildings
Building automation
People counting
Distinguishing

Applications needs:

- ✓ Cost Reduction
- ✓ Better Sensitivity
- ✓ Easy to use detectors (full digital, calibrated,…)
- ✓ Low power consumption

Uncooled IR application

Surveillance/defense

Surveillance
Border control
Security
Maritime
Law Enforcement

Ground vehicles
RWS / RCWS
LSA
DVE

Soldiers
TWS
Clip-on
Goggle

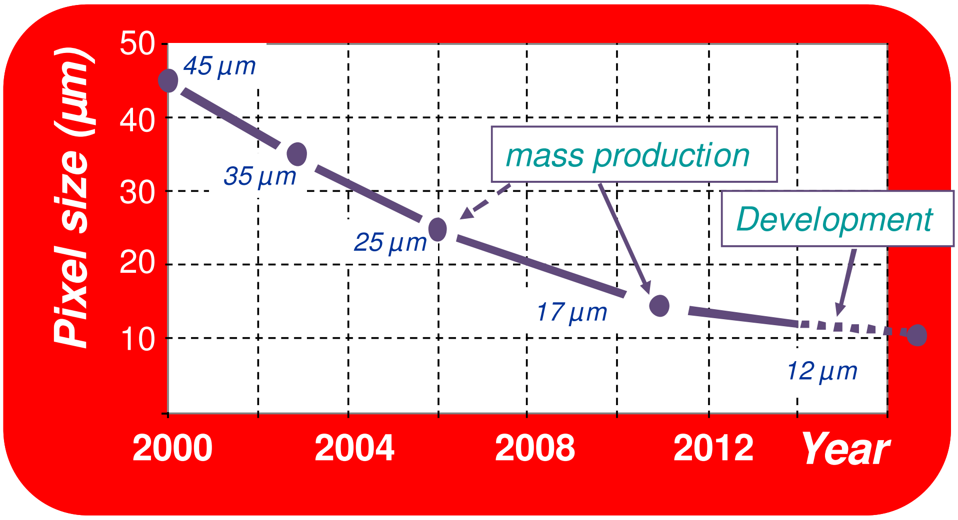
Soldiers
UAV
UGS

Applications needs :

- ✓ Higher resolution for range improvement
- ✓ Better Sensivity for range, Optics Size and Weight
- ✓ SWaP products for portable equipments

Microbolometer technology

Pixel pitch reduction



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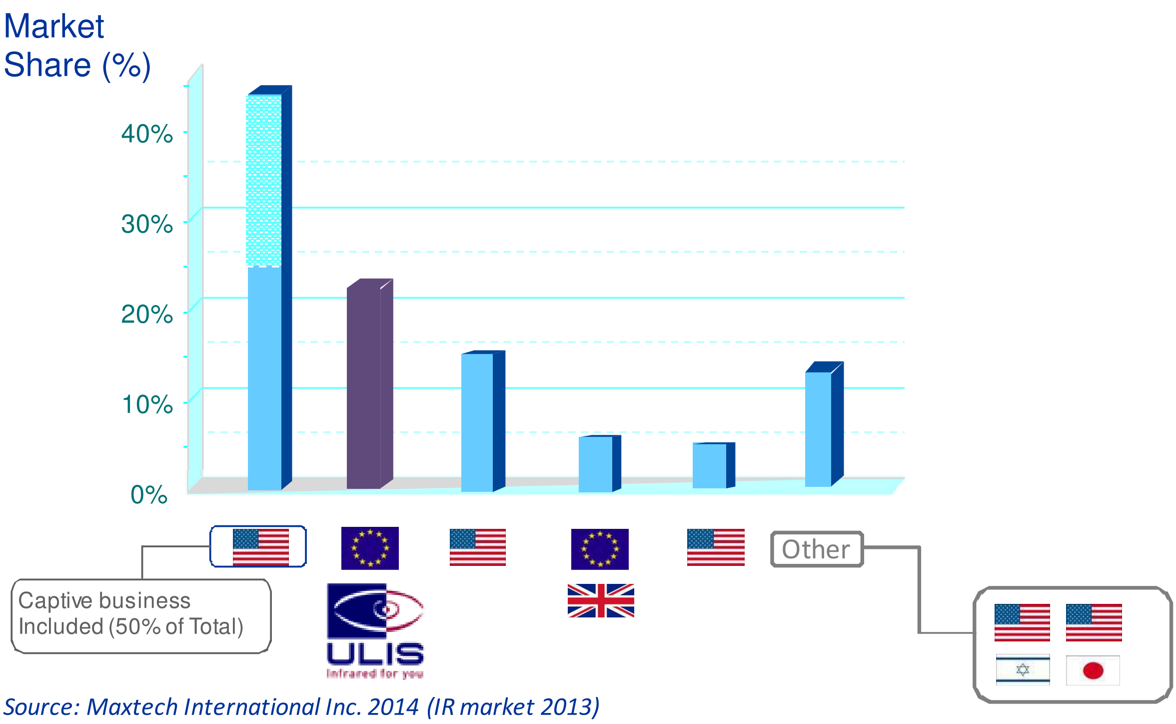
Uncooled IR Detector manufacturers



Source: Maxtech International Inc. 2014 (IR market 2013)

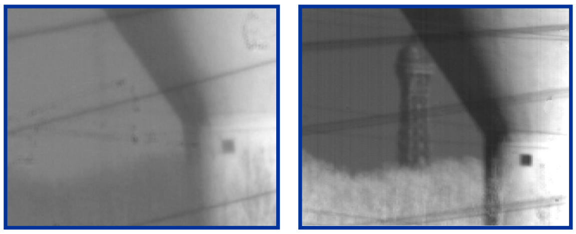
SOFRADIR

Some thermal IR IMAGES

Particular case of SWIR/InGaAs

SWIR detection advantages

- **Vision through haze and mist**
  => Increased detection range
  - Weak atmospheric absorption
  - Better albedo contrasts (vs. Visible)

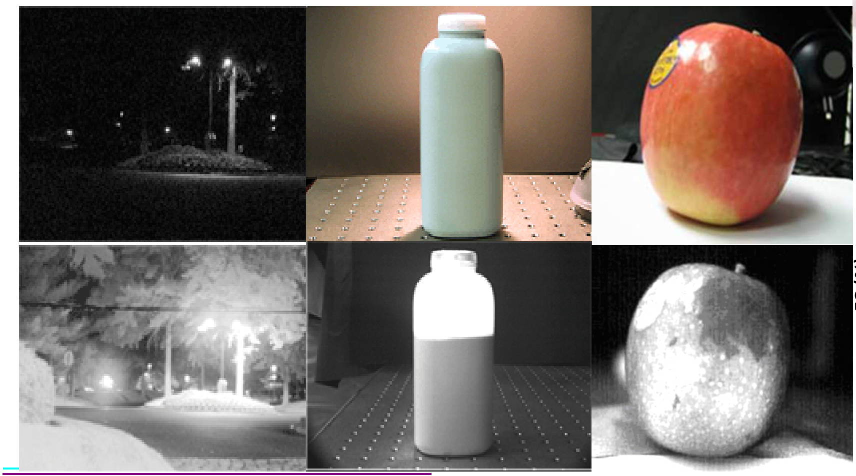


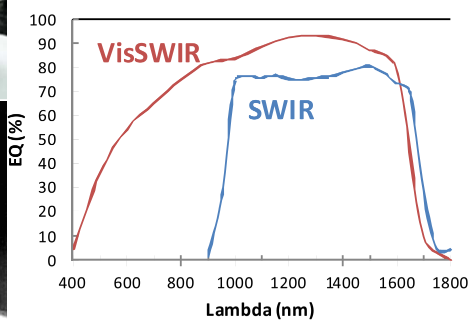
- **Images are « visible-like »**
  - Easy interpretation,
  - Better identification than thermal imaging

- **Camouflage pattern detection**
  - Optimized contrasts vs. visible

SOFRADIR SWIR 640x512 @ 15µm

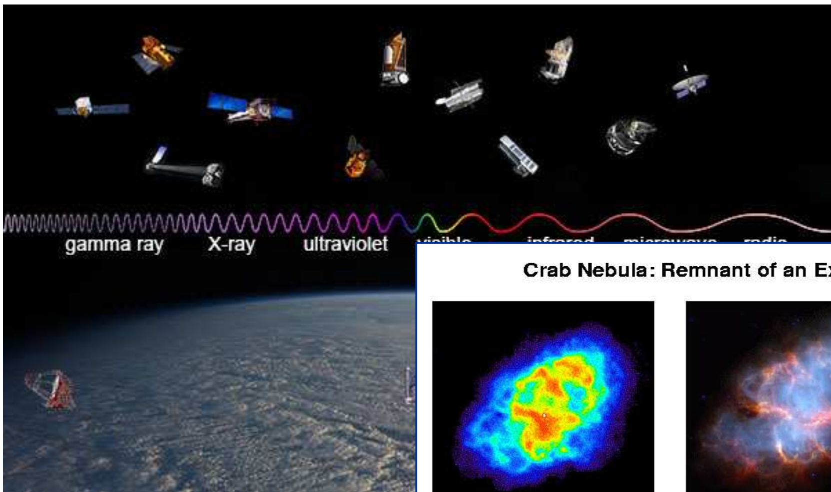
Array format	640x512
Pixel size	15µm
Dark current	≤ 0.15pA @ -0.2V
Response Non-Uniformity (%)	≤ 10%
Noise	< 30 e- (high gain)
Max Frame rate	300 FPS – 8 outputs
Video Output rate	18 MPixels/s
Operating Temperature	-20°C to +70°C

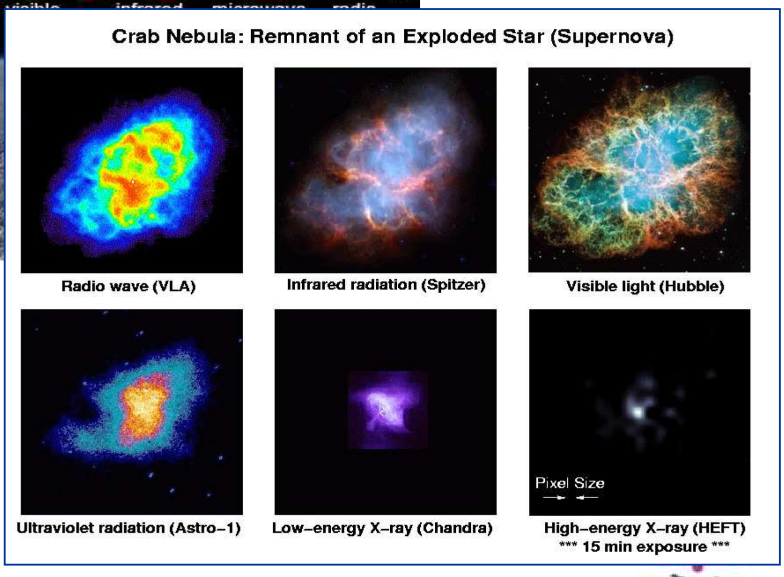




SPACE applications

Space imagery



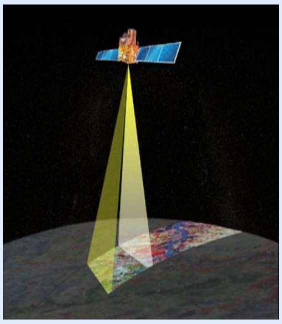


Space Applications

Military applications

- Surveillance
- Mission preparation
- Early Warning System

Civilian applications



- Meteorology
- Agriculture surveillance
- Global warming studies

Deep space science, Astronomy

- Planet studies
- Asteroids studies
- Telescopes

Sofradir: the European leader

- 70 Flight Models already delivered over the past decade
- 20+ FMs planed for launch in 2015-2016

Onboard Ariane 5

2014 JAXA hyperspectral HAYABUSA-2 probe to study "1999 JU3" asteroid.

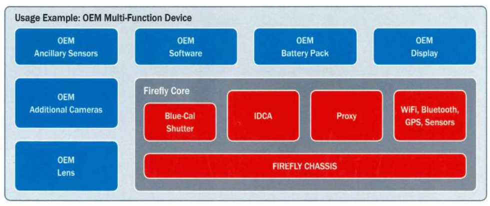
METEOSAT: 3rd Gen MTG FCI + IRS

Commonalities with visible Image sensors

Selex ES
A Finmeccanica Company

Cooled IR: SELEX FIREFLY: A game changer?

- Concept : single board camera engine GPIO, RS232, I2C, Native android device,
- Of the shelf Advanced CPU, GPU and DSP. All in one chip, GPS, Gyros, USB, Ethernet…
- Hardware + Linux kernel + additional libraries, applications…
- Ready for augmented reality…



Main features
- Medium waveband (3.7-5µm)
- 640 x 512 format
- 16µm x 16µm pixels
- Negligible pixel blur
- >160K operation
- Long life linear cooling engine
- 60 frames per second
- Software Extensible (including OpenCL)
- Native Android Device
- GPIO interfaces to control peripheral devices
- 3 camera channels with image fusion
- Bidirectional video streaming
- WiFi, Bluetooth, Gigabit Ethernet, GPS

Key benefits
- Compact
- Low power
- Fast time to image
- Instant image from standby
- Rapid system development
- Reduced through-life costs
- All-in-one core for multi-function devices
- Ideal augmented reality platform

TECHNICAL SPECIFICATION

IDCA	
Spectral bandwidth	3.7µm - 4.95µm
f-number	f/4
Cold stop	19mm above FPA
NETD	25mK (typical)
Operating temperature	>160K
Readout modes	IWR
Charge handling capacity	7Me-
Frame rate	60Hz
ADC resolution	14 bits
Cooler operating life	>25,000h
Camera core	
Operating System	Android
Free Camera channels	2
Video outputs	HDMI, DSI
Networking interfaces	WiFi, Bluetooth, USB 3.0, Gigabit Ethernet
Peripheral interfaces	I2C, SPI, RS232, UART, user defined
Video streaming codecs	H.264, JPEG, lossless All bidirectional, full screen or picture-in-picture display
Data storage	10GB internal + SD card interface
Integrated sensors	3-axis accelerometer and gyroscope, temperature, GPS
Man machine interface	Fully customisable by the system integrator
Power input	5V - 12V
Power consumption	5W steady state 1W instant image standby
Image processing	
Calibration	Integrated high-speed multi-point calibration
Automatic Gain and Offset (AGO)	Histogram based, user configurable
Enhancements	Edge enhancement, local contrast enhancement, tone mapping, electronic image stabilization
Colour palettes	User defined 24bit RGB
Iconography	Vector, bitmap, and text overlays with transparency Custom icons loaded from .png Scaling and rotation Network interface for displaying iconography
Distortion correction	Support for parametric correction of distortion in lens or display optics
Customisation	Proprietary processing algorithms can be provided by the system integrator

Uncooled IR: Towards Consumer applications

384 x 288 17µm pitch
Price ~3500$ January
Price ~1500$ December

80x60 17µm pitch
Price ~1000$ January
Price ~250$ December

206 x 156, 12µm pitch
Price ~250$

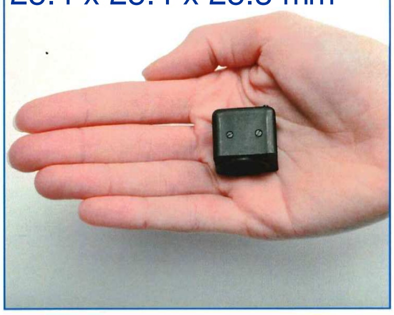
SWIR miniaturization: Nano-SWIR

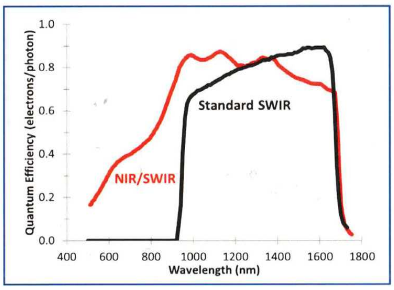
UTC Aerospace Systems

FEATURES

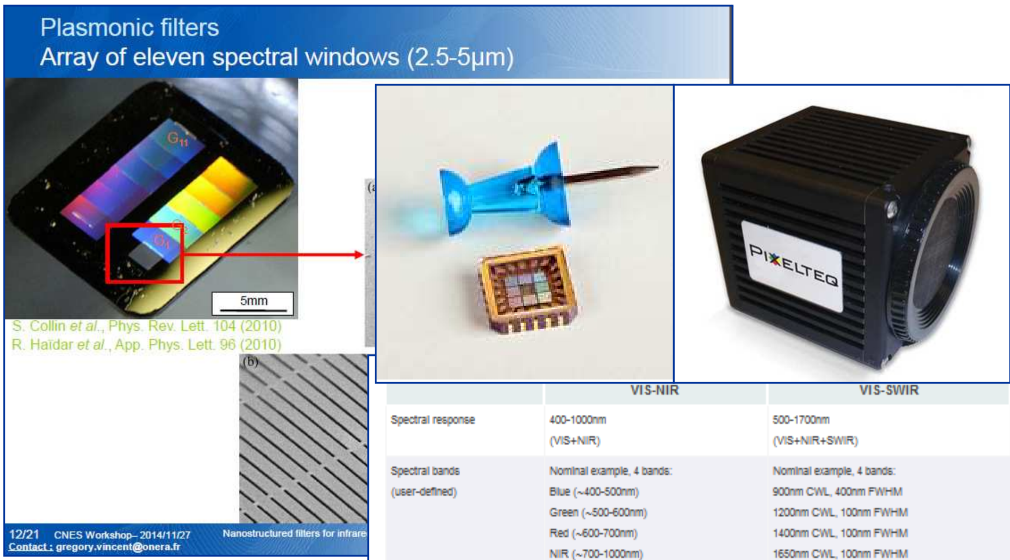
- 640 x 512 pixel format, 15 µm pitch, 30 Hz full frame rate
- 1.7 W power consumption
- High sensitivity 0.9 to 1.7 µm spectrum response imager; NIR/SWIR, from 0.7 to 1.7 µm
- Digital 12-bit base Camera Link® output
- Compact size less than 1 in^3
- On-board, real time non-uniformity corrections

25.4 x 25.4 x 25.3 mm





Spectral filtering at pixel level

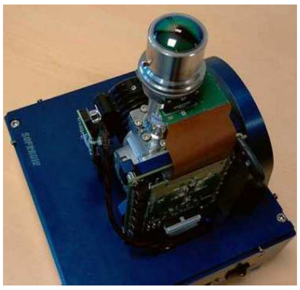


	VIS-NIR	VIS-SWIR
Spectral response	400-1000nm (VIS+NIR)	500-1700nm (VIS+NIR+SWIR)
Spectral bands (user-defined)	Nominal example, 4 bands: Blue (~400-500nm) Green (~500-600nm) Red (~600-700nm) NIR (~700-1000nm)	Nominal example, 4 bands: 900nm CWL, 400nm FWHM 1200nm CWL, 100nm FWHM 1400nm CWL, 100nm FWHM 1650nm CWL, 100nm FWHM
Sensor	Scientific CCD, silicon 512 x 512 px 24µm pixel pitch	Solid state InGaAs 640 x 512 px, 15µm pixel pitch
Active area	12.3mm H x 12.3mm V	9.6 x 7.68mm
Digital output	USB 2.0, 16 bit	CameraLink, 14 bit

Integrated optics

ONERA

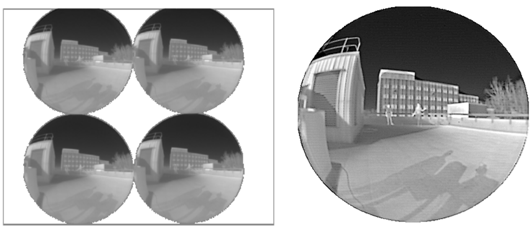
- **Example 1**

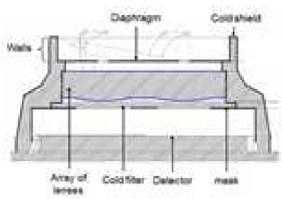


- Less constraints due to cold exit pupil.
- Less constraints due to optical height for wide FOV
- Athermalized optic

→ Allows more **compact system**.

- **Example 2: « Super-resolution » by combining shifted images.**





- **Other possibilities:**
  - Multi-hyperspectral,.. 3D applications.

Common trends with visible imagers

Easy to use and integrate in system

Lower power consumption

Better resolution

New features:
Color, Active Imaging, TOF, High Speed Imaging, HDR

Same drivers, similar solutions:

This will drive the use of advanced CMOS for Digital, dedicated ASIC, 3D stacking, Wafer Level packaging, Wafer level optics…

Thank you for your attention