Tutorial: IR photodiodes and arrays: 2-6 and 3-5's material systems

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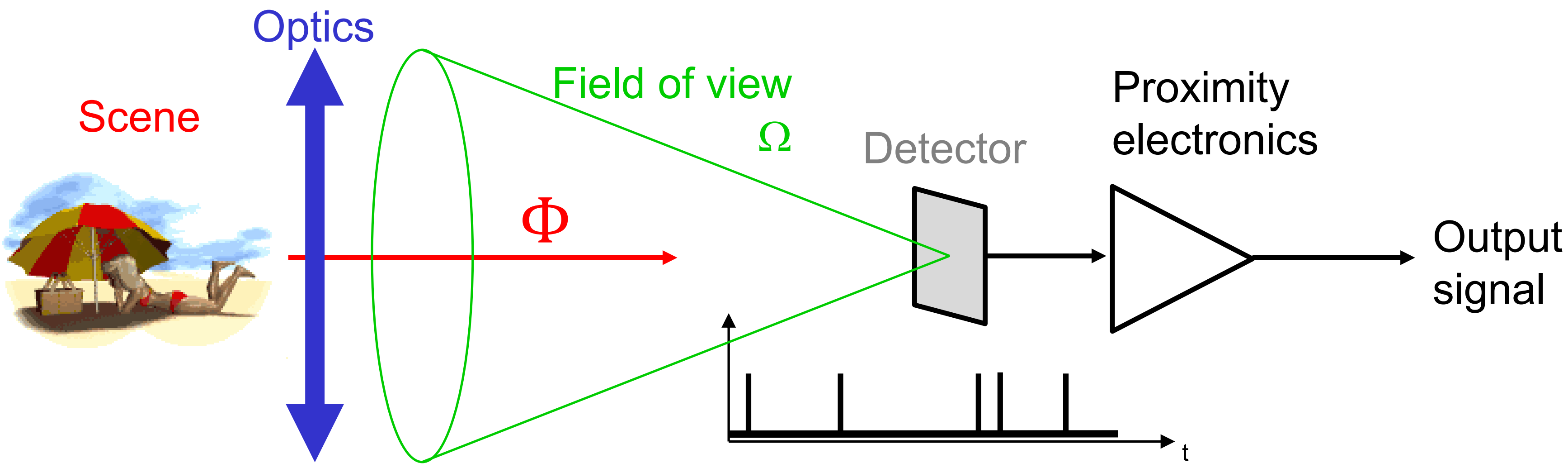
CNES Workshop 2023

Agenda

1. **Introduction**
2. **Material systems**
3. **Focus on MCT as the big player**
4. **Stability**
5. **Radiation hardnes**
6. **Focus on T2SL as the challenger**
7. **Conclusion**

Detection by integration...

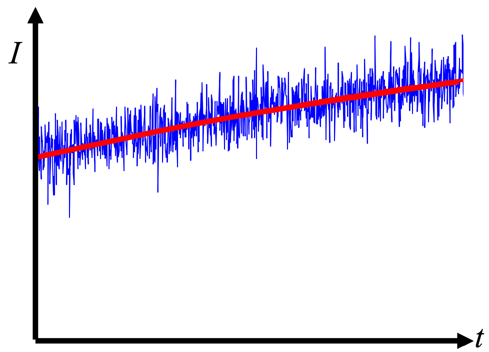


- Quantum detector = photon-electron conversion → Quantum Efficiency QE

- Detected quantity = Photon flux $\Phi = N/T_{int}$

→ Poisson statistic $\sigma_N^2 =< N >$ for a given integration time T_{int}

$$SNR = \frac{<N>^2}{\sigma_N^2} =< N >$$ optimum



- Proximity electronics→ Additional read out noise

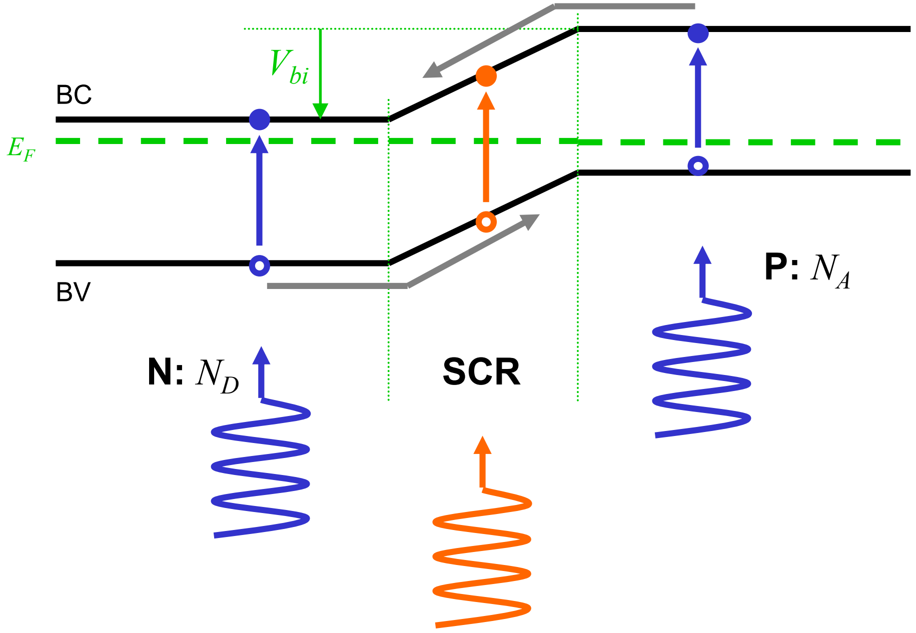
A good detector requires:

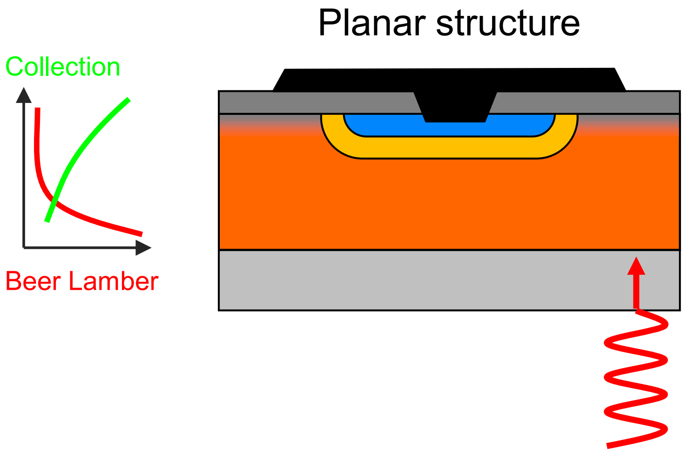
- **High QE in order no to loose incoming information**
- **Low additional noise (dark current or RO noise) in order not to degrade this information**

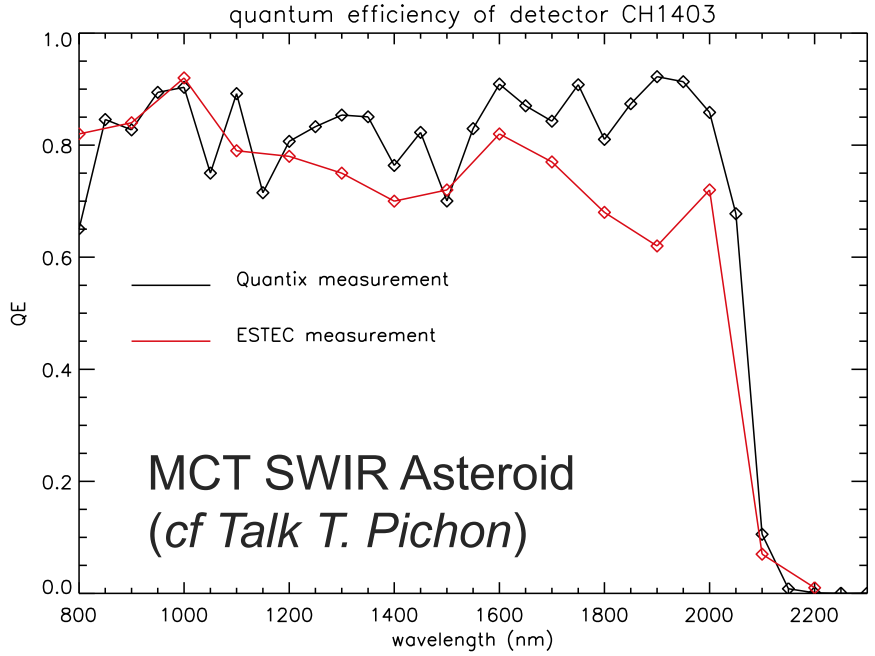
QE in PN junctions for IR

- Collected photocurrent limited by minority carriers
  - N side: holes h+
  - P side: electrons e-

  } Diffusion
  - Space charge region (SCR) = depletion







- Usually the diode is asymmetric: dominated by one side
- QE is a tradeoff between:
  - Absorption and thickness : $e^{-\alpha \times th}$
  - Collection efficiency
    (usually related to diffusion, ie mobility and carrier lifetime)

  } The thicker the better

- Direct gap bulk ➔ high QE reachable
- QE measurement remains difficult….

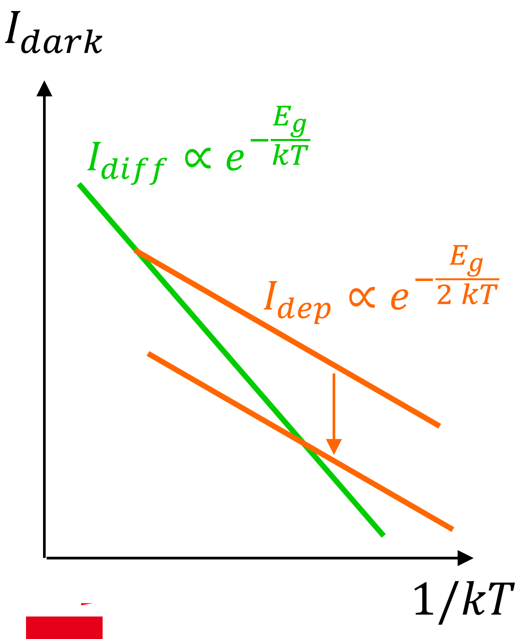
Dark currents in PN junctions for IR

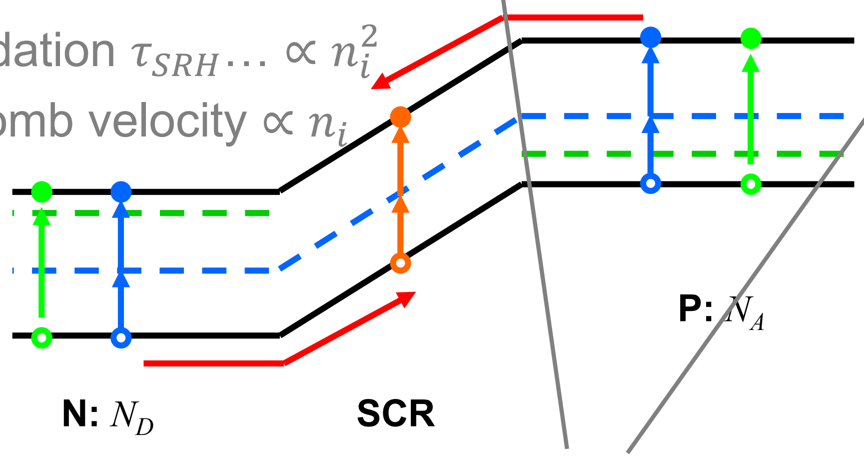
- N and P sides : Auger et SRH generation → diffusion limit
- SCR:
  - No Auger in SCR
  - SRH in SCR= GR
- Surface currents
  - Local degradation $\tau_{SRH} \ldots \propto n_i^2$
  - Surface recomb velocity $\propto n_i$

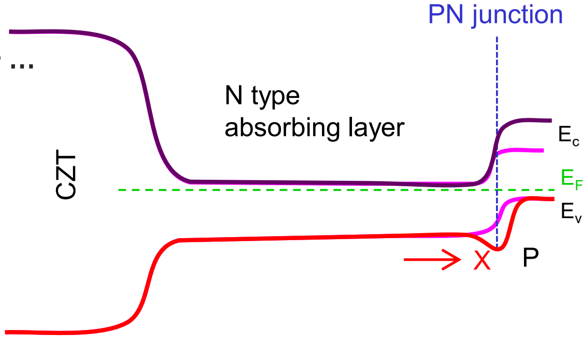
$$I_{SCR} = q \frac{n_i}{2\,\tau_{SRH}} V_{SCR}$$

$$I_{diff} = q \frac{n_i^2}{N_{dop}} \frac{V_{diff}}{\tau}$$

$$\frac{1}{\tau} = \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{rad}} \ldots$$

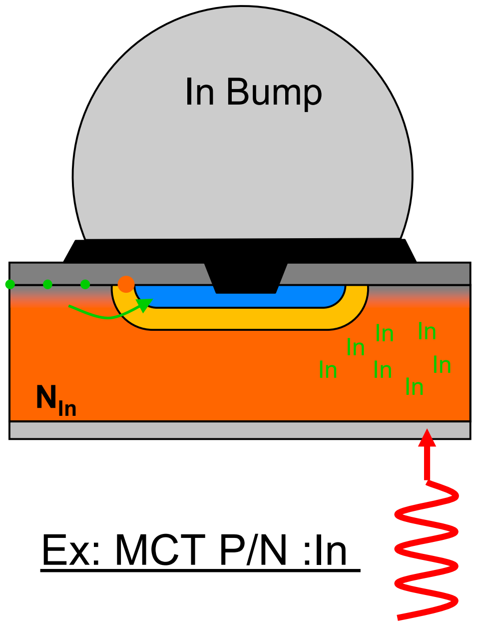




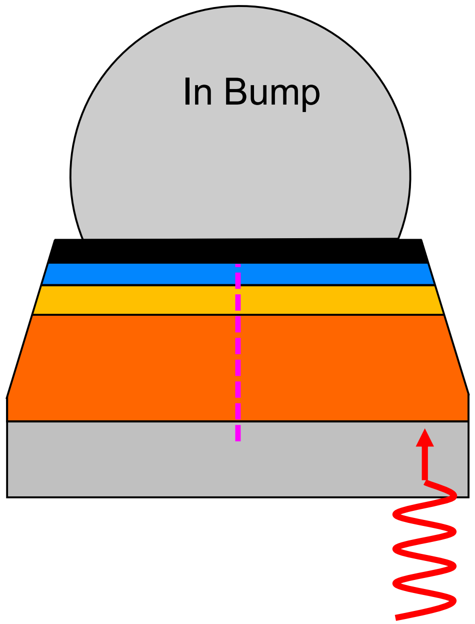


$$n_i \propto e^{-\frac{E_g}{2kT}}$$

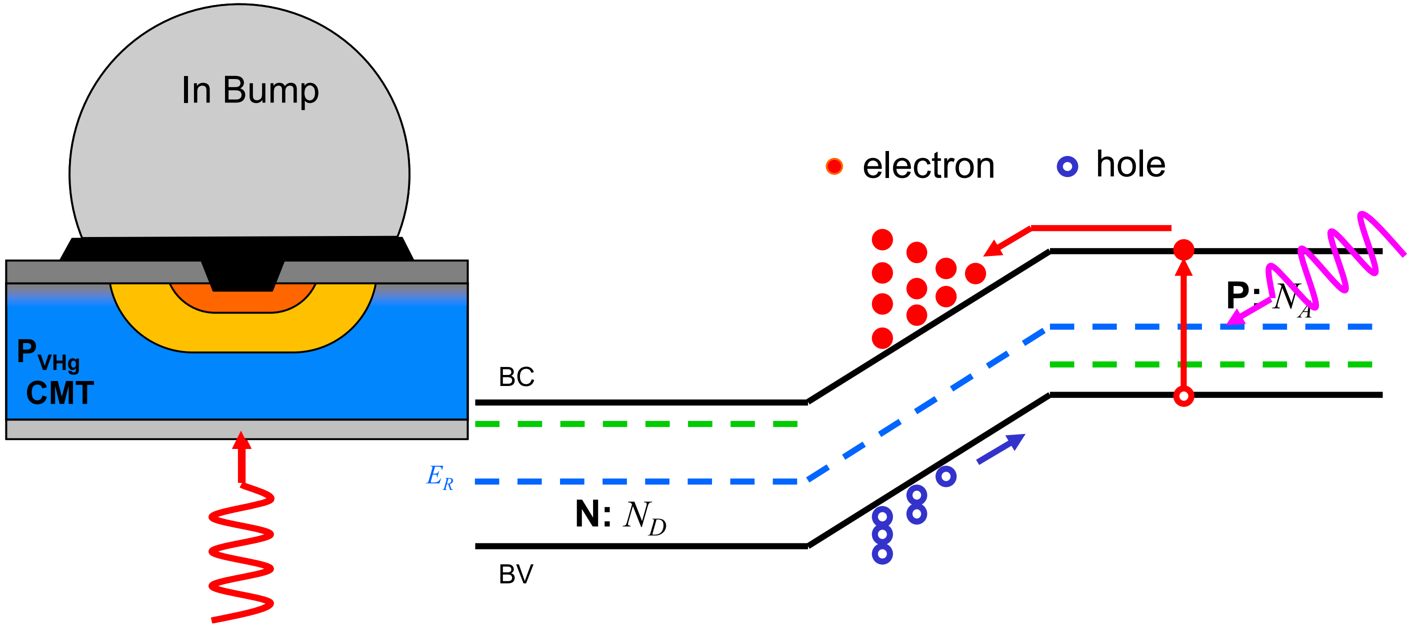
Thermal behaviour is dominated by n_i



Ex: MCT P/N :In



Impact ionization for Avalanche photodiodes



MCT shows :

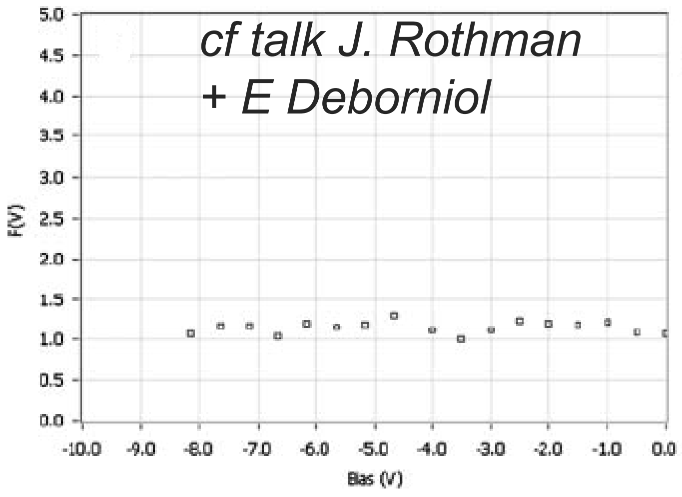
- Very high gain
- Close to unity XS noise
  - Single e- multiplication (no hole Xcation)
  - quasi deterministic $P_{ionisation}$
- /!\ tunnel current limitation

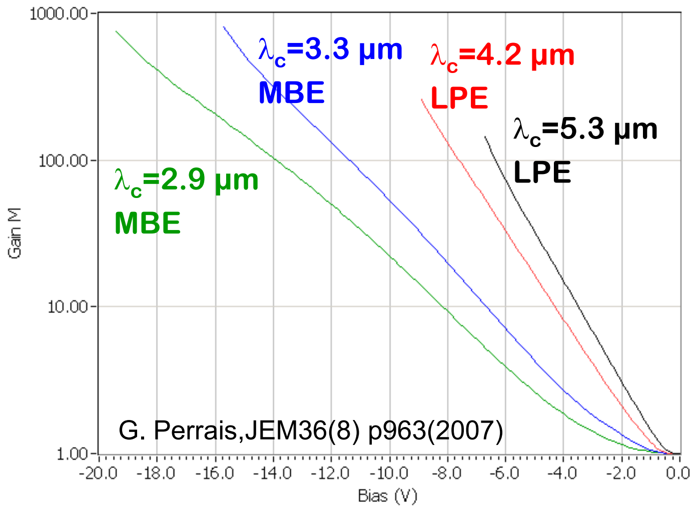
APD = Avalanche Photodiode
Photocurrent pre-amplification in the jonct
→ Overcome read out electronic noise

$$i_n = \sqrt{2qI} \text{ before amplification}$$

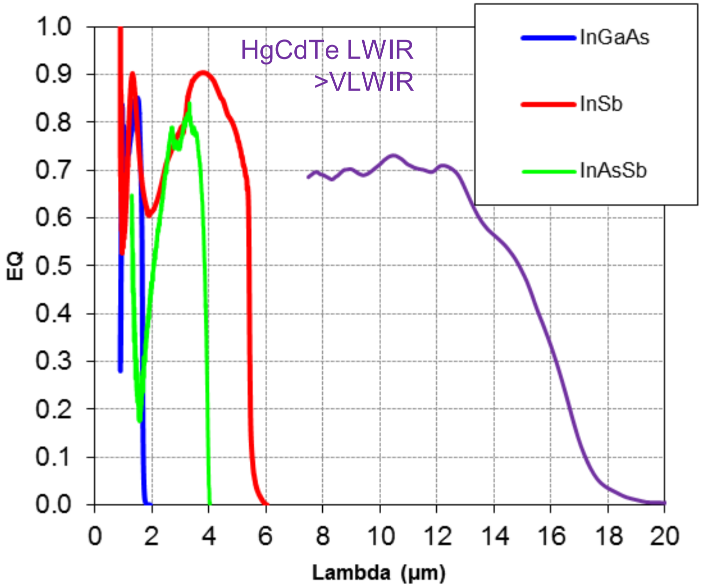
$$i_n = M \times \sqrt{2qI \times F} \text{ with gain } M$$

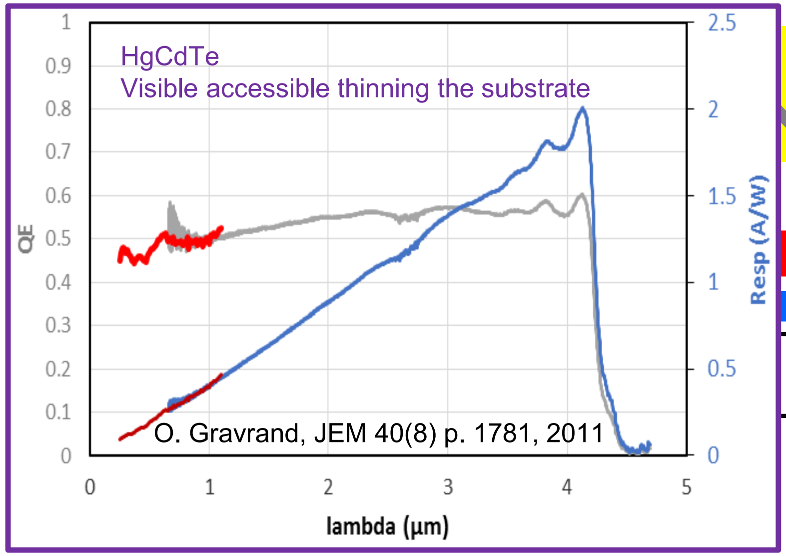
$$F = \frac{RSB_{in}}{RSB_{out}} \quad \text{XS noise}$$

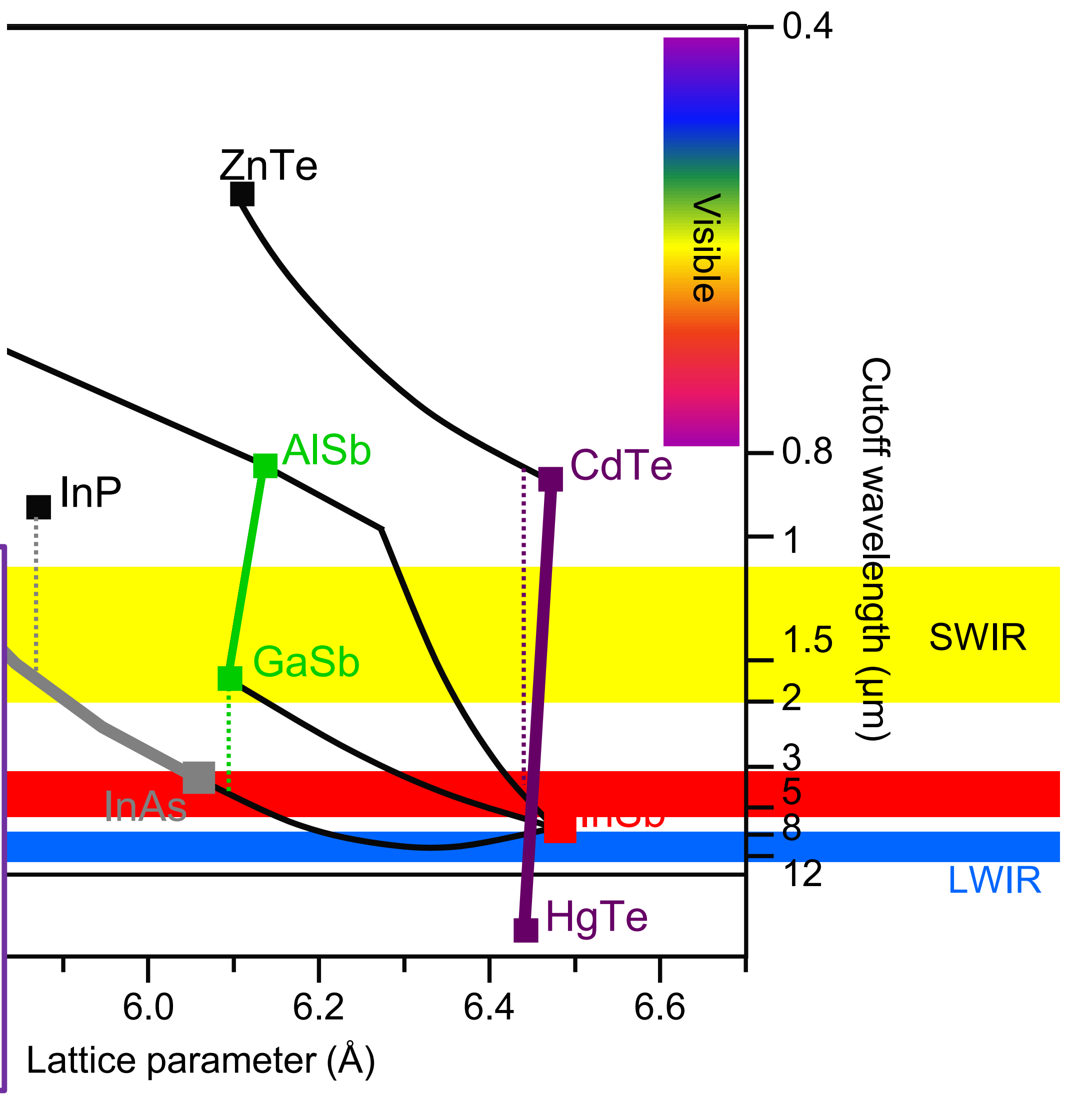


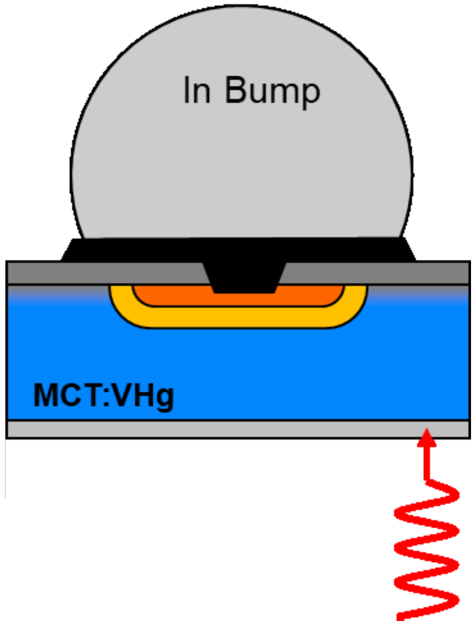


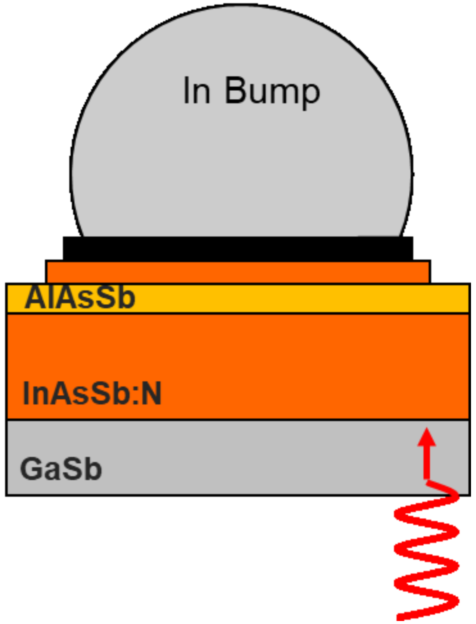
Spectral versatility is a material issue











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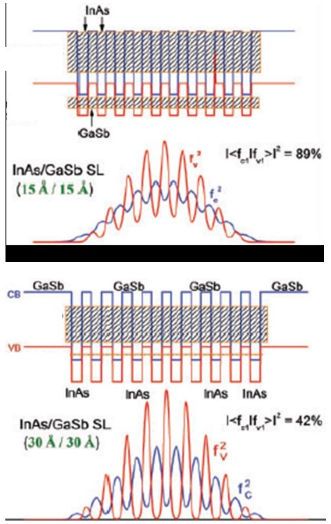
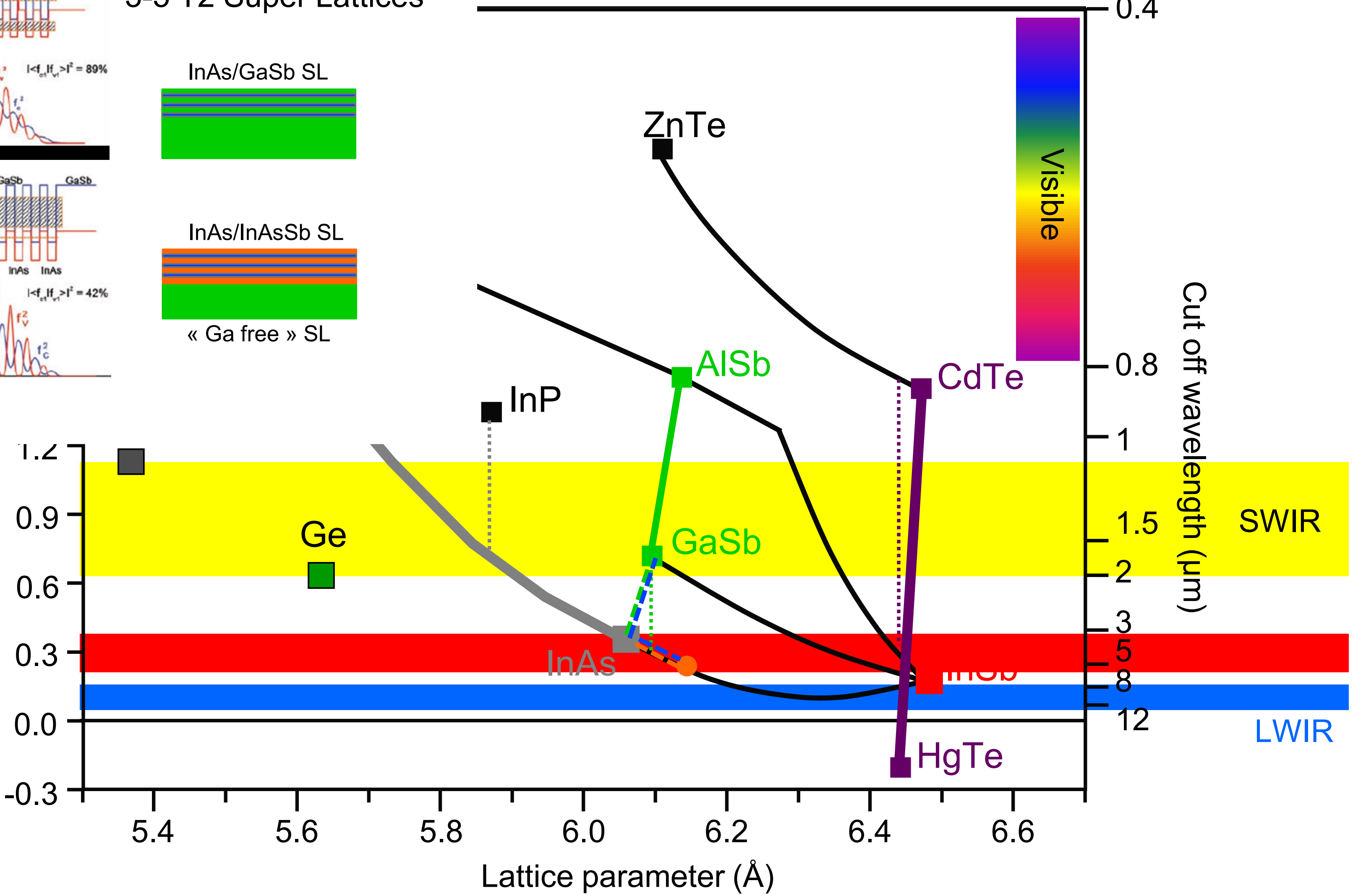
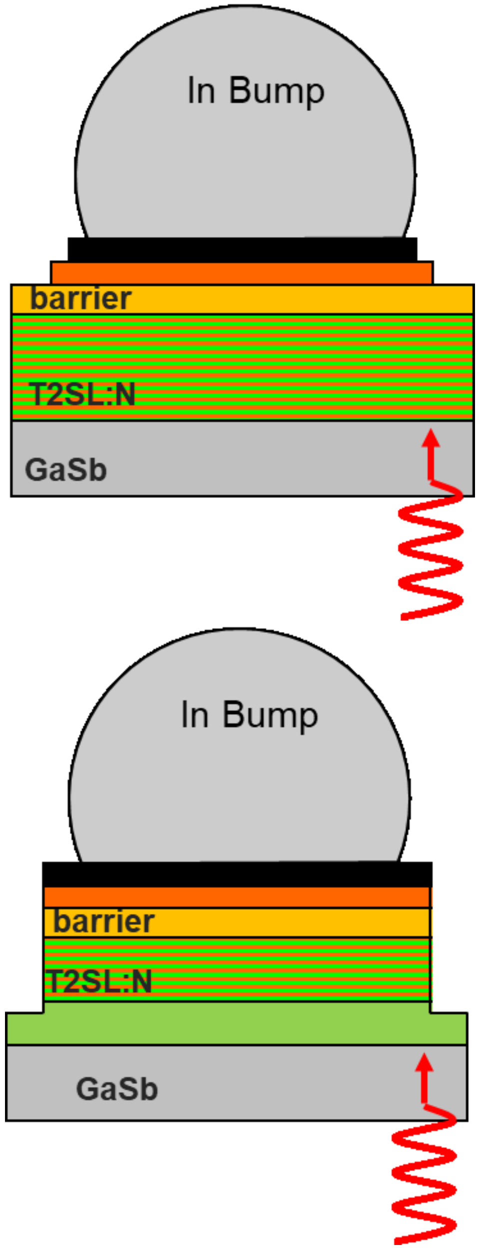
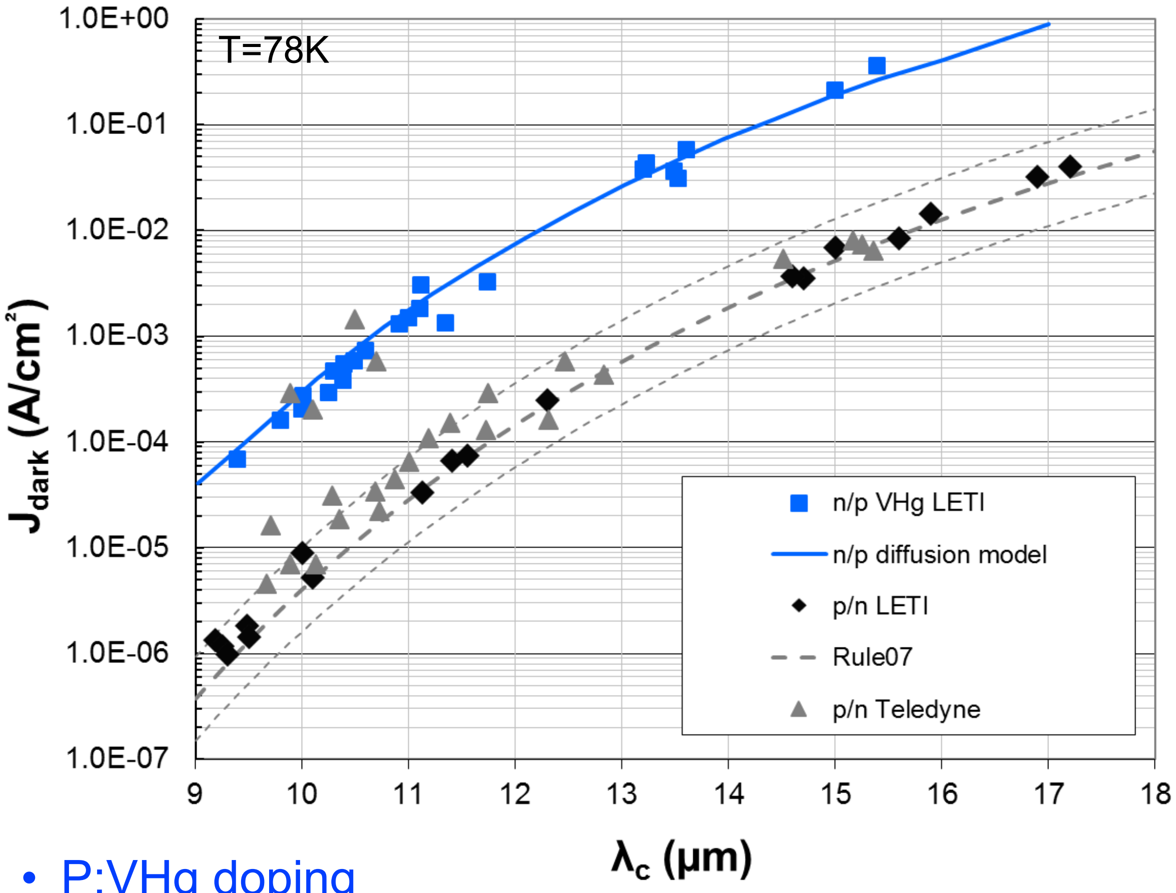


3-5 T2 Super Lattices





MCT: Switch from VHg to extrinsic N:In doping



O. Gravrand, *SPIE* 636118–10 (2006)

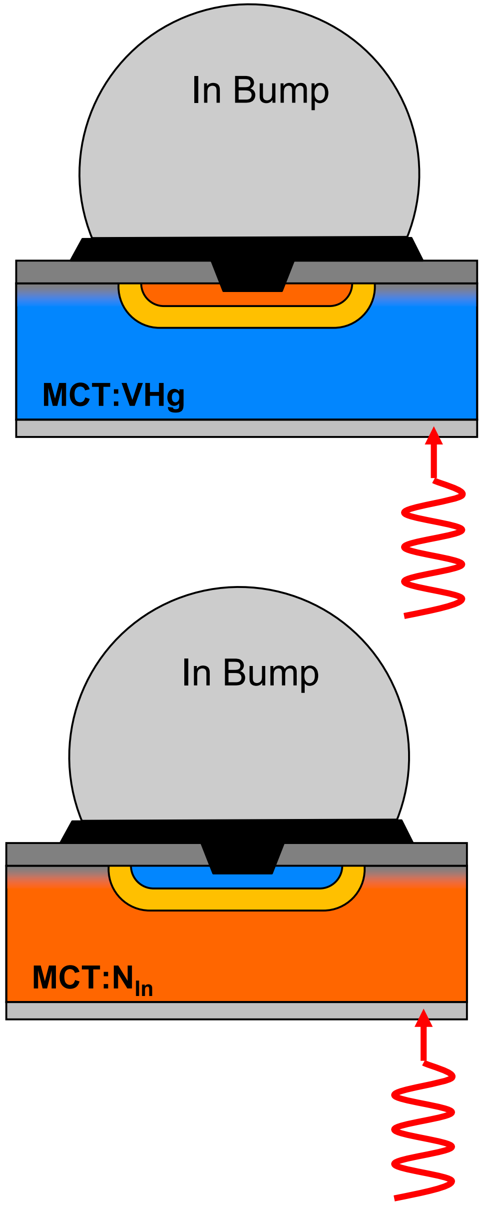
O. Gravrand, JEM *38*(8), (2009)

N. Baier, SPIE87042P (2013)

O. Gravrand, JEM 45(9) (*2016*)

W. Tennant, JEM, 37(9), p1406 (2008)

T. Chuh, SPIE 5563 p19 (2004).

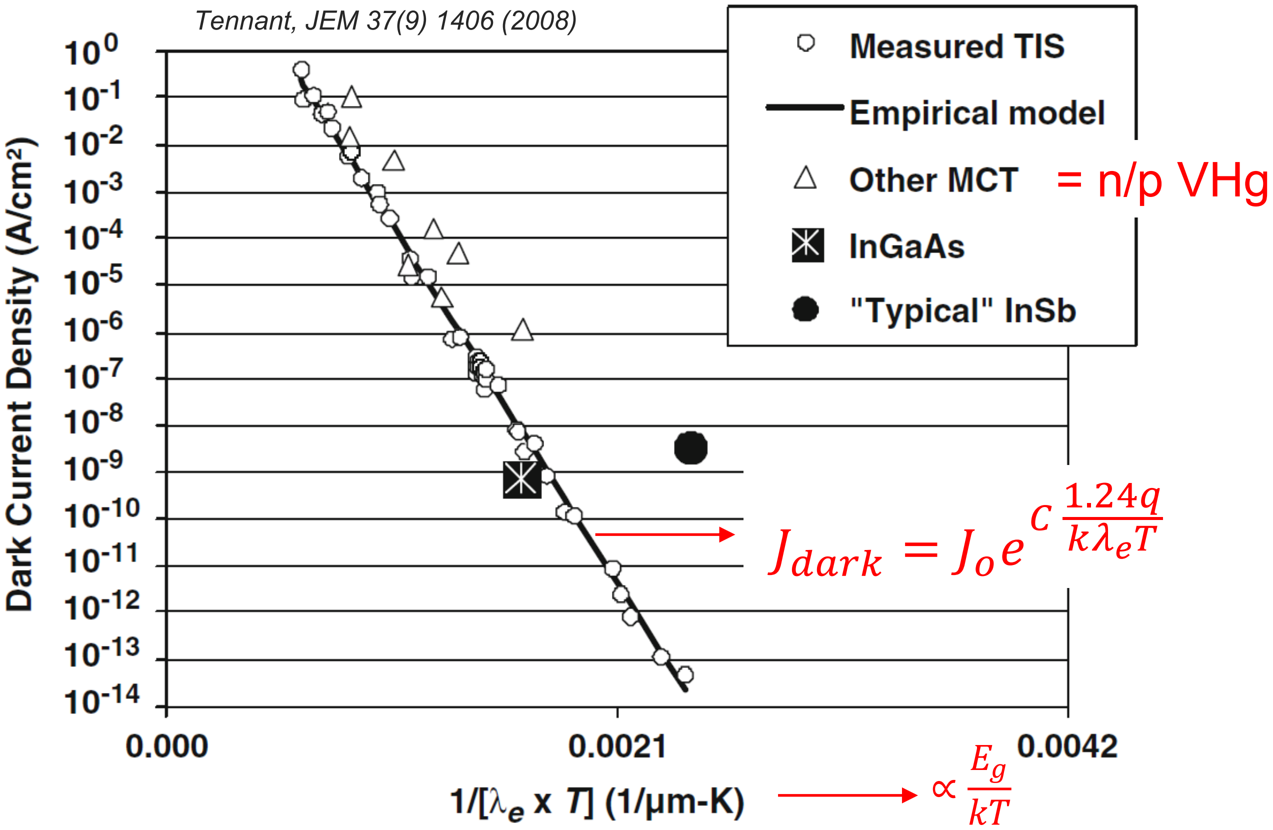


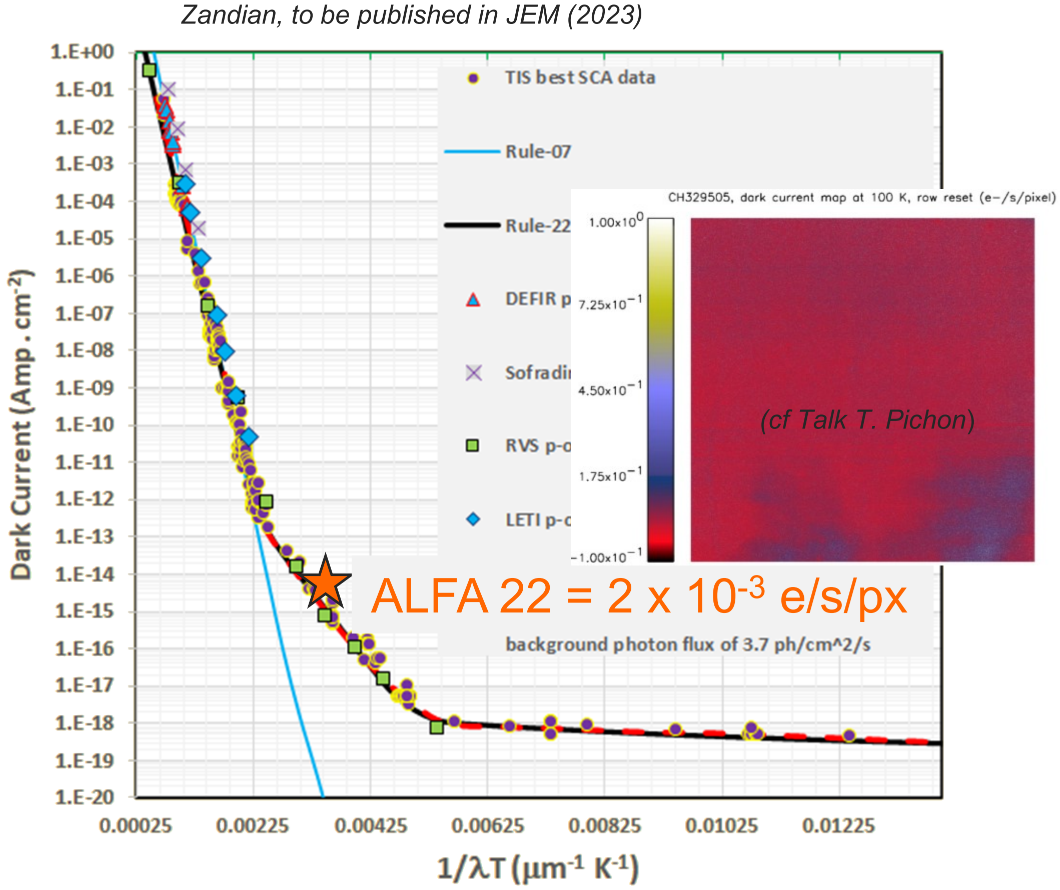
- P:VHg doping
  - → Short lifetime (~ns), SRH VHg recombinaison
- Extrinsic N:In doping
  - → Longer lifetime (~µs) Auger1
  - → Larger $L_d = \sqrt{kT\mu\tau}$ → higher EQ

→ Gain close to x100 on I_{dark}

What is exactly this Rule 07?
now Rule 22, when will it end?

$$J_{dark} = J_o(\lambda) \times \left[e^{-n_1 \frac{1.24q}{\lambda kT}} + C_2 e^{-n_2 \frac{1.24q}{\lambda kT}} \right] + \alpha\, \lambda^2 T$$



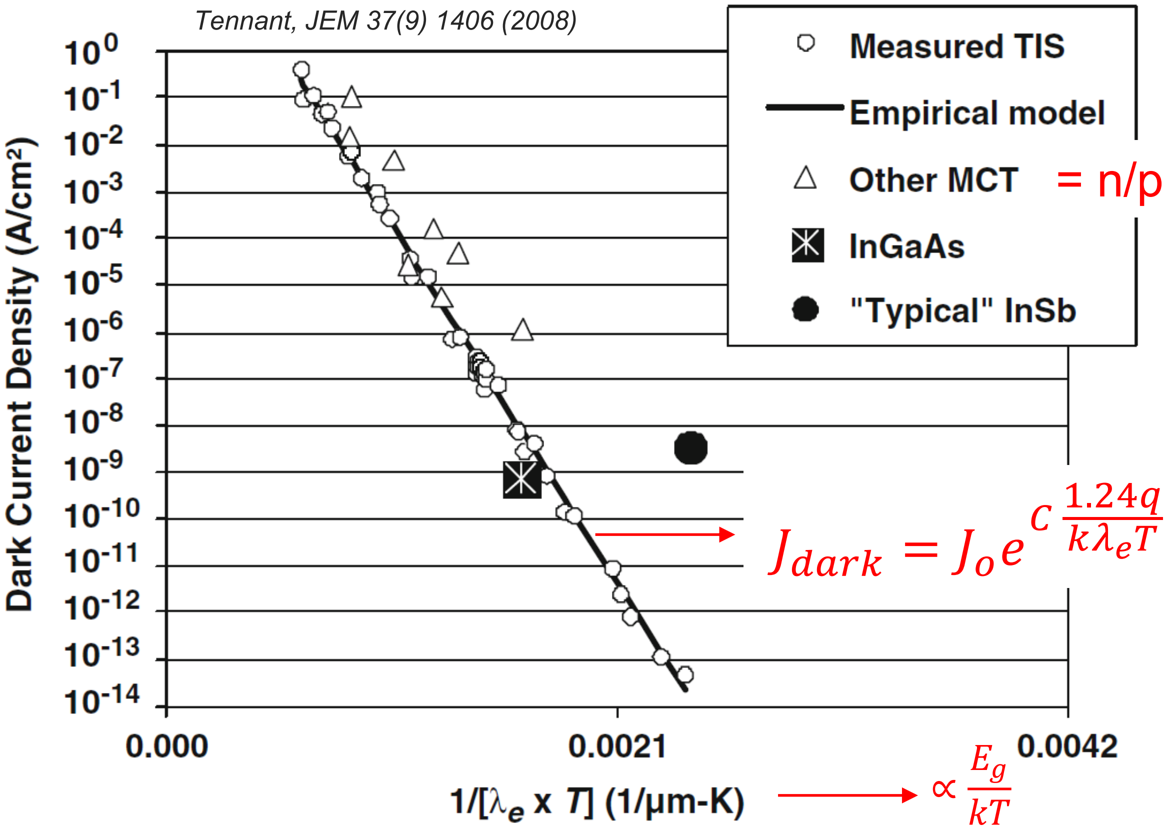


- **Rule07** is an easy to compute empirical law
- « good » p/n MCT diode diffusion dark current

- **Rule 22** to go down to very low currents
- Teledyne claims e-/month @ very low T°
- ALFA data in line with this description

What is exactly this Rule 07?
then law 19, now Rule 22, when will it end?

Tennant, JEM 37(9) 1406 (2008)

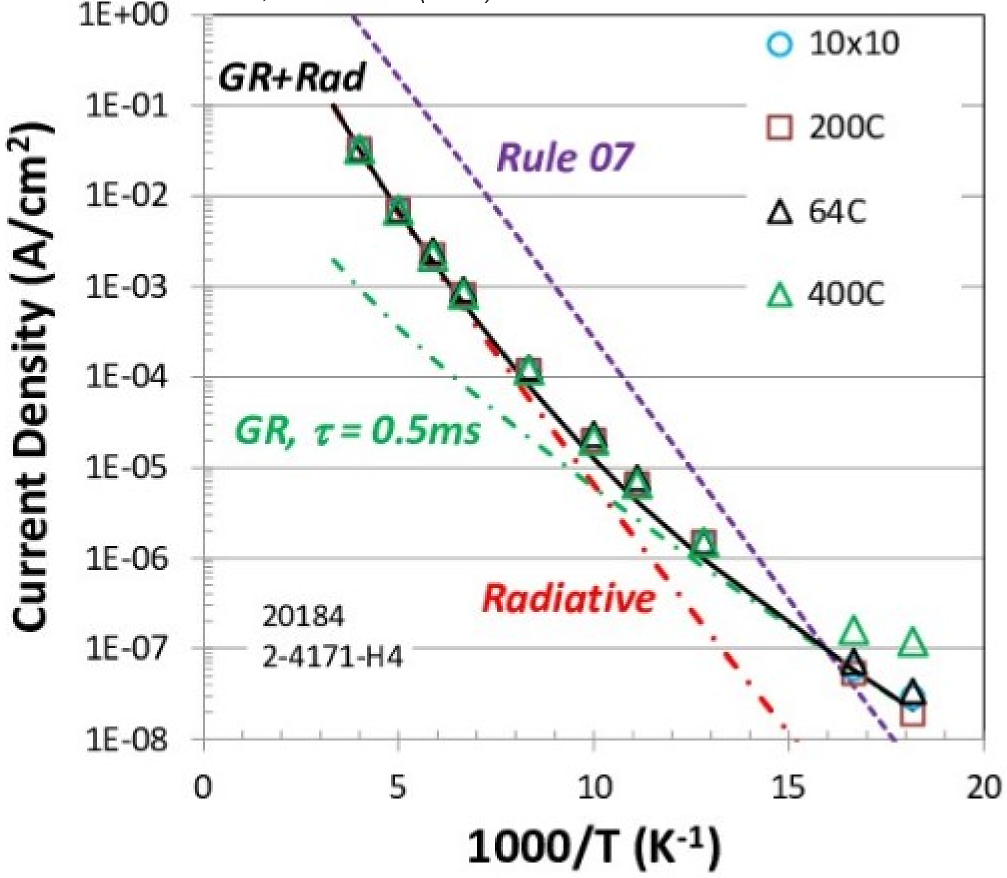


= n/p VHg

$$J_{dark} = J_o e^{C \frac{1.24q}{k\lambda_e T}}$$

$$\propto \frac{E_g}{kT}$$

Lee, SPIE11407 (2020)



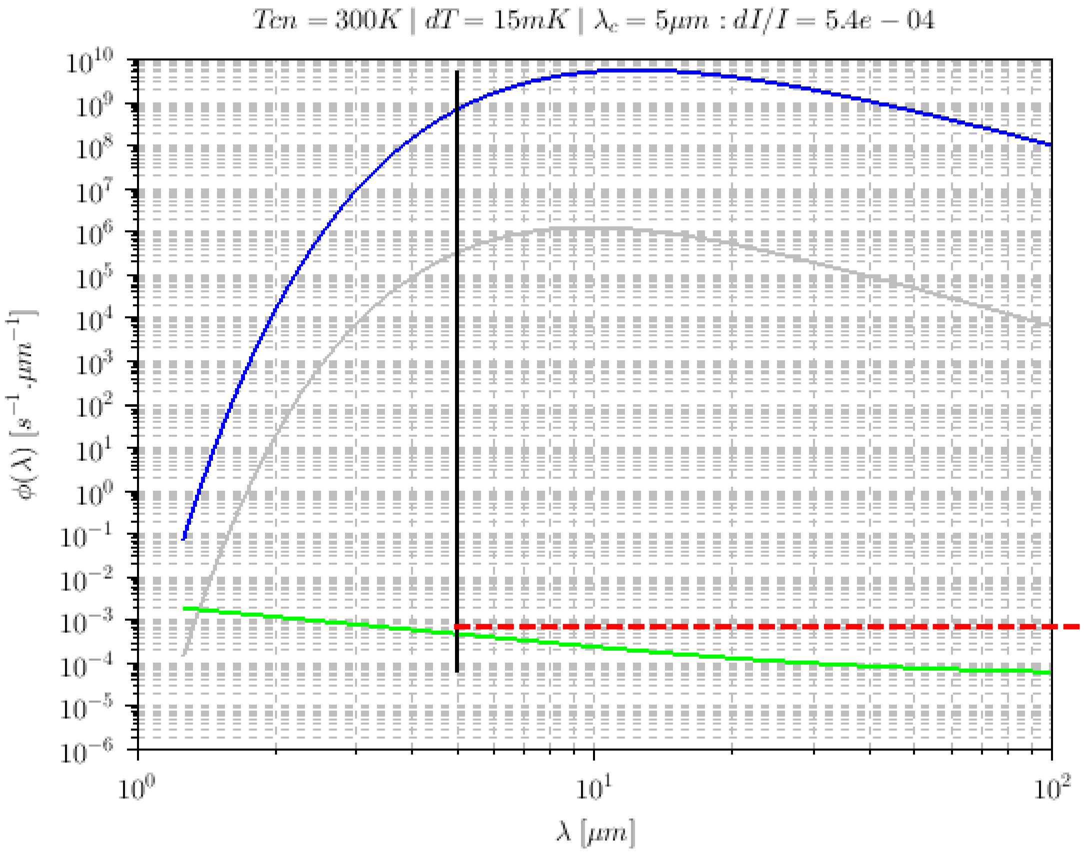
- Rule07 is an easy to compute empirical law
- « good » p/n MCT diode diffusion dark current

- Even lower current are demonstrated with a fully depleted structure = **law19**
- Seen at DEFIR and AIM

LeGoff, JEM (2023)
To be publihded

Hanna, JEM 49(11) (2020)

The need for very high stability in IR imaging…



$\phi(\lambda)$ = Flux @ 300K BB

$d\phi(\lambda)$ = delta Flux
300.015K - 300K

15mK NETD case

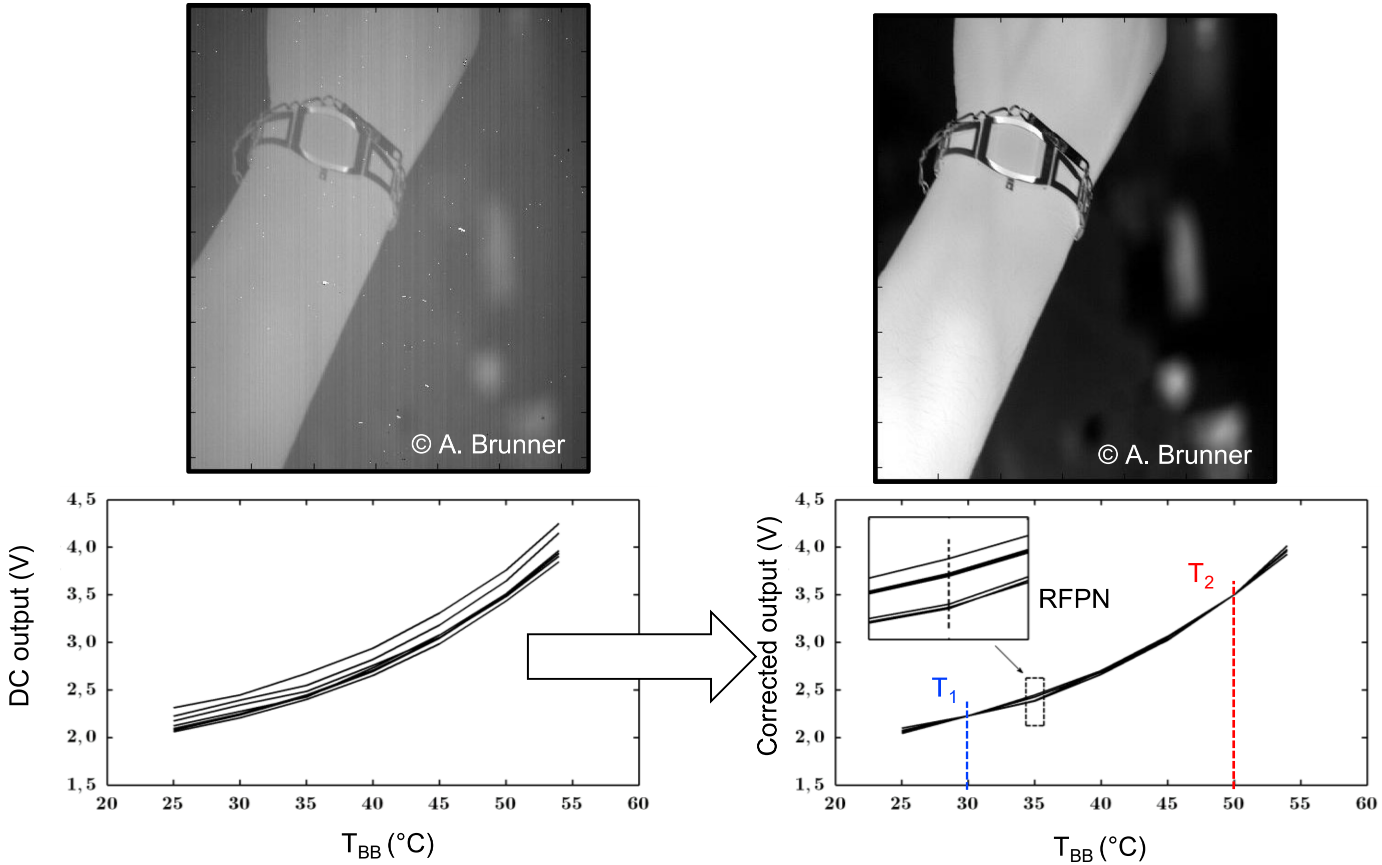
$\frac{d\phi}{\phi}$

Ex :
$dT = 15mK$, $T_{cn} = 300K$ (pitch 15µm)
→ $\frac{dI_{bb}}{I_{bb}} = 5\ 10^{-4}$

- In an ambiant IR image, all pixels are sensing very similar fluxes (high common BB background)
- IR imaging is a contrast imaging (≠ visible imaging)
- Need of a very high accurate/stable correction/calibration (10^{-4} typically)

Calibration = NUC stability

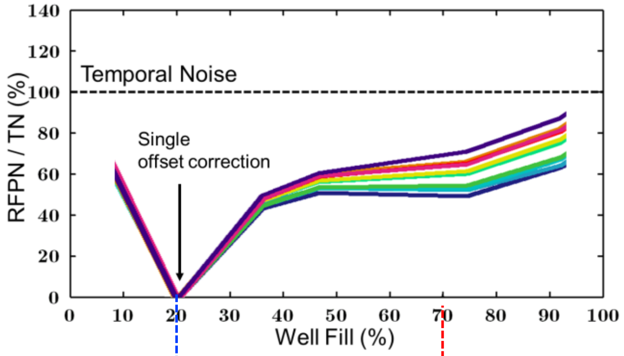
- Unfortunatelly, all pixels are not identical…
- 2 point correction usually used
  - Gain ⇔ Response x ROIC gain
  - Offset ⇔ Dark current + ROIC Offset

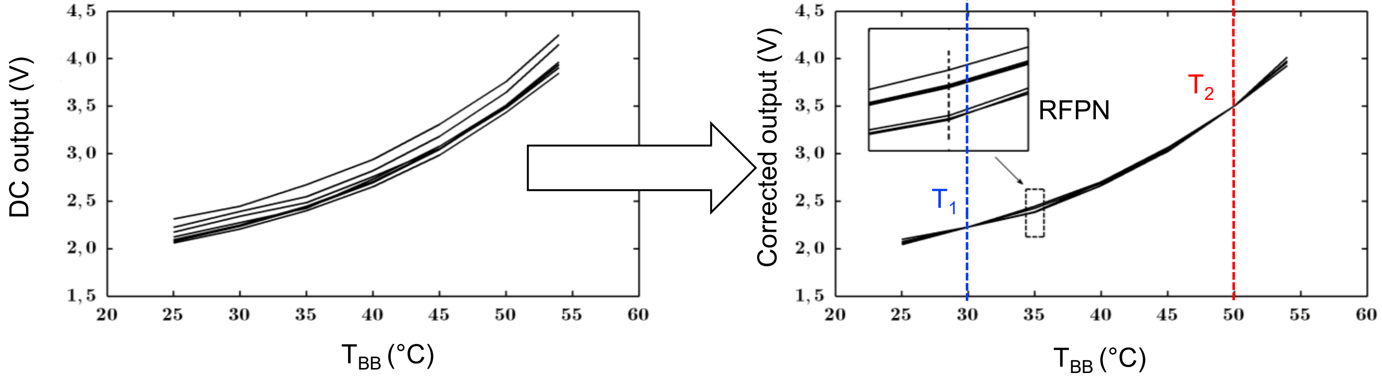


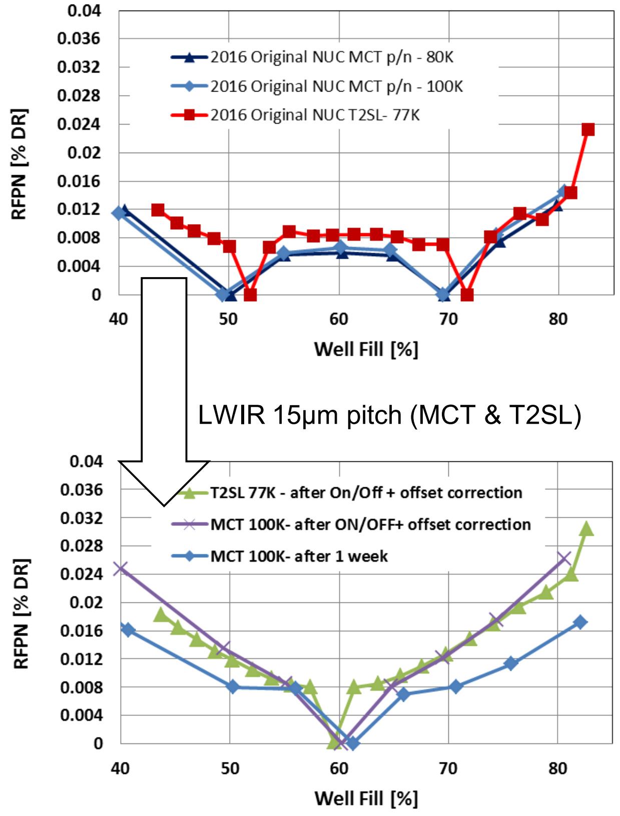
Calibration = NUC stability

- Unfortunatelly, all pixels are not identical…
- 2 point correction usually used
  - Gain ⇔ Response x ROIC gain
  - Offset ⇔ Dark current + ROIC Offset
- **RFPN = spatial RMS noise after correction**
  - RFPN depends on Well Fill
- Issue : RFPN drift…
  - Slow drift of offset and gain
  - Usually dominated by offset

- RFPN must remain low with a single offset correction





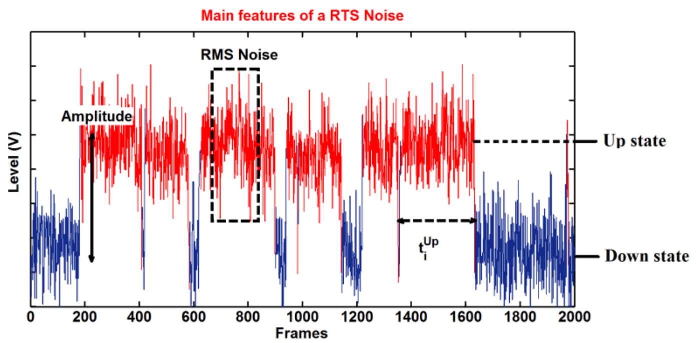


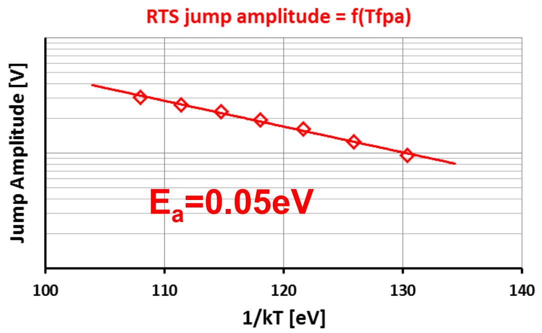
Rubaldo (2017), SPIE10177-49

Klipstein (2016), SPIE 98190T-1

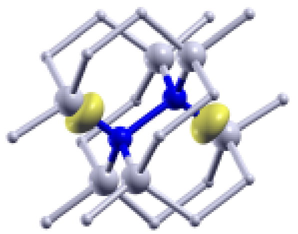
Dealing with LF noise, RTS is another issue

- RTS pixels
  - Dark current discrete fluctuations
  - Thermally activated : limiting the operating T°: Higher and faster at higher temperature
  - $E_g/2$ activation energy : suggests depletion current

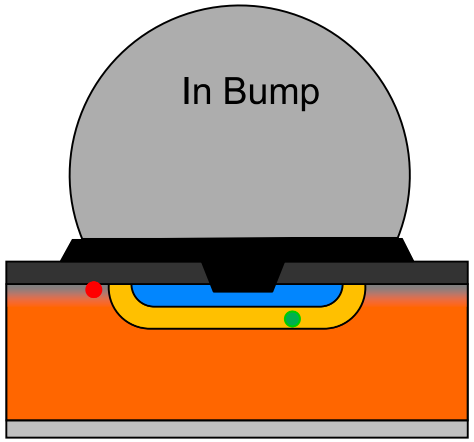




MCT LW [Brunner et al, JEM, vol. 43, No. 8, 2014]



A Jay, IEEE Trans on Nuclear Science, 2018, 65 (2), pp.724-731.



  - Usually RTS density is correlated with noise distribution tails
  - Metastable defects related to …
    - the SCR volume
    - The interfaces

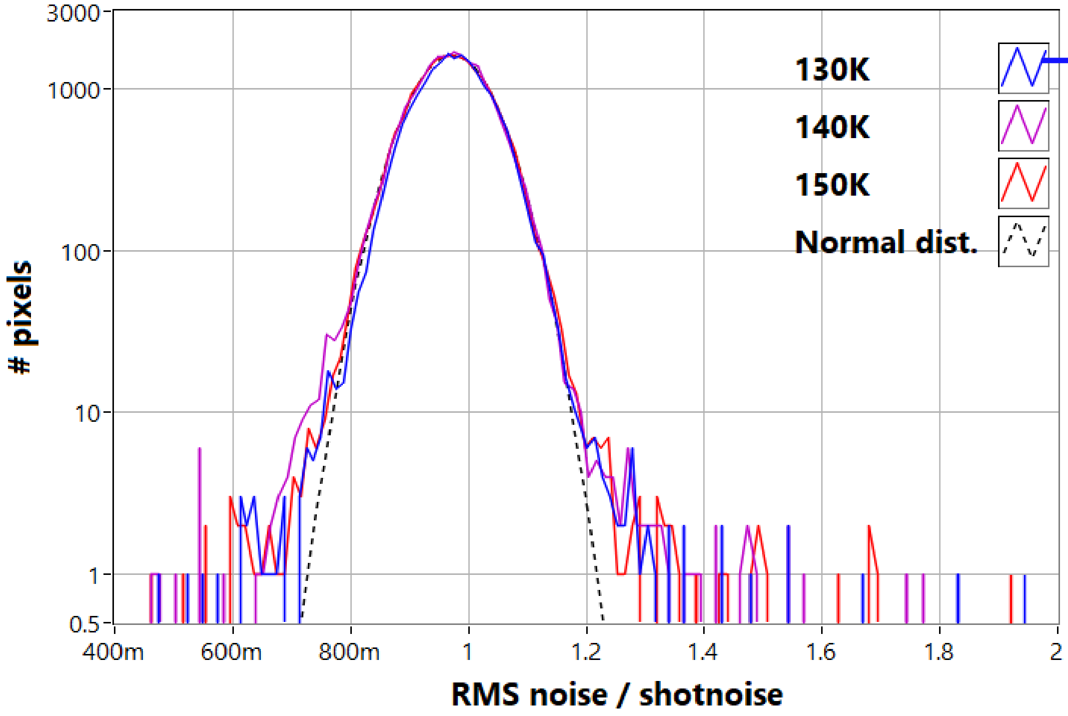
- Due to its weak Hg bounds and ionic nature, MCT is usually considered to be less stable than III-Vs…

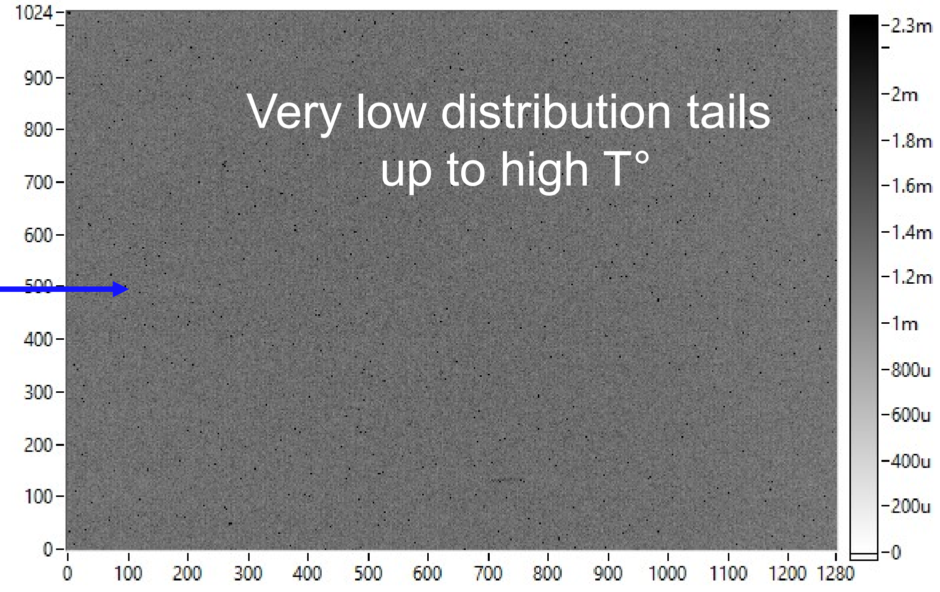
Stability: Difference between II-VI and III-V?

- Strong efforts to mitigate those effects on both sides
- MCT = **New generation** p/n for encreased stability and small pitches @ DEFIR
  - pitch 7.5 µm
  - MW red
  - Target ope. T° 130K

+ ongoing dev^{nt} in LW band

O. Gravrand, SPIE 12107 (2022)
N Baier, SPIE 13454 (2023)



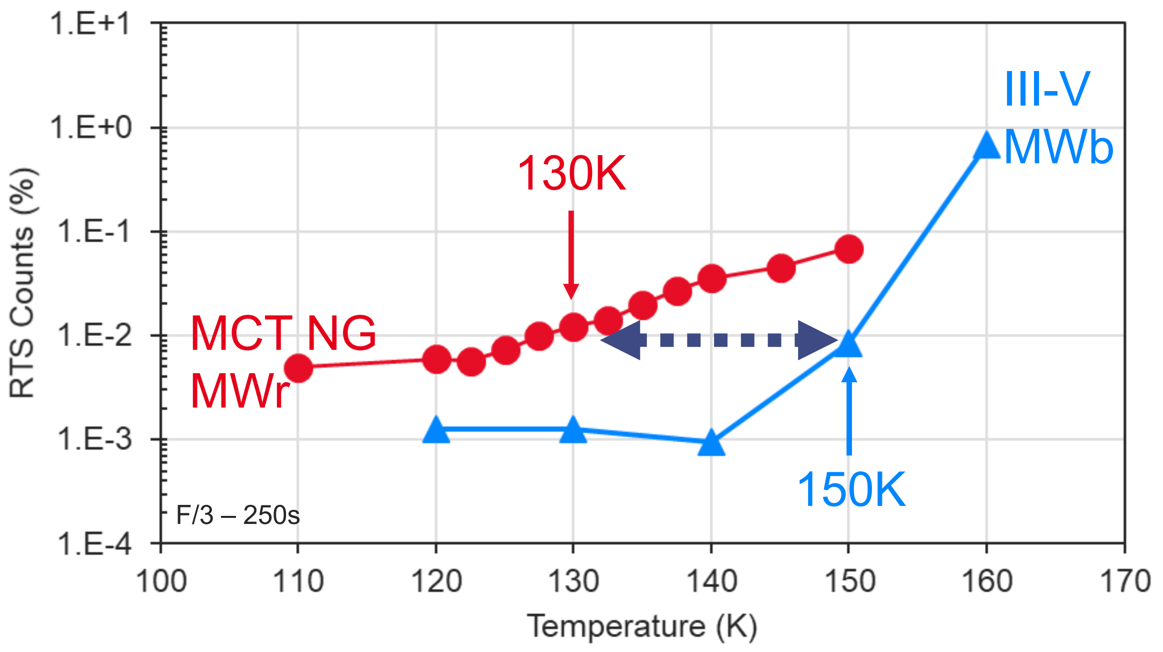


T°	130K
λ_c	5.1µm
QE	**≈ 85%**
Op (I)	**99.92%**
Op (noise)	**99.97%**

Stability: todays fight between II-VI and III-V?

- Strong efforts to mitigate those effects on both sides
- MCT = New generation p/n for encreased stability and small pitches @ DEFIR
  - pitch 7.5 µm
  - MW red
  - Target ope. T° 130K
- Comparison with III-V by Lynred
  - Pitch 7.5µm (same ROIC)
  - MW blue
  - Target ope. T° 150K
- RTS counts with T° : similar

Rubaldo, SPIE 1254-33 (2023)



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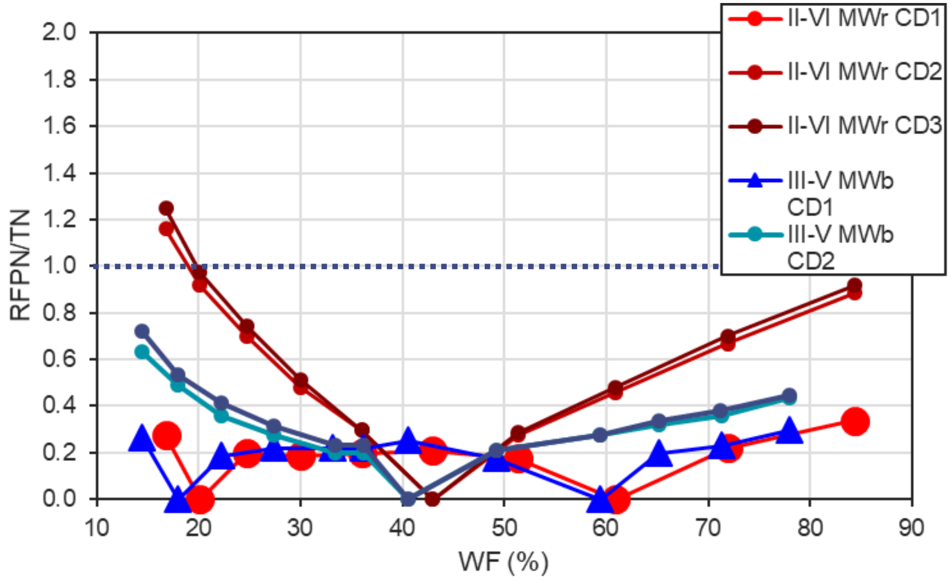
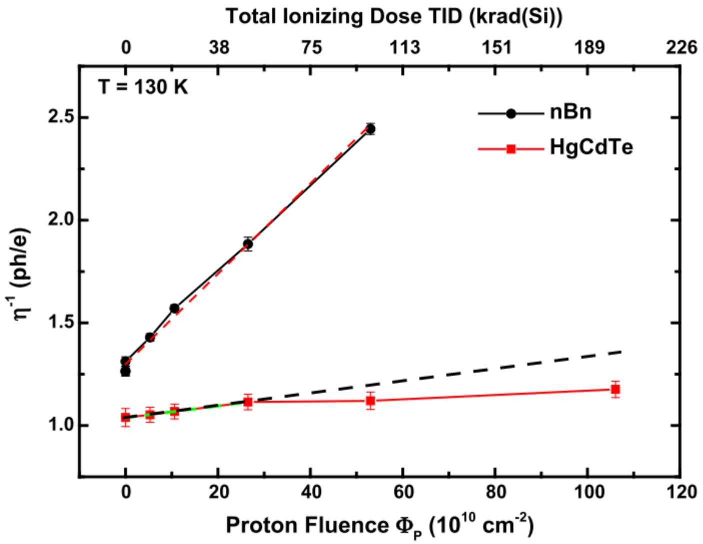
Rubaldo, SPIE 1254-33 (2023)

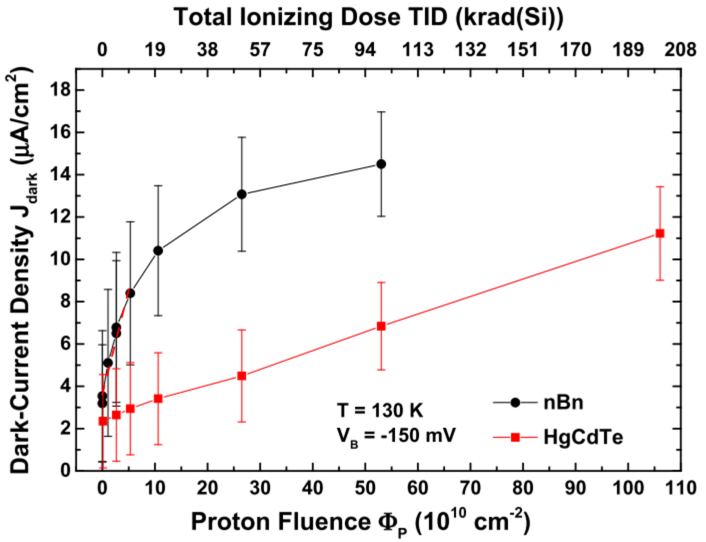


- RTS counts with T° : similar
- RFPN evolution with cool down (CD)

Radiation hardness…

- InGaAs showed significant degradation on Spot 4 = Initial trauma? S. Barde, IEEE Trans Nuc Sci 47(6) (2000)
- MCT has the reputation of a rather radhard material system
- Previous work form AFRL suggest an advantage to MCT (ionic vs covalent crystal?) Jenkins 2017, JEM46(9) p5405





- On going work in the french community to build our own point of view
- See the « radiation effects » session with C. Bataillon, S. Dinand and M. Benfante PhD’s

T2SL
Isabelle Ribet ONERA

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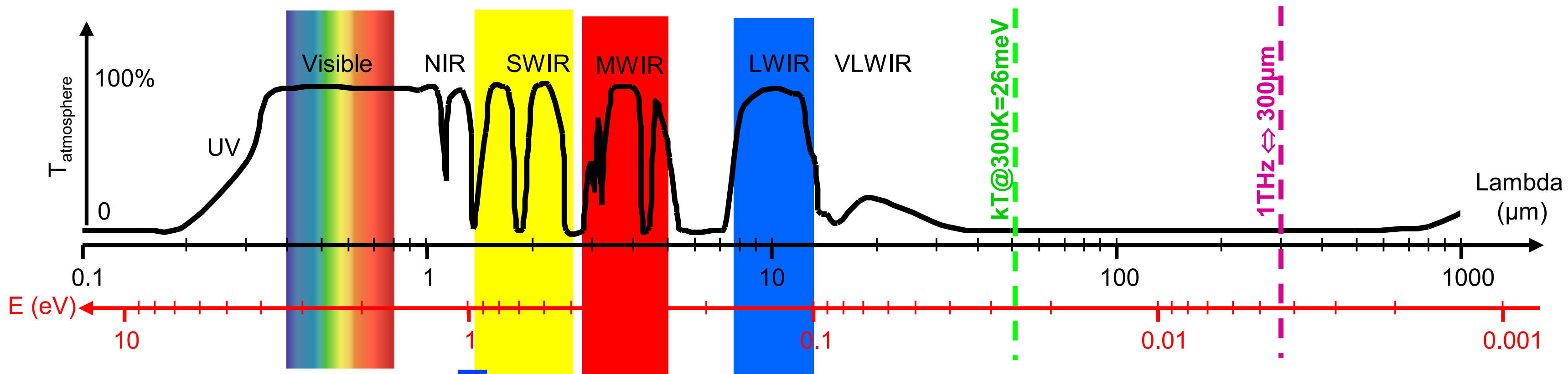
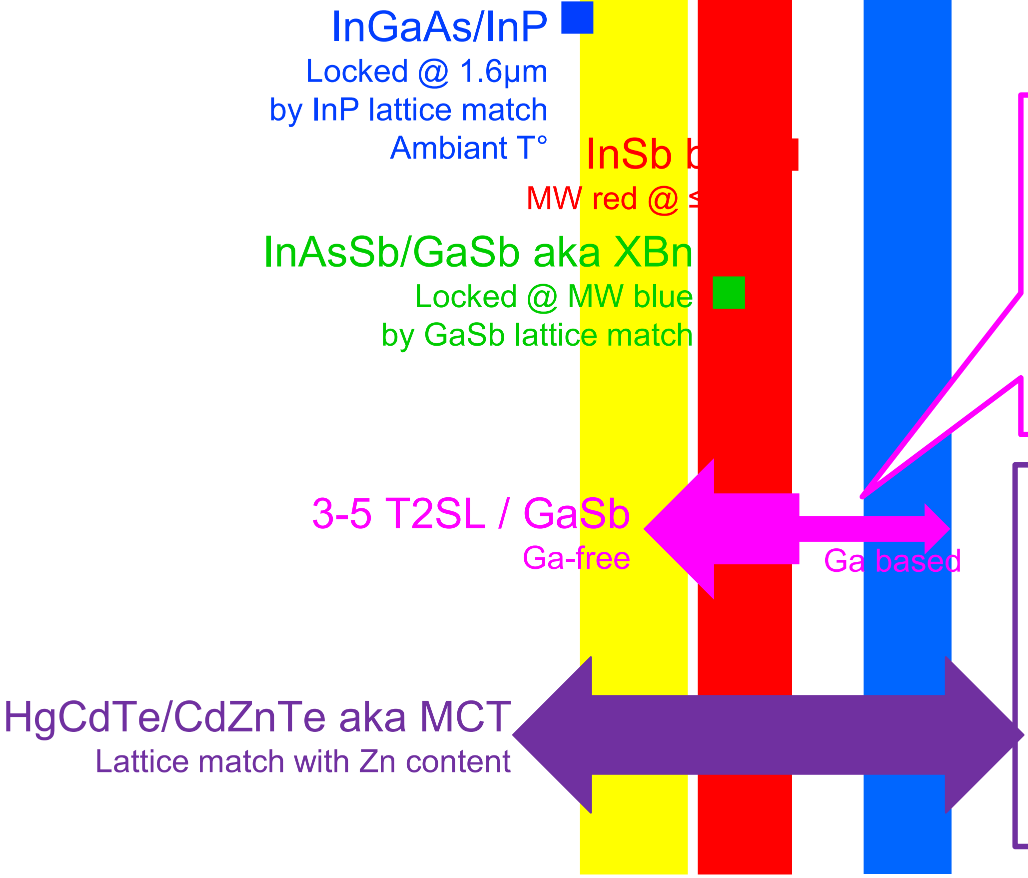
Conclusion





3-5 materials for spectral niches

3-5 SL for spectral versatility
HOT MW red with Ga-free (US)
Large area substrates
QE still limited in LW-VLW ?
Usually high dark current (vs QE)
Issues with radiation damage?

2-6 MCT for spectral versatility and high performances
High QE
Very low dark background
Noiseless avalanche accessible
Fully depleted structures?
Yield issues for stability & blinkers