Quantum Cascade Detector at 5 micrometers

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Thales Research and Technology

Presentation of the device

- Principle of a QCD
- Description of the sample

Characterization of the QCD

- Absorption and responsivity spectra
- Resistivity
- Noise and detectivity

Modeling of electronic transport

- Presentation of the model
- Some results and discussion
- QCD vs QWIP

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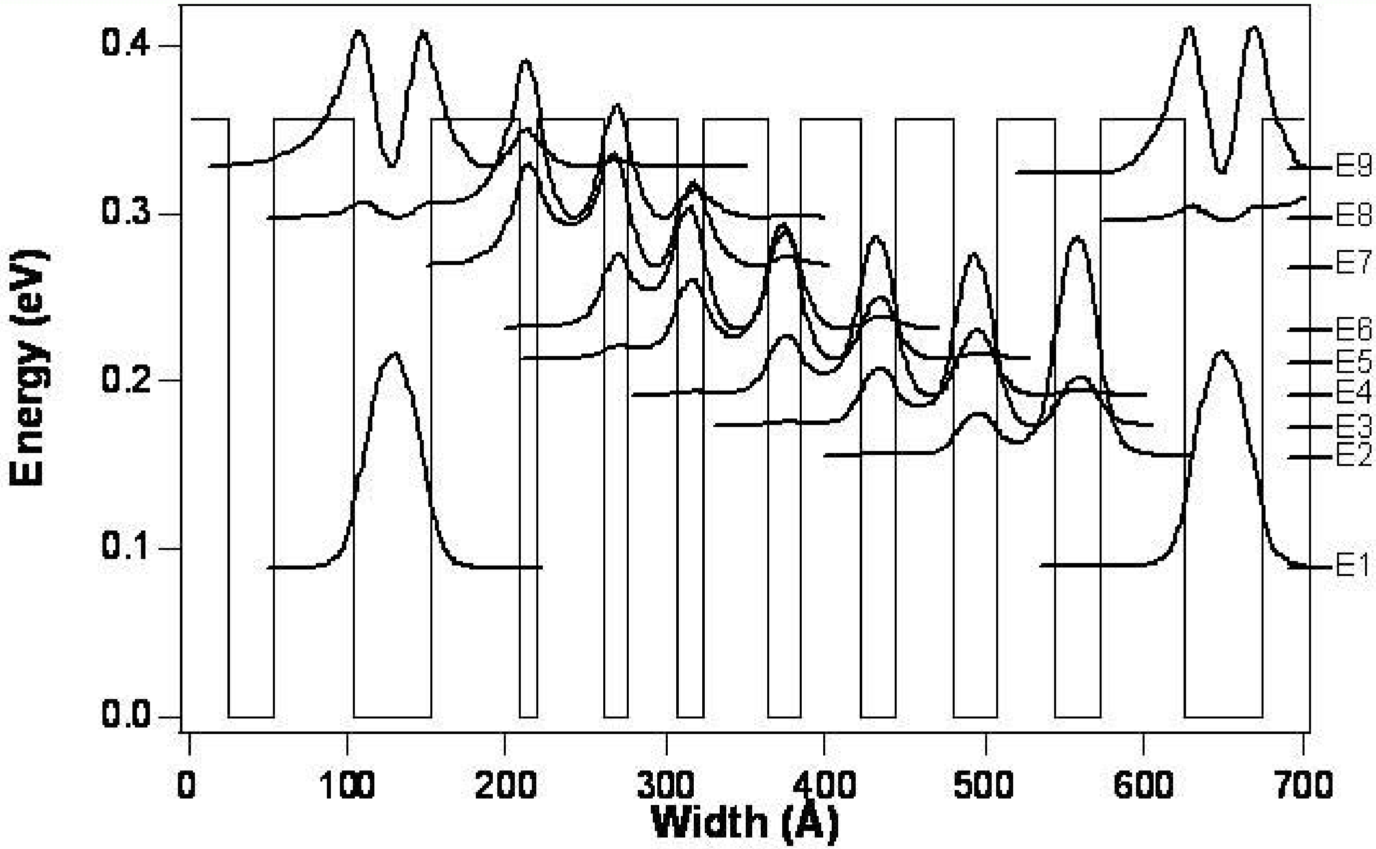
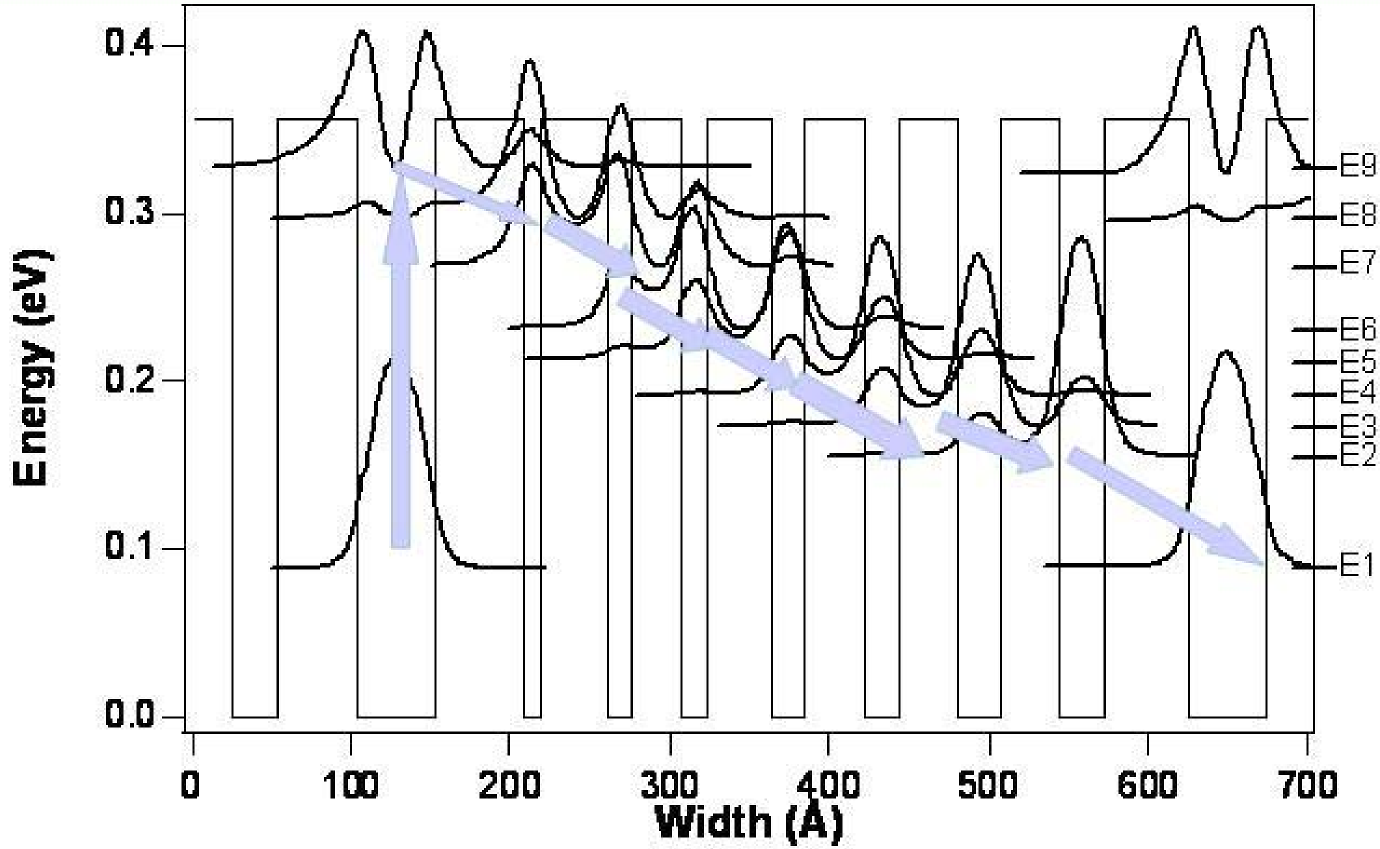
Presentation of the sample



- 40 periods of 8 barriers and quantum wells
- <u>Quantum Wells</u> : GaAs, thickness between 11 and 30 Å
- <u>Barriers</u> : AlGaAs, 44% Al, thickness between 30 and 60 Å
- 1st Quantum Well Si n-doped : Nd = 5 10^{11} cm^{-2}

Principle of detection



- Thales patent “Détecteurs à cascade quantiques” (2001)
- Many QCDs have been demonstrated at Neuchatel (2.5 µm, 5.3 µm, 9 µm, 16.5 µm, 84 µm) and Paris (8 µm and 5.7 µm)

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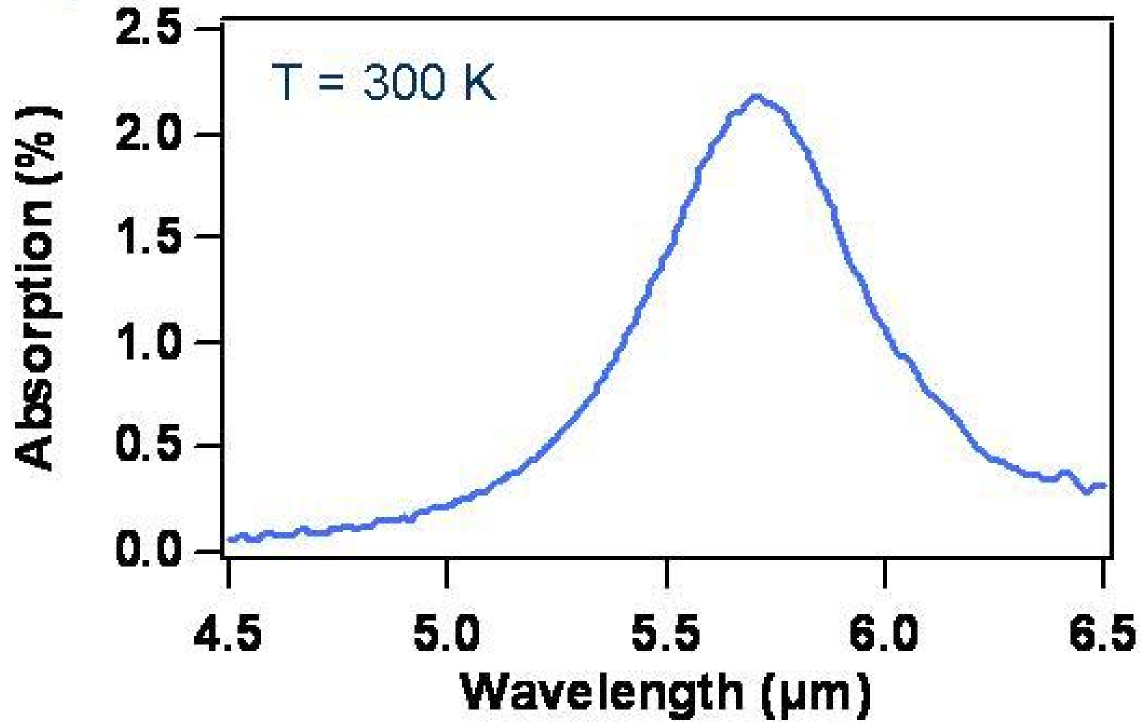
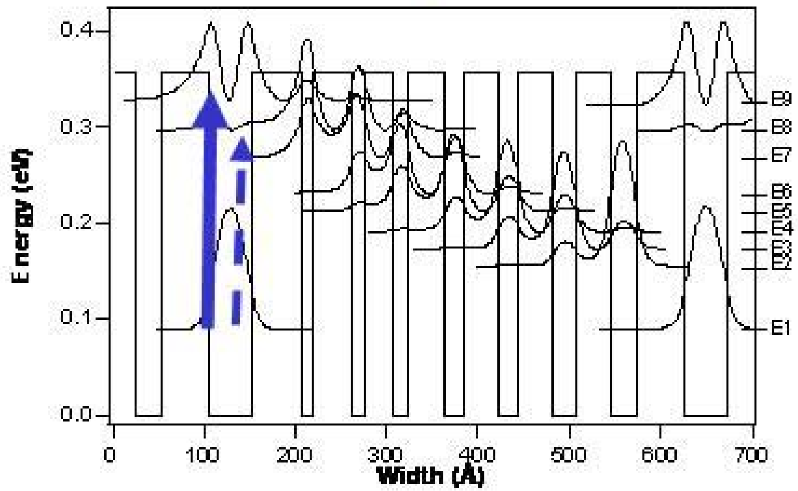
Characterization : Absorption



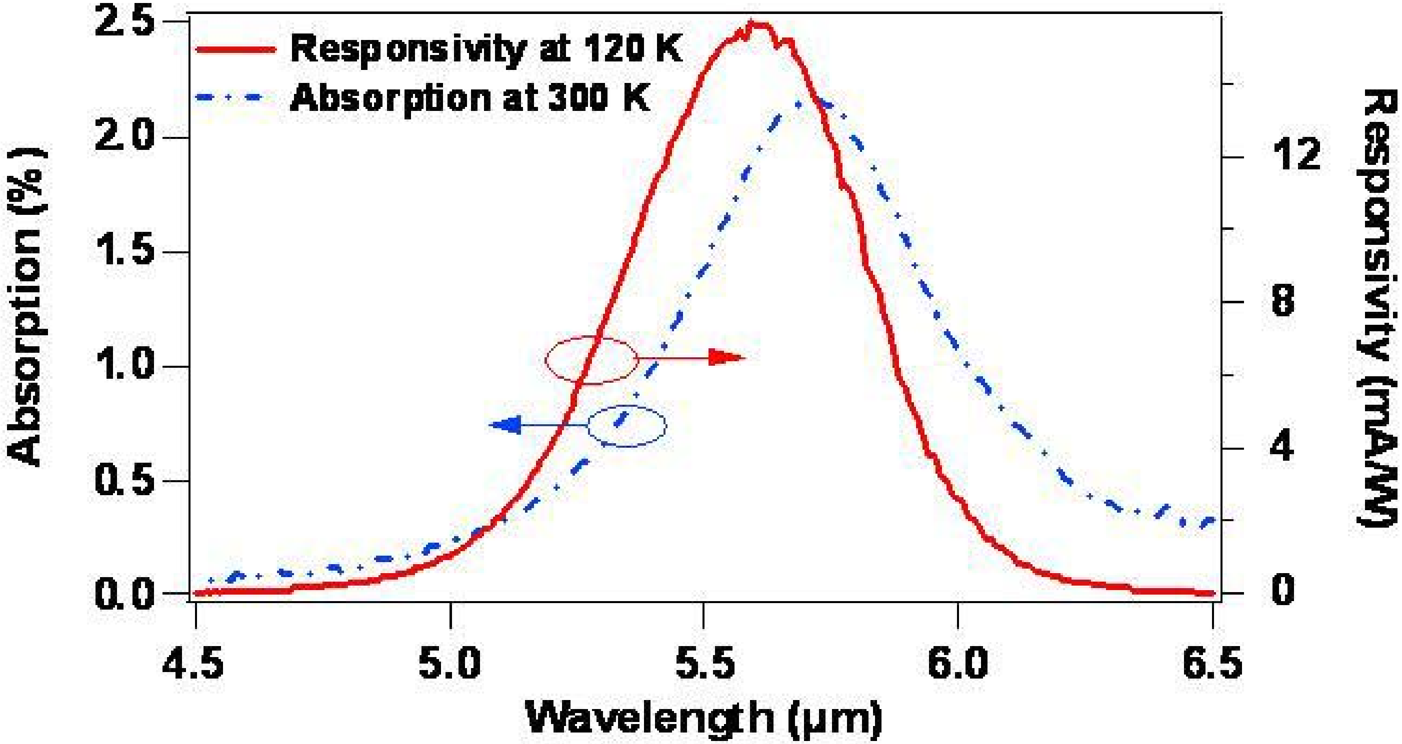
Absorption peak :

λ = 5.7 µm



- Multipath absorption measurement on a full wafer
- Doping concentration deduced from absorption coefficient : Nd = 10^{12} cm^{-2}
- % Al deduced from DDX measurement : 47 %

Characterization : Responsivity



Responsivity at peak, for a 100µm×100µm pixel, at 120 K, at 0 V and with an optical coupling grating :

R = 15 mA/W

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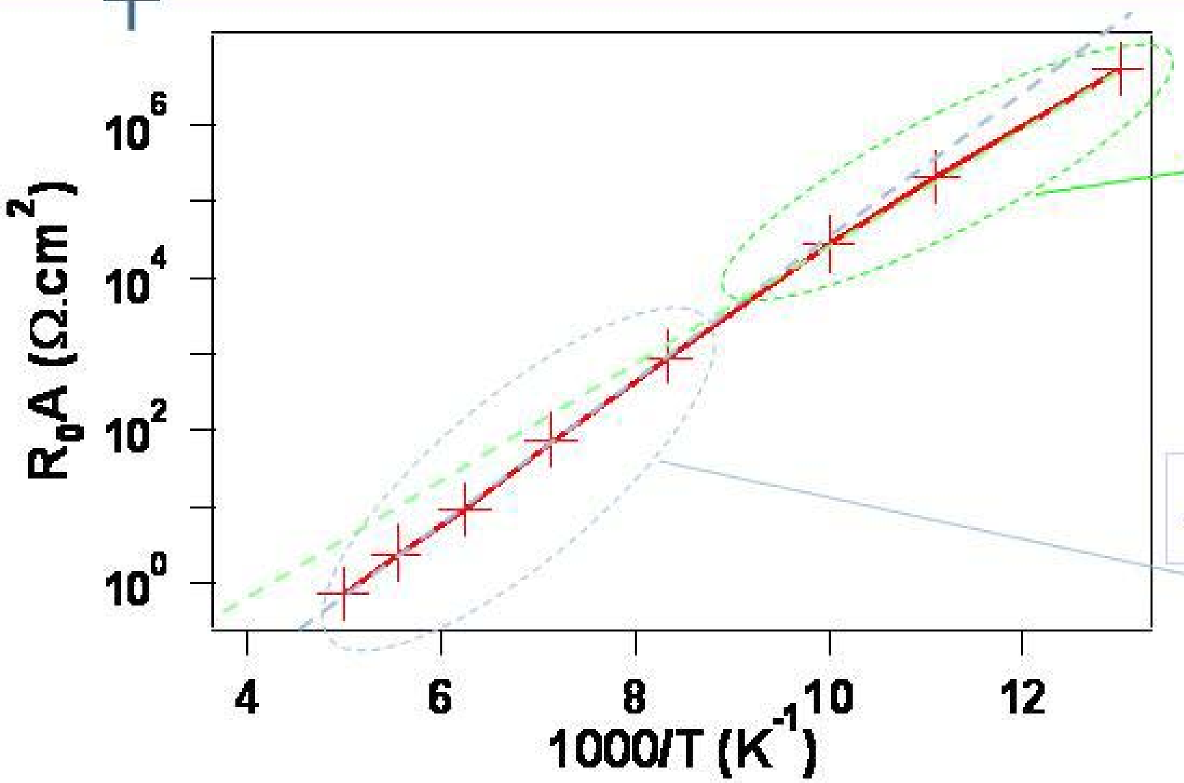
Characterization : resistivity

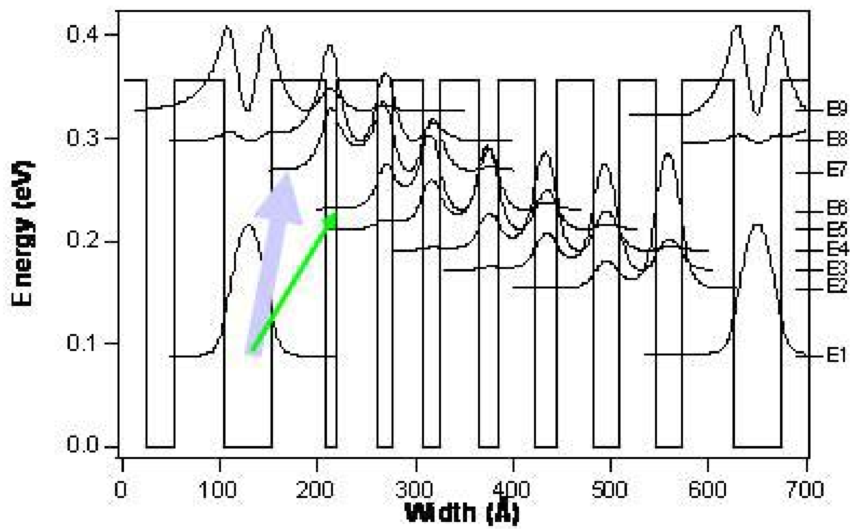


Activation energy Ea ≈ 150 meV

Transition E1 - E6

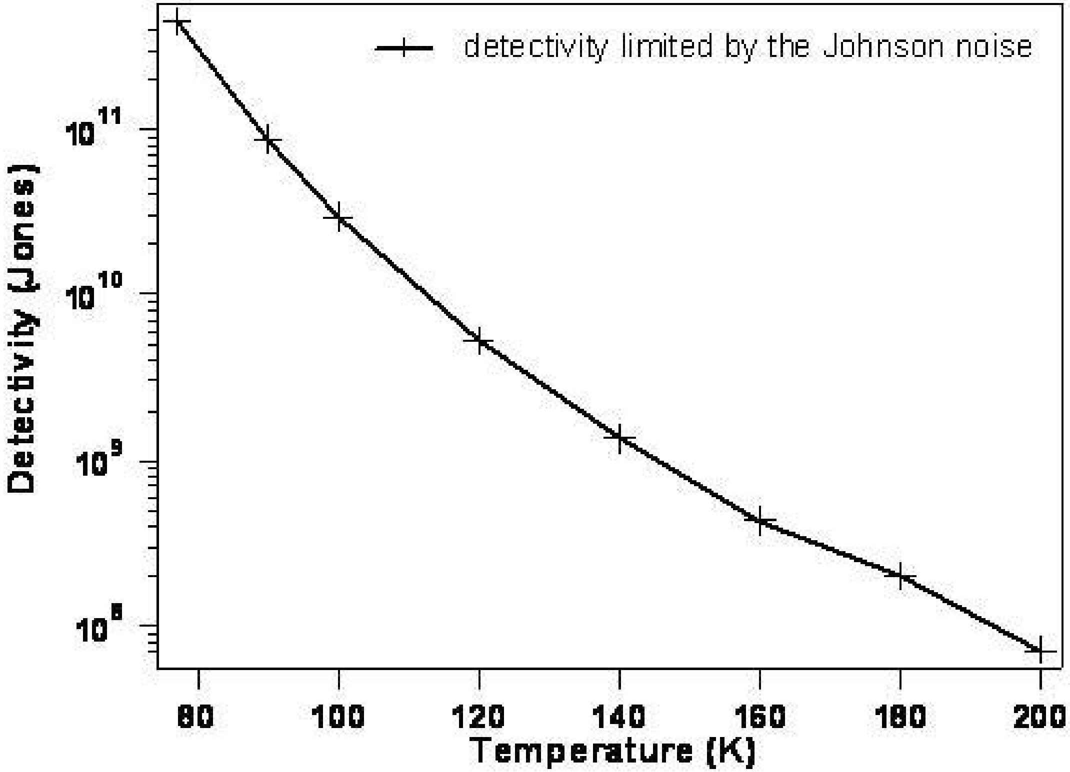
Activation energy Ea ≈ 180 meV

Transition E1 - E7



- High resisitivity :
  - 5 10^6 Ω.cm² @ 77 K
  - 2.7 10^4 Ω.cm² @ 100 K

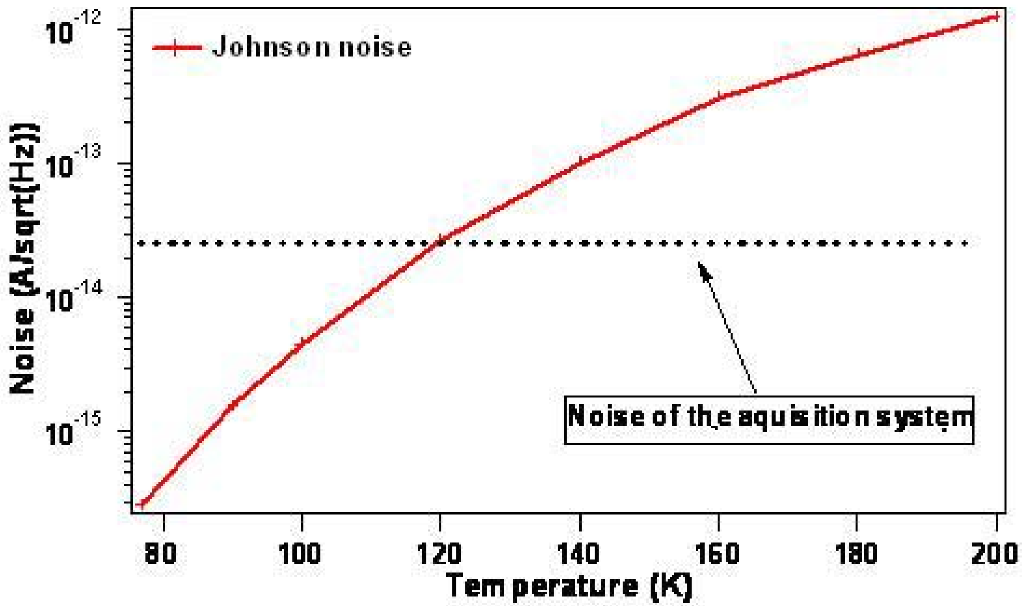
- leakage current due to transition toward a high energy level (E7)



D* = 1.2 10^9 Jones

at 140 K, for a 100µm square mesa, with an optical coupling grating, at 0V

- One order of magnitude lower than MCT
- Due to lower quantum efficiency (same situation than QWIPS)



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Hypothesis on the model

1 ⇨ Electron/LO-phonons interaction = dominant scattering process

2 ⇨ The electronic mobility is higher inside a cascade than between two consecutive cascades

- ➘ Intra and inter-cascade transitions classification
- ➘ Introduction of quasi Fermi levels associated with each cascade

3 ⇨ Low applied bias (calculation of R_0A, and photovoltaïc operation) : The electric field will be considered as a perturbation

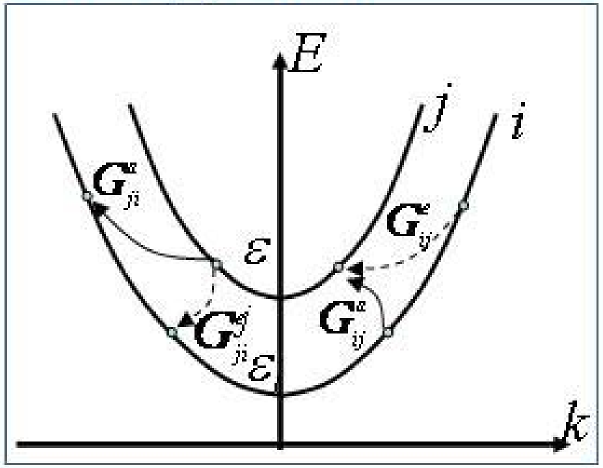
1 ⇨ Predominant scattering process : Electron/LO-phonons interaction

Neglected scattering mechanisms :
- Interface roughness scattering
- Acoustic phonons scattering
- Electron-electron interactions

May not be true at very low temperature (see Leuliet et al. Phys. Rev. B 2006)
- not a problem for infrared detection application

$$G^a_{ij} = \int_{\varepsilon_j - \hbar\omega_{LO}}^{\infty} S^a_{ij}(E) f(E)\left(1 - f(E + \hbar\omega_{LO})\right) n_{opt} D(E)\, dE$$

$$G^e_{ij} = \int_{\varepsilon_j + \hbar\omega_{LO}}^{\infty} S^e_{ij}(E) f(E)\left(1 - f(E - \hbar\omega_{LO})\right)\left(1 + n_{opt}\right) D(E)\, dE$$



- Sij* single state transition rate to subband j
- Gij global transition rate from subband i to subband j

At thermodynamical equilibrium :

$$G^a_{ij} = G^e_{ji}$$

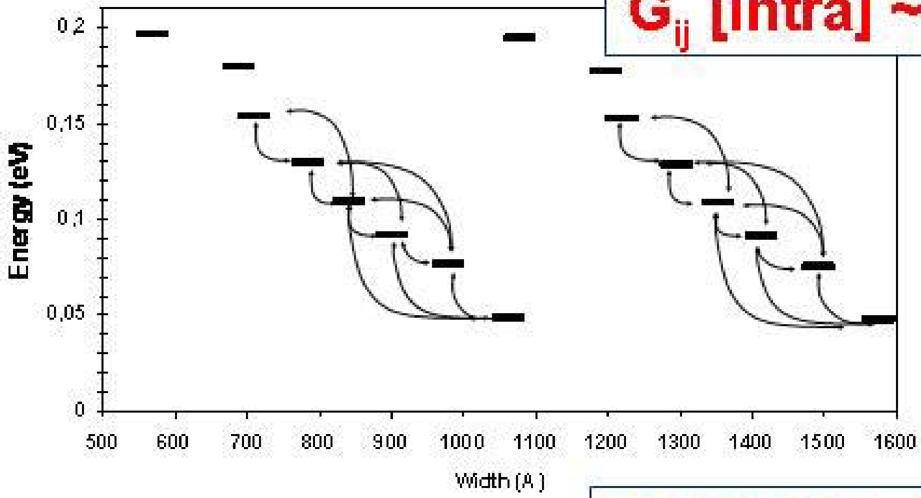
⇨ **The net current is zero**

*Ferreira and Bastard, *Phys. Rev. B*, **40**, 1074 (1989)

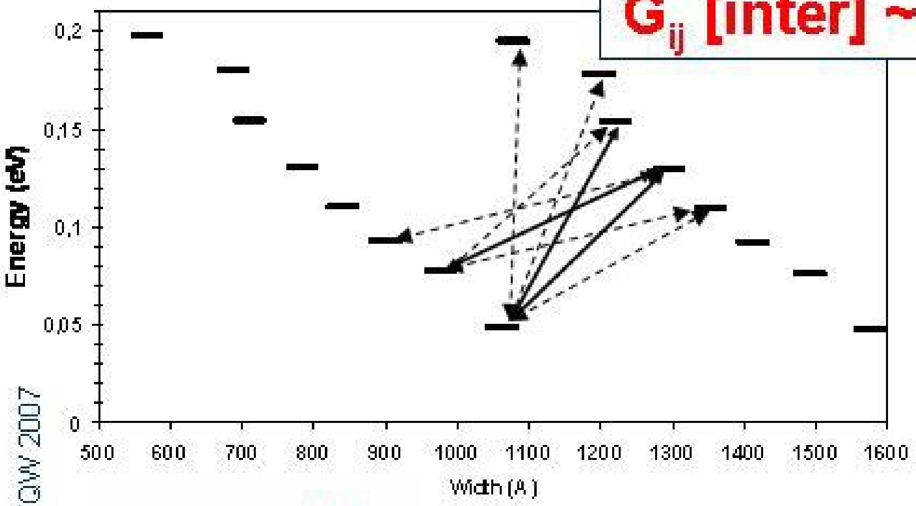
Hypothesis on the model

2 ⇨ Under bias, each cascade keeps its own quasi Fermi level

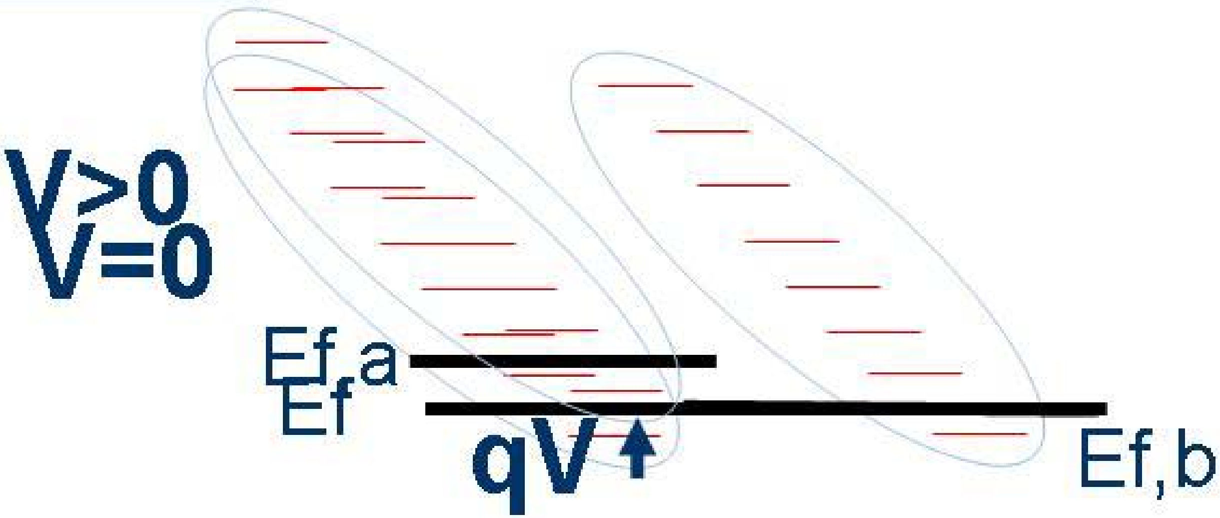
G_{ij} [intra] ~ 10^{20} / 10^{25} $m^{-2}s^{-1}$



G_{ij} [inter] ~ 10^{18} $m^{-2}s^{-1}$



- G_{ij} [intra] > G_{ij} [inter]
- each cascade at <u>quasi thermodynamical equilibrium</u>



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⇨ 3 - The bias considered as a perturbation

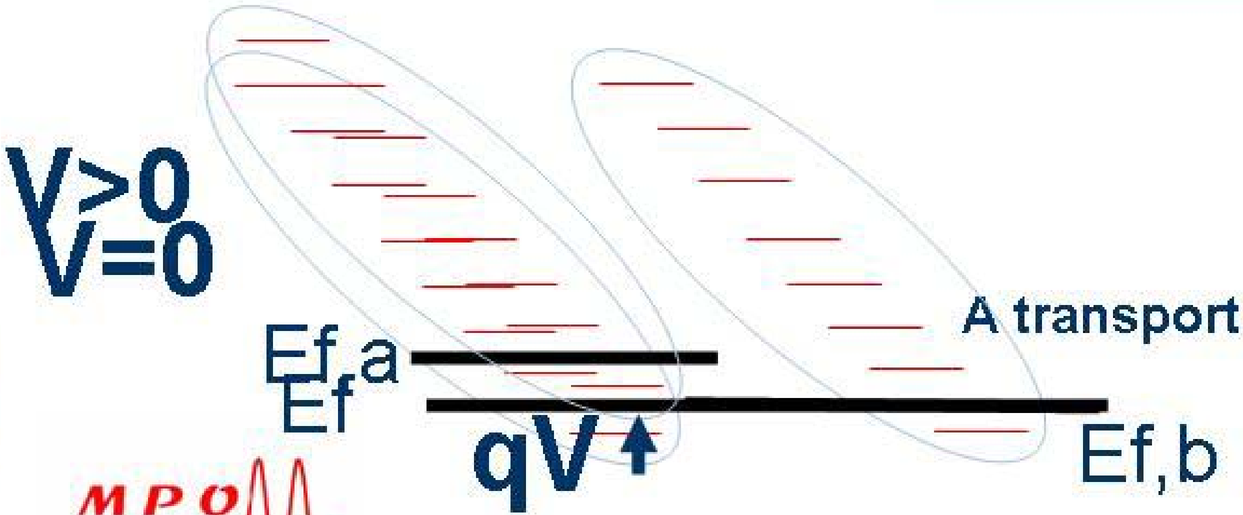
$$G_{ij}^{a}(V) = \int_{\varepsilon_j - \hbar\omega_{LO}}^{\infty} S_{ij}^{a}(E)\, f_A(E)\big(1 - f_B(E + \hbar\omega_{LO})\big)\, n_{opt}\, D(E)\, dE$$

The matrix elements do not depend on the very small applied bias

The bias breaks the Fermi level between subband i (cascade A) and subband j (cascade B)

Theses Fermi factors are different in G_{ij}^{a} and G_{ji}^{e}

$$G_{ij}^{a} \neq G_{ji}^{e}$$



A transport results from this non-equilibrium

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The electronic transport in QCDs described with an Einstein relation

$$J = q\sum_{i\in A}\sum_{j\in B}\left(G_{ij}(V) - G_{ji}(V)\right) = q\sum_{i\in A}\sum_{j\in B} G_{ij}^{eq}\,\frac{qV}{k_B T}$$

$$\Rightarrow R_0 A = \frac{k_B T}{q^2 \sum_{i\in A}\sum_{j\in B} G_{ij}^{eq}}$$

Einstein Relation

$$\frac{D}{\mu} = \frac{k_b T}{q} \quad \text{with} \quad D = \frac{l^2 \sum_{i\in A}\sum_{j\in B} G_{ij}^{eq}}{n_{2D}}$$

* C. Koeniguer et al., Phys. Rev. B, 74, 235325 (2006)

Discussion in relation to the model

The resistivity depends only on :

$$R_0 A = \frac{k_B T}{q^2 \sum_{i \in A} \sum_{j \in B} G_{ij}^{eq}}$$

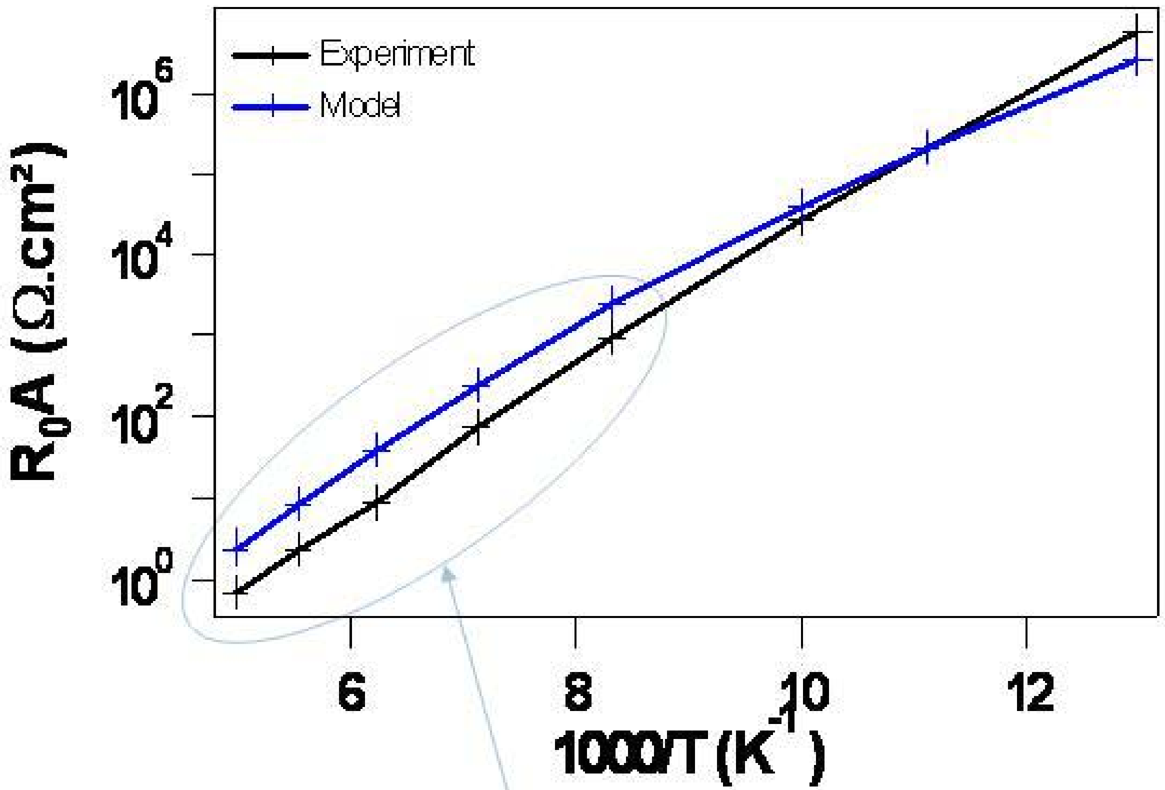
- the doping concentration
- the physical parameters of the sample (thickness of the wells and barriers, materials constants like effective masses or Al percentage ...)

which are include in the Gij terms :

$$G_{ij}^{a}(V) = \int_{\varepsilon_j - \hbar\omega_{LO}}^{\infty} S_{ij}^{a}(E)\, f_A(E)\left(1 - f_B(E + \hbar\omega_{LO})\right) n_{opt}\, D(E)\, dE$$

There is no <u>other adjustable parameters (no fit parameters)</u>

Modeling : Results



At high temperature, activation energy is in good agreement with the experiment

- less than one order of magnitude
- The differences are due to :
  - the differences between the expected and the real structure
  - the hypotheses of the model concerning the scattering mechanism

But there is no fit parameters

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- True photovoltaic use
- Long integration times (no dark current)

The user

- Spectral band
- Working distance
- Integration time
- Pixel size
- Working temperature

→ Number of incident photons

→ Max. number of stockable electrons

Q

The structure

- Doping level
- Applied bias (in a QWIP)
- Working temperature

→ Photo electrons + Dark electrons < Q

This condition usually limits the doping level and/or the working temperature
This has nothing to do with the detectivity

QCDs can work at higher doping levels than QWIPs : it may be interesting for low photon number application (4 µm, long distance...)

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- Performances of a QCD at 5.7 µm :
  - Responsivity at peak at 120 K : 15 mA/W
  - High Resistivity : $5\ 10^{6}\ \Omega.cm^{2}$ @ 77 K
- Model for electronic transport :
  - No other adjustable parameters except the doping concentration and the constants of the materials
  - Gives a good approximation of the resistivity
  - This gives to the possibility of a calculation of the performances of the detector and the system during its design (as a function of number of wells, doping...)

Thank you for your attention.

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