Van Hove singularities in intersubband transitions in multiquantum well photodetectors

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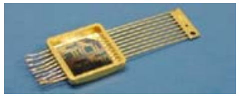
Context

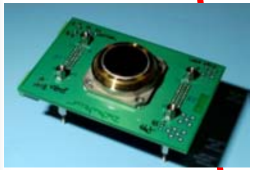
ONERA = French Agency for Aeronautics and Aerospace

Characterization of IR detectors

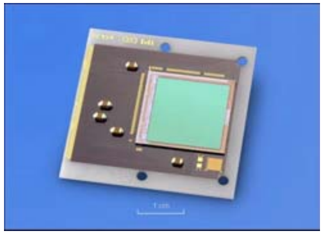
- Evaluation of the radiometric performances of IR sensors (MCT, Si:Ga, InSb, µbolometers, QWIPs….)
- Realization of innovative test benches :
  - Angular response measurements,
  - MTF measurements,
  - Spectral characterization, …
- Development of device models



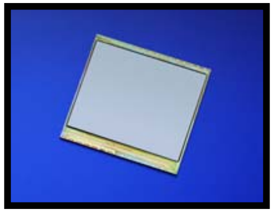
Single element QWIP “low-noise”
Fraunhofer Institut



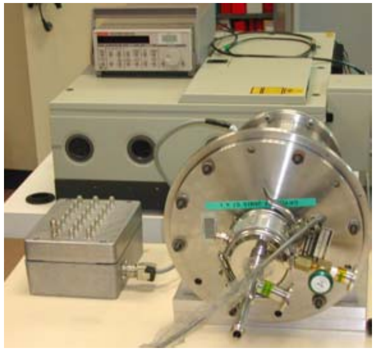
µbolometer
320×240 ULIS



1000x1000 "IRCMOS" array of MCT
CEA/LIR



640x512 array of QWIP
Thales-R&T



FTIR

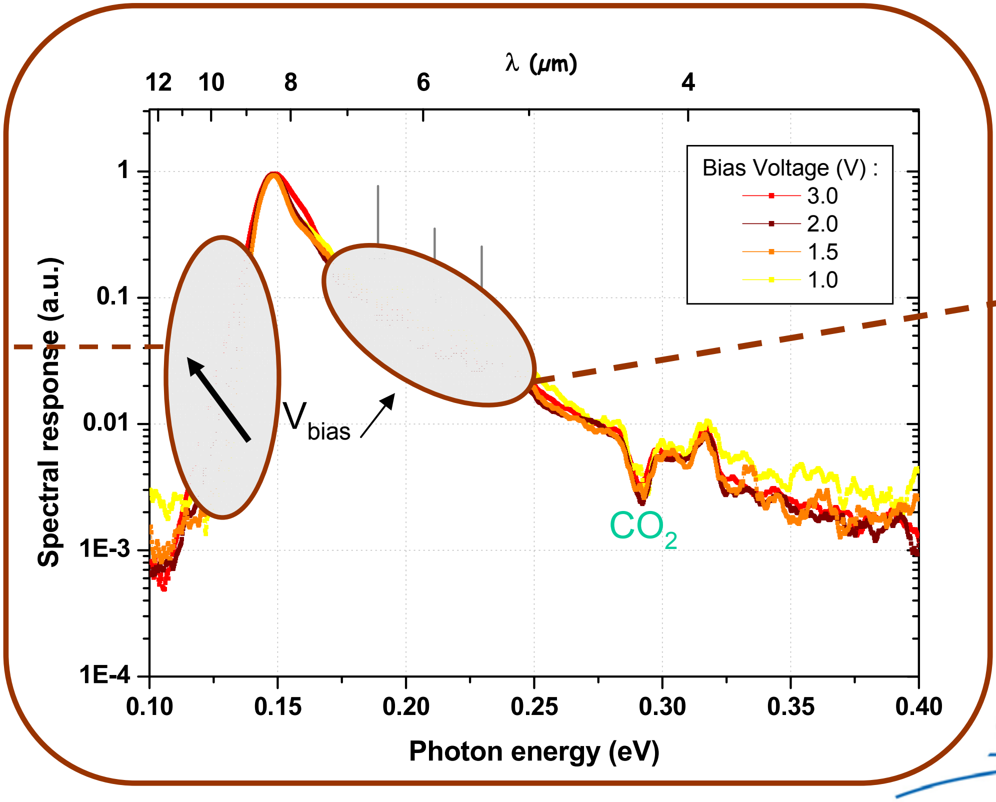
“BRASIL”*

* I. Ribet-Mohamed & al., *Infrared Physics and Technology*, *__49__ (2005), 119-131*

Introduction

- Purpose : Develop new experiments in order to enhance our knowledge on QWIP Physics

  - Idea : Log spectra of QWIP responsivity to allow off-band analysis



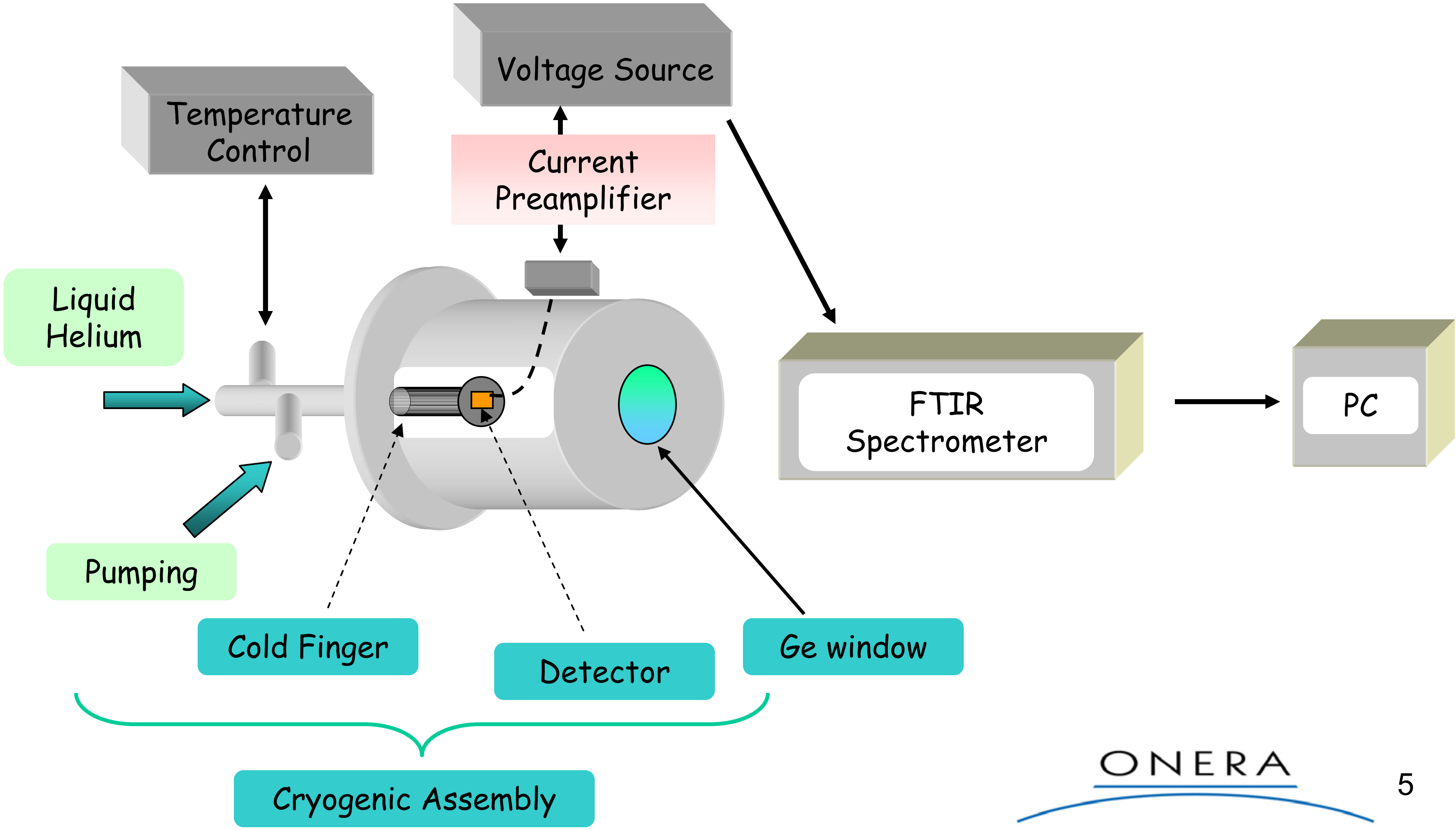
low energy part : cut-off affected by the applied electric field

High energy part : resonant features

Outline

- Experimental setup
- Theoretical model
- Main results

- *Test bench to perform spectral response measurements* :



Voltage Source

Temperature Control

Current Preamplifier

Liquid Helium

FTIR Spectrometer

PC

Pumping

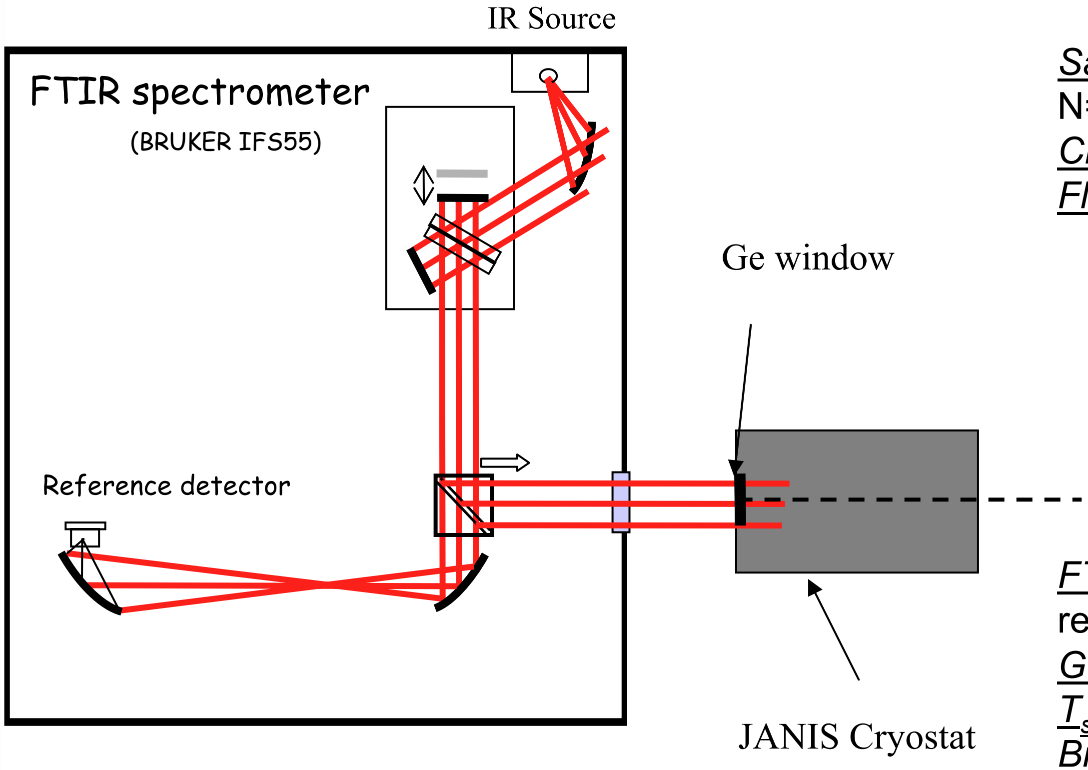
Cold Finger

Detector

Ge window

Cryogenic Assembly

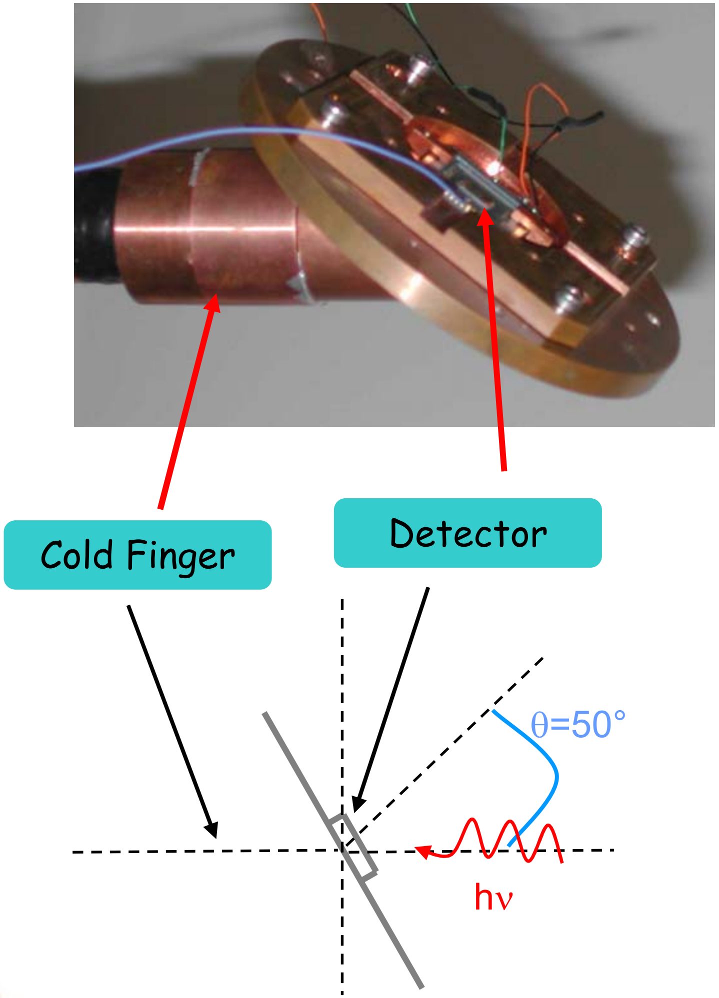
- *FTIR spectrometer :*



Sample : λ=8.5 µm,
N=40 QWs, pixel without grating
Cryostat : JANIS
Fluid : liquid Helium

FTIR parameters : f_{acq}= 5kHz,
resolution = 4cm^{-1}
Ge window (λ_{cut} ~16µm (625 cm^{-1}))
T_{sample} = 40K
Bias voltage : -3, -2, -1.5, -1 V

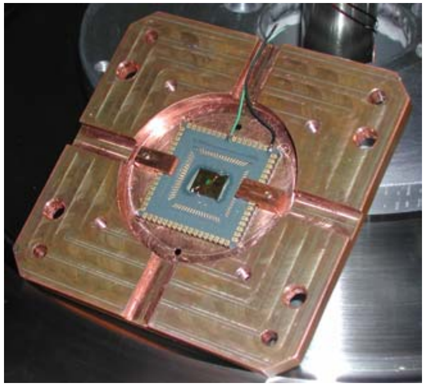
- *Characteristics of the single detectors under study :*



Sample :

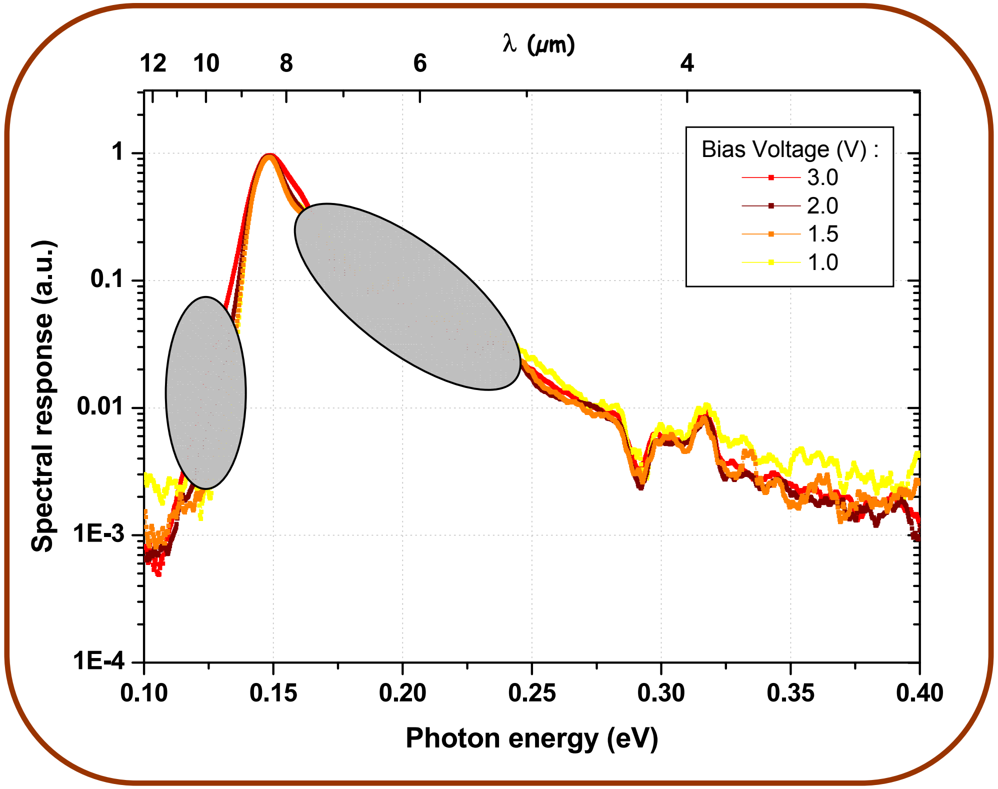
QWIP Thales - RT
λ=8.5 µm,
ϕ =100 µm^2
N=40 QWs
&
pixel without grating

Pixel illuminate
under
tilted incidence



** Note : An incidence angle of 50° on the sample leads to an angle of 13.8 ° on the quantum wells*

- *Experimental results* :



√ Photocurrent spectra studied over more than 3 orders of magnitude

√ Repeatability of the measurements

√ Same spectral response shape for several angles of incidence on the sample

√ New features in the spectral response at low and high energy !!!!

- *<u>Possible origin of high energy features</u> ?*

√ Calculation of QWIP absorption taking into account QW periodicity had never been done before

√ Solve numerically Schrödinger equation under applied electric field → Spurious resonances due to boundary conditions

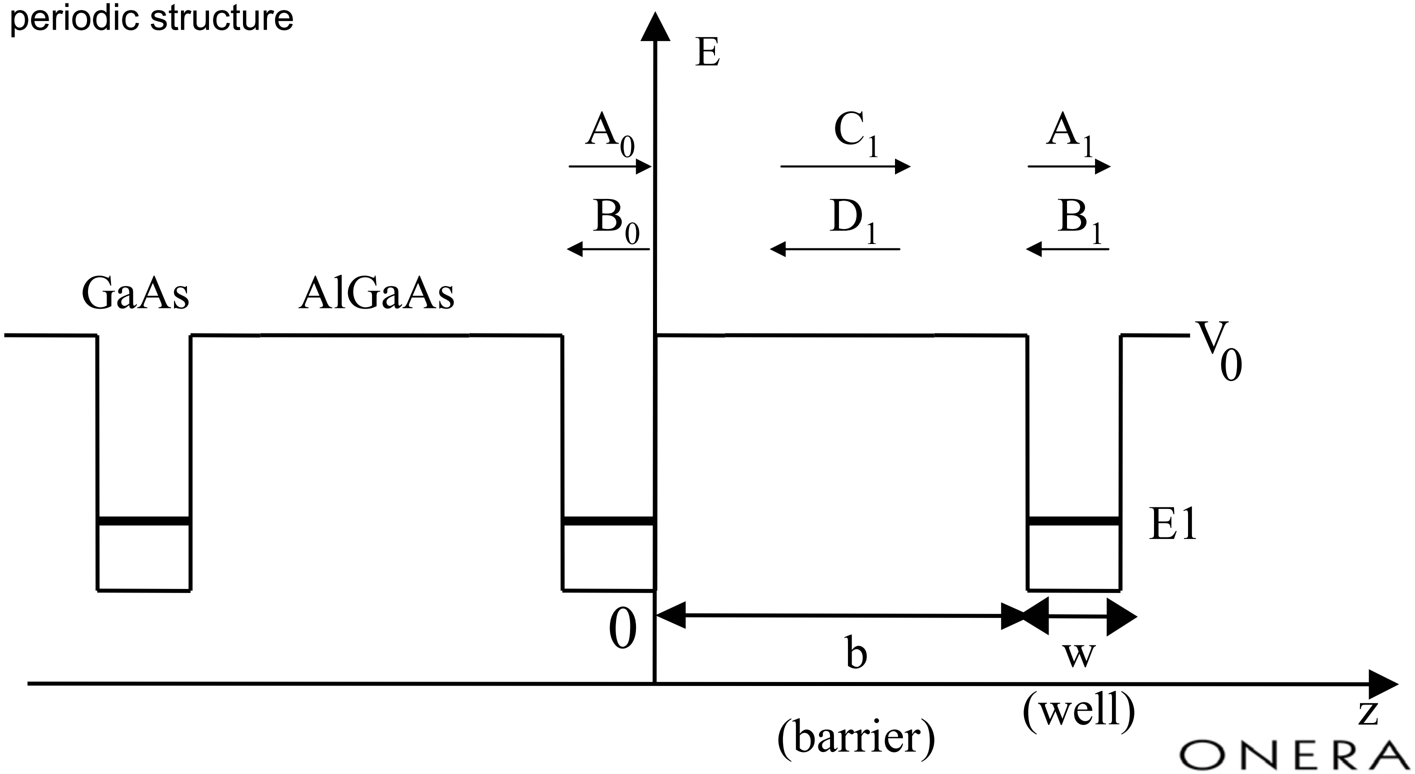
√ Features slightly affected by applied electric field

⇒ **Kronig-Penney approach**

- *Model* :

① Kronig-Penney model for multiquantum well structure :

√ Propagation matrix approach for a periodic structure



2 Schödinger equation for the envelope function*

$$\frac{-\hbar^2}{2m_{eff}}\Delta\Psi(z)+V\Psi(z)=E\Psi$$

$$\text{where } V=\begin{cases} V_0 & 0\le z<b \\ 0 & b\le z<b+d=L \end{cases}$$

We get for each $\xrightarrow{\hspace{2em}}$ period of the structure

$$\psi(z)=\begin{cases} A_0e^{ikz}+B_0e^{-ikz} & -d\le z\le 0 \\ C_1e^{ik_b(z-d)}+D_1e^{-ik_b(z-d)} & 0\le z\le b \\ A_1e^{ik(z-L)}+B_1e^{-ik(z-L)} & b\le z\le L \end{cases}$$

$$k=\sqrt{\frac{2m}{\hbar^2}E}$$

$$k_b=\sqrt{\frac{2m_b}{\hbar^2}(E-V_0)}$$

Using the boundary conditions at z=0, we find the matrix equation for the coefficients of the wave functions in region 0 and the barrier b :

$$\begin{bmatrix} C_1 \\ D_1 \end{bmatrix}=\overline{\overline{F}}_{b0}\begin{bmatrix} A_0 \\ B_0 \end{bmatrix}$$

Similarly, the boundary conditions at z=b give the matrix equation for region 1 and the barrier b :

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix}=\overline{\overline{F}}_{1b}\begin{bmatrix} C_1 \\ D_1 \end{bmatrix}$$

We have the transition matrix for one period consisting of one well and one barrier :

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix}=\overline{\overline{T}}\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \quad \text{where} \quad \overline{\overline{T}}=\overline{\overline{F}}_{1b}\,\overline{\overline{F}}_{b0}$$

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* *S.L. Chuang, Physics of Optoelectronic Devices (Wiley Interscience, New York, 1995)*

2 Schödinger equation for the envelope function

For the nth period, we find :

$$\begin{bmatrix} A_n \\ B_n \end{bmatrix} = \overset{=}{T}^{n} \begin{bmatrix} A_0 \\ B_0 \end{bmatrix}$$

The eigenvalues and eigenvectors
of the 2×2 matrix T are solutions
of the determinantal equation :

$$\overset{=}{T} \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = t \begin{bmatrix} A_0 \\ B_0 \end{bmatrix}$$

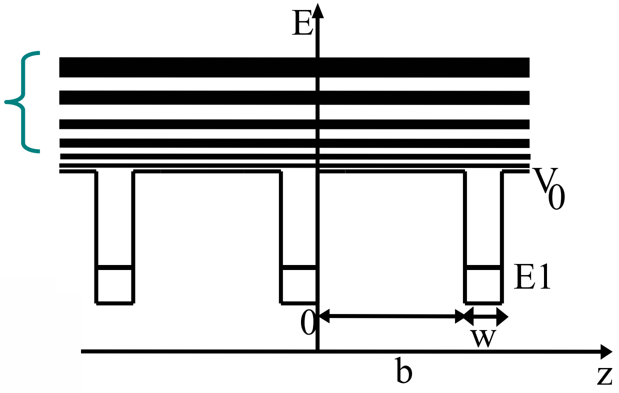
$$P = \frac{mk_b}{m_b k}$$

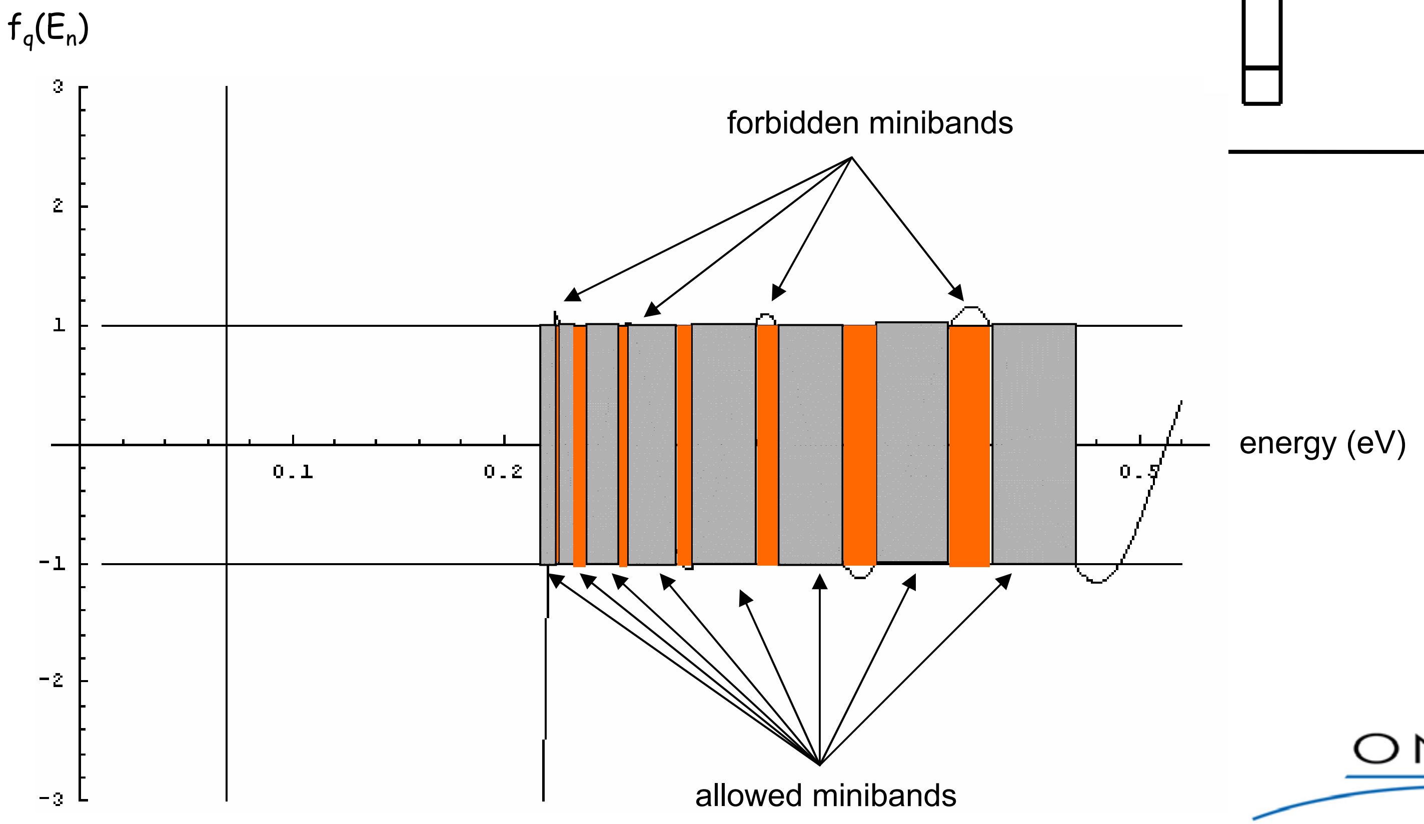
We get that the eigenequation is :

$$\cos(qL) = \cos(kw)\cos(k_b b) - \frac{1}{2}\left(\bullet + \frac{1}{P}\right)\sin(kw)\sin(k_b b) = f_q(E)$$

③ **Miniband :**

→ condition on the energy levels : $\left| f_q(E_n) \right| \leq 1$





4 Miniband dispersion :

- Bloch quantum state :

$$|n,k\rangle = u_{n,k}(z)e^{ikz}$$

Displays the periodicity of the QWIP structure

- Momentum matrix element between the bound state and the excited state:

$$\boxed{p_{1n}(k) = \left|\left\langle 1,k\left|\frac{\hbar}{i}\frac{d}{dz}\right|n,k\right\rangle\right| \Rightarrow p_{bn}(k) = \hbar\left|\int u_{1,k}(z)*\frac{d}{dz}u_{n,k}dz\right|}$$

- Fermi Golden Rule :

$$\boxed{P(h\nu) \propto \rho(E1+h\nu)p_{b,n}(k)^2}$$

- Absorption :

$$\boxed{\alpha \propto P(h\nu) * \text{Lorentzian}(\Gamma, h\nu)}$$

ONERA

- *Model : overview*

Remind the approach of our study

. Periodicity of the QWIP structure

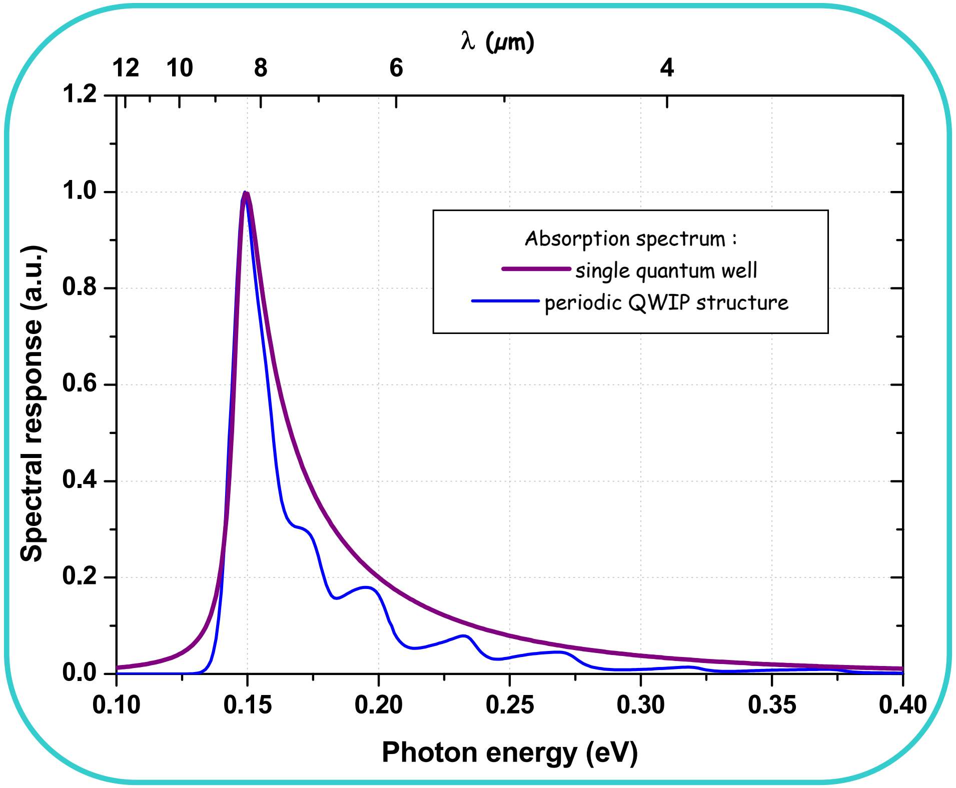
. Kronig-Penney approach

. Response modeled by taking into account quantum absorption

. Not included the already well known transport mechanisms

. Empirical parameters needed like x_{Al},b and w, Γ

- *Importance of QW periodicity* :



Purple line :

absorption spectrum obtained using the oscillator strength for the bound to continuum transition*

Blue line :

our Kronig-Penney approach

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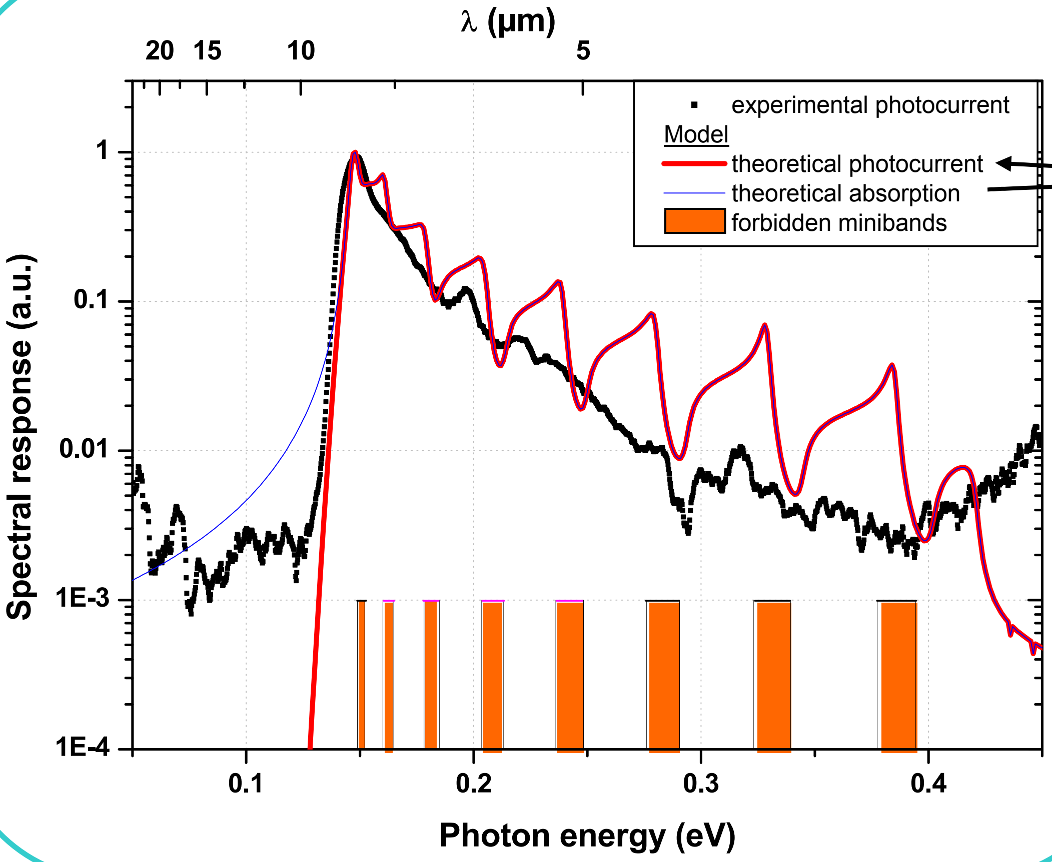
* *H.C. Liu, J. Appl. Phys., **73,** pp. 1-7 (1993)*

- *Comparison between an experimental QWIP log spectrum and our theoretical model* :



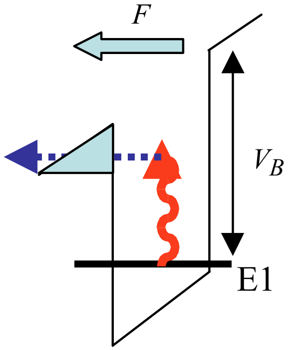
Taking into account of electric field assisted tunnelling

We noticed that the off-band response is non negligible (~1% in the 3–5 μm for a 8–12 μm detector)

- *Two important results* *

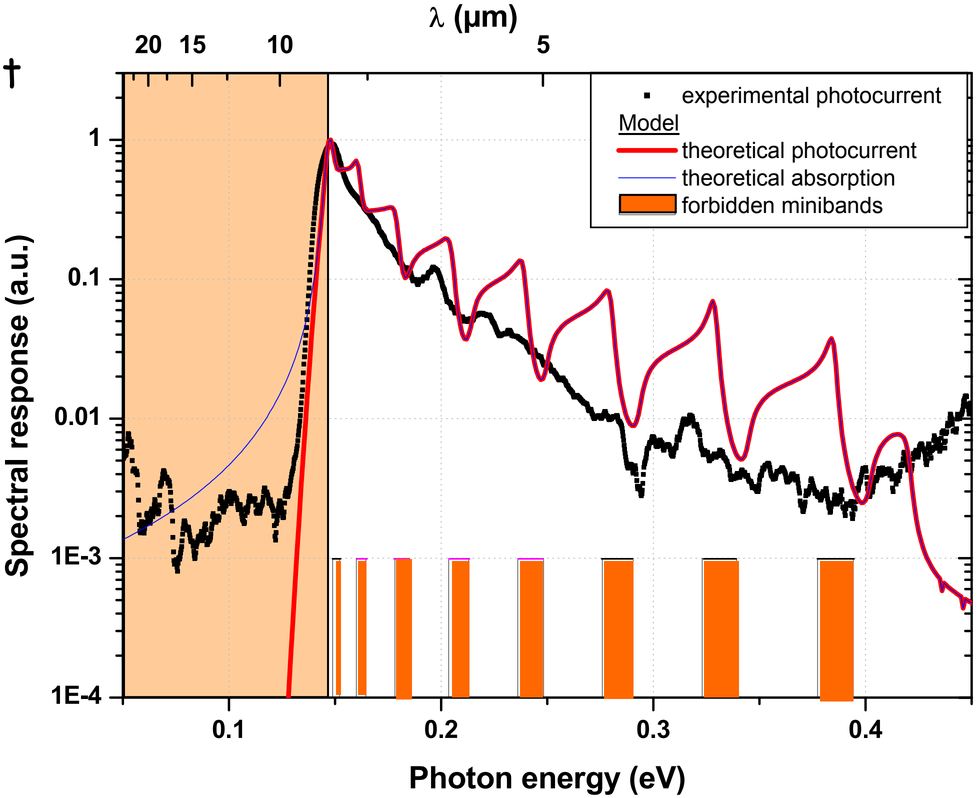
①

Low energy part :
Fowler-Nordheim effect



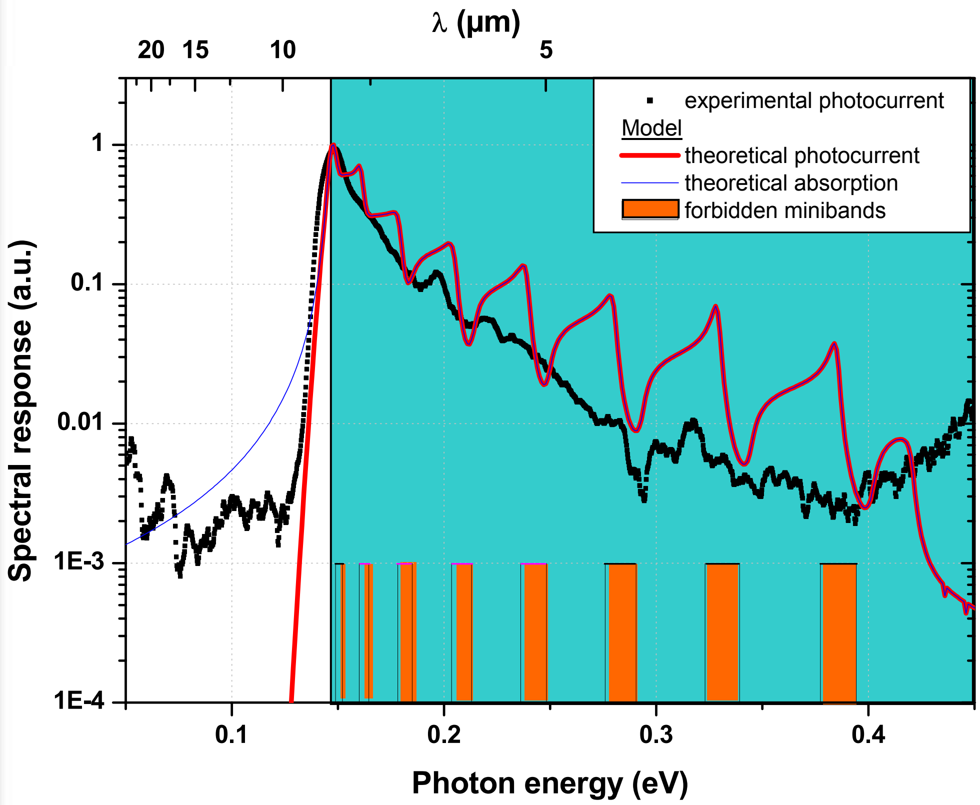
V_B-E1 : Ionization threshold

➡ Electric field assisted tunnelling

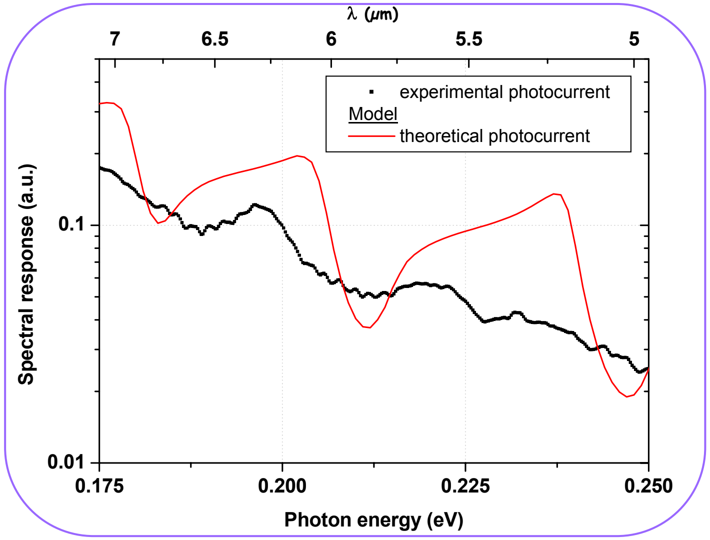


* J. Le Rouzo & al., Appl. Phys.Lett, **88,** 091117 (2006)

②



Van Hove singularities at the miniband edges



→ Critical points in the density of states

Conclusion

Electric field assisted tunnelling

&

Van Hove singularities

Phenomena which have been largely overlooked before

→ important role in the low and high energy parts of the QWIP photocurrent!

Authors are also grateful to colleagues from Thales-R&T for providing the samples

Thank you for your attention ...
Any question ?