Quantum Cascade Detector at 5 micrometers

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***Abstract*— A Quantum Cascade Detector (QCD) which operates between 5 and 6 micrometers will be presented. QCD operation has been characterized in terms of absorption, responsivity, resistivity, noise and detectivity. A theoretical model will be presented which explains the electronic transport mecanisms as a function of temperature.**

***Index Terms*— photodetection, mid-infrared, quantum wells structures.**

Quantum Cascade Detectors (QCDs) have been firstly presented in the 8-12 µm band [1]-[3]. Far-infrared photodetection near the THz range using QCD have been also proposed [4]. More recently, InP-based QCD structures have been introduced in the mid-infrared spectrum [5], around 5 and 9 µm. We will present here a QC detector, based on a GaAs/AlGaAs heterostructure, which has been fully characterized with diffraction gratings on top of the pixel, directly suitable for focal plane array integration. The structure is composed of 40 periods of 8 GaAs wells and 8 $Al_{0.44}Ga_{0.56}As$ barriers. The first well of each period is Si-doped (nominal doping concentration : 5 10^{11} cm^{-2}). The width of the wells and barriers are adjusted in order to create a quantum cascade of 9 energy levels, as it can be shown on figure 1. The principle of the detection in such a structure is the following: under illumination, electrons localized on the lowest energy level E_1 (based in the first quantum well of each period) are excited to higher subbands E_8 or E_9. They are then transferred to the next period through successive relaxations in the cascade using electron-LO phonons interactions.

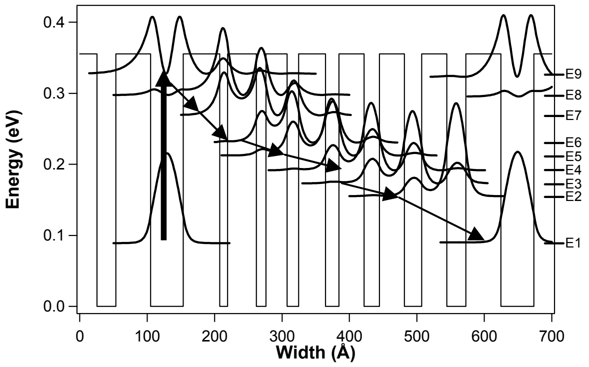

Fig 1. : Structure of one period. Square wave functions are represented for each energy level. Arrows represent the path of electrons which participate to the photo-current.

Figure 2 represents the absorption spectrum at 300 K of the sample. The device is characterized by only one absorption peak around λ=5.7 µm, near the expected transition equal to λ=5.9 µm. The oscillator strength of this transition deduced from simulation is equal to 81%. The device was designed to concentrate the oscillator strength around a single intersubband transition to decrease the influence of the other transitions and maximize the peak photoresponse.
Responsivity spectrum at 77 K is shown on figure 2 for a 100 µm-square pixel without optical coupling grating. This low temperature spectrum is blue shifted with respect to the absorption spectrum at room temperature, as usual for an intersubband transition. Peak responsivity measurement at λ=5.8 µm for a pixel with an optimized optical coupling grating is equal to 18 mA/W at 140 K. The evolution of the peak responsivity as a function of temperature is observed to be constant, showing that the electronic extraction is robust as a function of temperature. The Johnson noise limited detectivity of the device as a function of temperature therefore follows the R_0A parameter, where R_0 is the dynamical resistance at 0 V and A the pixel area.

Current-voltage characteristic measurements lead to the R_0A parameter. Figure 3 represents the evolution of this parameter as a function of the 1000/T where T is the temperature. Activation energy E_a can be deduced from this curve: $E_a=171\ meV$. This value corresponds to the electronic transition E_1-E_8. The energy level E_8 is indeed the first energy level characterized by a significant overlap of the corresponding wave function with the wave function of the first energy level E_1. This electronic

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transition acts as a bottleneck for electronic transfer between two consecutive cascades. At 140 K, the detectivity limited by the Johnson noise for a 100 µm square mesa (with optimized optical coupling grating), is equal to D*(λ=5.8 µm) =1.7 10^9 Jones (cm.Hz$^{1/2}$.W^{-1}). This is the highest detectivity reported for a QCD at such a temperature. This approaches the QWIP performances, and it will be shown why higher doping levels can increase again the QCD performances, thanks to the possibility of working at lower applied voltage.

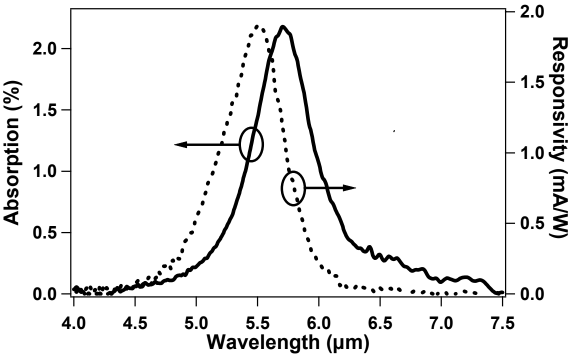

Fig 2. : Absorption and responsivity spectra. The solid line represents the absorption spectrum measured at 300 K. The dashed line represents the responsivity spectrum at 77 K for a 100µm×100µm pixel without any optical coupling grating.

The modeling of electronic transport in dark condition in a QCD will also be presented. In this model [6], we consider two consecutive cascades of energy levels and we assume that the transitions are governed by electrons-LO phonons interactions only. Under small bias voltage, the Fermi level splits off in two quasi Fermi levels, respectively associated with the two cascades. Each cascade stays at thermal equilibrium. This assumption relies on the fact that electronic transfers inside a cascade are far more efficient than inter-cascade transfers. Under these conditions, current-voltage characteristic can be calculated. It will be shown that the R_0A parameter can be evaluated with a simple formula:

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

where k_B is the Boltzman constant, T the temperature of the sample, q the electronic charge and G_{ij}^{eq} is the transition rate from the subband i of the first cascade A to the subband j of the second cascade B, evaluated at equilibrium. This expression, which can be interpreted as an Einstein relation adapted to the case of QCDs, traduces the fact that the electronic transport is described as a diffusion through all subbands.

The excellent agreement between this simple model and the experimental results will be shown for different types of QCDs. It must be noticed that for the first time the performances of an infrared detector can be calculated without any adjustable parameter except the doping density. The influence of the doping concentration on the performances will be studied in details, in order to optimize this crucial parameter. Finally, the specific advantages of quantum cascade detection at short infrared wavelengths (below 4 micrometers) will be developed.

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