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## Interface roughness transport in THz quantum cascade detectors

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Infrared Detectors based on a Quantum Cascade have been proposed to suppress the dark current which is a limiting factor in Quantum Well Infrared Photodetectors. Those detectors have been mainly designed for the mid-infrared wavelength. Operating in the Terahertz range involves a complete change of regime of transport since the photon energy is lower than the optical phonon energy. Thanks to a two dimensional model of transport, we have identified interface roughness as the key interaction in such a structure. Interface parameters, evaluated by scanning transmission electron microscopy, are used to study their influence on the resistance of the device.

In order to overcome the limiting factor of Quantum Well Infrared Photodetectors (QWIPs), a high dark current, photovoltaic detectors inspired from Quantum Cascade Laser (QCL) and named Quantum Cascade Detectors (QCD) have been designed<sup>1,2,3,4,5,6</sup>. They consist in several periods composed of different quantum wells. As in QWIPs, this device is unipolar and the infrared absorption occurs between two subbands. The separation in energy between the subbands corresponds to the detection wavelength. Unlike the QWIP, where the excited electron is extracted from the top subband by an external electric field, in QCDs, it escapes by resonant tunneling to the adjacent quantum well. Then, the electron cascades from subband to subband down to the next period. Such detectors were initially designed in 3-5 $\mu\text{m}$  and 8-12 $\mu\text{m}$  wavelength ranges. In this case, the involved energy differences between subbands and the operating temperatures are high enough for efficient longitudinal optical (LO) phonon emission and absorption. A previous study has determined LO phonons as the dominant scattering process in the transport without illumination.<sup>6</sup> However, this argument fails in Terahertz (THz) range as lower energies are involved. In this range, the dominant scattering process has still to be identified.

In this letter, first, we highlight the dominant interaction in a THz QCD, interface roughness (IR) scattering. Then, we use scanning transmission electron microscopy (STEM) measurements to extract the key parameters of IR:  $\Delta$  the magnitude of the roughness and  $\xi$  the mean distance between defects. Only few studies have been carried out to design a THz QCD, since only one other device has been presented.<sup>7</sup> The QCD under study is a GaAs-Al<sub>0.27</sub>Ga<sub>0.73</sub>As heterostructure. It consists in forty periods of 5 coupled quantum wells. The layer sequence in  $\text{\AA}$ , starting from the first barrier, is as follows: 75/**52**/30/**48**/50/**44**/60/**50**/68/**54**. Barriers are in bold. The first two wells of a period are doped with Si donors ( $3 \times 10^{17} \text{cm}^{-3}$ ) in the central third of the well. The photonic transitions  $E_5-E_1$  and  $E_4-E_1$  are expected to lead to a maximum absorption at 70 $\mu\text{m}$ . This device, designed and grown by the University Paris Diderot and the III-V Lab, will be presented and characterized in a future publication.

In the THz range, the dominant interaction is *a priori* difficult to identify. For this purpose, we used a hopping transport code<sup>8</sup> between two dimensional states based on the Fermi Golden Rule. Wave functions were evaluated using a two band kp model. All the following scattering processes are taken into

account in our simulation: interaction between electron and LO phonon (LO), acoustical phonon (AC), alloy disorder (AL), interface roughness (IR), ionized impurities (II) and electrons (EE). We have evaluated the different relaxation rates in the cascade for each of the six processes. Calculations have been made for an electron hopping from the bottom of the initial subband ( $K_i = 0$ ), at a temperature of 10K. The interaction parameters are given in ref 8. Table I presents the intracascade scattering rates ( $1/\tau_{ij}$ ), and between two different cascades ( $1/\tau_{i'j'}$ ). The numbering system of the levels is the same as in ref 6. Interface roughness is identified as the main interaction, the corresponding rates  $1/\tau_{ij}$  are at least one order of magnitude above the others. As LO phonon interaction in 3-12 $\mu$ m QCD, IR can be considered as the interaction which has to be taken into account when evaluating the transport properties in THz QCDs. Since these scattering rates have been appraised, the net scattering rates  $G_{ij}$  between two levels can be deduced. The  $G_{ij}$  are taking into account both population of each level and scattering rates.  $G_{ij}$  are given by:  $G_{ij} = \int_0^\infty f_{FD}(E_i)(1 - f_{FD}(E_f)) \cdot \frac{1}{\tau_{ij}(E_i - E_f)} dE_i$  with  $f_{FD}$  the Fermi Dirac distribution. We assume an electronic population at the equilibrium, since the intrasubband relaxation is faster than the intersubband one<sup>9,10</sup>.

tab. I: Scattering rates (Hz) for different processes at  $K_i=0$ , under an arbitrary low electric field and at  $T=10$ K. The numbering of the level allocates the number five to the highest level in energy and the number one to the lowest level of a cascade. The prime sign is used for the levels in the neighbouring cascade.

Process	$1/\tau_{54}$	$1/\tau_{43}$	$1/\tau_{32}$	$1/\tau_{21}$	$1/\tau_{53}$	$1/\tau_{42}$	$1/\tau_{31}$	$1/\tau_{5'1}$	$1/\tau_{4'1}$
AL	$9.5 \times 10^{10}$	$8.3 \times 10^9$	$1 \times 10^{10}$	$3.3 \times 10^9$	$1.2 \times 10^{10}$	$2.1 \times 10^8$	$3.5 \times 10^8$	$3 \times 10^{10}$	$6.3 \times 10^{10}$
<b>IR</b>	<b><math>4.2 \times 10^{12}</math></b>	<b><math>3.4 \times 10^{11}</math></b>	<b><math>4.5 \times 10^{11}</math></b>	<b><math>1.3 \times 10^{11}</math></b>	<b><math>4.1 \times 10^{11}</math></b>	<b><math>7.2 \times 10^9</math></b>	<b><math>1.4 \times 10^{10}</math></b>	<b><math>9.9 \times 10^{11}</math></b>	<b><math>2.4 \times 10^{12}</math></b>
II	$1.5 \times 10^{11}$	$6.3 \times 10^9$	$7.5 \times 10^{10}$	$4.6 \times 10^{10}$	$1.7 \times 10^9$	$2.5 \times 10^8$	$3.1 \times 10^9$	$3.1 \times 10^7$	$2.3 \times 10^8$
EE	$1.4 \times 10^9$	$2.4 \times 10^8$	$5.3 \times 10^8$	$5.1 \times 10^8$	$2.4 \times 10^8$	$1.3 \times 10^6$	$4.6 \times 10^6$	$1.3 \times 10^8$	$8.3 \times 10^8$
AC	$5.7 \times 10^9$	$4.7 \times 10^8$	$7.1 \times 10^8$	$6 \times 10^7$	$5.5 \times 10^8$	$1.23 \times 10^7$	$2.3 \times 10^7$	$2.1 \times 10^9$	$4.8 \times 10^9$

The  $G_{ij}$  are used for the calculation of  $R_0 A$  (where  $R_0$  is the resistance per period of the pixel and  $A$  the area of the pixel), via the following relation  $R_0 A = \frac{k_b T}{e^2 \sum_{i \in C} \sum_{j \in C'} G_{ij}}$ , where  $C$  designates one cascade and  $C'$  the following one. Figure 1 represents  $R_0 A$  as a function of  $1000/T$  for the different scattering processes. Electron-electron scattering calculation has not been performed due to uncertainties on position in energy of the different subbands and a high consuming calculation time. As predicted by the scattering rates, the limiting process is the IR. It leads to a low value of  $R_0 A: 10^{-5} \Omega \cdot \text{cm}^2$  per period, whereas around  $10 \Omega \cdot \text{cm}^2$  per period has already been reported in THz QCD<sup>7</sup> and  $10^2 \Omega \cdot \text{cm}^2$  per period are often reported for  $10 \mu\text{m}$  QCDs. Such a difference results from three combined effects. First the doping level of our structure is thirty times higher than the previously reported doping<sup>7</sup>, which also reduces the  $R_0 A$  of two to five decades (depending on the temperature), but in compensation increases the absorption of the device. Add to this the injection of the electron on the upper levels of the cascade is not so good due to an unoptimized design of the associated wave function concerning the transport. This results from a bad positioning of the fourth level of the cascade which tends to send back the electrons to the lowest level rather than into the cascade. Last point, the interfaces are not as sharp as expected, see FIG. 2, which also reduces the  $R_0 A$  as explained below. A way to improve the  $R_0 A$  value may consist in applying a higher electric field on the QCD, thus the transition  $i \rightarrow i'$  would lose its elastic behaviour and the transport via interface roughness interaction would become less efficient. The increase of the  $R_0 A$  factor at high temperature (low  $1000/T$ ) may be explained by possible transitions between levels with higher energies in the cascade. For a moderate temperature, the  $R_0 A$  presents a low dependence on lattice temperature as the initial Fermi factor can be considered as constant. At low temperatures,  $R_0 A$  increases, it may be attributed to the population filling of the final subband.

Now, we only focus on the interface roughness interaction, since it prevails on the others at least from one order of magnitude. The evaluation of the net scattering rate allows us to conclude that: (i) The

relaxation inside a cascade is done step-by-step. This is a major difference from the 10 $\mu$ m structure where LO phonon scattering allows the electron to jump towards different subbands. Here, since the coupling is driven by an elastic process, the first neighbour jump prevails. (ii) Once an electron is promoted over the excited state 5, it tends to go back to the previous cascade ( $G_{1,5}=8\times 10^{16} \text{ m}^{-2}\text{s}^{-1}\sim G_{5,4}=3.6\times 10^{17} \text{ m}^{-2}\text{s}^{-1}$ ). We can thus assume a drop of the Fermi level between two cascades.

In order to evaluate the parameter  $\Delta$  (roughness magnitude) and  $\xi$  (mean distance between defects) most of the authors used indirect ways such as mobility measurements<sup>11,12</sup> or measurements under magnetic field<sup>13</sup>. We choose an alternative way by using STEM imaging, giving direct access to  $\Delta$  and  $\xi$ . A different sample is used for this experiment. It is described in ref. 5 and corresponds to a 9 $\mu$ m QCD. As mentioned above, in such a device, dark transport is not dominated by IR. Despite the absorption wavelength, the 9  $\mu$ m QCD has an aluminium proportion in the barriers close to the THz one, 34% vs 27%, respectively. Since this parameter rules the IR scattering, in a first approximation, we can assume roughness to be similar in both QCDs. Figure 2(a) presents the STEM image of the 9  $\mu$ m QCD. It was acquired at 200 keV with a JEOL JEM 2200FS scanning transmission electron microscope equipped with a CEOS aberration-corrector. HAADF-STEM images (also called high-resolution Z contrast images) were obtained with a half-angle probe of 30 mrad, the inner and outer half-angles of the annular detector (called upper-HAADF detector in this machine) were, respectively, 100 mrad and 170mrad. A cross section along the growth direction (FIG. 2 (b)) presents the shape of the interfaces, they are not rigorously abrupt. We observed a gradient in the alloy concentration. The gradient of alloy concentration is as large as two or three monolayers (ML). FIG. 2 (c) presents a cross section along a well interface. We observe an irregularity at the interface between GaAs and AlGaAs. The averaged value of the correlation length is equal to  $\xi=10\pm 3\text{nm}$  period. The magnitude of the irregularity has the same order of magnitude as the interface alloy gradient, *i.e.* two or three ML:  $\Delta=0.6$  to  $0.9\text{nm}$ . Those values are in a good agreement with those found in the literature<sup>8</sup>  $\xi=6.5\text{nm}$  and  $\Delta=0.3\text{nm}$  for typical GaAs heterostructure. Those measured parameters are corroborating the dominant role played by IR *a posteriori*.

Finally we studied the influence of  $\xi$  and  $\Delta$  on the  $R_0A$  factor, for typical values around the experimental ones. As expected, an increase of the magnitude of the IR leads to a lower  $R_0A$ . An increase of the roughness magnitude leads to a shift of  $R_0A$  curve with a quadratic dependence in  $\Delta$ . The dependence of  $R_0A$  upon the  $\xi$  parameter is not obvious since IR acts as a filter in momentum space for the electron. FIG. 3 presents the typical behaviour of  $R_0A$  as a function of  $1000/T$  for different  $\xi$  values. An increase of  $\xi$  leads to a decrease of  $R_0A$ .

To summarize, IR is identified as the main scattering process in a THz QCD. This interaction prevails over all the others at least from one order of magnitude. We used STEM imaging system to estimate the IR characteristic parameters and we finally studied how those growth-dependant parameters influence the performances of the QCD. Decreasing the number of wells leads to a reduced number of interfaces and as a consequence limits the elastic behaviour of each transition, and thus should improve the structure performances.

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FIG. 1  $R_0A$  per period as a function of  $1000/T$  for the different processes. The LO phonon process is not indicated on this graph since the associated  $R_0A$  is much larger.

FIG. 2 (a) High resolution Z-contrast image of the 9  $\mu\text{m}$  QCD structure prepared by  $\langle 110 \rangle$ . Corrected cross-section and its intensity profile along the growth direction (b) and along a well interface (c).

FIG. 3  $R_0A$  per period as a function of  $1000/T$ , for  $\Delta = 2\text{ML}$  and different values of  $\xi$ , for the THz device.

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