Discerning Intraband Absorption Spectra Techniques for QDIPs and QWIPs

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Abstract

This article presents a special single-beam FTIR method for obtaining intraband absorption spectra of detector structures based on quantum dots (QDs), underlining the different polarization dependence behavior of these devices when compared to quantum well infrared photodetectors (QWIPs). Using selection rules that characterize intraband absorption of light in nanostructured materials as central argument, it also shows that important insight into the electronic transitions in quantum dot infrared photodetectors (QDIPs) is possible with the proposed method.

Introduction

A well known FTIR spectroscopic technique, widely used to obtain intraband absorption spectra of QWIPs, basically consists of 5 steps:

1. The sample is positioned so that the IR beam passes through the layers of its active region under an angle of approximately 45°;
2. A polarizer is positioned so that the IR beam reaches it in either s- or p-polarization mode;
3. The sample is scanned using the polarizer alternately in the s and p positions;
4. Background spectra are run, again using the polarizer both in the s and p positions;
5. To obtain the absorption spectrum for the active region of the QWIP, these single-beam spectra are processed according to the relation:

\[
\text{absorption spectrum} = \frac{\text{sample}(s)/\text{background}(s)}{\text{sample}(p)/\text{background}(p)}
\]

This method takes advantage of the so-called polarization selection rule for QWs, which states that no intraband absorption takes place when the electric field of the IR radiation is parallel to the interface between the QW layers [1] [2]. This rule allows the sample's s (s) spectrum to be regarded as a reference spectrum for absorption that does take place in the active region of the QWIP when the incident IR radiation is p-polarized.

It is a very convenient method because there is no need to manipulate the sample between s and p scans, only the polarizer must be adjusted. This assures that the radiation that reaches the sample has the same intensity when each of these two scans are run. For QDIPs, however, as the mentioned selection rule does not apply, other strategies need to be sought for obtaining absorption spectra.

Methods and Results

1. Transmittance, absorptivity and absorbance

Physical quantities describing absorption and transmission of radiation of a certain wavelength \( \lambda \) travelling through a transparent material are not always defined in the same way and with the same name by the various fields of study that contemplate these phenomena. The definitions and terminology adopted in this article are those suggested by Christy et al. [3].

Transmittance is, then, defined by:

\[
y = \frac{I}{I_0}
\] (1)

where \( I_0 \) is the intensity of radiation that reaches the sample and \( I \) is the intensity that is transmitted (Figure 1).
Absorptivity is defined by:

\[ \tilde{A} = \frac{I_a}{I_0} \]  

where \( I_a \) is the intensity of radiation that is absorbed.

Assuming that the transparent material does not scatter radiation and is not fluorescent, then:

\[ I_s = I_0 + I_a \quad \text{and} \quad I_s + \tilde{A} = 1 \]  

On the other hand, according to the Lambert-Beer law:

\[ I_t = I_0 e^{-\alpha L} \]  

where \( \alpha \) is the absorption coefficient of the material and varies with \( \lambda \). While equation (5) implies that:

\[ \ln \left( \frac{I_t}{I_0} \right) = -\alpha L \]  

it is convenient to define another physical quantity, called absorbance:

\[ A = \log \left( \frac{I_0}{I_t} \right) \]  

The advantage of using absorbance (instead of absorptivity) is that its behavior in relation to the optical path is linear, which means that:

(I). The sum of the absorbances of two stretches of the optical path is equal to the absorbance of the two stretches together;

(II). The length of the optical path through a certain material is proportional to the absorbance through that path.

2. A general technique for absorption spectra

The intensity sensed by the FTIR spectrometer's detector brings the information of the absorption that takes place in the sample. But it also brings the changes of intensity due to the presence of all the other elements that constitute the optical path, from the source down to the detector (Figure 2). Besides, the source itself has its own characteristic emission spectrum, and the detector its own detection spectrum as well. All this interfering information can be dealt with by performing two measurements, one including the sample, where the intensity \( I_o \) reaching the detector becomes:

\[ I_{\text{sample}} = I_0 e^{-A_1 - A_2 - A_3 - A_4 - A_5 - A_6} / 0.434 \]  

and another not including it, where \( I_o \) becomes:

\[ I_{\text{reference}} = I_0 e^{-(A_1 + A_2 + A_3 + A_4 + A_5 + A_6)} / 0.434 \]  

The absorbance of the sample could then be sorted out by calculating the difference between the logarithms of the two measured intensities:

\[ A_{\text{sample}} = \log \left( \frac{I_{\text{reference}}}{I_{\text{sample}}} \right) \]  

3. Laboratorial hindrances and spectral processing

In the case of nanostructured photodetectors, the interest lies particularly in the absorption taking place in the active region of the sample and this is what the desired absorption spectrum must show. To obtain this result, the reference spectrum must include the absorption taking place in the substrate. The solution is forging a piece with the...
same dimensions as the sample from a substrate wafer identical to the one used to grow the sample on and replacing the sample with it when performing the reference measurement. The use of this artifice brings two laboratorial hindrances. One is cleaving and polishing a substrate to obtain a piece of precise dimensions. The other is positioning the sample and the substrate exactly in the same region of the IR beam when preparing each scan. Because it is difficult to make sure that the positioning is the same, it is also uncertain that the intensity $I_0$ of radiation reaching the sample is the same as the one reaching the piece of substrate.

A consequence of these two hindrances is that the processing represented by equation (10) might not result in the desired elimination of the reference spectrum from the sample spectrum. Instead of obtaining the absorbance in the active region, the outcome is often a spectrum similar in shape to the reference spectrum or to the sample spectrum. When this is the case, in order to compensate for laboratorial inaccuracies resulting from the two above described hindrances, and taking advantage of the linear behavior of the absorbance in relation to the optical path, a subtraction factor $F_S$ can be included in equation (10). Then:

$$A_{\text{sample}} = F_S \log(I_{\text{reference}}) - \log(I_{\text{sample}})$$

It is important to observe that the use of subtraction factors, as of any other spectral processing, must conform rigorous criteria in order to avoid distortions in the spectral information [4].

4. Wave-guide configuration

It is desirable that the IR beam crosses the active region several times before it emerges from the sample on its way to the spectrometer’s detector. This is usually accomplished by adopting, when performing the scans, a spacial arrangement whereby the beam traverses the sample as it would in a wave guide. For this purpose, each end of the sample must be chamfer-polished with an angle of 45º, as seen in Figure 3.

The wave-guide configuration in no way interferes with the theoretical development presented here, but enhances the mentioned need of cleaving and polishing a piece of substrate with the same dimentos as the sample.

5. Polarization dependence

Quantum-mechanical calculations for optical intraband transitions in QDs characterized by cylindrical symmetry (which is the case for most self-assembled QDs) state that radiation whose electric field is parallel to $z$ (growth direction) only participates in transitions implying no change in angular momentum $(\Delta m=0)$, while radiation whose electric field is perpendicular to $z$ only participates in transitions implying change in angular momentum $(\Delta m= \pm 1)$ [5][6].

When this selection rule for photon absorption in QDs is taken into consideration, the appreciation of polarization dependence in the QDIPs' absorption spectra allows for insight into the kind of eletronic transitions involved in each absorption peak. This is instrumental when investigating, among transitions whose energy and oscillator strength have been calculated via simulation, the ones to be most probably involved in the absorption peaks. Polarization dependent spectra may be obtained by simply introducing in the proposed procedure a polarizer positioned so that both the sample and reference scans are performed with s-polarized and, alternately, with $p$-polarized radiation. The spectra should, in turn, be processed in the same way described above, where no polarization was mentioned. Three interesting absorption spectra for each sample can thus be produced, namely the non-polarized, the s-polarized and the $p$-polarized ones, as seen in the example presented next.

6. Case study

Below is an application of the described method. It was part of an investigation of the intraband electronic transition processes of an IR photodetector based in QDs coupled with QW (Figure 4). Two samples of this photodetector, only differing in the presence of Si dopant in the InAs self-assembled QDs, were scanned. The resultant absorption spectra can be seen in Figure 5.
The QDIP’s active region is composed of 10 periods, as indicated in the schematized structure of layers, on the left. Each period includes a layer of QDs coupled with a QW. On the right, a diagram of the conduction band profile. Further details on the device can be found in Ref. [7].

Absorption spectra of two QDIPs having the structure described in Figure 4 and differing in that the QDs in sample 1072 are doped while sample 1071 is undoped. A subtraction factor of 1.2 was used to obtain the unpolarized 1072 sample spectrum. For the other spectra, no subtraction factor was needed.

By appreciating the spectra of sample 1071, while bearing in mind the selection rule for QDs, it becomes clear that the transition involved in the 9 μm peak implies change in the angular momentum. Similarly, the spectra of sample 1072 show that the transition involved in the 12 μm peak implies no change in the angular momentum of the electron and cannot therefore be produced by normally incident radiation.

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References below: