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Optimization of digital image processing to determine quantum dots' height and density from atomic force microscopy

J.E. Ruiz[a,b,*], S. Paciornik[c], L.D. Pinto[a,b], F. Ptak[d], M.P. Pires[b,e], P.L. Souza[a,b]

[a] *Pontifícia Universidade Católica do Rio de Janeiro, Laboratório de Semicondutores, LabSem, CETUC, Rio de Janeiro, RJ, Brazil*
[b] *Instituto Nacional de Ciência e Tecnologia em Nanodispositivos Semicondutores - DISSE - PUC-Rio, RJ, Brazil*
[c] *Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Engenharia Química e de Materiais, Rio de Janeiro, RJ, Brazil*
[d] *Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Física, Rio de Janeiro, RJ, Brazil*
[e] *Universidade Federal do Rio de Janeiro, Instituto de Física, RJ, Brazil*

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ABSTRACT

An optimized method of digital image processing to interpret quantum dots' height measurements obtained by atomic force microscopy is presented. The method was developed by combining well-known digital image processing techniques and particle recognition algorithms. The properties of quantum dot structures strongly depend on dots' height, among other features. Determination of their height is sensitive to small variations in their digital image processing parameters, which can generate misleading results. Comparing the results obtained with two image processing techniques – a conventional method and the new method proposed herein – with the data obtained by determining the height of quantum dots one by one within a fixed area, showed that the optimized method leads to more accurate results. Moreover, the log-normal distribution, which is often used to represent natural processes, shows a better fit to the quantum dots' height histogram obtained with the proposed method. Finally, the quantum dots' height obtained were used to calculate the predicted photoluminescence peak energies which were compared with the experimental data. Again, a better match was observed when using the proposed method to evaluate the quantum dots' height.

1. Introduction

Quantum dots (QDs) can, in principle, improve the performance of different optoelectronic devices such as lasers [1], photodetectors [2] and solar cells [3]. It is well known that the properties of these nanometric structures strongly depend on their shape, size and composition [4], therefore a morphological characterization of the QDs is imperative. In the design, manufacture and optimization of devices based on QDs, it is then fundamental to properly and as accurately as possible characterize them. However, this may present a problem since the measurements are on a nanometer scale, where a small error in the dimensions can lead to major differences in device performance. Therefore, it is important to develop a reliable method to morphologically characterize the QDs. Atomic Force Microscopy (AFM) 3D images have been extensively used to determine the height and areal density of surface QDs [5,6]. The AFM images are usually digitally processed using a commercial software, which usually comes with the equipment, to determine the sample characteristics but, depending on the image analysis, different results can be obtained from the same AFM image.

In this work, we propose an optimized method to digitally process the AFM images to more accurately determine both the height and density of the QDs.

2. Experimental details

The investigated samples have the following structure: an InP buffer layer is deposited on a (100) oriented InP substrate followed by a layer of quaternary material (InGaAlAs) lattice-matched to the substrate. Both layers are grown at 630 °C. After lowering the temperature to 520 °C, the InAs QDs are nucleated on this surface. After 12 s at this temperature the 10 nm InP capping layer is deposited while the temperature is ramped up. Then, a second layer of the quaternary material is grown at 630 °C, on which the free standing QDs are deposited. A scheme of the sample is shown in Fig. 1. The QDs are nucleated according to the Stranski-Krastanov growth mechanism where, prior to the development of the quantum dots, a wetting layer is formed [7].

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* Corresponding author at: Pontifícia Universidade Católica do Rio de Janeiro, Laboratório de Semicondutores, LabSem, CETUC, Rio de Janeiro, RJ, Brazil.

E-mail addresses: jose1989@ele.puc-rio.br, joseruiz1989@hotmail.com (J.E. Ruiz).

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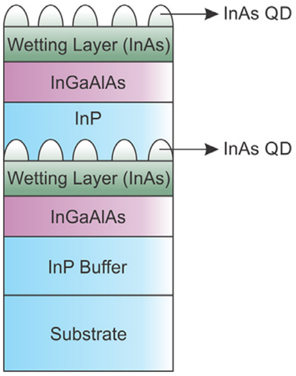

Fig. 1. Sample structure.

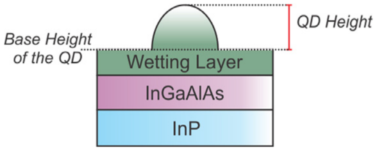

Fig. 2. Detail of QD height.

The samples were grown by metalorganic vapor phase epitaxy (MOVPE), a method which can be used under various conditions, leading to different QD size distributions. The optical and morphological properties of QD samples can be characterized with different techniques.

The AFM measurements were performed on a NX-10 scanning probe microscope (Park Systems). The microscope was operated in non-contact mode (NC-AFM), using a steep silicon tip, with a nominal radius of 8 nm. In this method, the tip, which is mounted on a cantilever, oscillates near its resonant frequency. As the tip scans the samples' surface, attractive forces between the tip and the sample causes a shift in the amplitude and frequency of oscillation of the cantilever. The AFM feedback system was set to track the changes in the amplitude, adjusting the tip-sample distance to maintain it at a constant value.

In our experiment, the tip was set to oscillate at a driving frequency of ∼ 76 kHz. Images were taken at several different locations, at a scan rate of 1 Hz, with scanning sizes of 2 μm × 2 μm and 1 μm × 1 μm with 1024 lines. Resulting topographic images were plane processed, and all images were taken at ambient air with ∼ 45% RH and at room temperature ∼ 23 °C.

3. Description of the problem

The proper way to determine the height of a QD from AFM images is to obtain the difference between its maximum and base heights, as shown in Fig. 2.

Most technological applications require a high QD density. Therefore, a one a by one height analysis of a large number of QDs is an inefficient and time-consuming process. Thus, image processing methods are available to automate this procedure. The widely used WSxM software [8] contains the so-called *flooding* method [9] that performs these measurements automatically. However, this method does not estimate the QD height with enough accuracy. The *flooding* method allows one to detect the highest (hills, dots) or lowest (holes, valleys) features of an image. With the most common option (*find hills*), all the hills with height above a given threshold are considered as dots. This threshold is chosen by the user and its value is extremely important because the determined height of each QD directly depends on this choice. The estimated height of each QD is just the difference between the value of the maximum height of each object and the value of its threshold, as schematically represented in Fig. 3.

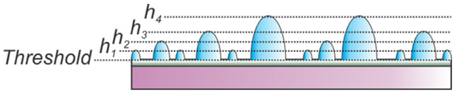

Fig. 3. Scheme of a sample surface with QDs and a process to determine their height.

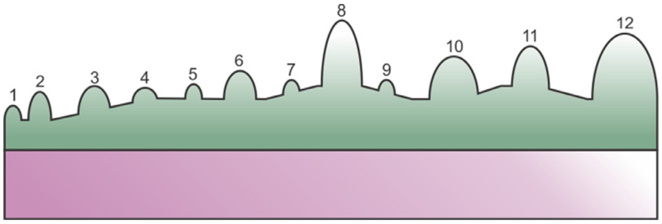

Fig. 4. Scheme of sample surface with QDs on top of an uneven background.

Actually, the base height of each quantum dot varies across the sample, as depicted in Fig. 4, which is exaggerated for clarity reasons. An AFM image depicting this phenomenon is shown in Fig. 5(a). In this image of a sample surface the intensity of each pixel represents the surface height. In the contrast enhanced image of Fig. 5(a), the variation of the surface height is revealed by the grey scale. The height profiles across two QDs, 1 and 2 in the same figure, are depicted in Fig. 5(b), showing that the QDs have in fact a different base line.

In such situations, selecting a global threshold is not an appropriate strategy. A low threshold, as in Fig. 6(a), leads to an overestimation of many QDs' heights and an underestimation of their density. An intermediate threshold, as in Fig. 6(b), implies in the underestimation of the height of some QDs and an overestimation of others. A high threshold, as Fig. 6(c), underestimates the height of some QDs and excludes many others. Thus, it is impossible to find a single accurate global threshold to accurately evaluate the QDs' heights.

This effect is clearly shown for an AFM image in Fig. 7. The images on the left column show the effect of increasing thresholds in the detection of QDs. The yellow outlines show the detected regions in each case. The plots on the right column are height profiles along the two white lines drawn on the left column image. The filled areas represent the detected QDs for the different threshold values. Fig. 7(a) shows the dot distribution height profile when a very low threshold is used. In this situation many QDs and other regions of the image are considered as a single large object as revealed by region number 4. In this case, just a few QDs are correctly identified (QDs 1, 2 and 3 in the same plot). As the threshold increases (Fig. 7(b) and (c)) more and more QDs are detected, but on the other hand, their heights are not accurately determined, as evidenced by the line plots on the right column.

As an example, in the plot of Fig. 7(b) the height of the QDs identified by numbers 1 to 3 are underestimated, while those for the QDs identified as 4, 5 and 6 are more accurate. The used threshold in this evaluation incorrectly considers region 7 as a single object. By further raising the height of the threshold some dots may be eliminated. This is what is observed in the plot of Fig. 7(d), where the QD between numbers 3 and 4 is unaccounted for. Additionally, in the same figure, the base height for the other QDs is clearly wrong.

4. Description of the proposed method

An alternative to the limitation of the global threshold is the use of an adaptive, or local, threshold. In this approach, a window