Semiconductor thin film’s topographic and roughness characterization through confocal microscopy

Caracterização topográfica e de rugosidade de filme fino semiconductor por microscopia confocal
Caracterización topográfica y de rugosidad de película delgada semiconductora mediante microscopia confocal

Abstract
Thin film’s characterization is a highly demanded technique due to its wide use in engineering and sciences. Laser Scanning Confocal Microscopy (LSCM) is a highlight of modern microscopy, combining high sensitivity and speed, enabling the detection of super resolution images and quantitative data analysis in terms of mapping surface irregularities. A confocal microscope allows to capture a region of interest, discarding unnecessary light beams and enabling 3D images construction. Nowadays semiconductor materials are getting more and more relevant on modern society. Its applications highlight due to its capacity of obtain a high performance on micro electronical devices. This paper aims to demonstrate the use of a confocal microscope as an effective tool for topographic mapping, as well as for investigation of roughness parameters applied to a SiNx thin film semiconductor sample. The equipment made possible to collect data and proceed a meticulous analysis over the material’s surface.

Keywords: Confocal microscope; Roughness; Topography; Semiconductor.

Resumo
A caracterização de filmes finos é uma técnica de alta demanda devido a sua vasta utilização em engenharia e ciências. A Microscopia Confocal de Varredura a Laser (MCVL) é um marco da microscopia moderna, aliando alta sensibilidade e velocidade, possibilitando a detecção de imagens de super resolução e análise de dados quantitativa em termos de mapeamento de irregularidades superficiais. O microscópio confocal permite a captura de uma região de interesse desprezando feixes desnecessários e possibilitando a construção de imagens 3D. Atualmente os materiais semicondutores estão se tornando cada vez mais relevantes na sociedade moderna. Suas aplicações se destacam pela capacidade de obter alto desempenho em dispositivos microeletrônicos. Este estudo tem como objetivo demonstrar o uso do microscópio confocal como uma ferramenta eficaz para o mapeamento topográfico, bem como para a investigação dos parâmetros de rugosidade aplicados a um filme fino de SiNx semiconductor. Através deste equipamento foi possível coletar dados e realizar uma meticulosa análise da superfície do material.

Palavras-chave: Microscópio confocal; Rugosidade; Topografia; Semiconductor.

Resumen
La caracterización de películas delgadas es una técnica muy demandada por su amplio uso en ingeniería y ciencias. La Microscopía Confocal de Barrido Láser (MCBL) es un hito de la microscopía moderna, que combina alta sensibilidad y velocidad, lo que permite la detección de imágenes de súper resolución y análisis de datos cuantitativos en términos

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de mapeo de irregularidades de la superficie. El microscopio confocal permite la captura de una región de interés, descartando haces innecesarios y permitiendo la construcción de imágenes 3D. Actualmente, los materiales semiconductores son cada vez más relevantes en la sociedad moderna. Sus aplicaciones destacan por su capacidad para lograr un alto rendimiento en dispositivos microelectrónicos. Este estudio tiene como objetivo demostrar el uso del microscopio confocal como una herramienta eficaz para el mapeo topográfico, así como para la investigación de parámetros de rugosidad aplicados a una película delgada de SiNx semiconductor. A través de este equipo fue posible recolectar datos y realizar un minucioso análisis de la superficie del material.

Palabras clave: Microscopio confocal; Rugosidad; Topografía; Semiconductor.

1. Introduction

According to Sabatini (2012), advances in optics and electronics occurred mainly during the nineties. From there emerged more stable and powerful lasers in terms of efficiency. This age was considered a virtual explosion due to the quick advance of processing speed in computers, which came up as a result of the increase in the storage capacity for a large volume of data, in late 1990s. This fact has optimized the number of applications in which confocal microscopy fits.

Considering the modern confocal microscopes as fully integrated electronic systems, where the microscope acts as the central axis, its configuration is arranged using one or more electronic detectors, in addition to a computer responsible for providing the image for previewing, to process, produce and store data. Also, its configuration counts with laser systems working in alongside selected devices and a mounting scan-beam. Renzelli (2014) argues that in most cases, the integration of various components is so complete that scientists often refer to the confocal microscopy technique as a collective digital imaging system capable of producing electronic images.

There are three different types of microscopes: confocal, scanning and conventional, and confocal microscope stands out among them for its higher resolution. In this context, resolution means the minimum separation between two points when microscope still promoting a contrast between them. According to Hovis (2010) is his paper The Use of Laser Scanning Confocal Microscopy in Materials Science, confocal microscope was invented in 1955 by Minsky (Minsky, 1988). In terms of confocal microscopy this resolution is possible due to the light source be extremely punctual (usually a laser), able to illuminate just a small region of the sample. Furthermore, the detector is also punctual and also detects just a small area (Sheppard, 2002).

Plenty of studies are being developed in the confocal microscopy field. Badon et al. (2019) have a recent work about an augmented variant of this, where the named Multi Z confocal microscope is a versatile manner to obtain simultaneous multiplane imaging with no need of axial scanning, with the advantage of no scan pre-calibration being required for the system. Deguchi et al. (2010) brings Lissajous microscope, a volumetric confocal microscopy technique aiming a unique 3D scanning speed. Chia et al. (2018) presents a new multiplexed holographic non-axial-scanning confocal microscope, where is possible to acquire optically sectioned images from different depths simultaneously.

According to Oliveira (2012), although the operation of confocal microscope presents similarities comparing to a widefield microscope, there are significant differences between both of them. Confocal microscopy allows us to increase the image contrast, it also enables the construction on three-dimensional images ensuring a great definition in projection. It is possible due to exceptional technique used in confocal microscopy, a combination of optical microscopy features and computing principles, signal acquisition and data processing.

Confocal microscopes are divided into three types: Laser Scanning Confocal Microscope (LSCM), Spinning-Disk Confocal Microscope and Programmable Array Microscope (PAM). Typically, they consist on laser (light source which will be projected at the sample), scanner (responsible for moving the laser and promote its focus into sample line by line), Z (a control used to focus the image and acquire images through Z and X axis), among others. Also, it is worth mentioning that operational controls are easy, practical, and quick (Leica Manual).
According to Deguchi et al. (2010), LSCM is the current standard for 3D characterization on biological field, providing optical sectioning alongside synchronous multi-channel imaging. One of the biological applications would be image generation in a specific layer of structure inside a semi-transparent biological sample (Xiao, 1988).

Duocastella (2014) points out the confocal microscope as a standard imaging technique for many science fields and specially to materials science, highlighting a key aspect of the technique as the ability to reject out of focus light, on which considering a sample, one is allowed to obtaining optical sections on this. In other words, is possible to use a detection pinhole in order to obtain optical sectioning, physically rejecting out of focus background (Tsang et al., 2021).

Topographical mapping of materials is a frequent practice in science, which involves analysis of surfaces. For example, in engineering fields it is useful to quantify the abrasion of metals and welded joints subjected to corrosion. Odontology considers topographical mapping a useful way for investigating the influence of feeding at dentine. In some cases, this analysis is crucial once the roughness can influence the material performance, if that is directly related to the conservation of the area (Gravalos et al., 2010).

Material surface’s roughness can be described as a set of irregularities, as small protrusions and recesses that characterize the final surface. In this paper the roughness and topography of a limited area of a thin film semiconductor sample was investigated, aiming to find and characterize surface defects and so, to show how confocal microscopy can be useful to map materials surfaces meticulously standing out of traditional methods of microscopy.

In materials science, Hoheisel (2001) argues that the confocal principle is well adapted to investigate polymers, ceramics, wood and others. The authors opted to exhibit the use of LSCM in a particular materials segment where semiconductors reside.

Silicon applications are the core of modern microelectronics, representing over of 90% of semiconductors production and being used also in solar cells (Fisher, 2012; Dullweber et al. 2013). Due to its application in electronical devices, it must be ideally surface defect absent.

Efforts are being made to identify semiconductors surface defects. Shankar (2005) observed the majority of surface inspections are made manually by professional experts, through visual inspection. Chien (2020) presents a machine learning method to classify visible defects. This paper, on the other hand, brings confocal microscopy as an alternative tool to identify and also quantify this defect, giving relevant information regarding the defect dimensions according to roughness patterns. Once surface roughness is known as a relevant parameter that has direct influence on tribological behaviour of surfaces, it’s worth investigating a thin film semiconductor sample in this context.

A silicon thin film is a layer of silicon film deposited on a cheap substrate. Ordinary substrates can be metallurgical-grade silicon, stainless steel, graphite, ceramics, or even glass. They are massively used on solar cells, and present great potential due to its highly desirable properties (physical, chemical, and also electrical) in addition to the fact of enabling new device technologies. (Szlufcik, 1997; Kaloyeros, 2020).

2. Methodology

The staple sample for this study is a thin film semiconductor, consisting of a thin micrometrical silicon film deposited on a glass substrate. It is worth mentioning that the sample had a silicon nitride film in its surface (SiNx, where 0 < x < 1.33) aiming to increase the thermal performance of the glass for some further applications. Defects on this superficial layer was investigated through confocal microscope LEICA DCM 3D, used to qualify the sample and LEICA as auxiliary software to generate images and proceed materials characterization. Authors come up with a quantitative research through data collection, analysis and evaluation, basing in descriptive methods to highlight confocal microscope particularities and its contributions to materials science.
This paper’s data was elaborated based on DIN 4762 and ISO 4287/1, where they bring general terminology and parameters for roughness surfaces, in addition to DIN 4768 which elucidates roughness measurement methodology and standards. This set of international standards states average roughness Ra as the arithmetic mean value for all deviations of midline roughness profile within Im measurement length. The mean roughness Rq (DIN 4762/1 E) is the mean square value of all deviations of roughness profile R from the median line within Im measuring length. Rz is the mean value for the single roughness depth Zi obtained in five individual measurement lengths le within the roughness profile. RzDIN corresponds to the average value Rv of several individual measuring lengths according to DIN 4762. The maximum roughness Rmax is the highest roughness value obtained from Ie evaluation (DIN, 1998). Figure 1 exhibits the arrangement:

![Figure 1](image-url)

Source: Authors.

The LEICA confocal microscope used is able to perform measurements at high speed, with high resolution (approximately 0.1 nm). This way, it reveals a high-quality image combined with 3D topography. Details of methodology are as following:

The procedure involves placing the sample at a sample holder and then, the lens of 10x is chosen. It is necessary to use the control buttons of joystick to approximate the surface of the lens. It slowly moves the microscope, until the image becomes focused. It is worth to point out that if the sample presents low reflectivity, it must be oriented using the light control button to increase the amount of light. When the sample is in focus, the intensity of the light must be adjusted. If any part of the image shows regions in red, it means that the image is saturated due to excessive light intensity.

Aiming to obtain topographic mapping and roughness measurements, the first step is to choose the proper mode at microscope and thus obtain the confocal image for the sample. Once the sample has been focused and the acquisition parameter has been selected, it is important to ensure that the range for Z scan offset is appropriate. If the interval is too large, the mapping will take a long time. If the interval is too small, some zones may be lost during confocal mapping.

The referential point must be positioned behind the image. For that, it was necessary to move the focus to a reliable region (region in which the image was blurred) using a joystick, and then move the focus forward.

After selecting the area and Z range of digitalization, the software calculates the amount of information in the image pertaining to each plan. Each image requires a large amount of memory RAM, which is limited by the selected resolution, the Z range and the available memory of the computer.
For this sample, measurements and relevant data were obtained considering an area of image totalizing 5 parallel lines and after this, it was possible to export the raw data, save the roughness graphs obtained and topographic images, achieving successfully the materials characterization. Figure 2 exhibits how the 5 lines are distributed in order to investigate the whole surface.

**Figure 2** – Placement of lines to map the thin film surface.

### 3. Results and Discussion

Table 1 shows the data obtained experimentally for each one of the 5 lines that represents all the sample area according to standards.

| Semiconductor Sample | Line 1 | Line 2 | Line 3 | Line 4 | Line 5 |
|----------------------|--------|--------|--------|--------|--------|
| Ra (µm)              | 0.012  | 0.012  | 0.011  | 0.012  | 0.012  |
| Rq (µm)              | 0.015  | 0.015  | 0.014  | 0.016  | 0.015  |
| RzDIN (µm)           | 0.061  | 0.060  | 0.061  | 0.067  | 0.054  |
| Rmax (µm)            | 0.087  | 0.080  | 0.080  | 0.082  | 0.073  |

Source: Authors.

Those results show there was no significant discrepancies in the values obtained for the parameters. It reveals the sample presented a flat and well-polished surface, which is highly recommended for its possible applications. Statistical measurements for parameters are shown in Table 2.

| Semiconductor Sample | Average | Standard Deviation |
|----------------------|---------|--------------------|
| Ra (µm)              | 0.0118  | 0.0004             |
| Rq (µm)              | 0.0150  | 0.0007             |
| RzDIN (µm)           | 0.0606  | 0.0046             |
| Rmax (µm)            | 0.0804  | 0.0050             |

Source: Authors.
Roughness parameters presented low deviations. It can be explained through the thin film surface, once there was not a large number of protrusions or recesses on this. However, it was possible to capture a defect revealed due to a high precision and detailed surface mapping obtained with confocal microscopy. Figure 3 shows the 3D image in a topographical survey obtained over a defect at the sample. In order to allow this 3D image, the microscope was axially parallelized and so, multifocal detection was enabled.

**Figure 3 -** Topographic survey for a chosen area at the sample.

This 3D topographical mapping is an ally to characterize layers on materials separately. We can see it considers a depth of 1.82 micrometres on the superficial layer, and the defect is mostly concentrated at one area.

Figure 4 shows the defect are in colour scale, corresponding to topography, where the blue colour means the points closest to the surface and the red ones means the highest points of the defects found in a scan of 2 micrometres depth.
The defect belongs to the silicon nitride’s thin film on the surface of the glass substrate, which is mainly used in applications of high strength and high temperature. The mapping of this small inclusion reveals how confocal microscopy can be used to investigate even the surfaces with smaller details, proceeding this way a high-quality surface characterization.

4. Final Considerations

Confocal microscopy offers several advantages over conventional widefield microscopes. It has the ability to control the depth of field, reducing peripheral information to focal plan, increasing the contrast and image quality.

Superficial roughness can be described by means of many parameters, and the most common calculated is the roughness average (Ra), quite important aspect to be analysed on silicon semiconductors due to its application.

All the parameters of the semiconductor roughness obtained according to DIN standards had a low standard deviation, and it is due to the SiNx superficial layer contains a low amount of imperfections.

It was possible to identify relevant information about the sample surface’s characterization, as roughness in small scale (micrometres), superficial topography and the 3D reconstruction of a small imperfection, described in terms of colour in order to make the identification easier. It reveals how confocal microscopy can be useful to mapping different surface patterns presenting high performance, considering it can obtain data from many thicknesses. All those data were measured quickly and with many details, due to the easy handling of equipment.

Considering all the above-mentioned facts, the confocal microscope enables a higher resolution of both axial components (lateral and vertical). This way, confocal technology proves to be one of the most important advances achieved by optical microscopy in recent years.

The author’s suggestions for future papers, on the same basis, include the investigation of another class of materials such as metals, ceramics and polymers. It can be quite useful to detail superficial characterization of cracks and ruptures due to
fatigue or behaviour stress under loadings (tension, compressive, bending and torsion), obtaining a 3D reconstruction considering a specific depth. Furthermore, mapping and quantifying its roughness or even as a key tool for materials selection for those which application requires a refined homogeneous surface.

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