Structural and Optical Properties of nanostructured hybrid LiNbO3/Silicon wafer for Fabricating Optical Modulator

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Abstract. In this paper, a tattoo removal Q switching Nd: YAG laser, with a 6 nanosecond pulse duration, 2000 mJ power, frequency of pulses of 5 Hz was used to deposit of layer by layer of Silicone oxide, pure silicone, and lithium niobate for fabricated an optical modulator. The deposited layer by layer samples were analysed and characterized using the (XRD) X-ray diffraction, optical properties (UV-Vis spectroscopy) and photoluminescence (PL), and Atomic force microscopy AFM. Then we investigated of the deposited layers using. The XRD results showed the existence of different tops for all classes that have been deposited, Also, the optical and luminous results showed that only two peaks appeared, namely the top of the lithium niobate layer at the violet wavelength region with the limits of 368 to 381 nm, as well as the top of the silicon oxide layer within the middle of the visible wavelengths range and within the limits of 551 nm.

Keywords: Pulsed laser Deposition; optical preparation; structural properties; optical modulator; layer by layer deposition.

1. Introduction

Lithium niobate (LiNbO3) Electro–optic (EO) modulators that topic for tremendous studies during the last years, precisely when the wireless communication systems became commercially available due to their attractive features and capable of unprecedented data rates, namely, high bandwidth and low dispersion effects [1-5], silicon photonics which commonly used in integrated optical devices relies mainly on the free-carrier dispersion effect [6-9]. Unfortunately, free-carrier dispersion is intrinsically absorptive and nonlinear, which degrades the optical and may cause distortion in the modulated signal and it provides high-bandwidth. For decades, Lithium niobate (LiNbO3) that consider a key technological material in many domains due to its piezoelectric, pyroelectric, photo-refractive, strong electro-optic (EO) effect and high intrinsic modulation bandwidth[10-14] that made it suitable for different applications such as optical telecommunications and system components, optical waveguides and switch production, memory units and electro optical modulator such as Mach-Zehnder modulator (MZM).[15-19]. However, Mach-Zehnder modulator (MZM) based on the heterogeneous LN /silicon platform used in photonic links that have strong EO effect which defined by changes in the refractive index of matter due to the application of an external physical action/electric field [20-23], MZM as important as a low dispersion loss in the signal that travelling through an optical path and large modulation bandwidth [24-27].

In this paper, we will provide an overview of the present state of deposition of nano and micro structures of Lithium Niobate (LiNbO3) electro-optical modulator a silicon substrate using pulse laser deposition method [28-31]. The proposed of Mach-Zehnder modulators based on a hybrid integration platform of silicon and lithium niobate nanoparticles technique that it shows a large EO bandwidth, high modulation efficiency and low on-chip insertion loss.
[32-36]. The diameter of grains and the surface roughness also studied using X-ray diffraction (XRD) and Atomic force microscopy (AFM) because its important part of our work and application on MZM optical modulator [37-40].

2. Experimental work

3. The hybrid LN / silicon Mach-Zehnder modulator structure was concern, the deposited on silicon substrate (111) (with optimum thickness of the SiO₂ (012) buffer layer by pulsed laser deposition technique using a tattoo removal Q switching Nd:YAG laser with a 6 ns pulse duration, 2000 mJ power, and 5 Hz of the frequency of pulses [41-43]. Samples were exposed for different laser pulses in each layer, another layer of Silicon (302) waveguide deposited on the oxide layer as well as on the top Si waveguides an X-cut thin film lithium niobate (012) layer formed as shown in figure (1). The achieved films have smooth surface and sharp interface that assistance the interactions was occure to serve phase modulators that support all other passive functions causes in the bottom SOI circuit. The sample was placed at a distance ~4 cm from the target. In order to ensure a constant angular distribution of the ejected matter from the target, the target and the substrate are continuously rotated to achieve smooth surface and sharp interface.

The properties of the structure for the deposited nanofilms layer by layer were tested using the X-ray diffractometer (X’Pert Pro MRD PW3040 system) equipped with radiation Cu-Kα and wavelength of 0.15418 nanometer. The photoluminescence (PL) spectra were tested by the system of spectroscopic (Jobin Yvon model HR 800 UV) depending on the laser of the He-Cd at room temperature. The spectrophotometer UV–vis double-beam (Shimadzu 1800, Japan) was used to test the optical reflectance. The atomic force microscopy (AFM) (SPM-9600, Shimadzu, Japan) was used for testing the topographic, surface roughness, RMS values, and the sizes of grains for the nanofilms layer by layer.

![Figure 1](image-url)

Figure 1. (a) PLD deposition process. (b) Cross-section of the MZM with silicon waveguide, SiO₂ layer between the LN features and the silicon substrate.
4. Results and discussion

5. 3.1. Structural properties

The pattern of the X-ray diffraction of the MZM deposited nano films layer by layer silicone oxide, pure silicone, and lithium niobate nano structures are presented in the fig. 2. All the peaks observed are indicates that, the nanostructures of all deposited successfully layers on the silicone substrate by pulsed laser deposition method, the XRD pattern shows multi diffraction peaks, where the diffraction peaks of the nano LiNbO$_3$ films are appears of the polycrystalline at diffraction angles of $2\theta = 24.1, 33.125^\circ$, and $38.625^\circ$, for the correspond to the (012), (104), and (006) planes respectively, the diffraction peaks of the pure silicone nano films are appears also of the polycrystalline at diffraction angles of $2\theta = 25.125^\circ$, and $40.075^\circ$, for the correspond to (111), and (302) planes respectively, and the diffraction peaks of the nano silicone oxide films are appears of a single crystalline at diffraction angle of $2\theta = 44.723^\circ$ for the correspond to (222) plane.

The sizes of the crystallite for the deposited nanofilm are calculated basis of the equation (1) of Scherrer as follows [44, 45]:

$$D = \frac{0.94 \lambda}{\beta \cos \theta}$$  \hspace{1cm} (1)

where the $\lambda$ value are the wavelength incident X-ray are equal 1.5406 Å, the value of the $\beta$ is the (full width at half maximum) of the peak, and finally the $\theta$ is the diffraction angle at which the peak of a particular orientation occurs. The size of the crystallite for the main peak of the nano LiNbO$_3$ films presented at peak of (012) are equal of 67 nm.

6. 3.2. Optical properties

7.

8. 3.2.1. Photoluminescence

The photoluminescence spectra of the MZM grown layer by layer on the silicon substrate at 300°C was presented in figure (3) using PLD technique, . The measured sample demonstrated the appearance of two absorption peaks, the first at the wavelength of 381 nanometers, i.e. at the violet and the ultraviolet emission region, and this represents the work area of the lithium niobate nanoparticle where the calculated optical energy gap pf this Nano film equal to 3.25, and the second at the wavelength of 551 nanometers, i.e. at the green working emission region and this represents the working area of the silicon oxide nanoparticles where the calculated optical energy gap of this nano film at value of 2.25. The values of the optical energy gap of the incident photon were calculated from the equation (2) [46, 47]:

$$E_g (eV) = \frac{1.24}{\lambda (\mu m)}.$$  \hspace{1cm} (2)
From the PL spectrum, it’s clear that the nano LiNbO$_3$ where it works at the UV emission region films, and its intensity is higher than the other peak of the SiO$_2$ that works at the visible emission region, this higher intensity is related to high crystallinity and for the small size of the grains for deposited nanofilms. The PL spectra exhibit that the deposited nanofilms have sufficient quality to be used in optoelectronics applications and optical devices.

**Figure 3.** Photoluminescence spectrum (PL) for MZM layer by layer nanostructure

**9. 3.2.2. UV-vis**

The values of the spectra for the optical reflectance of grown nanostructure at the ranges of wavelengths about 200-800 nm was presented in Fig. 4. The average values of the reflectances in the visible and near-infrared light regions are It escalates and descends differently. The average reflection values are lower on the LiNbO$_3$ region, as a result of related to the smaller sizes of the grains compared with the grains of the silicon oxide, and also as results of the attributed to the high crystallization enhancement, these results are fully consistent with the XRD results.

**Figure 4.** Reflectance diagram for MZM layer by layer nanostructure

The function of the Kubelka–Munk and the Tauc plots are used to estimate the values of the optical energy gap for the deposited nanostructure [48, 49]. In the formula of the K–M, the \((F(R)\) was used, as present in Eq. (3), where the R values are the reflectance.

\[
F_{KM} = \frac{(1-R^2)}{2R}
\]  

(3)

The value of the optical bandgap of the deposited layer by layer nanostructure is presented in Figs. 5. The deposited nanofilms show two values of the optical band gaps. The smaller value is related to the nano LN films and its value is about 2.23 eV, and the large value is related to the nano SiO$_2$ films and its value is about 3.32 eV, where these presented values are related to
the difference in the sizes of the grains for the layer by layer nanostructures. These results for the energy gap values are entirely in agreement with the optical energy gap values computed from the luminosity and presented previously.

Figure 5. Optical energy band gap diagram for MZM layer by layer nanostructure

10. 3.2.3 Refractive Index, $n$

The values of the refractive indices represent the most important of the all-optical constants for the deposited LiNbO$_3$ nanofilms. The refractive indices values as a function of the wavelengths were computed using the values of the optical reflectance VS the values of the wavelength as presented in Fig. 6. Where the refractive index values, $n$ of the deposited LiNbO$_3$ nanofilms were computed depending on the formula (4) [50, 51],

$$n = n_s \left(\frac{1 + \sqrt{R}}{1 - \sqrt{R}}\right)^{\frac{1}{2}}$$  \hspace{1cm} (4)

where the $n_s$ value is for the refractive index for the substrate, the values of $R$ is the reflectance. The refractive index value for substrate of silicon we used 3.4434 according to previous work [52, 53], and the refractive index of the deposited nano films are about 2.346.

Figure 6. Refractive index diagram for MZM layer by layer nanostructure
11. 3.3. Morphological studies
The AFM is used to study the topography of the surface of the LiNbO₃ optical modulator. It has been demonstrated to the prepared samples within the scanned area (2 cm×2 cm) revealed a uniform distribution of grains over the surface with a distinguished decrease in their sizes. Also, it is noted that as shown in Figure 7 the range of grain size at <=10% diameter and <=90% diameter from 30 to 65nm, that means the average grain size 49.77 nm, surface roughness is 8.52nm and the root mean square (RMS) 9.84 nm, these, these values are obtained from the test device and the readings that we provided with the tester.

Figure 7. AFM images for MZM layer by layer nanostructure

12. Conclusions
The nanostructured hybrid of LN / silicon optical modulator was successfully prepared at 300 °C using Pulsed Laser Deposition (PLD) technique on Si substrates. The structural properties (the results of the XRD) shows multi diffraction peaks for all deposited layers MZM (LN, SiO₂, and Si layers). It also showed that one of the peaks prevailed for each layer that was deposited, where shows prevailed the diffraction angle for 2θ =24.1, for corresponding to the (012) plane for nano LN film, prevailed the diffraction angle for 2θ =40.075°, for corresponding to the (302) plane for nano SiO₂ film, and the diffraction peak of the nano silicon oxide films are appears of a single crystalline at a diffraction angle of 2θ =44.723° for the correspond to (222) plane. The spectra of the PL and the spectra of the UV–vis of the nano deposited films layer by layer shows two optical energy band gaps related to LN and SiO₂, it also showed a great match in these values in different tests. The AFM result shows a uniformity, denser, clarity in the distribution of the particle and the roughness in surfaces. The value of grain size at <=10% diameter and <=90% diameter from 30 to 65nm respectively.

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