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NANO COATING DESIGNS OF RUBY LASER RESONATORS

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In this paper, we study the change in the optical properties of ZnO as a function of the particle size and we investigate its use with bulk GaSb for the design of multi-layer reflection optical coating with quarter wavelength thickness for a GaAs substrate .We developed a MATLAB version 10 software to describe the reflectivity of the coating as a function of particle size, refractive index and energy gap. It computes the reflectivity as a function of the wavelength for vertical and oblique incidence. The calculation is based on the Brus model and uses the Characteristic Matrix Theory as a theoretical basis. The results indicate that the maximum value of the reflectivity at the interface Air/GaSb/Nano ZnO/GaAs is(Rs=100%,Rp= 99.8719 %) for oblique incidence at ($\theta = 45^{\circ}$) and (R=99.9885%) for a perpendicular incidence when the particle size of the coating material is P_s = 2.6 nm, and by using four layer of coating Air/GaSb/NanoZnO. We suggest this could be used the design of reflective coatings for ruby laser resonators.

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1. Introduction

Nanoscale semiconductors are unique materials offering options for developing innovative future devices. Nanoscale particles may display very different properties compared to Bulk Materials [1] .The physical cause of this change results from the quantum confinement which affects the quantization of Electrons energy levels [2]. Quantum dots are very small semiconductor particles, only several nanometers in size, so small that their optical and electronic properties differ from those of larger particles. They are a central theme in nanotechnology. Many types of quantum dot will emit light of specific frequencies if electricity or light is applied to them, and these frequencies can be precisely tuned by changing the dots' size, shape and material, giving rise to many applications. The term quantum dots refer to any system in which the electrons are bound in three dimensions. The change in the semiconductor properties when going from regular sizes to nanostructures is called Quantum confinement. When the crystallite size decreases, the distance between energy levels increase (separated energy levels), then, the effect of the quantum confinement appears on the energy gap and the density of states of material. Thus, the electronic and optical properties depend on particle sizes. In the case of quantum dots in which the electrons are bound in all the three directions, the system may be described as being zero-dimensional; therefore, the Quantum confinement appears when particle structure dimensions are smaller or equal to the de Broglie wavelength of the electron [2, 3].

2. Theory

2.1 Effective Mass Approximation (EMA)

This model is used to illustrate how the energy gap in the quantum dots depends on particle size. Commonly known as the Brus model it is one of the most widely used optical

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models[4]. It is based on the values of both the effective mass of both the electron and the hole. The change in the energy gap is given by the so called Brus equation[4]:

$$\Delta E_g = \frac{\hbar^2\pi^2}{2r_{ps}^2}\left[\frac{1}{m_e^*}+\frac{1}{m_h^*}\right]-\frac{1.786\,e^2}{\varepsilon\, r_{ps}}-\frac{0.124e^4}{h^2\varepsilon^2}\left[\frac{1}{m_e^*}+\frac{1}{m_h^*}\right]^{-1} \quad (1)$$

where:r_{ps} is a the particle radius(the quantum dot is considered spherical), m_e^* is the effective mass of the electron,m_h^* is the effective mass of the hole, and ε is a relative permittivity, with$E_g^{bulk}$the bulk energy gap and, $E_g^{nano}(r_{ps})$the energy gap in the quantum dots, also known as the effective energy gap, equation (1) becomes [5]:

$$E_g^{nano}(r_{ps}) = E_g^{bulk} + \frac{\hbar^2\pi^2}{2r_{ps}^2}\left[\frac{1}{m_e^*}+\frac{1}{m_h^*}\right]-\frac{1.786\,e^2}{\varepsilon\, r_{ps}}-\frac{0.124e^4}{h^2\varepsilon^2}\left[\frac{1}{m_e^*}+\frac{1}{m_h^*}\right]^{-1} \quad (2)$$

The second term in the right side of equation (2) shows that the Energy gap changes in inverse proportion withr_{ps}^2. Namely, the energy gap decreases when particle size increases. The change in energy gap due to the small size of the third and last term can be ignored compared to the second term, with these approximations, equation (2) becomes:

$$E_g^{nano}(r_{ps}) = E_g^{bulk} + \frac{\hbar^2\pi^2}{2r_{ps}^2}\left[\frac{1}{m_e^*}+\frac{1}{m_h^*}\right] \quad (3)$$

It can be observed that the energy gap increases when the particle sizer_{ps} decreases, This is significant when the particles radius becomes smaller or equal to the Bohr radius of the

Acetone($\alpha_\circ$) which define as [6]:

$$\alpha_\circ = \frac{4\pi\varepsilon_\circ\varepsilon_r\hbar^2}{e^2}\left[\frac{1}{m_e^*}+\frac{1}{m_h^*}\right] \quad (4)$$

where $\varepsilon_\circ$ *and* ε_r are the vacuum permittivity and permittivity of semiconductor respectively.

2.2 The Characteristic Matrix of Multilayer Coating

In general, the characteristic matrix of a system consisting of q thin films on a substrate, can be expressed by the following equation [7]:

$$\begin{bmatrix}B\\C\end{bmatrix} = \left\{\prod_{r=1}^{q}\begin{bmatrix}cos\delta_r & isin\delta_r/\eta_r\\ i\eta_r sin\delta_r & cos\delta_r\end{bmatrix}\right\}\begin{bmatrix}1\\ \eta_m\end{bmatrix} \quad (5)$$

The phase thickness is given by:

$$\delta_r = 2\pi n_r d_r cos\theta_r/\lambda$$

Wherein B and C respectively stand for the electric and magnetic fields, and is the optical permittivity and equation (5) is defined known as the modified characteristic matrix [8]. It contains all the information necessary for the extraction of the reflectivity (R) and transmittance (T) for multi-layer structures [9]. Figure(1) shows a system consisting of two thin films on a substrate. Then, there are three terms (c, b and a).

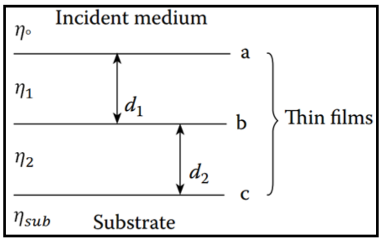


Fig. 1. A system composed of two thin films on a substrate [10].

The two electric and magnetic fields are related to each other through the following relation [11]:

$$= \frac{H}{E}\eta \qquad (6)$$

in case of vertical incidence, ($\eta = y = n\gamma$) where:
y: is the medium permittivity for the vertical incidence
n:is the real part of the refractive index.
γ: is the Permittivity of free space.
y is numerically equal to(n)when measured in free space units so[12]:

$$\eta_0 = y_0 = n_0\gamma = n_0 \qquad (7)$$

for the first medium, then, for the second medium it is given by:

$$\eta_1 = y_1 = n_1\gamma = n_1 \qquad (8)$$

In the case ofan oblique incidence, P-Polarization and S-Polarization are expressed by the two equations [13]:

$$\eta_p = n/\cos\theta \qquad (9)$$

$$\eta_s = n\cos\theta \qquad (10)$$

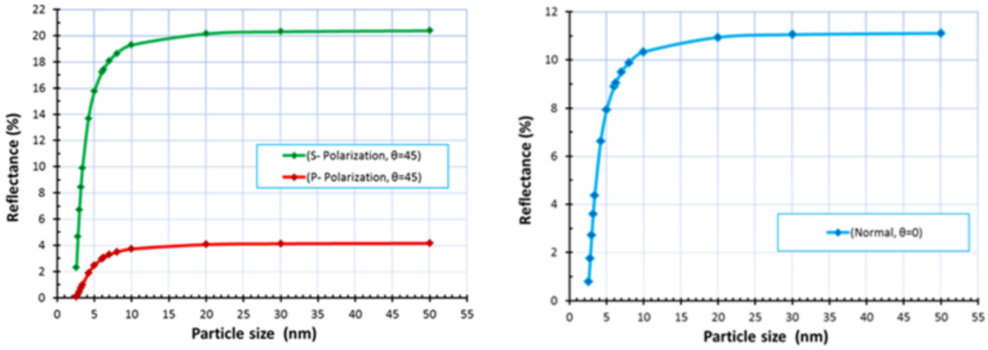
where θ is theincidence angle in the first medium and is connected with the refraction angle through Snell’s law [13].

3. Application Part

We developed a MATLAB(version 10) program to compute the reflectivity, refractive index and energy gap as a function of the size of ZnO particles in a thin film .This program was conceived with the goal of optimizing reflective optical coatings by tuning the particles size for the 694 nm wavelength region of the electromagnetic spectrum.

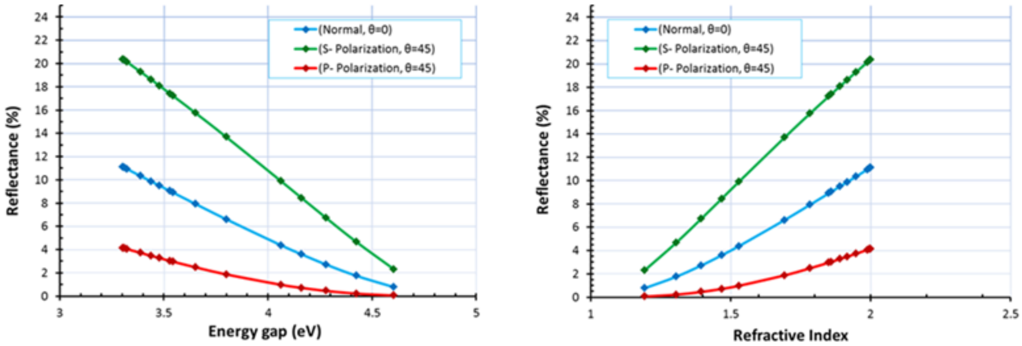
3.1 Reflectivity of ZnO based coating as a function the Particle Size

The reflectivity of ZnO based coatings has been calculated as a function of particle size (Ps = 2R) [14] .The angles ($0^o$and 45^o) are chosen to calculate the reflectivity values . Through figures (2) to (4), it can be noticed that the optical properties of ZnO coatings change depending on the particle size. When the size decreases to be less than the bulk size (20-50 nm), both the energy gap and the refractive index are changed. The refractive Index decrease , while the energy gap increases causing the reflectivity value to increase. These changes are very small until the particle size becomes smaller or equal to the Bohr radius of the excitation. We obtain a minimal reflectivity R= 0.7768 for vertical Incidence for Rs= 2.3204 % , Rp= 0.0538 % while at Incidence angle 45^o . This increase is Reflectance of ZnO could be taken advantage of producing reflective surfaces.



(a) *(b)*

Fig. 2. (a) ZnO Reflectance as a function of the particle size at incidence angle 45°. (b)ZnO Reflectance as a function of the particle size in case of vertical incidence



(a) *(b)*

Fig.3. (a) ZnO reflectance change as a function of the energy gap. (b)ZnO reflectance, as a function of the refractive Index.

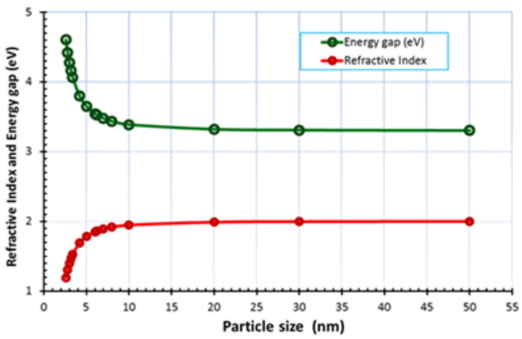
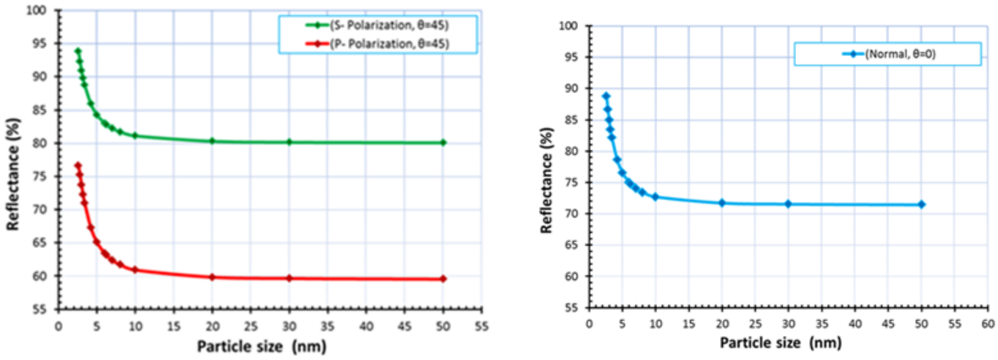


Fig. 4. Refractive index and energy gap of ZnO a function of change in particle size.

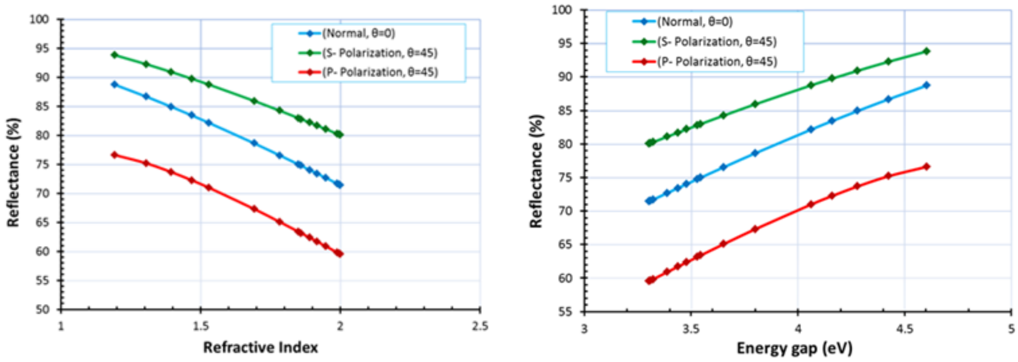
3.2 Suggested Design of an Air/GaSb/NanoZnO coating on bulk GaAs

First, the silicon with a refractive index n = 3.3 was coated with a layer of Air/GaSb/NanoZno as shown in figures5 and 6. The design (Air / HL / Sub) is proven to give the best reflectance at the design wavelength λ=694nm. The design(Air/GaSb/NanoZno/GaAs) shows a constant Reflectance at the particle size of the Coating material from (20-50 nm) where the effect of the Quantum confinement at the size is virtually non-existent, at the particle size from (7-20 nm), can be observed increasing in the value of design Reflectance. This increase results from the slight decrease in the coating refractive index. At the particle size becomes smaller Ps<7nm, the decrease in the coating refractive index is accelerated as a result of the Quantum confinement which highly increases when the particle size approaches the Bohr radius of ZnO. This results in the increase of the reflectivity, which approaches its maximal value of (Rs=93.8314%,Rp=76.6081%)for oblique incidence at($\theta = 45^{\circ}$) and (R=88.7304 %) for a perpendicular incidence when the particle size of the coating material is $P_s = 2.6$ and by using one layer of coating.



(a) (b)

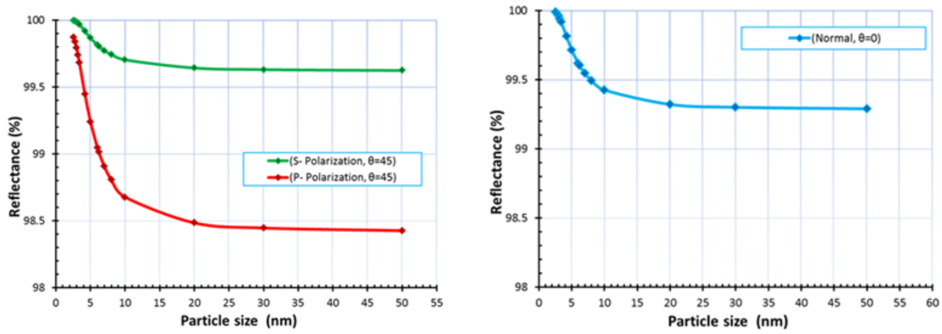
Fig. 5. (a)Design Reflectance for Air/GaSb/NanoZno/GaAs as a function of the particle size at 45^{o} angle at the design wavelength n_{sub}=3.3, L=0.25λ_o, and λ_o=694 nm. (b)Design Reflectance for Air/GaSb/NanoZnO/GaAs, as a function of particle size , for the vertical incidence at the designing wavelength n_{sub}=3.3, L=0.25λ_o, and λ_o=694 nm.



(a) (b)

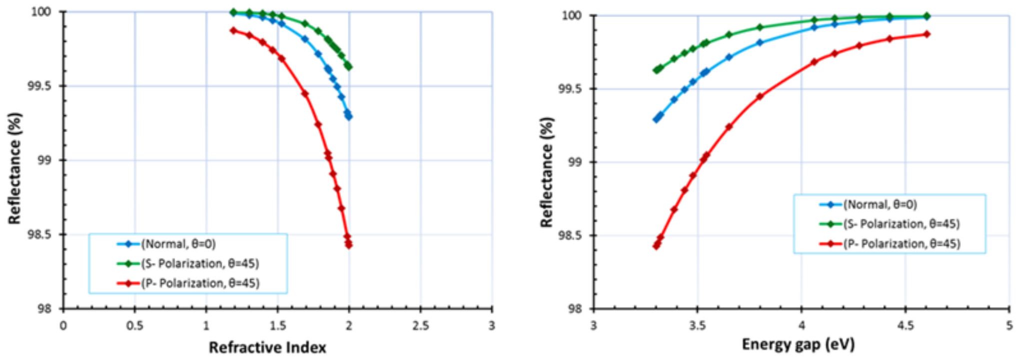
Fig. (6): (a) Reflectance of Air/GaSb/NanoZnO/GaAs as a Function of the Refractive Index.
(b) Design Reflectance of Air/GaSb/NanoZno/GaAs as a function of the energy gap.

By adding four layers of Air/GaSb/NanoZnO coating, the reflectivity increases to 100% fora particle size of P_s=2.6nm, this is shown in Figs 7 and 8.



(a) (b)

Figure (7): (a) Reflectance of Air/GaSb/NanoZno/GaAs as a function of particle size for a 45^{o} angle incidence, at the design wave length n_{sub}=3.3, L=0.25λ , and λ_o=694 nm (b)Reflectance of Air/GaSb/NanoZno/GaAs as a function of the particle size for vertical incidence at the design wavelength n_{sub}=3.3, L=0.25λ_o , and λ_o=694 nm.



(a) (b)

Fig. 8. (a) Reflectance Air/GaSb/NanoZno/GaAs as a function of the refractive index. (b) Reflectanceof Air/GaSb/NanoZno/GaAs as a function ofthe energy gap.

Table 1 shows the change in the reflectivity of(Air/GaSb/NanoZno) for the vertical and oblique incidence with particle size Ps = 2.6nm as the number of layers is increased.

Particle size (nm)	N=number of coating layer	Refractive Index nano	R	R_s	R_p
2.6	1	1.1933	88.7304	93.8314	76.6081
2.6	2	1.1933	98.8282	99.5269	95.648
2.6	3	1.1933	99.8838	99.9646	99.2486
2.6	4	1.1933	99.9885	100	99.8719

From the above data it can be noted that the four-layer Air/GaSb/NanoZnO coating provides a reflectivity of virtually 100% at nominal wavelength. This coating could therefore me advantageously considered for many applications like coating of ruby laser resonator instead of gold which is so expensive. From our experimented this coatings, also can used in Nd:YAGlaser and optimized for different regions of the spectrum to many optical applications which working in visible and near infrared spectrum.

4. Conclusions

The optical coatings reflectance depends on the refractive indexes of the used material and the incidence angle. The refractive index coefficients can be tuned through controlling the particle size of coating material to allows designing optical reflective coating at the wavelength (694 nm) of nearby Infrared range by using Bulk GaSb and Nano ZnO on a substrate of bulk GaAS, to obtain a high reflectivity compared to bulk ZnO. The highest reflectivity is obtained by using four layers of Air/GaSb/NanoZnO coating with quarter wavelength thickness. A 100% reflectivity is reached at the designing wavelength when the particle size of the coating is P_s=2.6nm. These prosperities can be used in optical instruments such as lasers, optical telescopes, microscope, and interference measurements as well as consumer products such as cameras and binoculars.

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