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Effect of Indium Nanocrystals on the Structural and Optical Properties of Gallium Arsenide

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Abstract

In this study, the structural and optical properties of indium (In) nanocrystals doped GaAs using Sol-gel method at different concentrations were investigated via X-ray diffraction technique, Transmission electron microscope and ultra violet spectroscopy. From the results, it can be shown that the InGaAs films possess polycrystalline structure with (220) crystallographic direction for InAs and (002) crystallographic direction for GaAS. In the absorbance-wavelength spectra, it is shown that absorbance increases with increase in concentration of dopant with corresponding wavelength except at 0.2% concentration which shows a blue shift of the first excitons absorption peak at 260 nm. Correspondingly the transmittance spectra decrease with the increase in the concentration except for 0.2% of InNCs doped GaAs that shows a decrease due to the increase in the scattering of the photon by the crystals. Also, there was a decrease in band gap energy as a result of introducing InNCs into the host material.

Keywords: GaAs, Doping, Concentration, InNCs

INTRODUCTION

Modern electronic devices such as integrated circuits (IC) are dominated by a single host material such as silicon, phosphorus and germanium. However, these materials have some basic limitations. These include lower carrier mobility and the indirect nature of its energy-gap as compared to GaAs. These properties limit its applications in the field of high speed/frequency electronics and optoelectronics. GaAs is one of the most technologically important and most investigated group III-V compound semiconductor materials, and is formed by combining as (group -V) and Ga (group-III) elements from the periodic table [1]. It was first produced by Goldchmidt in the 1920's. According to the energy band diagram definition, the nature of the GaAs band gap is direct. The direct band gap ensures excellent optical properties of GaAs as well as superior electron transport in the conduction band. This property makes GaAs superior over other semiconductor materials which have an indirect band gap, used in optoelectronics applications. Specifically, GaAs possesses higher carrier mobility than Si, and preferably used in high frequency devices. As Si device scaling for future generations of complementary metal oxide semiconductor (CMOS) circuits becomes increasingly difficult [2,3]. GaAs and Ge are intrinsically faster semiconductors than Si [4,5].

The properties of nanocomposite materials do not depend only on their individual parents, but also on the morphology and interfacial characteristics. Combining the properties from the parent components into a single material could generate new exciting materials with novel properties when compared to conventional microscale counterparts. It is for this reasons that the unique and improved properties of

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nanocomposite materials had gained a number of interests from researchers as it is utilized in a variety of industrial applications [6,7].

Therefore, to enhance the technological application of GaAs, the idea of nanocrystals materials was introduced. Nanocrystals are material particles having at least one dimension smaller than one hundred nanometers based on quantum dots and composed of atom of either single or poly-crystalline arrangement. Incorporation of these materials with semiconductor compound such as GaAs modified the electronics devices for technological applications [1].

The mechanisms of how gallium arsenide doping at various concentrations and temperatures to modify the structural, electrical, chemical and optical properties of the material obtain for possible technological applications still need to be understood. Hence this work investigates the effect of doping concentration of the dopant (InNCS) on the host (GaAs) material on the optical and structural properties, using Agueous sol-gel method.

Materials and method

General Comment

The materials used for the purpose of the study include; Glass substrate, indium nitrate precursor (90 Mg,), cotton wool, knife, Sodium laurel sulphate, excess methanol, Gallium acetate, pyridine, barosilicate beakers, 100ml syringe and Spatula.

Preparation of the films and deposition

All the glass substrate and other materials were cleaned using sodium laureth sulphate.

90mg, 0.05mmol of the purified [In($\eta^5 - C_5H_5$)] was put in beaker, then an excess of methanol (1ml, 39.5mmol, 8vol%) was added. The initial solution was darked, within 5min a cloudy brown suspension progressively appears, after stirring at room temperature. Equal amount of gallium arsenide was added to pyridine in a separate barosilicate beaker, for an emulsified melted solution to occur, after been mounted on a heating block. One of the beakers filled with GaAs and was heated at a temperature of about 250 k at the sample, then the indium nanoparticles were heated between 1145k and140k for various doping level.

Second step is mixing the solution of the two beakers in a doping ratio, then apply on a glass substrate in other to develop the thin film. Considering the general formula, that is to say $In_xGa_{1-x}As$. The GaAs which is the host material with a unit amount of 100u, 90u, 80u, 70u, 60u and with a corresponding dopant unit amount of 0, 10u, 20u, 30u, 40u which is the indium atom. And all the unit concentrations of the dopant were used in percentage. For sample x = 0 = GaAs, x = 0.1 =$In_{0.1}GaAs_{0.9}$, x = 0.2 = $In_{0.2}GaAs_{0.8}$, x = 0.3 = $In_{0.3}GaAs_{0.7,}$ x = 0.4 = $In_{0.4}GaAs_{0.6.}$ Where x as an important parameter stands for mole ratio for each doping stages, and the doping conditions are normally far from equilibrium because the incoming molecules are very reactive.

Fourth step. Films were then thermally annealed at the temperature of 200°C for 15 minutes with a control voltage outlet. All the profile doping was carried out by sol-gel method. Hence the concentration of indium doping at various level was 0.1 0.2, 0.3, and 0.4%.

Characterization

The variations of absorbance, transmittance and absolute specular reflectance of the films with wavelength of light incident on them were measured using a dual beam UV-vis- spectrophotometer in the photon wavelength range of 200nm to 1200nm.

The morphological properties was obtained using a TEM

The structural property was obtained using XRD

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Results and Discussion

Transmission Electron Microscopy

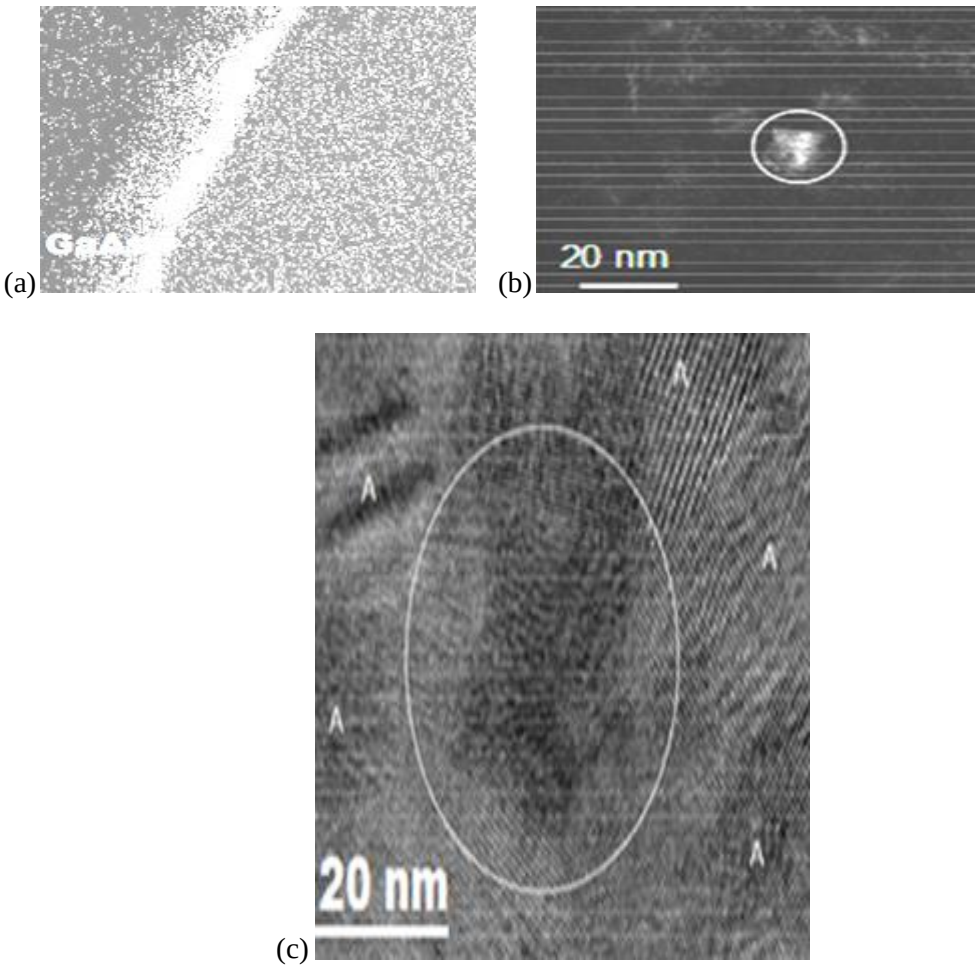

Figure 4.1Transmission electron microscopy (TEM) images of GaAs:In films: (a) bright-field, (b) dark-field, and (c) high-resolution

Figure 4.1(a) shows our typical bright-field TEM image of GaAs films: From the figures, close-up views of the polycrystalline GaAs layers containing In-rich clusters. The dark-field image in Fig.4.1(b) was obtained using the in {110} diffraction spot. A ~12 nm diameter feature is circled in Fig. 4.1(b). The high-resolution image in Figure 4.1 (c) reveals an In NC located at the boundary of multiple GaAs crystallites, each labeled "A," which presumably serves as a Nanocrystals nucleation center.

XRD analysis

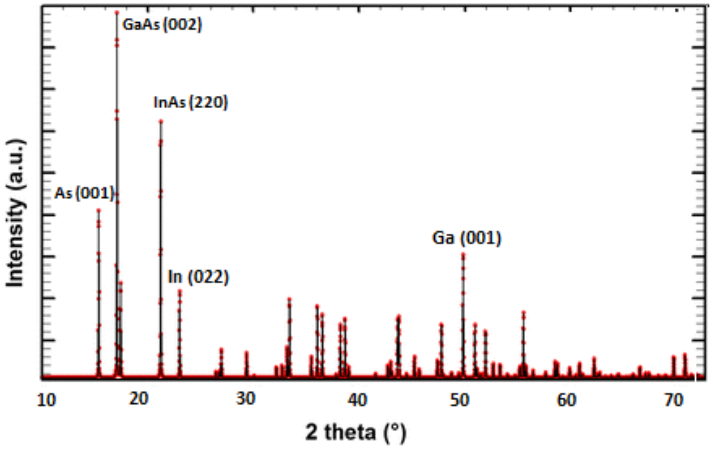

Figure 2. **The XRD Patterns of in NCs doped GaAs**

The crystal direction was found to be in (220) plane and (002) plane for the InAs and GaAs glass sample at 35.322° and 55.060° respectively. Other peaks which are approximately located at 42° and 33° correspond to (022) plane for in and (001) plane for Ga. These results are in good agreement with similar study [8]. Finally, we have summarized other crystallographic data in Table 1.

TABLE 1: Crystallographic data obtained from XRD spectra

	GaAs	InAs	As
Crystal system	Cubic	Zinc blende	Hexagonal
(hkl)	(002)	(220)	(001)
space distance d (Å)	1.85	2.22	2.69

Optical Porperties of the fabricated films

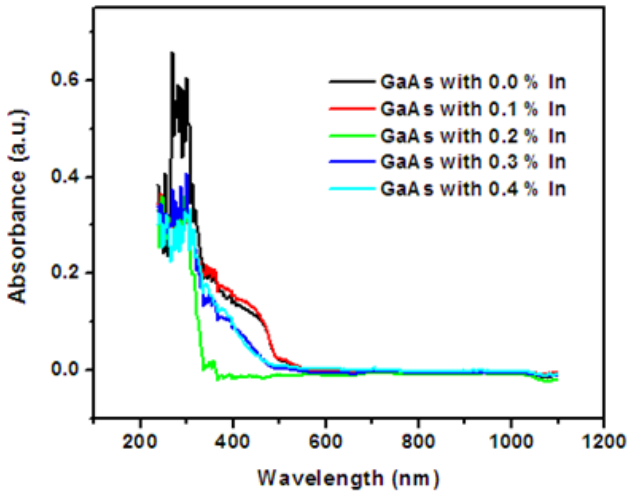

Figure 3. The combined absorption of GaAs at different indium concentration

From the above figure, at 0.0 concentrations the absorbance versus wavelength plot within the wavelength range of 200-1200 nm was seen absorbing in the UV region with absorbing peaks observed within the wavelength range of 250–300 nm.

At concentration of 0.1%, there was an increased in fall at absorbance range of about 520 nm due to little structural changes that occur,as a result of adsorption between the GaAs and the In NCs thereby leading to better photodegradation [9].

As the concentration of indium is 0.2%, the absorbance spectra noticed a blue shift which could be attributed to unstable disorder in the crystal nature of the material [10,11,12]. When the concentration is around 0.3%, a yield in the opposite behavior leading to a red shift as a large probability of the allowed direct transition of carrier mobility between the balance band and the conduction band thereby given a material a better conducting ability.

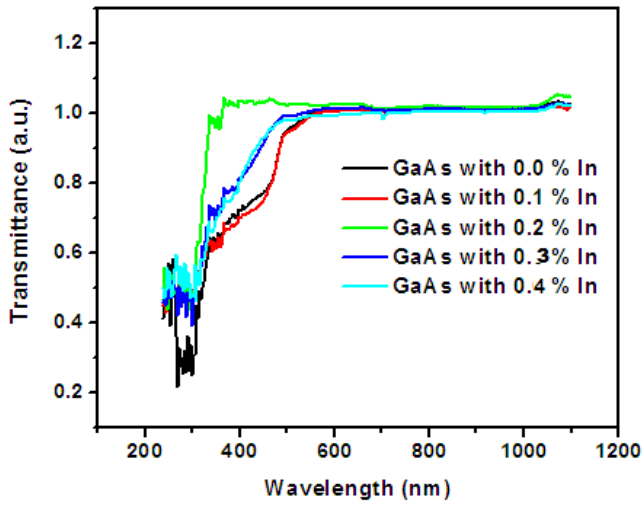

Figure 4. transmittance spectral at different indium concentration.

From the above figure, the material with 0.2 % In NCs shows a good transmittance, this is because the refractive index of the added content to the host material is dispersive. It maintains a constant transmittance at ~1.0 from a wavelength of 370 nm. When different concentration (0.1, 0.3 and 0.4%) of indium NCs were introduced, there was rise in transmittance from 310 -450 nm. Above the 450 nm, there was a constant transmittance. Similar trend follows for the undoped content. The decreased in transmittance at 0.1, 0.3 and 0.4 % doping concentrations may be due to the increased in the scattering of photons by crystal defects created by percentage of doping content which is in accordance with the findings of other workers [13].

Figure 4.9 below shows the spectral reflectance curves as a function of wavelength. Reflectance is calculated from absorbance and transmittance using the equation below

$$R = 1 - (A + T) \qquad \textbf{3.0}$$

When R is reflectance, A is absorbance and T is transmittance.

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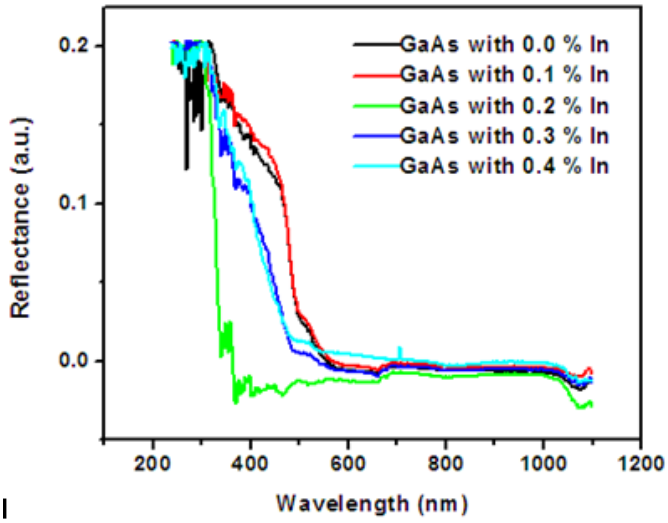

Figure 5. The reflectance spectral at different indium concentration

From the figure, it shows the reflectance curve versus wavelength of the doped materials at different doping concentration, from the curve it shows that, at 0.2% concentration the reflectance is more pronounce because of the high index of refraction of the material which attribute to a higher reflectivity. Also the angle of reflection at 0.2% concentration is greater than any other functionalised materials, hence more reflectance. This occurs at a wavelength of 350 nm in the UV region [14]. Introducing (0.1, 0.3, 0.4)% concentration shows decreased in reflectance due to the increase in the opacity nature of the doped material, and it occur at a wavelength ranging from 500-520 nm there after maintained constant reflectance.

Evaluation of the band gap energy of dopped and undopped at different indium concentration.

The optical band gap E_g was estimated by the following relation which is known as the Tauc plot [14]:

$\alpha h\nu = A(h\nu - Eg)^n$,

The exponent n depends on the type of band transition. n = 1/2 and 3/2 corresponds to indirect allowed and indirect nature of band transition, A is the edge width parameter representing the film quality, which is calculated from the linear part of this relation and Eg is the optical band gap of the material.

To determine the possible transition $(\alpha h\nu)^{1/n}$ vs $h\nu$ is plotted and corresponding Eg values are obtained by extrapolating the straight line portion of the graph on $h\nu$ axis.

α=is the absorption coefficient that can be calculated from absorbance spectra given as:

$$\alpha = \frac{2.303A}{d}$$

Where d is the thickness and A is the absorbance.

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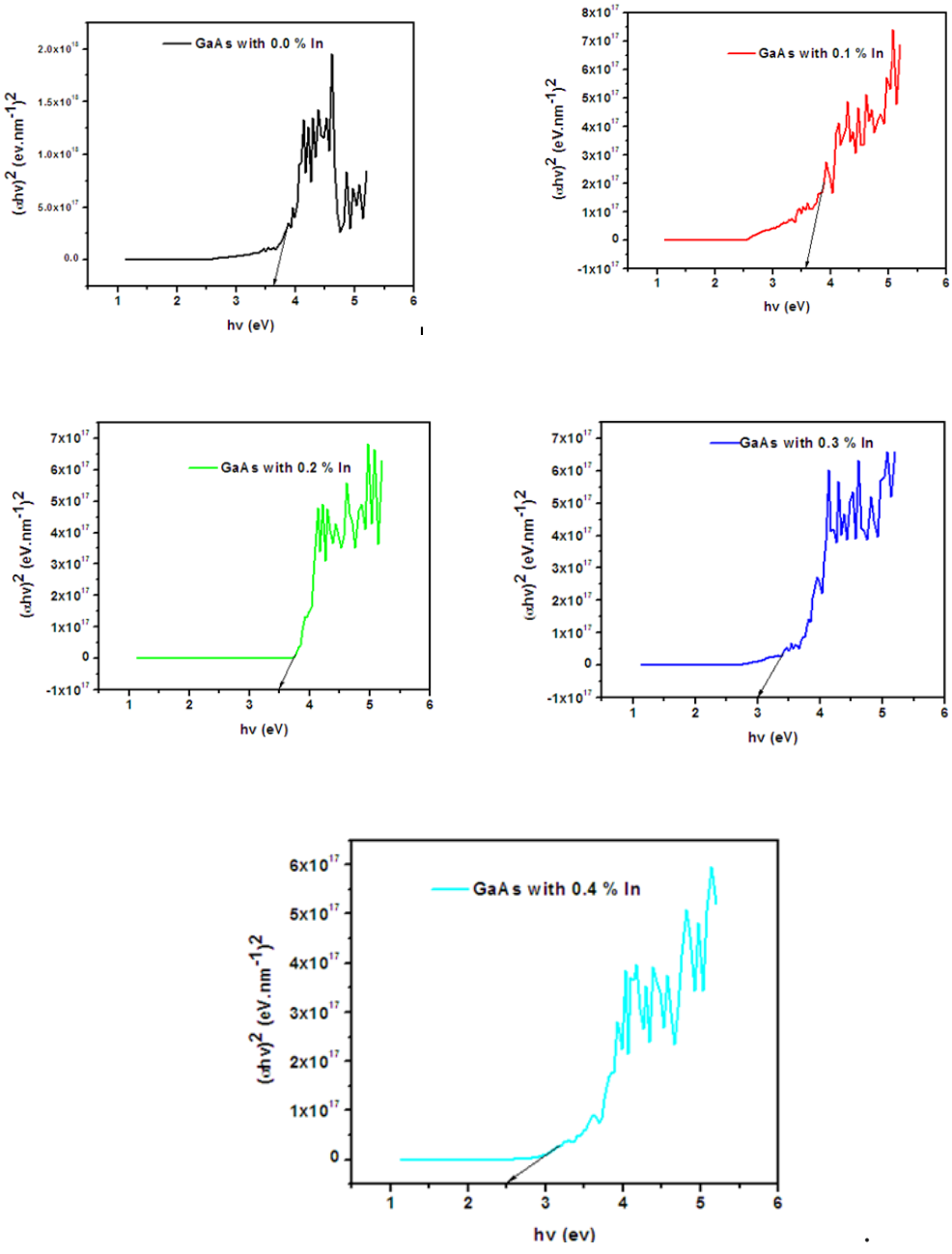

Figure 4.14 The variation of $(\alpha hv)^2$ with photon energy at 0.1, 0.2, 0.3 and 0.4 %.

Figure 4.10, shows the band gap energy of the semiconductor material without indium NCs doping with an approximate energy band gap value of 3.57ev.When indium NCs were introduced with different concentrations, we observed a decrease in band gap ranging from 3.57-2.50 eV. The decrease in band gap was due to little disorder in the crystals nature of the host material as the concentration is increased [15] The band gaps with different concentration are 3.57 eV (0.1 %), 3.5 eV (0.2 %), 3.0 eV (0.3 %) and 2.5

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eV (0.4 %). There was abruptly decrease in band gap energy which indicates that there is increased in crystals perturbation yielding to crystal size de-quantization [16]. The variation can also be attributed to the large disparity in the electro negativity and the atomic size between In and Ga in $In_xGa_{1-x}As$. The indium atom brings several perturbations in the host crystals [12].

CONCLUSION

Optical, morphological and structural properties of prepared samples of indiumnanocrystal doped GaAs were investigated by in cooperation of indium nanocrystals materials into GaAs layer via TEM, UV-vis, and XRD. From the structural properties of the doped materials, it was found that GaAs is an alloyed of gallium arsenide and indium arsenide with a change in the crystal structure from cubic to hexagonal, we have also obtained the crystallography direction data from XRD patterns indicating that InAs is in (220) crystallographic direction and GaAs with (002) crystallographic directions. An excellent surface morphology is obtained from our TEM. In the absorbance-wavelength spectra, it shows that absorbance increases with increase in concentration with corresponding wavelength except at 0.2% concentration which shows a blue shift of the first excitons absorption peak at 260 nm. The transmittance spectra decreases with the increase in the concentration except for 0.2% of InCs doped GaA, due to the increase in the scattering of the photon by the crystals. Similarly the reflectance decreases due to increase in the opacity as the concentration increases, and appear high at 0.2% which attributed to the high refractive index.

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