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Amorphous-Ga_2O_3/GaAs(100) anisotype heterojunctions with amorphous-Ga_2O_3 n-type films grown by magnetron sputtering

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***Abstract*—In this work, the growth and characterization of undoped amorphous gallium oxide films (Ga_2O_3-a) and titanium (Ti) doped films (Ga_2O_3-a:Ti) grown by the magnetron sputtering method are reported. The doped films resulted n-type with electron mobilities in the range of 13.68(cm^2/Vs) to 35.11(cm^2/Vs) with carrier concentration of 1.0x10^{14}(cm^{-3}) to 5.0x10^{19}(cm^{-3}). Both kinds of films were used in the construction of anisotype Ga_2O_3-a:Ti/Ga_2O_3-a/p^+ GaAs (100) heterojunctions to demonstrate their potential application for the electronic device development.**

Keywords— Thin films, amorphous gallium oxide, magnetron sputtering, anisotype heterojunctions, electrical properties.

I. INTRODUCTION

Semiconductor technology has become so important that they have changed our way of life in many ways. They have provided fast communications and ushered in the information age by enabling high-performance computing and large-capacity data storage. These characteristics are fundamental to any electronic system. The technological research of semiconductors became notable with materials such as germanium (Ge) and silicon (Si) and from there, many compound semiconductors and various semiconductor alloys were developed. Currently, metal oxide semiconductors (MOS) constitute a family of semiconductors that provide unique properties, due to the large bandgap energy (Eg) that they usually have and make them attractive for applications in power devices, among others. In addition, because the Eg is large, the MOS are transparent to the ultraviolet (UV) region, which allows their use in various applications such as optoelectronics and communications, among others [1-2]. A family of MOS that is also relevant is the transparent amorphous semiconductors due to their large Eg, which, in the same way, are used in the construction of solar cells or research is being carried out for their application in the development of power electronic devices [3]. Great interest has generated the amorphous gallium oxide (Ga_2O_3-a) films as multifunctional oxide semiconductors, that on their own are n-type semiconductors with very low electron concentration [4,5], so it usually needs to be doped in order to obtain more suited properties for electronic device application. The most used dopants for Ga_2O_3 grown by conventional methods are Si, Nb, Cu, In, Mn, Eu and Sn [6]. Also, titanium (Ti) has be used to produce Ga_2O_3 ohmic contacts [7,8], suggesting that Ti has high solid solubility, and its possible use as a dopant. Under this hypothesis, an experimental study was carried out in this work to control Ga_2O_3-a electrical properties with Ti and in turn, using both kind of such films for the making of a heterojunction device with Ga_2O_3-a:Ti, Ga_2O_3-a, and p+ GaAs (100) [9-11].

II. METHODOLOGY

The methodology used in this work takes the idea from the results of Juarez-Amador [12], in which amorphous films of gallium oxide impurified with copper (Ga_2O_3-a:Cu) are grown by co-sputtering on glass substrates using a flow of 10 sccm ultra-high-purity Ar gas, producing a working pressure of 5.0 x10^{-3} (Torr). In this work, the sputtering method is used to grow Ga_2O_3 films [13] with electrical insulating properties. To confirm its electrical properties the produced films were characterized by the Hall-van der Pauw method. To dope the Ga_2O_3-a films with Ti, (Ga_2O_3-a:Ti), the co-sputtering method was also used including a Ti target; films were also electrically characterized, alongside SEM and XRD studies. The structural properties were analyzed by X-ray diffraction with a PANalytical X´Pert diffractometer with the CuKα radiation wavelength 1.5400598 (Å) in the range of 20-80° (2-Theta).

Finally, a set of Ga_2O_3-a:Ti and p+ GaAs (100) heterojunctions were produced considering the common cation between both semiconductors. p+ GaAs (100) with $6.15x10^{17}$ (cm^{-3}) concentration were used as substrates. For the Ga_2O_3-a:Ti films, the ohmic contacts were made with a vanadium-nickel alloy; and gold for p+ GaAs (100). For the correct operation of the ohmic contacts, the heterojunctions were annealed at 150(°C) in an inert Ar gas atmosphere. The GaAs substrates were formerly cleaned using standard procedures.

The characterization techniques used in the film analysis were scanning electron microscopy (SEM) using an HRSEM-AURIGA microscope, atomic force microscopy analysis (AFM), and secondary ion mass spectroscopy (SIMS). Current-Voltage (J-V) characterization of the heterojunction was done to find main electrical mechanism controlling the current flow.

III. RESULTS AND DISCUSSION

A. *Characterization of Ga_2O_3-a films*

The Ga_2O_3-a films were grown using the experimental conditions formerly mentioned; for the undoped Ga_2O_3-a films with an RF power of 150(W) electrical insulating films were produced confirming previously reported results [11]. The films were grown for 30 minutes producing a thickness of 25 (nm) as measured by a profilometer KLA Tencor P15. Otherwise, the Ti-doped films were grown by co-sputtering using an RF power of 150(W) for the Ga_2O_3 magnetron, and varying the DC power of Ti magnetron from 27.5(W) to 40(W) as shown is Table I. Ga_2O_3:Ti films resulted n-type with carrier mobilities from 13.68(cm^2/Vs) to 35.11(cm^2/Vs) and electron concentrations from 1.0 $x10^{14}$ (cm^{-3}) to $5x10^{19}$(cm^{-3})

TABLE I. ELECTRICAL PROPERTIES OF GA_2O_3-A:TI FILMS

Sample	Power relation(W)	Resistivity (Ω-cm)	Mobility (cm^2/Vs)	Concentration ($1/cm^3$)
1	150-27.5	1838.22	35.11	1.00E+14
2	150-30	26.236	19.61	1.00E+16
3	150-30	7.18	18.97	5.00E+16
4	150-40	0.2658	13.68	2.00E+18
5	150-40	0.0071	18.97	5.00E+19

Fig. 1 shows the SEM microphotographs of typical Ga_2O_3-a films surface, it is noticed a smooth and uniform surface. Fig 2 includes de XRD spectra on the grown samples, within the range where the main characteristic diffraction lines for the gallium oxide are observed, showing the amorphous character either in the undoped and Ti-doped samples.

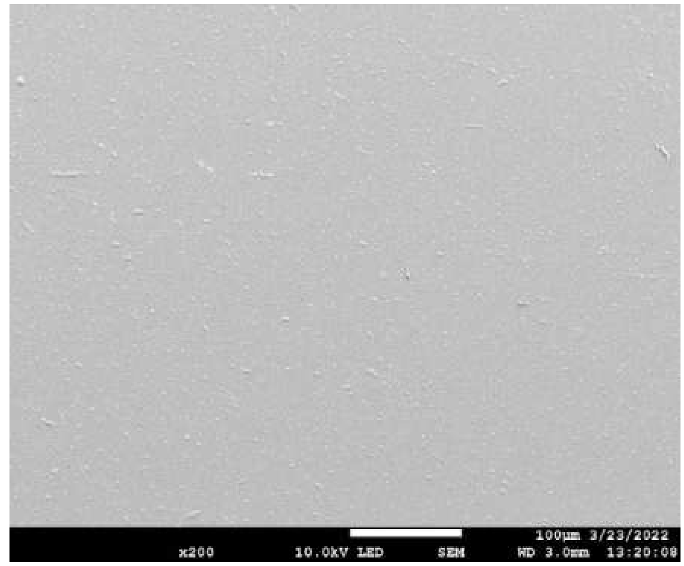

Fig. 1 SEM image for a Ga_2O_3-a:Ti film.

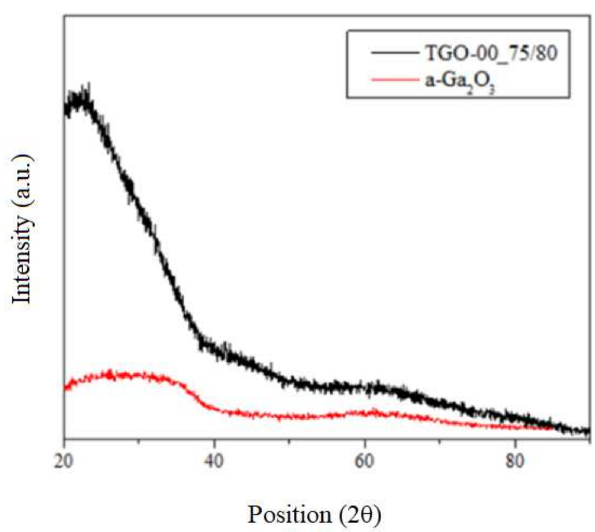

Fig. 2 XRD characterization for Ga_2O_3-a film

B. *Characterization of Ga_2O_3-a:Ti /Ga_2O_3-a(i) / p-type GaAs (100) heterojunction*

A SEM microphotograph of the produced heterojunctions is shown in Fig. 3, it can be observed the details of the ohmic contact and the nearby Ga_2O_3-a:Ti film with a smooth feature. AFM was also used to corroborate such findings as observed in Fig 4, where the studied sample resulted with an RMS roughness of 0.167 (nm).

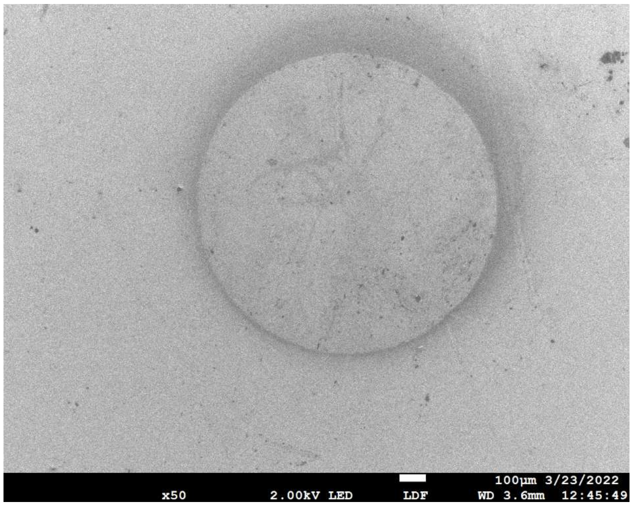

Fig. 3 SEM image for the *Ga_2O_3-a:Ti /Ga_2O_3-a(i) / p-type GaAs (100) heterojunction*

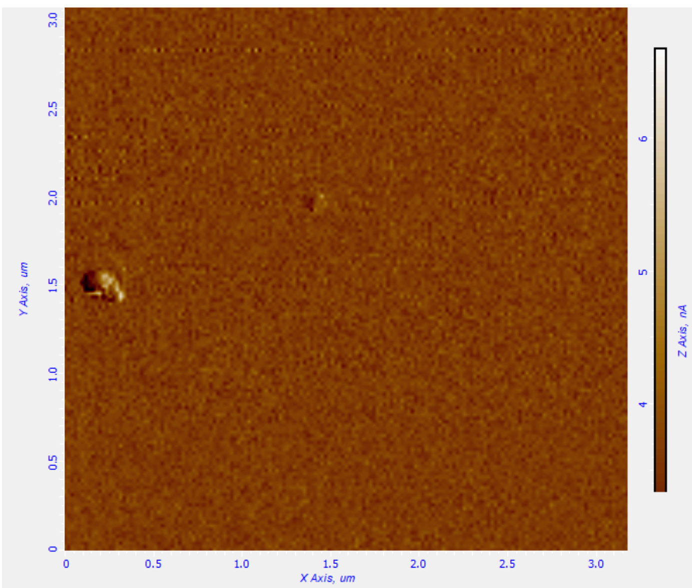

Fig. 4 AFM image for the *Ga_2O_3-a:Ti /Ga_2O_3-a(i) / p-type GaAs (100) heterojunction*

SIMS characterization was done to the heterojunction to find out its chemical composition, as presented in Fig. 5. The behavior shown for titanium suggests an exo-diffusion occurring from the Ga_2O_3-a:Ti film.

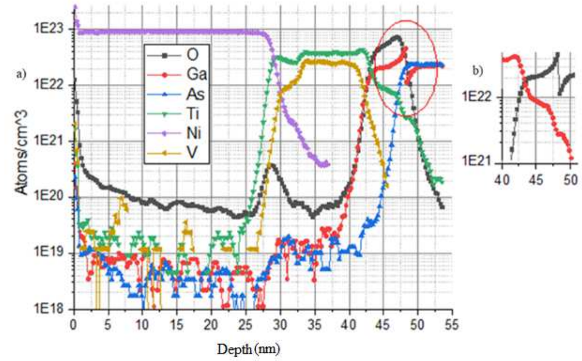

Fig. 5 SIMS studies for the *Ga_2O_3-a:Ti /Ga_2O_3-a(i) / p-type GaAs (100) heterojunction*

The measured J-V characteristics for the heterojunction are included in Fig. 7, where the asymmetrical behavior in forward and reverse bias reveals the formation of the energy barrier with clearly discernible transport mechanisms.

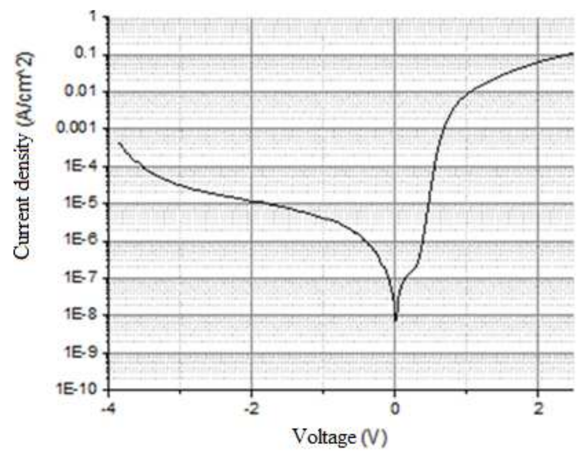

Fig. 7 J-V semi log curve for the *Ga_2O_3-a:Ti /Ga_2O_3-a(i) / p-type GaAs (100) heterojunction*

The J-V characteristic model for a biased device comprising an energy barrier has the form [14]:

$$J = J_0 \left\{ \exp\left(\frac{qV}{\eta\, kT}\right) - 1 \right\} \quad (1)$$

Where η is related to the ideality factor with a value equal to the unity when thermionic emission is the limiting carrier transport mechanism. Using (1) the ideality factors obtained for the forward biasing conditions are 1.26 and 4.92; these values suggest the influence of thermionic emission, generation-recombination, and mixed tunnel mechanism, among others. Moreover, due to the resultant electrical insulator behavior of the undoped Ga_2O_3-a film, the carrier flow is influenced by the intense electrical field in the heterojunction interface and the concentration of trap energy levels (Nt). Considering the continuity equation given by:

$$J(x) = e\, n(x) v(x) \quad (2)$$

Where $n(x)$ is the electron concentration in the undoped Ga_2O_3-a film and $v(x)$ is the carrier velocity. Within this high electrical field zone, the limiting mechanism are referred to the space charge limited (SCL) regime bounded by the trap-filled limit (TFL) and the Child´s law, accompanied by Ohm´s law at lower bias [15].

$$J_{Ohm} = e\, n_0\, \mu\, \frac{V}{d} \tag{3}$$

$$J_{TFL} = \frac{9}{8}\, \mu\, \varepsilon\, \theta\, \frac{V^2}{d^3} \tag{4}$$

$$J_{Child} = \frac{9}{8}\, \mu\, \varepsilon\, \frac{V^2}{d^3} \tag{5}$$

$$\theta = \frac{N_C}{g_n N_t} \exp\left(\frac{E_t - E_C}{kT}\right) \tag{6}$$

$$V_{TFL} = \frac{q N_t\, d^2}{2\, \varepsilon} \tag{7}$$

$$V_{tr} = \frac{8}{9} \times \frac{q n_0\, d^2}{\varepsilon\, \theta} \tag{8}$$

Where n_0 is the concentration of the free charge carriers in thermal equilibrium, V is the applied voltage, d is the thickness of the undoped Ga_2O_3-a film, ε is the static dielectric constant, θ is the ratio of the free carrier density to the total carrier (free and trapped) density, g_n is the degeneracy of the energy state in the conduction band, E_t is the trap energy level and N_t is the trap density.

The parameters described by the previous equations can be displayed representing the forward bias region of the J-V characteristics as shown in Fig. 8. The characteristics parameters are 0.02(V) for V_{tr} and 0.5(V) V_{TFL} . According to the experimental data of the J-V semi-log curve, it can be observed symmetric behavior at low bias. This suggests the intervention of electronic defects whose influence is noticed with a bias lower than ± 0.02(V) is usually related to shunt resistance.

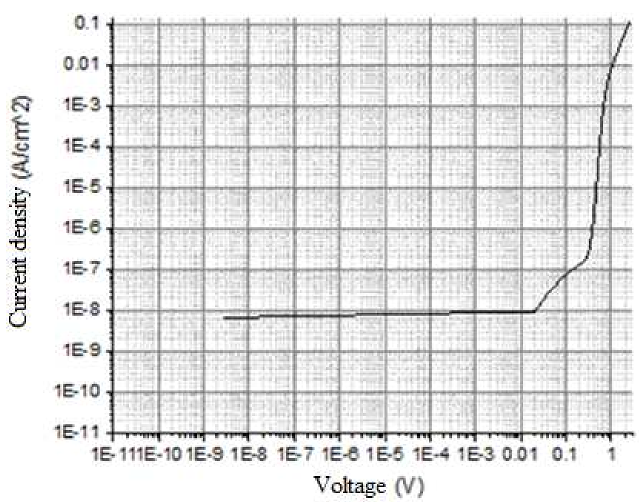

Fig. 8 J-V log curve for the *Ga_2O_3-a:Ti /Ga_2O_3-a(i) / p-type GaAs (100) heterojunction*

IV. Conclusions

In conclusion, undoped amorphous gallium oxide films and titanium doped amorphous gallium oxide films were grown on glass substrates by the magnetron sputtering technique, operating at room temperature. Studies by the X-ray diffraction technique carried out on the films indicate the amorphous nature of the produced films. X-ray diffraction results indicate that both kinds of samples resulted in an amorphous character. Undoped samples resulted in electrical insulating films. Otherwise, the Ga_2O_3-a:Ti films were n-type with mobilities from 13.68(cm^2/Vs) to 35.11(cm^2/Vs) and electron concentrations from 1.0 x10^{14} (cm^{-3}) to 5x10^{19}(cm^{-3}).

Ga_2O_3-a:Ti/Ga_2O_3-a (i)/GaAs(p+) heterojunctions were produced using the films previously described. The heterojunctions were characterized by SIMS, XRD, and electrically qualified through current-voltage characterization at room temperature. The electrical characteristics of the heterojunctions can be qualified as reasonable because it was possible to observe the J-V characteristics. In these measurements, it was possible to distinguish the characteristics conduction mechanism in the heterojunctions influenced by the amorphous nature of the Ga_2O_3-a films. The heterojunction limiting conduction mechanisms are related to the electrically insulating character of the amorphous Ga_2O_3 films.

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