γ-rays irradiation effects on dielectric properties of Ti/Au/GaAsN Schottky diodes with 1.2%N.

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1. Abstract:

Dielectric properties of As grown and irradiated Ti /Au/GaAsN Schottky diodes with 1.2%N are investigated using capacitance/conductance-voltage measurements in 90 - 290 K temperature range and 50-2000 kHz frequency range. Extracted parameters are interface state density, series resistance, dielectric constant, dielectric loss, tangent loss and ac conductivity. It is shown that exposure to γ-rays irradiation leads to reduction in effective trap density believed to result from radiation-induced traps annulations. An increase in series resistance is attributed to a net doping reduction. Dielectric constant (ε') shows usual step-like transitions with corresponding relaxation peaks in dielectric loss. These peaks shift towards lower temperature as frequency decrease. Temperature dependent ac conductivity followed an Arrhenius relation with activation energy of 153 meV in the 200–290 K temperature range witch correspond to As vacancy. The results indicate that γ-rays irradiation improves the dielectric and electrical properties of the diode due to the defect annealing effect.

2. Keywords:

γ-Rays irradiation, Dielectric relaxation, Dielectric constant, Dielectric loss, AC conductivity

3. Introduction

The search for new high speed devices that resist radiation is required for a number of useful applications. Among these semiconductor materials candidates, dilute nitride gallium arsenide (GaAsN) has been recently proposed (Shafi et al., 2011). Its electrical properties can be improved by adding a small nitrogen fraction, and can be tailored for many applications such as solar cells fabrication (Yamaguchi et al., 2012), infra-red lasers devices (Kondow et al., 1997), terahertz emitters and detectors (Park et al., 2009) and so on. The presence of some percent of nitrogen (N) induces an impressive diminution of forbidden band gap of GaAs semiconductor. Due to large electronegativity of nitrogen and its small covalent radius, forbidden band gap

decreases by approximately 0.1eV for each percent of nitrogen (N) in the alloy. Researchers (Tisch et al., 2002) suggested that this dependence of energy gap on small nitrogen fraction (0<x<5) can be calculated using empirical expression:

$$E_G^{GaAs1-xNx} = E_G^{GaAs} - 18.7 * x + 210 * x^2 \qquad (1)$$

For GaAsN alloys with 1.2%N concentration, the band gap is 1.22 eV. Furthermore, GaAsN show an increase in effective mass and decrease in life time carriers and their mobility. These changes make dilute alloy candidate to possible optoelectronic applications (Riechert and Steinle, 2005; Weltya et al., 2005; Yoona et al., 2005). Lately, irradiated Ti/Au/GaAsN Schottky diodes have attracted attention. Workers (Al Saqri et al., 2015) have investigated gamma irradiation effects on Ti/Au/GaAsN Schottky diodes using Laplace Deep Level Transient Spectroscopy (LDLTS). The gamma dose was 50 kGy (dose rate of 5.143 kGy/h).They showed that for samples with N content between 0.2% and 0.4%, the number of traps decreased after irradiation, whereas for samples with N content between 0.8% and 1.2 %, the number of traps remained the same. Workers (Bachir Bouiadjra et al., 2014) have investigated the electrical properties of same Schottky diodes at room temperature. They found that ideality factor and series resistance increase with increasing N% dilution in GaAs accompanied by a decrease in Schottky barrier height. They stated that interface states density increased when dilute nitride concentration increased. Researchers (Klangtakai et al., 2015) have also investigated gamma-ray irradiation effects on structural properties of $GaAs_{1-x}N_x$ films (N between 1.9 and 5.1 at%). They found that gamma-ray irradiation causes structural changes including displacement damage and gamma-ray heating.

In our previous work (Teffahi et al., 2016) we have characterized electrical properties of Ti/Au/$GaAs_{1-x}N_x$ Schottky diodes at room temperature using I-V and C/G-V-f techniques, The investigated parameters are ideality factor (n), series resistance (Rs), barrier height (Φ_B), doping concentration (N_D), relaxation time and density of interface states (Nss). We have shown a decrease in measured barrier height and an increase in extracted Ideality factor and the series resistance. The density of interface states distribution increase after radiation due to irradiation-induced defect (Al Saqri et al., 2015).

However, workers (Bobby et al., 2014) have deduced that irradiation with a cumulative dose of 10 Mrad improves electrical characteristics of Au/n-GaAs diodes. They found a decrease in series resistance and in ideality factor. Researchers (K. M. Yu and W. Walukiewicz, 2002) stated that pulsed laser annealing improves N incorporation in GaN_xAs_{1-x} thin films with synthesized films being thermally stable.

All above studies show that electrical properties of GaAsN Schottky diodes are complex and still raise numerous questions related to N concentrations and irradiation effects. In this paper, electrical and dielectric properties of as grown and γ-rays irradiated Au/Ti/GaAsN 1.2%N Schottky diodes are analyzed. The effect of γ-rays on interfaces states density , series resistance, permittivity, dielectric constant, loss factor (tan δ) and ac conductivity are examined over a wide temperature range [90 K-290 K] and frequency range [10 KHz-2 MHz].

4. Experimental details

As previously described (Teffahi et al., 2016), Schottky diodes are made of an n-GaAs substrate on top of which is grown a 0.1μm thick Si-doped (2.10^{18} cm^{-3}) epitaxial buffer layer of GaAsN followed by a 1μm thick Si-doped (3.10^{16}cm^{-3}) epitaxial active layer of GaAsN. At this stage, structures were ion irradiated at room temperature in a gamma cell Cobalt irradiator at a dose of 50 kGy with a 5.143 kGy/h dose rate. Then devices are processed in the form of circular mesas with different diameters for electrical characterization. A Ge/Au/Ni/Au sandwich layer was evaporated and alloyed to form an Ohmic contact to the bottom of n- GaAs substrates. Schottky contacts were formed by evaporation of Ti/Au on top of doped epilayer. Capacitance/Conductance-Voltage (C/G–V-T) measurements were carried out using an Agilent LCR meter (E4982a). Device temperature was changed using an ARS Closed Cycle Cryostat.

5. Results and discussions

1.2% N content Au/Ti/GaAsN Schottky diodes are dc biased from -2 to 0.8V with an added small ac sine signal at 1 MHz to allow deep traps to capture and release electrons. Figure (1) shows capacitance variation against bias voltage before and after irradiation at some preselected temperature. Capacitance decreased after irradiation. This is attributed to a decrease in donor concentration and to a change in dielectric constant at metal semiconductor interface after gamma irradiation (Shiwakoti et al.,

2017). Capacitance also decreased with decreasing temperature due to a continuous distribution of density of interface states (Nss) and change in series resistance (Bobby et al., 2016).

Figure (2) shows conductance variation bias voltage before and after irradiation at some preselected temperature. Conductance increases with increasing voltage and with decreasing temperature for both samples. However, its value decreased after gamma irradiation. This effect can be attributed to a decrease in net ionized doping concentration (Behle and Zuleeg, 1972; Karataş et al., 2005; Uğurel et al., 2008).

Series resistance temperature-voltage dependence in Figure (3) is obtained from C–V–T and G–V–T measurements according to (Bachir Bouiadjra et al., 2014; Nicollian et al., 1982):

$$R_s = \frac{G_m}{\left(G_m^2 + \omega^2 C_m^2\right)} \tag{2}$$

where C_m and G_m are measured capacitance and conductance and $\omega=2\pi f$ is the angular frequency. Series resistance was found strongly dependant on temperature and irradiation. Notice that series resistance has a peak for all diodes with peaks shifting towards positive voltage region. Rs temperature dependence is attributed to activation of interface states (Teffahi et al., 2016). Series resistance of irradiated samples has increased due to the decrease of carriers' mobility and carriers' removal effect (Behle and Zuleeg, 1972).

Obtained series resistance values are used to correct measured capacitance and conductance-voltage values. Therefore, measured capacitance and conductance values were corrected by eliminating the effect of Rs in order to obtain the real capacitance Cc and conductance Gc values. Corrected capacitance Cc and conductance Gc values were calculated using (Hill and Coleman, 1980):

$$C_C = \frac{\left[G_m^2 + (\omega C_m)^2\right] C_m}{a + (\omega C_m)^2} \tag{3}$$

And

$$G_C = \frac{\left[G_m^2 + (\omega C_m)^2\right] a}{a + (\omega C_m)^2} \tag{4}$$

where $a = C_m - \left[G_m^2 + (\omega C_m)^2\right]R_s$. After capacitance and conductance correction, Hill–Coleman method (Hill and Coleman, 1980) was used to find interface state density using:

$$D_{IT} = 2/(qA)(G_m/\omega)_{max}/((G_m/\omega)_{max}/C_{ox})^2 + (1 - C_m/C_{ox})^2 \quad\quad (5)$$

where A is rectifier contact area, ω is angular frequency, C_m and $(G_m/\omega)_{max}$ are capacitance and conductance at high forward voltage and C_{ox} is native insulator layer capacitance given by (Nicollian et al., 1982):

$$C_{ox} = C_m\left[1 + \left(\frac{G_m}{\omega C_m}\right)^2\right] \quad\quad (6)$$

The inset plot of Figure (3) shows active interface states density change against temperature for both as grown and γ-rays irradiated Schottky diodes. Active interface states densities increase with increasing temperature since interface states near the conduction band are more sensitive at high temperatures. These interface state density profiles show the presence of greater density of active localized interface taps in as grown than irradiated samples. Calculated values at 270 K are found to be about 6.04×10^{14} eV^{-1}.cm^{-2} and 7.77×10^{12} eV^{-1}.cm^{-2} for as grown and irradiated samples, respectively. Gamma rays are found to have an annealing effect that reduces interface states density (AURET et al., 1993; Goodman et al., 1994; Shafi et al., 2011).

The quality of interface contact and its temperature and frequency dependence can also be described in term of dielectric dispersion. Dielectric properties such as dielectric constant, dielectric loss and ac conductivity help to shed some light on 50 kGy γ-rays irradiation effects (Dokme and Altindal, 2011).

When a periodic electric field E is applied to a dielectric, a charge displacement D is created (Fröhlich, 1949; Sagadevan and Sundaram, 2014) with:

$$D = \varepsilon^* E \quad\quad (7)$$

where ε^* is the complex dielectric that describes the drop in electric field strength through dielectric due to inhomogeneity of interface. It can be expressed as:

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \quad\quad (8)$$

Where (ε') and (ε'') are the real and imaginary parts of permittivity.

The relative permittivity ε' of a dielectric is calculated from measured capacitance and conductance by taking:

$$\varepsilon^{'} = \frac{C_m}{C_0} \qquad (9)$$

Dielectric loss $\varepsilon^{''}$ of a dielectric is calculated by taking:

$$\varepsilon^{''} = \frac{G_m}{\omega C_0} \qquad (10)$$

Tangent loss (tan δ) is derived from equation (8) as:

$$tan\delta = \frac{\varepsilon^{''}}{\varepsilon^{'}} \qquad (11)$$

The ac conductivity (σ_{ac}) is derived as:

$$\sigma_{ac} = \omega C tan\delta \left(\frac{d}{A}\right) = \varepsilon^{''} \omega \varepsilon_0 \qquad (12)$$

Dielectric constant ($\varepsilon^{'}$) and dielectric loss ($\varepsilon^{''}$) of Ti/Au/GaAsN Schottky diodes with 1.2%N content, calculated from measured impedance data using equations (9) and (10), are shown in Figures (4) and (5), respectively. Figure (4) shows dielectric constant versus temperature dependence at various frequencies. $\varepsilon^{'}$ is quasi constant for temperatures below 170 K then increase almost linearly with increasing temperature due to space charge polarization related to ionic atoms and hoping charges at interface. Such results mean that temperature increases displacement and disorder at interface (Strzalkowski et al., 1976). Dielectric constant decreases after irradiation. At 250 K, for example, dielectric constant is about 6.51 for as grown and 5.28 for gamma irradiated Schottky diodes. Gamma irradiation decreases existing disorder in as grown diodes and improves interface quality by annealing interface traps (Bobby et al., 2016). Dependence of dielectric constant on frequency is shown only for as grown Ti/Au/GaAsN Schottky diodes and not on γ-rays irradiated ones. There is a decrease in dielectric constant with increasing frequency. Such behavior can be explained by the fact that when frequency is raised, interfacial dipoles have less time to orient themselves in alternating field direction (Fröhlich, 1949).

Dielectric loss is proportional to energy loss in dielectrics. It presents two relaxation peaks at 200 K and 270 K, Figure (5). These peaks correspond to polarization effect of interface states. Interfacial polarization appears when electric field produces a separation of mobile positive and negative charges (Mustafaeva et al., 2009). These peaks shift towards lower temperature as frequency decreases. This is due to the

contribution of interface states that cannot follow the ac signal at high frequencies (Swamy et al., 2016). Joule heat may be produced by electrons and ions drift current in Schottky contact witch dissipate part of energy as heat in dielectric. Figure (6) shows loss tangent temperature dependence for various frequencies. Loss tangent increase with increasing temperature; at high temperature more charge participate to conduction. After irradiation a reduction in charge yields a decrease in thermal loss. Hence, the decrease in loss tangent of irradiated diodes is interpreted on basis of 'annealing effect' of γ-rays. N incorporation decreases the activation energy of dielectric relaxation, thus the dielectric plots shift to lower temperature.

Figure (7) shows ac conductivity σ_{ac} temperature dependence for various frequencies. σ_{ac} shows two peaks with different intensities around 200 K and 270 K. Both peaks are slightly shifted towards lower temperatures when frequency decreases. After irradiation, σ_{ac} decreased due to donors' concentration reduction. σ_{ac} also decreased with decreasing temperature and applied frequency. This is due to charges freezing effect. From ac conductivity evolution with temperature, it is possible to plot Arrhenius function (El Sayed, 2014; Maldzius et al., 2010):

$$\sigma_{ac} = \sigma_0 e^{\frac{E_a}{kT}} \qquad (13)$$

where σ_0 is pre-exponential factor, E_a is activation energy and kT is thermal energy. From the linear part of the inset plot of Figure (7) it is possible to calculate σ_0 from the intercept and E_a from the slope at a defined frequency. E_a experimental values at 1 MHz are 153 meV and 86.7 meV in 200–290 K temperature range which correspond to As vacancy and shallow level in as grown and irradiated Ti/Au/GaAsN Schottky diodes (Al Saqri et al., 2015; Shafi et al., 2011).

The observed dielectric parameters do not refer to the bulk of the materiel, it's referring to interfacial contact. To separate the dielectric behavior of the bulk the modulus formalism is used, the electric modulus formalism presents certain advantages in interpreting the deep traps relaxation properties, as the conductivity relaxation becomes more prominent due to the suppression of the electrode effects.
The complex electric modulus is defined as the inverse quantity of the complex permittivity by equations (Abdel-Baset and Hassen, 2016; Tan et al., 2016):

$$M^* = M' + iM'' \qquad (14)$$

$$M^* = \frac{\varepsilon'}{\varepsilon'^2 + \varepsilon''^2} + i\frac{\varepsilon''}{\varepsilon'^2 + \varepsilon''^2} \qquad (15)$$

Where ε' and ε'' are the real and imaginary parts of the dielectric.

Figure (8.A) represents the real (M) variation against temperature and frequency of irradiated and as grown Schottky diode. At low temperature region, the magnitudes of M' is almost constant and tend to decrease with increasing temperature because of the thermally activated nature of the dielectric permittivity (Dohare et al., 2016).

The variation of the imaginary parts of the modulus (M) against temperature and frequency were presented in figure (8.B). The peak values of M'' were found to be lower than the values of ε'' that obtained from Figure (5). This indicates the removal of the electrode polarization. Up 150 k the M'' increase with increasing temperature due to charge polarization effects. Peaks were observed around 200 k, these peaks decrease with decreasing frequency and shift toward low temperature. These peaks correspond to relaxation process, the density of dipoles contributing to relaxation decrease with decreasing temperature(Shiwakoti et al., 2017). The presence of the peaks in irradiated diode at 270 k it might be interpreted by the traps generation.

6. Conclusion

Electrical and dielectric properties of as grown and gamma ray irradiated Ti/Au/GaAsN Schottky diodes with 1.2%N have been investigated in 90-290 K temperature range and 50-2000 KHz frequency range. Interface state density, series resistance, dielectric constant, dielectric loss, tangent loss and ac conductivity were extracted. It is shown that these parameters are strongly dependant on both temperature and frequency. Dielectric constant (ε') shows usual step-like transitions with corresponding relaxation peaks in dielectric loss. These peaks shift towards lower temperature as frequency decrease due to space charge polarization. The decrease in dielectric constant and loss tangent of irradiated diodes is interpreted on the basis of annealing effect of γ-rays. Gamma irradiation decrease existing disorder in as grown diodes and makes order at interface by annealing interface traps.

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Fig.1 Capacitance-voltage dependence of Ti/Au/GaAsN Schottky diodes at some preselected temperature.

Fig.2 Conductance-voltage dependence of Ti/Au/GaAsN Schottky diodes at some preselected temperature at some preselected temperature.

Fig.3 Series resistance -Tempetrature dependence of Ti/Au/GaAsN Schottky diodes. The inset shows the interface states density change for Ti/Au/GaAsN Schottky diodes.

Fig.4 Dielectric constant-temperature dependence for various frequencies

Fig.5 Dielectric loss-temperature dependence for various frequencies

Fig.6 Tangent loss-temperature dependence for various frequencies

Fig.7 Conductivity-temperature dependence for various frequencies. The inset shows Arrhenius plot of conductivity at 1MHz.

Fig.8. A. Temperature dependence of real modulus at constant frequencies B. Temperature dependence of imaginary part of modulus at constant frequencies.