Tunnel currents produced by defects in p-n junctions of GaAs grown on vapor phase

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Summary. With the purpose of assessing if the epitaxy on vapor phase technique “Close Space Vapor Deposition (CSVT)” is capable of produce thin films with adequate properties in order to manufacture p-n junctions, a study of invert and direct current was developed, in a temperature range of 94K to 293K, to junctions p-n of GaAs grown through the technique CSVT. It is shown that the dominant current, within the range $10^{-7}$ to $10^{-5}$ A, is consistent with a currents model of the type of internal emission form field, which shows these currents are due to the presence of localized states in the band gap.

1. Introduction

In the last three decades, the development of manufacturing p-n junctions technology has been accelerated, linking energy saving, efficiency, and sustainability. An important part of this development has been focused on the improvement of the characteristics and physical properties of typical materials such as GaAs, which is used in the production of electronic devices. Some examples are: almost null density defects, control of the profiles of doping, increase in carriers mobility and their current density with minor current dissipation. It has allowed the production of innovative materials as InGaP and CdTe, and, at the same time, original architectural designs with nanometric dimensions. Giving place to a great quantity of devices with high efficiencies ~40.8%[1], they have been used in different applications, such as electricity supply, electronic of potency, satellites and other as communication and medical equipment, such is the case of solar cells manufactured based on compounds III-V on monolithic multi-junction tandem arrangements based on InGaP/(In)GaAs/Ge, where the most important is the design and the manufacturing of the tunnel diode structure, due to its series connection. The design of the tunnel diode structure and the current adjustment, between the upper part (InGaP) and the inferior (GaAs) of the cell, must be optimized in order to achieve a high efficiency and conversion stability[2]. Other significant example is the interest of developing applications CMOS[3] with technology high-K gate stack that provides low thermal consumption, and high carriers mobility. An achievement of this technology is obtaining high performance p+/n junctions[4], as it gets a high quality in dielectric for the gates[5,6] and low resistant contacts[7].
Therefore, to accomplish a high performance of devices or applications is preponderant that the crystal growing systems have the capacity of obtaining materials with adequate physical properties as crystallinity, carriers concentration, mobility, electrical resistance; and allowing the possible production of different materials, without risk of contamination, to manufacture heterostructures.

This article describes the type of currents that occurs in p-n junctions of GaAs obtained through epitaxy technique in vapor phase CSVT[5,6,7]. The current-voltage measurements showed that in direct polarization the dominant current varies as $\exp(qv/ nkT)$, where $n = 3$ at room temperature, and $n > 3$ for lower temperatures, indicating the presence of a currents tunnel. It is shown that the variation of current density in the pre-avalanche range is qualitatively consistent with a model of tunnel effect, through local states in the gap.

The diffusion current is not present for any range of polarization at room temperature, even setting the junction in conditions where usually the diffusion current is increased faster than the recombination; this is, increasing the temperature for a given polarization. The concentration ranges in the studied junctions were $1\times10^{13}$, $1\times10^{16}$ cm$^{-3}$, and $3\times10^{17}$ cm$^{-3}$ on the layer "n" type, and $1\times10^{19}$ cm$^{-3}$ on the layer "p" type. A correspondence analysis between experimental and theoretical data indicates that exist defects on the junction that cause a local enlargement of the electric field and in consequence a current tunneling effect through the junction. The energies associated to local defects in the wide range of the band gap, besides the impurity accumulation disseminated within and around these defects, are probably caused by high temperature when the sample is exposed during growing (850°C < T<900°C) and generated by the metallurgical interphase.

2. Experimental procedure

The p-n Junctions were manufactured using water vapor as carrier gas, growing GaAs type "n", doped epitaxially with Te, over a GaAs (100) substrate type "p" with a Zn concentration of $1\times10^{19}$ cm$^{-3}$, obtained through the Czochralski. The layer thickness type "n" had an interval between 14 y 42 µm, and the substrate thickness always was approximately 350 µm. The metallization for the contacts were evaporated. The materials and masses are presented in the Table 1.

| Material   | Alloy for Ohmic Contact                           |
|------------|--------------------------------------------------|
| GaAs type "p" | Au-Zn (92.4 % Au-7.6 % Zn). Zn(14 mg). Au(170 mg). |
| GaAs type "n" | Au-Ge-Ni (83 % Au-11.4 % Ge-5.4 % Ni) Au(152 mg). Ge(21 mg). Ni(10 mg). |

To achieve an ohmic contact resistance, an annealing process was performed at 450 °C with “formingas”, which was flowing to 5 lt/min. The diodes were cleaved in a square shape of $\sim78 \times 10^{-4}$ cm$^2$ and the upper contact was given a star shaped, in order to promote a uniform polarization upon the p-n junction. Table 2 shows the experimental conditions of two series of representative p-n junctions, grown through the CSVT technique.
Table 2. Experimental conditions of two series of representative p-n junctions

| Junction p-n | SOURCE [cm⁻³] | SUBSTRATE [cm⁻³] | **T_F [°C]** | **T_S [°C]** | **V_r [mV]** | **ε [µm]** | **r_c [µm/min]** |
|--------------|---------------|------------------|--------------|--------------|--------------|------------|-----------------|
| *U10         | High Purity (∼10¹⁵) | P(Zn) 1×10¹⁹     | 850          | 780          | 0.80         | ~60        | 2               |
| *U20         | High Purity (∼10¹⁵) | P(Zn) 1×10¹⁹     | 850          | 780          | 0.80         | ~20        | 2               |

*The nomenclature U# summarizes the predominant characteristics in DELs series obtained during that growing.

**T_F = temperature of source, T_S = temperature of substrate, V_r = voltage of spray, ε = thickness of the deposited film, r_c = growing rate.

3. Results and discussion

3.1. Current-Voltage Reverse Characteristic

Figures 2a and 2b show the characteristic behavior of current-voltage to different temperatures to p-n junctions of the samples in Table 2. It is observed a monotonous growing of the current regarding the voltage, besides, the voltage for constant reverse current decreases with an increment of temperature.

![Figure 2a](image)

**Figure 2a.** Reverse current-voltage characteristic for DEL60 to different temperatures.

![Figure 2b](image)

**Figure 2b.** Reverse current-voltage characteristic for DEL60 to different temperatures.

This behavior is shown on Figure 3, and suggests that the current in the indicated range is due to emission for internal field or Zener effect.

The emission by internal field is observed in junctions highly doped in Si [8,9], Ge [10], InSb [11] y GaAs [12] where the electric field is relatively high, even if it is a low inverse voltage. It is possible that the effect of a high electric field, the electron move from the valence band, p type, towards the conduction band, n type, of the junction. It is a consequence of tunnel effect.
The expression that allows to calculate the tunneling current (Zener), based on the tunneling probability for transitions through localized levels in the "gap", is given by

\[ I = A \cdot V_a \cdot E \cdot \exp\left\{-\frac{\hbar}{q} \left(\frac{2m_f}{\hbar}\right)^{1/2} / E\right\} \]

(1)

where \( A \) is a constant for a given temperature, \( V_a \) is the applied voltage, \( E \) is the electric field in the junction, \( m_f \) is the tunneling effective mass, \( q \) is the electric charge, \( \hbar \) is the Planck constant divided by \( 2\pi \), and \( E_b \) is the energy barrier through which it is possible that the electron suffers a transition by tunnel effect.

In inverse polarization conditions, the minimum height of the energy barrier is equal to the "gap" energy of \( E_g = qV_g \). The calculus of the tunneling probability is considered a uniform electric field. The selected value for the electric field is the maximum value existing in the junction, for an abrupt junction is given by:

\[ E = 2(V_{bi} - V_a) / W \]

(2)

where \( V_{bi} \) is the inter-constructed voltage and \( W \) is the wide-band gap zone, given for:

\[ W = W_1 (V_{bi} - V_a)^{1/2} \]

(3)

being \( W_1 \) a constant. From here, the Zener tunneling constant is given then for:

\[ I = A \cdot V_a \cdot (V_{bi} - V_a)^{1/2} \cdot \exp\left\{-\alpha [V_{bi} - V_a]^{1/2}\right\} \]

(4)

and

\[ \alpha = \left(2\sqrt{2}/3\right) \left(V_g^{1/2}/\hbar\right) m_f^{1/2} \cdot W_1 \]

(5)

Equation (4) predicts that given a graphic of \( \log[I/V_a(V_{bi} - V_a)^{1/2}] \) vs. \( 1/(V_{bi} - V_a)^{1/2}\), then it may be obtained a straight line with a slope equal to \(-\alpha V_g^{1/2}\). Such graphic is shown in Figure 4, which describes the characteristic I vs. V in inverse polarization to 94.35 K and 293.73 K. The experimental data are well represented through a straight line with a deviation on the range of the high currents, probably for the beginning of the breaking point due to the avalanche. The slope of data at 293.73 K is equal to \(-17.557 V^{1/2}\), which corresponds to \(9.53 V^{-1}\) for \(\alpha\). The slope at 94.35 K increases to \(-24.098 V^{1/2}\) corresponding for \(\alpha = 13.08 V^{-1}\).
A theoretical value of $\alpha$ may be calculated from equation (5). Thus, assuming that the tunneling mass is equals to 0.063 m, and using the value of the wide-band gap of the dump area of the junction, it is obtained from the capacitance measurements. The value calculated of $\alpha$ is equals to 60.56 V$^{-1}$ and it is an independent variable of temperature.

An explanation about the absence of a good approximation between the experimental value and the theoretical prediction for $\alpha$ will be discussed later.

It is important to point out that all diodes grown through CSVT showed a very similar behavior to the previous one described, this means, the current is qualitative consistent with the model of the Zenner effect on the range 10$^{-3}$ A/cm$^2$ a 10$^{-1}$ A/cm$^2$.

### 3.2. Current-Voltage forward Characteristic

The current-voltage characteristic to different temperatures also was determined for the same p-n junctions discussed in the previous section, Figure 5.

Figure 5. Characteristic I-V direct to different temperatures.

Figure 6. Characteristic I-V direct.

where:

- $I_D = I_{0D} \cdot \exp\left(\frac{q\psi}{nkT}\right)$ represents the current due to an injection thermally activated upon the junction barrier, $n = 1$ denotes the diffusion current[12], and $I_{0D}$ is given by $I_{0D} = \left(\frac{D_n p_0}{L_n} + \frac{D_p n_0}{L_p}\right)$, being $D_n$, $D_p$, $L_n$, $L_p$ the coefficients and length diffusion on the "n" side and the electrons on the "p" side of the junction, respectively; $p_0$ and $n_0$ represent the concentration of holes and electrons in equilibrium on the side "n" and "p" of the junction, respectively;
- $I_R = I_{0R} \cdot \exp\left(\frac{qV}{nkT}\right)$, with $n = 2$ for the recombination on the region of spatial charge in those deep level traps [11], and $I_{0R}$ is given by $I_{0R} = \frac{qW}{2} \sigma \psi m^* N_i n_i$, being $q$ the electron charge, $W$ wide-band gap, $\sigma$ transversal section of the defect capture, $N_i$ the defect concentration, and $n_i$ the intrinsic carriers concentration of the semiconductor and
- $I_T = I_{0T} \cdot \exp(\alpha V)$ represents the current due to the tunnel effect.
The curves shown on Figure 6 only predominates a region of exponential behavior, which represent \( n = 2.95 \) for \( T = 322.98 \) K and \( n = 9.29 \) for \( T = 94.39 \) K. Large values of \( n \) and a relative steady state of the slope respect to the temperature show that the mechanism of current carrier, in this region, is not dominated by the thermic effect, but a tunnel effect mechanism. The deviation in the curves of Figure 6, above 0.8 V respect to the followed behavior on the range 0.2 a 0.8 V, are due to the resistant series effects of diode.

The exponential variation of DC current with the voltage, with independent slopes of temperature has been reported for p-n junctions of diamond[15], SiGe heterojunction bipolar transistor[16], GaAs[17], and GaN[18]. Chynoweth et al.[19] proposes a model for this exponential current, which is based on a tunneling mechanism involving energy level localized on the band gap. The basic process involves an electron tunneling from the conduction band on "n" side to inner gap state, until it takes a state in or nearby the valence band on the p side. The exact nature of the tunneling process is no determined, in other words, it is not specified if the tunneling is band to band by real localized states, as Chynoweth et al.[19] postulates, or, if the tunneling is band to impurity states near the valence band via intermediate virtual states, as is postulated by Butenko[20]. However, the elemental assumption is done on both cases and the expression derived from the model is experimentally verified, in its qualitative aspect, on the previous analysis.

The basic assumption done on the tunneling simple model, is that, the tunnel current is dominated by the variation of the tunneling probability, then the current can be described as:

\[
I = I_T \cdot \exp \left\{ -\left( \frac{\pi}{2} \right) \left( \frac{2m}{\hbar^2 / q} \right)^{1/2} \right\} 
\]

where \( I_T = AEaE \).

As, in the analysis case, the reverse characteristic, the electric field that is taken into account is the maximum developed in the junction, which is given in the equation (2). For the forward polarization of the barrier is given for:

\[
E_b = q \cdot (Vb - Va)
\]

Therefore

\[
I = I_T \cdot \exp\left[\alpha(Va - Vb)\right]
\]

Where \( \alpha \) is the same for the reverse characteristic and it is given for equation (5).

Qualitatively, equation (9) describes the experimental results, inasmuch indicates an exponential dependence of the forward current against the voltage, with an equal pendent to \( \alpha \) that is relatively independent of temperature. The experimental \( \alpha \) value is obtained from the current-voltage forward characteristic at 300 K is 6.64 V\(^{-1}\), whose carrier concentration in the epitaxial region (layer type "n") is \( 2.9 \times 10^{17} \) cm\(^{-3}\).

The characteristics in the forward case were also analyzed for the rest of diodes with different carrier concentration, therefore, different junction width. For diodes with carrier concentration of \( 1 \times 10^{16} \) cm\(^{-3}\), the value of \( \alpha \) at 300 K, was 10.04 V\(^{-1}\), it corresponds the theoretical value of 326.2 V\(^{-1}\). For diodes with concentration \( 1 \times 10^{17} \) cm\(^{-3}\) the experimental value of \( \alpha \) was 7.21 V\(^{-1}\).

4. Conclusions

The study shows that the current in reverse polarization is due to Zener tunneling. The dominant current in forward polarization, for the diodes obtained, is qualitatively consistent with a simple tunneling model involving states on the band "gap". The lack of a good quantitative concordance between the experiment and the theory is probably a consequence of imperfections in the junction that causes that the intensity of the electric field increases locally. The fact that the theoretical prediction for the parameter \( \alpha \) has been higher that the obtained from the analysis for currents, due to an internal field emission, indicating these
last ones are the expected for wider minor junction than the determined correspondents from capacitance data. Inasmuch the narrow junctions imply intense electric fields, the results suggest that can exist localized regions or defects concentration distributed along the junction that tend to increase the electric field, similar to microplasma sites (areas where the current flows through imperfect regions of p-n junction) that give as a result low voltage breaking [19,21,22]. Different studies for several materials, including GaAs, have shown a correlation between microplasma and dislocations sites [19,21,22]. The defects present on junctions or its surroundings can be dislocations, vacancies or stacking faults generated by the overheating that the wafer is exposed during growing, another possibility is that the defect concentration contained in the substrate (~900 EPD/cm²) were perturbing the p-n junction, since this coincides with the metallurgical junction or it is very close. It exists the possibility that during growing the contained Zn in the substrate, it spreads to the epitaxial layer and the contained Te in the epitaxial layer spreads to the substrate or this has lost As. No matter the case, they will form defects that will result in the intensification of the electric field in the p-n junction. For instance, it is possible to introduce dislocations (high superficial concentration conditions and temperatures > 750 °C) during the diffusion process [20], due to the net adjustment between the widespread region and the crystal non-diffused [22]. Dislocations are being observed diffusion inducted in p-n junctions of GaAs formed through Zn diffusion [23], besides the precipitated contained upon these dislocations [18]. Residual impurities have been found on CSVT films (through SIMS) of Si, Cr, Fe, Mg and S of the interface [24], with concentrations of 5×10¹⁴ cm⁻³ to 10¹⁵ cm⁻³ for Mg and Fe, of 10¹⁶ cm⁻³ for Cr and S and higher to 10¹⁷ cm⁻³ for Si. Besides the impurities accumulation in the interface are increased when growing temperature increases, which indicates that probably exist impurities diffusion towards the epitaxial layer [25] and the substrate, then is probable that the metallurgical junction, that is strongly "disturbed", influences over the p-n junction behavior, since the effect of the defects (dislocations, vacancies, micro-defects or stacking fault) upon the electrical properties of the p-n junction take a greater importance when exists an impurity accumulation around these, so as can introduce a certain density of recombination centers. Goetzberger and Shockley [26] show that the reverse characteristics of current-voltage on its p-n junctions were caused by precipitates in the dump area, and it is assumed that the current was due to Zener tunneling caused by points of a intense electric field.

5. References
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