POOLE-FRENKEL ASSISTED EMISSIONS FROM A BARRIER TRAP IN AlGaN/GaN/Si HEMTs

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Abstract

Deep level transient spectroscopy measurements have been performed on AlGaN/GaN/Si HEMTs grown by molecular beam epitaxy. The DLTS spectra exhibit a dominant peak associated with a majority carrier trap having an activation energy of 0.54eV. Electron dynamics through a trapping center are strongly affected by electric fields. The characteristics of field-assisted emissions therefore provide further information on the physical nature of the centers. In the present work, we report a study of the electric field effects on the rate of electron emission from a trapping trap in AlGaN barrier. As has been found, the apparent activation energy of this electron trap decreases as the electric field increases. Such a behavior is consistent with Poole-Frenkel model. This means that the relevant trap is an ionized donor-like defect with a long-range Coulomb potential.

Keywords: DLTS measurements, AlGaN/GaN/Si HEMTs, field-assisted emissions, trapping center, Poole-Frenkel effect.
I. INTRODUCTION

Group-III nitride semiconductors and heterostructures have been recognized as belonging to the most promising materials for high-power electronic and optoelectronic devices [1]. AlGaN/GaN high electron mobility transistors (HEMTs) were proved as highly performant heterostructures for generation mobile telecommunication applications [2]. In addition, AlGaN/GaN HEMTs are useful to design devices aimed to operate at high-power, high frequency and high-temperature due to large breakdown voltages and large sheet carrier densities [3,4]. On the other hand, defects and impurities are unavoidable and hence can induce localized electronic states in the epilayers. Defects may be identified by means of their signatures, which provide ionization energies, charge states and capture cross sections. These features may be deduced by analyzing the emission rates of trapping defects [5]. As a parameter, the ionization energy can be deduced from the thermally activated emission. In the presence of an electric field, the relation between the ionization energy and emission rate becomes more complicated [6]. As a results, the emission rate of traps located in the electric field region can significantly increase because of the potential barrier lowering [7]. In AlGaN/GaN high electron mobility transistors, the electric field strength in the barrier may exceed $10^6$ V/cm. Hence, emission of electrons is strongly influenced by the built-in electric field [8]. Therefore, the enhancement of the electron emission in an electric field must be taken into account in determining the ionization energy of a defect.

In the present work, we report DLTS measurements performed on AlGaN/GaN/Si HEMTs. They revealed the presence of an active electron trap in the AlGaN barrier. We have determined the energy level of this trap from the thermal-assisted electron emission without and under an applied electric field. As has also been found, the ionization energy $E_i$ of the electron trap exhibits a lowering as the electric field increases. This allows to conclude that the binding potential of the electron trap is long range. In addition, the variation of $\Delta E_i = E_i (F) - E_i (F=0)$ versus $F$ suggests that this potential is approximately Coulombic. The paper is organized as follows. After a brief
introduction, we present, in section 2, results and discussion. Conclusion is summarized in section 3.

II. Experimental

The structures to be investigated consist in AlGaN/GaN HEMTs grown by molecular beam epitaxy on resistive silicon (111) substrate (4000-10000 Ω) using ammonia as the nitrogen precursor in a Riber compact 21 reactor. Details on the epitaxial growth are reported elsewhere in Ref.[9]. The epitaxy has been made as follows: a 50 nm AlN nucleation is at first grown on Si (111) substrate followed by a 0.5 μm thick GaN/AlN sequence and a 30 nm thick undoped AlGaN layer grown on 2 μm GaN buffer and is capped by 1 nm GaN. Deep level transient spectroscopy has been used as a technique to characterize the electron traps in the AlGaN/GaN/Si heterostructures. Measurements were performed using double lock-in detection and a PAR 410 capacitance meter and recorded in the 20-325K temperature range.

III. RESULTS AND DISCUSSION

III.1 Electrical behavior of the electron trap

Fig.1 shows a DLTS spectrum obtained for an emission rate $e_n = 426$ s$^{-1}$, a reverse bias $V_0 = 3$ V, a pulse amplitude $\Delta V = 3$ V and a filling time $t_p = 0.5$ ms. It can be seen that only one DLTS peak occurs around 207K. The ionization energy $E_i$ was deduced from the variation of the emission rate versus the inverse of temperature and is of 0.43eV, as shown in the inset of Fig.1.

Figure 1: DLTS spectrum of an AlGaN/GaN/Si HEMT obtained for an emission rate $e_n = 426$ s$^{-1}$, a reverse bias $V_0 = 3$ V, a pulse amplitude $\Delta V = 3$ V and a filling time $t_p = 0.5$ ms. In the inset, is reported the Arrhenius plot for the observed electron trap.

The parameters that strongly influence the DLTS data are the reverse bias and the filling pulse amplitude. Therefore, we attempted to investigate the possibility that the ionization energy $E_i$ could be enhanced by an electric field. As well known, in a heavily-doped epilayer, the strength of the built-in electric field increases with doping content and varies linearly with the depth in the depletion region from the heterointerface where it is maximum. In experiments, the variation of $E_i$ versus $F$ is achieved by selecting a narrow depth within the depletion region in which $F$ can be considered as constant. A given elementary depth being selected by the filling pulse
amplitude, the measurements consist in making the difference between capacitance transients monitored for two pulses of slightly different amplitudes, while the reverse bias is kept constant. For each couple of pulses, the temperature variation of the DLTS peak versus the emission rate provides $E_i$ for the corresponding value of $F$. Details on the procedure are reported in Ref.[10]. In order to vary the electric field in a range as large as possible, we have selected layers exhibiting the lowest doping concentrations. Indeed, for a given reverse bias, the depletion zone is the largest. From the relevant signatures at different pulse amplitudes $1 \leq \Delta V \leq 3V$ and for a bias voltage $V_0 = -3V$, we have deduced the ionization energy of the observed electron trap as a function of the electric field. Results are depicted in Fig.2.

It is seen that the ionization energy $E_i$ regularly decreases as the electric field $F$ increases. In addition, we have verified that this change results in a Poole-Frenkel effect, since $E_i$ varies linearly with $F^{1/2}$, as illustrated in Fig.3. The Poole-Frenkel effect, indeed, corresponds to a decrease $\Delta E_i$ of the emission barrier induced by an applied electric field [11]. This work notices that this decrease is noticeable when the defect potential extension $R$ is such that the quantity $e F R$ ($e$: electron charge, $F$: electric field, $R$: range of the potential) is not negligible with respect to $E_i$. On the other hand, the Poole-Frenkel effects can reflect the potential shape, namely for a Coulomb potential. The case is experienced for a shallow donor state. For such a center, the ionization energy lowering is given by: 

$$\Delta E_i = e^{3/2} \varepsilon^{1/2} \pi^{1/2} F^{1/2}$$

where $\varepsilon$ is the dielectric constant. It, therefore, applies when there is an attractive potential between the emitted electron and the ionized defect, i.e when the defect is a donor. DLTS spectra were recorded for a reverse bias fixed at $V_0 = -3V$ and with increasing the filling pulse $\Delta V$ for different values of the emission rate $e_n$. The activation energies are found to range from 0.42eV at $2.12 \times 10^6$ V/cm to 0.46 eV at $1.6 \times 10^6$ V/cm. We also get a decrease in the ionization energy $E_i$ with increasing $F$, as expected by Poole-Frenkel model. Thus, the slope of the plot $E_i$ versus $F^{1/2}$ is of

![Figure 2](image_url)
1.6x10^{-6} \text{ V}^{1/2} \text{ cm}^{1/2}, \text{ which is close to the theoretical value } 2.3x10^{-6} \text{ V}^{1/2} \text{ cm}^{1/2} \text{ corresponding to a pure Coulombic potential. Extrapolation of } E_i \text{ at zero field gives the binding energy of the trap, which is of 0.54 eV.}

Figure 3: The change $\Delta E_i$ in the ionization energy $E_i$ as a function of the square root of the electric field.

A deep center having the same activation energy is observed in hydride vapor phase epitaxy grown GaN using both DLTS and transmission electron microscopy [13]. According to this reference, this defect is expected to be an antisite $\text{N}_{\text{Ga}}$. More later, a detailed study of the effects of electric field and temperature has been made on the rate of electron emission from the 0.54 eV deep trap in MBE grown AlGaN/GaN transistors [6]. It was concluded that the active center is located near the drain-edge of the gate contact. The reason of this assignment is the existence of higher electric fields in this region. In the barrier under the gate terminal, however, the electric field is relatively smaller. In the present study, an enhancement in electron emission is induced by high field strengths $F= 1.6-2.8 \times 10^7 \text{ V cm}^{-1}$. This agrees well with that reported in Ref [6]. Consequently, defect states located at the drain side are more likely to behave as electron traps. To estimate the density of the occupied traps, we have performed capacitance-voltage measurements at room temperature on the AlGaN/GaN/Si HEMTs investigated. As a result, we have obtained a relevant concentration $N_T$ in the order of $2.18 \times 10^{14} \text{ cm}^{-3}$. It is worth to notice that this concentration is less low than those of residual donors in GaN-related heterostructures.

IV. CONCLUSION

A deep electron trap has been observed in MBE grown AlGaN/GaN/Si HEMTs by using DLTS measurements. The energy level of this trap shows strong field dependence with an activation energy of 0.54 eV at zero electric field. The field-enhanced emission has been explained as due to a Poole-Frenkel effect. Concerning the physical origin of the observed electron trap, it is expected to be the $\text{E}_2$ center located at the edge of the gate contact near
the drain side. The major problem to solve is how operate in the growth process in order to extenuate the unsuitable effects of this deep trap.

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References


