Journal of Electron Devices, Vol. 11, 2011, pp. 538-543

© JED [ISSN: 1682 -3427]

Journal of Electron Devices
www.jeldev.org

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

Hana MOSBAHI[1], Malek GASSOUMI[1], Houcine MEJRI[2], Christophe GAQUIERE[3], Mohamed Ali ZAIDI[1], Hassen MAAREF[1]

[1]Laboratoire de Micro-optoélectronique et Nanostructures, Département de Physique, Faculté des Sciences de Monastir, 5019 Université de Monastir.
[2]Laboratoire d'Electronique et de Microélectronique, Département de Physique, Faculté des Sciences de Monastir, 5019 Monastir-Tunisia and Unité de Recherche de Mathématiques Appliquées et Physique Mathématique, Ecole Préparatoire aux Académies Militaires, Sousse-Tunisia.
[3]Institut d'Electronique, de Microélectronique et de Nanotechnologie IEMN, Département Hyperfréquences et Semiconducteurs, Université des Sciences et Technologies de Lille, Avenue Poincaré, 59652 Villeneuve d'Ascq Cedex, France. malek.gassoumi@iemn.univ-lille1.fr

Received 9/09/2011, online 16/09/2011

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 significatly 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 being 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 $e_n = 426s^{-1}$, a reversed bias V_0=3V, a pulse amplitude ΔV = 3V and a filling time t_p = 0.5ms. 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.

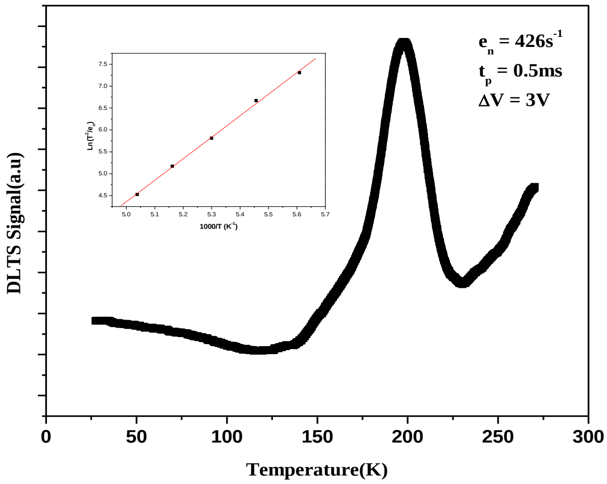

Figure 1: DLTS spectrum of an AlGaN/GaN/Si HEMT obtained for an emission rate e_n = 426 s^{-1}, a reverse bias V_0 = -3V, a pulse amplitude ΔV = 3V and a filling time t_p = 0.5 ms. In the inset, is reported the Arrhenius plot for the observed electron trap.

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 keeped 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.

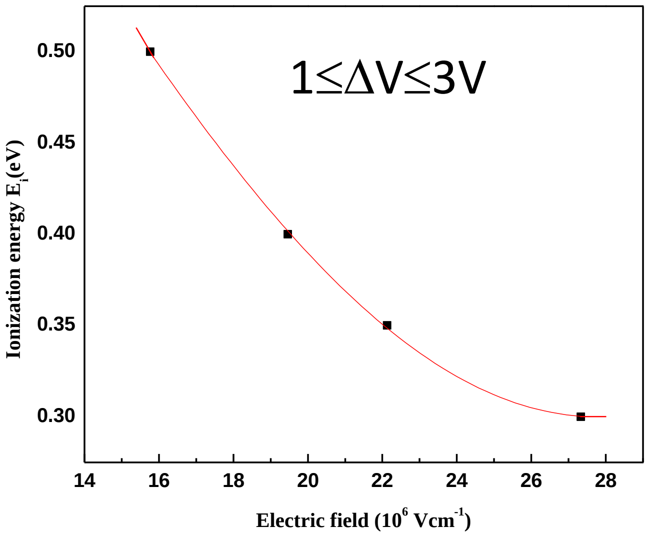

Figure 2 : Variation of the ionization energy E_i of the electron trap versus the electric field F.

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 ΔE_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: $\Delta E_i = e^{3/2}\ \varepsilon^{-1/2}\pi^{-1/2}\ F^{1/2}$ [10.12] where ε 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 ΔV for different values of the emission rate e_n. The activation energies are found to range from 0.42eV at $2.12x10^6$ V/cm to 0.46 eV at $1.6x10^6$ 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

1.6×10^{-6} $V^{1/2}cm^{1/2}$, which is close to the theoretical value 2.3×10^{-6} $V^{1/2}$ $cm^{1/2}$ corresponding to a pur Coulombic potential. Extrapolation of E_i at zero field gives the binding energy of the trap, which is of 0.54 eV.

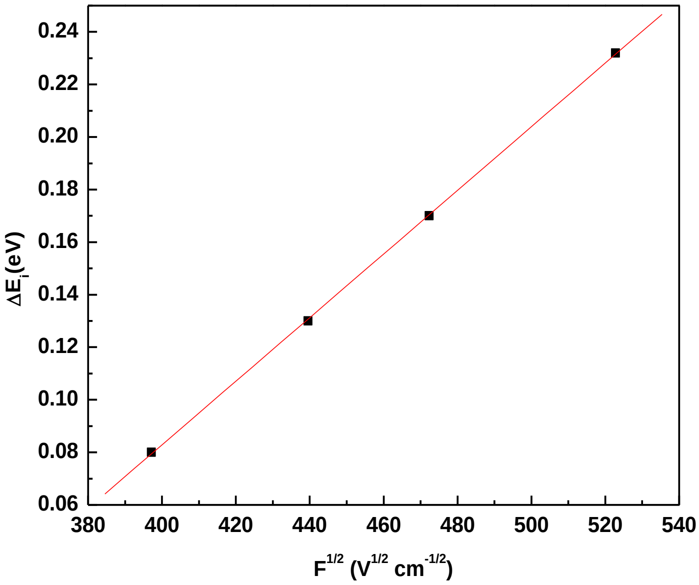

Figure 3: The change ΔE_i in the ionization energy E_i as a function of the square root of the electric field.

A deep center heaving 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 N_{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 $\times 10^{7}$ Vcm^{-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 $2.18 \times 10^{14}cm^{-3}$. It is worth to notice that this concentration is less low than those of residuel 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 E2 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.

Acknowledgements

This work has been supported by " Comité Mixte de Coopération Universitaire (CMCU) France-Tunisie" under the project " 08G1305" between the IEMN-Lille and Monastir University.

References

[1] V.V.Buniatyan, V.M.Aroutiouniam, "Wide gap semiconductor microwave devices," Journal of Physics D: Applied Physics, **40**, 6355-6385 (2007).

[2] M.Dammann, et al. "Reliablity and degradation mechanism of AlGaN/GaN HEMTs for next generation mobile communication systems," Journal of Microelectronics Reliability, **49**, 474-477 (2009).

[3] M.A.Khan, Q.Chen, J.W.Yang, M.S.Shur, B.T.Dermott, J.A.Higgins,"Microwave operation of GaN/AlGaN-doped channel heterostructure field effect transistors," Journal of IEEE Electron Devices Letters, **17**, 325-327 (1996).

[4] Y.F.Wu, B.P.Keller, P.Fini, S.Keller, T.J.Jenkins, L.T.Kehias, S.P.Denbaars, U.K.Mishra,"High Al-content AlGaN/GaN MODFET's for ultrahigh performances", Journal of IEEE Electron Devices Letters, **19**, 50-53 (1998).

[5] D.V.Lang," Deep-level transient spectroscopy: A new method to characterize traps in semiconductors," Journal of Applied Physics, **45**, 3023-3032 (1974).

[6] O.Mitrofanov and M.Manfra,"Poole-Frenkel electron emission from the traps in AlGaN/GaN transistors," Journal of Applied Physics Letters, **95**, 6414-6419 (2004).

[7] J.G.Simmons,"Poole-Frenkeel Effect and Schottky Effect in Metal-Insulator-Metal Systems", Journal of Physical Review, **155**, 657-660 (1967).

[8] O.Mitrofanov and M.Manfra, "Dynamics of trapped charge in GaN/AlGaN/GaN high electron mobility transistors grown by plasma-assisted molecular beam epitaxy," Journal of Applied Physics, **84**, 422- 424 (2004).

[9] V.Hoel, N.Vellas, C.Gaquiere, J.C.De Jeager, Y.Cordier, F.Semond, F.Natali and J.Massies, ," High-power AlGaN/GaN HEMTs on resistive silicon substrate", Electron Lett.**38**, 750 (2002).

[10] M.Zazoui, S.L.Feng and J.C.Bourgoin,"Electric field effect on electron emission from the DX centre in GaAlAs," Journal of Semiconductor and Science Technology, **6**, 973-978 (1991).

[11] J.Frenkel, ," On Pre-Breakdown phenomena in Insulators and Electronic Semi-Conductors", Phys.Rev, **54**, 657 (1938).

[12] M.A.Zaidi, J.C.Bourgoin and H.Maaref, "Poole-Frenkeel-assisted emission from deep levels in electron-irradiated germanium," Journal of Semiconductor and Science Technology, **4**, 739-741 (1989).

[13] Z.-Q.Fang, D.C.Look, J.Jasinski, M.Benamara, Z.Liliental-Weber and R.J.Molnar, "Evolution of deep centers in GaN grown by hydride vapor phase epitaxy," Jouranl of Applied Physics Letters, **78**, 2001, 332-334 (2001).