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A study of electrically active traps in AlGaN/GaN high electron mobility transistor

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(Received 29 August 2013; accepted 10 October 2013; published online 25 October 2013)

We have studied electron conduction mechanisms and the associated roles of the electrically active traps in the AlGaN layer of an AlGaN/GaN high electron mobility transistor structure. By fitting the temperature dependent I-V (Current-Voltage) curves to the Frenkel-Poole theory, we have identified two discrete trap energy levels. Multiple traces of I-V measurements and constant-current injection experiment all confirm that the main role of the traps in the AlGaN layer is to enhance the current flowing through the AlGaN barrier by trap-assisted electron conduction without causing electron trapping.

AlGaN/GaN based High Electron Mobility Transistors (HEMTs) typically use a Schottky gate contact, which is often associated with device performance issues such as high gate leakage current, low on/off ratio, and shallow subthreshold swing, etc. While extensive research efforts have been made to find the possible physical origins of the excess leakage current,1–3 little has been reported on current conduction mechanism(s) in the AlGaN barrier. Our previous Electron Tunneling Spectroscopy (ETS) study4 has suggested that there exist electrically active traps both in the bulk of AlGaN and at the AlGaN/GaN interface, and these traps may be energetically located within a band of 0.5 eV below the conduction band minimum (Ec) of AlGaN. In this Letter, we present the extraction of trap energy levels by fitting the temperature dependent I-V curves to the Frenkel-Poole theory. In addition, the role of these traps in electron transport is also discussed.

Shown in Fig. 1 is the AlGaN/GaN based HEMT structure under study, along with the measured multi-frequency C-V (Capacitance-Voltage) curves. A 300 nm-thick smooth GaN layer and a 23 nm-thick 28% AlGaN layer are sequentially grown on the rough layer of an 150 nm-thick GaN in a Veeco rf-plasma molecular beam epitaxy system. Ti/Au is deposited as the gate electrode by the use of an e-beam evaporator. The detailed device fabrication process and the I-V characteristics for a similar HEMT device have been reported elsewhere.4–6 Figure 2 shows the temperature dependent J-V characteristics measured in a wide temperature range, from 300 K to 570 K. In order to see whether these J-V curves fit the F-P conduction model expressed in Eq. (1), one needs to know the electric field in the AlGaN, which can be approximated by the use of Eq. (2)7

\[ J = \exp \left( \frac{-q(\Phi_B - \sqrt{qE/\pi e})}{kT} \right) \]

where \( J \) is the current density, \( \Phi_B \) is the field-effect trap energy, and \( E \) is the electric field in the tunnel barrier (which is AlGaN in this case, and the corresponding electric field is denoted as \( E_{AlGaN} \) herein)

\[ E_{AlGaN} \sim \frac{\sigma_p - \varepsilon n_{2DEG}(V)}{\varepsilon e_0}, \]

where \( \sigma_p \) is the fixed polarization charge; \( \varepsilon \) is the dielectric constant of AlGaN; \( n_{2DEG} \) is the density of the 2DEG (Two Dimensional Electron Gas) as a function of the gate voltage, which can be obtained by integrating the C-V curve shown in Figure 1 (Ref. 8 and 9).

As Eq. (1) can be rearranged into the following forms:

\[ \ln(J/E_{AlGaN}) \sim 1/T, \]

\[ \ln(J/E_{AlGaN}) \sim \sqrt{E_{AlGaN}}, \]

a linear dependence of \( \ln(J/E_{AlGaN}) \) both on \( 1/T \) and on \( E_{AlGaN}^{1/2} \) would strongly suggest that the electron conduction is governed by the F-P conduction mechanism, and we will see next that this is indeed the case. As shown in Fig. 3, \( \ln(J/E_{AlGaN}) \) is linearly proportional to \( E_{AlGaN}^{1/2} \) for

FIG. 1. Multi-frequency CV curves measured at room temperature, along with the schematic cross-section of the device under study.

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temperatures ranging from 300 K to 570 K. Furthermore, Fig. 4(a) shows that \( \ln(J/E_{\text{AlGaN}}) \) is also linearly proportional to \((1/T)\) for each specific \(E_{\text{AlGaN}}\) used in this study. The field-dependent \(U_B\) for each specific \(E_{\text{AlGaN}}\) can be readily obtained from the slope of the temperature-dependent F-P characteristics shown in Fig. 4(a).

It is interesting to note that the linear fitting in Fig. 4(a) exhibits two slopes for each specific electric field in the temperature range of 300 K–390 K, and 429 K–570 K, respectively. Based on the two slopes, we plot the resulting \(\Phi_B\) as a function of \(E_{\text{AlGaN}}^{1/2}\) in Figs. 4(b) and 4(c), respectively. The intrinsic trap energy without the field effect, \(\Phi_{B0}\), is then obtained by extrapolating to zero field. As shown in Figs. 4(b) and 4(c), two discrete intrinsic trap energies are obtained: \(\Phi_{B01} = 0.28 \text{ eV}\) and \(\Phi_{B02} = 0.45 \text{ eV}\) below the \(E_c\) of the AlGaN. The aforementioned conduction mechanism and the extracted trap energy levels are consistent with the findings in Ref. 11. The result is also in good agreement with the 0.5 eV energy band of the electrically active traps in the AlGaN barrier identified in our previous ETS study. The physical origin of these traps is still being investigated, but it could be caused by defects related to oxygen or alloy fluctuations.

To examine the role(s) of these traps in the current conduction mechanism, we carried out repeated I-V measurements following constant-electron-current injection on the same device. Fig. 5 shows 5 traces of \(J-V\) curves as the gate voltage is swept repeatedly from 0 V to \(-5 \text{ V}\). The fact that the multiple \(J-V\) traces fall on top of one another is a good indication that the electrons passing through the AlGaN barrier are not trapped by the existing electron traps. For the constant-current injection experiment, two current levels, 1 \(\mu\text{A/cm}^2\) and 100 \(\mu\text{A/cm}^2\), are chosen (as indicated by the dashed lines in Fig. 5) while the change in the gate voltage is monitored during the injection period. As shown in the inset of Fig. 5, the gate voltage remains basically unchanged after a total fluence of 1.2 C/cm\(^2\) of electron injection, indicating negligible net electron trapping. These results suggest that electron conduction across the AlGaN barrier is dominated by F-P hopping through the traps without trapping, as depicted in the middle of Figure 2.

In summary, we have identified F-P conduction as the main trap-assisted electron transport mechanism through the AlGaN barrier, and based on the temperature and field-dependencies of the \(J-V\) characteristics, we are able to extract the trap energy levels, which are consistent with the findings of our previous ETS study. The primary role of the electrically active traps in the AlGaN barrier of the AlGaN/GaN HEMT has been determined to enhance...
This work was supported partially by the Office of Naval Research (ONR) under the MURI DEFINE program, and partially by the National Science Foundation (NSF) under Contract No. MRSEC DMR 1119826.


FIG. 5. Multiple I-V traces measured at negative gate biases. The inset shows the sampling of gate voltage during the injection period at two current injection levels: 1 μA/cm² and 100 μA/cm².