Dynamic On-resistance and Tunneling Based De-trapping in GaN HEMT

Zhu, L.; Teo, K.H.; Gao, Q.

TR2015-047 June 2015

Abstract

GaN HEMT dynamic on-resistance was measured by the pulsed IV method. Temperature-independent de-trapping was observed in GaN HEMT dynamic on-resistance measurement. Similar results were also observed by Dr. Jesus del Alamo's group at MIT. The origin of the temperatureindependent de-trapping is still unclear. It is speculated by Jesus del Alamo's group that this temperature-independent detrapping happens through electrons tunneling from the interface layer to the channel instead of through thermal activation. Our experimental results indicate that electrons tunnel from the interface layer into gate may also be possible, especially for those traps located near the gate. A quantum mechanical model based on Fermi's Golden rule is developed. The modeling result agrees with the experiment and helps to support our theory of the fast temperature- independent de-trapping process.

IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC)

Dynamic On-resistance and Tunneling Based De-trapping in GaN HEMT

Li Zhu and Koon Hoo Teo
Mitsubishi Electric Research Laboratories,
Boston, MA, USA

Qun Gao
Dept. of Electrical and Computer Engineering,
University of Florida,
Gainesville, FL, USA

***Abstract*—GaN HEMT dynamic on-resistance was measured by the pulsed IV method. Temperature-independent de-trapping was observed in GaN HEMT dynamic on-resistance measurement. Similar results were also observed by Dr. Jesus del Alamo's group at MIT. The origin of the temperature-independent de-trapping is still unclear. It is speculated by Jesus del Alamo's group that this temperature-independent de-trapping happens through electrons tunneling from the interface layer to the channel instead of through thermal activation. Our experimental results indicate that electrons tunnel from the interface layer into gate may also be possible, especially for those traps located near the gate. A quantum mechanical model based on Fermi's Golden rule is developed. The modeling result agrees with the experiment and helps to support our theory of the fast temperature- independent de-trapping process**

Keywords—Trap, Tunneling, GaN HEMT, Modeling, lifetime, dynamic on-resistance, pulsed IV.

I. Introduction

Among the wide band gap power semiconductor devices, GaN HEMT is the most promising due to its high electron mobility, high breakdown field, etc. [1, 2]. However, lattice mismatch and current process issues introduce more defects than silicon devices. The defects, usually behaves like traps and potentially could degrade the performance of the device, especially in the RF applications [3]. In this paper, the traps mechanisms in GaN HEMT are for the first time being studied both experimentally and theoretically through a quantum mechanical model.

The traps in GaN HEMT are studied by measuring dynamic on-resistance. Dynamic on-resistance exhibits the transient response of the channel resistance immediately after the device is turned on from the high voltage off state or the high power state. Here only the transient response from the off state to the on state is measured. A pulsed I-V method developed by Alamo's group [4] was employed. Here only the transient response from the off state to the on state is measured.

To get a low loss and fast response power switching device, a low dynamic on-resistance is desired. Our experiment results show that the dynamic on-resistance is higher than the fully de-trapped device's on-resistance immediately after switching on and then decreases. The dynamic on-resistance decreasing implies trapped electrons in the gate during the high voltage off state is de-trapped. There are two kinds of dynamic on resistance decreasing. One is the fast decreasing which doesn't depend on temperature. Another one is the slow decreasing which happens faster as temperature increases. It is well recognized that the slow decreasing is due to electrons de-trapped through thermionic emissions, so it is temperature depended. The fast decreasing observed in our experiment was first reported by Alamo's group. They believed this fast decreasing comes from electrons tunneling from the AlGaN layer to the GaN layer. Our experiment results indicate that electrons tunneling from the AlGaN layer to the gate may also cause this fast decreasing dynamic on resistance.

To further study this temperature independent fast de-trapping, a model calculating tunneling based de-trapping life time is built. This model uses Fermi's Golden rule. The modeling results suggests that the electrons trapped near the gate has a lifetime close to the measured lifetime from our experiment.

II. Experiment

The experiment was performed by applying pulsed voltages to GaN HEMT as shown in Fig. 1. During the on state, Vgs=1V and Vds varies from 0.1V to 0.7V. During the off state, Vgs=-5V and Vds=20V. The on state duration varies from 10^{-7} second to 50 second. The duty cycle is 10%. The drain current, Id, is measured immediately after the on state is switched on. The devices were put in a temperature controlled chamber and measured from -20°C to 70°C.

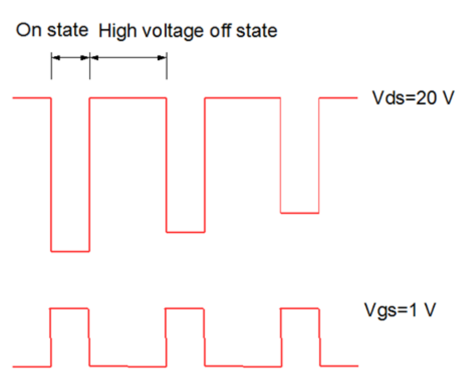

Fig. 1 Pulses for Vgs and Vds.

Fig. 2 illustrates the processes of de-trapping in GaN HEMT. It is believed that during the high voltage off state, electrons flows from gate to the AlGaN layer and some are trapped there. These trapped electrons screen gate voltage at some level, which then introduces current lag. As the device is biased to on state, the trapped electrons are de-trapped. Depending on the bias, temperature and locations of the traps, electrons may go to channel or the gate.

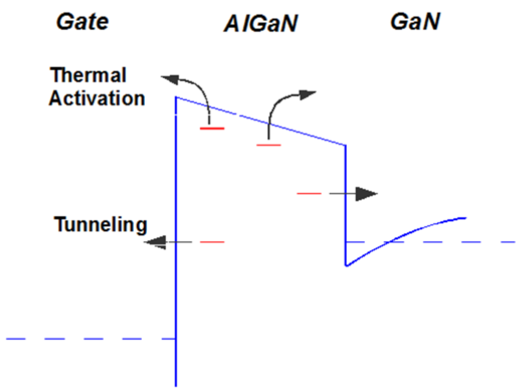

Fig. 2 De-trapping process in GaN HEMT during the on state.

Fig. 3 shows normalized dynamic on-resistance vs. time at different temperature. The dynamic on-resistance is normalized to the resistance at 50 second, at which time the device is almost completely de-trappedd. Two kinds of dynamic on-resistance processes are found, which indicate that there is de-trapping. One is between 10^{-7} second and 10^{-5} second (in the yellow circle), which is defined as the fast de-trapping. Another is in the long time region and the time decreases from 10 second to 10^{-2} second with increased temperature (in the red circle), which is defined as the slow de-trapping. It is obvious that the fast de-trapping is temperature independent and often exists. The slow de-trapping is temperature dependent. The slope representing the de-trapping process moves to the left, which means that this temperature dependent slow de-trapping process becomes faster as temperature increases. Our measurement result agrees with [4]. In [4], it explained the fast de-trapping is a result of electrons tunneling from the interface layer to the channel. Out measurement indicates that electrons may also tunnel from the interface layer to the gate for those traps that are physically located near the gate.

Fig. 4 shows the lifetime extracted from Fig. 3 using an algorithm developed at Mitsubishi Electric Research Laboratories. It should be noted that the values of the lifetime usually are continuous. This algorithm only gives dominating lifetime, at which time the dynamic on resistance changes most. The yellow box labels lifetime of the temperature independent fast de-trapping. The lifetime of temperature dependent slow de-trapping is in the red box. It is not difficult to find that the lifetime of temperature independent fast de-trapping doesn't change, while the lifetime of the temperature dependent slow de-trapping decreases as temperature increases.

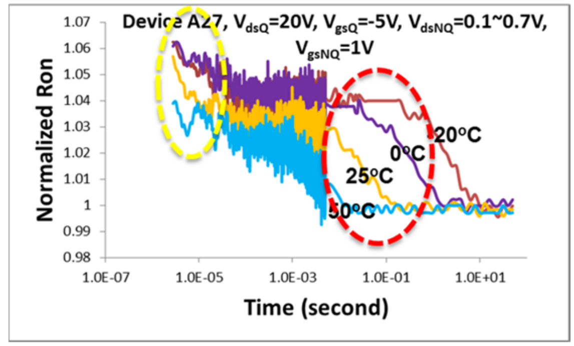

Fig.3 Normalized Ron vs. Time. All measured Ron is normalized to the Ron at 50 s.

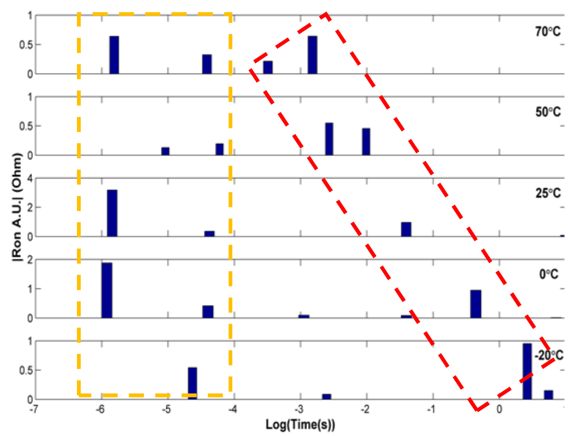

Fig. 4 Lifetime spectra for Ron. Here Ron is dynamic on resistance.

To get the thermal activation energy, an Arrhenius plot is given in Fig. 5. The blue dot represents the slow de-trapping and the other two are the fast de-trapping. Linear regression is used to fit the dots. The thermal activation energy is around 0.65 ev, which is extracted from the slope of the slow de-trapping line. The other two lines indicate that the fast de-trapping is not temperature dependent, so the slopes of these two lines do not represent thermal activation energy.

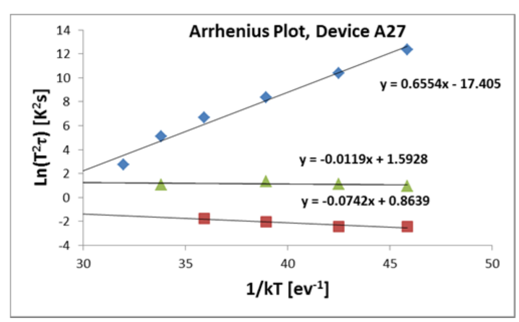

Fig.5 Arrhenius plot of lifetime spectra from Fig. 3.

III. A QUANTUM MECHANICAL MODEL

In the previous section, the experiment results show a temperature independent fast de-trapping process besides of the normally observed temperature dependent slower de-trapping process. The slow de-trapping due to the thermal activation has been well studied, but this fast de-trapping process is still not very clear. Due to its temperature independent character, this fast de-trapping process is hypothesized to be a tunneling process. A quantum mechanical model is developed to study this tunneling based de-trapping. The model is based on Fermi's golden rule, which can be expressed as,

$$T_{i\to f} = \frac{2\pi}{\hbar}\langle f|H'|i\rangle^2\rho \qquad (1)$$

where $T_{i\to f}$ is transition rate from initial state $|i\rangle$ to final state $|f\rangle$. For our case, the initial state is equivalent to a plane wave in the gate and the final state is the state in a trap. ρ is the density of final states. H' is the time independent perturbing Hamiltonian. Lifetime τ can be expressed as,

$$\tau = 1/T_{i\to f} \qquad (2)$$

The transition rate given in Equation (1) is a general version. For de-trapping, we can rewrite (1) to,

$$\begin{aligned} T_{i\to f} &= \frac{2\pi}{\hbar}\left|\int \psi^*{}_f(r)\mathrm{H}'(r)\psi_i(r)dr\right|^2\rho \\ &= \frac{2\pi E_t{}^2}{\hbar}\left|\int \psi^*{}_f(r)\psi_i(r)dr\right|^2\rho \\ &= \frac{2\pi E_t{}^2\sigma_i^2}{\hbar V}\left|\int \xi(z)\psi_i(z)dz\right|^2\rho \end{aligned} \qquad (3)$$

Equation (3) shows the transition rate for de-trapping. σ_i is the cross section for trap, which takes place of the transverse integration. H' and simplified to E_t, the activation energy of the trap. Here the volume V can be cancelled by ρ, which is the tri-dimensional density of states. Here ρ is the total density of states per unit energy. The unit is not /m^{3}J. In other words, $\rho = DV$. D is the density of states per J and per m3. Each item in (6) is either known or can be solved. Thus, the transition rate can be calculated, as well as the lifetime [5, 6].

The wave functions of the initial and final states can be calculated by numerically solving Poisson's and Schrodinger equations. Poisson's equation gives the potential profile of the device. Schrodinger equation gives the energy levels and wave functions.

A trap can be treated as a quantum dot, whose energy states are quantized. The confinement of the trap states is assumed to be a parabolic confinement, which has been proven to be a reasonable approximation for quantum dot confinement potential [7, 8]. This parabolic potential profile is used in the Schrodinger equation.

Fig. 6 shows the two wave functions of electrons in the gate and in the trap. The red line is the wave in the gate and the black one is the wave in the trap. The gate thickness is assumed to be 200 nm. The trap is at the interface layer near the gate. It is obvious that the wave in the gate is a plane wave in the gate and diminishes exponentially while it penetrates into the AlGaN layer. The trapped wave is mainly in the trap and quickly diminishes when out of the trap. The two wave functions overlap which means electrons can tunnel between gate and trap.

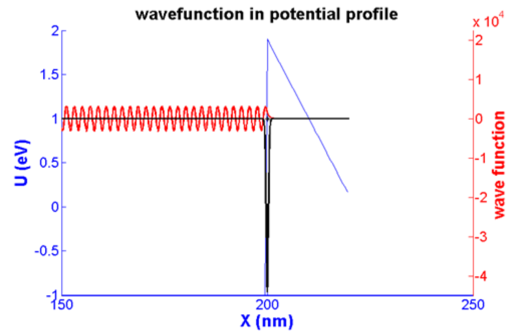

Fig. 6 Overlap of electron wave in Gate (red) and wave in the trap (black). 200 nm is interface of Gate and AlGaN layer.

After inserting the wave function into equations (2) & (3), the tunneling lifetime can be solved. Fig. 7 shows the modeled tunneling based de-trapping lifetime vs. the distance from gate at 25^{o}C. It is shown that electrons located less than 2 nm to the gate have a lifetime of 10^{-4} second and 10^{-6} second. The trap lifetime through thermal activation is 0.5 second. This means that electrons are more likely to de-trap through tunneling than by thermal activation for those traps physically near the gate. However, as the traps are located far from the interface, the thermal activated de-trapping dominates.

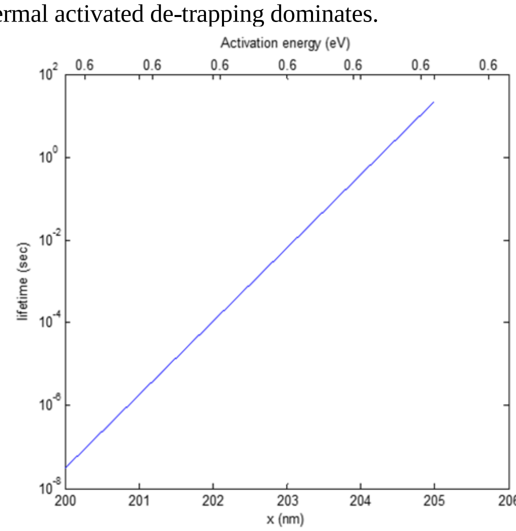

Fig. 7 Modeled lifetime at different location. The lifetime is based on electrons tunneling from AlGaN layer to gate.

It is important to take note that as temperature increases, the thermal activation lifetime decreases, which can be as small as the tunneling based lifetime near the gate. When this happens, the de-trapping can either take place through tunneling or thermal activation.

IV. SUMMARY

Two kinds of de-trapping were observed in the GaN HEMT dynamic on-resistance measurement. One is the temperature-independent fast de-trapping and another one is the temperature-dependent fast de-trapping. We believe that this fast de-trapping could be through tunneling from the interface layer to the gate, other than from the interface layer to channel for those traps that are physically located near the gate. A quantum mechanical model was developed, which agrees well with our experimental results and shows that the electrons near the gate are more likely to de-trap through tunneling than by thermal activation. However, as the traps located deep in the AlGaN layer, thermal activation de-trapping dominates.

ACKNOWLEDGEMENT

We would like to thank Dr. Jesus del Alamo for providing the necessary resources in his lab at MIT and helpful suggestions for the dynamic on-resistance measurement.

REFERENCES

[1] U. K. Mishra, P. Parikh, and W. Yi-Feng, "AlGaN/GaN HEMTs-an overview of device operation and applications," *Proceedings of the IEEE,* vol. 90, pp. 1022-1031, 2002.

[2] U. K. Mishra, W. Yi-Feng, B. P. Keller, S. Keller, and S. P. DenBaars, "GaN microwave electronics," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 46, pp. 756-761, 1998.

[3] C. Lee, L. Witkowski, M. Muir, H. Q. Tserng, P. Saunier, H. Wang, *et al.*, "Reliability evaluation of AlGaN/GaN HEMTs grown on SiC substrate," in *High Performance Devices, 2002. Proceedings. IEEE Lester Eastman Conference on*, 2002, pp. 436-442.

[4] J. Donghyun and J. A. del Alamo, "Methodology for the Study of Dynamic ON-Resistance in High-Voltage GaN Field-Effect Transistors," *Electron Devices, IEEE Transactions on,* vol. 60, pp. 3190-3196, 2013.

[5] R. Clerc, A. Spinelli, G. Ghibaudo, and G. Pananakakis, "Theory of direct tunneling current in metal–oxide–semiconductor structures," *Journal of Applied Physics,* vol. 91, pp. 1400-1409, 2002.

[6] F. Jiménez-Molinos, F. Gámiz, A. Palma, P. Cartujo, and J. A. López-Villanueva, "Direct and trap-assisted elastic tunneling through ultrathin gate oxides," *Journal of Applied Physics,* vol. 91, pp. 5116-5124, 2002.

[7] A. F. Terzis and S. Baskoutas, "Binding energy of donor states in a GaAs quantum dot: effect of electric and magnetic field," *Journal of Physics: Conference Series,* vol. 10, p. 77, 2005.

[8] C. A. Duque, N. Porras-Montenegro, M. d. Dios-Leyva, and L. E. Oliveira, "Shallow-donor states in spherical quantum dots with parabolic confinement," *MRS Online Proceedings Library,* vol. 692, pp. null-null, 2001.