UDC 621.382.323

SIMULATION OF THE FOWLER–NORDHEIM TUNNELING CURRENT THROUGH THE GATE DIELECTRIC OF ALGAN/ALN/GAN MIS-HEMT

V. Volcheck[1], F. Novikau[1], V. Pashkevich[1], D. Hvazdouski[1], K. Hulikava[2]

[1]Belarusian State University of Informatics and Radioelectronics, Minsk, Republic of Belarus,
vlad.volchek@bsuir.by

[2]JSC “INTEGRAL” – the Management Company of the Holding "INTEGRAL", Minsk, Republic of Belarus

Abstract: in metal–insulator–semiconductor high electron mobility transistors (MIS-HEMTs) based on GaN, two main conduction mechanisms contribute to the gate leakage current. At low electric fields across the gate dielectric, the dominant mechanism is Poole–Frenkel emission. At sufficiently high electric fields, the gate leakage current is primarily governed by Fowler–Nordheim tunneling. The latter process is strongly dependent on the applied electric field and the dielectric properties, which makes it a critical factor in the design of the gate stack. In this paper, we estimated the Fowler–Nordheim tunneling current through the thin SiO_2 gate dielectric of an AlGaN/AlN/GaN MIS-HEMT at low to medium reverse and forward gate-source biases. It is shown that the leakage current through ultrathin 2–4-nm SiO_2 layers may cause electrical breakdown of the gate dielectric, when the device is biased at less than ±20 V.

Keywords: Fowler–Nordheim model, gallium nitride, gate dielectric, high electron mobility transistor, silicon dioxide, simulation, leakage current, tunneling current.

I. INTRODUCTION

In field-effect transistors that have a metal–insulator–semiconductor gate structure, the conductance of the dielectric layer would ideally be considered zero. However, for devices with very thin gate dielectrics, significant conductance is measured at the gate contacts. The gate leakage current is responsible for the degradation in device performance over time. This reliability issue is important because the lifetime of electronic parts has to be guaranteed. There are a variety of conduction mechanisms across an insulating layer, but only two main conduction processes are relevant in MIS-HEMTs. At low electric fields across the gate dielectric, the dominant mechanism is Poole–Frenkel emission. At sufficiently high electric fields, the gate leakage current is primarily governed by Fowler–Nordheim tunneling. We estimated the Fowler–Nordheim tunneling current through the thin SiO_2 gate dielectric of an AlGaN/AlN/GaN MIS-HEMT at low to medium reverse and forward gate-source biases.

II. SIMULATION DETAILS

The device structure is shown in Fig 1. Its active area consists of a 5.2-μm GaN buffer layer, a 2-nm AlN spacer and a 15-nm $Al_{0.2}Ga_{0.8}N$ barrier layer. The source-gate and gate-drain distances are equal to 4.5 and 16 μm, respectively. The gate length is 2 μm.

When the electric field across the dielectric is very high, electrons may tunnel from the metal Fermi level into the dielectric conduction band. The Fowler–Nordheim equation [1] describes the tunneling current through the dielectric and has the following form:

$$J_{FN} = AE^2 \exp\left(-\frac{B}{E}\right), \tag{1}$$

where E is the electric field intensity (V/m) and

$$A = \frac{q^2}{8\pi h m_{eff} \varphi_b}, \tag{2}$$

$$B = \frac{8\pi \left(2 m_e m_{eff}\right)^{0.5} \left(q\varphi_b\right)^{1.5}}{3qh}, \tag{3}$$

where q is the elementary charge (C), h is the Planck constant ($m^2 \cdot kg \cdot s^{-1}$), m_{eff} is the effective electron mass (in non-dimensional units), φ_b – barrier height (eV), m_e is the electron mass (kg).

For Fowler–Nordheim tunneling simulations, the effective electron mass in SiO_2 is usually an adjustable parameter, with values ranging from 0.3 to 0.5. In this work, we used a value of 0.4 [2]. For the work function of the gate metal, a value of 5 eV was assigned, which corresponds to nickel [3], since Ni/Au is a standard

choice for Schottky gates of MIS-HEMTs based on GaN. For the electron affinity of SiO_2, we set a value of 0.9 eV [4]. As a result, the barrier height between the metal and the gate dielectric equals 4.1 eV. Finally, the *A* and *B* coefficients are $9.40 \cdot 10^{-7}$ A/V^2 and $3.59 \cdot 10^{10}$ V/m, respectively.

III. SIMULATION RESULTS

The Fowler–Nordheim model can be implemented using either the self-consistent or the post-processing scheme. In the first case, the tunneling current is directly added to the current continuity equations. In the post-processing version, the tunneling current is calculated from the solution to the device equations at each bias step. In Fig. 2, the drain current vs gate-source voltage characteristics of the MIS-HEMT under consideration are presented. The thickness of the SiO_2 gate dielectric is varied from 4 to 10 nm. The characteristics were obtained by the post-processing method thus precluding the gate current from being added to any terminal current. The drain-source voltage is 0.1 V.

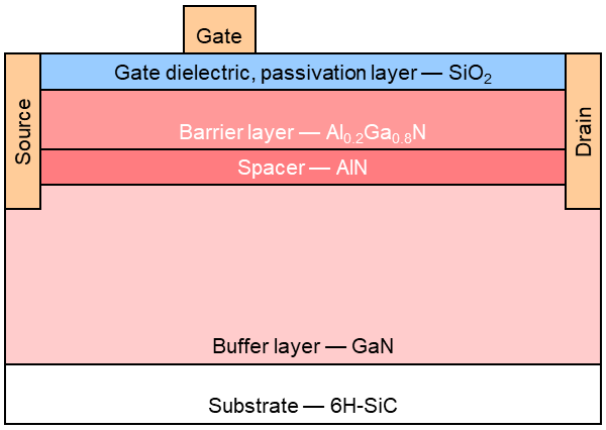


Figure 1. AlGaN/AlN/GaN MIS-HEMT device structure

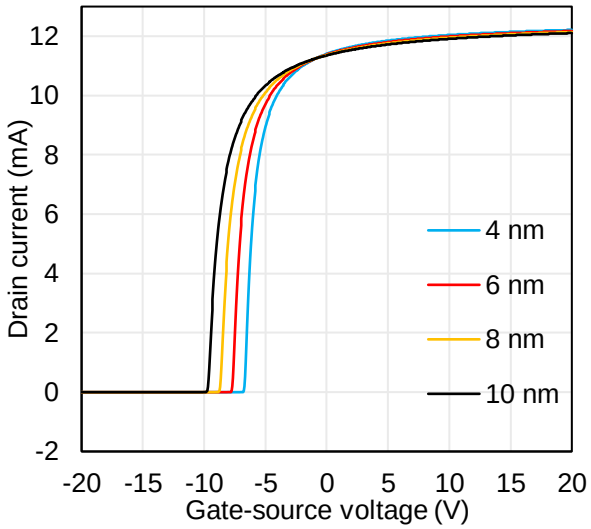


Figure 2. Drain current vs gate-source voltage characteristics for 4–10-nm-thick SiO_2 gate dielectrics

A potential barrier as high as 4.1 eV between the gate metal and SiO_2 makes the device normally off and shifts its threshold voltage deep into the negative range. The device structure with a 10-nm-thick SiO_2 layer exhibits a threshold voltage of around –10 V. The negative and forward gate current vs gate-source voltage characteristics are shown in Figs. 3 and 4 respectively.

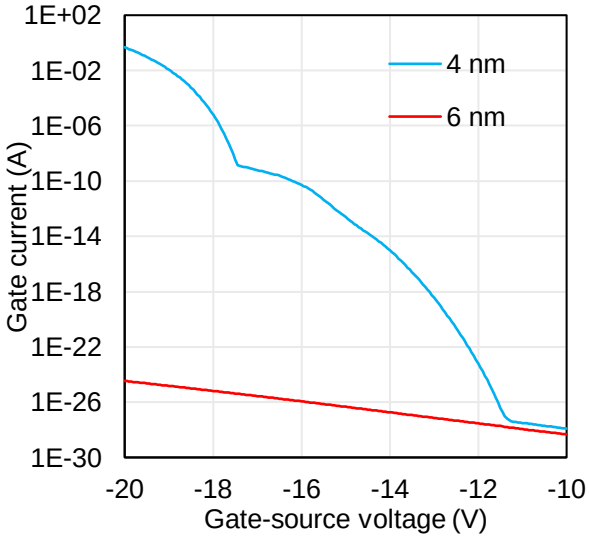


Figure 3. Gate current vs gate-source voltage characteristics for 4 and 6-nm-thick SiO_2 gate dielectrics. The gate is negatively biased

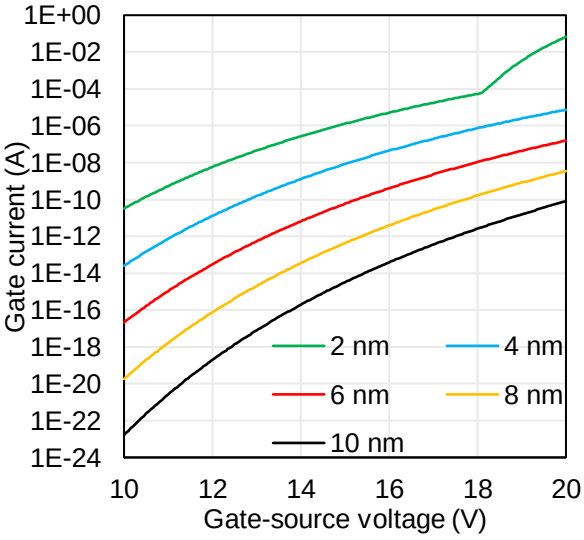


Figure 4. Gate current vs gate-source voltage characteristics for 2–10-nm-thick SiO_2 gate dielectrics. The gate is positively biased

According to our simulation results, the device structures with gate dielectric thicknesses of 6 nm or thicker can withstand high negative biases up to at least –20 V. However, a thinner 4-nm gate dielectric leads to electrical breakdown of the MIS-HEMT at approximately –11 V. The situation is entirely analogous for positive biases, where the gate leakage current of the device structure with an ultrathin 2-nm SiO_2 layer begins to rise sharply at +18 V.

IV. CONCLUSIONS

The Fowler–Nordheim tunneling current through the thin SiO_2 gate dielectric of an AlGaN/AlN/GaN MIS-HEMT at low to medium reverse and forward gate-source biases was simulated. It was shown that the leakage current through ultrathin 2–4-nm SiO_2 layers may cause electrical breakdown of the gate dielectric when the device is biased at less than ±20 V. Further study is needed to determine the SiO_2 gate dielectric thickness and the gate metal that allow the device to operate within the ±30 V range.

ACKNOWLEDGEMENTS

This work is funded by grant 26-1033Б from JSC “INTEGRAL” – the Management Company of the Holding "INTEGRAL" and by grant 5.3.01 of the State Program of the Scientific Researches “Photonics and Microelectronics”.

REFERENCES

[1] Complete Transient Simulation of Flash EEPROM Devices / S. Keeney [et al.] // IEDM Technical Digest. 1990. P. 201–204. https://doi.org/10.1109/IEDM.1990.237193.

[2] Lenzlinger, M. Fowler-Nordheim Tunneling into Thermally Grown SiO_2 / M. Lenzlinger, E. H. Snow // Journal of Applied Physics. 1969. Vol. 40, № 1. P. 278–283.

[3] Baker, B. G. Photoelectric Work Function Measurements on Nickel Crystals and Films / B. G. Baker, B. B. Johnson, G. L. C. Maire // Surface Science. 1971. Vol. 24, No. 2. P. 572–586. https://doi.org/10.1016/0039-6028(71)90282-2.

[4] Monte-Carlo Simulation and Experimental Study of the Effect of Internal Charging on the Electron Emission Yield of Amorphous SiO_2 Thin Films / Q. Gibaru [et al.] // Journal of Electron Spectroscopy and Related Phenomena. 2022. Vol. 261. Art. No. 147265. https://doi.org/10.1016/j.elspec.2022.147265.

МОДЕЛИРОВАНИЕ ТОКА ТУННЕЛИРОВАНИЯ ПО МЕХАНИЗМУ ФАУЛЕРА – НОРДГЕЙМА ЧЕРЕЗ ПОДЗАТВОРНЫЙ ДИЭЛЕКТРИК AlGaN/AlN/GaN-МДП-ТВПЭ

Волчёк В.С.[1], Новиков Ф.П.[1], Пашкевич В.Э.[1], Гвоздовский Д.Ч.[1], Гуликова Е.А.[2]

[1]Белорусский государственный университет информатики и радиоэлектроники, Минск, Республика Беларусь, vlad.volchek@bsuir.by

[2]ОАО «ИНТЕГРАЛ» – управляющая компания холдинга «ИНТЕГРАЛ», Минск, Республика Беларусь

Аннотация: основной вклад в ток утечки через затвор со структурой металл–диэлектрик–полупроводник транзистора с высокой подвижностью электронов (МДП-ТВПЭ) на основе нитрида галлия вносят два физических механизма. При слабых полях в подзатворном диэлектрике преобладающим механизмом является эмиссия Пула – Френкеля. При достаточно больших полях ток утечки через подзатворный диэлектрик состоит преимущественно из тока туннелирования по механизму Фаулера – Нордгейма. Последний процесс показывает сильную зависимость от величины электрического поля и свойств диэлектрического материала, что делает его критически важным при проектировании структуры затвора транзистора. В этой статье выполнена количественная оценка тока туннелирования по механизму Фаулера – Нордгейма через тонкий слой подзатворного диэлектрика SiO_2 МДП-ТВПЭ со структурой AlGaN/AlN/GaN при малых и средних значениях обратного и прямого напряжения затвор–исток. Показано, что ток утечки через сверхтонкие (толщиной 2–4 нм) слои SiO_2 может вызывать электрический пробой подзатворного диэлектрика при напряжениях менее ±20 В.

Ключевые слова: диоксид кремния, моделирование, модель Фаулера – Нордгейма, нитрид галлия, подзатворный диэлектрик, ток туннелирования, ток утечки, транзистор с высокой подвижностью электронов.