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Modelling and Simulation of Normally-Off AlGaN/GaN MOS-HEMTs

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***Abstract*—The article presents the results of modelling and simulation of normally-off AlGaN/GaN MOS-HEMT transistors. The effect of the resistivity of the GaN:C layer, the channel mobility and the use of high-κ dielectrics on the electrical characteristics of the transistor has been examined. It has been shown that a low leakage current of less than 10^{-6} A/mm can be achieved for the acceptor dopant concentration at the level of 5×10^{15} cm^{-3}. The limitation of the maximum on-state current due to the low carrier channel mobility has been shown. It has also been demonstrated that the use of HfO$_2$, instead of SiO$_2$, as a gate dielectric increases on-state current above 0.7A/mm and reduces the negative influence of the charge accumulated in the dielectric layer.**

***Keywords*—gallium nitride, MOS-HEMT, high electron mobility transistor, AlGaN, GaN, simulation**

I. INTRODUCTION

HIGH ELECTRON MOBILITY TRANSISTORS (HEMTs) based on the AlGaN/GaN heterostructures can be used for power electronics owing to the excellent electro-physical properties of III-N materials, such as high critical electric field and high carrier concentration and mobility of two-dimensional electron gas (2DEG) in the channel [1]. The use of silicon as the substrate material for the epitaxial growth of AlGaN/GaN HEMT structures, seems to be particularly attractive which allows to obtain high-quality epitaxial layers, on large diameter substrates (6 inches). One of the essential requirements for such applications is an enhancement mode (normally-off) operation. Conventional AlGaN/GaN HEMT structures are not suitable for power devices due to normally-on operation, resulting from the strong piezoelectric effects in III-N materials. There are several approaches allowing to realize normally-off mode operation e.g. etching of AlGaN barrier layer under the gate electrode [2], surface modification using fluorine plasma[3], the introduction of p-type GaN or AlGaN layer [4], or the use of recessed gate MOS-HEMT structure [5]. Among these solutions only the use of MOS-HEMT structure potentially resulting in high threshold voltage above 1V and low gate current value in both "on" and "off" state of the transistor. This paper presents the results of modelling and simulation of electrical characteristics of the normally-off AlGaN/GaN MOS-HEMT. The effect of the key design elements on the electrical parameters of the device, in particular, threshold voltage (V_{TH}), off-state and the maximum drain current in the on state (I_{DS}^{max}) were shown. Simulations were performed using the Silvaco ATLAS simulation package [6].

II. SIMULATION DETAILS

Figure 1 shows the structure of the normally-off AlGaN/GaN MOS-HEMT used in the simulations.

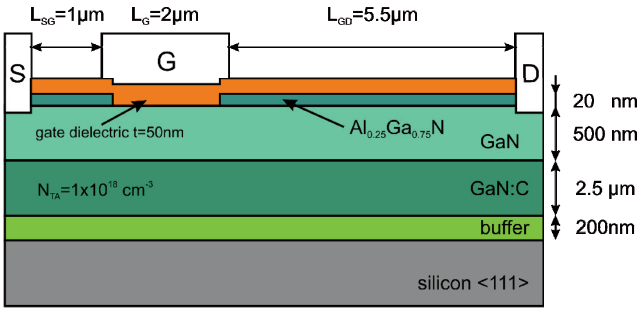

Fig. 1. Cross section of normally-off AlGaN/GaN MOS-HEMT structure

The transistor structure consists of the buffer layer on a silicon substrate ($\langle 111 \rangle$ orientation), a highly resistive carbon doped GaN layer with a thickness of 2.5μm, undoped GaN layer with a thickness of 500 nm and Al$_{0.25}$Ga$_{0.75}$N barrier layer having a thickness of 20nm . To ensure high resistivity of GaN:C layer a deep acceptor trap level located at 0.9eV [7] above the valence band and traps density 1×10^{18} cm^{-3} was introduced. A shallow donor traps concentration 1×10^{15} cm^{-3} [8] was assumed for all nitrides layers. The recess depth in Al$_{0.25}$Ga$_{0.75}$N barrier layer under gate electrode and thickness of gate dielectric was 20 and 50nm, respectively. For the initial simulation the relative permittivity of gate dielectrics was 3.9 (SiO$_2$). The carrier mobility in the channel was set to 200 cm^2/Vs, taking into account possible surface roughness. 2DEG mobility between source and gate or gate and drain electrode was 1500 cm^2/V, which is typical value for AlGaN/GaN HEMTs. The source-gate L$_{SG}$ and gate-drain L$_{GD}$ distance, was 1 and 5.5 μm respectively. Gate length L$_G$ was set to be 2 μm. The ohmic contacts resistance for source and drain regions

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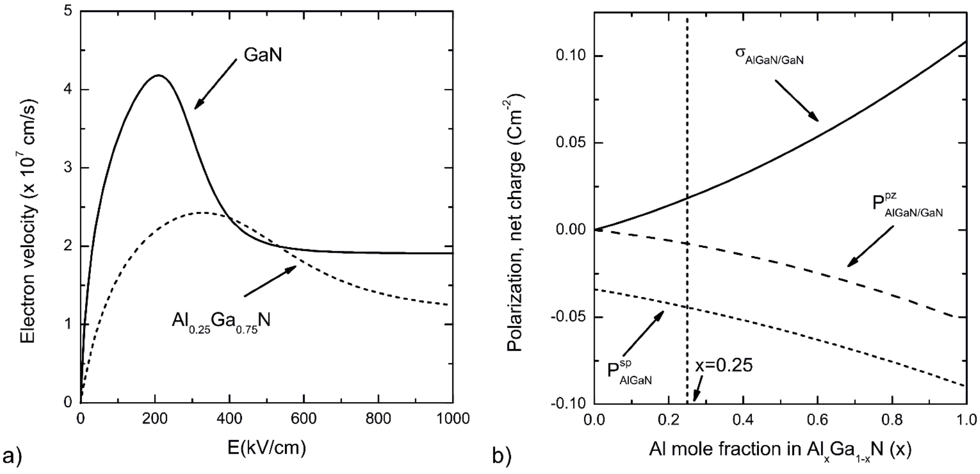

Fig. 2. Modelled a) electron velocity dependence on electric filed in GaN and Al$_{0.25}$Ga$_{0.75}$N, b) polarization dependence on the Al mole fraction in Al$_{0.25}$Ga$_{0.75}$N

(R$_c$) was 0.6 Ωmm. The self-heating effects were neglected during simulation.

The most important models included in simulation are electric filed dependent mobility of 2DEG and composition dependent physical properties of nitride layers. The band gap of $Al_xGa_{1-x}N$ depending on the aluminium content is described by following formula [9]:

$$E_{g(Al_xGa_{1-x}N)} = E_{g(AlN)}x + E_{g(GaN)}(1-x) - 1.3x(1-x) \tag{1}$$

where band gap of GaN is 3.42eV and band gap of AlN is 6.2eV.

The relation of field dependent mobility of GaN and Al$_{0.25}$Ga$_{0.75}$N has the form [10]:

$$\mu_n = \frac{\mu_0 + v_{sat}\frac{E^{N1-1}}{E_c^{N1}}}{1 + A\left(\frac{E}{E_c}\right)^{N2} + \left(\frac{E}{E_c}\right)^{N1}} \tag{2}$$

where model parameters for GaN and Al$_{0.25}$Ga$_{0.75}$N are given in the Table I. Calculated based on this model electron velocity profiles ($v = \mu \times E$) are shown in Fig. 2a.

All nitrides in wurtzite structure, such as Al$_x$Ga$_{1-x}$N, GaN, AlN, InN, In$_x$Ga$_{1-x}$N or In$_x$Al$_{1-x}$N are polar materials. This is associated with the large difference in electronegativity between atoms forming compound. Therefore, nitrides exhibit spontaneous polarization (nonvanishing polarization vector parallel to the c-axis of the crystal) and exhibit a strong piezoelectric effect. Therefore, at the interface of two nitride semiconductors are nonvanishing polarization vector and the resulting charge. The net polarization charge at Al$_x$Ga$_{1-x}$N/GaN interface can be calculated by following formula [9]:

$$\sigma = (P^{sp}_{GaN}) - (P^{sp}_{Al_xGa_{1-x}N} + P^{pz}_{Al_xGa_{1-x}N}) \tag{3}$$

where P^{sp} is spontaneous and P^{pz} is piezoelectric polarization. The relationship for spontaneous in Al$_x$Ga$_{1-x}$ is [9]:

$$P^{sp}_{Al_xGa_{1-x}N} = -0.09x - 0.034(1-x) + 0.0191x(1-x) \tag{4}$$

TABLE I
PARAMETERS OF CARRIER MOBILITY MODELS

Parameter	GaN	Al$_{0.25}$Ga$_{0.75}$N
v$_{sat}$(cm^2/s)	1.91×10^7	1.126×10^7
μ_0(cm^2/Vs)	1500	300
E$_c$(kV/cm)	220.9	380.5
N1	7.2	5.27
N2	0.78	1.03
A	6.19	3.12

and piezoelectric polarization in Al$_x$Ga$_{1-x}$ layer on relaxed GaN [9]:

$$P^{pz}_{Al_xGa_{1-x}N/GaN} = -0.0525x + 0.0282x(1-x) \tag{5}$$

The above relations are depicted in Fig. 2b.

III. RESULTS OF SIMULATION

In standard HEMT structure at the gate bias of V$_{GS}$=0V there is a high concentration of 2DEG at the region between source and drain in quantum well at the AlGaN/GaN interface. In normally-off MOS-HEMT structure, etching of Al$_{0.25}$Ga$_{0.75}$N barrier layer under gate region results in depletion of 2DEG at V$_{GS}$=0V. A conductive channel in the GaN layer can be formed by applying a positive bias to the gate electrode and turns the transistor on. Electron concentration profiles in “off” (V$_{DS}$=20V, V$_{GS}$=0V) and “on” (V$_{DS}$=20V, V$_{GS}$=20V) state are presented in Fig. 3. A set of transfer characteristics within V$_{DS}$ range from 1 to 20V is presented in Fig. 43a. The threshold voltage for the simulated MOS-HEMT structure was 1.39 V. In Fig. 4b a set of output characteristics within V$_{GS}$ range from 0 to 20V is depicted. Maximum output current I$^{max}_{DS}$ in the on-state (V$_{DS}$=20V, V$_{GS}$=20V) was about 300mA/mm.

A. Influence of Acceptor Traps Concentration in GaN:C Layer

In the case of HEMT and MOS-HEMTs AlGaN/GaN transistors on Si substrates it is important to obtain high

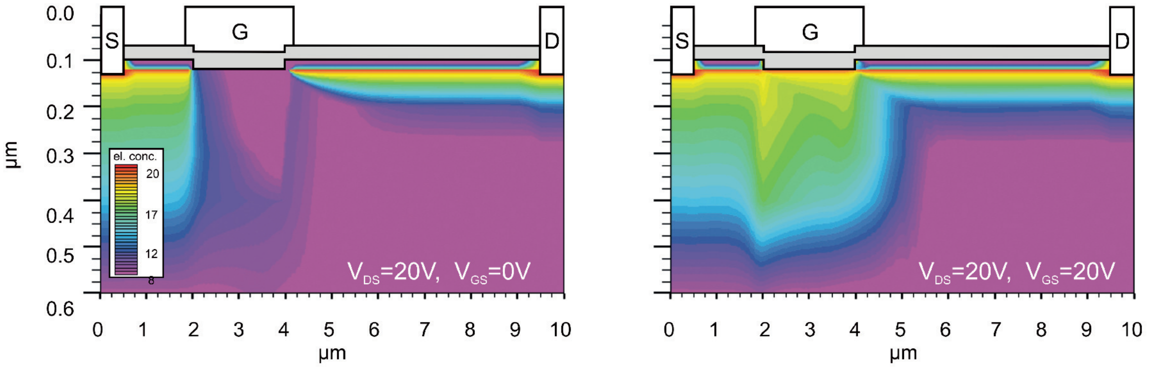

Fig. 3. The distribution of electron concentration in AlGaN/GaN MOS-HEMT in off- (V$_{DS}$=20V, V$_{GS}$=0V) and on-state (V$_{DS}$=20V, V$_{GS}$=20V)

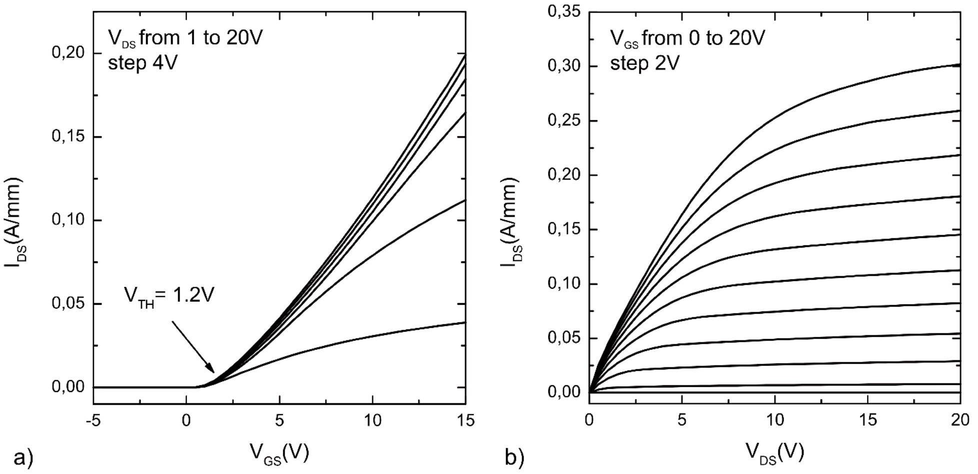

Fig. 4. Transfer (a) and output (b) characteristics of AlGaN/GaN MOS-HEMT

resistivity GaN layers between the channel and the substrate to prevent short channel effects and substrate leakage currents in the off-state. GaN epilayers often have background n-type conductivity due to unintentional introduction of oxygen or silicon atoms during growth, which act as a shallow donors. The high resistivity GaN buffer layers can be achieved by deep acceptor doping eg carbon or iron atoms. This creates deep acceptor traps which can compensate background shallow donors. In order to investigate the effect of acceptor traps concentration in GaN:C buffer layer on the leakage current, the concentration of traps was varied from 1×10^{18} cm^{-3} to 1×10^{15} cm^{-3}. The transfer characteristics of the MOS-HEMT for assumed values of acceptor traps concentration are presented in Fig. 5a.

The off-state current strongly depends on the acceptor traps concentration. For the highest concentration of 1×10^{18} cm^{-3} the leakage current reaches the level of nA/mm. The decrease of acceptor traps concentration up to the level of 5×10^{15} cm^{-3} causes an increase in the leakage current to μA/mm. When analysing the off-state current, a sharp increase is observed for acceptor traps concentration of about 5×10^{15} cm^{-3}, the value close to the concentration of shallow donor traps in GaN or AlGaN layers (Fig. 5b). It is not possible to turn the transistor off for the traps concentration of 1×10^{15} cm^{-3} cm^{-3}. The current in the off-state is about 50 mA/mm. The significant current is flowing across interface between silicon substrate and GaN:C layer for. For N$_{TA}$=1 $\times$ 10^{18} cm^{-3} the current is mainly flowing in GaN layer under gate region as can be seen in Fig. 6.

B. Influence of Channel Mobility on AlGaN/GaN MOS-HEMTs Parameters

To ensure low on-state resistance, it is necessary to obtain high carrier mobility in the channel region. Mobility values reach 250 cm^2/Vs [11] for normally-off AlGaN/GaN MOS-HEMTs. These values are still much lower than the electron mobility in the two-dimensional electron gas due to the existence of high density of interface states at the interface between gate dielectric and GaN. Additionally, the carriers can be scattered due to interface roughness caused by the dry etching of AlGaN layer. To gain insight into how a decrease in channel mobility affects the maximum current in the on-state values of μ_{ch} was sequentially reduced from 200 to 20 cm^2/Vs. The effect of channel mobility on the output characteristics is illustrated in Fig. 7a. With the decrease of mobility from 200 to 20 cm^2/Vs, the maximum current in the on-state is reduced by more than 80% to less than 0.05 A/mm

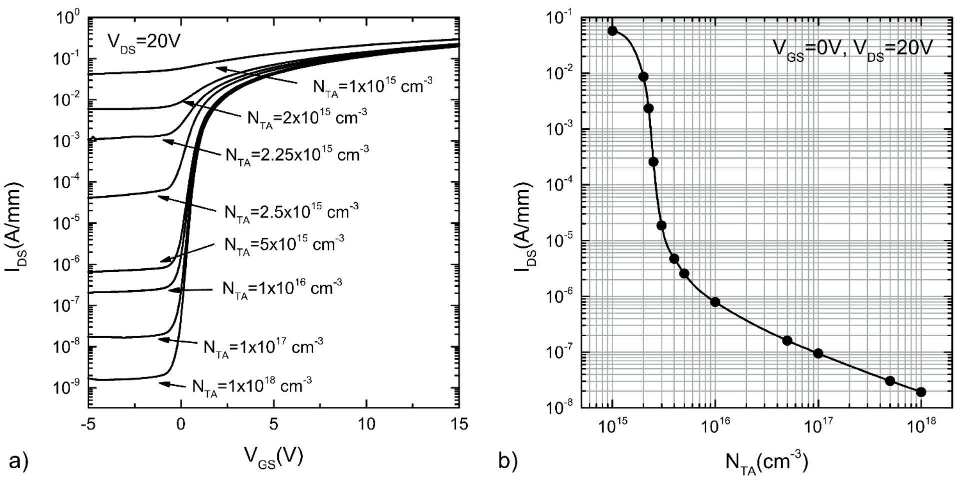

Fig. 5. The dependence of a) AlGaN/GaN MOS-HEMT transfer characteristics and b) off-state current (V_{DS}=20V, V_{GS}=0V) on the concentration of carbon atoms in GaN:C layer

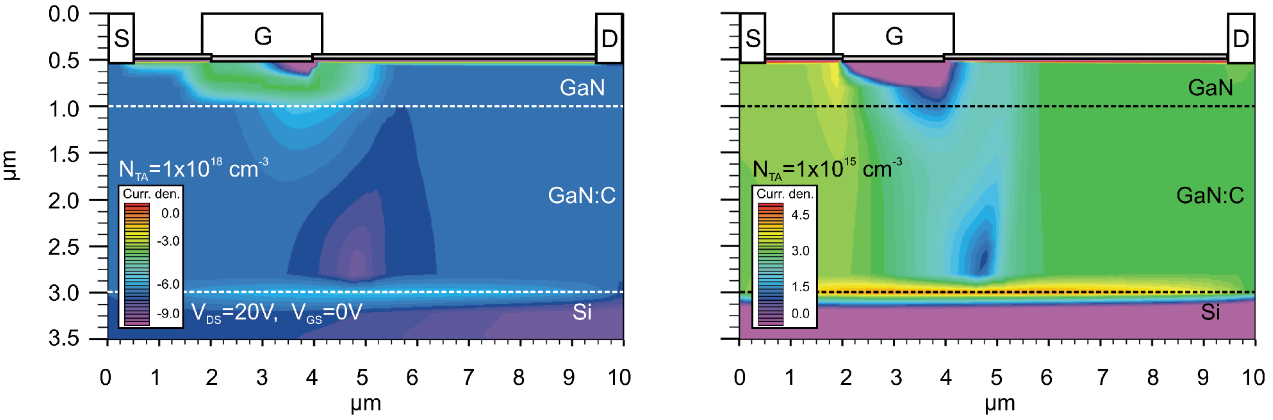

Fig. 6. Total current density in AlGaN/GaN MOS-HEMT in off-state (V_{DS}=20V, V_{GS}=0V) acceptor traps concentration N_{TA}=1 $\times$ 10^{18} cm^{-3} (left) and N_{TA}=1 $\times$ 10^{15} cm^{-3} (right). Note different log scale in both figures

(Fig. 7b). In this case, the on-state resistance is limited by channel resistance.

C. Influence of Relative Permittivity (ϵ_r) of Gate Dielectric on AlGaN/GaN MOS-HEMTs Parameters

One of the mostly used gate dielectrics for fabrication of AlGaN/GaN MOS-HEMTs and GaN MOSFETs is silicon dioxide – SiO_2[12]. The main advantage of SiO_2 is high barrier value between conduction bands of GaN and dielectric layer[13]. The research on the use of other dielectric materials are conducted, particularly on the high dielectric constant materials (high-κ) such as aluminium oxide (Al_2O_3 ϵ_r=8-9)[14] and hafnium oxide (HfO_2 ϵ_r=15-20)[15]. The use of dielectric layers with a high dielectric constant results in better conductivity modulation in the transistor channel and the increase of maximum current in the on-state. With the increase of dielectric constant from 3.9 (SiO_2) up to 15 (HfO_2) the on-state current (V_{GS}=15V, V_{DS}=20V) increases from 0.2 A/mm to 0.68 A/mm (Fig. 8a).

At the same time the use of high-κ dielectrics reduces the influence of the charge accumulated in the gate dielectric layer (Q_{eff}) on the characteristics and electrical parameters of the transistor. Figure 6b shows the change in the threshold voltage and the on-state current due to the sign and value of the charge accumulated in the dielectric. In the case of SiO_2 layer the changes in those parameters are much larger than in the case of HfO_2 (Fig. 8b). Particularly important are changes of the threshold voltage. The positive value of Q_{eff} reduces the threshold voltage and in the worst case it is switching operating mode of the device from normally-off to normally-on. With a density of positive charge at the level of 1×10^{12} cm^{-2} in case of SiO_2 the threshold voltage is reduced to a negative value of -0.83V. At the same level of positive charge the threshold voltage is still positive for HfO_2 layers (0.78V).

IV. CONCLUSION

The article presents the results of modelling of normally-off AlGaN/GaN MOS-HEMTs. Maximum positive threshold voltage V_{TH}=1.39V and the maximum on-state current I_{DS}^{max}=0.3A/mm were achieved. The effect of deep acceptor

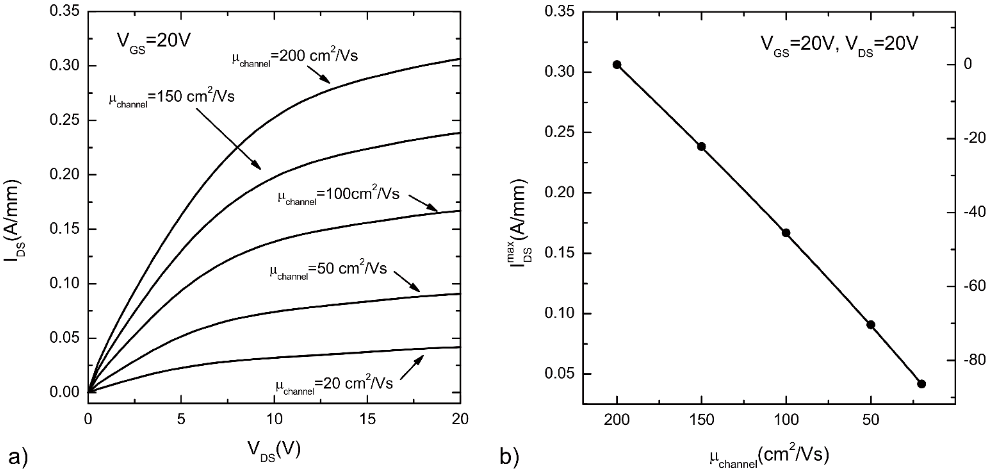

Fig. 7. The effect of channel mobility on a) AlGaN/GaN MOS-HEMT output characteristics and b) on-state current (V_{DS}=20V, V_{GS}=20V)

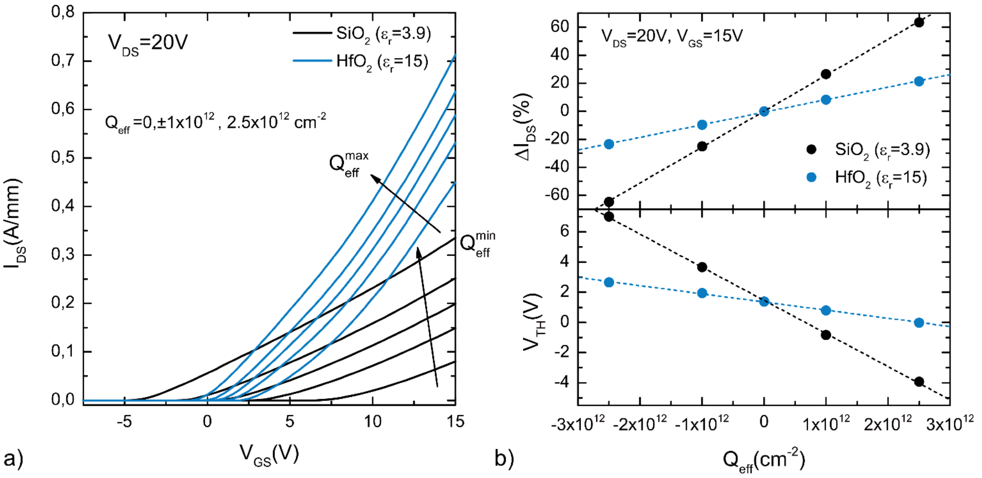

Fig. 8. The effect of effective charge density on a) AlGaN/GaN MOS-HEMT transfer characteristics and b) on-state current (V_{DS}=20V, V_{GS}=15V) and the threshold voltage for different gate dielectric SiO_2 (ϵ_r=3.9) and HfO_2 (ϵ_r=15)

traps concentration in GaN:C layer on the off-state current has been shown. To avoid a high leakage current, the acceptor traps concentration must be at least five times higher than a background shallow donors concentration. In case of shallow donors concentration of 5×10^{15} cm^{-3} acceptor traps concentration should be above 1×10^{16} cm^{-3}. The limitation of the maximum on-state current by the low carrier channel mobility was presented as well. To achieve maximum on-state current above 200 mA/mm μ_{ch} should be more than 100 cm^2/Vs. The application of high-κ dielectrics in normally-off MOS-HEMTs results in maximum on-state current increase and reduction of the negative effect of the effective charge accumulated in the dielectric layer on the threshold voltage. For ϵ_r=15, positive Q_{eff} of the order of 10^{12} cm^{-2} reduces V_{th} and I_{DS}^{max} only by 0.6V and 20%, respectively. This values are still better than in the absence of Q_{eff} in SiO_2 gate dielectric. It follows that, from the device performance point of view, high-κ dielectrics should be applied in technology of normally-off AlGaN/GaN MOS-HEMTs.

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