4 CONCLUSION

Substitution of iron by cobalt in Fe-Mo-Cu-B system leads to formation of fully amorphous ferromagnetic state. Increased Co content leads to increase of Curie temperature of the amorphous phase. The temperatures of transformation into nanocrystalline state, however, are not significantly affected, although the magnitude of changes of electrical resistivity increases with increasing Co content. Excellent correspondence between transformation behavior during linear heating regimes was observed for electrical resistivity and magnetization measurements. Magnetization behavior was correlated also with measurements of magnetoresistance, showing distinct differences between paramagnetic and ferromagnetic sample. Alloys with low or no cobalt content exhibit unusual effect, where partial crystallinity is observed in the sample layer with higher quenching rate.

Acknowledgement

Support of the Slovak Grant Agencies for science (VEGA 5/09625, APVT-51-052705, APVT-51-021102 and SO 51038 06 03) and SAS Centre of Excellence "Nanomart" is acknowledged.

REFERENCES


1 INTRODUCTION

It is well known that future devices used in new communication systems need to operate simultaneously at higher frequencies (higher speed, larger bandwidth) and higher powers. Unfortunately, Si-based and GaAs-based devices cannot fulfill this requirement, as it follows from their fundamental material and electronic transport parameters. Schematic frequency vs power diagram for devices using various semiconductor materials is shown in Fig. 1 [1]. Materials with higher bandgap, such as SiC and GaN (3.4 eV), clearly dominate. However, the natural advantage of GaN over SiC is the possibility of making heterostructures using AlGaN, InGaN or InAlN. Since recently GaN-based transistors are under systematic study by various academic and industry research groups. An expressive progress concerning the preparation and performance of AlGaN/GaN heterostructure field-effect transistors (HFET) can be observed [2]. This can be demonstrated by recently reported total output power of 179 W at 2 GHz on 48 mm wide (i.e. 3.7 W/mm power density) single-chip HFET by Device Research Labs of NEC Corp. [3]. In spite of these record power data they are still some material and device issues, which need to be solved concerning mass production of AlGaN/GaN HFET devices. One key problem at the preparation of GaN-based devices is the lack of native substrates [4]. The material structure needs to be grown as lattice-mismatched to the substrate such as sapphire, Si or SiC. High gate leakage currents and DC/RF drain current dispersion, which limit microwave output power, as well as performance degradation belong to the main questions concerning the device preparation. Various tasks such as material structure optimisation [5], dielectric passivation [6] and field-modulating gate plate [7] are used to suppress or eliminate these effects. Recently an application of gate insulator, i.e. preparation of MISHET devices, has been shown as a perspective alternative for the preparation of reliable GaN-based transistors [8].

In this paper, an influence of a SiO2 insulator, deposited on the un gated surface access region as well as below the gate, on the performance of AlGaN/GaN HFETs is investigated. The DC and RF performance of unpassivated and passivated HFETs and passivated MOSHFETs, prepared on the same material structure, is compared. It is shown that SiO2 passivated MOSHFETs exhibit higher output power than simultaneously prepared Schottky-gate HFET counterparts.

Fig. 4 The dependence of electrical resistivity on applied external magnetic field - magneto resistance plots. Points on the right represent measurements with orientation of sample plane perpendicular to the applied magnetic field. On the left the orientation is parallel to the magnetic field.

Fig. 1. Schematic frequency vs power diagram for devices on various semiconductor materials [1].
2. DEVICE PREPARATION

Experimental basis for the study reported here was the simultaneous fabrication of unpassivated and SiO2-passivated AlGaN/GaN HFETs and SiO2 gate insulator AlGaN/GaN MOSFETs. The material structure for all devices consisted of 3 µm thick undoped GaN and 30 nm thick undoped AlGaN/GaN layers grown on insulating 4H-SiC substrate by LP-MOCVD (Cree-GaN Durham). The device processing consisted of conventional FET fabrication steps. At first mesa etching isolation using argon sputtering was performed. After that ohmic contacts were prepared by evaporating multilayered Ti/Au/Ni/Au sequence followed by rapid thermal annealing at 850°C for 30 s in a N2 ambient. The ohmic contact resistance of 0.22–0.35 Ω mm was measured using the transmission-line method. The Schottky gate metallization consisted of a Ni/Au double-layer patterned by e-beam lithography. Devices with a gate length of 0.3-0.9 µm and a gate width of 100 µm and 200 µm (two fingers) were prepared. Van der Pauw patterns with an active area of 0.3 × 0.3 mm² were processed simultaneously with HFET devices. A SiO2 layer of 10 nm nominal thickness was deposited by PECVD to fabricate the passivated HFETs. To prepare the MOSFETs, the same oxide-thickness was chosen as for passivated HFETs and PECVD was applied as well.

3. SiO2/AlGaN/GaN HETEROSTRUCTURE CHARACTERISATION

The material structure was characterized by Hall effect measurements on van der Pauw patterns and C-V measurements on HFET devices itself. It was well known that dielectric passivation of AlGaN/GaN heterostructure compromises surface states and thus induces an increase of the sheet carrier density in the 2DEG channel [9]. This effect was confirmed on our samples investigated. Hall effect data yielded a sheet carrier density of 7.1×10¹⁸ cm⁻² and 9.2×10¹⁸ cm⁻² for unpassivated and passivated AlGaN/GaN heterostructure, respectively. The carrier mobility of 1835 cm²/Vs and 1670 cm²/Vs in unpassivated and SiO2-passivated material structures, respectively. The passivation induced sheet carrier density Δn = 2.1×10¹⁸ cm⁻² and partial decrease of the mobility are in good agreement with our previous investigations (Δn = 1.5×10¹⁸ cm⁻² after SiN₃ passivation) [9].

Figure 2 shows the capacitance-voltage characteristics typical for unpassivated AlGaN/GaN HFET and passivated SiO2/AlGaN/GaN MOSFET. The C-V curves show sharp transitions and negligible hysteresis. The sheet carrier density can be evaluated from the capacitance and threshold voltage as

\[ n_s = \frac{C_v V_{th}}{	ext{V}_{th}} \]  

Values of 7.6×10¹⁸ cm⁻² and 9.2×10¹⁸ cm⁻² for unpassivated HFET and passivated MOSFET, respectively, are in excellent agreement with mentioned above Hall data. Similarly, from the zero-bias capacitance of HFET we can evaluate the AlGaN thickness d_{AlGaN} = t_{HFET} - 29.4 nm, to the nominal thickness of 30 nm. From the zero-bias capacitance of HFET and MOSFET considering that

\[ C_{HFET} \sim C_{MOSFET} \sim \frac{1}{t_{AlGaN}} \left( \frac{d_{AlGaN}}{t_{AlGaN}} \right)^{2/3} \]  

and using AlGaN and SiO2 layer permittivities ε = 9.2 and 3.9 respectively, we extracted the TiO2 thickness of 10 nm. A saturation of the MOSFET capacitance at higher gate voltages indicates that the capacitance of SiO2 insulator only is measured. Our preliminary evaluation of the SiO2 surface states density from the single-frequency capacitance and conductance measurements indicates that Δn = 1.1×10¹⁸ cm⁻². This value is in good agreement with results published before on SiO2/GaN structures [10].

4. DEVICE PERFORMANCE

It is well known that AlGaN/GaN HFETs exhibit relatively high gate leakage currents. For simple undoped and unpassivated AlGaN/GaN heterostructure, as used here, the gate leakage currents of about 10⁶ A/mm (Vgs = -6 V) are usually observed. They can be about one order of magnitude lower if passivation is used. We reported recently that another alternative to suppress the gate current is by using undoped GaN cap on top of the heterostructure, which enhances the Schottky barrier height [5]. Leakage currents of about 10⁵ A/mm were found on passivated GaN/AlGaN/GaN devices. Figure 3 (full lines) shows typical two terminal gate-source I-V characteristics of unpassivated AlGaN/GaN HFET and passivated SiO2/AlGaN/GaN MOSFET.

![Fig. 2 Capacitance-voltage characteristics of unpassivated AlGaN/GaN HFET and passivated SiO2/AlGaN/GaN MOSFET](image)

Values of 7.6×10¹⁸ cm⁻² and 9.2×10¹⁸ cm⁻² for unpassivated HFET and passivated MOSFET, respectively, are in excellent agreement with mentioned above Hall data. Similarly, from the zero-bias capacitance of HFET we can evaluate the AlGaN thickness d_{AlGaN} = t_{HFET} - 29.4 nm, to the nominal thickness of 30 nm. From the zero-bias capacitance of HFET and MOSFET considering that

\[ C_{HFET} \sim C_{MOSFET} \sim \frac{1}{t_{AlGaN}} \left( \frac{d_{AlGaN}}{t_{AlGaN}} \right)^{2/3} \]  

and using AlGaN and SiO2 layer permittivities ε = 9.2 and 3.9 respectively, we extracted the TiO2 thickness of 10 nm. A saturation of the MOSFET capacitance at higher gate voltages indicates that the capacitance of SiO2 insulator only is measured. Our preliminary evaluation of the SiO2 surface states density from the single-frequency capacitance and conductance measurements indicates that Δn = 1.1×10¹⁸ cm⁻². This value is in good agreement with results published before on SiO2/GaN structures [10].

![Fig. 3 Two terminal gate-source I-V characteristics of unpassivated AlGaN/GaN HFET and passivated SiO2/AlGaN/GaN MOSFET](image)

Typical static output characteristics of AlGaN/GaN MOSFETs are shown in Fig. 4. Low output conductance and minimal thermal effects are observed. A drain saturation current of 1.09 A/mm is obtained at 1 V on the gate. This is comparable value to that known on state-of-the-art passivated AlGaN/GaN HFETs. The threshold voltage is close to -11 V opposed to about -6 V observed commonly on HFETs. This is expected due to additional serial capacitance of the insulator and as it follows from the C-V measurements (Fig. 2). Thus, the peak extrinsic transconductance gm of 118 mS/mm is slightly lower than reported on HFETs. For comparison, a drain saturation current of 0.75 A/mm and a peak extrinsic transconductance of 165 mS/mm were found on unpassivated HFETs processed simultaneously on similar AlGaN/GaN material structures.

![Fig. 4 Output characteristics of SiO2/AlGaN/GaN MOSFET (Vgs = 1 V, Vds = 2 V)](image)

Small signal RF characterisation of the devices was carried out by on-wafer S-parameter measurements up to 60 GHz. Figure 5 shows an example of the short circuit current gain (β) and the unilateral power gain (GU) as a function of frequency for SiO2/AlGaN/GaN MOSFET with 0.7 µm and 200 µm gate length and width, respectively. An exponential gain cut-off frequency fT of 24 GHz and a maximum frequency of oscillation fMAX of 40 GHz are evaluated from these data at GU = 15 V and Vgs = -7 V biases. These are fully comparable values with those reported on state-of-the-art AlGaN/GaN HFETs. The fT-CUT product of 16.8 GHz cm is even slightly higher than commonly reported for AlGaN/GaN HFETs [12]. This follows from lower decrease of the transconductance than of the gate capacitance for MOSFET comparing to HFET. fT is proportional to the ratio of gm and Coss. The cut-off frequency ratio fMAX/fT = 1.7 is a reasonable value. All these, i.e. static and small-signal microwave performance of MOSFET devices prepared, indicate on a good quality of used SiO2 without degradation of the carrier mobility in the channel. Thus, a great potential in application of GaN-based MOSFETs is documented.

Finally, microwave power measurements were performed using an on-wafer load pull measurement system. Output power sweeps of these devices were conducted at 7 GHz. Impedance matching was accomplished with automatically-adjusted tuners. The devices were biased to an Vgs, Vds point which corresponds to the class A operation. The output power Pout, gain G and power-added efficiency PAE as a function of the input power Pin were measured and the output power density was evaluated. As expected, the peak output power increases nearly
2. DEVICE PREPARATION

Experimental basis for the study reported here was the simultaneous fabrication of unpassivated and SiO2-passivated AlGaN/GaN HFETs and SiO2 gate insulator AlGaN/GaN MOSFETs. The material structure for all devices consisted of 3 μm thick undoped GaN and 30 nm thick undoped AlGaN layers grown on insulating 4H-SiC substrate by LPE (Cree GaN Durham). The device processing consisted of conventional FET fabrication steps. At first mesa etching isolation using argon sputtering was performed. After that ohmic contacts were prepared by evaporating multilayered Ti/Al/Ni/Au sequence followed by rapid thermal annealing at 850 °C for 30 s in a N2 ambient. The ohmic contact resistance of 0.22–0.35 Ω-mm was measured using the transmission-line method. The Schottky gate metallization consisted of a Ni/Au double-layer patterned by e-beam lithography. Devices with a gate length of 0.3 – 0.9 μm and a gate width of 100 μm and 200 μm (two fingers) were prepared. Van der Pauw patterns with an active area of 0.3 x 0.3 mm2 were processed simultaneously with HFET devices. A SiO2-layer of 10 nm nominal thickness was deposited by PECVD to fabricate the passivated HFETs. To prepare the MOSFETs, the same oxidization was chosen as for passivated HFETs and PECVD was applied as well.

3. SiO2/AlGaN/GaN HETEROSTRUCTURE CHARACTERISATION

The material structure was characterized by Hall effect measurements on van der Pauw patterns and C-V measurements on HFET devices itself. It was well known that dielectric passivation of AlGaN/GaN heterostructure compensates surface states and thus induces an increase of the sheet carrier density in the 2DEG channel [9]. This effect was confirmed on our samples investigated. Hall effect data yielded a sheet carrier density of 7.1 x 10^{12} cm^{-2} and 9.2 x 10^{12} cm^{-2} and a carrier mobility of 1835 cm²/Vs and 1670 cm²/Vs on unpassivated and SiO2-passivated material structures, respectively. The passivation induced sheet carrier density Δn = 2.1 x 10^{12} cm^{-2} and partial decrease of the mobility are in good agreement with our previous investigations (Δn = 1.5 x 10^{12} cm^{-2} after Si3N4 passivation) [9].

Figure 2 shows the capacitance-voltage characteristics for passivated AlGaN/GaN HFET and passivated SiO2/AlGaN/GaN MOSFET. The C-V curves show sharp transitions and negligible hysteresis. The sheet carrier density can be evaluated from the capacitance and threshold voltage as:

\[ n_s = C_{ox} V_{th} \]

Values of 7.6 x 10^{12} cm²/Vs and 9.2 x 10^{12} cm²/Vs for unpassivated HFET and passivated MOSFET, respectively, are in excellent agreement with values mentioned above Hall data. Similarly, from the zero-bias capacitance of HFET we can evaluate the AlGaN thickness d_{AlGaN} = t / c = 29.4 nm, considering the thickness of 30 nm from the zero-bias capacitances of HFET and MOSFET considering that:

\[ C_{HFET} = \frac{1}{C_{MOSFET}} + \left( \frac{d_{SiO2}/AlGaN/AlGaN} {\varepsilon_{AlGaN}} \right) \]

and using AlGaN and SiO2 layer permittivities ε = 9.2 and 3.9 respectively, we extracted a thickness of 12 nm. The nominal thickness of the SiO2 was 10 nm. A saturation of the MOSFET capacitance at higher gate voltages indicates that the capacitance of SiO2 insulator only is measured. Our preliminary evaluation of the SiO2 surface states density from the single-frequency capacitance and conductance measurements indicates that D_N = 1.1 x 10^{12} cm^{-2} eV^{-1}. This result is in agreement with results published before on SiO2/GaN structures [10].

4. DEVICE PERFORMANCE

It is well known that AlGaN/GaN HFETs exhibit relatively high gate leakage currents. For simple undoped and passivated AlGaN/GaN heterostructure, as used here, the gate leakage currents of about 10^4 A/mm (Vgs = -6 V) are usually observed. They can be about one order of magnitude lower if passivation is used. We reported recently that another alternative to suppress the gate current is by using undoped GaN cap on top of the heterostructure, which enhances the Schottky barrier height [5]. Leakage currents of about 10^4 A/mm were found on undoped GaN/AlGaN/GaN devices. Figure 3 (full lines) shows typical two-terminal gate-source I-V characteristics of unpassivated AlGaN/GaN HFET and passivated SiO2/AlGaN/GaN MOSFET. The data for HFET with GaN cap [5] are shown for comparison too (dashed line). Very low gate currents, ~5 x 10^{-10} A/mm at Vgs = -6 V were measured on SiO2/AlGaN/GaN MOSFETs. Nearly identical currents, 7 x 10^{-10} A/mm at Vgs = -10 V, were reported before if Si3N4 gate insulator was used [11].

Typical static output characteristics of AlGaN/GaN MOSFETs are shown in Figure 4. Low output conductance and minimal thermal effects are observed. A drain saturation current of 1.09 A/mm is obtained at 1 V on the gate. This is comparable to the value that known on state-of-the-art passivated AlGaN/GaN HFETs. The threshold voltage is close to -11 V opposed to about -6 V observed commonly on HFETs. This is expected due to additional serial capacitance of the insulator and as it follows from the C-V measurements (Figure 2). Thus, the peak extrinsic transconductance of 98, 918 mS/mm is slightly lower than reported on HFETs. For comparison, a drain saturation current of 0.75 A/mm and a peak extrinsic transconductance of 165 mS/mm were found on unpassivated HFETs processed simultaneously on similar AlGaN/GaN material structure with the same gate length.

Small signal RF characterisation of the devices was carried out on wafer S-parameter measurements up to 60 GHz. Figure 5 shows an example of the short circuit current gain (βPS) and the unilateral power gain (GU) as a function of frequency for SiO2/AlGaN/GaN MOSFET with 0.7 μm and 200 μm gate length and width, respectively. An extrinsic short external gain cut-off frequency f1 of 24 GHz and a maximum frequency of oscillation fMAX of 40 GHz are evaluated from these data measured at VDS = 15 V and VGS = -7 V biases. These are fully comparable values with those reported on state-of-the-art AlGaN/GaN HFETs. The f1/fMAX product of 16.8 GHz μm is even slightly higher than commonly reported for AlGaN/GaN HFETs [12]. This follows from lower decrease of the transconductance than of the gate capacitance for MOSFET compared to HFET. GU is proportional to the ratio of βPS and C0. The cut-off frequency ratio fMAX/f1 is a reasonable value. All these, i.e. static and small-signal microwave performance of MOSFET devices prepared, indicate on a good quality of used SiO2 without degradation of the carrier mobility in the channel. Thus, a great potential in application of GaN-based MOSFETs is documented.

Finally, microwave power measurements were performed using an on-wafer load pull measurement system. Output power sweeps of these devices were conducted at 7 GHz. Impedance matching was accomplished with automatically-adjusted tuning. The devices were biased to an VDS = 2V point which corresponds to the class A operation. The output power POUT gain G and power-added efficiency PAE as a function of the input power P Mattis measured and the output power density was evaluated. As expected, the peak output power increases nearly...
REFERENCES


CONVERSION OF DIELECTRIC DATA FROM THE TIME DOMAIN TO THE FREQUENCY DOMAIN

Vladimir Durman, Jaroslav Ležák
Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Department of Electrotechnology Illicova 3, 83219 Bratislava, Slovak Republic Phone: +421 265 201 612, Fax: +421 265 425 922, E-mail: vladimirdurman@stuba.sk

Summary: Polarization and conduction processes in dielectric systems can be identified by the time domain or the frequency domain measurements. If the system is in a linear one, the results of the time domain measurement can be transformed into the frequency domain, and vice versa. Commonly, the time domain data of the absorption conductivity are transformed into the frequency domain data of the dielectric susceptibility. In practice, the relaxation processes are mainly evaluated by the frequency domain data. In the time domain, the absorption current measurements were preferred up to now. Recent methods are based on the recovery voltage measurements. In this paper a new method of the recovery voltage data conversion from the time domain into the frequency domain is proposed. The method is based on the analysis of the recovery voltage transient based on the Maxwell equation for the current density in a dielectric. Unlike the previous published solutions, the Laplace transform used to derive a formula suitable for practical purposes. The proposed procedure allows also calculating of the insulation resistance and separating the polarisation and conduction losses.

1. INTRODUCTION

Failure-free operation of equipment for electric power production and distribution is nowadays of first-rate importance. Failures of power transformers, generators and cables caused by the insulation breakdown give rise to considerable financial losses. They also can directly or indirectly endanger a human life. Therefore researchers have developed methods for electric insulation condition assessment and prediction of insulation operation life. The general tendency in the field of diagnosis methods is the application of so-called non-destructive methods, i.e. methods that work with the voltage, which does not exceed the operational voltage of insulation systems [1]. These methods do not affect the insulation life. Frequently used is a category of methods known as the dielectric spectroscopy. The dielectric spectroscopy is based on current or voltage measurements in the time domain and also capacitance and tan δ measurements in the frequency domain. Insulation resistance is measured in parallel with application of the dielectric spectroscopy methods. The assessment of an insulating system is based obviously on evaluating its dielectric response during a long-term operation. Here, the well-known methods of absorption current and recovery voltage measurement can be used. The recovery voltage method is better resistant to the background noise, but there are still problems with evaluation of the results and their conversion into the frequency domain. This problem is treated in the next lines.

2. THEORETICAL BACKGROUND

The dynamic properties of dielectrics are usually represented by the impulse response h(t) - response of the system resulting from Dirac impulse δ(t).

Supposing that the electric field is the system input signal and the polarization P(t) is the system output signal, the system response to an arbitrary electric field E(t) is

\[ P(t) = \int_{-\infty}^{t} E(t - \tau) d\tau \]  

(1)

The electric field E(t) generates a total current density \( \mathbf{j}(t) \) which is the sum of conduction, vacuum and displacement current densities [2]:

\[ \mathbf{j}(t) = \mathbf{j}_c(t) + \mathbf{j}_d(t) + \mathbf{j}_m(t) \]

(2)

where \( \mathbf{j}_c(t) \) is the conduction current which does not depend on time or frequency. If the input signal is a step-electric field \( E_0 \), the current density is given by:

\[ \mathbf{j}_d(t) = E_0 \delta(t) \]  

(3)

The function \( \delta(t) \) is known from literature as the dielectric response of the system. As it is seen from (3), the dielectric response can be measured as a variable part of the current after application of a step voltage to the measured object. The complex dielectric susceptibility \( \chi \) is simply the Fourier transform of the dielectric response:

\[ \chi(\omega) = \mathcal{F}^{-1}\{h(t)\exp(-j\omega t)dt\} \]  

As the measurements of polarization currents in dielectrics are often influenced by noise, the measurement of recovery voltage is preferably used instead of it. During the recovery voltage measurement a constant voltage \( U_0 \) (electric field \( E_0 \)) is applied to the test object for \( 0 < t < t_1 \). This time period must be long enough for settling of all the polarization processes. In the time period \( t_1 < t < t_2 \) the object short-circuited and then it is left in open-circuit condition. The voltage on the test object