SCIENTIFIC REPORTS

OPEN

Received: 28 April 2015
Accepted: 18 August 2015
Published: 14 September 2015

AlGaN/GaN Metal-Oxide-Semiconductor High-Electron-Mobility Transistor with Polarized P(VDF-TrFE) Ferroelectric Polymer Gating

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Effect of a polarized P(VDF-TrFE) ferroelectric polymer gating on AlGaN/GaN metal-oxide-semiconductor high-electron-mobility transistors (MOS-HEMTs) was investigated. The P(VDF-TrFE) gating in the source/drain access regions of AlGaN/GaN MOS-HEMTs was positively polarized (i.e., partially positively charged hydrogen were aligned to the AlGaN surface) by an applied electric field, resulting in a shift-down of the conduction band at the AlGaN/GaN interface. This increases the 2-dimensional electron gas (2-DEG) density in the source/drain access region of the AlGaN/GaN heterostructure, and thereby reduces the source/drain series resistance. Detailed material characterization of the P(VDF-TrFE) ferroelectric film was also carried out using the atomic force microscopy (AFM), X-ray Diffraction (XRD), and ferroelectric hysteresis loop measurement.

GaN has become a very promising candidate for high voltage and high power applications[1–4], mainly due to its wide energy bandgap E_g (3.4 eV), large conduction band offset ΔE_C between $Al_xGa_{1-x}N$ and GaN (up to 1.78 eV for AlN), high two-dimensional electron gas (2-DEG) density of the order of ~1×10^{13} cm^{-2}, and high electron saturation velocity (up to 1.5×10^7 cm/s)[5–11]. Substantial progress has been made in GaN power devices with the demonstration of off-state breakdown voltages of up to several kV[12–24]. The highest off-state breakdown voltage of 10.4 kV was achieved in AlGaN/GaN high electron mobility transistors (HEMTs) on sapphire with an on-resistance R_{on} of 186 mΩ·cm^2 [25]. On the other hand, although GaN power devices, such as AlGaN/GaN HEMTs, have achieved a lower on-resistance than that of silicon devices for a given off-state breakdown voltage, they have yet to achieve an on-resistance value close to the theoretical limit of GaN. Reasons for this could be the poor contact resistance between the ohmic contact and the AlGaN/GaN layer, and relatively high sheet resistance in the source/drain access regions.

At another front, it has been reported that a ferroelectric film, such as poly[(vinylide nefluoride-co-trifluoroethylene)] [P(VDF-TrFE)] and Pb(Zr, Ti)O_3 (PZT), with a large remnant polarization P_r can modulate the 2-DEG density of the AlGaN/GaN heterostructure, without degrading the

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Ferroelectric material	P(VDF-TrFE)	$PbTiO_3$	$SrBi_2Nb_2O_9$	$BiFeO_3$
Remnant Polarization P_r (mC/cm^2)	4.8	53	11.46	95
Coercive Field E_C (MV/cm)	1.2	0.75	0.034	0.012
Deposition Method	Spin coating	MBE[1]	PLD[2]	LDMOCVD[3]
Deposition Temperature (°C)	25	600 ~ 650	400	630
Reference	This work	28	29	30

Table 1. Comparison of P(VDF-TrFE) with other ferroelectric materials. Liu *et al.* [1]MBE: Molecular Beam Epitaxy. [2]PLD: Pulsed Laser Deposition. [3]LDMOCVD: Liquid Delivery Metal Organic Chemical Vapor Deposition.

carrier transport within AlGaN/GaN heterostructure[26,27]. As shown in Ref. 26 and 27, the carrier density of AlGaN/GaN heterostructure with P(VDF-TrFE) or PZT can be significantly modulated by changing the external electric field. However, the effect of integrating P(VDF-TrFE) or PZT gating into AlGaN/GaN HEMTs (at a device level) has not been investigated so far. As shown in Table 1, compared to other ferroelectric materials ($PbTiO_3$, $SrBiNb_2O_9$, and $BiFeO_3$), P(VDF-TrFE) has a large coercive field E_C of 1.2 MV/cm and a large remnant polarization P_r of 4.8 μC/cm^2. Especially, P(VDF-TrFE) can be deposited at a room temperature using a cost-effective spin coating method, as compared to other ferroelectric materials, which require a sophisticated vacuum system with a high temperature process, such as molecular beam epitaxy (MBE), liquid delivery metal organic chemical vapor deposition (LDMOCVD) etc. The advantage of depositing the P(VDF-TrFE) film at room temperature by spin-coating is to avoid the interfacial diffusion and chemical reaction between P(VDF-TrFE) and the underlying AlGaN layer, which normally happens in a high temperature deposition process[28–30]. These make P(VDF-TrFE) as an attractive material which can be integrated into the AlGaN/GaN HEMTs for performance enhancement. The ferroelectricity of the P(VDF-TrFE) film originates from the molecular dipoles associated with partially positively charged hydrogen (H) and partially negatively charged fluorine (F). The all-trans conformation of chain molecules and their parallel packing cause the alignment of all molecular dipoles in one direction, inducing a large spontaneous polarization when an external field is applied. The large coercive field of the P(VDF-TrFE) film also requires a large depolarization field to flip the dipole direction and ensures dipole stability.

In this article, the P(VDF-TrFE) ferroelectric polymer gating was applied on the AlGaN/GaN metal-oxide-semiconductor high-electron-mobility transistors (MOS-HEMTs) for the first time for the reduction of source/drain series resistance. The P(VDF-TrFE) film was deposited over the AlGaN/GaN MOS-HEMTs, and the P(VDF-TrFE) film in the source/drain access regions was positively polarized (i.e., partially positively charged hydrogen was aligned to the AlGaN surface) by an applied external electric field. When the P(VDF-TrFE) film is polarized, the aligned positively charged H can shift down the conduction band of the AlGaN/GaN heterostructure and increase the 2-DEG density, similar to the effect of a GaN/AlN/GaN triple cap layer on the AlGaN/GaN heterostructure[31–32]. Compared to the device with unpolarized P(VDF-TrFE) film, the source/drain series resistance $R_{S/D}$ for device with polarized P(VDF-TrFE) film was reduced by 16%.

Results and Discussion

Circular test structures made of Au (80 nm)/P(VDF-TrFE) (500 nm)/Au (80 nm)/Si wafer were fabricated together with the AlGaN/GaN MOS-HEMTs. These test structures were used to measure the leakage current and the polarization of the P(VDF-TrFE) film. Figure 1(a) shows the schematics of these test structures and the β-phase P(VDF-TrFE), where partially negatively charged F and partially positively charged H of P(VDF-TrFE) are separately aligned on the opposite sides of the carbon molecular chain. The top view of the optical image of one of the test structure is also shown in Fig. 1(a). The P(VDF-TrFE) test structure was baked at 135 °C for 20 hours to form the crystalline β-phase P(VDF-TrFE), which was confirmed by a X-Ray Diffraction (XRD) scan as shown in Fig. 1(b). A strong peak with a full width at half maximum (FWHM) of 0.6° located at ~20° in the XRD scan indicates the formation of β-phase P(VDF-TrFE). In addition, the surface morphology of the P(VDF-TrFE) film was characterized using Atomic Force Microscopy (AFM). Based on the area size of 3 μm by 3 μm, the P(VDF-TrFE) film has a root-mean-square (RMS) roughness of 5 nm [inset of Fig. 1(b)]. The leakage current of the P(VDF-TrFE) test structure remained around 4.3×10^{-9} A when a voltage of 50 V was applied between the top and bottom electrodes Fig. 1(c). A low leakage current of the P(VDF-TrFE) film is essential for integration in the AlGaN/GaN MOS-HEMTs. Otherwise, surface leakage through the P(VDF-TrFE) film can degrade the device performance. Ferroelectric hysteresis loops of P(VDF-TrFE) was measured as a function of drive voltage as shown in Fig. 1(d). This was performed on the test structure by using a Radiant Technology Precision LC. From Fig. 1(d), remnant polarization P_r of 4.8 μC/cm^2 (~charge density of 3.0×10^{13} cm^{-2}) and coercive voltage V_c of 60 V were obtained. These values are close to the previously reported ones[33–34].

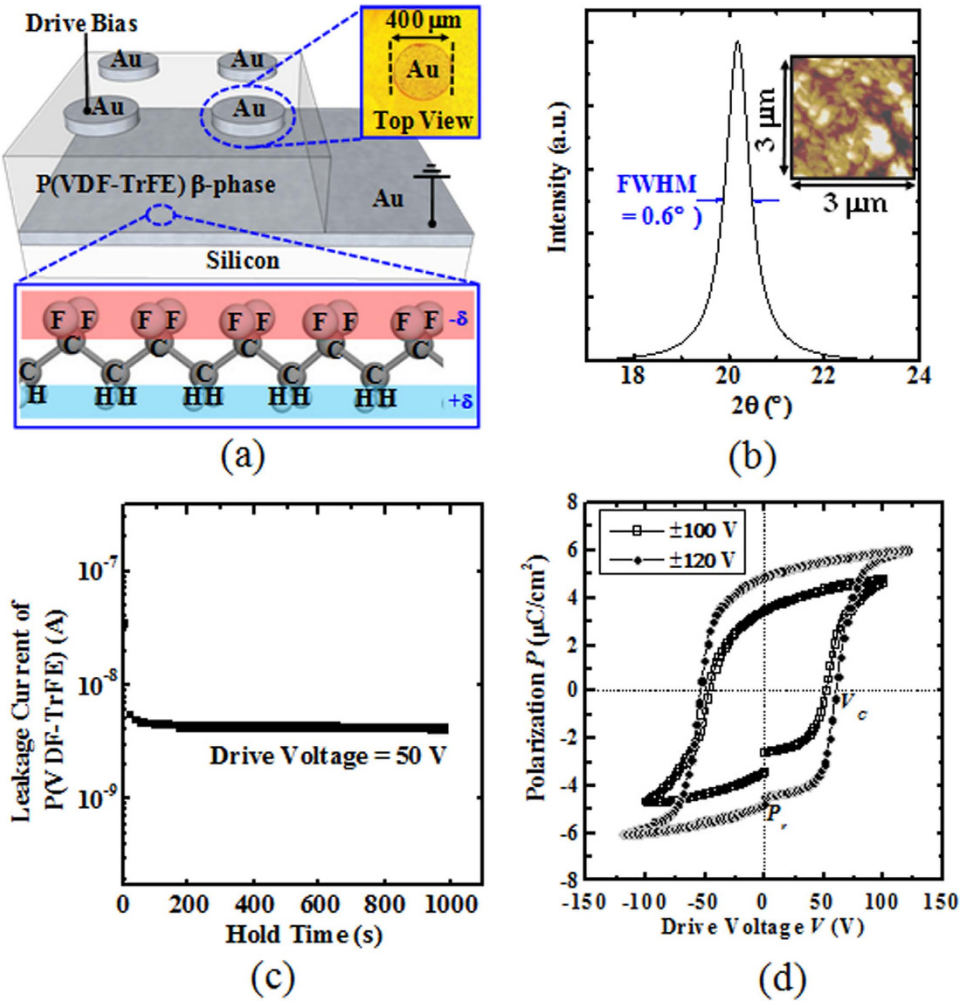

Figure 1. (**a**) Schematic of a P(VDF-TrFE) test structure: Au/P(VDF-TrFE)/Au/Si (The diameter *d* of the Au pad is 400 μm). Top-view of the test structure obtained by optical microscope is shown at the top-right corner. A schematic of the β-phase P(VDF-TrFE) is also shown at the bottom. (**b**) XRD and AFM (inset) scans of the P(VDF-TrFE) film after baking at 135 °C for 20 hours. A strong peak with a full width at half maximum (FWHM) of 0.6° located at ~20° indicates the formation of β-phase P(VDF-TrFE). The AFM scan shows the P(VDF-TrFE) film surface with a root-mean-square (RMS) roughness of 5 nm. (**c**) Leakage current of P(VDF-TrFE) measured using a Au/P(VDF-TrFE)/Au/Si test structure. The leakage current of P(VDF-TrFE) as a function of time was measured with a bias of 50 V applied between the top and bottom electrodes. (**d**) Polarization charge as a function of drive voltage ($P - V$) for the Au/P(VDF-TrFE)/Au/Si test structure. Remnant polarization P_r and coercive voltage V_c are 4.8 μC/cm^2 and 60 V, respectively. The coercive field is E_c 1.2 MV/cm.

As illustrated in Fig. 2(a), the P(VDF-TrFE) molecular dipoles are normally randomly distributed without polarization (i.e., partially positively charged H and partially negatively charged F are randomly aligned with respect to the AlGaN surface). Upon applying an external electric field across the P(VDF-TrFE) film (gold electrode is grounded and source/drain pads are negatively biased), partially positively charged H will be aligned to the AlGaN surface, resulting in a large spontaneous polarization which can increase the 2-DEG density of AlGaN/GaN heterostructure in the access regions [$n_1 > n_0$ as shown in Fig. 2(b)]. In order to understand the effect of the polarized P(VDF-TrFE) film on 2-DEG density, TCAD simulations were performed. The energy band diagram along the line AB [as shown in Fig. 2(a,b)] was examined for the AlGaN/GaN heterostructure with both polarized and unpolarized P(VDF-TrFE) films. Energy band alignments for the $Al_{0.25}Ga_{0.75}N$/GaN heterostructure along the blue line AB with unpolarized (solid lines) and polarized (dash lines) P(VDF-TrFE) film, calculated using the Synopsys Sentaurus simulator, is shown in Fig. 2(c). The polarized partially positively charged H of P(VDF-TrFE) film were treated as fixed positive charges with a density of 3.0×10^{13} cm^{-2} (~remnant polarization P_r of 4.8 μC/cm^2) on the AlGaN surface in Fig. 2(c). Upon the application of an external electric field, the conduction band of AlGaN layer was bent downward due to the polarization of the

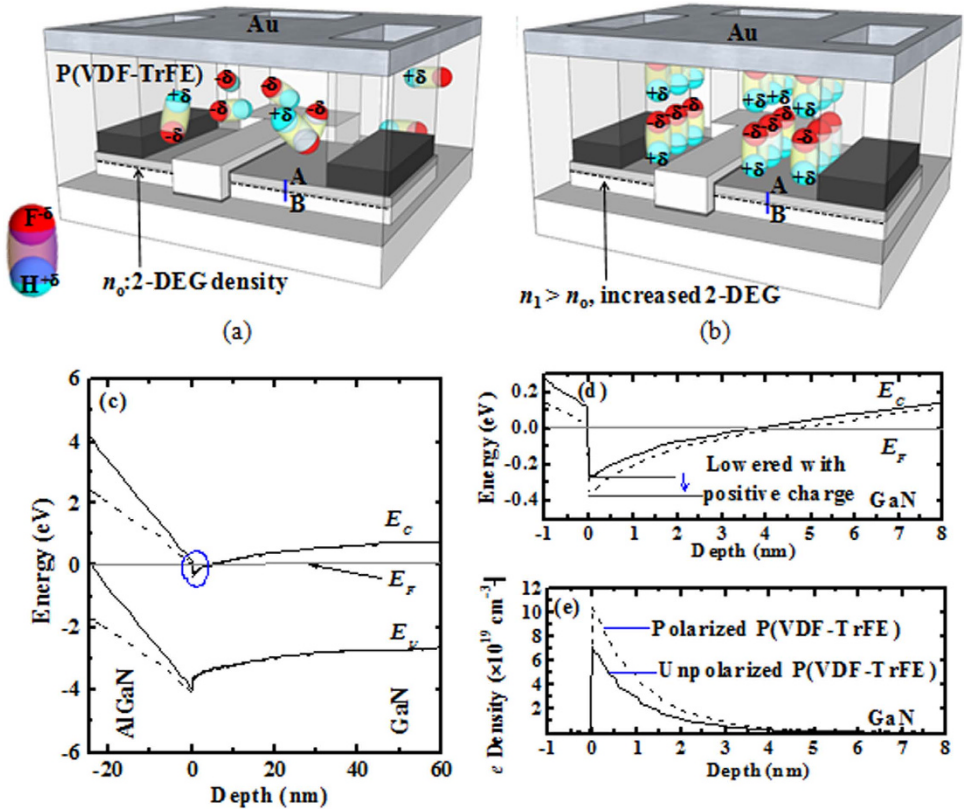

Figure 2. (**a**) Schematic of an AlGaN/GaN MOS-HEMT with an overlaying P(VDF-TrFE) film and a gold (Au) electrode. Without polarization, the dipoles in the P(VDF-TrFE) film are randomly distributed. The 2-DEG density of AlGaN/GaN heterostructure without polarization is n_0. (**b**) Schematic of AlGaN/GaN MOS-HEMTs with a positively polarized P(VDF-TrFE) film (i.e. positively charged H atoms aligned to the AlGaN surface). The 2-DEG density with polarization for AlGaN/GaN heterostructure is n_1, which is larger than the value of n_0 as shown in (**a**). (**c**) Energy band diagram of the $Al_{0.25}Ga_{0.75}N$/GaN heterostructure from a TCAD simulation (Synopsys Sentaurus simulator) along the blue line AB [shown in Fig. 1(a,b)] with unpolarized (solid lines) and positively polarized (dash lines) P(VDF-TrFE) gating (Positive charge density 3.0×10^{13} cm^{-2} on the AlGaN surface is used in the calculation here). (**d**) Zoomed-in band alignment and (**e**) Electron distribution profile of the circled region in Fig. 1(c) in the access region of the AlGaN/GaN MOS-HEMT with unpolarized (solid lines) and polarized (dash lines) P(VDF-TrFE) gating.

P(VDF-TrFE) film. The zoomed-in view of the circled region in Fig. 2(c) is shown in Fig. Figure 2(d). The conduction band in both AlGaN and GaN regions is lowered, thereby increasing the 2-DEG density in the triangular quantum well at the AlGaN/GaN interface[35]. In addition, the electron distribution profiles for both cases are shown in Fig. 2(e). The electron density was enhanced after polarizing the P(VDF-TrFE) film. The 2-DEG density was obtained by integrating the electron density along the depth from AlGaN/GaN interface as shown in Fig. 2(e). In Fig. 3(a), the 2-DEG density was plotted as a function of the positive charge density on the AlGaN surface, and 2-DEG density is about $13.6 \times 10^{13}\,cm^{-2}$ for the positive charge density of $3.0 \times 10^{13}\,cm^{-2}$. With a larger amount of the polarized positive charge in P(VDF-TrFE) film over the AlGaN/GaN access regions, the 2-DEG density was further increased.

In following section, the electrical results of the AlGaN/GaN MOS-HEMTs with unpolarized and polarized P(VDF-TrFE) gating will be discussed. First of all, the P(VDF-TrFE) film was polarized by an applied external electric field. This was achieved by grounding the Au electrode, and applying a drive voltage on the source/drain pads. The drive voltage was swept first from 0 V to the positive maximum voltage, then back to negative maximum voltage, and then to 0 V, so that the electropositive H atoms can be aligned to the AlGaN surface. The applied voltage should be larger than the coercive voltage of 60 V for P(VDF-TrFE), so that the P(VDF-TrFE) film can be polarized. The maximum applied drive voltage on the source/drain pads was ± 120 V. Ferroelectric hysteresis loops of the P(VDF-TrFE) film on AlGaN/GaN MOS-HEMTs were measured and shown in Fig. 3(b). As shown in Fig. 3(b), the measured remnant polarization P_r of P(VDF-TrFE) on the AlGaN/GaN MOS-HEMTs is around 2.5 μC/cm^2, which is smaller than the 4.8 μC/cm^2 obtained from the P(VDF-TrFE) test structure. This could be due to the asymmetry of the electrodes used (one is Au and the other is Ti/Al pad), as compared to those used in the P(VDF-TrFE) test structure[36].

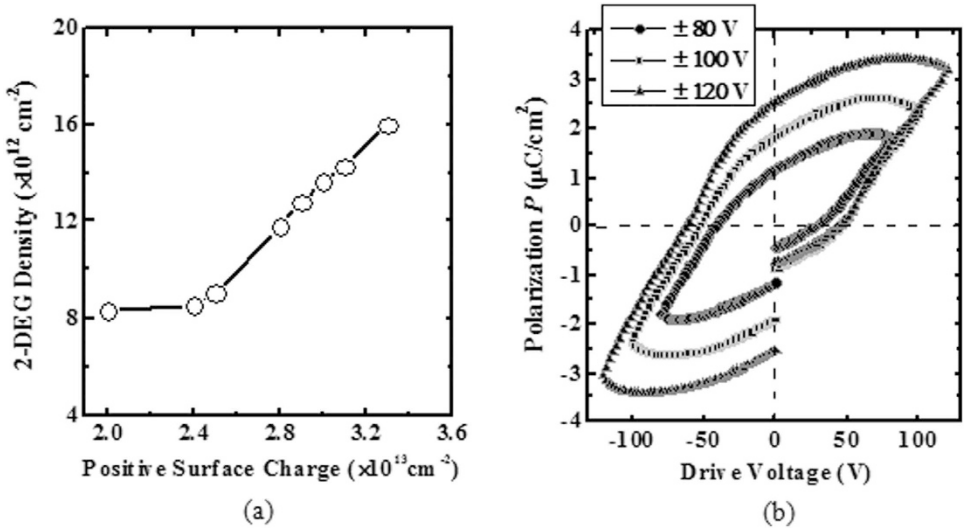

Figure 3. (**a**) Simulated 2-DEG density for $Al_{0.25}Ga_{0.75}N$(25 nm)/GaN heterostructure as a function of positive charge density on the AlGaN surface. (**b**) Polarization as a function of drive voltage (P – V), for AlGaN/GaN MOS-HEMTs with P(VDF-TrFE) gating. The voltage is biased between the Au electrode (grounded) and the source/drain pads. The Au electrode was grounded, and the drive voltage applied on the source/drain pads was swept from 0 V to the positive maximum voltage, then back to the negative maximum voltage, and then to 0 V.

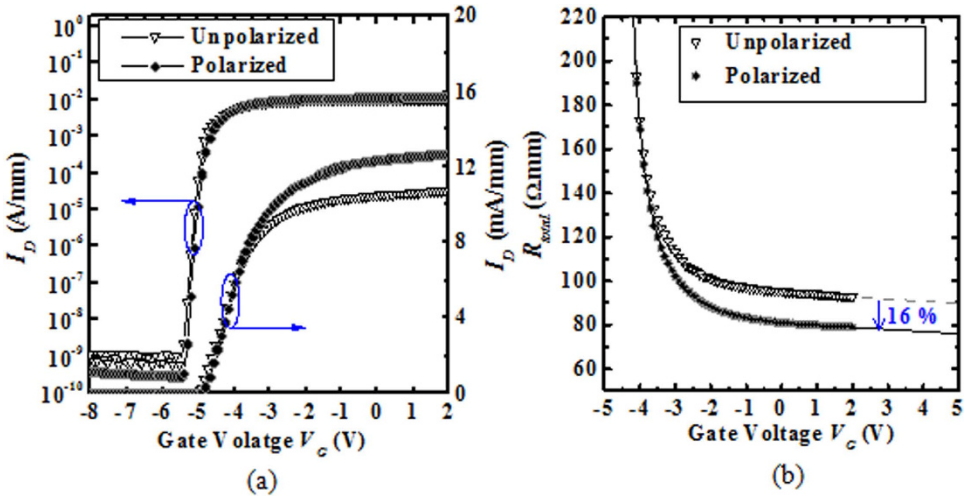

Figure 4. (**a**) I_D – V_G (left: semi-log scale, and right: linear scale) transfer characteristics at $V_D = 1$ V of AlGaN/GaN MOS-HEMTs with unpolarized and (±120 V) polarized P(VDF-TrFE) gating. V_{th} is −4.8 V for both devices. Both polarized and unpolarized results came from the same device. (b)Total resistance R_{Total} ($V_D = 1$ V) as a function of gate voltage V_G for AlGaN/GaN MOS-HEMTs with unpolarized and (±120 V) polarized P(VDF-TrFE) gating.

Figure 4(a) shows the I_D – V_G transfer characteristics of the AlGaN/GaN MOS-HEMTs with unpolarized and (±120 V) polarized P(VDF-TrFE) gating. The sub-threshold swing S did not degrade after the polarization of the P(VDF-TrFE) gating, which is 80 mV/decade in each case. There is also no change in the threshold voltage V_{th}, which is around −4.8 V for both cases. This is expected since the polarization of the P(VDF-TrFE) gating only modulates the 2-DEG density in the access regions. The total resistance R_{Total} is defined here as the resistance measured between the source and drain pads of the device using a small drain voltage (say $V_D = 1$ V) and under a large applied gate voltage V_G. The value of the source/drain series resistance $R_{S/D}$ is defined as $R_{S/D} = R_{Total} - R_{Channel}$, where $R_{Channel}$ is the resistance of the channel under the gate. For a very large gate-overdrive V_G - V_{th} (V_G -$V_{th} \gg V_D$) with a small fixed V_D, $R_{Channel}$ becomes very small compared to $R_{S/D}$, and $R_{S/D}$ can be estimated from the R_{Total} versus V_G plot. As shown in Fig. 4(b), the source/drain series resistance $R_{S/D}$ is reduced from 90.8 Ω.mm to 76.7 Ω.mm

after polarizing P(VDF-TrFE) gating, or by 16% for the AlGaN/GaN MOS-HEMTs with the (±120 V) polarized P(VDF-TrFE) gating, as compared to that of the AlGaN/GaN MOS-HEMTs with the unpolarized P(VDF-TrFE) gating.

$R_{S/D}$, which is attributed by the contact resistance and the resistance of the source/drain access region, can be estimated using the equation below:

$$R_{S/D} = 2R_C + R_{sh}\left(\frac{2L_T + L_{GS} + L_{GD}}{W}\right)W, \quad (1)$$

where R_C is the contact resistance, R_{sh} is the sheet resistance of source/drain access region, L_T is the transfer length from source and drain contact pads, and W is the device width (70 μm). From the fabricated transmission line method (TLM) test structure without the P(VDF-TrFE) film, a contact resistance R_C of 10.8 Ω.mm and a transfer length L_T of 29 μm were obtained[37]. Here, it is assumed that the contact resistance R_C was not affected by the P(VDF-TrFE) film, since the P(VDF-TrFE) gating is used to modulate only the resistance of the source/drain access region. With a known source/drain series resistance $R_{S/D}$, a contact resistance R_C, and a transfer length L_T, the sheet resistance R_{sh} of source/drain access region for the AlGaN/GaN MOS-HEMTs with unpolarized and (±120 V) polarized P(VDF-TrFE) gating can be estimated to be 887 Ω/□ and 706 Ω/□, respectively, using the Equation (1). The bulk resistivity can be estimated by using the following Equation:

$$\rho = 1/(n_s \mu e), \quad (2)$$

where ρ is the bulk resistivity, n_s is the carrier density, μ is the carrier mobility, and e is the magnitude of electronic charge[38]. The bulk resistivity $\rho_0$of the AlGaN/GaN heterostructure without the P(VDF-TrFE) gating is estimated to be 488 Ω.cm using Equation (2), with a given electron mobility μ_n of 1600 $cm^2/V{\cdot}s$ and the[2]-DEG density n_s of 8×10^{12} cm^{-2}. Since the sheet resistance R_{sh} is proportional to the resistivity ρ, resistivity $\rho_1$of AlGaN/GaN heterostructure with the polarized P(VDF-TrFE) gating can be estimated using the relationship below:

$$\rho_1 = \rho_0(R_{sh1}/R_{sh0}), \quad (3)$$

where R_{sh0} is the sheet resistance of AlGaN/GaN heterostructure without the P(VDF-TrFE) gating and R_{sh1} is the sheet resistance of AlGaN/GaN heterostructure with the polarized P(VDF-TrFE) gating. The bulk resistivity ρ_1 is calculated to be 388 Ω.cm using Equation (3). Using the simulated 2-DEG density n_s of 13.6×10^{12} cm^{-2} and the calculated resistivity of 388 Ω.cm for the AlGaN/GaN MOS-HEMTs with the polarized P(VDF-TrFE) gating, its electron mobility can be estimated to be 1184 $cm^2/V{\cdot}s$. This is smaller than that of the device with the non-polarized P(VDF-TrFE) gating. The polarized P(VDF-TrFE) gating in the source/drain access region not only increases the 2-DEG density, but also decreases the electron mobility, which could be attributed to an increase of electron-eletron columb scateering within the 2-DEG channel. Depending on the roughness of the AlGaN/GaN interface, the decrease of electron mobility at very high 2-DEG density (more than 10^{13} cm^{-2}) could be due to an increase in the interface roughness scattering, since the average distance of the 2-DEG to the AlGaN/GaN interface becomes smaller for a very high 2-DEG density[39].

Source/drain series resistance reduction for AlGaN/GaN MOS-HEMTs using a polarized P(VDF-TrFE) ferroelectric polymer gating in the access regions is reported in this work for the first time. A crystalline β-phase P(VDF-TrFE) film was formed after baking at 135 °C for 20 hours, and large remnant polarization and high coercive voltage for P(VDF-TrFE) were obtained. For the AlGaN/GaN MOS-HEMTs with a positively polarized P(VDF-TrFE) polymer gating, the conduction band of AlGaN layer is shifted downward due to the polarization of the P(VDF-TrFE) film, resulting in the lowering of the conduction band at AlGaN/GaN interface, thereby increasing the 2-DEG density in the triangular quantum well. The effect of the polarized P(VDF-TrFE) gating in the source/drain access region not only increases the 2-DEG density, but also decreases the electron mobility possibly due to increased AlGaN/GaN interfacial scattering or electron-electron coulomb scattering. Overall, however, the total series resistance is reduced for the AlGaN/GaN MOS-HEMTs with the positively polarized P(VDF-TrFE) gating. To conclude, series resistance reduction can be achieved in AlGaN/GaN MOS-HEMT using a polarized P(VDF-TrFE) gating.

Methods

Preparation and characterization of P(VDF-TrFE) film. The P(VDF-TrFE) solutions (3 wt%) were prepared by dissolving P(VDF-TrFE) (70/30% mol) powder in mixed solvent of dimethylformamide (DMF) and Acetone(50: 50 in volume). The solutions were stirring at 1000 rpm for 2 hours at 50 °C on the hot plate. The thin films were deposited by spin coating the solutions at 1000 rpm for 20 s. The thin films were dried at 70 °C for one hour then transferred to oven and bake at 135 °C for 20 hours to form β-phase. AFM and XRD were employed to characterize the surface morphology and crystal structure of P(VDF-TrFE) films.

Fabrication and characterization of AlGaN/GaN MOS-HEMTs. The AlGaN/GaN structure was grown by metal-organic chemical vapor phase deposition (MOCVD) on a 2-inch sapphire substrate. The epitaxial layers consist of a 25 nm undoped $Al_{0.25}Ga_{0.75}N$ barrier layer formed on a 2.7 μm undoped GaN layer, which was grown on a 300 nm Fe-doped GaN buffer layer. The electron Hall mobility μ_n and the 2-DEG density n_s were measured to be 1600 $cm^2/V{\cdot}s$ and $8 \times 10^{12}\,cm^{-2}$, respectively. The fabrication process includs mesa isolattion by Cl_2 (10 sccm)/BCl_3 (20 sccm) reactive ion etching (RIE), gate dielectric deposition (15 nm Al_2O_3) by atomic layer deposition (ALD), gate metal (100 nm TaN) by magnetron sputtering system, gate electrode definition using standard photolithography, the source/drain contacts [Ti (20 nm)/Al (120 nm)/Ti (10 nm)/Pt (100 nm)] deposition by E-beam, alloying process (650 °C, 30 s) in N_2 ambient. P(VDF-TrFE) with a 75/25 molar ratio was spin-coated on the devices and baked at 135 °C for 20 hours. An 80 nm-thick gold (Au) film was then deposited by sputtering and patterned as an electrode for the P(VDF-TrFE). Gold is a chemically inert metal, and can avoid the reaction with the P(VDF-TrFE) film to form an non-ferroelectric layer near the interface between gold and the P(VDF-TrFE)[40]. The device in this work has a gate length L_G of 2 μm, a gate-to-source distance L_{GS} of 5 μm and a gate-to-drain distance L_{GD} of 15 μm. The ferroelectric hysteretic measurement on the test structure and devices were performed by using Radiant Technology Precision LC.

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Acknowledgements

The authors would like to acknowledge the financial support from National Natural Science Foundation of China (Nos. 61504083, 51371120, 51302174, 61306126, and 21104045), the Science and Technology Foundation of Shenzhen (JCYJ20140418095735601), Science and Technology Commission of Shanghai Municipality (project number: 12ZR1453000), Nanshan District Key Lab for Biopolymer and Safety Evaluation (No.KC2014ZDZJ0001A), National Science Foundation of Shenzhen University (grant no.201501), Natural Science Foundation of Shenzhen University (grant no. 000062), and the Special Research Foundation of Shenzhen Oversea High-level Talents for Innovation and Entrepreneurship (Grant No. KQCX20120807153115869).

Author Contributions

X. Liu and J. Wu fabricated the device and wrote the manuscript. J. He and D. Tang performed the electrical measurements. Z. Liu and P. S/O Somasuntharam did the simulation work, and D. Zhu, W. Liu, P. Cao and S. Han helped in preparation of PVDF materials. L.S. Tan helped in the result discussion. Y. Lu, W. Yu and S. Chen supervised the project. All the authors discussed the results and reviewed the manuscript.

Additional Information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Liu, X. *et al.* AlGaN/GaN Metal-Oxide-Semiconductor High-Electron-Mobility Transistor with Polarized P(VDF-TrFE) Ferroelectric Polymer Gating. *Sci. Rep.* **5**, 14092; doi: 10.1038/srep14092 (2015).