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AlN metal-semiconductor field-effect transistors using Si-ion implantation

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Abstract
We report on the electrical characterization of Si-ion implanted AlN films and demonstration of AlN channel metal-semiconductor field-effect transistors (MESFETs). The ion-implanted AlN films with Si dose of 5×10^{14} cm^{-2} exhibit n-type characteristics after annealing for surface temperatures over 1230°C. The ion-implanted AlN MESFETs provide good drain current saturation and stable pinch-off operation even at 250°C. The breakdown voltage is 2370 V for drain-to-gate spacing of 25 μm. These results show the great potential of AlN-channel transistors for high-temperature and high-power applications beyond GaN electronics.

1. Introduction

AlN is an attractive material for high-temperature and high-power applications due to its high critical electric field (E_c) of 12 MV/cm, high thermal conductivity of 320 W/cmK, and a high band-gap energy of 6 eV. Despite these excellent material properties, AlN-channel transistors have not been reported yet. Dislike GaN, AlN allows no polarization induced doping to generate electron conduction due to the lack of suitable higher band-gap materials for hetero-structures. The formation of an AlN channel requires impurity-doped AlN films. In this study, we report on the electrical characterization of Si-ion implanted AlN films and the first demonstration of AlN-channel transistors using a metal-semiconductor field-effect transistor (MESFET) architecture.

2. Si-ion implantation into AlN

High Si dose between 5×10^{14} and 1×10^{16} cm^{-2} was implanted into 1-μm-thick AlN films grown on sapphire by metal-organic vapor-phase epitaxy. To recover the ion-implantation damage, the AlN films were thermally annealed between 1160 and 1800°C in a nitrogen ambient.

Surface morphology

Despite no protective caps, the annealed AlN films with Si dose below 2×10^{15} cm^{-2} had small surface roughness (less than 1 nm (rms)) (Fig. 1 (b)). On the other hand, the AlN films annealed at 1600°C had a step-and-terrace structure due to partial decomposition of AlN surfaces (Fig. 1 (c)). Finally, the 1800°C annealing caused numerous cracks in the AlN films. The AlN films with a Si dose of 1×10^{16} cm^{-2}, or average Si density of 8×10^{20} cm^{-3}, showed a surface roughness of 13 nm (rms) after thermal annealing at 1230°C due to ion-implanted damage (Fig. 1 (e)).

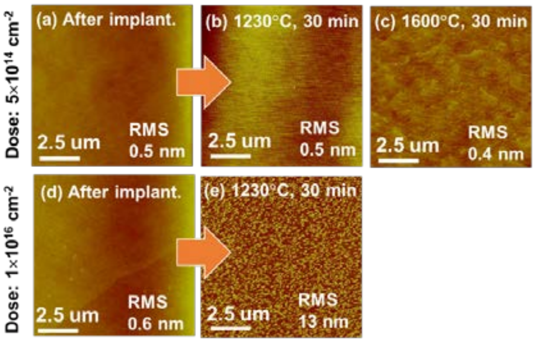

Fig. 1: Surface morphologies of ion implanted AlN films before annealing for Si-dose of (a) 5×10^{14} cm^{-2} and (d) 1×10^{16} cm^{-2}, and after annealing at (b) 1230°C, (c) 1600°C for Si-dose of 5×10^{14} cm^{-2}, and (e) 1230°C for Si-dose of 5×10^{14} cm^{-2}.

Electrical performance

After the Si implantation and activation annealing, the AlN samples where dipped HCl for 1 min, a Ti/Al/Ni/Au metal stack was deposited, followed by annealing at 800°C for 30s in a N_2 ambient for contacts. A 200-nm-deep mesa isolation was performed by Cl_2-based reactive-ion etching.

The ion-implanted AlN films with a high dose > 1×10^{15} cm^{-2} were insulating even after high temperature annealing of 1700°C (Tab.I). On the other hand, the ion-implanted AlN films with a Si dose of 5×10^{14} cm^{-2} showed n-type conductance after annealing between 1230 and 1600°C, in good agreement with other reports [1]. Annealing temperatures of 1160°C were too low to recover the implantation damages, while 1800°C decomposes AlN at 8 nm/min. This decomposition may be prevented by using suitable cap materials.

Table I: Conditions of Si-ion implantation and annealing for AlN

Ion-dose density (cm^{-2})	Incident angle (degree)	Average Si density (cm^{-3})	Annealed temperature (°C)	Electrical property
5×10^{14}	7	4×10^{19}	**1160**	Insulator
5×10^{14}	7	4×10^{19}	**1230**	Conductive
5×10^{14}	7	1×10^{19}	**1600**	Conductive
5×10^{14}	7	7×10^{18}	**1800**	Insulator
$\mathbf{1\times10^{15}}$	5	5×10^{19}	1230	Insulator
$\mathbf{2\times10^{15}}$	0	5×10^{19}	1230	Insulator
$\mathbf{2\times10^{15}}$	0	3×10^{19}	1700	Insulator

After the thermal annealing at 1230°C, the 100-nm-thick ion-implanted AlN films with a Si dose of 5×10^{14} cm^{-2} , or the average Si density of 4×10^{19} cm^{-3}, showed an electron mobility (μ_s) of 130 cm^2/Vs and electron concentration (n_s) of 6×10^{13} cm^{-3}, which were determined at room temperature by Hall-effect measurements. The very low electron concentration are mainly attributed to the high Si ionization energy of 0.3 eV at room temperature [2].

Ion-implanted AlN films annealed at 1600°C showed up to 300 nm Si diffusion, which reduced the average Si density to 1×10^{19} cm^{-3}. The current-voltage curve of transmission-line method (TLM) patterns were measured. The ion-implanted AlN films annealed at 1600°C showed an ohmic behavior (Fig. 2 (a)). The specific contact resistivity and sheet resistance are estimated to be 2×10^{-3} Ωcm^2 and 2×10^{5} Ω/sq, respectively, from Fig. 2 (b). The optimization of the metal structure and alloy annealing conditions is expected to further reduce the contact resistance.

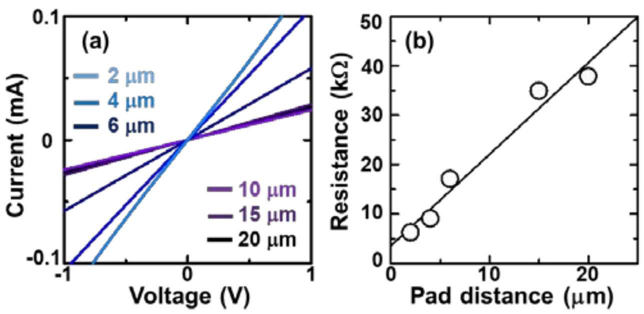

Fig. 2: (a) Current-voltage characteristics of TLM pattern and (b) extracted resistance plotted versus pad distances for Si-ion implanted AlN films annealed at 1600°C.

3. Device characteristics

AlN MESFETs were fabricated using the ion-implanted AlN films with a Si dose of 5×10^{14} cm^{-2} after annealing at 1230°C (Fig. 3 (a)). The AlN MESFETs have a normally-on operation and sharp pinch-off characteristics for gate voltage < -10 V. The drain current in these devices is effectively modulated by gate voltages and shows good saturation (Fig. 3 (b)). The maximum drain current, transistor on/off ratio, and maximum transconductance were 9×10^{-6} A/mm, above 100, and 7×10^{-7} S/mm, respectively. The limited transistor on/off ratio of the AlN MESFETs arise from the high source/drain contact resistance.

The AlN MESFETs provide good drain current saturation and stable pinch-off operation even at 250°C (Fig. 3 (c)). The maximum three-terminal breakdown voltage at room temperature was 2370 V for a gate-drain length of 25 µm (Fig. 3 (d)). The leakage current was below 3×10^{-7} A/mm at 2000 V. The effective E_c of the three terminal breakdown is 1.0 MV/cm, which is higher than GaN-channel transistors due to the high E_c of AlN. Further high breakdown voltage of the AlN MESFETs are expected in devices with a field-plate structure. These results show the great potential of AlN-channel transistors for high-temperature and high-power applications.

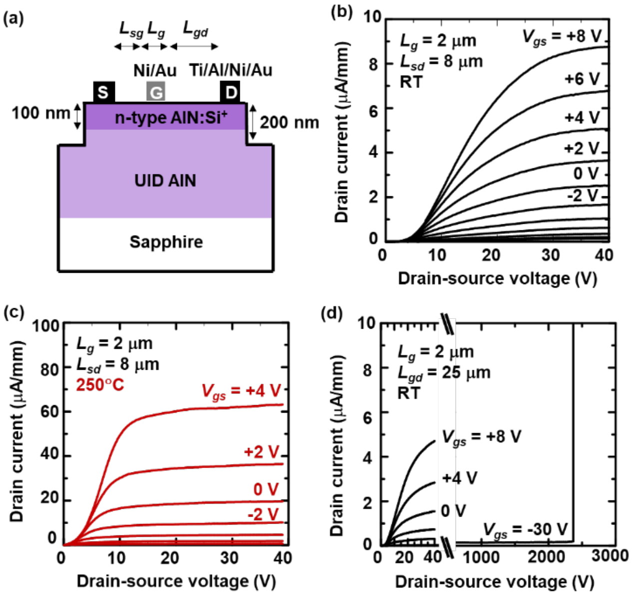

Fig. 3: (a) Schematic of AlN MESFETs by Si-ion implantation. DC output characteristics of ion-implanted AlN MESFET at (b) room temperature and (c) 250°C. three-terminal breakdown voltage eas a function of gate-to-drain spacing at room temperature.

4. Conclusions

We report on the electrical characteristics of Si-ion implanted AlN and demonstration of an ion-implanted AlN MESFETs. The ion-implanted AlN layers with Si dose of 5×10^{14} cm^{-2} exhibited n-type characteristics after thermal annealing over 1230°C in a nitrogen ambient, showing the sheet carrier concentration of 6×10^{8} cm^{-2} and an electron mobility of 130 cm^2/Vs. Ion-implanted AlN MESFETs with a gate length of 2 µm have a maximum drain current of 8.7 µA/mm for gate voltage of +8 V and an on/off current ratio over 100 at room temperature. The AlN MESFETs can be further improved by reduction of the source/drain contact resistances and increase of the carrier concentrations in the AlN channel layer. At 250°C, excellent transistor pinch-off is achieved without permanent degradation. The maximum three-terminal breakdown voltage is 2370 V for drain-to-gate spacing of 25 µm. The AlN-channel transistors show promise as high-temperature and high-power devices.

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References

[1] M. Kanechika & T. Kachi, Appl. Phys. Lett. **88**, 202106 (2006).
[2] Y. Taniyasu, M. Kasu, and T. Makimoto, Appl. Phys. Lett. **89**, 182112 (2006).