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Doping Design and Two-Dimensional Electron Gas Density in AlGaN/GaN Heterostructure Field-Effect Transistors for High-Power Applications

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1. Introduction

AlGaN/GaN heterostructure field-effect transistors (HFETs) have recently emerged as the attractive transistors suitable for high-temperature and high-power microwave applications. Since the significant advantage of AlGaN/GaN HFETs for high-power applications is ascribed to their high two-dimensional electron gas (2DEG) density due to the large polarization effects [1-3], increasing the 2DEG density is indispensable for further improving high-power device performance. Understanding the 2DEG properties in the HFETs with thin AlGaN barrier layers is especially important, because reducing the AlGaN barrier thickness is inevitably required for higher device performance. From this point of view, we have investigated the doping design and the 2DEG densities in the HFETs with thin AlGaN layers.

A critical problem not to be fully utilized the high 2DEG capacity has been revealed in the conventional modulation doping (MD) design for the HFETs with thin AlGaN layers. Moreover, a back-doping (BD) design has been proposed that makes it possible to obtain high 2DEG densities in the HFETs with thin AlGaN layers.

2. Results and Discussion

2.1 2DEG Density and AlGaN Barrier Thickness

All the HFET samples in the present report were grown on SiC(0001) substrate by low-pressure metal organic vapor phase epitaxy (MOVPE) at 300 Torr. Figure 1 shows the relation between the 2DEG density and the AlGaN barrier thickness in undoped $Al_{0.3}Ga_{0.7}N$/GaN HFETs, indicating that the 2DEG density decreases with decreasing the AlGaN layer thickness (d). The 2DEG density for d=120 Å is shown to be reduced to $7x10^{12}$ cm^{-2}, although that for d=250 Å is as high as $1.4x10^{13}$ cm^{-2}.

Although we can increase the 2DEG density by performing carrier doping into AlGaN layers for any HFET, however, carrier doping should be less effective for the HFETs with thinner AlGaN layers because the possible amount of carrier supply is reduced as the doping region decreases. Hence, in the following sections, we concentrate on the HFETs with a thin AlGaN layer of 120 Å, and examine the 2DEG properties for pursuing higher 2DEG densities.

2.2. 2DEG Properties in Conventional MD-HFETs

The conventional MD-HFETs (MD: modulation doping) had the following structure: 40 Å undoped $Al_{0.3}Ga_{0.7}N$/50 Å Si-doped $Al_{0.3}Ga_{0.7}N$/30 Å undoped $Al_{0.3}Ga_{0.7}N$/1 μm undoped GaN/1000 Å AlN/SiC(0001). The Si concentration was $(0\text{-}4)x10^{19}$ cm^{-3}. The total thickness of the $Al_{0.3}Ga_{0.7}N$ layer was thus as thin as 120 Å. Since simultaneously obtaining high 2DEG densities and high 2DEG mobilities is essential for actual device operation, we show in Fig. 2 the relation between the 2DEG density and 2DEG mobility in MD-HFETs. Figure 2 reveals that the 2DEG density more than $1.5x10^{13}$ cm^{-2} cannot be attained even with a very high doping concentration of $4X10^{19}$ cm^{-3}. This indicates that the maximum 2DEG density in these HFETs is limited by the AlGaN layer thickness, since the inherent 2DEG capacity for $Al_{0.3}Ga_{0.7}N$/GaN HFETs is more than $2x10^{13}$ cm^{-2}. Such situation does not occur in GaAs-based HFETs whose 2DEG capacity is $3x10^{12}$ cm^{-2} at largest.

2.3. 2DEG Properties in BD-HFETs

For overcoming the above situation and obtaining higher 2DEG densities, we propose a back-doping design in the AlGaN/GaN HFET where an asymmetric double-heterostructure is employed and carrier doping is performed not only in the surface-side AlGaN layer but also in the underlying AlGaN layer whose Al composition is not as high as that of the surface-side AlGaN layer. In this structure, electrons are efficiently supplied also from the back-doped AlGaN barrier layer to the GaN channel, with the help of the negative polarization charges at the heterointerface between the GaN channel and the underlying AlGaN barrier layer.

The BD-HFETs had the following structure: 40 Å undoped $Al_{0.3}Ga_{0.7}N$/50 Å Si-doped $Al_{0.3}Ga_{0.7}N$/30 Å undoped $Al_{0.3}Ga_{0.7}N$/250 Å GaN/100 Å Si-doped $Al_{0.09}Ga_{0.91}N$/1 μm AlGaN (gradual Al composition)/SiC(0001). The Si concentration in the underlying $Al_{0.09}Ga_{0.91}N$ layer was $(0\text{-}1)x10^{19}$ cm^{-3}. The structure of the surface-side of the $Al_{0.3}Ga_{0.7}N$ layer in BD-HFET was completely the same as that in MD-HFETs. Figure 3 show the relation between the 2DEG density and 2DEG mobility in BD-HFETs, indicating that the maximum 2DEG density is as high as $2.8x10^{13}$ cm^{-2}. This value is almost the twice of the maximum 2DEG density obtained with MD design ($1.5x10^{13}$ cm^{-2}). The 2DEG mobility is around 850 cm^2/Vs, which is relatively high considering the very high 2DEG density of $2.8x10^{13}$ cm^{-2}.

3. Summary

The doping design and the 2DEG densities in the HFETs with thin AlGaN layers have been examined for high-power applications. A critical problem has been revealed in the conventional MD design, which stems from the situation that the possible amount of carrier supply becomes less than the inherent 2DEG capacity. This situation is specific to GaN-based HFETs. As an effective solution for the problem, a BD design has been proposed that makes it possible to obtain high 2DEG densities in the HFETs with thin AlGaN layers. With BD design, the 2DEG density well beyond $2x10^{13}$ cm^{-2} has been obtained even for the AlGaN layer as thin as 120 Å, leading to a record value of the mobility-density product of $2.4x10^{16}$ $(Vs)^{-1}$. The BD design is thus effective to obtain high 2DEG densities for thin AlGaN barrier layers, and promising for high-power applications.

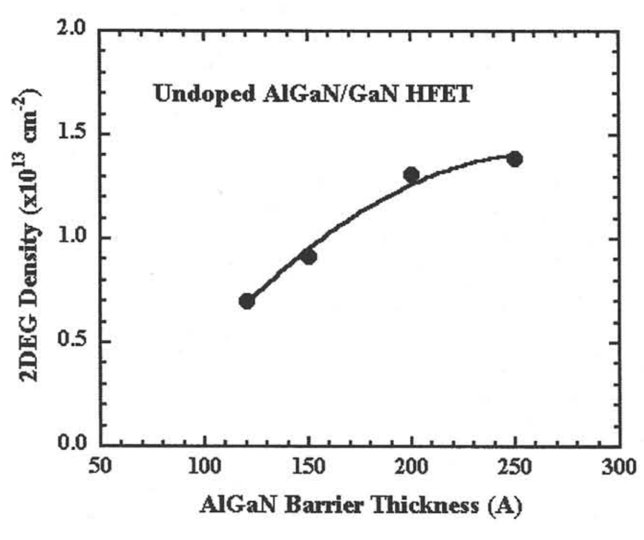

Fig. 1 Relation between 2DEG density and AlGaN barrier thickness in undoped $Al_{0.3}Ga_{0.7}N/GaN$ HFET at room temperature.

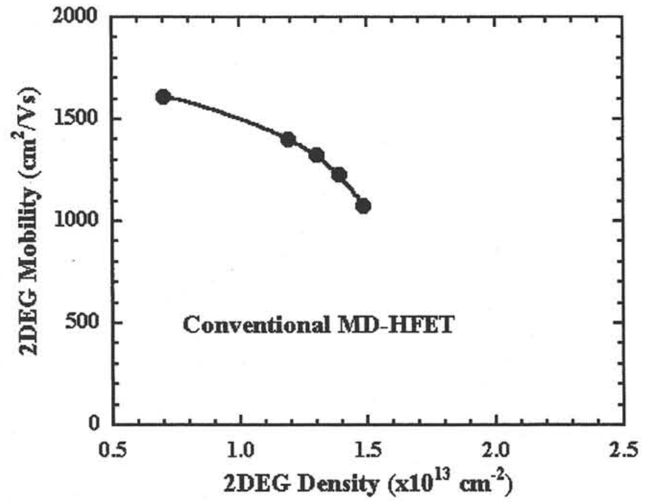

Fig. 2 Relation between 2DEG density and 2DEG mobility in conventional MD $Al_{0.3}Ga_{0.7}N/GaN$ HFET at room temperature. The thickness of $Al_{0.3}Ga_{0.7}N$ layer is 120 Å.

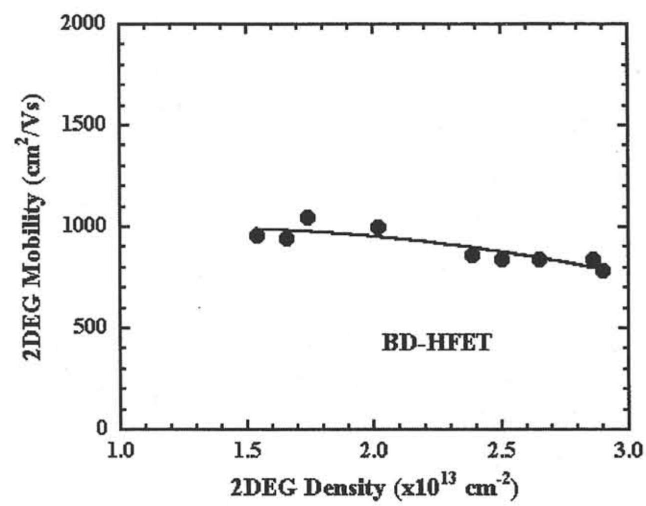

Fig. 3 Relation between 2DEG density and 2DEG mobility in conventional BD $Al_{0.3}Ga_{0.7}N/GaN$ HFET at room temperature. The thickness of $Al_{0.3}Ga_{0.7}N$ layer is 120 Å.

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