Growth of Si delta-doped GaN by metalorganic chemical-vapor deposition

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Si delta-doped GaN has been grown by metalorganic chemical-vapor deposition. A very high peak density and narrow full width at half maximum (FWHM) of the carrier profile are obtained. It is found that the peak carrier density of Si delta doping increases with the doping time and SiH_4 flow rate, while the FWHM of the carrier profile decreases with both increasing doping time and SiH_4 flow rate. Some saturation in the carrier density has also been observed for relatively longer doping time. Except for a broadened carrier distribution in GaN induced by Si diffusion due to high growth temperature, the Si delta-doping properties in GaN are found to be similar to those of GaAs. © *2000 American Institute of Physics.* [S0003-6951(00)03340-4]

There has been rapid progress in short-wavelength light-emitting diodes and laser diodes based on III-nitride semiconductors. Due to their high electron saturation velocity and high chemical stability, group-III nitrides also have become the most promising material for high-temperature and high-power field-effect transistors, including metal–semiconductor field-effect transistors and high electron mobility transistors.[1–4] Si delta-doped (δ-doped) GaAs and InGaP III–V compound semiconductors have been well studied for improving the performance of high electron mobility transistors. There are several advantages for the use of delta doping when compared to homogeneous doping, such as enhancing the two-dimensional electron gas density along with enhanced mobility, reduced parallel conduction, and improved breakdown voltage.[5,6] Moreover, the incorporation of delta doping into the laser structure of GaAs-based semiconductors has demonstrated some important improvements in the laser's performance, e.g., lowering the laser's transparency current density, increasing the modulation bandwidth of quantum well (QW) lasers and improving the temperature-related stability of QW lasers.[7,8]

Recently, Kim *et al.* have reported Si δ-doped GaN layer growth with low-pressure metalorganic chemical-vapor deposition (MOCVD), and found that the delta doping of Si in GaN was very different from that of Si delta doping (δ doping) in GaAs.[9] The Si delta-doping density increases and then decreases with an increase in delta-doping time, and the use of a postpurge step in the ammonia ambient reduces the Si delta-doping density. However, doping conditions which affect the properties of the Si δ doping were not studied in detail. For high-performance device applications, it is important and necessary to further investigate delta doping in III–V nitride materials. In this letter, we report a study of parametric dependencies of carrier concentration in Si δ-doped GaN. The parameters include δ-doping time and SiH_4 flow. The capacitance–voltage ($C-V$) profiling technique was employed to investigate carrier density and distribution of the Si δ-doped GaN. We found that the Si δ doping in GaN and GaAs is not different, except that the carrier distribution is broader in GaN caused by Si diffusion due to the high growth temperature of GaN.

The samples for this study were grown by a horizontal atmospheric pressure MOCVD on (0001) sapphire substrates. Trimethylgallium (TMG) and ammonia were used as precursors with H_2 as a carrier gas, and 10 ppm silane (SiH_4) diluted in H_2 was used as the doping precursor. The substrate was first cleaned in flowing H_2 at 1100 °C, and then the temperature was reduced to 500 °C for the growth of a nominal 30-nm-thick GaN layer. Si delta doping was induced, after a 1.5-μm-thick undoped GaN was grown at 1080 °C at a growth rate of 3 μm/h. The growth process of Si δ-doped GaN is similar to that of GaAs with the delta doping achieved by a so-called ''interruption-growth procedure'' period.[10] The detailed growth procedure of a delta doping layer in GaN was as follows. First, the growth process of the undoped GaN layer was interrupted by venting the TMG flow and following a 10 s pre-δ-doping H_2 purge step, while flowing ammonia continuously through out the process. Then, SiH_4 flow was introduced into the reactor for a certain period of time (δ-doping time) to dope the nongrowing GaN surface. The SiH_4 flow rate was varied from 2 to 20 sccm and the doping time from 15 to 120 s. Finally, SiH_4 flow was stopped and TMG flow was started into the reactor with or without a H_2 postpurge step to resume growth of a 0.2-μm-thick undoped GaN cap layer. An Al/Ti guard ring Ohmic contact was formed, and a Schottky barrier was formed by depositing Pd pads (400 μm diam) in the guard ring. The Ohmic contact metals were alloyed at 650 °C for 30 s. The carrier profiles of Si δ-doped GaN were measured using a capacitance–voltage profiling technique at 300 K and 1 MHz.

$C-V$ profiles of the Si δ-doped GaN with two different flow rates and doping times are shown in Fig. 1. The carrier distribution is usually affected by the dopant diffusion and

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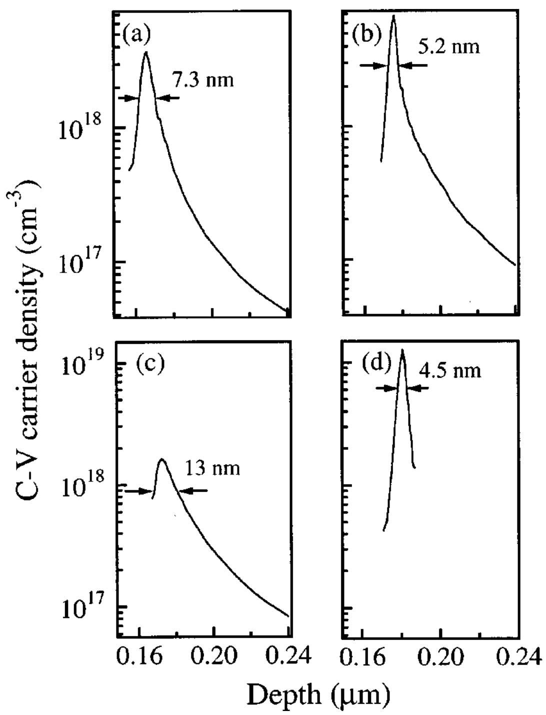

FIG. 1. $C-V$ profile of Si delta-doped GaN grown with different doping times and SiH_4 flow rate (a) 60 s, 2 sccm; (b) 60 s, 5 sccm; (c) 15 s, 20 sccm; and (d) 30 s, 20 sccm.

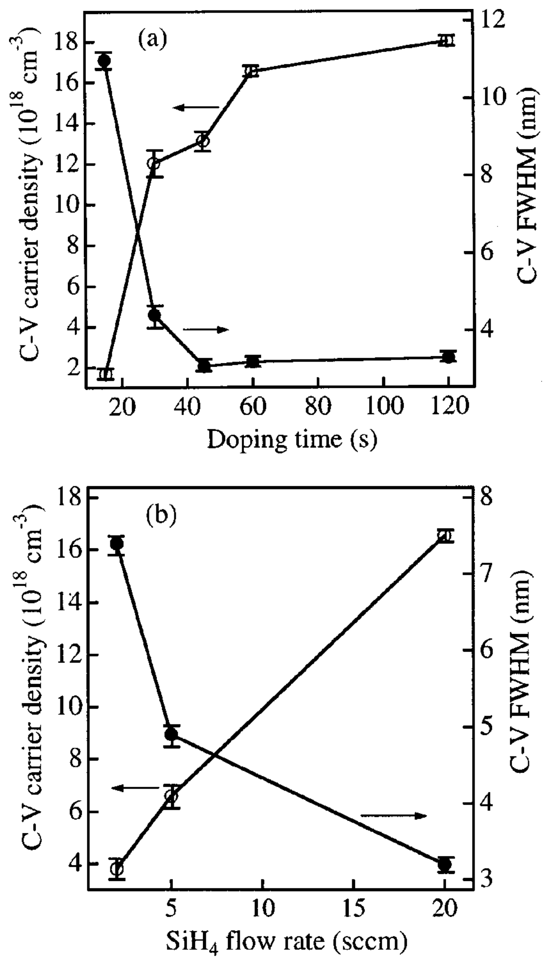

FIG. 2. Dependence of the peak carrier density and FWHM of Si delta-doped GaN on (a) delta-doping time with 20 sccm SiH_4 flow rate and (b) SiH_4 flow rate with 60 s δ-doping time.

segregation. However, at the very high growth temperature of 1080 °C, the $C-V$ measurements show a high peak carrier density and narrow full width at half maximum (FWHM), this is completely comparable with those obtained for Si delta-doped GaAs grown at temperatures ranging from 550 to 700 °C. In addition, a change in carrier density was not observed between samples with and without a postpurge step, indicating that the thermal decomposition efficiency is small for Si doping in GaN. No significantly asymmetric broadening of the carrier profile towards the surface direction induced by segregation is observed. The carrier distribution of Si delta-doped GaN is obtained ranging within a few atomic monolayers.

Figure 2 demonstrates that the peak carrier density and the value of the FWHM of Si δ-doped GaN depends on the doping time and SiH_4 flow rate. As can seen in Fig. 2(a), the peak carrier density gradually increases with delta-doping time and saturates at long doping times. It may suggest that the Si delta-doping process is dominated by the Si adsorption process, and an equilibrium between the adsorption and desorption process is nearly established when the doping time is more than 45 s. This short time indicates that the Si adsorption process itself is strong. Figure 2(b) shows the variation of the peak carrier density and $C-V$ FWHM as a function of the SiH_4 flow rate, with a constant doping time of 60 s. It can be seen from Fig. 2(b) that the peak carrier density increases near linearly with the SiH_4 flow rate. A decrease of the $C-V$ FWHM with both increased doping time and SiH_4 flow rate is also observed. It should be mentioned that Si delta doping in GaN shows similar properties as that in GaAs.

Si δ doping ideally should be confined to a single atomic monolayer by the growth interruption technique. However, the doping profile will be broadened by dopant diffusion and segregation processes. Variation of the $C-V$ FWHM with sheet carrier density can be calculated by a self-consistent method if we assume that the samples have an ideal delta-doping profile and the $C-V$ FWHM corresponds to the spatial extent of the ground-state wave function.[11] It is interest-

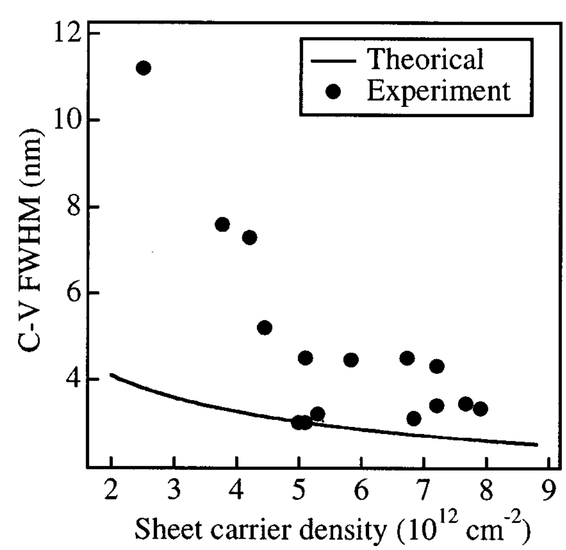

FIG. 3. $C-V$ FWHM of Si delta-doped GaN as a function of sheet carrier density. The solid circles are the experimental data. The solid line is the theoretical calculation results by the analytic variational method.

ing to compare the theoretical variation of the $C-V$ FWHM as a function of sheet carrier density for Si delta-doped GaN to experimentally observed values. As shown in Fig. 3, a large deviation is observed between the experimental and theoretically calculated values. This is in contrast with the case of Si delta-doped GaAs where experimental data fit well with the theory. The broadened FWHM of Si delta-doped GaN can be contributed to the Si diffusion at the higher growth temperature of GaN.

In summary, Si δ-doped GaN grown by MOCVD has been studied. Even though the growth temperature is as high as 1080 °C, a very high peak carrier density and narrow $C-V$ FWHM carrier profile are obtained. The Si delta-doping peak density increases with the doping time and SiH_4 flow rate and saturates at longer doping times. The $C-V$ FWHM decreases with both increasing the doping time and SiH_4 flow rate. The Si delta-doping properties in GaN are similar to that of GaAs, but the FWHM of the carrier profile in GaN is broader, which may be due to Si diffusion at the considerably high growth temperature in GaN.

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