InN grown on GaN/sapphire templates at different temperatures by MOCVD


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Abstract

InN epitaxial layers were grown on GaN/sapphire templates by metalorganic chemical vapor deposition (MOCVD) at various temperatures. It was found that surfaces of these samples were all reticular and the sample surface became rougher as we increased the growth temperature. It was also found that growth rate increased with increasing growth temperature and the growth rate could reach 470 nm/h for the InN epitaxial layer grown at 675 °C. Furthermore, it was found that we achieved the highest mobility of 1300 cm²/Vs and the lowest carrier concentration of 4.6 × 10¹⁸ cm⁻³ from the InN epitaxial layer grown at 625 °C.

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1. Introduction

Indium nitride (InN) is an interesting material that has attracted much attention in recent years. Compared with other III-Nitride materials, such as GaN and AlN, it has been shown that InN has higher electron drift velocity and smaller effective mass [1–7]. These good electron transport properties make InN suitable for high speed and high frequency electronic device applications. Instead of widely recognized 1.9 eV, it has been shown recently that InN exhibits narrow direct band gap energy of around 0.7 eV [8–10]. This also makes InN potentially useful as light emitter for fiber optic communication and potentially useful for solar cell applications. This also means that InₓGa₁₋ₓN could cover a wide spectral range between ultraviolet and infrared. To realize InN-based devices, we need to understand its material properties. It is also necessary to grow high quality InN epitaxial layers. However, the growth of high quality InN film is very difficult due to the lack of suitable substrate materials that are matched with InN in terms of both lattice constant and thermal expansion coefficient.

It has been shown that it is possible to grow InN with reasonably good quality by epitaxial layers by molecular beam epitaxy (MBE) [11–14]. To grow high quality InN epitaxial layers by metalorganic chemical vapor deposition (MOCVD) is even more difficult. It is known that one need to grow InN epitaxial layers at relatively low growth temperatures so as to prevent InN from dissociation. However, cracking efficiency of nitrogen precursor, NH₃, is small at low temperatures. Indeed, it has been shown that quality of the InN epitaxial layers grown by MOCVD is poor in general [15–21]. Recently, Bi et al. reported the growth of InN epitaxial layers on sapphire substrates by two-step
MOCVD [22]. They found that optimal growth temperature of InN was 425 °C while no InN could be formed on sapphire substrates when the growth temperature was higher than 500 °C. Singh et al. characterized MOCVD grown InN epitaxial layers prepared with various growth conditions [23]. However, they varied growth parameters such as V/III ratio and the growth temperature simultaneously. Thus, it is difficult to clearly understand the effects of growth temperature on the crystal quality of InN epitaxial layers. In this paper, we report the growth of InN epitaxial layers on GaN/sapphire templates by MOCVD. In contrast to the work of Singh et al., we prepared InN epitaxial layers at various growth temperatures without changing the other growth parameters. Physical, optical and electrical properties of the prepared InN epitaxial layers will also be discussed.

2. Experimental

The InN epitaxial layers used in this study were all grown on GaN/sapphire templates by MOCVD. Details of the growth could be found elsewhere [24–26]. During the growth, trimethylindium (TMIn), trimethylgallium (TMGa) and ammonia (NH₃) were used as the source materials of In, Ga and N, respectively. The GaN/sapphire templates were prepared by depositing a 30-nm-thick 520 °C grown GaN nucleation layer and a 2-μm-thick 1120 °C grown GaN buffer layer on (0001) sapphire (Al₂O₃) substrates using H₂ as the carrier gas. During the growth of these GaN layers, we kept the reactor pressure and V/III ratio at 200 mbar and 20:21, respectively. InN epitaxial layers were then deposited onto the GaN/sapphire templates using N₂ as the carrier gas at various temperatures. During the growth of InN, we kept the V/III ratio and chamber pressure at 18000 and 200 mbar, respectively.

After the growth, we used field emission scanning electron microscope (FESEM) to evaluate surface and cross-sectional morphologies of the samples. We also measured carrier concentrations and mobilities of the samples by Hall effect measurements in standard van der Pauw configuration.

3. Results and discussion

Figs. 1a–e show top view SEM photographs of the InN epitaxial layers grown at 500 °C, 550 °C, 575 °C, 625 °C and 675 °C, respectively. In contrast to previously reported direct growth of InN on sapphire substrates [21], it was found that InN could be grown on GaN/sapphire templates even at 675 °C. It was also found that surfaces of these samples were all reticular. For the samples grown below 600 °C, it was found that surface morphologies were densely twisted grains and the grain size increased with the increase of growth temperature, as shown in Fig. 1a–c. It was also found that voids exist in the samples grown at high temperatures, as shown in Fig. 1c–e. Recently, it has been shown that these voids are originated from the InN/GaN interface and could result in peeling off of layers and delamination [27]. Figs. 2a–e show cross-sectional SEM photographs of the InN epitaxial layers grown at 500 °C, 550 °C, 575 °C, 625 °C and 675 °C, respectively. It was found that surface of the InN epitaxial layer grown at 500 °C was reasonably smooth. However, it was also found that sample surface became rougher as we increased the growth temperature. The rough surfaces observed from

![Top view SEM photographs of the InN epitaxial layers grown at (a) 500 °C, (b) 550 °C, (c) 575 °C, (d) 625 °C and (e) 675 °C.](image1)

![Cross-sectional SEM photographs of the InN epitaxial layers grown at (a) 500 °C, (b) 550 °C, (c) 575 °C, (d) 625 °C and (e) 675 °C.](image2)
the samples prepared at high temperatures should be attributed to dissociation of InN. Furthermore, it was found that large voids exist at the InN/GaN interface for the InN epitaxial layer grown at 575 °C. Due to the large mismatches in lattice constant and thermal expansion coefficient between InN epitaxial layers and the underneath GaN/Sapphire templates, 575 °C-grown InN epitaxial layer should suffer from large strain [28]. We believe the large voids at InN/GaN interface were formed during cooling process, as shown in Fig. 2c. On the other hand, strain relaxation might occur as we further increased the growth temperature. As shown in Fig. 2d and e, we thus observed smaller voids at InN/GaN interface for the samples grown at 625 °C and 675 °C. Here, we define surface roughness as the maximum thickness variations observed in these cross-sectional SEM photographs. With such definition, it was found that thickness variation was 288 nm for the InN epitaxial layer grown at 675 °C. As shown in Fig. 3, it was also found that thickness variation decreased as the growth temperature was decreased. Such an observation suggests that columnar growth mode was preferred for the InN epitaxial layers grown on GaN/sapphire templates. We can also calculate growth rate of InN epitaxial layers from these cross-sectional SEM photographs. As also shown in Fig. 3, it was found that growth rate increased with increasing growth temperature. Similar trend was also observed by Singh et al. [23]. However, they reported lower growth rates at the same growth temperature probably due to the lower V/III ratio and thus insufficient supply of NH3 in their study. Previously, it has been reported that MOCVD growth rate of InN on sapphire substrates saturated at 630 °C [16]. No such saturation was observed for our InN on GaN/sapphire templates. This again indicated that the columnar growth mode was preferred for the InN epitaxial layers grown on GaN/sapphire templates. It was found that growth rate could reach 470 nm/hr for the InN epitaxial layer grown at 675 °C.

Fig. 4 shows measured Hall mobility and carrier concentration as functions of InN growth temperature. It was found that carrier mobilities were low while carrier concentrations were high for the InN epitaxial layers grown at low temperatures. This is probably due to the poor crystal quality when the growth temperature was too low so that In and N atoms could not migrate to proper sites on sample surfaces. It is also possible that the poor crystal quality is related to the low decomposition rate of NH3. It was also found that we achieved the highest mobility of 1300 cm2/Vs and the lowest carrier concentration of 4.6 x 1018 cm−3 from the InN epitaxial layer grown at 625 °C. On the other hand, carrier mobility decreased while carrier concentration increased as we further increased the growth temperature. This is again due to the large dissociation of InN at high growth temperatures.

4. Conclusions

InN epitaxial layers were grown on GaN/sapphire templates by MOCVD at various temperatures. It was found that surfaces of these samples were all reticular and the sample surface became rougher as we increased the growth temperature. It was also found that growth rate increased with increasing growth temperature and the growth rate could reach 470 nm/h for the InN epitaxial layer grown at 675 °C. Furthermore, it was found that we achieved the highest mobility of 1300 cm2/Vs and the lowest carrier concentration of 4.6 x 1018 cm−3 from the InN epitaxial layer grown at 625 °C.

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