PHOTOLUMINESCENCE CHARACTERISTICS OF GaN LAYERS GROWN ON SOI SUBSTRATES AND RELATION TO MATERIAL PROPERTIES

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ABSTRACT

GaN layers were grown by MOCVD on Silicon on Insulator (SOI) substrates in an effort to improve the material quality compared to more traditionally employed sapphire substrates. Their photoluminescence properties are reported and found to exhibit an intense and relatively large PL band around 3.47eV at low temperature (7K). This is about 10meV lower than the PL energy of samples grown on sapphire substrates and suggests the presence of lower strain in the layers which is expected for compliant growth on SOI substrates. The shape of the main PL peak appears to indicate that Silicon diffusion takes place from the substrate during growth. The behavior of the PL spectra is studied as a function of temperature. The GaN films show good overall electrical properties with Hall mobilities at room temperature in the range of 150 to 300cm^2/Vs and background carrier concentration from 2.9 to 3.9×10^{17}cm^{-3}. The promising optical and electronic features of these layers could be of great interest for the development of high quality optical and electronic devices.

INTRODUCTION

In spite of the impressive results of S. Nakamura et al. [1] who recently announced a lifetime of more than 10,000 hours for the blue laser diode grown on a sapphire substrate using lateral overgrowth on silicon dioxide stripes, the seek of alternative substrates for the growth of GaN material is still a challenging subject. In this respect, the use of silicon carbide has attracted a lot of attention due to very attractive properties (lower lattice mismatch with GaN, higher thermal conductivity, lower electrical conductivity) in spite of the high cost of SiC wafers [2]. An alternative way to reduce the dislocation density in GaN layers is to use the properties of compliant substrates such as Silicon on Insulator (SOI) [3-5] or even SiC on SOI [6]. Such substrates are interesting for their large size but also for their compatibility with silicon allowing monolithic integration as well as, for their low thermal resistance, permitting better power dissipation.

In this work, we have studied the optical properties of GaN layers grown by MOCVD on SOI substrates by means of photoluminescence and compare the results with electrical (Hall) measurements as well as with Secondary Ion Mass Spectrometry (SIMS) data.

MOCVD MATERIAL GROWTH ON SOI AND CHARACTERIZATION

GaN samples were grown in the modified EMCORE low-pressure (60torr) MOCVD system at the University of Michigan, using H_2 as carrier gas, and trimethylgallium (TMGa) and Ammonia (NH_3) as Ga and N precursors, respectively. The SOI substrates used for growth were fabricated by SIMOX (separation by implanted oxygen) technology. Thicknesses of silicon overlay and SiO_2 buried layers were 53nm and 81nm respectively. GaN buffer growth temperature was 500°C and layer growth temperature was 940°C. No intentional doping was performed during growth. Different thicknesses of GaN layers were grown under different growth conditions. Table I summarizes layer thickness, V/III ratio and growth rate for each of the samples.

Table I: GaN on SOI sample thickness and growth parameters.

Sample	GaN thickness (μm)	V/III ratio	Growth rate (μm/h)
A	1.20	3000	1.2
B	2.42	1500	1.2
C	2.00	750	2.0

Photoluminescence experiments were performed using an Argon ion laser emitting at a wavelength of 334nm as selected by an intra-cavity prism. Measurements were performed at low temperature (7K) and also as a function of temperature in a helium cooled cryostat. The photoluminescence signal was detected by a Hamamatsu GaAs photomultiplier cooled at -20°C.

Reflectivity measurements were performed at near normal incidence using a Xenon lamp dispersed through a monochromator. Detection was made through a Silicon photodiode operating in a photovoltaïc mode.

PHOTOLUMINESCENCE RESULTS

PL spectra recorded at 7K from the GaN/SOI samples are reported in Fig. 1 together with the spectrum of a reference sample (silicon doped GaN layer grown on a sapphire substrate), because of similar lineshapes in these samples.

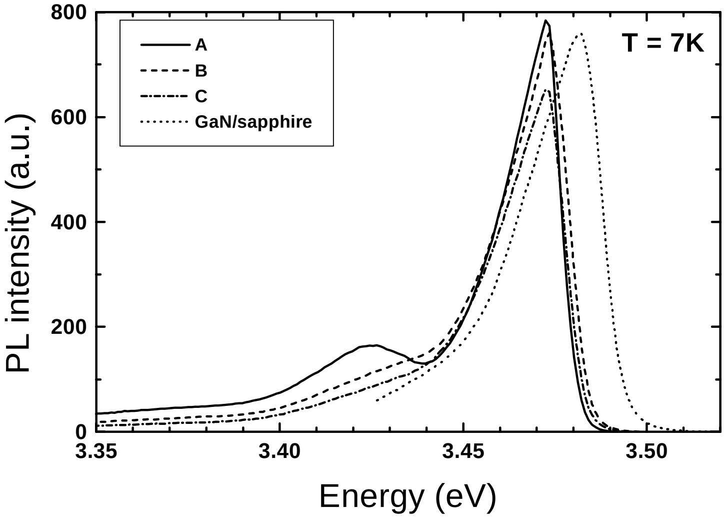

Figure 1: 7K PL spectra of GaN/SOI samples, and of a reference sample (Si doped GaN layer grown on sapphire).

The PL spectra of GaN/SOI samples exhibit mainly two transitions: one intense near bandgap transition around 3.47eV and another one arising at a lower energy around 3.41eV. The PL spectra were studied as a function of temperature, and the evolution of the PL spectrum in sample A is reported as a function of temperature in Fig. 2. As can be seen in the insert of Fig. 2, the main energy peak transition is decreasing with increasing temperature as is commonly observed for bandgap related transitions in GaN [7]. However, the 3.41eV is shown to blue-shift when the temperature is increased. Such a behavior may be attributed to some defect level thermally emptied as the temperature is increased, thus involving a defect level in the bandgap.

Low-temperature PL spectra with 3.41eV recombination band are often observed in GaN [8-10], but its origin is still the subject of some controversy: either a free to bound transition D^0h involving an oxygen donor level [8] or due to the formation of bound excitons on c-axis screw dislocations. Other authors [10] claim, from spatially resolved cathodoluminescence and time-resolved photoluminescence, that it is strongly correlated to a bound exciton, without any correlation with dislocation networks, but rather with some structural disorder at interface.

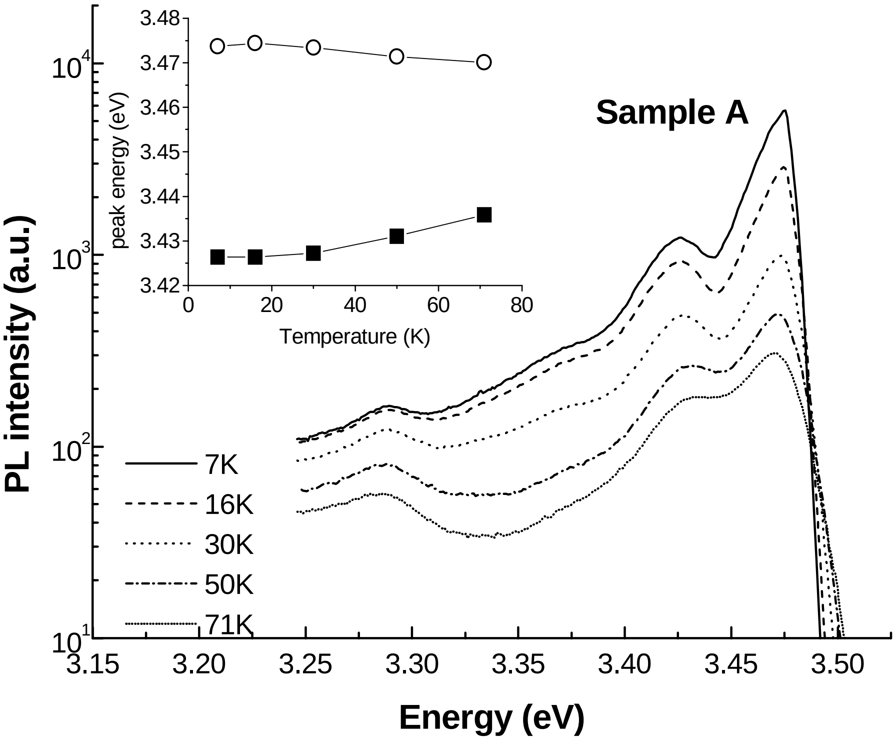

Figure 2: Evolution of PL spectrum in sample A as a function of temperature.

In our sample series we indeed observe the 3.41eV line being more intense in sample A which is the thinnest sample. This is consistent with the attribution of the line to some interface defect. This line does exist also in the reference sample (GaN:Si/sapphire), although it is much less intense. It appears therefore that it does not strongly depend on the nature of the substrate and is probably more related to some structural disorder at the interface. This is in agreement with Fischer's report [10] rather than the possibility of introduction of some impurity during growth.

STRAIN EFFECTS IN GaN ON SOI AND COMPLIANT GROWTH CONFIRMATION

Strain effects were studied in GaN grown on SOI in an attempt to evaluate the compliant features of this growth approach. For this purpose, it is important to understand first the near bandgap transition. In order to obtain the physical origin of this transition, low temperature reflectivity measurements were performed and fitted using a mathematical model [11] of the reflectivity as a function of incident photon energy. Quantitative results from reflectivity and photoluminescence measurements are reported in table II for all GaN/SOI samples as well as PL results for the GaN:Si/sapphire reference sample. Excitonic transitions in the reflectivity spectra are rather broad, leading to uncertainty in the determination of exciton energy reported in Table II. We have also reported in this table the carrier concentration and mobility as determined from room temperature Hall measurements. These results show the possibility of good mobility and background carrier concentration characteristics by growth of GaN on SOI as previously reported by the authors [3-5].

Table II: Reflectivity, photoluminescence and Hall characteristics of the GaN/SOI samples and of the GaN:Si/sapphire reference sample.

Sample	A exciton (reflectivity) (eV)	PL energy (eV)	FWHM (meV)	Hall carrier density (cm^{-3})	Hall mobility ($cm^2\ V^{-1}\ s^{-1}$)
A	3.478 (±8)	3.473	23	3.9×10^{17}	320
B	3.474 (±5)	3.473	21	2.8×10^{17}	178
C	3.476 (±5)	3.473	21	2.9×10^{17}	257
GaN:Si/Sapphire	–	3.482	25	6.6×10^{18}	167

As can be seen from the comparison between reflectivity and photoluminescence measurements, the A exciton always arises at an energy slightly higher than PL energy, indicating that the main PL transition in the samples is due to the neutral donor bound exciton D^0X recombination, independent of sample type. The energy shift (about 6meV) measured between A and D^0X is in good agreement with literature [12].

The D^0X recombination in the GaN/SOI samples lies at an energy lower than that measured in the GaN/sapphire sample: a 10meV red shift is observed between bandgap energies on both types of substrates. This is an indication for a lower strain state in the GaN layer grown on a SOI substrate as compared to the sample grown on sapphire. According to theoretical calculations from B. Gil et al. [13], this corresponds to a decrease of the biaxial compression close to 6kbar in the GaN/SOI samples. These results are of extreme importance for proving that compliant growth does indeed take place in our GaN on SOI growth approach.

The full width at half maximum of the main PL peak is relatively large in all the GaN/SOI samples (about 20meV) as compared to PL spectra of undoped GaN layers on sapphire (about 5meV). However, it is similar to the FWHM measured in silicon doped GaN/sapphire as can be seen in Fig. 1 and Table II. In such doped samples, the PL FWHM is shown to increase with increasing doping level [14,15]. Therefore, it is reasonable to assume that silicon may have diffused inside the GaN layer from the SOI substrate during growth due to the high growth temperature.

STUDY OF THE GaN-SOI SUBSTRATE INTERFACE

In order to evaluate the possibility of silicon diffusion taking place at the GaN-SOI substrate interface, SIMS (Secondary Ion Mass Spectrometry) was performed and the silicon profiles recorded in each of the samples are reported in Fig. 3. Silicon was found to be present in all samples and spread in the GaN layer from the substrate interface reaching eventually a low background level away from the interface. The increase of the Si profile near the surface does not appear to be related to this mechanism and is most likely resulting from adsorbed dust at the surface.

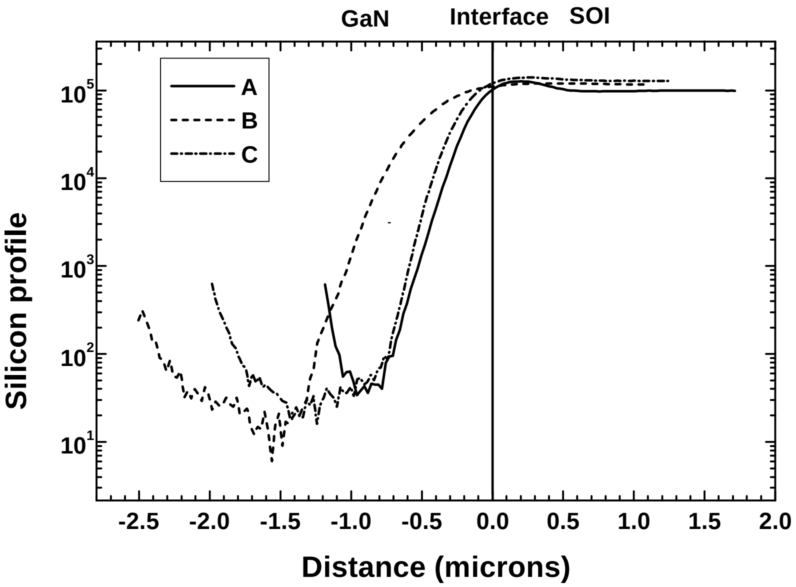

Figure 3: Silicon profile from substrate interface in GaN/SOI samples.

Let us first compare the silicon profiles between sample A and B, which were grown under same growth conditions, except the V/III ratio which is higher in sample A than in B (cf. Table I). One sees that the silicon diffusion from the interface is more important in sample B. As the V/III ratio is lower in B than in A, a higher nitrogen vacancy concentration is expected in sample B, thus favoring the solid state diffusion of silicon in the GaN layer through the nitrogen vacancies. In that case, silicon atoms diffusing from the substrate may occupy nitrogen sites rather than gallium sites, and are therefore not expected to all act as donors: part of them may remain electrically neutral or even acceptor-like. This is indeed in good agreement with Hall measurements as can be seen in Table II where the residual electron density is shown to be reduced in sample B as compared with sample A in spite of a higher silicon density in sample B as compared to sample A. This is also consistent with the FWHM of the bandgap PL transition which is narrower in sample B than in sample A, indicating a lower electrical activity of silicon atoms introduced from the substrate into the layer during the growth in sample B.

During the growth of sample C, the V/III ratio was again decreased as compared to growth of samples B and A. This should increase again the silicon diffusion in the layer. However, the growth rate was also increased for sample C and this is expected to decrease the silicon diffusion. Both parameters are compensating each other, and give a silicon diffusion profile similar to that of sample A. However, because of the lower V/III ratio of sample C, we expect a higher nitrogen vacancy concentration, leading to a lower silicon concentration in donor site. This is confirmed by the Hall measurements (Table II) showing that the free carrier density is lower in sample C than in sample A.

The silicon diffusion during the growth is correlated to the decrease of mobility observed from Hall measurements: samples A and C are shown to exhibit rather good and comparable values of Hall mobility with similar silicon profiles, while sample B has a lower mobility and a higher silicon diffusion in the layer.

Overall, it appears that silicon diffuses from the substrate inside the GaN layer during the growth of GaN on SOI. This leads to an increase of residual carrier density in the GaN layer, and also to a reduction of carrier mobility. SIMS silicon profiles could finally be used to show the way that the V/III ratio and growth rates may influence diffusion at the GaN-SOI substrate interface.

CONCLUSION

From the study of PL, Hall and SIMS characterization in GaN layers grown on SOI substrates, we have shown that the use of SOI substrates is reducing the biaxial compression in the GaN layer by about 6kbars as compared to GaN layers grown on sapphire. This confirms that compliant growth is indeed taking place in GaN on SOI. Silicon is shown to diffuse inside the layer during the growth, inducing an increase of residual carrier density. However, the carrier mobility remains still fairly high exceeding 300cm^2/Vs. The silicon diffusion from the substrate is shown to be controlled by growth parameters such as growth rate and V/III ratio. Growth on compliant substrates such as SOI allows one to obtain good electrical and optical quality layers, promising for device application.

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