The Optical and Electrical Characterization of Si−doped AlGaN

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I. INTRODUCTION

The ternary $Al_x Ga_{1-x} N$ has for many years been touted as a promising material for optoelectronic applications in the blue to UV wavelength range. Its direct, tunable bandgap, which extends from 3.42 (x = 0) to 6.2 eV (x = 1), makes $Al_x Ga_{1-x} N$ ideal for the manufacture of UV optoelectronic devices such as visible− and solar−blind detectors.[1] The commercial development of such devices has been slowed by many factors, amongst others the lack of a suitable substrate and the difficulty in obtaining conducting, high composition $Al_x Ga_{1-x} N$ layers.[2] Most studies, to date, have focused on the optical and electrical properties of undoped $Al_x Ga_{1-x} N$ as a function of Al content. Recently, Si−doped $Al_x Ga_{1-x} N$ has also received some attention.[3,4] In this paper, we present the results of optical and electrical measurements performed on Si−doped $Al_x Ga_{1-x} N$ over the x = 0.2 to 0.5 composition range.

II. EXPERIMENT

The $Al_x Ga_{1-x} N$ layers characterized in this study have been grown by low−pressure metalorganic vapor phase epitaxy (LP−MOVPE). The growth was performed in a horizontal Aixtron AIX200RF reactor at 1180 °C on *c*−oriented sapphire substrates. Trimethylaluminium, trimethylgallium and ammonia were used as precursors, while the growth pressure was 20 mbar. To improve the quality of the epitaxial layers, a low temperature AlN buffer layer was first deposited prior to the growth of the $Al_x Ga_{1-x} N$ epilayer. Silicon doping of the layers was achieved by introducing a fixed silane flow of 2.37 nmol/min during growth. The 300 K electrical properties of the samples were measured using Hall effect and variable frequency capacitance−voltage (C−V) measurements. The C−V measurements were performed at measuring frequencies below the donor emission rate, thus yielding the total $N_D - N_A$ (donor minus acceptor concentration) value instead of the free electron concentration, which is given by Hall measurements. Ohmic contacts were fabricated by the thermal evaporation of Ti/Al, while thick Ni Schottky diodes exhibited good rectifying properties. The Ti/Al contacts exhibited good ohmic behavior after annealing at 500 °C for 10 min in a nitrogen ambient. The optical properties of the layers were studied by variable temperature photoluminescence (PL), using a 20 mW frequency doubled argon−ion laser (λ = 244 nm). The Al content of each layer was determined by energy−dispersive spectroscopy (EDS), while the layer thicknesses (typically 1 µm) were measured by cross−sectional scanning electron microscopy.

III. RESULTS AND DISCUSSION

Figure 1 shows the 300 K electrical properties of Si−doped $Al_x Ga_{1-x} N$ over the investigated composition range. The electron concentration and the mobility are both seen to decrease with increasing Al content. At low compositions, the Hall effect and C−V measurements give very similar results, with the two techniques yielding progressively different values for higher compositions.

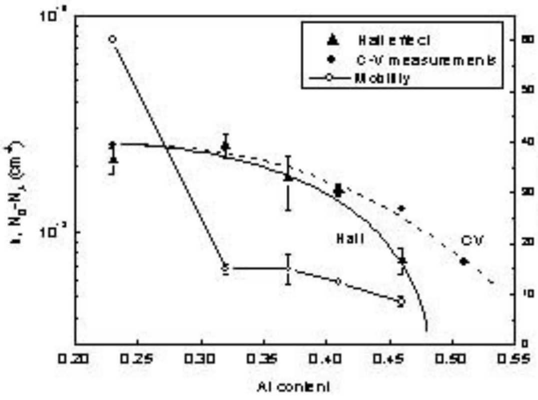

Figure 1: The electrical properties of Si-doped $Al_xGa_{1-x}N$.

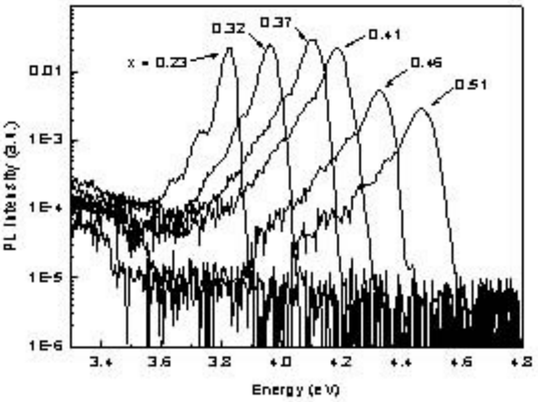

Figure 2: 12 K PL spectra of Si-doped $Al_xGa_{1-x}N$.

Since it has been reported [6] that Si incorporates linearly with the silane flow up to a composition of $x = 0.5$, the atomic Si incorporation is expected to be the same for the different compositions. We believe that the drop in the electron concentration obtained by Hall effect measurements is dominated by the deepening of the Si donor level, whereas the systematic decrease in $N_D - N_A$ is attributed to the intrinsic compensation by Al−vacancies.[5] The decrease in the mobility with increasing Al content is a consequence of both increased alloy scattering and cracking of the material.

The optical properties of the Si−doped $Al_x Ga_{1-x} N$ layers were studied by PL measurements over the 12 to 300 K temperature range. Figure 2 shows the 12 K PL spectra of Si−doped $Al_x Ga_{1-x} N$ over the $x = 0.2$ to 0.5 composition range. The main feature in each of the spectra is the neutral donor−bound exciton (D_o, X). The position of the (D_o, X) peak is seen to shift towards higher energies with increasing Al content due to the increase in the $Al_x Ga_{1-x} N$ band gap with increasing compositions. The increase of the full−width at half−maximum (FWHM) with increasing composition is a common feature of $Al_x Ga_{1-x} N$ alloys and has been attributed to alloy disorder.[7−9]

Figure 3 shows the temperature dependence of the PL intensity for the same set of samples. The temperature dependence of the (D_o, X) peak intensity can be fitted using the following equation:[10] ,

$$I = I_o / [1+ A_1 \exp(-E_1 /kT) + A_2 \exp(-E_2 /kT)] \qquad (1)$$

where A_1 and A_2 are constants, and E_1 and E_2 the PL activation energies of two non−radiative recombination channels.

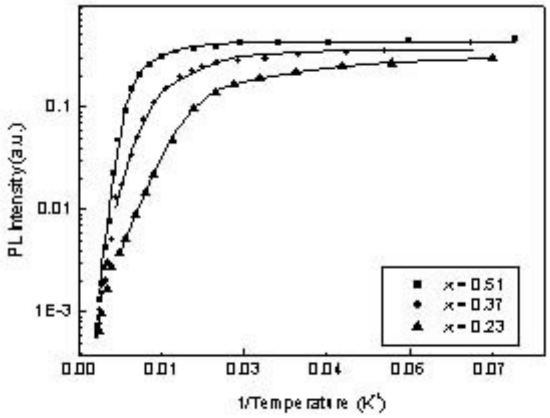

Figure 3: Temperature dependence of the (D^0, X) peak intensity of $Al_xGa_{1-x}N$, for $x = 0.23$, 0.37 and 0.51.

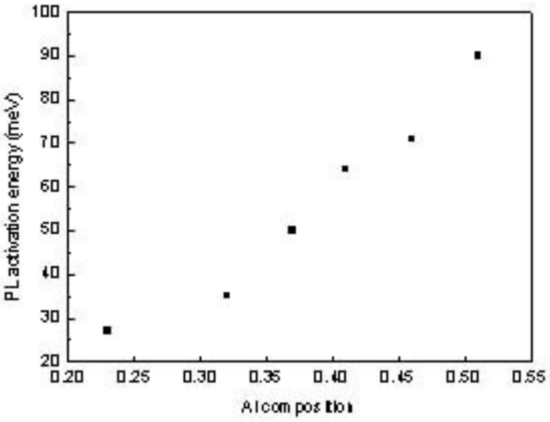

Figure 4: PL activation energy for Si-doped $Al_xGa_{1-x}N$.

In figure 3, the intensity was only fitted over the temperature range for which the excitons were still bound to neutral donors. This yields a more accurate value of the PL activation energy as compared to when fitting over the entire temperature range.[9] Figure 4 shows the PL activation energy composition dependence of the Si−doped $Al_x Ga_{1-x} N$ layers.

It is seen in figure 4 that the PL activation energy gradually increases with increasing Al content. This behavior is unlike the trend reported for undoped $Al_x Ga_{1-x} N$, where a sudden increase in the PL activation energy has been observed at approximately $x = 0.4$. [7] This abrupt increase is generally attributed to the residual doping of unintentionally doped $Al_x Ga_{1-x} N$ layers by oxygen. Oxygen has been shown to become a localized DX state at approximately $x = 0.3$, thus causing a sudden increase in the donor activation energy and decrease in the free electron concentration.[11] Since all our undoped low composition ($x < 0.3$) material was non−conductive ($\rho > 10^7$ ohm.cm), we assumed a negligible residual oxygen content in this study. The gradual increase in the PL activation energy observed in figure 4 is therefore most likely due to an increase in the Si donor binding energy with increasing compositions. This increase could then explain the drop in the free electron concentration with increasing Al content observed in figure 1.

IV. CONCLUSIONS

In summary, we have studied the electrical and optical properties of Si−doped $Al_x Ga_{1-x} N$ over the $x = 0.2$ to 0.5 composition range. It was shown that the 300 K free electron concentration decreases with increasing composition. This has been attributed to the deepening of the Si donor level below the conduction band, and is consistent with variable temperature PL measurements, which revealed that the PL activation energy gradually increases with Al composition. These results can successfully explain the previous difficulties experienced by many groups attempting to produce conductive high composition AlGaN layers.

V. ACKNOWLEDGEMENTS

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