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High Quality Al-Ga-In-N Heterostructures Fabricated by MOVPE Growth in Multiwafer Reactors

D. Schmitz, R. Beccard, O. Schoen, R. Niebuhr, B. Wachtendorf, Holger Juergensen
AIXTRON GmbH

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Abstract

We present results on the growth of Al-Ga-In-N films in multiwafer reactors with 7x2" wafer capacity. The design of these reactors allows the combination of high efficiency (TMGa efficiency for GaN around 30%) and excellent uniformity. Results on the growth of all materials from the Al-Ga-In-Nitride family are presented in detail. GaN is grown with an excellent optical quality and very good thickness uniformity below 2% across 2" wafers. The material quality is shown by electron mobility of more than 500 cm^2/Vs at an intentional Si-doping of approximately $1x10^{17}$ cm^{-3}. Controlled acceptor doping with Mg yields carrier concentrations between $5x10^{16}$ and 10^{18} cm^{-3}. The layer thickness uniformity of the films are better than 2% over a 2" wafer area. GaInN is grown with PL emission wavelengths in the visible blue region showing a uniformity better than 1.5 nm standard deviation. The film thickness uniformity represents the same figures as obtained for the binary. The compositional uniformity of AlGaN is in the sub 1% range corresponding to a wavelength variation below 1 nm.

The fabrication of heterostructures from these binary and ternary materials is described as well as results from the characterization of these structures. The results show that reliable and efficient production of Al-Ga-In-Nitride based optoelectronic devices can be performed in multiwafer reactors.

1. Introduction

Since GaN and it's Al- and In-containing alloys were found to be the material of choice for short wavelength optoelectronics much work has been done to develop MOVPE processes. Within this the fabrication of high quality Al-Ga-In-N heterostructures for device applications is of special interest. After the introduction of the first commercially available nitride based blue LED by Nichia Chemical [1] the raising demand for blue and green Ultra-High-Brightness LEDs led to the development of MOVPE reactors for high throughputs. We designed MOVPE reactors with up to 7x2" wafers loading capacity for high temperature processes such as the GaN growth. The Planetary Reactor® is well adopted for high efficiency combined with an outstanding uniformity across the entire 2" wafer. Single layers as well as heterostructures were grown and investigated.

2. Experimental

All growth experiments were carried our with an AIXTRON AIX2000HT Planetary Reactor® with a loading capacity of 7x2" wafers. This reactor offers fast heating and cooling rates due to its RF-coil heater and its water cooled reactor walls. In figure 1 a cross section of this reactor is shown while in figure 2 a photograph of the opened reactor is given. As sources we used TEGa, TMGa, TMIn, TMAl and NH_3. P-type doping was achieved with DCp_2Mg n-type doping with SiH_4 respectively. All layers were deposited on sapphire substrates following a GaN nucleation layer grown at temperatures below 600°C. For the deposition of GaN and AlGaN the temperatures were chosen in regions above 1100°C while GaInN was grown at temperatures around 800°C. As carrier gases with the AIX2000HT reactor N_2, H_2 and mixtures of these gases can be used. One important advantage of these systems is the fact that the growth pressure can be flexibly varied during the run between 100 and 1000 mbar without compromising the material properties of the various layers in a structure. For the characterization we mainly used non-destructive wafer topography. For thickness measurements we used reflectivity mappings. Carrier concentrations were determined by sheet resistance measurements in combination with the layer thickness. To monitor the composition of ternary material PL-mapping was used. Hall measurements were used to gain the value of carrier mobilities. TEM images gave informations about interface roughness.

3. Results

As mentioned before the AIX2000HT reactor produces GaN with excellent uniformities. Thickness uniformities within the 2% standard deviation range across the entire 2" wafer are easily and reproducibly achieved for all Nitrides. figure 3 shows a film thickness map of a 2 µm GaN layer with an outstanding uniformity. For this 2" wafer the standard deviation is below 0.75% which is an excellent value. These uniformities are obtained by an extremely accurate temperature management. All temperatures relevant for the process are monitored and controlled. This management leads to a very stable growth process of the nitrides which are very sensitive to temperature variations. Another proof for the excellent temperature homogeneity are the maps of the sheet resistance of Si- and Mg-doped GaN. In figure 4a a map of the sheet resistance of a Si-doped n-type GaN layer is shown. A standard deviation of only 1.7% shows high uniformity of the sheet resistance and therefore in combination with the thickness homogeneity a very uniform electron distribution across the entire 2" wafer. In figure 4b the sheet resistance map of a Mg doped GaN layer is shown. In this case the carrier concentration variation is higher with a standard deviation of 16%. This is partly due to the fact that for acceptor activation the layers were annealed in a RTA oven with temperature homogeneity worse than in the MOVPE reactor so that the deviation for p-type doped material is mainly explained by this inhomogeneity. The good electrical properties of the deposited GaN is displayed in figure 5 where the electron mobility in dependence of the electron concentration of Si-doped GaN is shown. Mobilities of more than 500 Vs/cm^2 for $n= 1x10^{17}$ cm^{-3} were achieved. As for device applications such as LEDs and lasers, the ternary alloys GaInN and AlGaN are important materials. We investigated their growth behavior, too. For optoelectronics the composition of InGaN which usually is used as the active layer material is of great importance. We found the In-content dependent only on the TMGa/TMIn-ratio in the gas phase for growth temperatures below approximately 800°C. At higher temperatures a decrease of the In-incorporation with increasing temperatures was observed. This behavior was reported by other groups, too [2], and is caused by an out-diffusion of In out of the layers due to its high vapor pressure. Besides the composition uniformity the homogeneity of the PL-intensity at peak wavelength is another point to care about to gain most similar devices out of the wafers. For the barrier material AlGaN the composition is of major interest. Composition uniformities were measured by using room temperature PL. In figure 6, figure 7 and figure 8, the peak wavelength, full width at half maximum (FWHM) and intensity of the PL signal at peak wavelength mappings of an InGaN layer with an emission wavelength of 461 nm are presented. In particular, the peak wavelength is one of the best ever reported values for InGaN grown in a multiwafer reactor. For AlGaN with about 8% Al content the standard deviation of the emission peak wavelength is only 0.25 nm what corresponds with a composition deviation of less than 1%. The PL mapping is shown in figure 9. All ternary nitride materials grown with AIX2000HT reactor proved to be satisfying for producing heterostructures for device applications. After the growth and characterization of single layers we deposited heterostructures. Heterostructures with very abrupt interfaces (interface sharpness better than 8Å) were demonstrated. Multi-quantum wells, as seen in figure 10, were also fabricated. The very sharp interfaces were made possible by the patented fast run-vent-switching which is a very useful feature of the AIX2000HT system.

4. Conclusions

The growth of GaN and its ternary alloys has been presented with outstanding homogeneity of thickness, composition and doping incorporation. Heterostructures such as AlGaN/GaN multiquantumwells with very sharp interfaces were demonstrated. The grown and characterized material was shown to be very well suited for LED and laser device application. The AIXTRON AIX2000HT reactor system has been proven to be the tool of choice for GaN based optoelectronic devices mass production.

References

[1] S. Nakamura, T. Mukai, M. Senoh, *Jpn. J. Appl. Phys.* ***30***, L1998 (1991).

[2] S. Keller, B. P. Keller, D. Kapolnek, A. C. Abare , H. Masui , L. A. Coldren, U. K. Mishra, S. P. Den Baars , *Appl. Phys. Lett.* ***68***, 3147-3149 (1996).

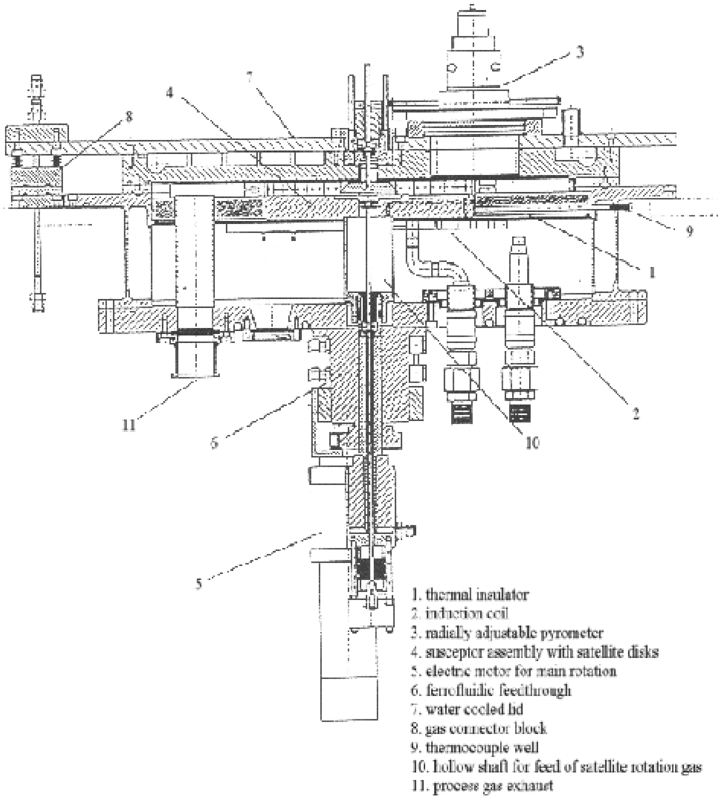


Figure 1. Cross section of an AIX2000HT reactor.

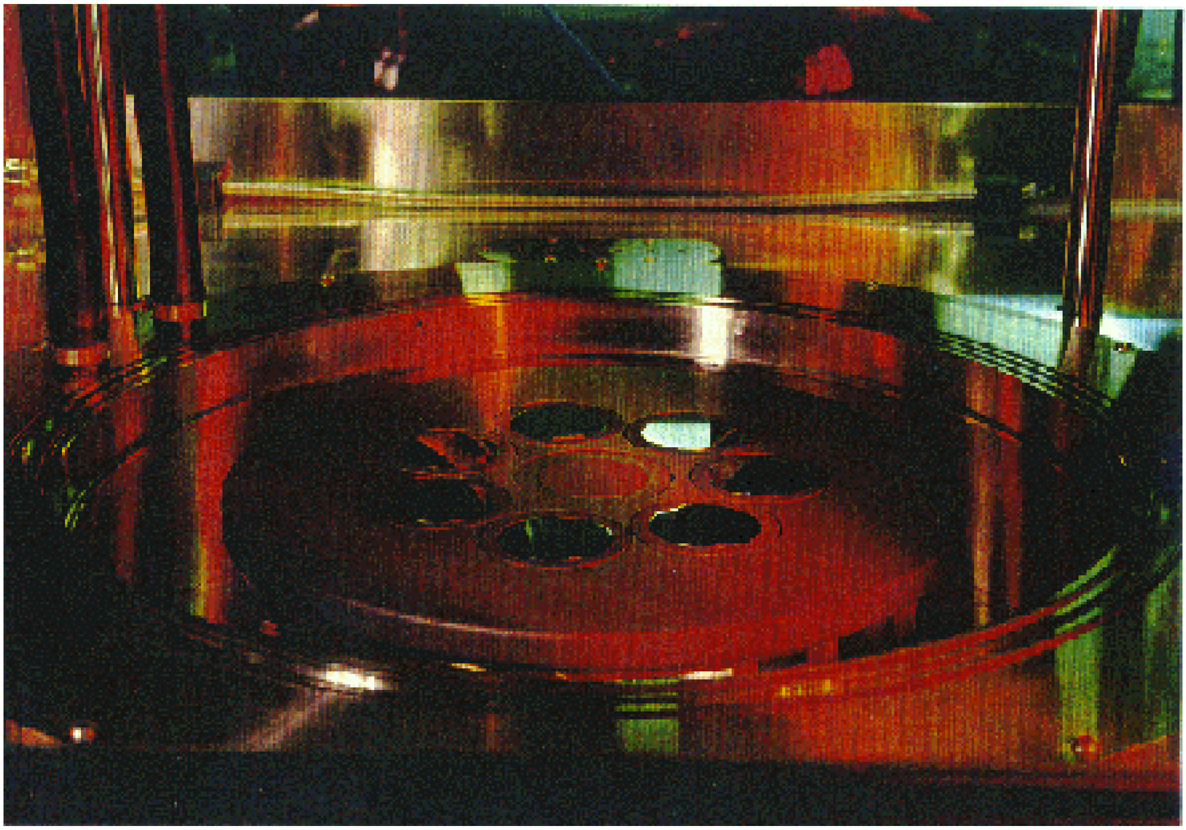
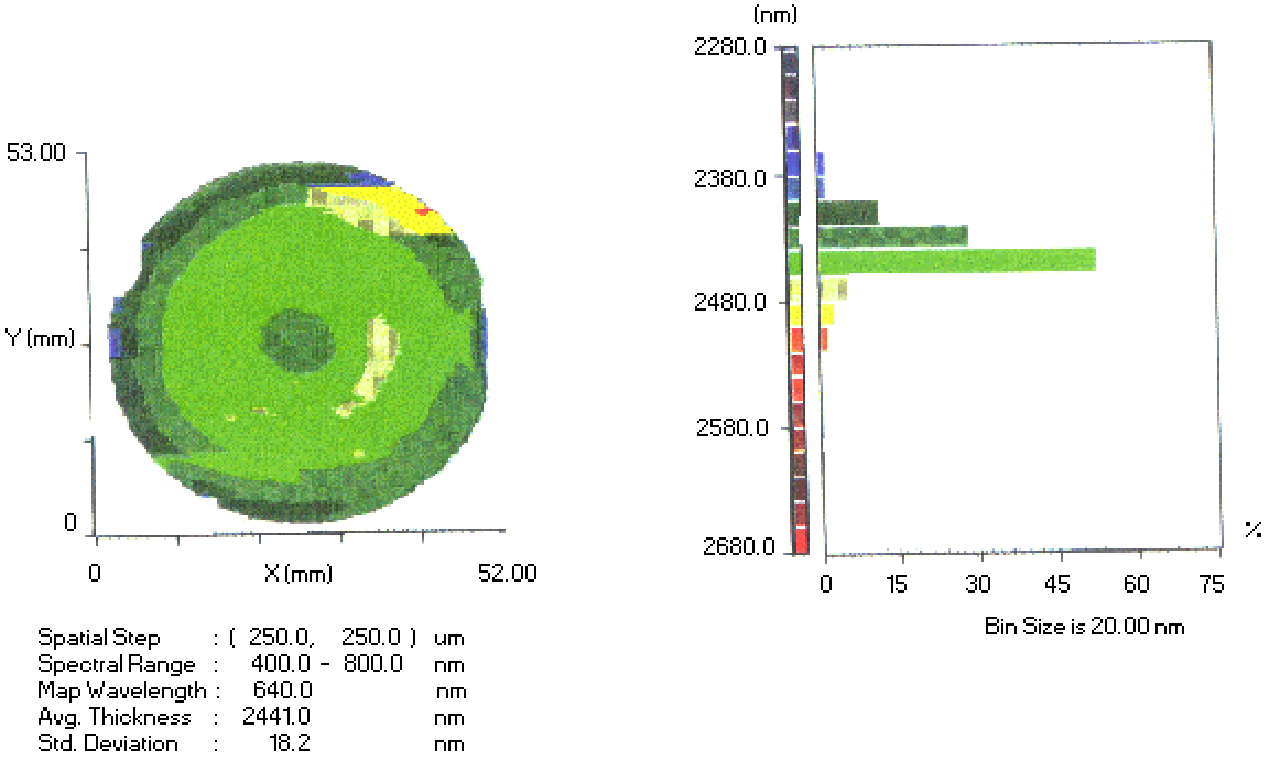
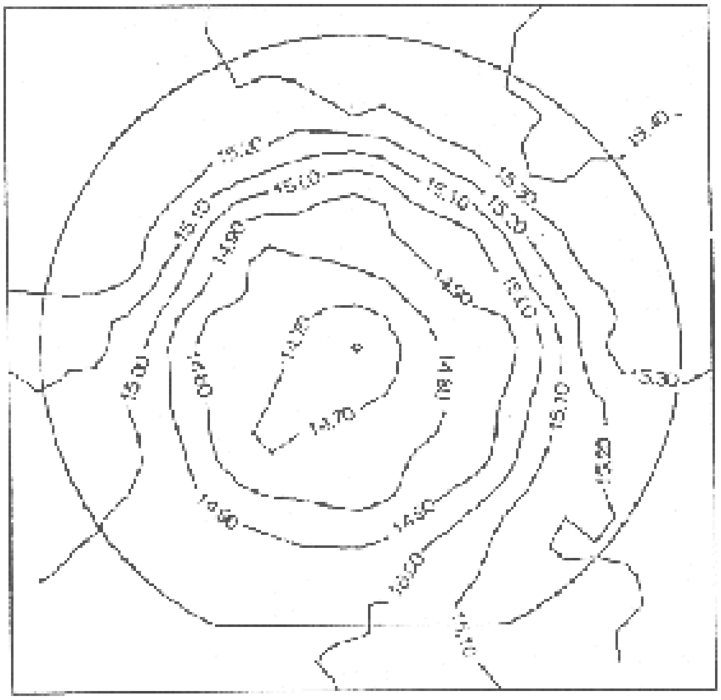


Figure 2. Photograph of an opened AIX2000HT reactor.



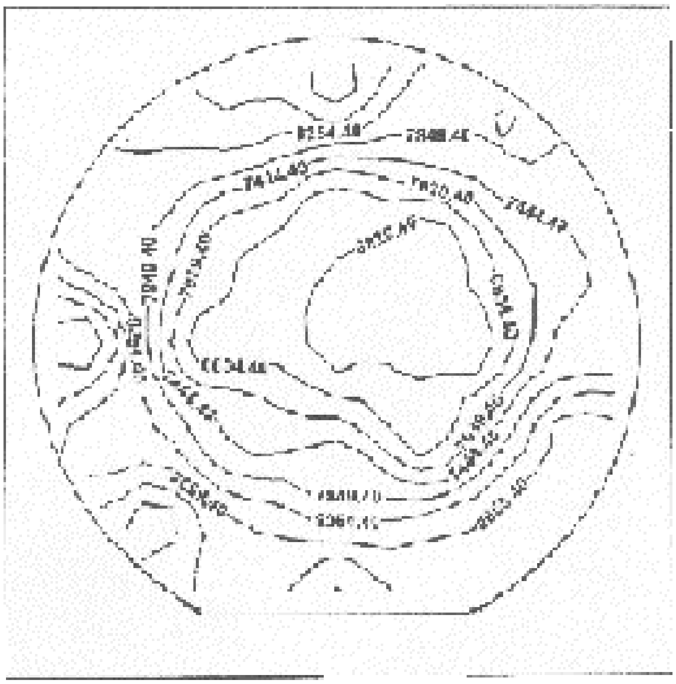
Spatial Step	: (250.0,	250.0)	um
Spectral Range	: 400.0 -	800.0	nm
Map Wavelength	: 640.0		nm
Avg. Thickness	: 2441.0		nm
Std. Deviation	: 18.2		nm

Figure 3. Thickness uniformity of a GaN-layer across a 2" wafer



Number of points	:	25
Average measurement	:	15.06 ohm/sq.
Max. value	:	15.43 ohm/sq.
Min. value	:	14.59 ohm / sq.
Variation in measurement	:	5.556 %
Std. dev. from avarage	:	0.25 ohm/sq.
Uniformity of wafer	:	1.66 %

Figure 4a. Sheet resistance map of a GaN:Si layer across a 2" wafer



Number of points : 25
Average measurement : 7871. ohm/sq.
Max. value : 9878. ohm/sq.
Min. value : 5824. ohm/sq.
Variation in measurement : 51.501 %
Std. dev. from average : 1260.23 ohm/sq.
Uniformity of wafer : 16.01 %

Figure 4b. Sheet resistivity map of a GaN:Mg layer across a 2" wafer

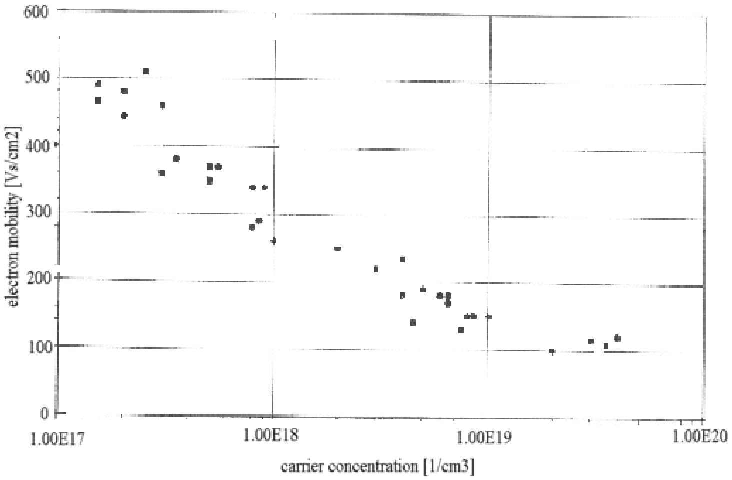
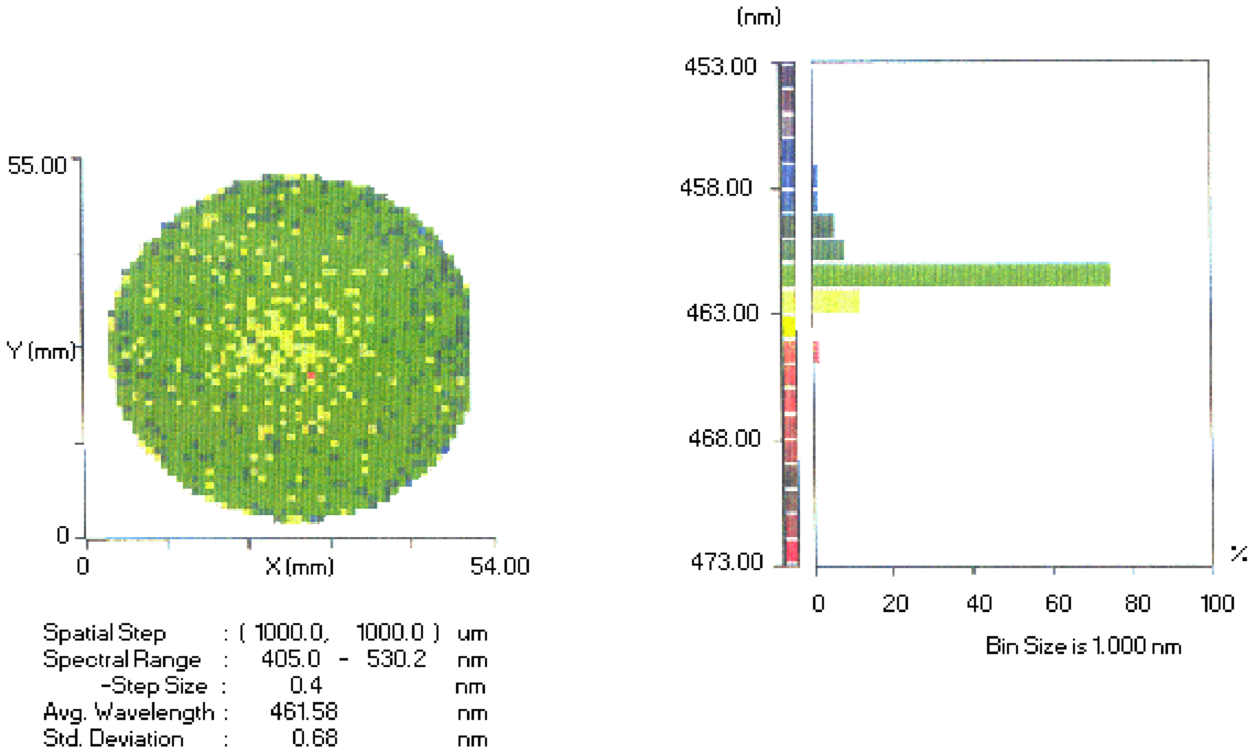


Figure 5. Electron mobility in dependence of carrier concentration for GaN:Si



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Spatial Step      : ( 1000.0,   1000.0 )  um
Spectral Range    :   405.0  -   530.2    nm
      -Step Size  :     0.4               nm
Avg. Wavelength   :   461.58              nm
Std. Deviation    :     0.68              nm
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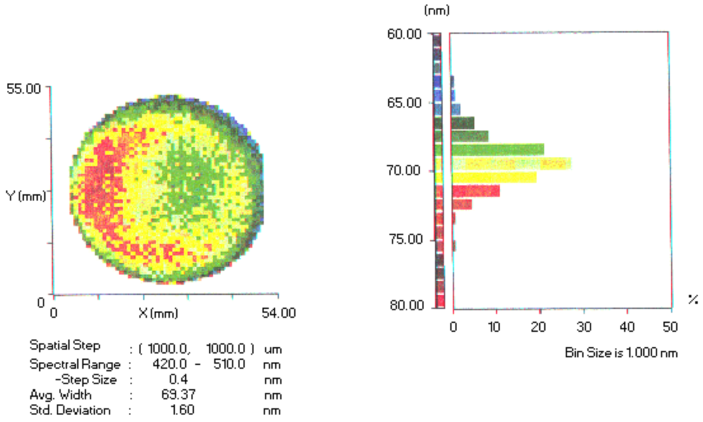
Figure 6. PL-emission wavelength map of high uniform InGaN



```
Spatial Step     : ( 1000.0,   1000.0 )  um
Spectral Range   :   420.0  -   510.0    nm
     -Step Size  :     0.4               nm
Avg. Width       :    69.37              nm
Std. Deviation   :     1.60              nm
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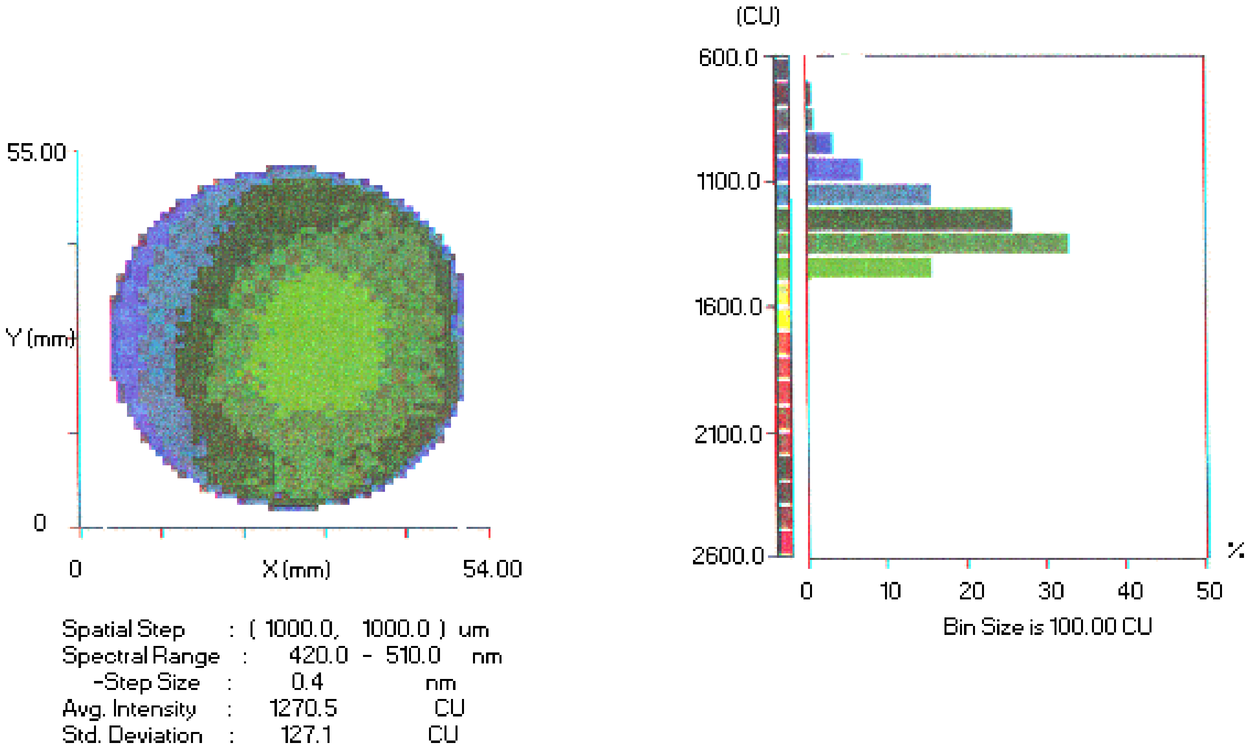
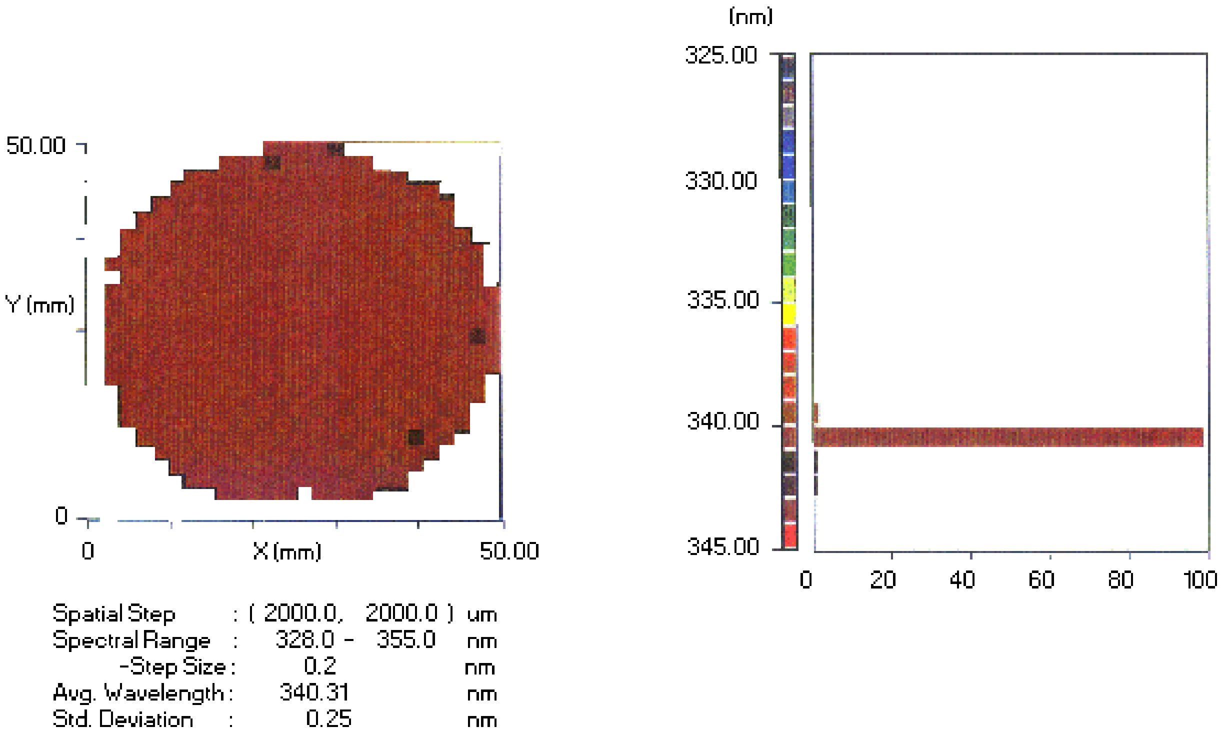
Figure 7. FWHM at peak wavelength of the InGaN layer shown in figure 6.



Spatial Step : (1000.0, 1000.0) um
Spectral Range : 420.0 - 510.0 nm
-Step Size : 0.4 nm
Avg. Intensity : 1270.5 CU
Std. Deviation : 127.1 CU

Figure 8. PL-intensity map of an InGaN layer across a 2" wafer



Spatial Step : (2000.0, 2000.0) um
Spectral Range : 328.0 - 355.0 nm
-Step Size : 0.2 nm
Avg. Wavelength : 340.31 nm
Std. Deviation : 0.25 nm

Figure 9. PL-map of peak wavelength across a 2" wafer with an AlGaN layer

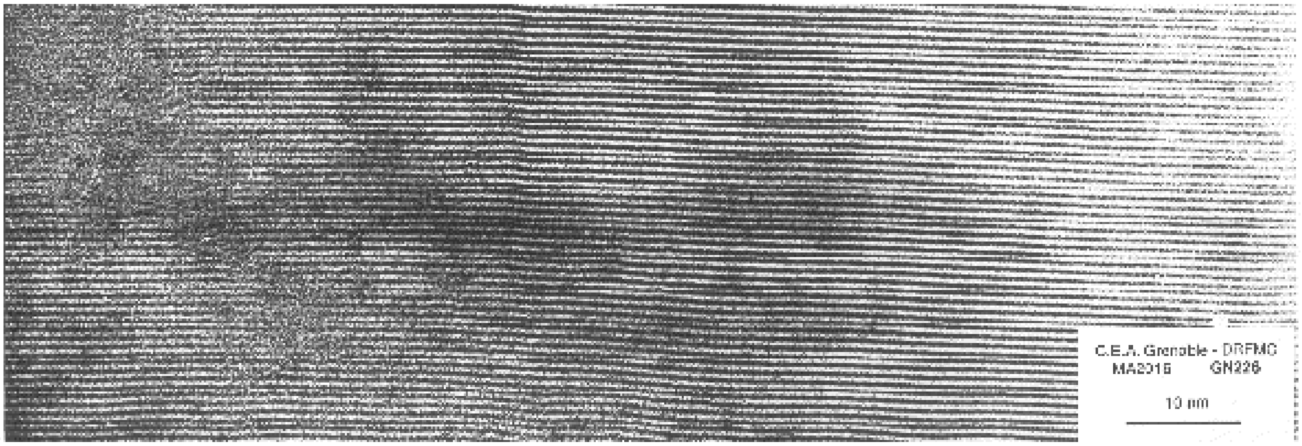


Figure 10. TEM image of an AlGaN/GaN multiquantumwell