Invited paper

OPTO-ELECTRONICS REVIEW **10**(4), 237–242 (2002)

Advances in MOCVD technology for research, development and mass production of compound semiconductor devices

K. CHRISTIANSEN, M. LUENENBUERGER, B. SCHINELLER, M. HEUKEN, and H. JUERGENSEN

AIXTRON AG*, Kackertstr. 15-17, D-52072 Aachen, Germany

The recent years have seen a continuous transfer of exciting new technologies from basic research institutions to high yield mass production and into our everyday lives. Devices made from novel semiconductor compounds can be found in products ranging from consumer electronics to high speed backbone communication networks. This includes high power infrared laser diodes for glass fiber applications, ultra-high brightness light emitting diodes for display and lighting, high power blue and UV laser diodes for mass storage as well as all types of transistors made from silicon, III-V compounds and silicon-carbide.

To facilitate the easy and straigtforward transfer from research scale experimental setups to large area substrates for mass production AIXTRON offers the whole scale of epitaxy solutions from single wafer systems to large scale production machines for up to 95 wafers. The easy configurability of the systems in terms of up-scaling of wafer sizes up to 7×6 inch for phosphides and arsenides and up to 8×4 inch for nitride materials in concurrence with easy maintenance, high reproducibility and high uniformity across the wafer and from wafer to wafer make the AIXTRON systems the ideal solution for mass production. The growth principle common to all AIXTRON MOCVD systems allows the easy up-scaling of established processes to larger configurations, even from single wafer AIX 200 systems to production type Planetary Reactors®.

Add-ons like in-situ monitoring of the growth process by reflectometry (EpiTune® I and EpiTune® II) or Reflectance Anisotropy Spectroscopy (Epi-RAS®) help in a considerable reduction of the development time and costs, hence improving innovation cycles and the time-to-market of novel devices since the growth of the material can be monitored in real time.

Keywords: MOCVD technique, doping uniformity, in-situ charactrization, GaN, AlGaAs, AlGaInP.

1. Introduction

Industry forecasts predict a steady growth of the compound semiconductor market due to a variety of applications accessible by these material systems. The worldwide optoelectronic components sector with data transmission and data storage applications and the light emitting diode segment with predicted growth rates of up to 40% and over 24%, respectively, account for the lion's share of this total predicted growth [1,2,3]. In- and outdoor lighting, large scale video displays, infrared telecommunication for backbone data networks, mobile communication and data storage are among the applications relying on cheap, efficient and reproducible devices fabricated from III-V compounds. Equipment manufacturers must, therefore, provide the industry with the tools it requires to deliver these demands to compete in this interesting and fast growing market.

AIXTRON as the world's leading manufacturer of metal-organic chemical vapor deposition (MOCVD) equipment meets these demands by supplying the industry with multiwafer Planetary Reactors® with ever higher productivity. The productivity of an MOCVD system is primarily driven by the depositable wafer area, the uniformity across the wafers, their reproducibility from wafer to wafer and run to run, and the number of runs per day.

This paper elaborates on the achieved results for the material families of (Al)GaAs, GaInP, AlInGaP and (In)GaN, with a focus on electrical, optical and structural data. Van-der-Pauw Hall-effect measurements, non-contact sheet resistance mapping, room temperature photoluminesence (PL) mapping and high resolution X-ray diffraction (XRD) were used to quantify the results.

2. Experimental and results

2.1. Phosphorus and arsenic containing materials

GaAs-based HEMT and HBT target the market of 10 GBit/s amplifiers for metro area networks (MAN). The layout of such amplifiers requires the monolithic integration of active and passive elements requiring large area growth technologies with a focus on yield, reliability and uniformity. To meet these demands we have developed the AIXTRON Planetary Reactor®, which, in its 5×4 inch configuration, is already qualified for the production of InP-based HBTs for 40 GBit/s backbone data transmission amplifiers. To increase the wafer area depositable per run the 7×6 inch configuration was built.

*e-mail: info@aixtron.com
phone: +49-241-8909-0, fax: +49-241-8909-40

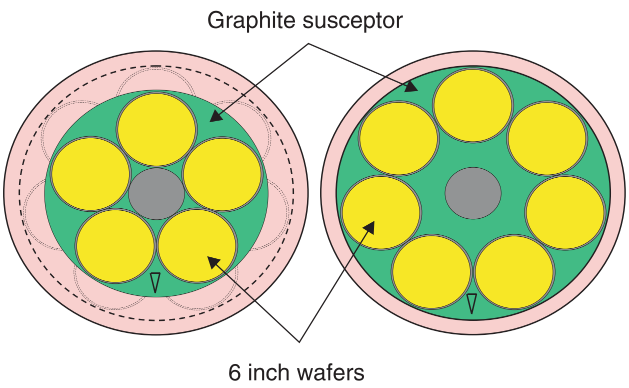

Fig. 1. Layout of the AIX 2600G3 susceptor in the 5×6 inch (left) and 7×6 inch (right) configurations.

Fig. 2. Photo of the reactor chamber of the AIX 2600G3 in the 7×6 inch configuration.

Figure 1 shows a schematic of the susceptor of the AIX 2600G3 in the 5×6 inch (left) and the 7×6 inch (right) configurations. Figure 2 shows a corresponding photo of the reactor chamber. The gases enter the reactor chamber through the central inlet in the reactor lid (not visible in the photo) and stream radially outward across the deposition zone. The susceptor is heated by RF induction heating from below and rotates at rotation frequencies of typically 10 rpm. In addition the wafer discs are rotating utilizing AIXTRON's patented Gas Foil Rotation® technique. This double rotation insures highest uniformities.

To assess the performance of the system for the growth of p-HEMT and HBT structures we have investigated the p- and n-type doping uniformities of GaAs, and the n-type doping of $Al_{0.3}Ga_{0.7}As$ and GaInP. Figure 3 shows the achieved on-wafer doping uniformities of GaAs on 6 inch of 1.24% and 1.1% standard deviation of the sheet resistance at carrier densities of 8×10^{17} cm^{-3} and 3×10^{19} cm^{-3} for n- and p-type, respectively. The corresponding wafer to wafer reproducibilites in the same run were of ±0.4% and ±0.7%, respectively. In analogous experiments n-type doping levels of 1×10^{17} cm^{-3} (σ_{onW} = 1.26%) and 1×10^{18} cm^{-3} (σ_{onW} = 3%) were achieved for $Al_{0.3}Ga_{0.7}As$ and GaInP, respectively. These values satisfy the demands of p-HEMT and HBT applications and insure excellent yield in mass production on large wafers.

Besides the need for excellent electrical data, the mass production of semiconductor devices demands the control of composition and thickness. Figure 4 shows the thickness uniformity of a 2 µm thick $Al_{0.3}Ga_{0.7}As$ layer on a 6 inch GaAs wafer. The standard deviation was determined to be 0.17%.

Low cost of ownership is dependent on the efficient utilization of the precursor materials, notably the metalorganic sources. By tuning of the total carrier gas flow the growth maximum of the semiconductor can be neatly tuned radially in the reactor chamber. To investigate the dependence of the growth rate on the position along the susceptor

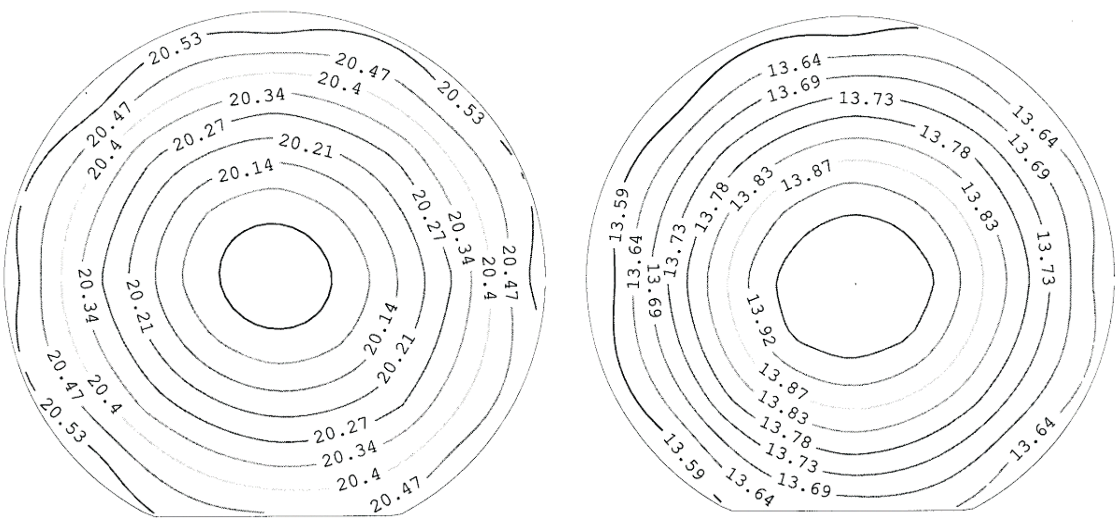

Fig. 3. Doping uniformities on 6 inch for n-type GaAs (left) and p-type GaAs (right). At 8×10^{17} cm^{-3} (n-type) and 3×10^{19} cm^{-3} (p-type) standard deviations of the carrier concentration of 1.24% and 1.1% were achieved, respectively. The uniformity from wafer to wafer was within ±0.4% and ±0.7% for n- and p-type material, respectively.

 © 2002 COSiW SEP, Warsaw

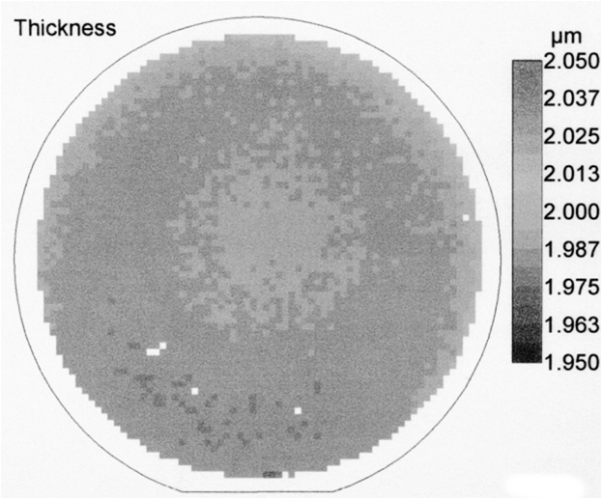

Fig. 4. Thickness uniformity of 6 inch $Al_{0.3}Ga_{0.7}As$. This 2 μm thick layer exhibited a standard deviation of 0.17%.

radius AlAs/GaAs distributed Bragg reflectors (DBR) were grown with one 6 inch disc intentionally stopped. High resolution X-ray spectra were recorded across the diameter of the 6 inch wafers which showed a decrease of the satellite spacing. This indicates a gradient in layer thickness, hence growth rate, from the center to the rim of the susceptor. This gradient can be utilized to tune the thickness uniformity by rotating the discs through the depletion gradient. In XRD profiles of a rotated 6 inch wafer from the same run the fringes are equidistant across the wafer diameter indicating an excellent thickness uniformity of the layers. The wafer appeared green to the unaided eye without any visible color changes and inhomogeneities. Reflectance measurements showed an average reflected wavelength of 552.4 nm with an overall standard deviation of 3.1 nm corresponding to 0.5%. The efficiency of the group-III precursors was found to vary with the carrier gas flow rate from 40% up to 54% with the highest values obtained at the low end of the carrier gas flow rate range.

With the 7×6 inch layout a valueable configuration is added to the repertoir of AIXTRON's Planetary Reactor® concept. The excellent homogeneities and reproducibilities known from other configurations offer the device manufacturer the possibility to expand his production capacity without the need for extensive process adaptations.

2.2. Nitrides

InGaN multi-quantum well (MQW) structures are at the heart of todays modern blue-green and white emitters. The market for conventional devices such as blue and green light emitting diodes (LED) as well as emerging applications like white lighting LEDs and blue to ultra-violett lasers, has grown steadily over the past years. Large area outdoor displays, indoor lighting as replacements for incandescent and flourescent lamps and blue-UV lasers for data storage are at the heart of the market. As for the phosphides and arsenides the demands for higher production capabilities increases with the introduction of larger wafer sizes. To meet these demands we have introduced the AIX 2000/2400/2600G3 HT MOCVD system which can be fitted with the 6×2, 11×2, 5×3, 7×3, 8×4 and 24×2 inch configurations. Thus, this system is capable to meet the needs of future applications such as high temperature and high frequency monolithic devices which will demand wafer sizes of at least 4 inch.

Figure 5 shows a photo of the AIX 2600G3 HT in the 24×2 inch configuration. To assess the performance of the system we have chosen to investigate the properties of 5 period multi-quantum-well (MQW) structures consisting of InGaN wells and GaN barriers emitting around 470 nm which is a prominent wavelength for blue LED applications. The entire quantum well stack was grown at constant temperature without temperature cycling between barrier and well. Figure 6 shows 24 PL mappings of wafers grown in the same run and their respective position on the susceptor. The InGaN material system is inherently sensitive to slight variations in process conditions due to the material's miscibility gap which is large in the middle of the In/Ga composition range. The mean wavelength over all wafers was 472 nm with a wafer to wafer standard deviation of 1.2 nm, or an equivalent of $\Delta\lambda_{max-min}$ = 4.2 nm, which are excellent values fit for mass production requirements.

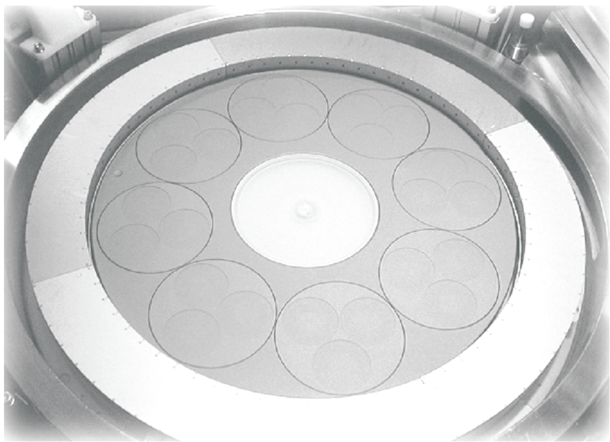

Fig. 5. Photo of the reactor chamber of the AIX 2600G3 HT in the 24×2 inch configuration.

Table 1 shows corroborative data for the run mentioned above and a second run at around 522 nm. The observed increase in spread with increasing wavelength results from increased phase separation for material approaching compositions in the middle of the miscibility gap.

Tab. 1. Typical on-wafer and wafer-to-wafer standard deviations of the wavelength for two different wavelength regimes. The structures consisted of 5 period multi quantum wells.

Wavelength	On-wafer std. dev. (typical)	W2W spread of mean value
472.2 nm	1.6 nm	±2.1 nm
522.3 nm	1.7 nm	±4.2 nm

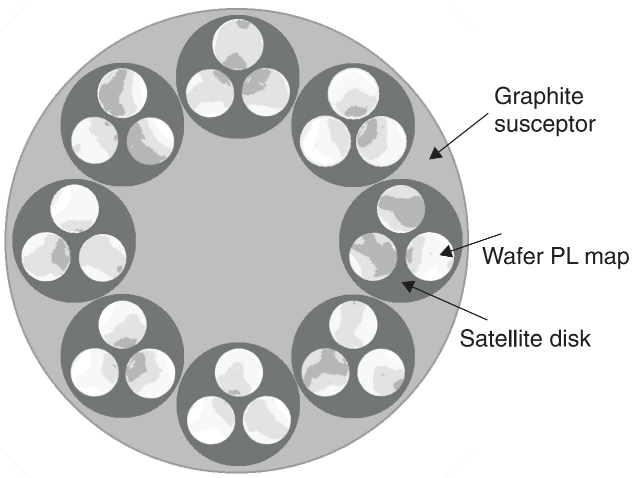

Fig. 6. PL maps of InGaN MQW structures at 472 nm grown in the same run as a function of wafer position on the susceptor. The minimum to maximum wavelength spread was 4.2 nm which corresponds to a standard deviation of 1.2 nm.

Optically pumped laser emission was investigated on similar MQW structures with differing In-concentrations. The highest achieved lasing wavelength was measured to be 469.5 nm at room temperature with a lasing threshold of 900 kW/cm^2 [4–6].

One additional important aspect of production yield is the reproducibility of the growth runs as a function of time. To assess the AIX 2600G3 HT's stability we have grown 7 consecutive runs using the same unchanged growth recipe. No etching or bakeout procedures were performed in between the individual runs. The wavelength stability of the MQW structures was measured using photoluminescence mapping. The evaluation yielded at mean wavelength of 461.8 nm and a spread of 3.9 nm from the maximum to the minimum wavelength. The distribution of the wavelengths as a function of the growth run was found to be statistical, hence indicating no drift of the system.

These results show that the AIX 2600G3 HT system is a tool that satisfies the industry's requirements for mass

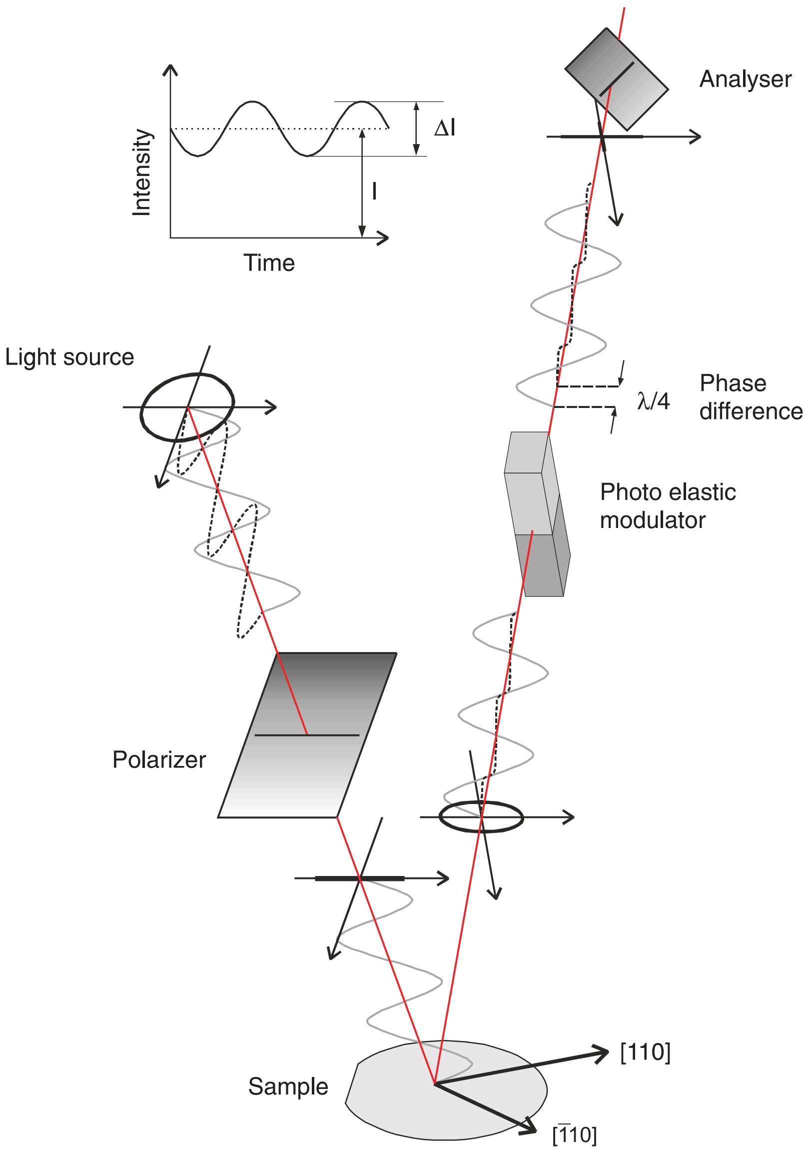

Fig. 7. Schematic of the principle of an RAS measurement.

 © 2002 COSiW SEP, Warsaw

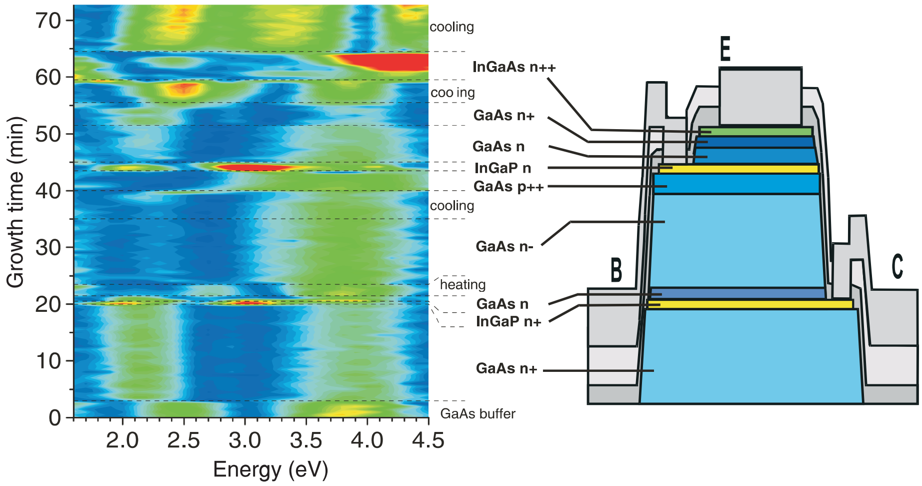

Fig. 8. In-situ monitoring by EpiRAS® in the example of a HBT layer structure (from).

production MOCVD systems in the fast and exciting field of group-III nitrides.

2.3. In-situ characterization

In-situ characterization, the ability to directly observe the growth of the semiconductor material in the reactor chamber, has been well known in molecular beam epitaxy (MBE) in the past. However, powerful methods of in-situ characterization have found their way into more production oriented growth methods like MOVPE. We developed different in-situ methods that both deliver valuable information on the growth of the layers and, therefore, speed up the optimization loops in the development of MOVPE processes. All methods can be used in small scale horizontal tube reactors as well as in large production type multiwafer systems. In the latter case each wafer can be measured and the obtained results can be assigned. This allows for a diagnostic of the wafers even before the growth run is finished.

Reflection anisotropy spectroscopy (RAS, EpiRAS®) measures the difference between the normal-incidence optical reflectance of light polarized along the two principal axes in the surface as a function of photon energy (Fig. 7). Since many semiconductors are cubic and therefore optically isotropic, only the anisotropy of the uppermost atomic layers will result in a change of polarisation. Therefore, the method is sensitive to the properties of the wafer's growth front and can give valuable information about the doping concentrations, the composition and the crystalline quality of the material. Figure 8 shows a false colour plot of the RAS signal for a GaAs/GaInP HBT run. The different layers are clearly identifiable in the time resolved false colour plot. The growth specialist can now utilize his database to speed up the optimization process for the device fabrication.

In the case of a material system with clearly different indices of refraction between an underlying layer and the layer to be probed, time-resolved Fabry-Perot like reflectance is utilized to determine the growth-rate and the crystalline quality of the growing wafers. These methods, *EpiTune® I* and *EpiTune® II*, can be applied in the case of nitride semiconductor structures where a step in refractive indices is present at the interface between the growing device structure and the sapphire wafer or in selected phosphorus and arsenic containing device structures. In addition, features in the traces at the beginning of the layer growth can be distinguished by the experienced process engineer, thus speeding up time to market for new processes and devices. Figure 9 exhibits such a trace for the case of an InGaN MQW structure as described above. The different steps like nucleation, anneal, buffer and MQW growth can be clearly distinguished.

In addition to the sole measurement of the reflectivity as a function of time, *EpiTune® II* offers the possibility to measure the emissivity corrected temperature for each wafer. A high repetition rate of the pyrometric temperature measurement and the probing of the reflectivity through the same optical path facilitate an accurate determination of the emissivity corrected temperature, since pyrometry and

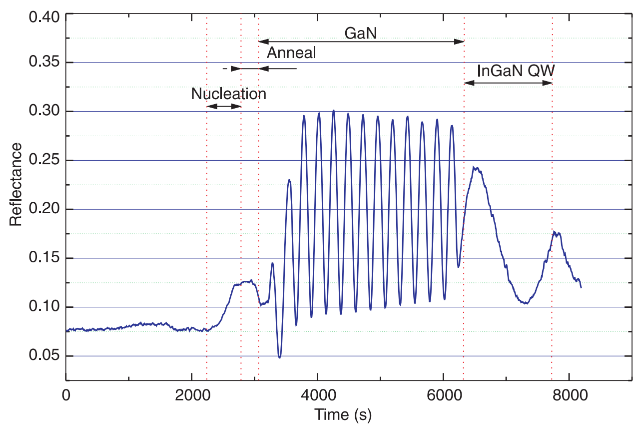

Fig. 9. In-situ reflectometry for an InGaN MQW growth run.

reflectometry are practically performed on the same point on the wafer.

In summary, these in-situ tools offer the possibility for efficient process development and monitoring, since the material can be observed directly during the growth process. In process development the fine tuning of process parameters can be directly evaluated in the observed spectra and traces saving cost and time and guaranteeing a quick time-to-market of new devices. In addition, a quick and reliable method of yield evaluation and process stability control can be established in the fab, since the in-situ measurement results are stored for each wafer individually, allowing an easy tracebility of device results to epitaxial growth. This enhances the accuracy of yield prediction even before a wafer is processed into devices, thus lowering production costs and increasing a stable device production output.

3. Conclusion

MOVPE has established itself as the method of choice for mass production of modern compound semiconductor devices. The easy transferrability of process conditions from tool to tool, the hands-on control of processes by direct monitoring of the growing layer, the low cost of ownership, the high yield and the high volume throughput that the Planetary Reactor® MOVPE growth technique offers are among the main deciding factors for the choice of Planetary Reactor® MOVPE for the industry's production capabilities.

References

1 ElectroniCast, *Compound Semiconductor Magazine* **8**(2), 26, (2002).

2 According to Investec Inc., Equity Research, July 16, 2002

3 Strategies Unlimited, presented at Strategies in Light 2002, Feb. 6-8, 2002.

4 G.P. Yablonskii, E.V. Lutsenko, V.N. Pavlovskii, I.P. Marko, A.L. Gurskii, V.Z. Zubialevich, O. Schoen, H. Protzmann, M. Luenenbuerger, B. Schineller, and M. *Heuken, Phys. Stat. Sol.* (a) **188**, 79 (2001).

5 G.P. Yablonskii, E.V. Lutsenko, V.N. Pavlovskii, I.P. Marko, A.L. Gurskii, V.Z. Zubialevich, A.V. Mudryi, O. Schön, H. Protzmann, M. Luenenbuerger, B. Schineller, M. Heuken, H. Kalisch, and K. Heime, *Appl. Phys. Lett*. **79,** 1953 (2001).

6 B. Schineller, H. Protzmann, M. Luenenbuerger, G. Gerstenbrandt, M. Heuken, G.P. Yablonskii, A.V. Mudryi, E.V. Lutsenko, V.N. Pavlovskii, and V.Z. Zubialevich, presented at the *Inter. Conf. on the Physics of Semicond*. (ICPS), Edinburgh, Scotland.

7 B. Schineller, H. Protzmann, M. Luenenbuerger, G.P. Yablonskii, E.V. Lutsenko, V.N. Pavlovskii, V.Z. Zubialevich, M. Heuken, and H. Juergensen, presented at the *Inter. Conf. on Nitride Semiconductors* 4 (ICNS 4), Denver, Colorado, USA.

8 B. Schineller, H. Protzmann, M. Luenenbuerger, G. Gerstenbrandt, M. Heuken, E.V. Lutsenko, V.N. Pavlovskii, V.Z. Zybialevich, and G.P. Yablonskii, presented at *EXMATEC 2002*, Budapest, Hungary.

9 J.-T. Zettler, K. Haberland, M. Zorn, M. Pristovsek, W. Richter, P. Kurpas, and M. Weyers, *J. Crystal Growth* **195**, 151 (1998).

 © 2002 COSiW SEP, Warsaw