Design and Applications of Large Area RDRs

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In recent years, MOVPE has become a versatile and economic production technology for most compound semiconductor applications. At EMCORE we continue to develop and improve high-speed Rotating Disk Reactors (RDRs). Our reactor technology has become accepted worldwide for high-throughput single and multi-wafer MOVPE systems. Our system is configured in accordance with the productivity and user friendliness of Si device processing equipment.

Various traditional MOVPE reactor technologies are contrasted in Figure 1a through 1d and the cover photo; RDRs have inherent advantages in flow dynamics that enable growth to be laterally uniform, abruptly switchable, and robust against variations in process parameters [1]. To produce high quality materials, we have developed precise pressure/flow (carrier and reactants) control with high speed pressure balanced gas switching, materials of construction that minimizes chemical memory, sharp reactant concentration transitions, and uniform temperature in the deposition region, among other capabilities. These capabilities are needed to repeatedly produce films of uniform thickness and composition, with atomic layer interfaces, and sharp dopant and alloy transitions.

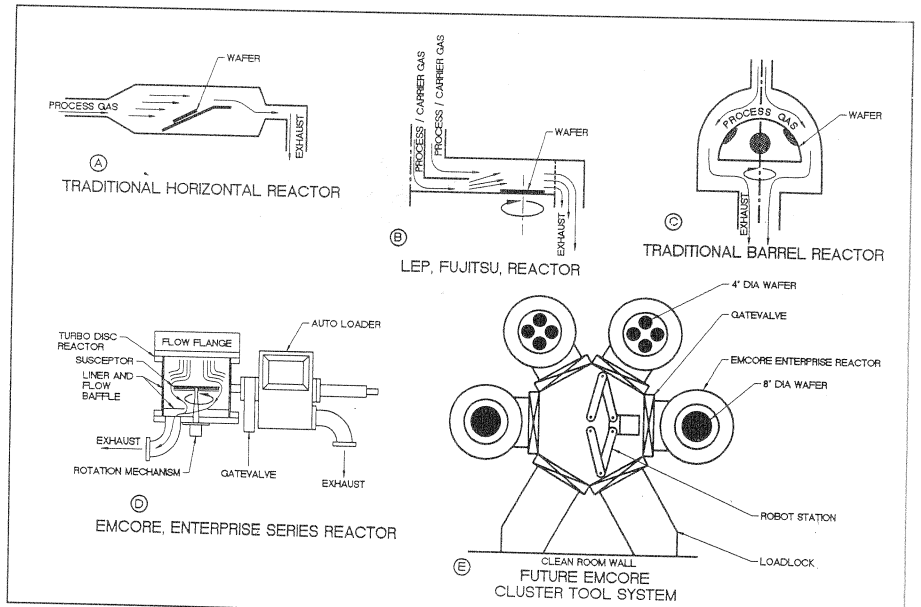
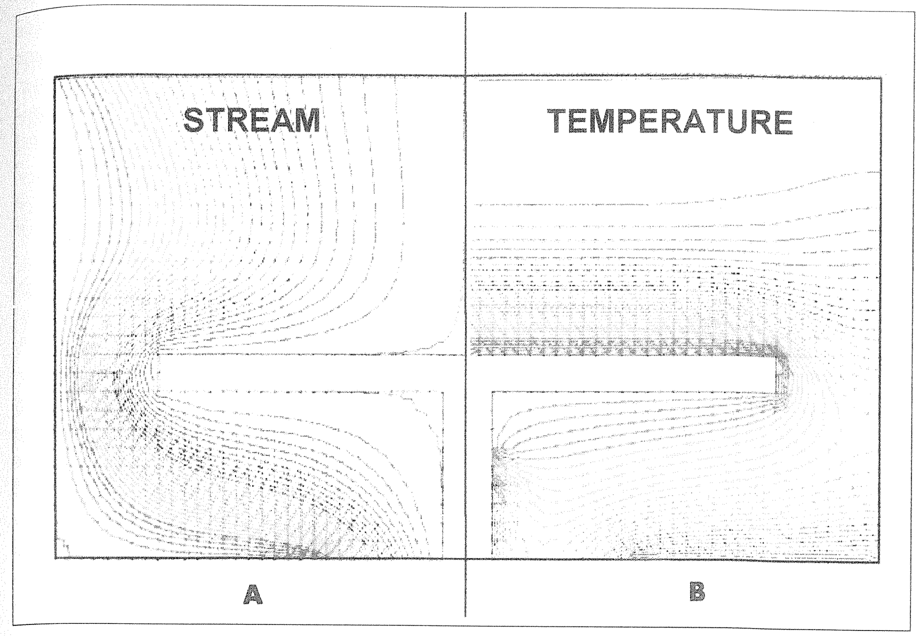


Figure 1. Schematic comparison of MOVPE reactor geometries: (a) traditional horizontal tube reactor, (b) horizontal reactor with planetary rotation, (c) traditional barrel reactor, (d) conventional, loadlocked, high speed RDR, and (e) future cluster tool configuration of RDRs.

In addition to the advantageous reactant flows in RDRs, the sharp temperature gradients associated with the flow dynamics of the RDR minimiz particulate incorporation via the thermophoresis effect [2]. The reactant input distribution is adjustable for uniformity and the two eactant streams are kept separate until just above wafer surfaces by the flow dynamics, minimizing all pre-reactions. This is particularly important for materials such as InGaP, GaN, and other materials produced with highly reactive precursors.

The stainless steel construction, modularity and MESC compatibility allow for the immediate integration of our RDR systems with silicon device processing cluster tool platforms, process modules and analytic stations. The cluster tool platform configuration (shown in Figure 1e) can be used with 4 to 8 facets (tool ports), upon which additional modules, wafer holding stations or loading/unloading modules can be mounted. The central robot can transport wafers or platters up to 200 mm (8-in) in diameter from any location in the system to any other location or cassette. Thanks to the MESC standards the same system configuration will be compatible with the next generation of cluster tools which handle 300 mm (12-in) or even 400 mm (16-in) substrates.

By scientifically engineering our RDR systems we have been able to produce the broad range of materials listed in Table I. In particular, recent developments include growth of GaN, SiC and $BaSrTiO_3$. The symmetric design is particularly well suited to the implementation of non-intrusive optical and gas in-situ monitors for real time process control.



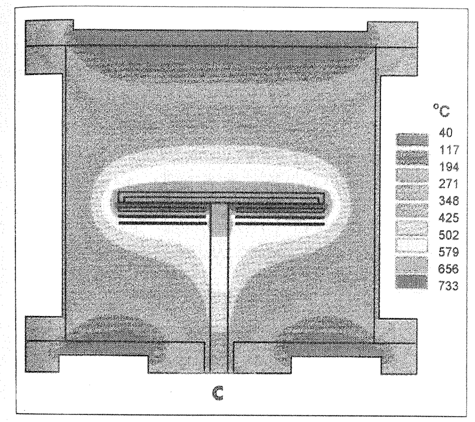


Figure 2. Computational fluid dynamical modeling of RDR showing (a) dynamic contours of stream and (b) showing dynamic countours of temperature, (c) shows static thermal modelling of the system.

In addition to the excellent material results, RDRs are engineered to meet the financial needs of device manufacturers. Cost-effective production requires:

1. Systems that can simultaneously deposit uniform layers over multiple wafers, for long deposition processes, or high throughput batch or single wafer systems which address device structures with short deposition cycles,

2. Sophisticated process control that guarantees reproducible and flexible growth of the complex semiconductor alloy ultra-structures required by advanced microelectronic and photonic devices, and ultimately

3. Integration into computerized manufacturing lines with industry standard cluster tools for automated manufacturing.

MOVPE RDRs are an eloquent and rugged solution to present and future production needs.

Experiment

All the experimental results reported in this work were achieved either on a Discovery pilot production or on an Enterprise production series RDR system installed in the EMCORE Research Laboratory. The generic reactor assembly has been described in the past and will be briefly reviewed here. The growth reactor, as shown schematically in Figure 1d, is of stainless steel configuration with moybdenum support members in the hot zones. For the III-V results reported here, a fixed graphite filament is used to radiatively heat the 175 mm or 300 mm diameter rotating wafer carrier assembly. Alternatively, if higher temperatures are required, say approaching 1600°C for SiC, the radiative filament is replaced by an rf inductively coupled heater. TMI, TMGa, TMAl, PH_3, NH_3, and AsH_3 were used as the precursors and hydrogen as the carrier gas for III-V and nitride film deposition. The AlAs/GaAs Bragg reflector was grown typically at 675°C, InGaP typically at 670°C and InGaAlP at 770°C. The GaN films are formed at 1050°C and SiC at 1350 to 1600°C. The rotation rate was varied from 400-800 rpm, the pressure from 15-80 Torr and the total flow from 20-50 slm. Oxide results are

Table I. Partial listing of the materials grown in EMCORE RDR systems [3-7].

	Grown Materials
IV-IV	Polysilicon, SiC, Diamond, SiGe
III-V	GaAs, AlGaAs, InP, InGaAsP, InGaP, InGaAlP, InSb, GaN,
II-VI	ZnSe, CdTe, HgCdTe, ZnTe, CdZnTe, CdSeTe
METALS	Al, Cu, W, Pt
OXIDES	YBCO, $BaTiO_3$, MgO, ZrO, SiO_2, ZnO, ZnSiO, $SrTiO_3$,

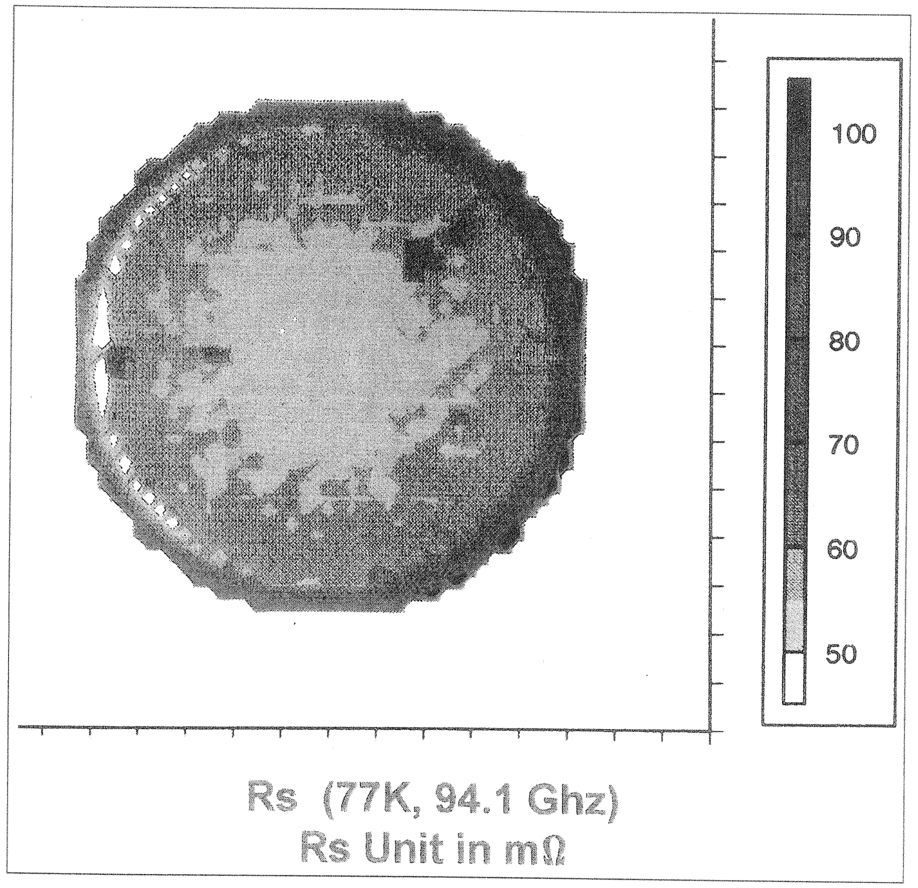


Figure 3. Microwave surface resistance uniformity: mapping of superconducting 2-in diameter $YBa_2Cu_3O_7$ film.

produced with a wide variety of reactants and N_2O or O_2 as the oxidizer with or without plasma enhancement.

A sophisticated real-time hierarchical process control system enabled the flexible and reproducible growth of the structures. A proprietary PC-based spreadsheet schedules run parameters. A dedicated technology display system continuously depicts, records and monitors the system events and a dedicated PLC controls process steps. The control system monitors and maintains all process parameters and notifies the user of any irregularities. The data logging features allow for monitoring of the system economics, predictive maintenance and source change-out, as well as development of operating statistics.

Results

In designing our production system, we have used extensive experimentation, as well as thermodynamic and computational fluid dynamic modeling tools, to ensure laminar flows, proper reactant distribution, and thermal uniformity across the deposition area. Extensive modeling of RDRs has been performed by several organizations including EMCORE, CREARE and Sandia National Laboratories. Such modeling studies confirmed that our RDR systems are scalable to larger dimensions. Figure 2 a and b shows the dynamically modeled contours of steam and temperature. The insert in Figure 2 shows the thermal characteristics of a water cooled reactor at typical III-V deposition temperatures.

The breakthrough of Nichia's GaN Blue LED [8] has stimulated great interest in an MOCVD-based GaN production technology. For the present, this production technology addresses high brightness blue and green LED technology. Due to the high growth temperature and high volume of ammonia required for MOCVD growth of GaN, recirculation and premature gas phase reaction have been a primary concern for reactor design. A low mixed convection parameter is produced by utilizing a high rotation rate of the disk and therefore laminar flow is obtained even at temperatures as high as 1600°C (more than sufficient for carbides and nitrides).

By operating at reduced pressures (< 76 Torr), the gas phase reactions can be reduced while maintaining high growth rate (thin boundary layer), in a high speed RDR. Based on this principle, we have grown highly uniform transparent GaN films on (001) Al_2O_3 at temperatures > 1000°C with smooth surface morphology, good crystallinity and a low doping background [7].

Table II. Heteroepitaxial Oxide Material Structures.

Heteroepitaxial Growths	Substrates (100)
(001)YBCO.(100)$SrTiO_3$/(001)YBCO	$LaAlO_3$
(001)YBCO/(100)$SrTiO_3$/(001)YBCO/(100)CeO_2 >	YSZ
(001)YBCO/(100)CeO_2(001)YBCO	$LaAlO_3$
(001)YBCO/(100)CeO_2/(001)YBCO/(100)CeO_2	YSZ
(100)Pt/(100)$Ba_{0.8}Sr_{0.2}TiO_3$/(100)YBCO	$LaAlO_3$
(100)Pt/(100)$Ba_{0.8}Sr_{0.2}TiO_3$/(100)Pt	MgO
(001)YBCO/(100)$SrTiO_3$	$LaA1O_3$
(001)(YBCO/(100)CeO_2	$LaAlO_3$
(100)$MgAl_2O_4$	Si
(100)MAl_2O_4/(100)CeO_2	YSZ or $LaAlO_3$
(001)YBCO/(110)MgO	m-plane Sapphire

This series of reactors which can simultaneously deposit on up to 6-50 mm wafers or 3-75 mm wafers, and uses a loadlock for rapid turn around.

EMCORE's Discovery series 5000 oxide systems, which hold 1-125 mm or 3-50 mm substrates, have achieved major breakthroughs in the deposition of advanced oxide thin films by MOCVD and plasma-enhanced MOCVD (PE-MOCVD). The Series 5000 systems are designed with complete process control capabilities, including high temperature source operation for production of the following thin film materials: Y-Ba-Cu-O (YBCO), Bi-Sr-Ca-Cu-O (BISSCO) superconductors, Ba-Ti-O (BTO), Sr-Ti-O (STO), Ba-Sr-Ti-O (BST), Ta_2O_5 dielectrics, Pb-La-Ti-O (PLT), Pb-Zr-Ti-O (PZT) ferroelectrics, K-Nb-O ($KNbO_3$), Li-Nb-O ($LiNbO_3$) nonlinear optical materials, and template layers such as CeO_2, $MgAl_2O_4$, MgO, and Y-stabilized ZrO_2.

Moreover, the Research Lab at EMCORE has been dedicated to developing the systems and process technology for MOCVD processing of advanced oxide materials for over five years. Deposition of heteroepitaxial trilayered structures of YBCO/$SrTiO_3$/YBCO was successfully demonstrated by this group using all MOCVD processing. This is the first demonstration showing that MOCVD is capable of integrating dissimilar oxides for device applications. In addition, large-area depositions (up to 5-in wafers) of high quality epitaxial YBCO films, heteroepitaxial YBCO/$SrTiO_3$/YBCO trilayer structure, high permittivity $Ba_{1-x}Sr_xTiO_3$ (BST) films, epitaxial Pt thin films, low permittivity $MgAl_2O_4$ films, and lattice template layer such as CeO_2 and MgO have been accomplished by EMCORE's Research Laboratories group.

BST growth over 5-in diameter areas has been demonstrated with thickness uniformity of 1.6% at an average thickness of approximately 1250 Å. BST thin films have excellent dielectric and insulating properties for device applications, (particularly DRAMS). The relative permittivity of the MOCVD BST thin films is in the range of 600-800 at zero bias-field and in the frequency range of 100 kHz - 1 MHz. The leakage current through the BST thin films were no higher than 8 x 10^{-8} A/cm^2 at 2 V operation.

EMCORE has also developed YBCO deposition process. Thickness uniformity of 1% across 75 mm diameter $LaAlO_3$ substrates has been demonstrated for YBCO growth. The film thickness is about 4200 Å. the surface resistance, Rs (77K, 95 GHz) mapping data show that the BYCO wafers have single Rs value of 50 across the 75 mm diameter wafers except the areas within 5 mm away from the wafer edge. The critical current density, Jc (77K, 0T) and transition temperature, Tc, of the YBCO films are 2-4 x 10^6 A/cm^2 and 89-90 K, respectively, across the wafers.

Currently, EMCORE is collaborating with Westinghouse on high-TC superconductivity, and is producing substrates with both front and backside coatings of films which demonstrate the properties mentioned above. Figure 3 shows the microwave surface resistance uniformity on a 50 mm $YBa_2Cu_3O_7$ wafer.

Through our modelling and experimental efforts, we have scaled our 175 mm diameter reactors to a larger geometry, high throughput Enterprise production system, which can sequentially process 300 mm (12-in) diameter susceptors that hold either of 17-50 mm, 4-100 mm or 1-200 mm substrates. We have also used finite element analysis to determine the static heat flow characteristics of the mechanical members of the reactor.

As previously mentioned, an important design goal was to achieve a uniform substrate temperature. A keynote of the EMCORE design success story has been the matching of experiment to theory. A recent innovation at EMCORE has been the ability, for the first time, to thermally map the temperature uniformity of the wafer and wafer carrier while under full rotation. By using this technology we have truly produced temperature uniformities of ±1-2°C on 2" and 4" wafers in our ENTERPRISE and Discovery systems. Figure 4 shows such a thermal mapping under operating conditions. Figure 4a and b, shows the temperature distribution for 50 mm and 100 mm diameter substrates dynamically imaged on the rotating wafer carrier under gas flow conditions using a scanning pyrometric technique. The sharp wafer to substrate temperature jump is an artifact of the difference in emissivity between the materials. We have demonstrated that a multi-zone heater produces a temperature uniformity which is < ±2°C for the 100 mm diameter wafer and < ±1°C for the 50 mm diameter wafer over the temperature range from 500°C to 900°C. The wafer image is distorted by the "rectangular" mapping of the rotating wafer carrier. To the best of our knowledge this is the first thermal imagery and measurement of a dynamic (rotating @ 1200 rpm) CVD wafer carrier. The details of this experimental set-up are reviewed in upcoming papers to be published [9].

Bragg reflectors

The major device application for Bragg reflectors is in vertical cavity surface emitting lasers (VCSEL) where the mirrors must have extremely high reflectance and be extremely uniform, and for the LED's reflecting buffer layers [10]. Another application of Bragg reflectors that

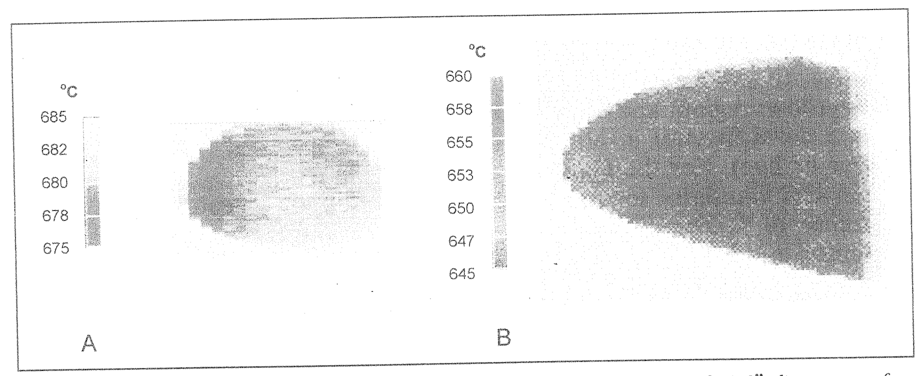
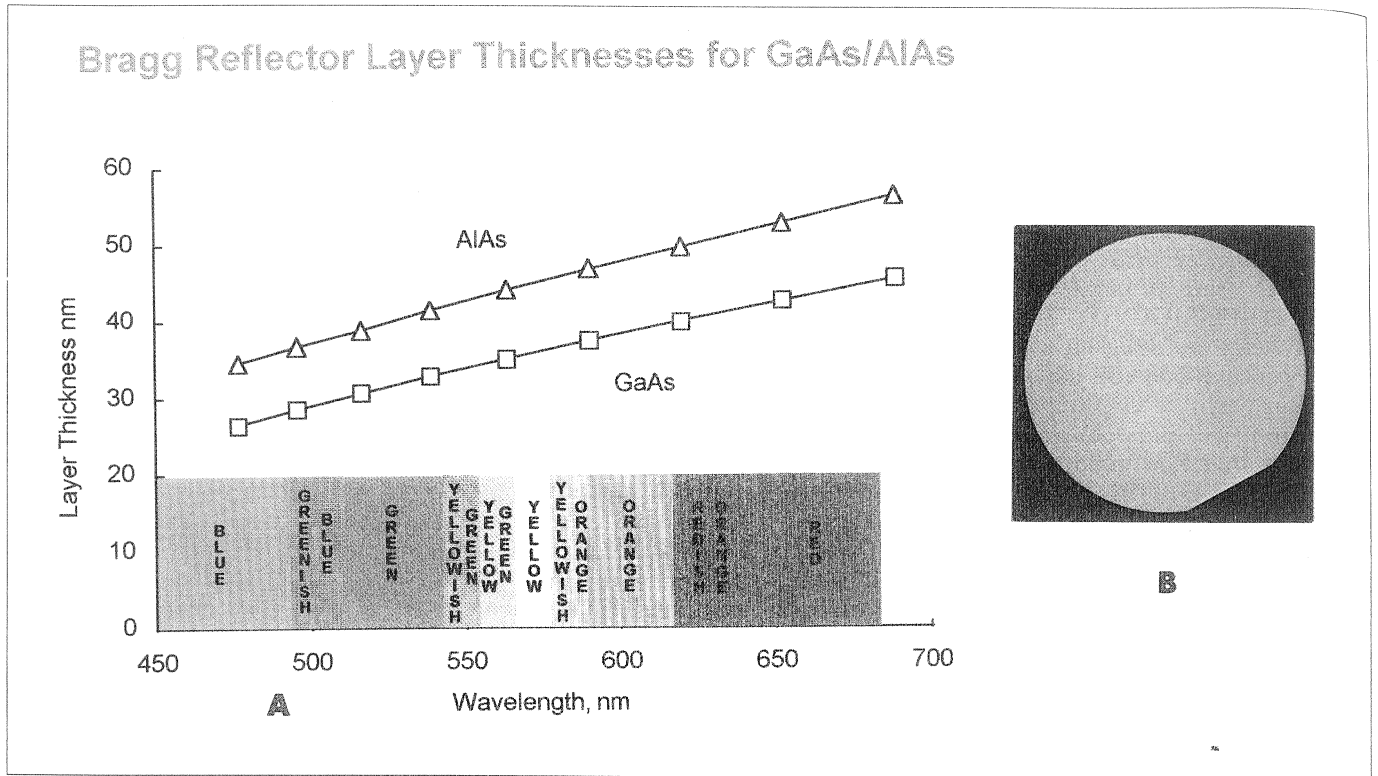


Figure 4: Real time, dynamic thermal imaging of temperature uniformity of a) 2" diameter wafer showing < ±1.3°C and b) 4" diameter wafer (showing < ±2.5°C: both under flow and rotating at 1200 rpm using multizone heater.



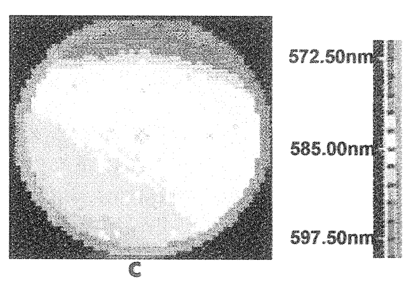


Figure 5. (a) Colour (or hue) sensitivity chart for AlAs/GaAs Bragg reflectors and, (b) photograph of a typical 100 mm AlAs/GaAs Bragg reflector produced in the ENTERPRISE system and 5c is a reflection mapping of the film.

has met widespread acceptance is their use for evaluating deposition uniformity for MOCVD and MBE systems. This is a rapid, low cost and sensitive technique if the layer thicknesses are chosen so that the reflectance maximum falls in the visible region.

The use of Bragg reflectors to demonstrate uniformity compares favourably with other techniques but does not give an absolute thickness. Figure 5 shows the calculated thicknesses needed for GaAs and AlAs [11], taking into account the variation of refractive index with wavelength [12].

The typical human eye is most sensitive to colour change in the green-yellow region and can easily see a 5 nm difference in wavelength (colour or hue). For the GaAs/AlAs system this translates to a thickness difference of -1.2%. EMCORE has demonstrated the growth of multiple 50 mm, 75 mm and 100 mm wafers with GaAs/AlAs Bragg reflectors, across the spectrum, showing better than 1% uniformity. We have previously used TEM studies to demonstrate that RDR systems can also produce monolayer abrupt interfaces [13]. Figure 5b is a photograph of a typical 100 mm yellow-green 20 period Bragg reflector, one of four wafers simultaneously produced in the ENTERPRISE system. Figure 5c is a mapping of the reflectance spectra of a similar 100 mm Bragg wafer showing <0.9% peak wavelength reflectivity uniformity. SEM thickness uniformity measurements of a thick film, (taken along the 100 mm wafer diagonal parallel to the susceptor diameter), also confirms the thickness uniformity. We find that the thickness uniformity can be easily adjusted by controlling the reactant distribution into the reactor. This adjustment is relatively insensitive to process temperature and is typically only changed for widely different material systems.

In addition to deposition of GaAs/AlAs in our new large system, we have also deposited InGaP on multiple 2-in wafers. After only a few runs, we have been able to demonstrate uniform, morphologically smooth and highly crystalline lattice matched films. PL mapping confirms that less than 1 nm uniformities can be produced in this difficult material system. The PL uniformity implies a high degree of compositional uniformity control as 1.0 nm wavelength control corresponds to -0.2% in the In molar fraction.

Environment

An important concern for the compound semiconductor industry is the environmental impact of device processing [14]. With reactant efficiencies exceeding 40% matched with a well proven effluent scrubbing system and short cycle times between growths using the loadlock, the production cost per wafer and the environmental impact are found to be dramatically lower than in competitive system technologies.

The high utilization efficiency makes this system ideal for use of alternative and highly expensive reactants. The high reactant efficiency results in a clean system which does not require opening for several hundred microns of deposition. This is extremely important because it minimizes process down-time and increases user safety. To extend operation even longer we have borrowed from Si device processing technology and demonstrated, in the past [15], in-situ plasma cleaning of our reactors. Figure 6 shows an example of etching rates at the base of the reactor when a plate electrode is used at the base of the reactor.

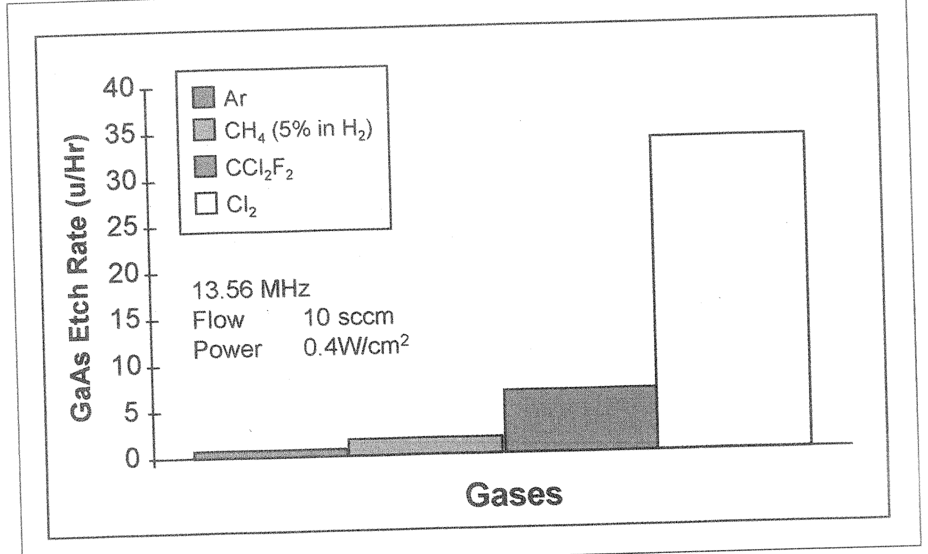


Figure 6: Etching rate for 4 different gas mixtures.

Costs

An ever important factor to producers is the ability to choose the correct reactor to meet production needs. EMCORE has developed a Cost of Ownership (COO) model which encompasses the system and operational costs as a function of projected throughputs.

Key inputs to a COO are capital costs, throughput, up-time, process, consumables, and gas utilization. Statistical operational data in combination with actual component maintenance are used in uptime calculations. This established spreadsheet program is an invaluable tool in choosing an optimum processing technology.

Using proven process data, it is simple to confirm that millions of square inches of epi can be produced per year in a cluster tool operation. Complete understanding of true cost of ownership matched with system flexibility are the important factors governing value and productivity.

Summary

In conclusion, modelling and experimental techniques were used to scale a RDR to form a large area production scale system which efficiently delivers uniform films over large areas in both GaAs/AlAs and InGaAlP materials. This production system triples the deposition area of the well established EMCORE GS/3300 reactor (7-in diameter susceptor). RDR systems, in general, have been shown to meet the needs of a wide variety of material systems, as listed in Table I and II. The process parameters have scaled in accordance with theory and experience. With total flows of -50 slm and a growth pressure in the -15-30 Torr range, we have produced a variety of films with <0.9% thickness uniformity and with a high degree of compositional uniformity.

We have developed a RDR technology that produces superior results on compound semiconductors and related materials and is immediately compatible with established silicon processing tools. By forming a generic MESC-compatible platform for compound semiconductor production we have developed the first true production tool for these strategic materials. RDR systems are now compatible with automated wafer handling which opens the door to the next generation of compound semiconductor device production.

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References

1. C. Biber, et al., J. Crystal Growth, 123 (1992) p. 545-554. W.G. Breiland and G.H. Evans, J. Electrochem. Soc. 138 (6) (1991) p. 1806-1816. G.S. Tompa, et al., J. Crystal Growth, 93 (1988) p. 220-227.

2. R.W. Davis, E.F. Moore, and M.R. Zachariah, J. Crystal Growth, 132 (1993) 513-522; D.I. Fotindas and K F Jensen, J. Crystal Growth 102 (1890) p743.

3. J.M. Dallasásse et al., J. Appl. Phys. 66 (2) 1989; 482-487; N. Holonyak Jr., et al., App. Phys. Lett., 54 (11) 1989 p. 1022-1024., G.S. Tompa et al., J. Crystal Growth 93 (1988) p. 228.

4. P.L. Anderson et al, J. of Crystal Growth, in press 1994; G.S. Tompa et al., Appl. Phys. Lett. 55 (62) (1989). G.S. Tompa et al., J. Crystal Growth 107 (1991) p. 198-202.

5. K.H. Young, et al., Appl. Phys. Lett. 61 (5) 1992; W.J. DeSisto et al., Appl. Phys. Lett. 60 (23) 1992; P.A. Zawadzki, J. Elec. Mat. V19 N4 (1990) p357-362.

6. R.A. Stall et al., Mat. Res. Soc. Proc. ULSI-VII 1992 P.115-121; G.S. Tompa et al, Mat. Res. Soc. Symp. Proc. V 282 (1993) p.323-328.

7. H. Liu, et al., 1994 Material Research Society Spring Meeting, San Francisco, CA, 1994.

8. S.Nakamura, et al., Appl. Phys. Lett. 64 (13), 1994.

9. A.I. Gurary, et al., Presented at ICOMVPE-VII, Japan, 5/31/94 Abstract P3-1 to be published in J. Crystal Growth.

10. Y.A. Wu et al., 51st IEEE Device Res. Conf., paper IIIB-3, 1993; R.P. Schneider and J.A. Lott, Electron. Lett. 20, 830 (1993).

11. P.Yeh, "Optical Waves in Layered Media", Wiley, New York, 1988.

12. S. Adachi, "Properties of GaAs", Inspec (EMIS Datareview 2), p513, 1990.

13. G.S. Tompa, et al., Proceedings of U.S. Conference on GaAs Manufacturing Technology, in press, 1994.

14. A.G. Thompson, et al., MRS Spring Meeting 1994, paper I5.1, and references contained therein.

15. S. Li et al., published in the GaAs Mantech 1991 proceedings, pp. 460-463.