Materials Science Forum Vols. 527-529 (2006) pp 135-140
online at http://www.scientific.net

Challenges in Large-Area Multi-Wafer SiC Epitaxy for Production Needs

Bernd Thomas, Christian Hecht, René Stein, and Peter Friedrichs

SiCED Electronics Development GmbH & Co. KG
Paul-Gossen-Strasse 100, D-91052 Erlangen, Germany
phone: +49+9131-731057, fax: +49+9131-723046, e-mail: bernd.thomas@siemens.com

Keywords: Epitaxial Layers, Hot-Wall CVD, Multi-Wafer CVD, Planetary Reactor

Abstract. The rapid market development for SiC-devices during the last years can be attributed particularly to the success in supplying high-quality SiC wafers and corresponding epitaxial layers. The device quality could be enhanced and the costs were reduced by enlarging the wafer size as well as by a significant progress in epitaxial growth of active layers by using multi-wafer CVD systems. In this paper we want to give an overview of CVD multi-wafer systems used for SiC growth in the past and today. We present recent results of SiC homoepitaxial growth using our multi-wafer hot-wall CVD system. This equipment exhibits a capacity of 5×3" wafers per run and can be upgraded to a 7×3" or 5×4" setup. By optimizing the process conditions epitaxial layers with excellent crystal quality, purity and homogeneity of doping and thickness have been grown. Issues like reproducibility, drift of parameters and system stability over several runs will be discussed.

Introduction

Today, SiC devices like Schottky Barrier Diodes (SBD) with blocking voltages from 300 V to 1200 V are commercially available. SBD's with higher blocking voltages and JFET-based switches are expected to be introduced in the near future. Bipolar diodes, MOSFET's and SIT's are currently under development. This trend must be supported by a continuous improvement of the SiC material base. During the last 8 years the wafer diameter could be enlarged from 35 mm to 3-inch used today. Epitaxial CVD systems were developed starting with single-wafer research reactors up to high-throughput multi-wafer machines. Besides material properties like crystal structure, purity and specular surface morphology it becomes more and more necessary to achieve excellent values in homogeneity of doping and thickness as well as excellent run-to-run and intra-run reproducibility in order to meet the requirements of production needs. To realize lower material costs, special attention must be paid to the reduced off-orientation for large area substrates which needs to evaluate new process windows. Additionally, equipment parameters, which are not directly related to the properties of epitaxial layers, are of great interest to utilize a cost-effective system for large-scale production.

Short historical review of SiC multi-wafer system development

Homoepitaxial growth of hexagonal SiC is typically performed in high temperature (1500 °C-1650 °C) CVD reactors. Mid of the nineties commercial CVD system suppliers started to develop customized single-wafer systems. Most of them adapted their reactors used for GaN deposition at temperatures of about 1200 °C to the higher growth temperature necessary for SiC epitaxy. A vertical single-wafer cold-wall system developed in close collaboration with Emcore Inc. was used by R. Rupp et al. [1] at Siemens. This reactor is based on the rapidly rotating TurboDisc® concept. F. Wischmeyer et al. [2] at Daimler Benz as well as A. Burk et al. [3] at Northrop Grumman used horizontal cold-wall reactors developed in cooperation with Aixtron AG. A horizontal hot-wall reactor type was designed at Linköping University in Sweden in collaboration with ABB AB and Epigress AB. O. Kordina et al. [4] demonstrated that epitaxial layers with extraordinary high purity at high growth rates can be grown by hot-wall CVD.

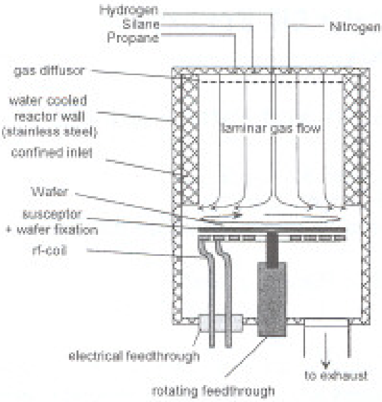

Fig. 1: Schematic of the cold-wall multi-wafer TurboDisc® reactor. (after R. Rupp [5])

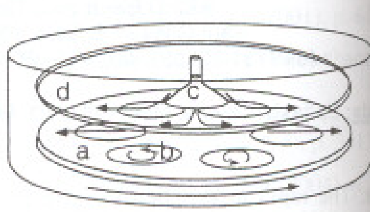

Fig. 2: Schematic of the cold-wall planetary reactor® showing a) susceptor, b) satellites (wafer holders), c) injection nozzle, and d) ceiling. (after A. Burk [7])

The ongoing quality improvement in SiC bulk crystal growth reaching wafer diameters up to inch, enabled a higher degree of material utilization and further cost reduction. This opportunity a the demand on cost-efficient realization of epitaxial layers made it reasonable to start the develo ment of CVD multi-wafer systems for SiC. At the end of the nineties first results on multi-wa epitaxy were published. Essentially two systems had been established. Firstly, 6×2" reactors bas on the rapidly rotating disc concept by Emcore Inc. were used by Rupp [5] and Karlsson (Fig. 1). The wafers are positioned outside the center of rotation close to the edge of the suscep plate. The susceptor rotates at ~ 500 rpm whereas the substrates are fixed in their position. For type layers on 2" wafers, Rupp et al. reported an inter-wafer homogeneity of doping and thickn of ±30% and less than ±10%, respectively. The run-to-run variation was ±10% for both, thickn and doping. Using 35mm wafers, Karlsson et al. referred an intra-wafer uniformity of doping a thickness of ±10% and ±2%, respectively. No data have been published about inter-wafer or run-t run homogeneity as well as to reproducibility.

Secondly, a horizontal cold-wall planetary reactor® supplied by Aixtron AG was used by Bu et al. [7] for epitaxial growth of up to 7×2" substrates at the same time (Fig. 2). The planetary rea tor® concept was originated by Frijlink et al. [8] for the growth of highly uniform GaAs and relat materials. Each wafer carrier – called 'satellite' – rotates about its central axis via gas foil levi tion. Additionally, the entire susceptor rotates about its center. This double rotation effectively a erages depletion effects of reagents in the gas flow direction as well as temperature and gas flo asymmetries. The use of this reactor type results in superior uniformity values. The intra-waf thickness and doping uniformities were reported to be ±0.5% and ±9.8% (sigma/mean), respe tively, on 35mm wafers. The average intra-wafer thickness and doping uniformities for 63 wafe with 35 mm diameter in 10 consecutive growth runs were ±3.8% and ±7.3%, respectively, at dopi levels of $\sim 1\times10^{16}$ cm^{-3}. The average wafer-to-wafer thickness and doping uniformities within the growth runs were ±8.6% and ±12.5%, respectively [7]. On 2" wafers with an edge exclusion of mm, the thickness standard deviation was ±3% and the doping uniformity was between ±7% a ±10% depending on the doping level.

In October 1999, Epigress AB became a member of the Aixtron Group offering the opportuni to combine the hot-wall reactor concept with the well-established planetary reactor® with gas f rotation. In 2000, our group expanded its epitaxial facilities by purchasing one of the first planeta hot-wall multi-wafer reactors. In comparison to the cold-wall planetary reactor® described above important feature of the new reaction chamber is the removable and actively RF-heated ceili

(Fig 3). In order to ensure high SiC growth rates, the temperature of the susceptor and the ceiling can be individually controlled. The reactor exhibits a modular chamber design for 7×2", 5x3", 7x3", and 6×4" configurations. First results of the 7×2" setup were published at the ICSCRM 2001[9]. Typical results for intra-wafer thickness and doping uniformities were ±0.4% and ±6.0% (sigma/mean), respectively. Superior wafer-to-wafer thickness and doping homogeneities of 0.6% and 3.6% (max-min/mean), respectively, could be achieved.

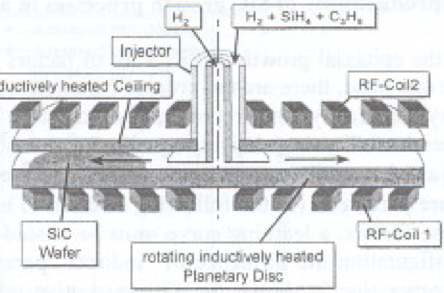

Fig. 3: Schematic of the Epigress Hot-Wall Planetary Reactor®.

Thus, at the beginning of the new century, SiC epitaxial layers with favorable attributes, combined with reduced costs of growth and high throughput in multi-wafer reactors, accomplished conditions for economical production of SiC devices.

Today's state-of-the-art of multi-wafer SiC CVD

During the last years it turned out that the vertical cold-wall systems, when compared with planetary systems, suffer from homogeneity problems on wafers with larger diameter, low growth rates, and Si cluster formation in the gas phase. Therefore, current results of only two different multi-wafer reactor types are published for epitaxial growth on 3" substrates: a warm-wall planetary system (CREE Inc.) and a hot-wall planetary reactor (SiCED GmbH & Co. KG).

For the 7×3" configuration A. Burk et al. (CREE Inc.) have modified their cold-wall system in a way that the ceiling is now passively heated to temperatures above silicon's melting point (1410°C) in order to minimize silicon supersaturation in the gas phase and the associated growth-rate reduction that would otherwise result [10]. Growth rates of 3-7 µm/h were used. The background doping of $<10^{14}$ cm^{-3} can be shifted from low n- to low p-type by adjusting the C/Si ratio. A. Burk et al. reported that they can grow complex multi-layer device profiles with intentional n-doping from 1×10^{15} cm^{-3} to $> 1\times10^{19}$ cm^{-3}, p-type doping from $\sim3\times10^{15}$ cm^{-3} to $> 1\times10^{20}$ cm^{-3}, and abrupt doping transitions in uninterrupted growth runs. The achieved uniformity values are shown in Table 1. Results of our 5×3" reactor configuration were published at the ECSCRM in Bologna last year [11]. The key data are listed in Table 1, too.

Table 1: Key data of 3" multi-wafer CVD systems

	7×3" warm-wall	5×3" hot-wall
Ref.	A. Burk [10]	B. Thomas [11]
Wafer orientation	(0001) 4°→[11$\bar{2}$0]	(0001) 4°→[11$\bar{2}$0]
Thickness homogeneity (σ/mean) intra-wafer wafer-to-wafer	3 % 1 %	2 % 1.6 %
Doping homogeneity (σ/mean) intra-wafer wafer-to-wafer	7 % 5 %	10 % 3.3 %
Run-to-run uniformity Thickness (σ/mean) Doping (σ/mean)	3 % 5 %	1.5 % 5 %

With both reactor types, very good layer properties and homogeneity values have been achieved for the SiC epitaxial growth on 3" substrates. Up to now, only sparse information was published about reproducibility of the process and productivity aspects. This will be done in the next section.

Reproducibility of SiC growth processes in a multi-wafer CVD reactor

In the epitaxial growth of SiC a lot of factors can influence the reproducibility of the process. O the one hand, there are the process parameters like temperature, pressure, gas flow etc. They ca very accurately and reproducibly adjusted by computer control, so that their influence o reproducibility is relatively small. On the other hand, there are parameters which can not b adjusted as easily, e.g. parasitic growth on reactor walls, cleaning of reactor components, change o spare parts, etc. (in the following referred to as "indirect" parameters). To minimize the impact o these factors, a learning curve must be passed through for each new system. For our 7×2" reac configuration the influence of "indirect" parameters on the normalized growth rate and nitroge incorporation is shown for 43 consecutive growth runs in Fig. 4. Growth parameters were ke constant unless indicated in the figure (change of C/Si ratio). All runs were supposed to meet th same thickness and doping specifications. Apart from the runs listed in the figure, calibration ru and "dummy" runs for coating of new reactor parts were accomplished.

It can be seen that e.g. cleaning procedures or changes of reactor parts can influence the grow rate up to 10%. It is obvious that the nitrogen incorporation reacts much more sensitive than th growth rate to identical changes. For instance, a cleaning of the reactor ceiling lowers the nitroge incorporation by ~15% whereas the growth rate is changed by only 5%.

In conclusion, various procedures are necessary to stabilize the growth conditions in order to im prove the reproducibility of the system. Using a well-prepared 5×3" reactor setup 19 n-type dope layers have consecutively been grown without an interruption by calibration or "dummy" runs. A growth parameters, except the growth time, were maintained constant. In Fig. 5 the minimal an maximal values of doping and thickness, averaged over 5 wafers per run, are shown. It can be se that the doping increases slightly from run to run by about 1%. This effect is caused by th continuous coating of the reactor walls. Therefore, the effective C/Si ratio near the wafer surface i supposed to be influenced by parasitic deposition. Its removal e.g. at the ceiling near the gas inl after the 8th run led to a drop of the doping concentration by about 8%. However, because of th complexity of the reactor hardware, it is not possible to clean the reactor before each run to hav well-defined and equal conditions at the beginning of growth. Thus, to counter systematic drifts an to achieve a better reproducibility it is necessary to slightly adjust the growth parameters.

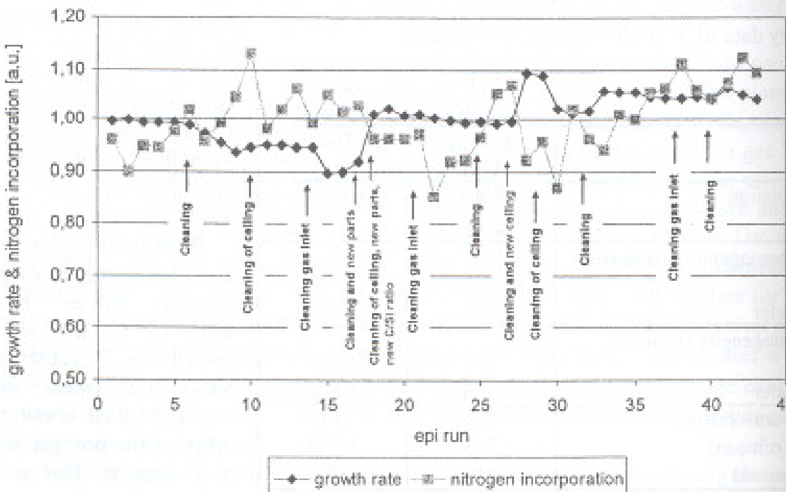

Fig. 4: Influence of "indirect" parameters on nitrogen incorporation and growth-rate reproducibility (7×2" hot-wall CVD system).

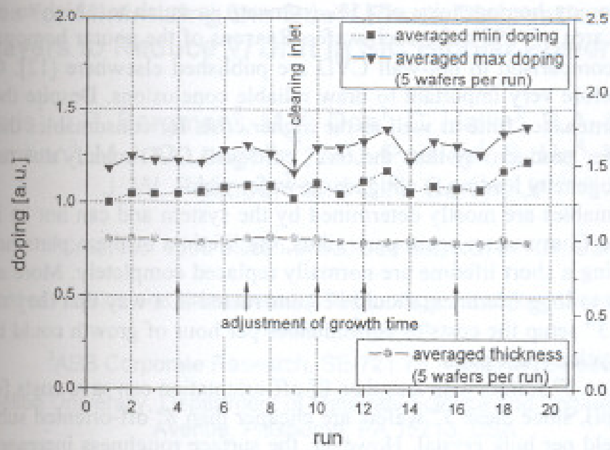

Fig. 5: Doping and thickness reproducibility of the 5×3" hot-wall CVD system.

The layer thickness was actively influenced by adapting the growth time resulting in an excellent thickness reproducibility of ~±1.5% (sigma/mean). The run-to-run reproducibility of the doping level without further corrections of growth parameters within the 19 runs is ~±5% for the used 5×3" reactor setup.

Productivity and Costs

Productivity and costs of the epi process are very closely connected. Besides the more or less straightforward attempt to simply increase the wafer capacity per run, additional, not easily neglectable cost factors are e.g. peripheral times of an epitaxial process, maintenance cycles, and costs of consumables. Peripheral times are for instance loading and unloading of the system, pumping times, heat-up and cool-down times, and cleaning time between succeeding runs. Maintenance comprises the time for total cleaning of the reactor and calibrations runs. Reducing the peripheral time or prolonging the maintenance cycle time will immediately increase the productivity of the process. But, short peripheral times and long maintenance cycles do not always guarantee high productivity. Table 2 shows some key data of our 2" cold- and hot-wall multi-wafer CVD equipments.

It is evident that the cold-wall system exhibits outstanding productivity factors. However, our main focus must still be the layer quality and usability for device production at wafer level. There-

Table 2: Key data of our 2" cold-wall and hot-wall CVD systems.

	2" hot-wall	2" cold-wall
Number of wafers per run	7	6
Thickness homogeneity (σ/mean) intra-wafer wafer-to-wafer	 2 % 10 %	 5 % 10 %
Doping homogeneity (σ/mean) intra-wafer wafer-to-wafer	 6 % 10 %	 15 % 10 %
Growth rate (μm/h)	4 to 8	3 to 5
Peripheral time (h:min)	2:20	1:00
Maintenance cycle time (h) (pure growth time)	10 to 15	30 to 90
Particles (cm^{-2})	1 to > 10	< 1
Cost factor of consumables (per μm)	2.5	1

fore, an intra-wafer doping homogeneity of 15% (σ/mean) is much too high to offer the device manufacturer a usable area of > 95% for each wafer. Reasons of the poorer homogeneity values of cold-wall systems in comparison to hot-wall CVD are published elsewhere [12]. Considering the system in total is therefore very important to draw reliable conclusions. Despite the poorer values for peripheral and maintenance time as well as the higher costs for consumables the 7×2" hot-wall system exhibits a higher productivity than the 6×2" cold-wall CVD mainly due to the drastically improved doping homogeneity leading to a higher on-wafer yield.

The costs of consumables are mostly determined by the system and can not be influenced very much. Main costs arise from reactor spare parts, thus, the lifetime of these parts has a great influence. Cheap parts having a short lifetime are normally replaced completely. More expensive parts which exhibit medium to long lifetimes, should be constructed in a way that they can be recycled. In our case, for the 5×3" setup the costs of consumables per hour of growth could be reduced by a factor of two using recycled spare parts.

In addition, growth on 3" wafers with less than 8° off-orientation can save costs for the total base material (wafer plus epi), since these 3" wafers are cheaper than 8° off-oriented substrates because of the higher wafer yield per bulk crystal. However, the surface roughness increases for epi-layers on 4° off-oriented wafers indicated by R_a and RMS values in comparison to the growth on 8° off-orientated substrates. The extended terrace width at the wafer surface caused by the smaller off-orientation results under certain conditions in stronger step formation, which is described as step-bunching [13]. Even after optimization of process parameters it was not possible to get the same results as on 8° off-oriented wafers, but the roughness could be reduced to an RMS value of 1.2 nm (20x20 μm^2)[11].

Using one shift conditions (5 working days, 10 h per day) the 5×3" CVD system is able to process about 80 epi-wafers per week for e.g. 300 V devices. We can state that summarized over hundreds of production runs, all of them met the specifications for the resulting devices.

Summary

In summary, favorable layer properties realized at single-wafer research reactors could be successfully transferred to highly productive multi-wafer CVD systems within a very short time scale. This represents a significant advance in the economical production of SiC epitaxial materials and devices. Further improvements in uniformity and run-to-run reproducibility, particularly on 3" diameter substrates, continued the trend of productivity enhancement and cost reduction for SiC epitaxial materials.

References

[1] R. Rupp, Y.N. Makarov, H. Behner, and A. Wiedenhofer: Phys. Stat. Sol. **202** (1997), 281

[2] F. Wischmeyer, D. Leidich, E. Niemann: Mat. Sci. Forum Vols. 264-268 (1998), 127

[3] A.A. Burk, and L.B. Rowland: Phys. Stat. Sol. (b) **202** (1997), 263

[4] O. Kordina, C. Hallin, A. Henry, J.P. Bergman, I. Ivanov, A. Ellison, N.T. Son, and E. Janzen: Phys. Stat. Sol. (b) **202** (1997), 321

[5] R. Rupp, A. Wiedenhofer, and D. Stephani: Mat. Sci. and Engineering B61-62 (1999), 125

[6] S. Karlsson, N. Nordell, F. Spadafora, and M. Linnarson: Mat. Sci. and Engineering B61-62 (1999), 143

[7] A.A. Burk, M.J. O'Loughlin, and H.D. Nordby: J. Cryst. Growth **200** (1999), 458

[8] P.M. Frijlink: J. Cryst. Growth **93** (1988), 207

[9] F. Wischmeyer, K. Christiansen, C. Hecht, R. Berge, D. Stephani, and H. Juergensen: Poster Presentation at ICSCRM 2001, Oct. 28. - Nov. 2., Tsukuba, Japan

[10] A.A. Burk, M.J. O'Loughlin, M.J. Paisley, A.R. Powell, M.F. Brady, R.T. Leonard, St.G. Müller, and S.T. Allen: Mat. Sci. Forum Vols. 483-485 (2005), 137

[11] B. Thomas and C. Hecht: Mat. Sci. Forum Vols. 483-485 (2005), 141

[12] B. Thomas, W. Bartsch, R. Stein, R. Schörner, and D. Stephani: Mat. Sci. Forum Vols. 457-460 (2004), 181-184

[13] T. Kimoto, A. Itoh, and H. Matsunami: Phys. Stat. Sol. (b) **202** (1997), 247