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Advances in Multi- and Single-Wafer SiC Epitaxy for the Production and Development of Power Diodes

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Abstract. In this paper, we present results of epitaxial layer deposition for production needs using our hot-wall CVD multi-wafer system VP2000HW from Epigress with a capability of processing 7×3" or 6×100mm wafers per run in a new 100mm setup. Intra-wafer and wafer-to-wafer homogeneities of doping and thickness for full-loaded 6×100mm and 7×3" runs will be shown. Results on Schottky Barrier Diodes (SBD) processed in the multi-wafer system will be given. Furthermore, we show results for n- and p-type SiC homoepitaxial growth on 3", 4° off-oriented substrates using a single-wafer hot-wall reactor VP508GFR from Epigress for the development of PiN-diodes with blocking voltages above 6.5 kV. Characteristics of n- and p-type epilayers and doping memory effects are discussed. 6.5 kV PiN-diodes were fabricated and electrically characterized. Results on reverse blocking behaviour, forward characteristics and drift stability will be presented.

Introduction

Within the last 10 years the market for SiC-based power diodes has been developed very rapidly. Schottky Barrier Diodes (SBD) with blocking voltages up to 1200V are on the market, SBD for higher reverse voltages and high-voltage PiN-Diodes are evaluated and qualified for potential applications. The cost/performance ratio was improved due to progress in the quality and size of the wafer material as well as by significant advances in the epitaxial growth of active layers.

The requirement of a cost-effective, reproducible and reliable epitaxial process led to the introduction of multi-wafer systems in 1998. Starting with multiple 35mm and 2" wafer capability, multi-wafer systems for processing large-area wafers with diameters up to 100mm are used today [1,2]. Key parameters like homogeneities of doping and thickness, run-to-run reproducibility and wafer throughput must be considered when evaluating epitaxial reactors and processes for certain applications. For the production of SBD in the voltage range up to 3 kV multi-wafer systems can fulfill the criteria given above, whereas single-wafer hot-wall reactors are mostly used for the development of high-voltage PiN-diodes.

In the first part of the paper, we present results of epitaxial layer deposition for the fabrication of SBD using our hot-wall multi-wafer reactor capable of processing 7×3" or 6×100mm wafers in a new 100mm setup. Results on SBD processed on 3" wafers in the multi-wafer system will be given to demonstrate the suitability for device production. In the second part, we show recent results for n- and p-type epitaxial growth using a single-wafer hot-wall reactor. For the characterization of epitaxially grown pn-junctions electrical results for 6.5 kV PiN-diodes will be presented.

Experimental Details

A multi-wafer VP2000HW Planetary Reactor with an actively heated ceiling built by Epigress was used for epitaxial layer deposition for the production of SBD in the voltage range up to 1700V. The experimental details of this system are published elsewhere [3]. Recently the system was upgraded together with Epigress to a larger 100mm setup suitable to hold a 7×3" or a 6×100mm susceptor configuration. For the development of high-voltage PiN-diodes a VP508GFR hot-wall reactor from

Epigress with a capacity of 3×2", 1×3" or 1×100mm was used for the deposition of n- and p-type layers [4]. Epitaxial layers were grown at temperatures between 1550 °C and 1650 °C using silane and propane as precursors and hydrogen as carrier gas. Nitrogen served as n-dopant. In the VP508GFR reactor Tri-methyl-aluminum (TMA) was used as precursor for p-doping.

Commercially available 3-inch and 100mm n-type 4H-SiC wafers with (0001) orientation (Si-face) and an off-orientation of 4° towards the <11-20> - direction were used as substrates.

Multi-Wafer CVD for Production of Schottky Barrier Diodes

Epitaxial Results. Starting with a 7×2" reactor setup in 2001, the wafer capacity of our multi-wafer reactor VP2000HW was increased to 5×3" followed by 7×3" up to 6×100mm today. Table 1 summarizes the properties of the different setups. With the increase in wafer diameter from 2" to 100mm the total wafer area that can be processed was enlarged by more than a factor of 3 while maintaining the layer properties necessary for the cost-effective production of SBD in the voltage range up to 1700V.

Table 1: Properties of epitaxial layers processed in different reactor setups since 2001.

Reactor setup	2"	3"		100mm	
Susceptor configuration	7×2"	5×3"	7×3"	6×100mm	7×3" new
Year of setup change	2001	2003	2005	2007	2007
Total wafer area [cm^2]	142	228	319	471	319
Intra-wafer doping homogeneity	6.0 %	10.0 %	4.1 %	8.5 %	6.5%
Intra-wafer thickness homogeneity	0.4 %	2.0 %	1.5 %	2.2 %	2.2%
Wafer-to-wafer doping homogeneity	2.7 %	3.3 %	1.4 %	6.1 %	4.8 %
Wafer-to-wafer thickness homogeneity	0.4 %	1.6 %	2.2 %	3.8 %	1.0 %
Results presented in Ref.	[3]	[2,3]	[5]	this work	this work

A mapping of the doping concentration and the layer thickness on a 100mm wafer is shown in Fig.1. The intra-wafer results are not as good as for the old 7×3" setup, but they are comparable to the layer properties we achieved for the 5×3" setup. A further improvement of the intra-wafer properties is expected with the ongoing process development and increased wafer-throughput after switching the production to 100mm wafers.

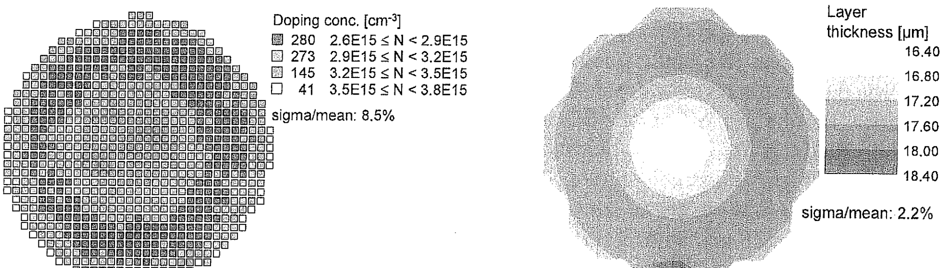


Fig. 1: Uniformity of doping (left) and thickness (right) on a 100mm wafer (6×100mm setup).

In Fig. 2a the wafer-to-wafer homogeneity of doping and thickness is shown for a full-loaded 6×100mm run. Subsequent runs were done with the 7×3" susceptor in the 100mm setup and process and hardware adjustments to improve the homogeneity were performed. The results for a full-loaded 7×3" run are shown in Fig. 2b. The wafer-to-wafer homogeneities are better than the values given for the 6×100mm run. As the adjustments made are independent of the susceptor used for the epitaxial process (6×100mm or 7×3") future 100mm runs should also benefit from these improvements and are expected to show equivalent good results.

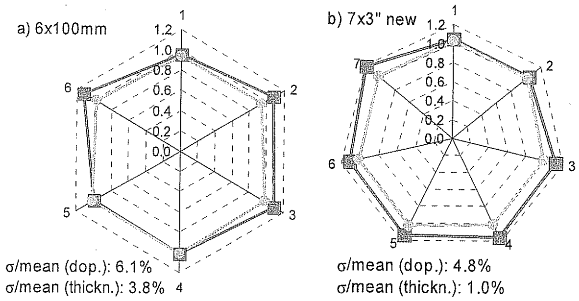


Fig. 2a: Wafer-to-wafer homogeneity of doping (squares) and thickness (circles) for a full-loaded 6×100mm run,
Fig. 2b: Wafer-to-wafer homogeneity of doping (squares) and thickness (circles) for a full-loaded 7×3" run in the improved 100mm setup after hardware and process adjustments.

Results for SBDs. With the 7×3" setup used since 2005 several thousands of wafers were processed for the production of SBD with blocking voltages between 300V and 1700V. More than 99% of the wafers did meet the epi layer specifications given by the device designers demonstrating an excellent reproducibility for growth rate and nitrogen incorporation.

As a measure of the overall "killer-defect" density the reverse blocking yield for a 3" wafer with 1200V SBD is shown in Fig. 3a. In spite of the large active area of 23mm^2 more than 70% of the devices passed the yield criteria (filled squares) representing a "killer-defect" density of less than 1.6cm^{-2}. In Fig. 3b the distribution of the epi yield (low-voltage blocking capability measured directly after the epitaxial process with a chip area of 2.08mm^2) for 100 wafers with epitaxial layers for SBD with blocking voltages of 1700V is given. The mean value of 92.6% reflects an average defect density of 3.7cm^{-2} demonstrating that the multi-wafer epitaxial process is well-suited for the volume production of high-power SBD.

Fig. 3a)

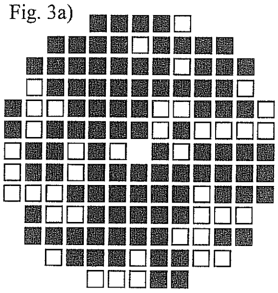
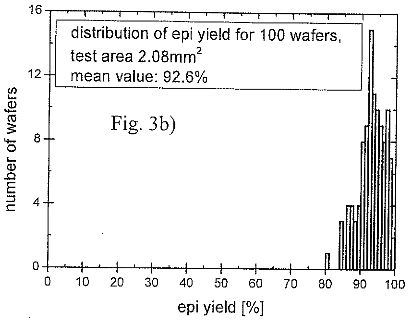


Fig. 3: a) Low-voltage blocking yield of a 3" wafer with 1200V SBDs and an active area of 23mm^2 (open squares: failed chips, filled squares: good chips), b) Distribution of low-voltage blocking yield after epitaxial processing of 3" wafers for 1700V SBD with an active area of 2.08 mm^2.



Single-Wafer CVD for Development of High-Voltage PiN-Diodes

Epitaxial Results. We already demonstrated that n- and p-type layers grown in the single-wafer hot-wall reactor VP508GFR exhibit excellent properties concerning doping and thickness homogeneity [5,6]. Typical values for epitaxial layers on 4° off-oriented 4H-SiC substrates are summarized in Table 2.

Table 2: Properties of epitaxial layers processed in the SW hot-wall reactor.

Dopant	n-type (~1e15 cm^{-3})	p-type (~1e18 cm^{-3})
Intra-wafer doping homogeneity	8.0 %	2.8 %
Intra-wafer thickness homogeneity	2.5 %	1.5 %
Background doping	< 5e14	< 5e14

For the growth of low-doped n-type and highly-doped p-type layers in the same reactor it is essential to minimize the doping "memory effect" leading to an increase of the background doping after p-doped runs in the high doping range [5]. Special procedures were applied to maintain the low background doping given in Table 2. In Fig. 4 the residual background doping after a highly p-doped run and consecutive overgrowth runs is shown. With special cleaning procedures the background could be decreased within a single-run below 5e14cm^{-3} (s. triangles & dotted line in Fig. 4).

Device Fabrication and Electrical Measure-ments. 6.5 kV PiN-diodes with an active device area of 5.7 mm^2 were fabricated on n-type drift layers with a continuously grown p-type emitter layer. In Fig. 5a the averaged reverse characteristic of 184 diodes is shown. Up to the onset of avalanche, the devices exhibit extremely low leakage currents. About 52% of the devices fulfill our strict yield criteria at 6.5 kV. The forward characteristic of a representative mounted diode at 25°C and 150°C before and after current stressing at 100A/cm^2 for 1h is shown in Fig. 5b. The diode exhibits a low forward voltage drop of 3.50V @ 25°C and 100A/cm^2. After current stressing only a slight increase of the forward voltage drop V_F (Δ=0.04V) at 25°C and no change of V_F at 150°C could be observed demonstrating an excellent drift stability although no special pretreatments were performed to minimize the overall basal plane dislocation density. In Ref. 7 details and possible explanations of this behaviour are discussed more in detail.

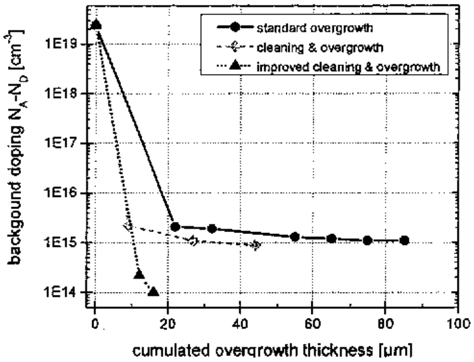
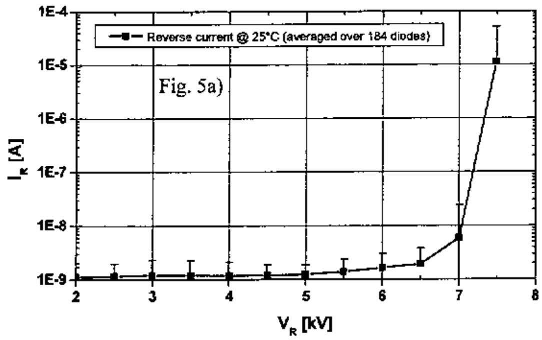


Fig. 4: Background doping versus cumulated overgrowth thickness with and without different cleaning procedures



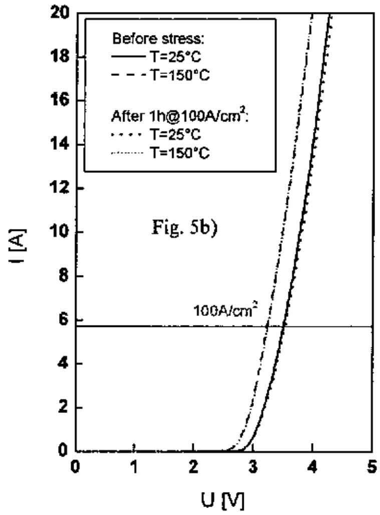


Fig. 5: a) Reverse characteristic of PiN-diodes at 25°C, averaged over 184 diodes and
b) Forward characteristics of a mounted PiN-diode at 25°C and 150°C before and after current stressing with 100A/cm^2 for 1h.

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