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Scaling of Chlorosilane SiC CVD to Multi-Wafer Epitaxy System

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Abstract
A SiC epitaxy process based on chlorosilane/propane chemistry has been successfully transferred from a single-wafer R&D system to a multi-wafer CVD reactor. The optimized process results in very smooth epi surface (RMS~0.24nm) and minimum surface pits (less than 0.5/cm^2). Both n-type and p-type doping in a wide range are demonstrated using nitrogen and aluminum, respectively. The high performance benchmarks for thickness uniformity (intra-wafer variation <1% and inter-wafer variation <1%) and doping uniformity (intra-wafer variation <6% and inter-wafer variation <3%) are achieved on 5 x 3-inch wafers. The carrier lifetime in these epilayers measured by μ-PCD is over 5 μs, the longest value reported so far for SiC epitaxial wafers.

Introduction

Multi-wafer planetary SiC epi reactors have been demonstrated to be a choice of growing large area 4H-SiC epilayers with high throughput and good uniformity for SiC device applications [1, 2, 7]. Silane and propane are typically used as precursor sources of silicon and carbon, respectively, to deposit SiC epitaxial films. Recent work on SiC epitaxy chemistry investigated the use of HCl, halocarbons, and chlorosilane precursors in order to suppress particle formation and promote growth rate [3, 4, 5]. A SiC epitaxy process based on chlorosilane/propane chemistry has successfully produced high quality 4H-SiC epilayers in a horizontal single-wafer hot-wall reactor in our group [3]. In this paper, we report detailed film analyses for samples deposited in a multi-wafer planetary reactor using chlorosilane / propane chemistry.

Experimental

A commercial multi-wafer (5x3" configuration) planetary reactor was used to deposit SiC epilayers on 3-inch 8-degree off-axis 4H-SiC n+ substrates. A chlorosilane precursor and propane are introduced into the reactor chamber with hydrogen carrier gas. Nitrogen and trimethylaluminum are used as dopant sources for n-type and p-type doping, respectively. The deposited epitaxial films were then characterized by a variety of techniques including FTIR, mercury probe C-V, AFM, SIMS, u-PCD (microwave photoconductivity decay), etc. The thickness uniformity was determined by 33-point FTIR mapping with 3mm edge exclusion, while the doping uniformity was determined by 9-point C-V mapping with 5mm edge exclusion.

Results and discussion

Consistent with the report on a horizontal hot-wall reactor [3], the use of chlorosilane precursor resulted in a minimum density of visible pits on the epi surface (less than 0.5/cm^2 on 3-inch wafers) with an epi thickness up to 30 um. The significantly reduced parasitic deposition on reactor kit was also observed compared to using silane precursor. At a typical growth rate of 5-6 um/hr, the deposited films show very smooth surface free of step bunching. As shown in Figure 1 AFM image, surface roughness less than 0.5nm is routinely obtained on 20 μm thick epi. The growth rate is

found to be linearly proportional to chlorosilane partial pressure as shown in Figure 2, which is similar to the single wafer chlorosilane based process [3]. It was also found that the growth rate in this multi-wafer reactor is slightly lower than that obtained on a horizontal single wafer reactor at the same precursor partial pressure [4].

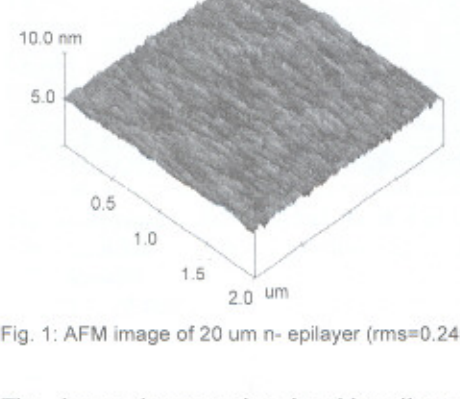

Fig. 1: AFM image of 20 um n- epilayer (rms=0.24nm)

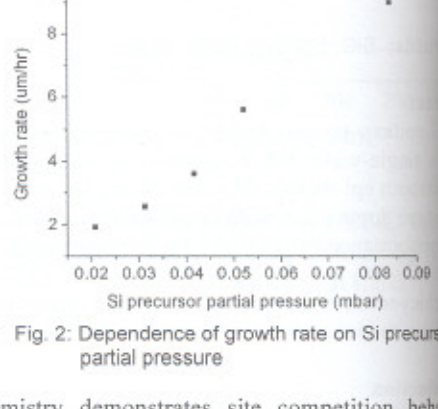

Fig. 2: Dependence of growth rate on Si precursor partial pressure

The dopant incorporation in chlorosilane chemistry demonstrates site competition behavior. Although the typical C/Si ratio required in this reactor is higher than that used in the horizontal single-wafer reactor, a low background doping less than $1x10^{14}$ cm^{-3} (n-type) has been routinely obtained. Intentional doping with nitrogen or aluminum has been demonstrated to produce a wide range of doping concentrations as shown in Figure 3. Data points for each process condition in Figure 3 are collected from different locations of the wafers. For doping higher than $5x10^{18}$ cm^{-3}, dopant concentration was determined by SIMS analysis, while the lower doping was measured by mercury probe C-V technique. An abrupt doping transition was achieved for continuous growth of multilayer device structures in this reactor by carefully controlling gas flows. As shown in Figure 4, a nitrogen concentration profile in a high-low-high doping sequence measured by SIMS exhibits abrupt interfaces.

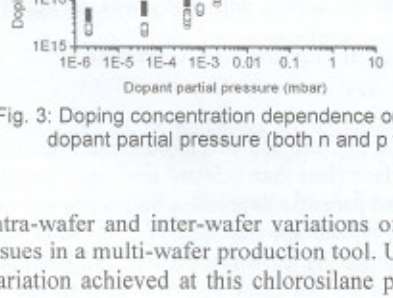

Fig. 3: Doping concentration dependence on dopant partial pressure (both n and p type)

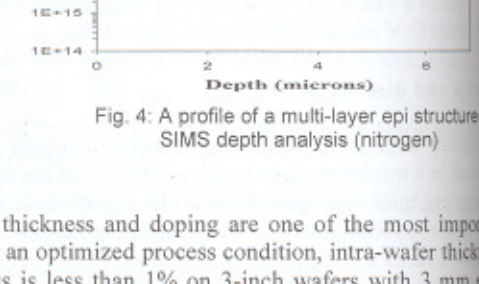

Fig. 4: A profile of a multi-layer epi structure by SIMS depth analysis (nitrogen)

Intra-wafer and inter-wafer variations of epi thickness and doping are one of the most important issues in a multi-wafer production tool. Under an optimized process condition, intra-wafer thickness variation achieved at this chlorosilane process is less than 1% on 3-inch wafers with 3 mm edge

exclusion as measured by FTIR. The best doping uniformity demonstrated on 3-inch wafers is about 6% with 5 mm edge exclusion as determined by 9-point C-V measurement. Figure 5 and 6 show the typical epi thickness contour map and doping contour map, where the concentric patterns are due to wafer rotation. The inter-wafer variation from a same run is typically less than 1% for thickness and less than 3% for doping, as shown in Table 1. These results are comparable to the best results reported on other multi-wafer reactors with silane/propane chemistry as shown in Table 2.

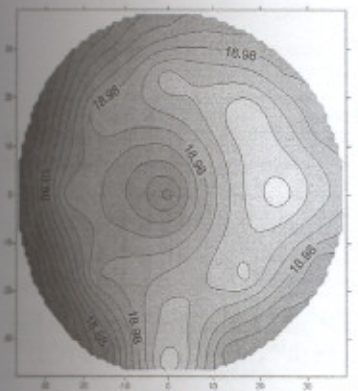

Fig. 5: A 3" epi thickness contour map measured by FTIR 33-point (mean = 18.957 μm, sigma = 0.072 μm)

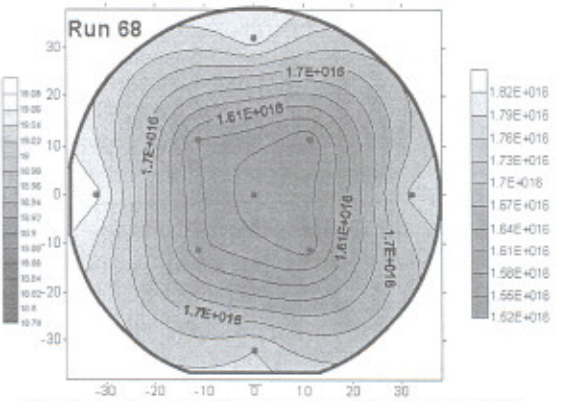

Fig. 6: A 3-inch epi doping contour map (9 test points) measured by mercury probe C-V technique (mean = 1.66×10^{16} cm^{-3}, sigma = 1.28×10^{15} cm^{-3})

	Wafer 1	Wafer 2	Wafer 3	Wafer 4	Wafer 5	Inter-wafer variation (sigma/mean)
Average thickness (um)	2.12	2.13	2.17	2.16	2.14	0.97%
Average doping (cm^{-3})	1.18×10^{16}	1.17×10^{16}	1.22×10^{16}	1.18×10^{16}	1.14×10^{16}	2.43%

Table 1: Inter-wafer variations of thickness and doping among 5 wafers from the same run

Report	Intra-wafer thickness variation	Inter-wafer thickness variation	Intra-wafer doping variation	Inter-wafer doping variation
Burk et al [2]	~0.5-1.1%	~1%	~2.3-5.2%	~5%
Thomas et al [1,7]	~1.5-2.5%	~2.2%	~3.4-4.8%	~1.35%
This work SiClx	~0.4-1%	~0.97%	~5.6-7.7%	~2.43%

Table 2: Comparison of epi thickness and doping uniformity with published results on other multi-wafer reactors with silane / propane chemistry.

Carrier lifetime in epilayers is one of the important metrics to gauge epilayer quality. The epilayers grown with chlorosilane process in this multi-wafer reactor are characterized by μ-PCD and time resolved photoluminescence (TR-PL) for lifetime measurement, respectively. Figure 7 shows a typical lifetime map of a 3-inch epiwafer measured by a modified WT 2000 μ-PCD system supplied from SemiLab Inc. Table 3 lists lifetime data measured on 5 epiwafers from a same run where they were tested at room temperature with an injection level of 5×10^{16} cm^{-3}. Carrier lifetime values as long as 5-6 μs are observed on these samples grown with the chlorosilane process, which are significantly higher than that (less than 1 μs) of epi samples grown with silane process. The difference in carrier lifetime among these five wafers is probably due to wafer variation. These long lifetime data were confirmed by TR-PL as well [6]. It is worthwhile to point out that decay curves in

μ-PCD testing typically have a fast component and a slow component. Fast decay represents excess carrier lifetime in the epi layer and slow decay is more likely related with carrier traps which can increase lifetime. The reported carrier lifetimes in this paper are all extracted from fast decay components. We believe that lower vacancy defect level in the epilayers grown with chlorosilane process is responsible for the exceptional carrier lifetime. It was reported that deep center concentration measured by DLTS in samples grown with chlorosilane chemistry is 5-10 times lower than that of samples grown with silane chemistry [8].

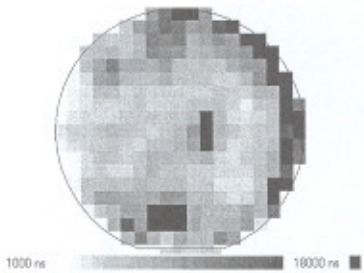

Fig. 7: A carrier lifetime map of a 3" epiwafer measured by μ-PCD

Wafer	Mean	Median	Sigma	Sigma/mean
1	1748	1338.6	79.88	5%
2	2694	1640.6	122.19	5%
3	1197	1044.9	45.35	4%
4	8497	5969.1	96.24	1%
5	11627	5158.2	157.06	1%

Table 3: Lifetime data (unit: ns) measured on 5 epiwafers from a same run (~30um, ~ $6x10^{14}$ cm^{-3} n-doping) by μ-PCD

Conclusion

In conclusion, a chlorosilane based SiC CVD chemistry has been successfully transferred from a horizontal hot wall system to a multi-wafer planetary reactor and used to deposit high quality SiC epitaxial films with smooth surface and low pit density. Both n-type and p-type doping in a wide range are demonstrated using nitrogen and aluminum, respectively. Epi thickness and doping uniformity achieved matches high performance results reported for silane based epi processes in other multi-wafer reactors. The long minority carrier lifetime values measured on these samples suggest high quality epilayers suitable for device fabrication. These results demonstrate that chlorosilane SiC epitaxy chemistry can be effectively scaled up for high volume commercial applications.

Acknowledgement

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