

Doping Efficiency and Long-Term Stability of Various SiC Epitaxial Reactors and Process Chemistries

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Abstract. Recent advances in SiC MOSFET technology allow significant reduction of on-state resistance of the active transistor cell, increasing thus relative contribution of the drift region comprised typically from epitaxial layer or stack thereof. Tight process control of thickness and doping of epitaxial layers is therefore gaining increasing importance. This paper summarizes some key factors and features of four state-of-the-art SiC epitaxial platforms and their impact on achievable epi parameters and wafer throughput.

Introduction

Breakdown voltage and on-state resistance of a SiC MOSFET transistor being one of the major DC parameters are tightly coupled and dependent on thickness and doping of the epitaxial layer as shown in Fig. 1.

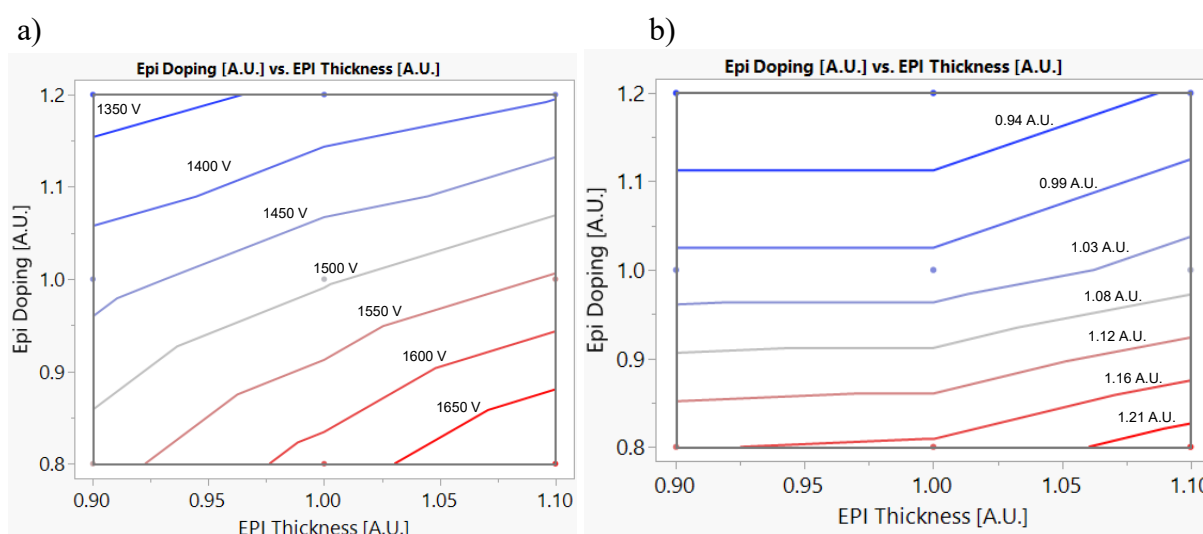


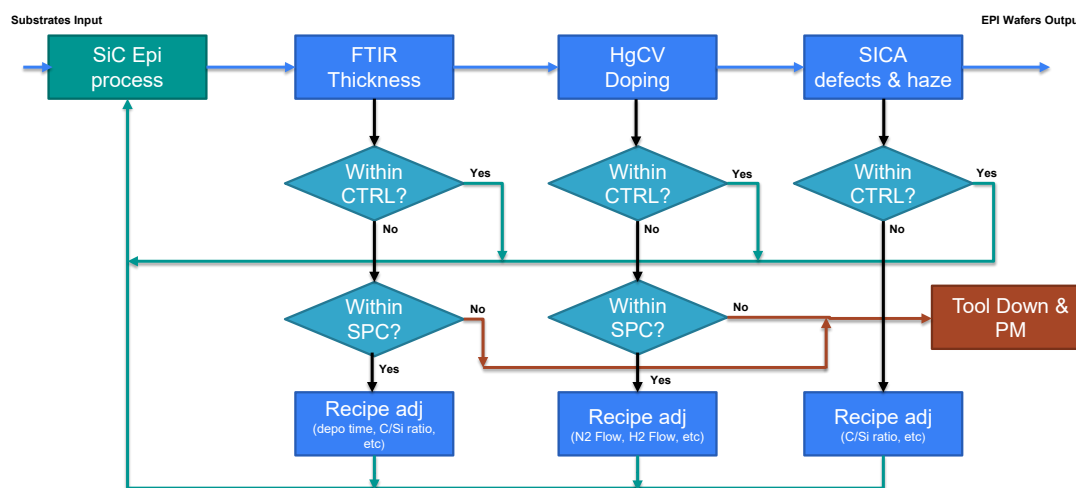
Fig. 1. Example of a) Bvds and b) Rdson trade-off for thickness and doping of epi layer.

Due to the opposite requirements on Bvds and Rdson, a precise control and long-term stability of both thickness and doping is crucial. The investigated epitaxial reactors include both vertical and horizontal chamber topologies, single wafer as well as multi wafer configurations with different chemistries for SiC growth as well as for doping, see Table 1. All these characteristics were confirmed having various impacts on long term stability of growth rate, doping efficiency and uniformities thereof.

Table 1. Reactor architectures used in this experiment.

	Reactor A	Reactor B	Reactor C	Reactor D
Topology	vertical	horizontal	horizontal	horizontal
Chamber	single wafer	multi-wafer	multi-wafer	single wafer
Chemistry	SiH ₄ /C ₃ H ₈ /HCl	SiH ₄ /C ₃ H ₈	TCS/C ₂ H ₄	TCS/C ₂ H ₄
Heating	Resistive	Induction	Induction	Induction

All investigated reactors were hot wall type where source gases decompose and react in the whole chamber volume that leads also to formation of deposits at the chamber interior [1]. These deposits in turn impact process conditions by influencing gas flows, C/Si ratio, partial pressures of the species, etc [2]. At the same time the deposits can absorb or emit various species and compounds, further impacting process conditions at the wafer surface resulting in memory effect or aging of the chamber. Besides, formation of deposit can increase the number of downfall particles [3, 4]. To keep the parameters of the epi layer within limits, a closed feedback loop needs to be established in the mass production, by constant adjustment of the epi process recipe based on metrology data from previous runs, see Fig.2. Depending on the architecture of the tool, the recipe adjustment may be needed every run or after few or many runs.

**Fig. 2.** Epitaxial process control flowchart showing closed feedback loop.

Results

Due to the delay in the metrology workflow, a well-behaved time drift of the tool is essential for effective recipe adjustment and high throughput of the tool. Figure 3 shows an example of a non-predictive tool drift. The doping efficiency, i.e., a flow of the dopant gas needed to achieve certain doping level, drifts both short term as well as long term. With more accumulated deposits, the memory effect of the chamber strengthens as they adsorb and release more nitrogen from previous runs.

This phenomenon seems to be more severe in reactors with rather large surface areas subjected to the parasitic growth conditions. Figure 3 further shows abrupt changes in the doping efficiency accompanied with abrupt shifts of growth rate. Due to the difficult predictability and fast swing, these variations possess serious risk for loss of process yield and throughput. It was found that such runaways are often caused by a formation of a positive feedback loop inside the process chamber or the gas injector system when deposits distort gas flows. Local gas mixture ratio or injector geometry further reinforces and accelerates rapid local growth of the deposits. It was observed that reactors with a certain geometry of the injectors may be also less susceptible to such sudden doping efficiency and growth rate runaways.

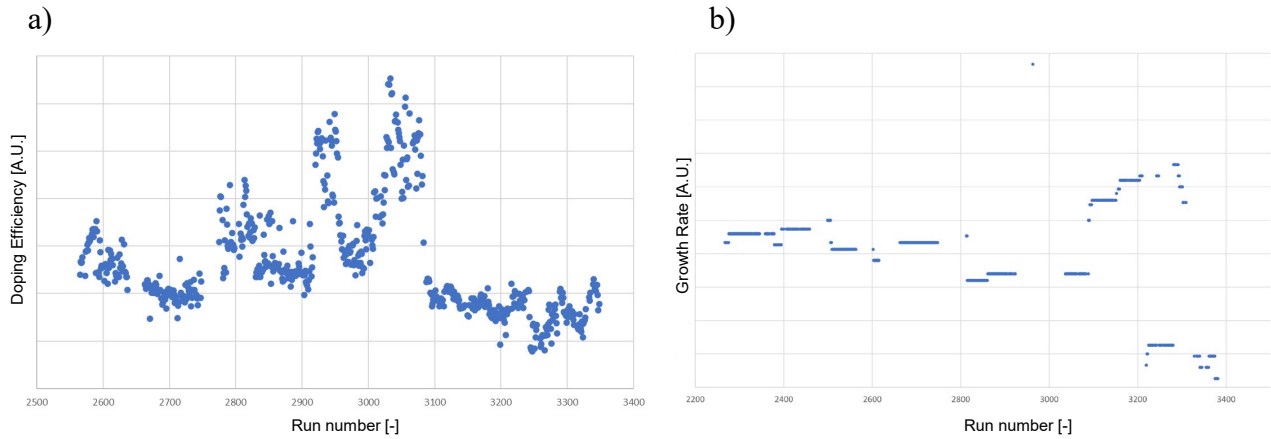


Fig. 3. Example of time evolution of a) doping efficiency and b) growth rate.

Figure 4 shows evolution of doping efficiency and growth rate during a shorter time frame around regular chamber cleaning. It can be observed that while the growth rate is still relatively stable before the chamber clean, the doping efficiency drifts significantly and requires frequent run to run adjustments of the dopant gas to keep the doping within specification. After the chamber clean, both doping efficiency and growth rate drop considerably and exhibit very high run to run drift for first several runs until they stabilize. Increased attention and frequent process adjustment is therefore needed not only before the chamber cleaning but also thereafter, as the seasoning of the chamber requires many runs that would otherwise decrease throughput of the tool if dummy wafers were used.

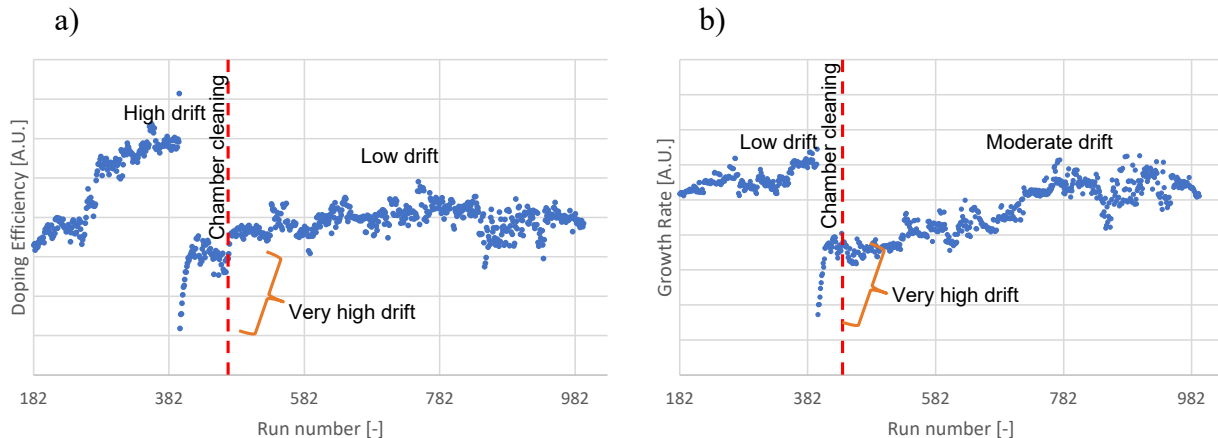


Fig. 4. Example of time evolution of a) doping efficiency and b) growth rate prior chamber cleaning and thereafter.

Beside the drift of the growth rate and doping efficiency, aging of the chamber in between the cleaning cycles and accumulation of deposits is also responsible for evolution of within-wafer thickness and doping uniformities, as shown in figure 5. Even the growth rate calculated as an average value for each wafer drifts slowly, predictably and can be thus easily compensated, the thickness uniformity within wafer deteriorates at much faster pace with accumulated deposit on the susceptor ring, see figure 5 b). Moreover, oftentimes a very abrupt deterioration of wafer uniformity within wafer is observed at the end of the susceptor cleaning cycle. After the susceptor cleaning, the uniformity immediately improves to initial values. This phenomenon is likely related to progressively increased surface thickness and surface area of accumulated deposits on the susceptor, disrupting gas flow as well as precursor consumption and distribution close to the wafer perimeter.

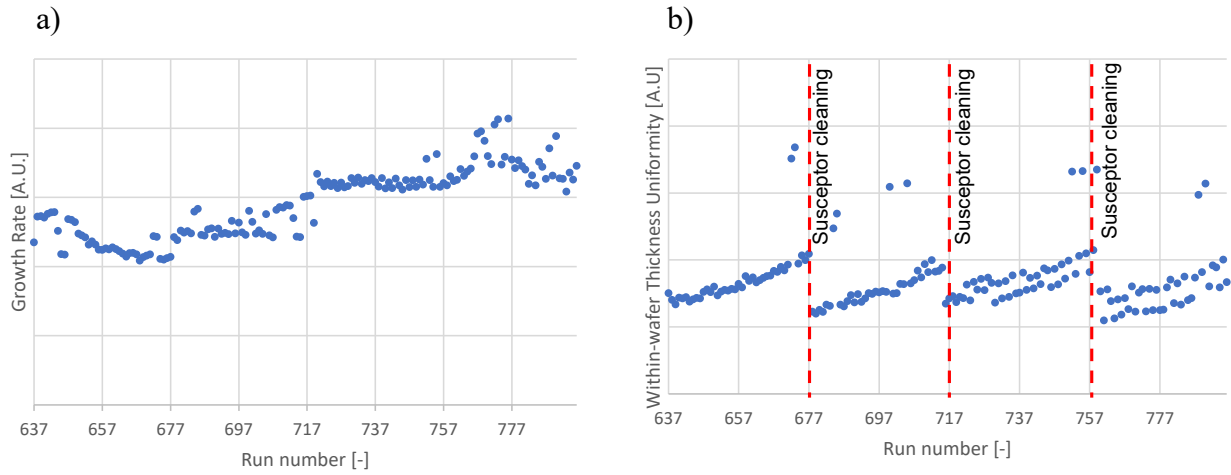


Fig. 5. Example of time evolution of a) growth rate and b) within-wafer uniformity in between susceptor cleaning cycles.

Figure 6 provides long term overview of doping efficiency evolution, including cleaning of susceptors, chamber ceiling and total chamber refresh. It can be observed that the doping efficiency drifted significantly more in the cycle preceding the first shown total refresh. This excursion was caused by window for pyrometer being covered by deposits, skewing thus the temperature reading. After the total chamber refresh, the doping drift during the susceptor cleaning cycle returned to standard levels. After the second total chamber refresh, the doping efficiency unexpectedly dropped and the drift during the susceptor cleaning cycles changed its pattern. The cause for the phenomenon was not identified.

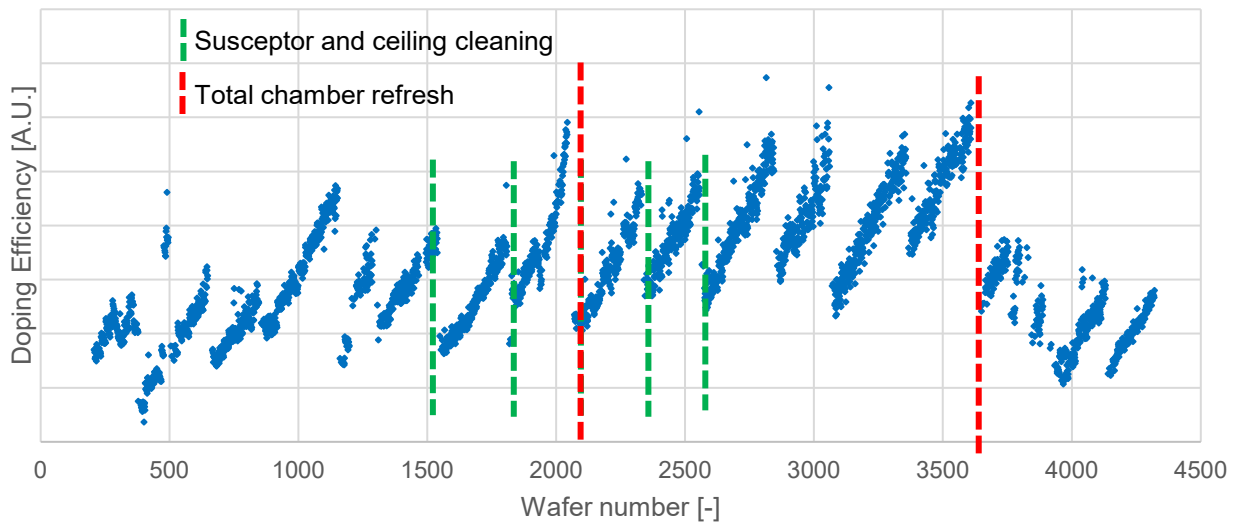


Fig. 6. Example of time evolution of doping efficiency in between susceptor cleaning cycles and total refresh cycles.

To compensate the doping drift and keep the doping level of the epitaxial layer in specification, a continuous adjustment of the dopant flow is needed, as shown in figure 7.

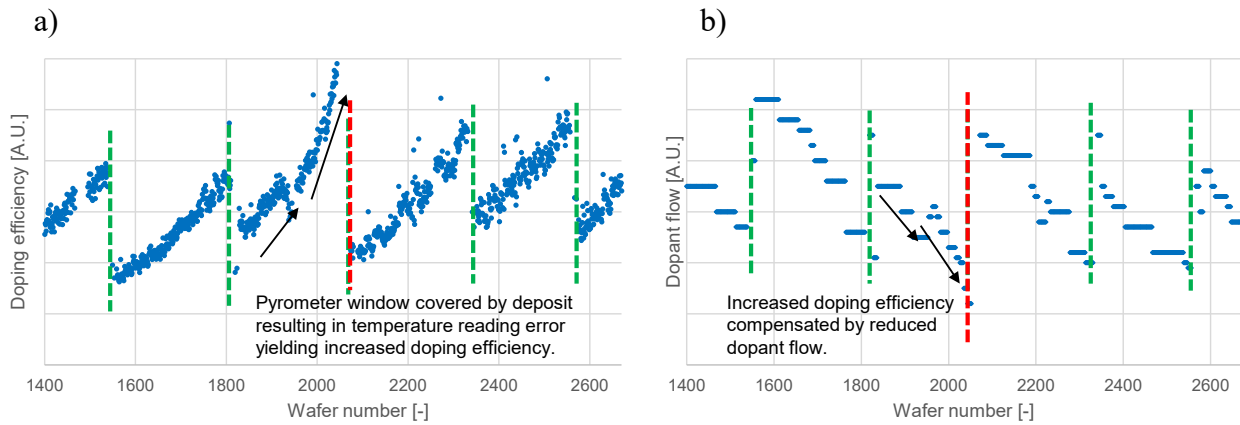


Fig. 7. Example of time evolution of a) doping efficiency and b) corresponding dopant flow to compensate.

To further minimize the doping efficiency drift, it is essential to minimize any excessive nitrogen concentration inside the process chamber, as the nitrogen atoms can be adsorbed and consequently released from various parts of the reaction chamber. A possible solution explored by some authors [5], [6] includes consideration of alternative dopant sources, preferably having a lower decomposition temperature and thus higher incorporation efficiency into the epitaxial layer. Hence significantly lower dopant gas flow may be sufficient to achieve a given doping level, resulting in less nitrogen atoms being adsorbed inside the process, reducing the doping efficiency drift of the tool.

The deposits inside the chamber and susceptor also alter gas flows and distribution of precursors, affecting growth rate and thickness uniformity within wafer, as shown in figures 8 and 9. To compensate, usually the deposition time is used to adjust rather than regulating the precursor flows to keep the growth rate constant, see figure 10. The same figure also shows example of improper and/or insufficient clean of chamber resulting in growth rate not resetting to expected level after the maintenance.

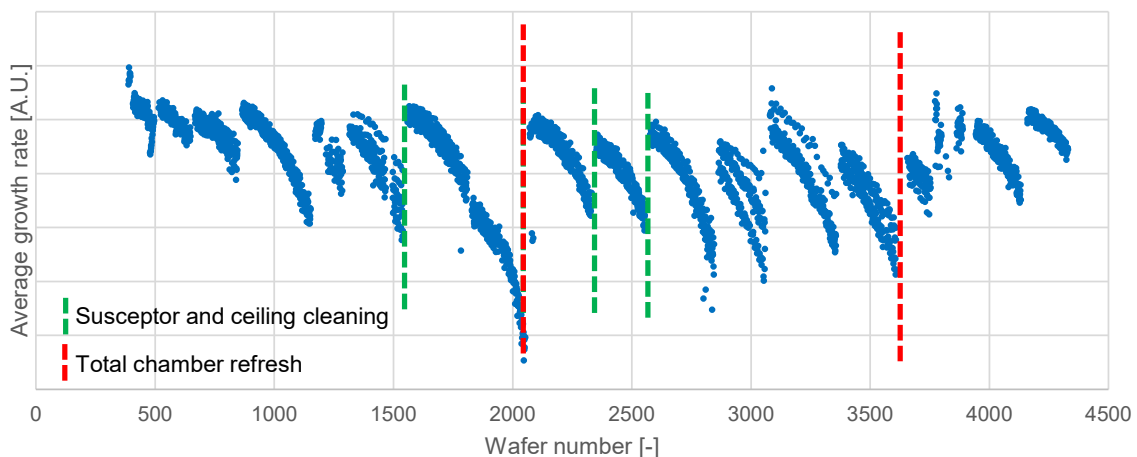


Fig. 8. Time evolution of growth rate corresponding with evolution of doping efficiency shown in figure 6.

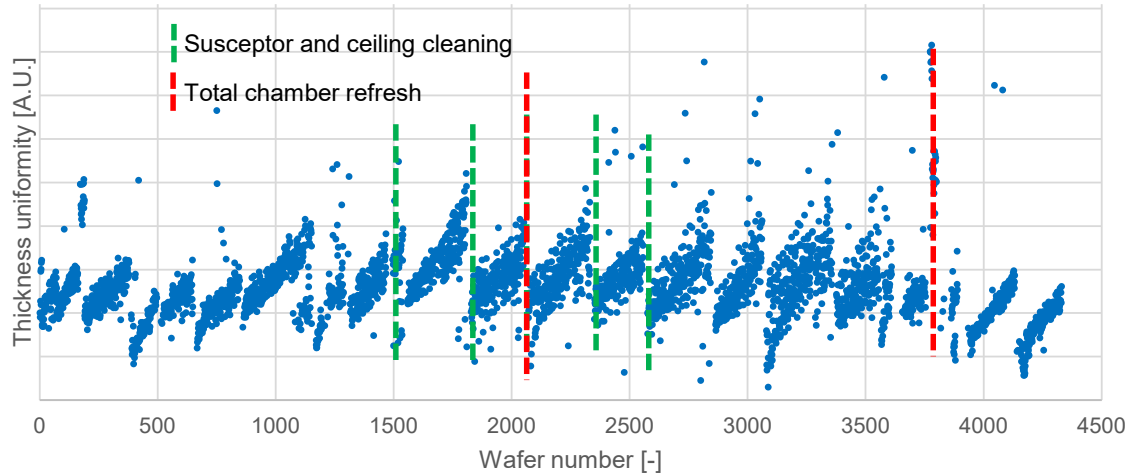


Fig. 9. Time evolution of thickness uniformity corresponding with evolution of growth rate as shown in figure 8.

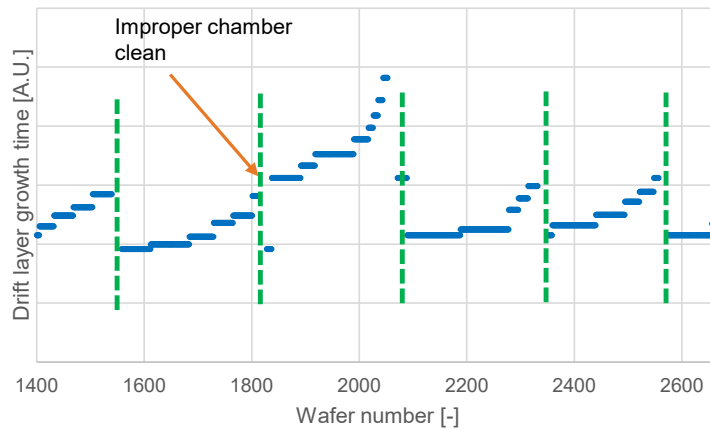


Fig. 10. Time evolution of growth rate with improper chamber cleaning resulting.

Summary

Several types of SiC epitaxial reactors were monitored to evaluate time evolution of epitaxial layer thickness and doping control in a mass production environment. Significant differences in both long-term and short-term stability of doping efficiency and growth rate between the platforms were observed. A strong effect of a susceptor and a chamber accumulated deposition on these parameters showed importance of setting-up suitable maintenance cycle times for individual parts replacement as well as overall reactor chamber cleaning. With known and predictable reactor drift, good control of epitaxial layer thickness and doping can be achieved. Our observations suggest that epitaxial reactors with smaller inner surface area and an alternative nitrogen dopant precursor can make reactor drift less significant and more predictable.

Acknowledgment

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