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SiC Epitaxial Layer Growth in a Novel Multi-Wafer VPE Reactor

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ABSTRACT

Preliminary results are presented for SiC epitaxial layer growth employing a unique planetary SiC-VPE reactor. The high-throughput, multi-wafer(7x2-inch) reactor, was designed for atmospheric and reduced pressure operation at temperatures up to and exceeding 1600 °C. Specular epitaxial layers have been grown in the reactor at growth rates from 3-5 μm/hr. The thickest layer grown to date was 42 μm. The layers exhibit minimum unintentional n-type doping of $\sim 1 \times 10^{15}$ cm^{-3}, room temperature mobilities of ~1000 cm^2/Vs, and intentional n-type doping from $\sim 5 \times 10^{15}$ cm^{-3} to $>1 \times 10^{19}$ cm^{-3}. Intrawafer thickness and doping uniformities of 4% and 7% (standard deviation/mean) have been obtained, respectively, on 35 mm diameter substrates. Recently, 3% thickness uniformity has been demonstrated on a 50 mm substrate. Within a run, wafer-to-wafer thickness deviation is ~4-14%. Doping variation is currently larger, ranging as much as a factor of two from the highest to the lowest doped wafer. Continuing efforts to improve the susceptor temperature uniformity and reduce unintentional hydrocarbon generation to improve layer uniformity and reproducibility, are presented.

INTRODUCTION

Vapor phase epitaxial (VPE) growth is currently the most practical means of SiC active layer formation. Prototype SiC VPE devices have already demonstrated performance exceeding that of Si and GaAs based devices [1,2]. Despite this, SiC material's technology including active layer formation is still immature. Several reactor configurations have been successfully developed for the growth of SiC epitaxial layers. All are constructed with high temperature materials such as quartz, graphite, and SiC. Most reactor designs require active water cooling. Hydrogen carrier gas along with silane and propane reagents are typically employed at atmospheric and reduced pressure and temperatures ranging from 1450-1600 °C. To reach these high temperatures, inductively heated SiC-coated graphite susceptors are typically employed. The most basic configuration utilized by Powell et al. [3], Karman et al. [4], Burk et al. [5], and other investigators, has been the water cooled(cold wall,) cylindrical, quartz, horizontal reactor. Kong et al. [6], and coworkers developed a multi-wafer barrel reactor. Kordina et al. [7] have developed a hot-wall reactor for the purpose of reducing the large (20-40 kilowatt) power requirements of the other reactors by using a hollow susceptor in an otherwise basic horizontal reactor. Most recently, Rupp et al. [8] developed the single wafer, rapidly rotating, vertical reactor.

With the exception of the barrel reactor, all of the above SiC reactors were designed for single wafer use. Historically, however, it has been difficult to achieve the epitaxial layer uniformities required for production of microwave devices in scaled-up multi-wafer cylindrical horizontal reactors or even barrel reactors when using large diameter wafers. In III/V epitaxial growth, two basic types of multi-wafer MOCVD reactors have met with the greatest success for 3 and 4-inch diameter wafers, the rapidly rotating vertical reactor [9] and the horizontal planetary reactor [10]. Now that we have achieved device quality SiC epitaxial layers with our single wafer horizontal reactor, we are currently developing a SiC multi-wafer planetary reactor to improve uniformity, reproducibility, and throughput. Fig. 1 contains a rough sketch of the SiC planetary reactor described below.

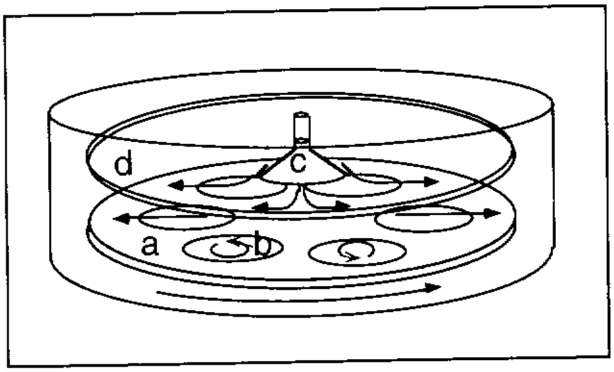

Fig. 1 Planetary SiC VPE Reactor Design showing, a) susceptor, b) satellites(wafer holders), c) injection nozzle, and d) ceiling.

As currently configured, the multi-wafer reactor is capable of growth on seven 2-inch diameter substrates at a time, greatly increasing layer throughput. The planetary reactor concept was originated by Frijlink et al.[11] and refined and commercialized by Aixtron [12] for the growth of highly uniform III-V compound semiconductors. In this design the gases enter from the center of the reactor and flow outward radially. Because of the increase in cross-sectional area, a drop in gas velocity occurs along the flow direction, which results in an increased but linear depletion of reagents. For diffusion limited growth, this yields a linear drop in growth rate. The rotation of the individual wafers about their central axis effectively averages this trend, yielding highly uniform layers. Additionally, the entire susceptor rotates about its center in order to further average any asymmetry in susceptor temperature or reagent flows. The means of rotating the susceptor and wafer holders is via a gas foil levitation. The end result of the planetary motion in the III-V case is ± 1 % thickness and doping uniformity both intrawafer and wafer-to-wafer [13].

In the case of the SiC planetary reactor, we are using roughly the same reactor design but have extended it from the typical < 800 °C III-V growth temperatures to the ~1600 °C temperatures required for SiC epitaxial growth by the use of RF induction heating, custom designed high-temperature materials and construction. The most obvious requirement of a multi-wafer, as opposed to a single wafer, reactor is the increased susceptor size (from ~75 to ~300 mm diameter) with the associated increased RF-power supply requirement and susceptor thermal stresses. As significantly, the reagent gases must now pass over the heated susceptor before reaching the wafers in both horizontal and vertical configurations. This requires that the graphite susceptor be SiC-coated to minimize uncontrolled hydrocarbon generation. Upstream reagent depletion and deposits can also impact epitaxial growth. Specific design challenges unique to the horizontal planetary configuration are, the relative proximity of the gas injection nozzle and ceiling to the hot susceptor(requiring careful thermal management), the presence of internal susceptor gas channels to enable satellite levitation, and the hot moving satellites themselves.

RESULTS

Over 450 growth runs and numerous growth chamber modifications have been accomplished to satisfy the diverse requirements described above. For example, extensive susceptor modifications were performed to eliminate catastrophic susceptor breakage, the nozzle was cooled to reduce prereaction, and the ceiling was allowed to get hotter to minimize Si-supersaturation induced coating. These and other improvements have allowed the growth of specular, reasonably pure and uniform SiC epitaxial layers described below.

Morphology-

The first requirement of epitaxy is to produce specular layers. Figure 2 contains a photomicrograph of a 42 μm thick layer grown in the planetary VPE reactor. The layer was grown

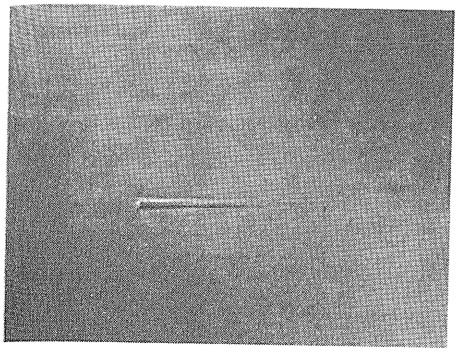

Fig. 2 Interference contrast photomicrograph of a specular ~42 μm 4H-SiC layer. The isolated feature is ~300 μm long.

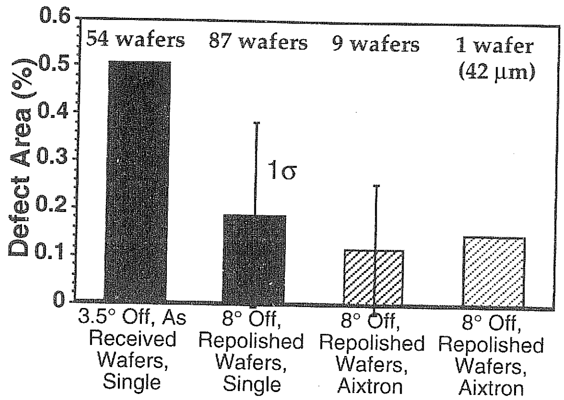

Fig. 3 A comparison of morphological defect area for the single and multi-wafer reactors.

at ~3 μm/hr for 15 hours. Other than the decoration of residual polishing scratches and pores, the layer is essentially featureless. The growth of such thick layers is a very severe test of morphology due to the inherent amplification of surface features by step-flow growth[14] and because of the integration with time of any *in situ* particulate or spurious coating related morphological defect source. Initial statistical data on percent defect area, as measured by an automated microscope with pattern recognition software, is presented in Fig. 3 for the ~42 μm thick layer and other layers of nominal 5 μm thickness grown in the multi-wafer reactor. These wafers compare very favorably with ones grown in our single wafer reactor.

Purity-

Reasonably low n-type background doping of approximately 1×10^{15} cm^{-3} has been measured by CV on unintentionally doped layers grown in the multi-wafer reactor. Figure 4 contains a SIMS profile revealing no more than mid 10^{14} atoms/cm^3 concentrations of aluminum and boron impurities, the primary compensating p-type impurities in SiC. The aluminum and boron detection limits for these measurements were approximately 3×10^{13} cm^{-3} and 6×10^{14} cm^{-3}, respectively. Room temperature mobilities shown in Fig. 5, as high as 1000 cm^2/Vs compare favorably with material grown in our single wafer reactor[15] and elsewhere[16]. Photoluminescence measurements also indicate good materials purity and quality having sharp P_0 and Q_0 nitrogen bound exciton lines and little evidence for aluminum or boron. The intrinsic exciton line, I_{75}, however, is still not as strong as observed in layers grown in the single wafer reactor.

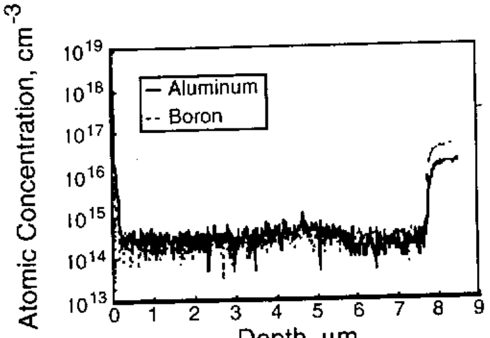

Fig. 4 SIMS measurement showing low aluminum and boron concentrations.

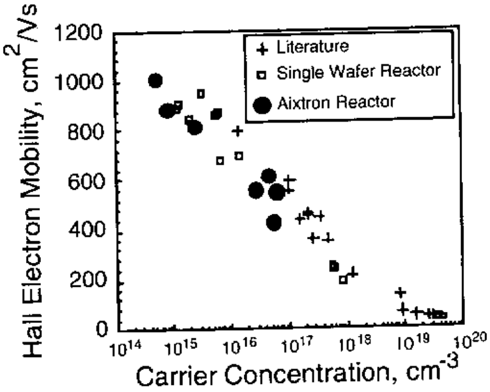

Fig. 5 Hall electron mobility on 4H-SiC layers from the literature [16](pluses), single wafer reactor(squares) and Aixtron reactor(circles).

Intentional Doping-

SIMS and CV measurements have indicated intentional n-type doping ranging from ~$5x10^{15}$ cm^{-3} to over $1x10^{19}$ cm^{-3} by the addition of nitrogen dopant and change of the input Si/C ratio. Transition abruptness is better than 200 Å/decade, similar to that observed in the single wafer reactor[17]. Intentional p-type doping has not yet been investigated.

Uniformity-

Figure 6 contains an overlay of five CV carrier concentration profiles taken from the center and periphery of a 35 mm diameter N^+ SiC wafer having an unintentionally doped 5 µm thick layer. The intrawafer thickness and unintentional doping uniformities are ~4% σ and 7% σ respectively. While not yet reaching the design goal of ±5% total variation, these values already exceed the uniformity of the wafers produced in our single wafer reactor by a factor of three. Limited multiple wafer runs have been accomplished to date. In a multi-wafer run, the average wafer-to-wafer thickness standard deviation varies from 4-14%. The wafer-to-wafer doping uniformity is currently much worse than this, ranging as much as a factor of two from the highest to the lowest doped wafer.

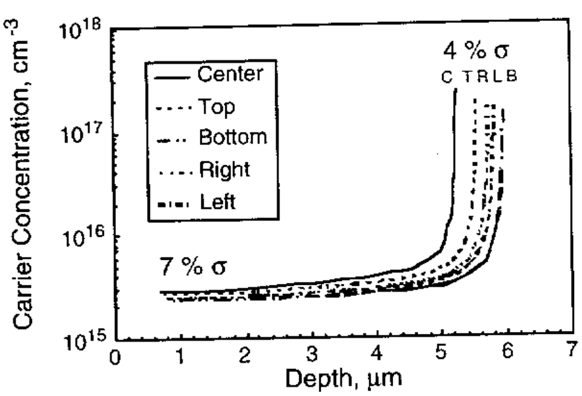

Fig. 6 Overlay of carrier concentration profiles from the center and periphery of a 35 mm diameter wafer.

Preliminary 2-inch wafer results-

Only a few two-inch diameter, 4H-SiC wafers have been grown upon to date in the multi-wafer reactor. These wafers were purchased as pre-production samples from Cree Research, Inc. Importantly, the resulting epitaxial layers were specular out to the edge of the wafers excluding the decoration of numerous ~1/4 inch long grain boundaries or striations at the wafer periphery. Impressively, the thickness standard deviation was ~3% over the entire wafer. The doping uniformity was however very poor, ~14%, in an area at the center of the wafer equivalent to that of a 1 3/8" wafer with the doping dropping precipitously towards the outer edge. This however was not attributable to the substrate, but to an aging susceptor, as will be discussed further below.

DISCUSSION

The preliminary results for the planetary SiC VPE reactor are very promising. Reliable planetary rotation has been achieved for the first time at 1600 °C with a large graphite susceptor. Excellent layer morphology has been demonstrated allowing the growth of thicker layers than has been previously possible in our single wafer reactor. Purity, n-type doping range, and layer abruptness sufficient for most device types has already been demonstrated. Intrawafer layer uniformity, while not yet matching the impressive intrawafer thickness uniformities (± 2.5 % total variation) reported by Rupp et al. [8] for their rapidly rotating single wafer reactor, has still greatly exceeded our previous capability. The high, ~$1x10^{16}$ cm^{-3}, p-type background reported previously[18] has now been greatly suppressed to less than ~$5x10^{14}$ cm^{-3}, by the reduction of exposed carbon on the susceptor and further optimization of process parameters. The demonstrated wafer-to-wafer thickness uniformity of 4-14%, while far from design goals, is comparable to the run-to-run variation in our single wafer reactor.

The primary remaining challenges facing the planetary SiC reactor are improvements in the intrawafer and wafer-to-wafer doping uniformity, reproducibility, and component lifetime. Typically, freshly coated susceptors exhibit reasonable intrawafer uniformity while ones showing SiC coating breakthrough (exposed graphite) have more p-type compensation at the wafer edge. One possible source of the doping nonuniformities and irreproducibility are the unintentional hydrocarbons generated from this exposed graphite. We are currently attempting to further reduce these uncontrolled sources of hydrocarbons.

The very large wafer-to-wafer doping nonuniformity has been correlated with a 30° C axial total variation in temperature. In-and-of-itself, this would not seem sufficient to cause a factor of two doping variation, particularly as the wafer-to-wafer thickness uniformity is 4-14%, but when combined with unintentional hydrocarbon generation from exposed carbon, this amount of temperature variation may be sufficient to alter the effective Si/C ratio at different locations on the susceptor. Regardless of the underlying mechanism, we have currently refined the susceptor design and successfully reduced the axial temperature variation to ~10° C. We are now investigating how this effects wafer-to-wafer doping uniformity.

CONCLUSIONS

In summary, preliminary growths from the planetary SiC VPE reactor have yielded wafers with very promising layer properties including excellent morphology and mobility, and reasonable purity and thickness uniformity. The capacity to grow simultaneously on seven wafers of up to 2-inch diameter has been verified. More work is required to further reduce background doping and improve doping uniformity and reproducibility.

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