SIC – Develop CVD Techniques Using Novel Chemistries for Epitaxial Growth of 4H-SiC

Problem Statement

OBJECTIVE: Develop Chemical Vapor Deposition (CVD) techniques using novel chemistries for epitaxial growth of 4H-SiC that allow lower than state-of-the-art growth temperatures while retaining state-of-the-art growth rates and improved material quality.

DESCRIPTION: In recent years, silicon carbide has proven its worth in the power electronics industry. High performance diodes and transistors are commercially available and are being designed into power conditioning systems from a wide range of industries. Transistors can be purchased with voltage ratings up to 1700 V while diodes are available up to 8 kV. Discrete 1200 V diodes and transistors are available with current ratings over 100 A. The low on-resistance, fast switching, high current density, and temperature tolerance provide significant system benefits over silicon devices. These system benefits often outweigh the higher cost of the SiC devices as compared to silicon. While the cost per amp of SiC continues to drop, the cost of SiC bulk material and epitaxy will never be as low as silicon due to the high temperatures and manufacturing methods required to produce SiC. For instance, Si epitaxy is typically grown at temperatures ranging from 1000 to 1200 degrees C with growth rates of hundreds of µm/min. SiC epi, however, is grown from 1500 to 1800 degrees C and, while growth rates above 100 µm/hr are possible, they are challenging to the system and material quality [1]. Because of this, epi cost and throughput remains a cost driver even for 1200 V devices with relatively thin epilayers (~10 µm). For even higher voltage devices (10s of kV) epilayer thicknesses quickly grow to over 100 µm. The challenge of growing thick layers while keeping growth rates and material quality high increase the costs dramatically. The addition of HCl or chlorinated silicon precursors such as chlorosilanes (SiHCl3 and SiCl4) has mitigated some of the deleterious side effects of pushing growth rate such as the formation of silicon droplets on the wafer or other surfaces in the reactor [1]. In addition to providing Cl, chlorinated precursors also appear to provide beneficial surface kinetics that benefit material quality and allow for lower growth temperatures. Chlorinated carbon precursors, chloromethane (CH3Cl) in particular, have been shown to produce high quality films at growth temperatures as low as 1300 degrees C [1][4]. Growth with chloromethane and chloromethane with HCl or chlorosilane has been shown to be more efficient than growth with hydrocarbons and HCl or chlorosilane alone [1]. Low temperature growth with CH3Cl and SiCl4 was also shown to produce very low donor concentrations (~3e14 1/cm^3) in films as thin as 5 µm [2], and much higher than typical acceptor concentrations of over 2e20 1/cm^3 [3]. Low temperature growth also has the benefit of allowing for selective area growth using an SiO2 mask [1]. Another area that needs to be investigated is the benefits of CH3Cl/SiCl4 growth on extremely low off-angle or on-axis substrates. Growth rates at 1300 degrees C using CH3Cl have not been shown to equal those of other precursors at much higher temperatures. However, the growth rate possible using CH3Cl/SiCl4 will increase with temperature and could possibly match the rate of other chemistries at still a much lower temperature. Even a more modest reduction in temperature of 100 degrees C could have a significant impact on tool life and throughput. The goal of this effort is to develop a production worthy 4H-SiC epitaxial growth process using chlorinated carbon precursors or other novel precursors with reduced growth temperature and improved material quality as compared to state-of-the-art.

For this exam, focus on the following…
Prepare a research and development proposal, per the instructions below, that if funded will allow you to demonstrate homoepitaxial growth of 4H-SiC using precursors including chlorinated carbon sources or other novel gases with similar effect. The new process should also be able to demonstrate growth rates $\geq$ 20 µm/hr with an ultimate goal of 50 µm/hr while maintaining good quality. Growth temperatures should be at least 100 degrees C less than state-of-the-art for similar growth rates. The n-type dopant concentration and uniformity as well as defect densities should be characterized through appropriate techniques.

REFERENCES:
1. H. Pedersen, S. Leone, O. Kordina, A. Henry, S. Nishizawa, Y. Koshka, and E. Janzén, “Chloride-Based CVD Growth of Silicon Carbide for Electronic Applications,” Chemical Reviews 2012 112 (4), pp. 2434-2453.;
2. S. P. Kotamraju, B. Krishnan, F. Beyer, A. Henry, O. Kordina, E. Janzén, and Y. Koshka, "Electrical and Optical Properties of High-Purity Epilayers Grown by the Low-Temperature Chloro-Carbon Growth Method," Materials Science Forum, 2012 717-720, pp. 129-132.;
3. B. Krishnan, S. P. Kotamraju, G. Melnychuk, H. Das, J. N. Merrett, and Y. Koshka, “Heavily Aluminum-Doped Epitaxial Layers for Ohmic Contact Formation to p-Type 4H-SiC Produced by Low-Temperature Homoepitaxial Growth,” Journal of Elec Materi 2010 39 (1) pp. 34-38.;
4. Y. Koshka, “Method for Epitaxial Growth of Silicon Carbide,” US Pat No. 7,404,858 (July 29, 2008).

KEYWORDS: Silicon Carbide, Epitaxy, 4H-SiC, Semiconductor

You are the Chief Technology Officer of a company that has specialized in creating low volume customized high reliability electronic systems for specific applications in demanding environments. Your CEO believes that the company’s expertise in micro to nanoscale materials, processing, and devices could provide a research and development path to meet DOD’s objectives in their solicitation. Your job is to define the research and development needed for new base technologies that would provide the platform for many future 4H-SiC based power amplification and conversion technologies, and perhaps even expansion into other harsh environment markets.

While meeting the DOD Phase I performance requirements are your priority, the cost of customized 4H-SiC based power systems will always be very high as compared to off the shelf commercial systems. In order to have potential to be competitive in other market applications which value compact, high-performance, it is desirable if your approach can be easily modified or adapted for lower price-point markets.

Your job as CTO is to deliver a complete proposal with your plan for the company to compete in this area to your CEO by your deadline.

<u>YOUR DELIVERABLE</u>
Your task is to write an internal proposal for your corporate officers describing your idea for research and development. The proposal should include the following:

- Executive summary (one page)
- Risk assessment roadmap form (one page)
- Full proposal (15 pages maximum)
- Appendix A: List of references (no page limit)
- Appendix B: Ranked list of intellectual property documents examined (no page limit)

<u>Most Importantly</u> – The significance and novelty of your creative solution, one that moves the boundaries of knowledge outward, will be the primary assessment focus of your review panel. The list below is just a minimum list of issues you might consider. There may be many more. The point is that your proposal ***should contain the evidence*** needed to make an effective and compelling case to your CEO in order to insure that she/he makes the right decision.

<u>At a minimum, be sure you address all of the following:</u>
Current Science and Technologies - What is already being done in this area by other researchers, companies and governmental institutions? Describe the current state-of-the-art for both the science and the implementation. Use diverse resources such as science literature, journals, conference proceedings, the internet, patents and other sources of existing public knowledge. ***<u>Cite all references you use and use quotes for any word-for-word transfer to your report.</u>***

Your Design Approach – What is the basis for your design approach to the problem? Why is your technology better than existing technologies? What technology attribute(s) make it likely to be selected by DOD? Address scientific *and* engineering aspects of these questions. Where relevant, consider: device size, weight and power (SWAP) requirements; materials of construction; critical components and considerations that comprise the complete device-level or subsystem-level solution; and what are the required prototyping and/or production methods, tools and costs? ***Even if you are not an expert in all of the technological areas required to bring the end-product to fruition, you should at least be able to intelligently discuss the other critical components, considerations and R&D requirements.***

Research & Development Plan - Describe a set of tasks and/or tests you will complete to demonstrate that your approach is effective and that your implementation of the solution is meritorious of further R&D. ***This is essentially your design of experiments. What are your objectives? What are the tasks required to achieve those objectives?*** Where applicable answer the following:

i) What are the key product specifications that you are targeting and how do they compare to the specifications of the existing solution(s) if any exist?
ii) What mathematical models and/or simulation constructs will you use to validate your approach, especially if prototyping and test trials are costly?
iii) What are the key dependent and independent variables that you must utilize and evaluate to confirm the proposed solution works?

Above all, be specific and detailed about the key tasks to confirm feasibility and validity of what you are proposing.

Cost Analysis – Identify cost and market issues that will impact the pricing strategy of the solution you have proposed. Identify Strengths, Weaknesses, Opportunities and Threats (SWOT) in the market place. If you are unfamiliar with the typical SWOT marketing analysis, I encourage you to 'google it'. Consider such things as: the major cost items that would impact the implementation; which elements of your implementation solution would be handled in-house versus externally-sourced; major risk elements that could drive up costs if the primary path item fails; costs of IP licensing needed, etc. Provide justification and/or reasoning behind your decisions. Estimate manufacturing cost for the total system as the technology reaches mature stage, so the marketing team can determine potential for penetrating other markets. Avoid subcontracting design, manufacture or assembly of any proprietary component outside the company, because the CEO is concerned with potential IP leakage.

Intellectual Property – In Appendix B, list in rank order of importance ***all*** commercial, academic, and governmental IP sources that were consulted while formulating the answer, including reference data. For instance, include the patent number; title; inventor name; and assignee name for a patent. Discuss the 3 most significant IP documents affecting your approach to your solution in the 15-page document. Compare strengths and weaknesses of these approaches relative to your own. Recommend how these IP threats should be handled.

Hint – Clearly state your hypothesized solution. Identify its innovation(s) and advantages relative to state of the art. Describe both existing data, and work needed to support each aspect of the hypothetical solution. Consider theoretical, fabrication, and characterization aspects: for each, identify software/equipment and methods to use, parameters to vary, anticipated outcomes, and possible alternatives in the event of unsatisfactory results. Discuss material, process, device, and systems aspects of your solution. *Refine* your hypothesized solution as you accumulate information and prepare the manuscript. **Remember**: clearly distinguish what is known from what is hypothesized or not known. What is needed to distinguish the important things to know?

Reference the 2020 PhD Candidacy Exam Guidelines document for general instructions.