High Quality, Low Cost Bulk Gallium Nitride Substrates Grown by the Electrochemical Solution Growth Method

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SunEdison / Sandia National Lab / Georgia Institute of Technology / Qynergy Corporation

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Mike Seacrist, Senior Fellow – Emerging Technologies R&D, SunEdison Semiconductor (formerly MEMC)

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Project Objective

- Develop electrochemical solution growth (ESG) of gallium nitride (GaN) into a technology capable of producing large area bulk GaN substrates

- Bulk GaN enables homoepitaxial growth of GaN layers for improved devices (ie. GaN epitaxial layers on bulk GaN substrate)
  - Vertical power devices with voltage / current capability beyond heteroepitaxial-based lateral GaN devices that could be competitive with SiC
  - GaN on GaN LEDs with much higher light output per device than GaN / Sapphire

- No existing bulk GaN technology currently combines all of the following elements: low cost, high volume, high growth rate, high quality, large area, thick GaN boule growth

- Bulk GaN does not grow readily from melt (like Si or GaAs) due to thermodynamic instability and low N solubility in liquid Ga

Technical Approach 1

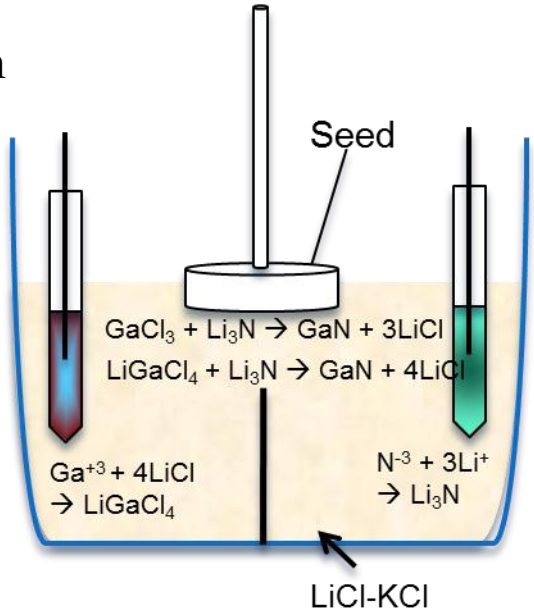
- Comparison of Growth Methods

Growth Method	Growth Rate (um/hr)	Diameter / Thickness (mm)	Dislocation Density (cm^{-2})	Status
High pressure N2 solution	1	25 / 10	10^2	Research
Ammonothermal	5	50 / 5	10^4	Research quantities
Hydride Vapor Phase Epitaxy (HVPE, on a substrate)	100	100 / 0.5 (wafer)	10^5-10^6	Commercial
GaN Epitaxy on Silicon	1	150 / 0.005	10^9	Commercial ($10M)
SiC (sublimation)	10^3	150 / 100	1-10	Commercial ($100M)
Silicon (melt)	$6*10^4$	300 / 2000	0	Commercial ($8B)

- Electrochemical Solution Growth is completely different approach
  - Goto et al demonstrated continuous nitrogen gas reduction with a high concentration of nitride ions in molten chloride salt at 450C/1atm (J. Electrochem Soc, 144 (1997))
  - Sandia (Waldrip et al) idea to continuously create nitride and metal (Ga) ion precursors electrochemically and use rotating disk induced flow to deliver them continuously to GaN seed crystal surface for growth (US Patent 2008)

Technical Approach 2

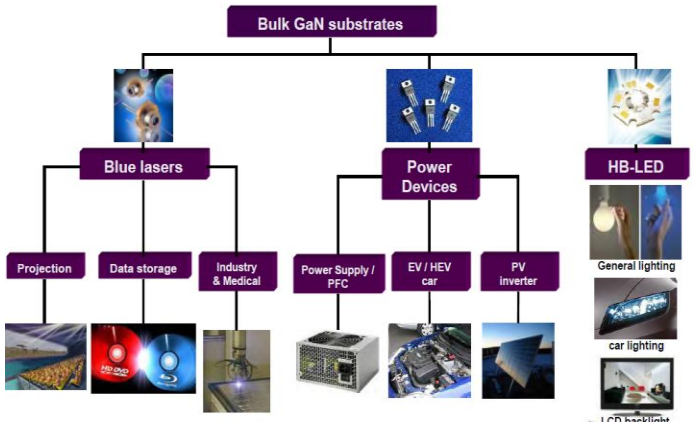
- ESG bulk GaN concept
  - Produce Ga and N ions in molten salt @ 500C / 1atm
  - Transport precursors via rotating seed fluid flow
  - Precursors react at / near seed surface
  - Driving force for GaN reaction via supersaturation
    - Observe nucleation/growth of GaN crystallites in solution
  - Challenge is to optimize system for growth at seed



- Project Team:
  - SunEdison, formerly MEMC (Seacrist): *company with > 50 years experience in electronic substrate development and manufacturing*…project lead, ESG modeling and new equipment concepts
  - Sandia/Qynergy (Waldrip): *inventor of ESG GaN*….growth science / experimentation
  - Georgia Tech (Dupuis): *wide bandgap materials/device expertise*…growth seeds and sample characterization

Transition and Deployment 1

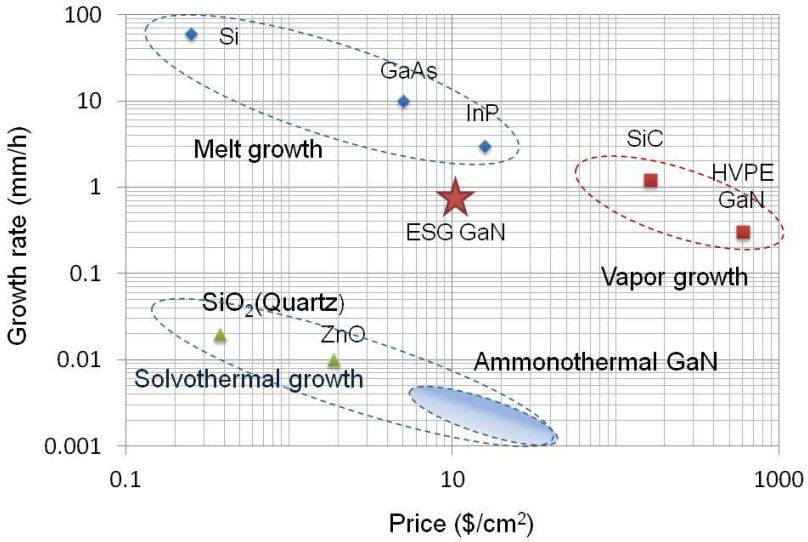
- ESG GaN substrates, in bulk form or with GaN epi added, are targeted to 1) power device and 2) optoelectronic device makers
- Project deliverables
  - Reproducible monocrystalline growth process with sustainable film growth rate of at least 0.5mm/hr scalable to >100mm substrate diameter and film thickness > 1mm, and with material quality competitive with HVPE



(Yole Development 2010)

GaN-based WBG power devices expected to exceed $1B by 2022 (IHS 2013)

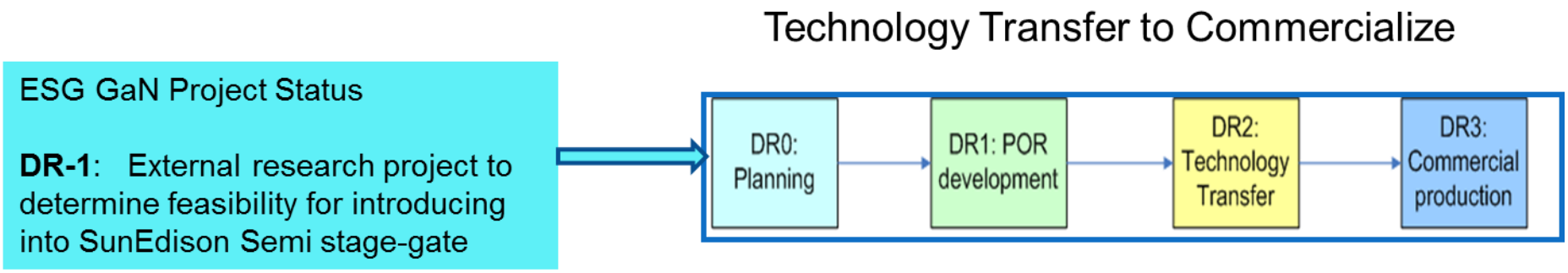
Substrate market for bulk GaN and GaN/Si expected to be ~ $200M by 2020 (IHS 2013)



Growth rate and wafer price for most common substrate materials (based on data from: Yole Research, 2011; T. Fukuda, Tohoku University NEXT program, 2010)

Transition and Deployment 2

- Decision on whether to pursue ESG GaN in SunEdison Semiconductor Technology Transfer process based on validation of research goals and assessment of commercial viability



- High volume manufacturing experience driving continuous improvements in ESG GaN substrate cost, quality, yield, throughput, scaling

- Worldwide sales/marketing / field engineering network to build the business

Measure of Success

- WBG semiconductors are driving smaller, faster, more efficient, and higher temperature power electronics as compared with silicon
  - Widespread adoption of efficient load architectures enabled by GaN-based power electronics and lighting can lead to a 25% reduction in world energy consumption ~ 2025 (Yole Development 2010)

- Success on ESG GaN substrate development (or significant improvements in other methods) leads to more rapid growth of GaN-based power devices, reducing cost per device through lower substrate cost and more devices per wafer at a larger substrate diameter

- Success on ESG GaN commercial substrate drives investment in a US-based growth / wafer manufacturing

Project Management & Budget

Started Sept 2012 (FY13Q1) as 3 year project

Year 1: *Crystalline GaN growth on Seed in existing Sandia reactor*

- Develop process to grow crystalline GaN on seed and characterize films…not achieved
- Develop growth models including electrochemistry….complete
- Model, design, and fabricate improved reactor concept…complete

Year 2: TBD….*Scale process in improved reactor, improve layer quality*

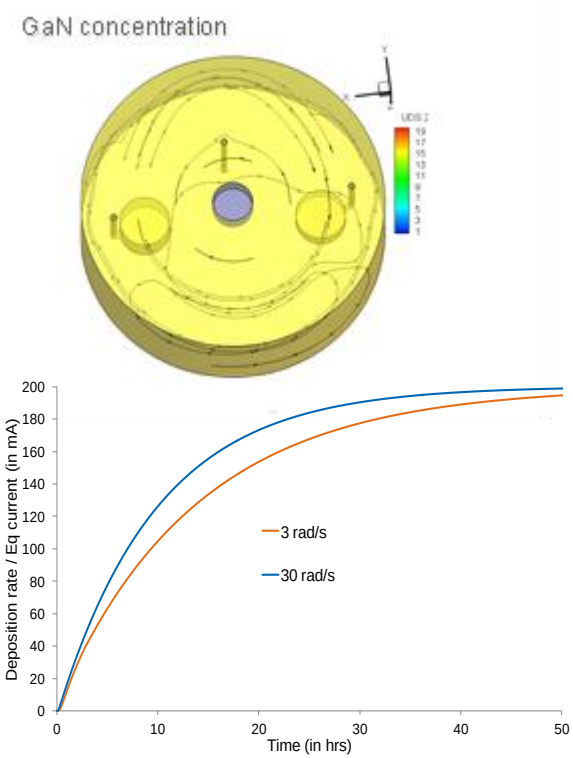
Year 3: TBD….*Device validation and decision on industrial scale-up*

Total Project Budget	
DOE Investment	$3,675,125
Cost Share	$920,00
Project Total	$4,595,125

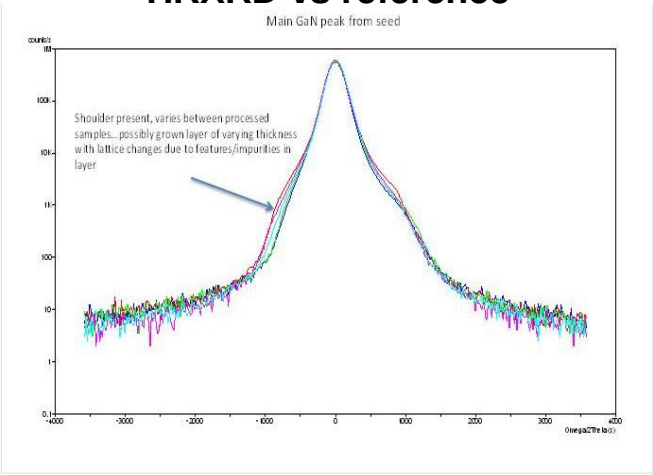
Results and Accomplishments

- The project is in budget period 1 extension through Aug 2015
  - ESG crystalline GaN film > 0.5um on seed must be demonstrated
    - To date, film deposition has been ~ 0.5um amorphous layer containing Ga, N, O, Al
    - Samples made with high purity hardware and high purity salt are currently in FIB/TEM characterization to determine if crystalline GaN growth on seed has been achieved
    - Plans for continuing project depend on results from the current work, specifically demonstration of crystalline GaN growth in ESG

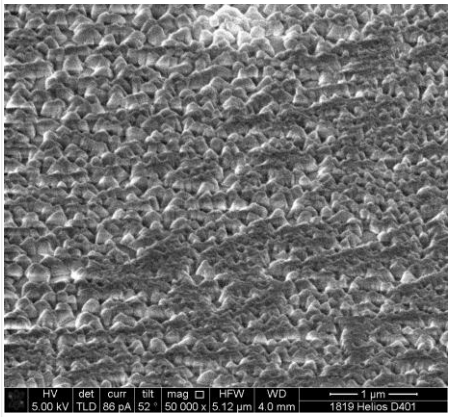
Developed ESG growth model



HRXRD vs reference



SEM surface view



- HRXRD indicates crystalline ESG GaN may have been grown on the MOCVD GaN seed.
- SEM surface view has appearance of growth.
- FIB/TEM in progress to determine if growth of crystalline GaN layer via ESG.