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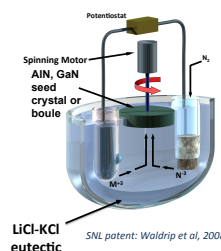
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Progress in the Development of Bulk Nitrides for High Power Electronics

1. Motivation

- Wide-bandgap semiconductors such as GaN have material properties that make them theoretically superior to Silicon for power electronics for energy storage systems
 - Gallium nitride and aluminum nitride promise to reduce the size, complexity, and cost of power conversion systems
 - However, one of the main materials barriers to widespread adoption remains the absence of an affordable, high quality, large area lattice-matched substrate on which to grow high quality high power devices
- Overall goal: Develop a growth technique capable of producing high quality, large area bulk nitrides that is economically viable**
- OE seed funding for GaN growth in previous years resulted in the 2012 award of the \$4.6M Innovative Manufacturing Initiative with SunEdison and Georgia Tech Research Institute
 - 20% cost share from SunEdison (St. Peters, MO)
 - Partner with Qynergy Corporation
 - FY13 OE project focus is reactor development and application of ESG to chemistries for novel nitrides (AlN, FeN₂) as opposed to GaN

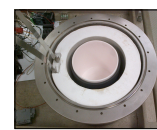
2. Sandia's patented Electrochemical Solution Growth (ESG) Technique



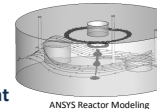
- Nitride compounds tend to decompose at temperatures far lower than their melting points → high temp, high pressure
- Traditional growth processes not economically viable
- ESG is a scalable, atmospheric pressure process based on the novel electrochemical reaction of nitrogen gas in a molten salt at ~450-500°C
- The unique ESG process leverages Sandia's molten salt electrochemistry expertise from thermal batteries**

3. FY13: Process Modeling, Hardware, Electrolyte Development

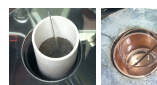
- Custom-built reactor developed
 - SunEdison developed next-gen reactor using ANSYS modeling
- Electrolyte purification techniques developed in FY12 scaled up
 - Acceptable initial purity
 - GaN successfully synthesized
 - Experiment throughput more than tripled
 - Electrolyte cost per experiment reduced from \$2500 to \$50
- Enables process scaling from 1cm² test coupons to 50 and 100mm diameter boules in FY14 and FY15**



Next-gen Reactor Development

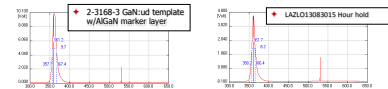
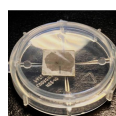


ANSYS Reactor Modeling

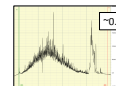


Molten Electrolyte Pre-purification Post-purification

4. FY13: Seeded Growth Advances



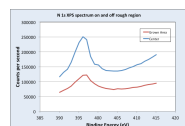
Photoluminescence spectra (a) pre-growth and (b) post-growth on the grown region



Alpha-step profilometry on raised, grown region

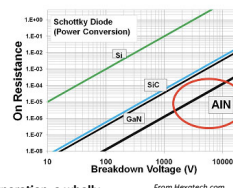
- NEW! Deposition occurring on the seed crystal, indicating that reactor fluid dynamics and hardware are properly functioning**
- XPS confirms presence of Ga, N in grown area, along with contaminants from reactor materials used to improve speed of development—but interfere with crystal growth (present reactor materials less expensive, have faster delivery times)
- New choice of inert reactor materials now required to advance growth process and obtain high quality crystal growth (FY14 work)

XPS confirms Ga, N, Ni, O, Al, C on and off rough regions



5. FY13: Aluminum Nitride Electrochemistry Development

- GaN hardware development under IMI is directly applicable to large-area AlN substrate development
- AlN power electronics theoretically outperform SiC by 6X
- Crystalline defects substantially lower the Critical Field and Breakdown Voltage—decrease performance and efficiency of high power electronics
- Bulk AlN is best substrate to realize high efficiency AlN power devices
- Bulk AlN limited to 1" diameter for several years by traditional crystal growth process limitations
- Large area substrates required to lower cost and improve yield
- New effort directed towards applying the scalable ESG process to AlN

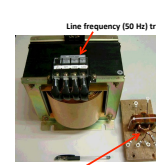
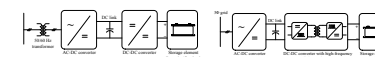


From Hexatech.com

Aluminum electrochemistry has been demonstrated to be viable in the ESG system

All GaN hardware and electrolyte developments are applicable to large area, high quality bulk AlN development

6. FY13: ESG for Novel High Frequency Transformers



High frequency (20 kHz) transformer

- Goal: Based on needs determined by systems engineering models, design and synthesize a new magnetic material for the core in a high frequency transformer DC-DC Link
- Transition metal nitrides have desirable properties but are impossible to synthesize in large quantities by traditional processing methods
- The unique capabilities of ESG likely make development of new magnetic nitrides possible

FY13: Contract let to **ASU** for systems modeling and determining materials performance parameter requirements

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