LA-UR-12-22109
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Title: The Energetic Neutral Atom Beam Lithography & Epitaxy (ENABLE) Capability at LANL

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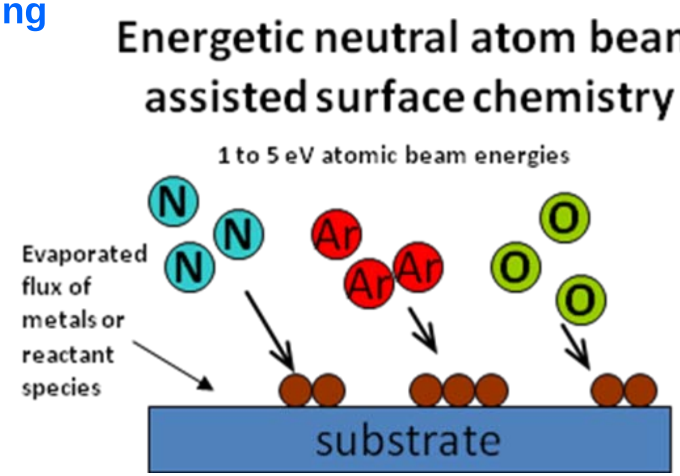
Intended for: presentation to potential technology transfer partner

The Energetic Neutral Atom Beam Lithography & Epitaxy (ENABLE) Capability at LANL: What is the Technology Driver

Advanced materials for energy security, ultrasensitive detection, and cancer screening

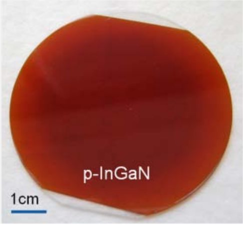
ENABLE lowers temperatures for growing nitride thin film materials and allows high-aspect-ratio nanoscale etching



Why our interest in the nitride materials?

In-rich InGaN is a "new" class of *semiconductor* material with tunable direct bandgaps (3.4 eV to 0.7 eV) ideal for applications in:

- **Ultra-high-efficiency photovoltaics (PV) for harvesting the *entire* solar spectrum**
- **High-efficiency multicolor LEDs for white-light Solid State Lighting**
- **Photoelectrochemical (PEC) H_2 production**
- **Solid State Laser Diodes**
- **High-Power Electronics, etc.**



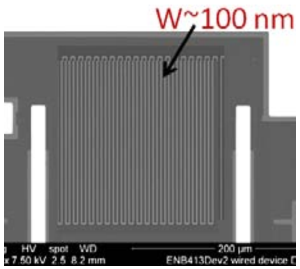
"red" In-rich InGaN film with 2.0 eV band gap grown by ENABLE

Growth of c-BN semiconducting films for solid-state neutron detection for ^{3}He replacement

NbN is a *superconducting* material ideal for fabrication of high-speed, low-noise single photon detection applications in:

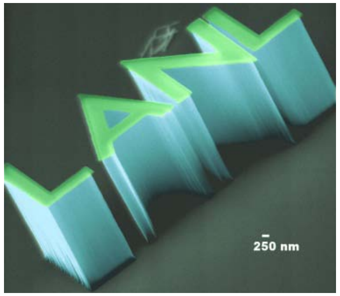
- **Space surveillance & nuclear threat detection**
- **Quantum science, biomolecular imaging**

SNSPD serpentine nanowire detector, T_c~13.2K



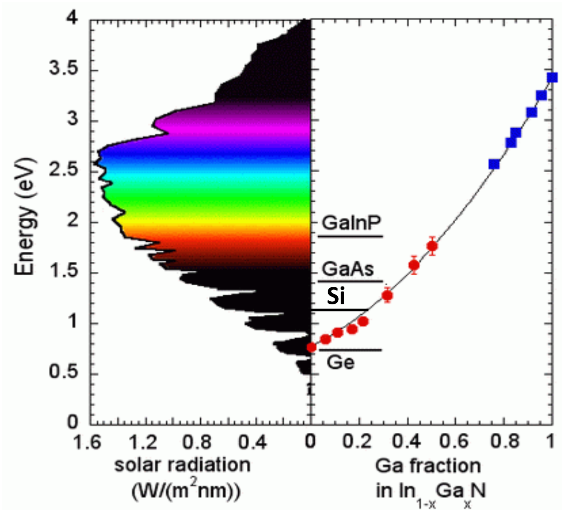
ENABLE-based high-aspect ratio etching of polymeric materials

- **Medical application in enhancing contrast and image resolution in digital mammography for breast cancer detection**
- **Other applications for fabricating complex nanoscale devices**

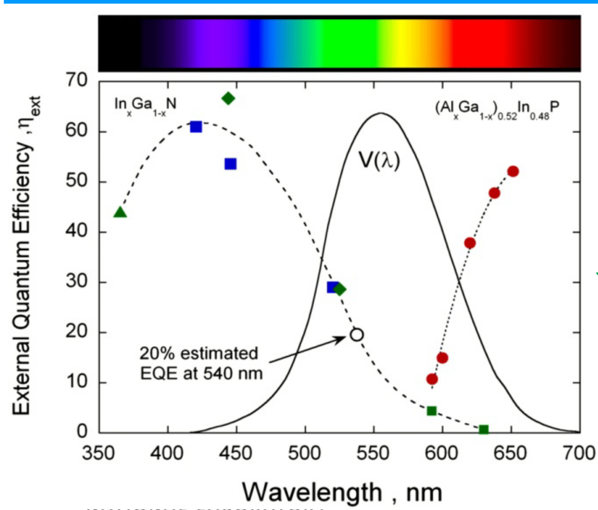


Neutral O-Atom nanoscale etching of masked polyimide films by ENABLE

Why InGaN materials are ideal for high efficiency PVs, efficient SSL, and PEC applications



Bandgaps in the InGaN alloy system cover virtually the entire solar spectrum



- **$In_{1-x}Ga_xN$ materials are thin film alloy semiconductors (0<x<1) with tunable direct bandgaps (0.7 eV to 3.4 eV)**
  - spans the *entire* visible solar spectrum
  - captures more photons for enhancing PV efficiency
    strong absorption ➔ active film can be <1 micron thick
  - high carrier mobilities GaN (~1000 cm^2/V·s, InN ~2000 cm^2/V·s)
  - high temperature tolerance, chemically inert
  - radiation resistant
- **InGaN-based PVs offer higher efficiencies & low costs**

  Example: A 50% efficiency football-field-size PV array could generate 5 MW of electrical power. With 500X concentration only 20 m^2 of film active area is needed.

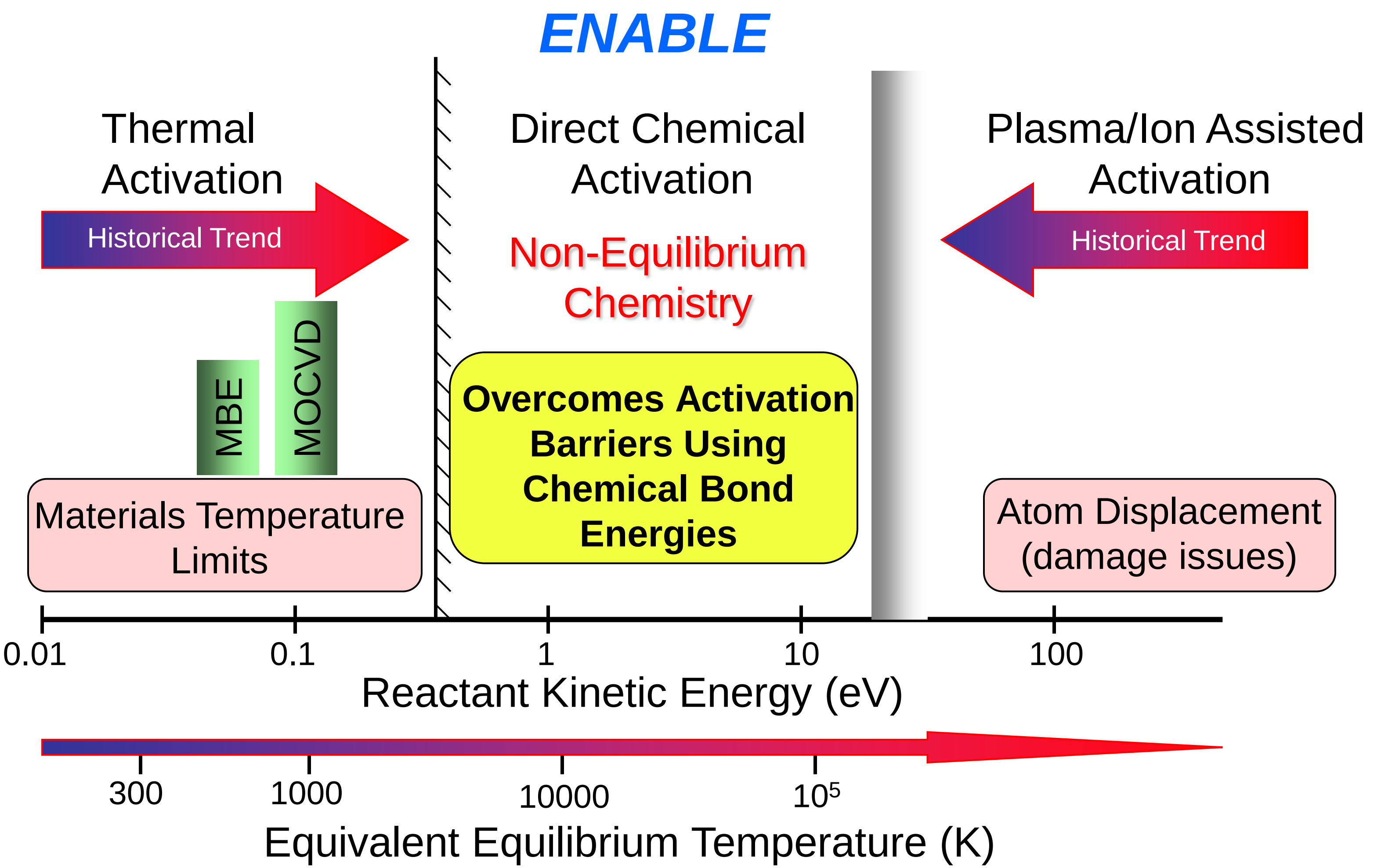
- **Challenges in making high-In-content InGaN materials**
  - high growth temperatures of existing growth techniques cause decomposition of high-In-content alloys
  - difficulty creating indium-rich InGaN, the *"green gap"* problem for LEDs
  - difficulties with p-type doping of InGaN
  - lack of inexpensive substrates for large areas

Conventional Growth of $In_{1-x}Ga_xN$ Thin Films

- **InN decomposes above ~600 C**
- **CVD growth technologies (few thousand systems worldwide—explosive growth)**
  - **Includes MOCVD, MOVPE, HVPE, etc**
  - **Growth temperatures typically range from 800 C to 1100 C**
  - **Most commercial GaN for devices produced by MOCVD (rates <10 μ/hr)**
  - **Limited ability to produce InN**
  - **Difficulties producing InGaN with In content > 15%**
- **MBE growth technologies (few thousand systems worldwide)**
  - **Includes MBE, RF-MBE, PA-MBE, etc.**
  - **Growth temperatures range from 500 C to 900 C**
  - **Generally yields *extremely high quality* GaN**
  - **Growth rate is typically much slower than CVD (rates <0.5 μ/hr)**
  - **Able to produce high quality InN**
  - **Producing InGaN with In content > 15% still challenging**

Problem: Generally high growth temperatures relative to In-rich InGaN

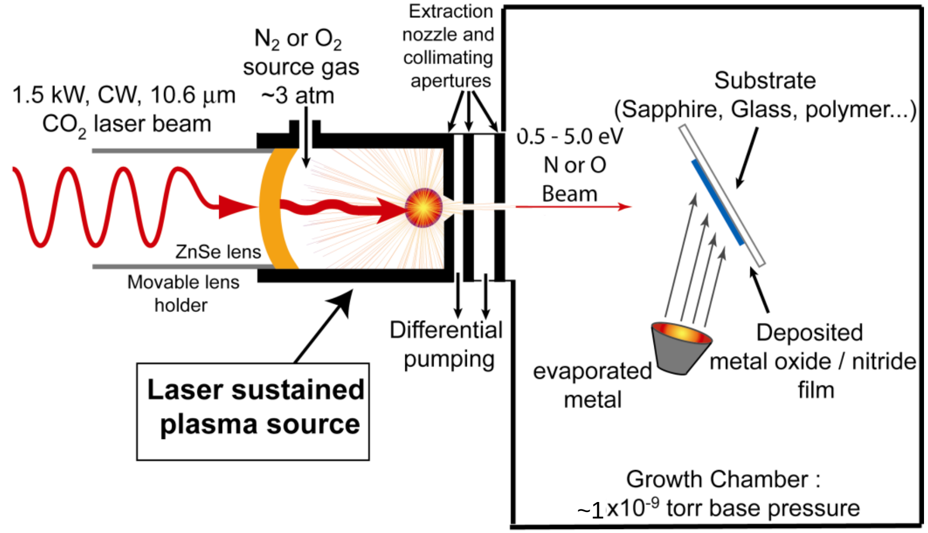
Thin Film Materials Chemistry
(overcoming barriers limiting materials quality)



Energetic Neutral Atom Beam Lithography & Epitaxy
(winner of a 2006 R&D 100 Award)

ENABLE System Characteristics

- **Energetic beam of neutral N atoms.**
  - **Kinetic energy tunable, 0.5 to 5.0 eV**
    - **➔ growth energy ~1.6 eV**
  - **High flux ~10^{17}atoms/ cm^2•sec**
- **Simultaneous deposition of Ga and/or In**
- **Typical growth rate ~3 µm/hr on 2" wafer**
- **Reactivity from N atom energy, not heat**
- **Lower temperature epitaxial growth**
- **N atom beam not NH_3 or plasma $N_x^{+?}$**
- **No toxic chemical precursors or hazardous waste stream**
- **Environmentally green process**
- **Inexpensive operating costs**

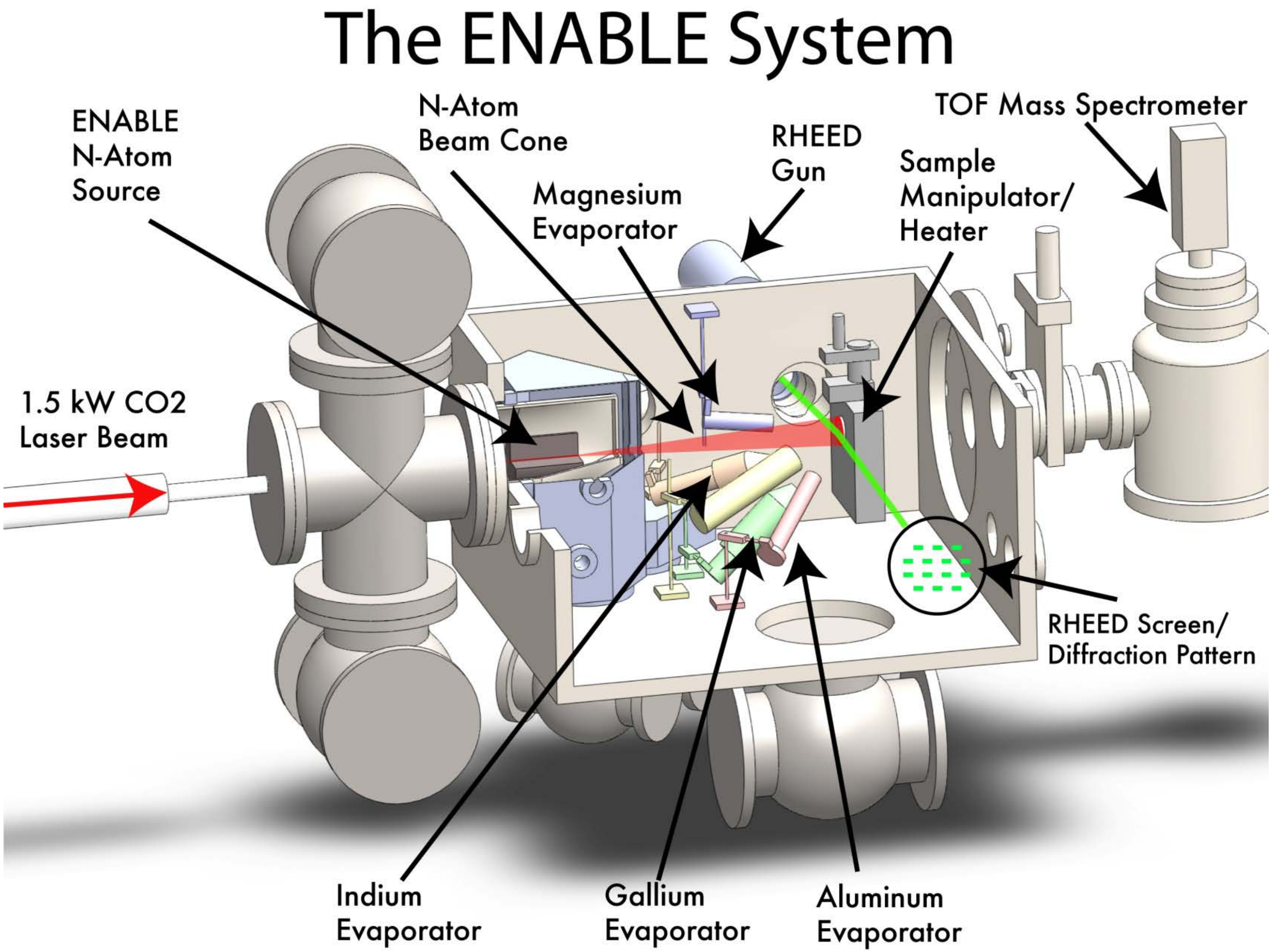


ENABLE is the only system in the world capable of providing an high-flux collimated beam of energetic N atoms (E_{KE} ~1 to 5eV) in an ultraclean MBE-like environment.
➔ *Winner of a 2006 R&D 100 Award*

ENABLE low temperature advantages for growing InGaN semiconductors

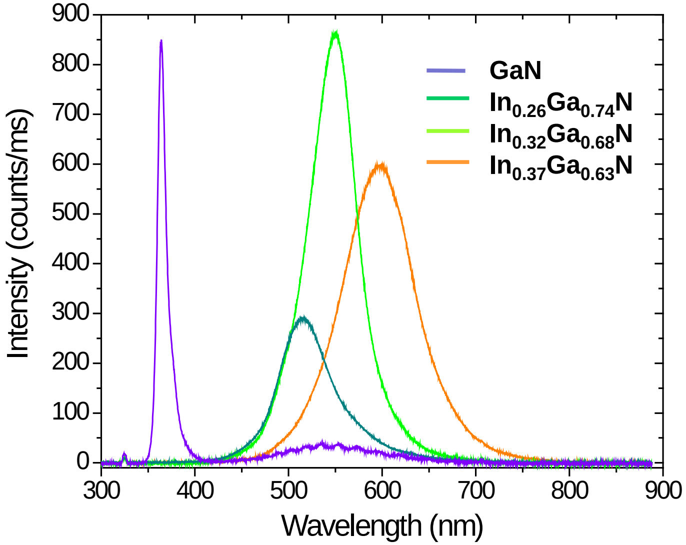
- **InGaN films can be grown over the *full alloy composition* range with excellent epitaxy & crystallinity**
- **Excellent compositional uniformity with no phase segregation**
- **Improved p-type doping resulting from lower growth temperatures**
- **More substrate options with excellent film epitaxy (Si, glass, etc.)**
- **Permits compositional grading for high-efficiency PV devices**
- **Growth rates on 50 mm wafer can exceed 3 microns/hr**
- **No toxic chemical precursors or hazardous waste stream**

System Diagram

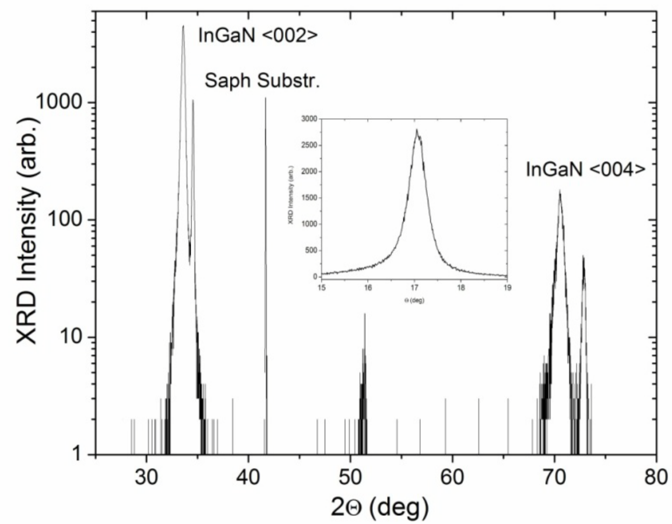


Successful growth of In-rich InGaN

- **PL data from ~750 nm thick InGaN films grown near 550 C plotted on same absolute intensity scale**

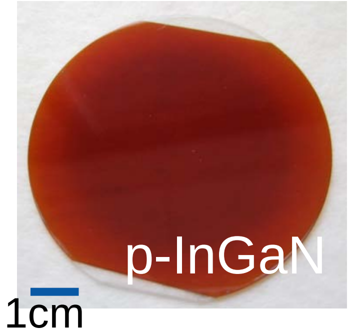


- **InGaN film <002> XRD typically:**
  θ-2θ: ~400 arc sec FWHM
  rocking curve: ~1000 arc sec FWHM



Progress indicates no limitations in creating highly luminescent InGaN films over the entire visible bandgap range

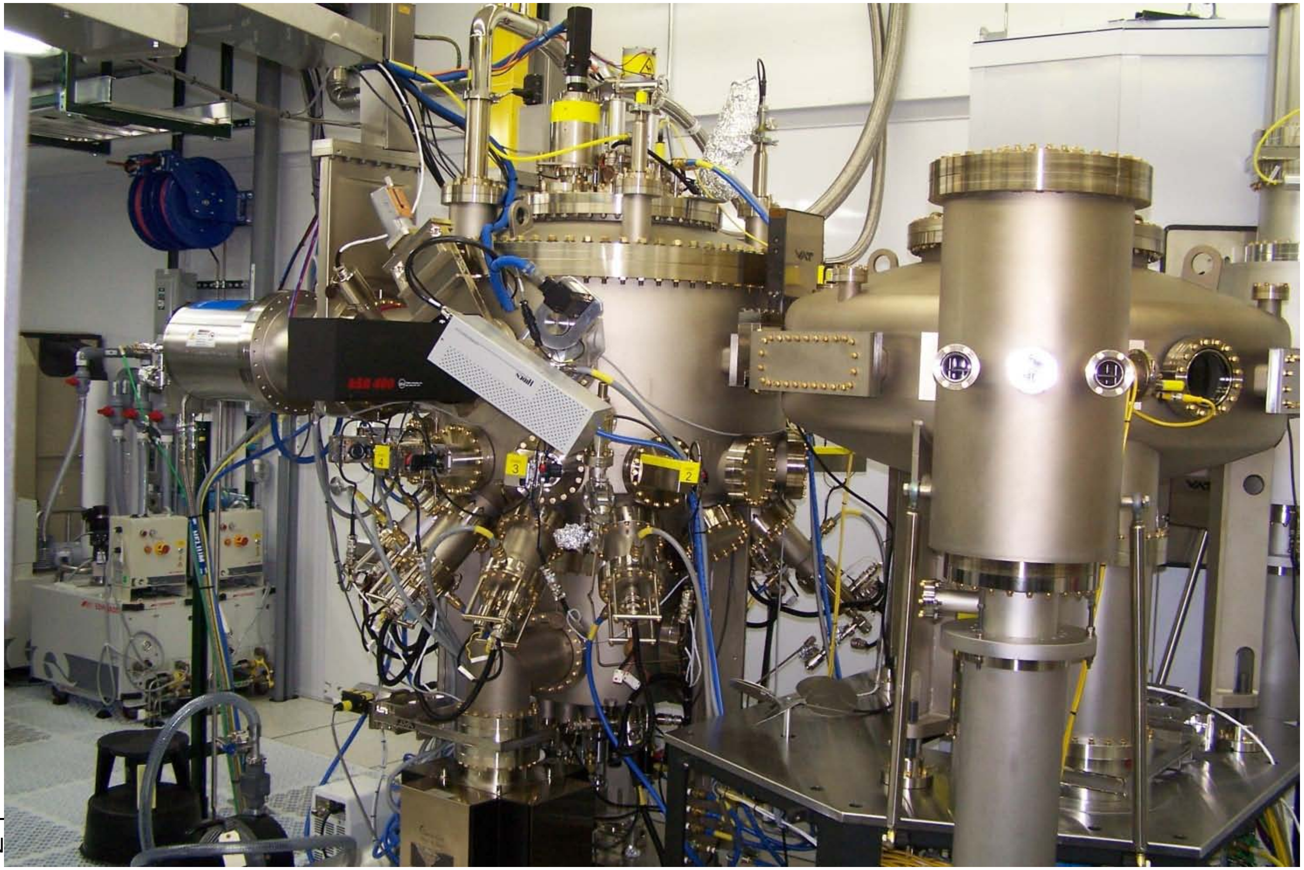
p-type InGaN film with 2.2eV band gap grown on sapphire



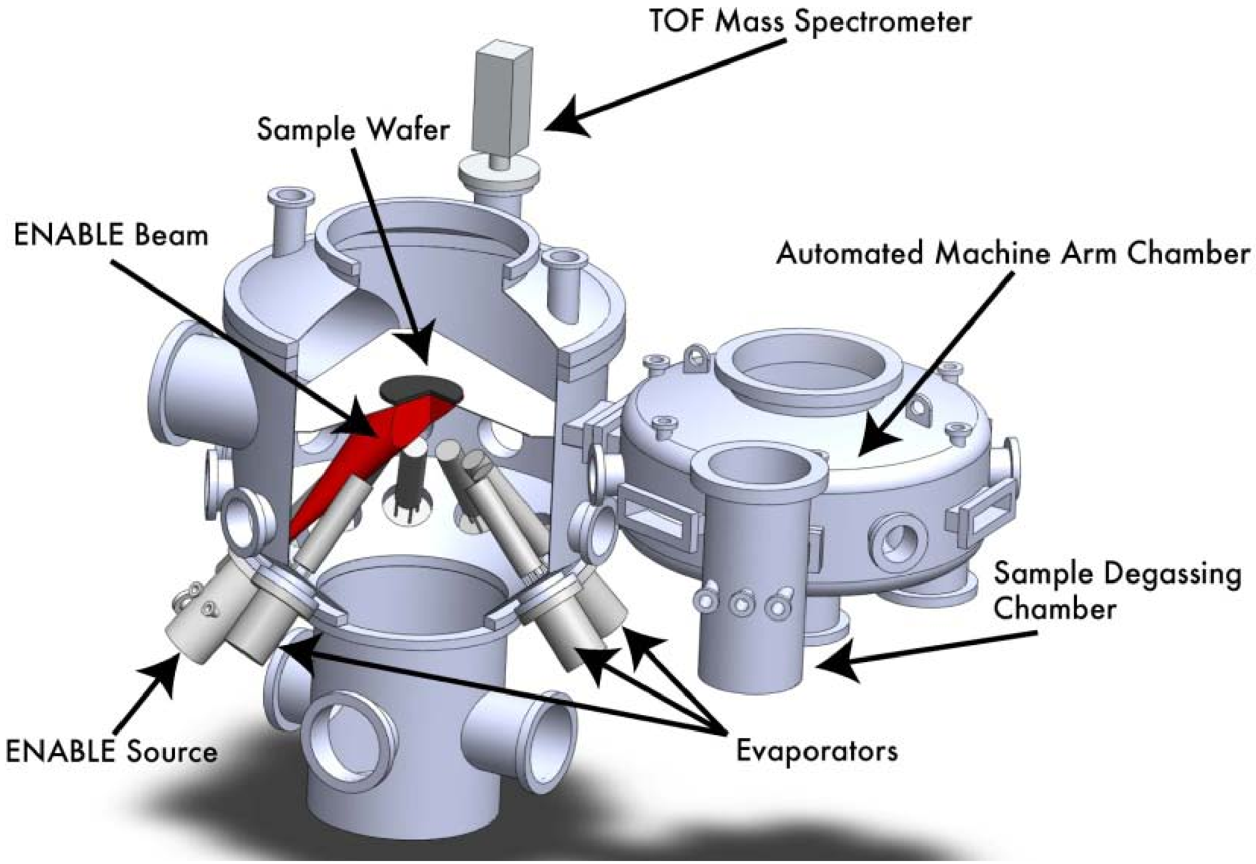
- **High-quality, thick, high-In-content InGaN films demonstrated at high growth rates in an MBE environment. → Best reported by anyone world-wide!**
- **ENABLE decreases growth temperatures, broadens the "growth window", and enhances p-type doping efficiency**
- **Currently creating InGaN p-n junctions with a wide range of In compositions for PV devices**
- **Currently scaling ENABLE technology to production platform (Veeco GEN 200 system) with 200 mm wafer size and >10 microns/hr growth rates (nitride emphasis but compatible with oxides)**

Veeco GEN200 large area $4M+ MBE platform

- **Veeco GEN200 system recently acquired with CRADA partner help, being brought online at LANL**
- **nextGEN ENABLE source designed for >200 mm wafer processing at growth rates >10 microns/hr on Veeco GEN200 platform (nitride emphasis, compatible with oxide films)**
- **Convert existing ENABLE system to large-area, high-aspect-ratio etching platform**



The nextGEN ENABLE System



Schematic view of nextGEN ENABLE system built on world-leading, production-grade MBE platform for 200 mm wafers

ENABLE Projects

- Growth of InGaN films for plasmonic enhancement of PV (LDRD)
- Growth of superconducting NbN for nanowire-based photon detection (LDRD)
- Growth of InGaN films for PEC water splitting (NREL/EERE)
- Growth of InGaN films for high-efficiency PV applications (Rose Street Labs CRADA partner with LBNL started in 2008, license options)
- Etching x-ray mammography grid structures for CRADA with Creatv Microtech (Phase II NIH sponsor, license options)
- Proposal to DOE Advance Manufacturing Initiative, partner with RSLE and LBNL
- ARPA-e pre-proposal for PV applications (partner with RSLE, LBNL, Veeco)
- Strong interest from Veeco in licensing ENABLE source technology (recent LANL visit)
- DARPA pre-proposal to Local Control of Chemistry (LoCo) Program

Intellectual Property Status & Marketing Potential

- Growing patent portfolio being constructed (currently 6 pieces of IP), consisting of both Background IP and Foreground IP
  - strong interest in nextGEN source technology licensing

Multiple market applications including, but not limited to:

- PV
- SSL
- H_2O splitting
- high-speed high-power switching electronics
- medical imaging
- exotic film growth for fundamental and applied research

Multiple >$10B markets