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# "Innovative Strain-Engineered InGaN Materials for High-Efficiency Deep-Green Emission"

**Sandia National Laboratories**
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# Project Team

| Activity | Personnel |
|---|---|
| Growth | Dan Koleske / Gerry Thaler |
| Optical Properties | Mary Crawford |
| XRD analysis | Steve Lee |
| ELO patterning & characterization | Steve Lee / Mike Smith / Mary Crawford |
| Low-defect GaN templates | Steve Lee |
| Growth Modeling | Mike Coltrin |
| Cathodoluminescence | Paula Provencio |
| TEM | David Follstaedt |
| Project Management | Mike Coltrin |

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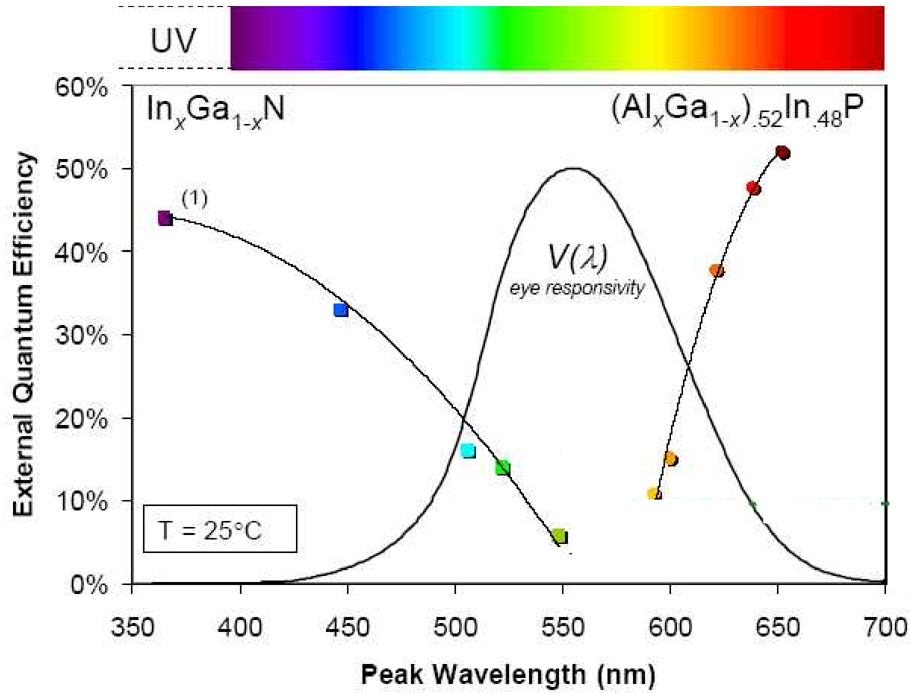
# Project Objective

**Develop high-efficiency deep-green ( ≥ 540 nm) light emitters based on strain - engineered InGaN materials**




**"High-Efficiency Semiconductor Materials, 1.1.2"**
**(Improve IQE across the visible spectrum and in the near UV – down to 360 nm)**

*Data courtesy of George Craford, Philips Lumileds



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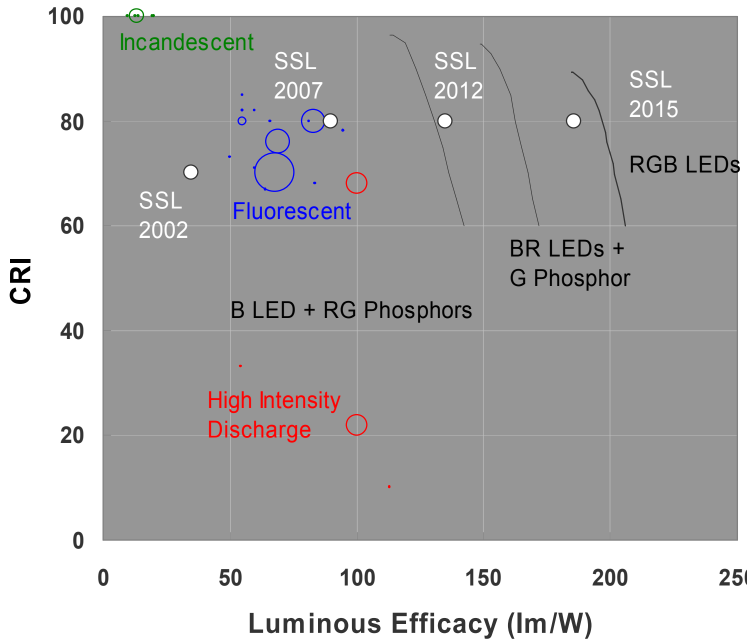
# Expected Benefits

- This project has the goal of more than **doubling the internal quantum efficiency of deep green ( ≥ 540 nm) InGaN LEDs**.
- Solid-state white lighting with **~ 200 lm/W** will require wall plug efficiencies of **~ 50%.**
- Higher In-content **InGaN LEDs** require the most improvement to reach this goal.
- This work will directly impact current and future **white lighting** using the **multi-chip approach**.
- This work will accelerate the adoption of solid-state white lighting for **commercial and residential applications**.



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# Materials issues in growth of InGaN for deep-green LEDs

- **Current LED designs:**
  - InGaN / GaN active regions grown on
  - basal plane of thick GaN (2-3 $\mu$m) templates grown on
  - thin low-temperature GaN layer grown on
  - sapphire (or SiC) substrates
- **Indium is required to push III-Nitride emission to longer wavelengths**
- **As Indium content increases, several materials issues arise:**
- **Lower growth temperatures are required**
  - causes a variety of defects: point defects, C & O impurities, V-defects
- **Lattice mismatch (and strain) increases**
  - strain-driven roughening (non-ideal QW interfaces)
  - internal polarization field reduces e – h overlap
  - both effects are thought to decrease the optical emission
- **High temperatures used for subsequent growth of p-GaN layer cause thermal degradation of InGaN quantum wells**



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# Critical Problems Addressed in this Project

- Strain-limited indium incorporation during coherent epitaxy of InGaN on GaN templates
- Strain-driven piezoelectric effect in InGaN MQWs, which limits recombination efficiency
- Incorporation of point-defects and impurities due to low-temperature InGaN alloy growth
- Thermal limitations on MQW alloy stability during subsequent p-side growth

# Benefits of Strain-Relaxed InGaN Templates

- **Lower the strain that limits incorporation of Indium**
  - strain alters the vapor-solid equilibrium
  - strain pulls solid composition toward lattice-matched value (away from the gas-phase composition)
- **Will enable longer-wavelength emission (deep-green, ≥ 540 nm)**
- **Allows higher growth temperature**
  - reduced density of point defects & impurities (associated w/ low-T growth)
- **Lower piezoelectric field in active-region QWs**
  - increased overlap of electron & hole wave functions
  - increased recombination efficiency and light emission
- **However, there is an important wavelength trade-off**
  - eliminates red-shift due to quantum-confined Stark effect (approx. 55 nm red-shift to produce 525 nm green emission from x=0.20 QWs)
  - should be more than off-set through increased In incorporation

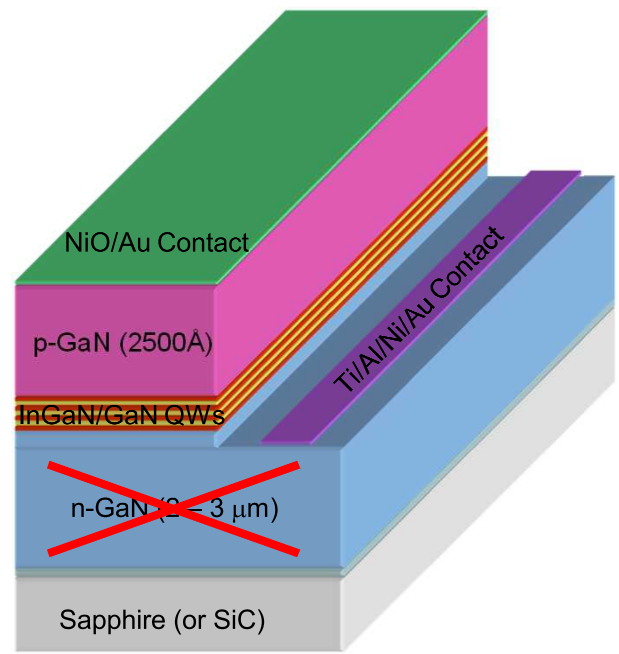
# Project Task Structure

- **Task 1:**
  - Planar Heteroepitaxy of Strain-Relaxed InGaN/GaN Templates
- **Task 2:**
  - Epitaxial Lateral Overgrowth of Strain-Relaxed InGaN Templates
- **Task 3:**
  - Growth of High-Indium Composition Active Regions on Strain-Relaxed InGaN
- **Task 4:**
  - Development of p-type Materials, Heterostructures, and Thermal-Activation Processes
- **Task 5:**
  - Evaluation of Internal Quantum Efficiency of Deep-Green Emitters

# Task 1: Planar Heteroepitaxy of Strain-Relaxed InGaN/GaN Templates

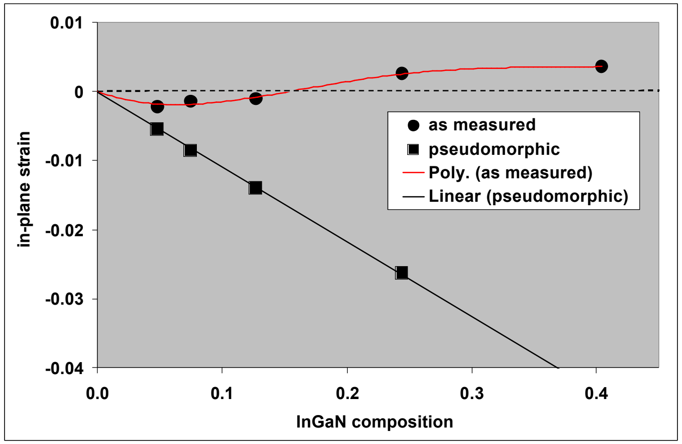
- **Goal: grow thick, strain-relaxed InGaN alloys on GaN using MOCVD**
- **Alter the deleterious strain-relaxation modes of InGaN on GaN**
  - elimination of misfit dislocations
  - eliminates accompanying V-defects (smoother surface morphology)
- **$In_xGa_{1-x}N$ compositions in the range x=0.08 – 0.16**
  - modeling strain-limited In-incorporation to assist growth studies
- **Four (proprietary) strategies for growing strain-relaxed InGaN**

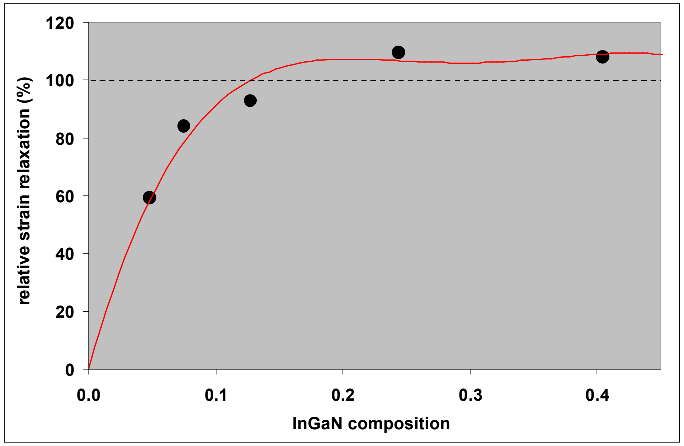
**Task 1:**
**strain-relaxed InGaN templates**



# Task 1- Approach 1: Progress-to-Date

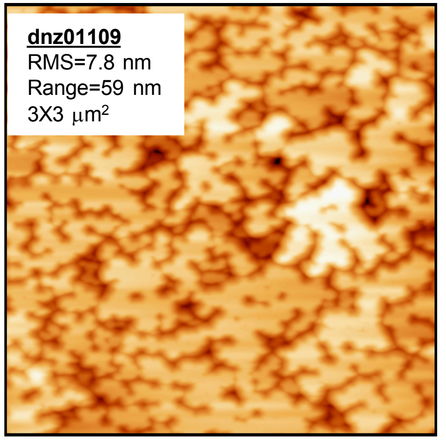
**XRD measurements of in-plane strain and strain relaxation in 150-nm-thick InGaN grown on GaN/sapphire**



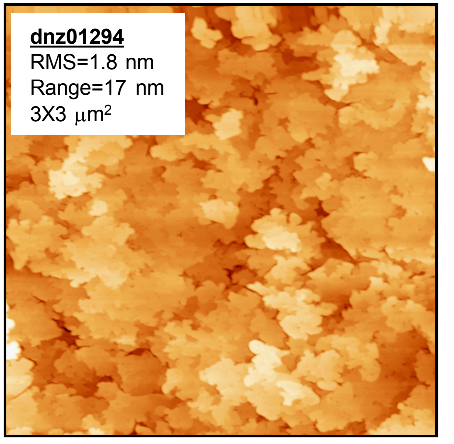




**Conclusion: substantial strain relaxation**

# Task 1- Approach 2: Progress-to-Date




**Strain-relaxed InGaN morphology using Approach 1 alone (~600 nm thickness; x=0.04): RMS roughness = 7.8 nm**




**Strain-relaxed InGaN morphology combining Approaches 1 & 2 (~600 nm thickness; x=0.04 – 0.10): RMS roughness = 1.8 nm**

## Conclusion:
## Approach 2 is effective in improving InGaN surface morphology

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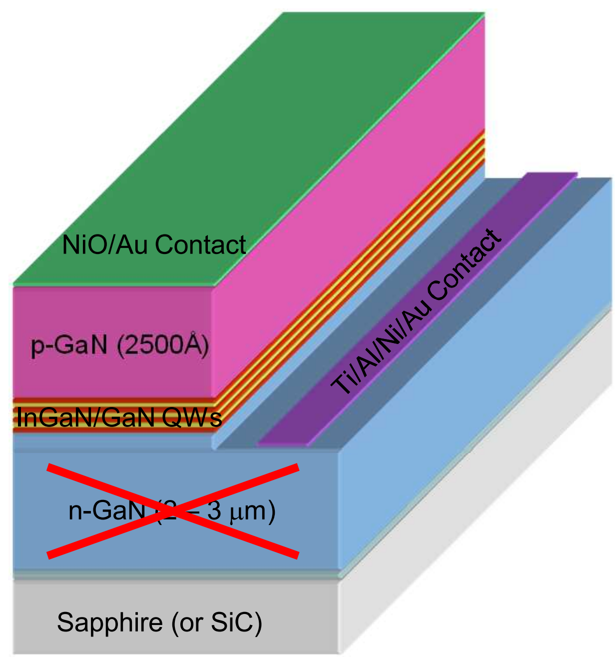
# Task 2: Epitaxial Lateral Overgrowth of Strain-Relaxed InGaN Templates

- **Goal: reduce threading-dislocation densities of strain-relaxed InGaN templates by developing InGaN ELO on patterned GaN (or InGaN)**
  - the small number of previous papers on InGaN ELO conclude that selective growth is possible using $SiO_2$ masks
  - anisotropic growth-rate ratio as high as ~2 (important for coalescence)
  - previous InGaN ELO concentrated on Quantum Dot or MQW growth
  - our aim is to grow thick InGaN templates by ELO

**Task 2: Epitaxial Lateral Overgrowth of strain-relaxed InGaN templates**

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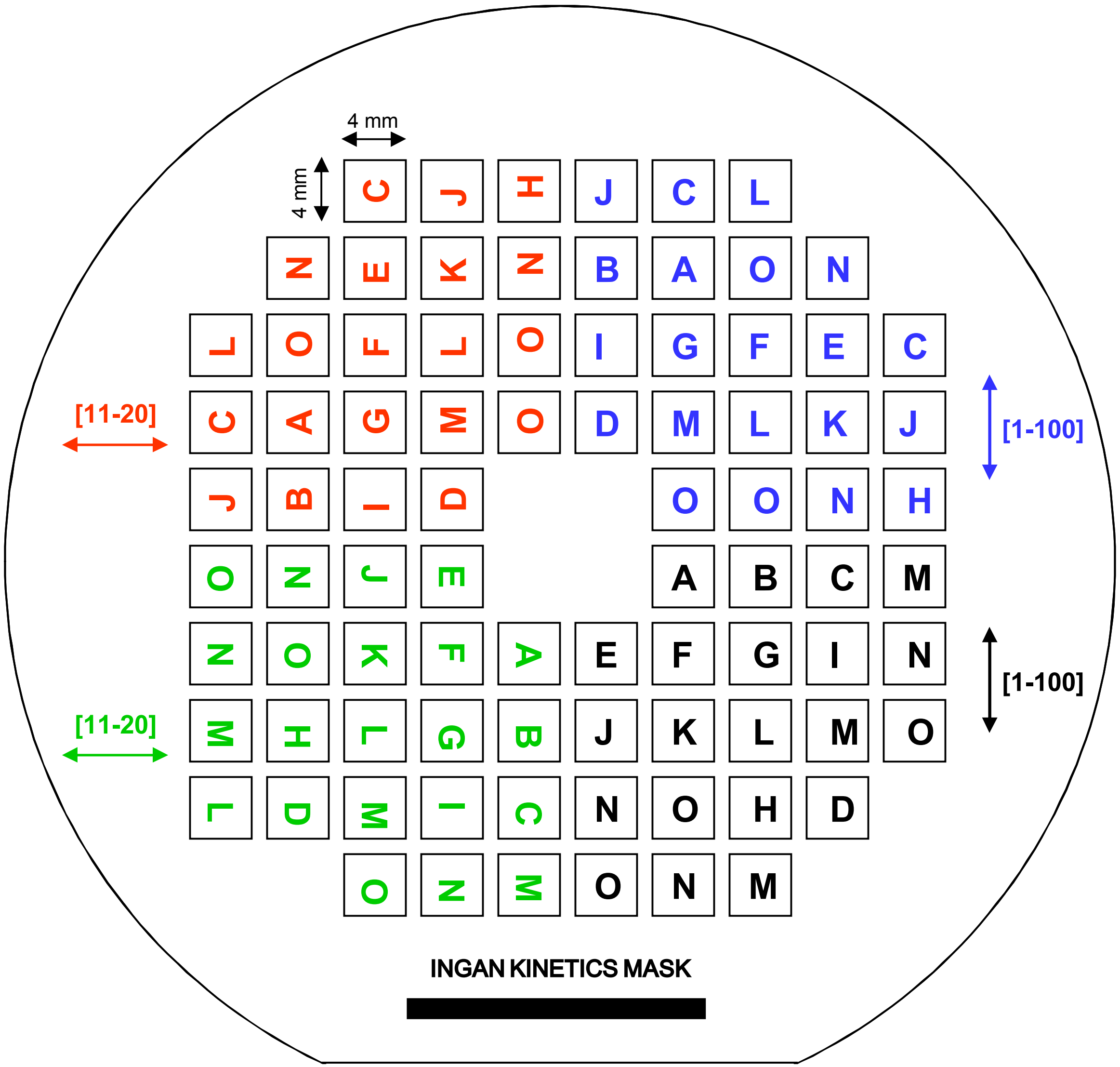
# Task 2: Progress-to-Date

**ELO mask designed and fabricated with 30 different combinations of pattern dimensions and line orientations to obtain a large amount of facet growth kinetics in a single run.**




| | window / | mask |
|---|---|---|
| A: | 12 μm / | 2.5 μm |
| B: | 8 μm / | 3.5 μm |
| C: | 8 μm / | 12 μm |
| D: | 4 μm / | 1 μm |
| E: | 4 μm / | 5 μm |
| F: | 4 μm / | 12 μm |
| G: | 4 μm / | 24 μm |
| H: | 2 μm / | 5 μm |
| I: | 2 μm / | 10 μm |
| J: | 2 μm / | 20 μm |
| K: | 2 μm / | 38 μm |
| L: | 2 μm / | 69 μm |
| M: | 2 μm / | 125 μm |
| N: | 2 μm / | 222 μm |
| O: | 2 μm / | 398 μm |

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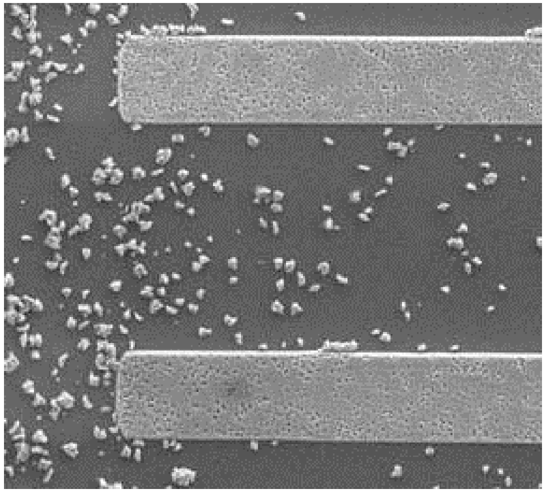
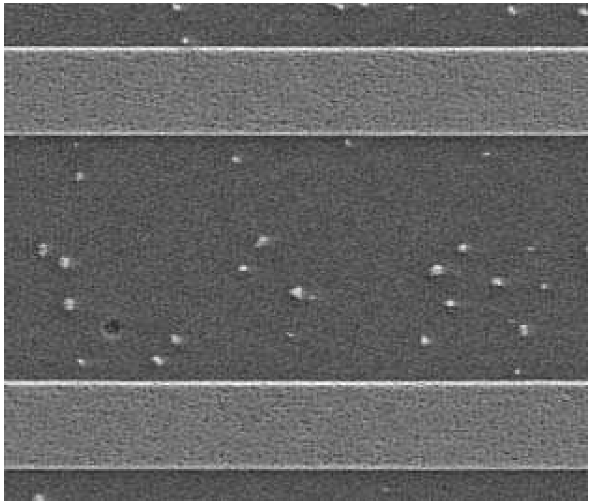
# Task 2: Progress-to-Date

**Epitaxial Lateral Overgrowth (ELO) of ~ 100 nm-thick InGaN (x ~ 0.05).**
**(12 μm $SiN_x$ masked regions separating exposed 4 μm GaN windows)**



**Region near the ends of 4 mm lines.**



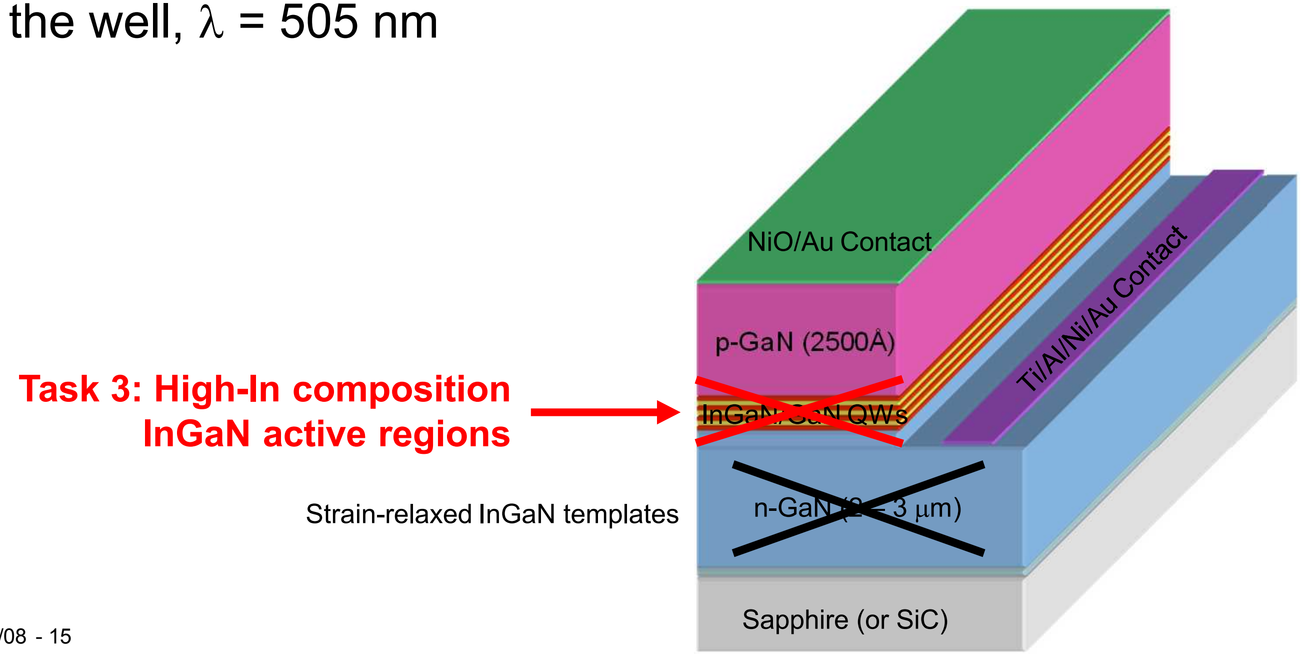
**Region far from "edge effects."**

## Conclusions:

- **Good selectivity for narrow masked regions**
- **Selectivity loss occurs as:**
  - **width of masked region increases**
  - **width of window region narrow**
- **Further experiments planned in this Budget Period**

# Task 3: Growth of High-Indium Composition Active Regions on Strain-Relaxed InGaN

- **Goal: Develop optimized techniques to grow high-In-composition InGaN / GaN (and $In_xGa_{1-x}N$ / $In_yGa_{1-y}N$) QW structures on our newly developed strain-relaxed InGaN templates**
  - amount of strain in QW will depend on underlying template composition
  - QW structure optimization depends upon:
    - temperature, pressure, growth rate, metalorganic precursor flow, ammonia flow, and carrier-gas composition
- **Year 1 Milestone:**
  - produce $In_xGa_{1-x}N$ active regions on strain-relaxed InGaN with x~0.21 in the well, $\lambda$ = 505 nm



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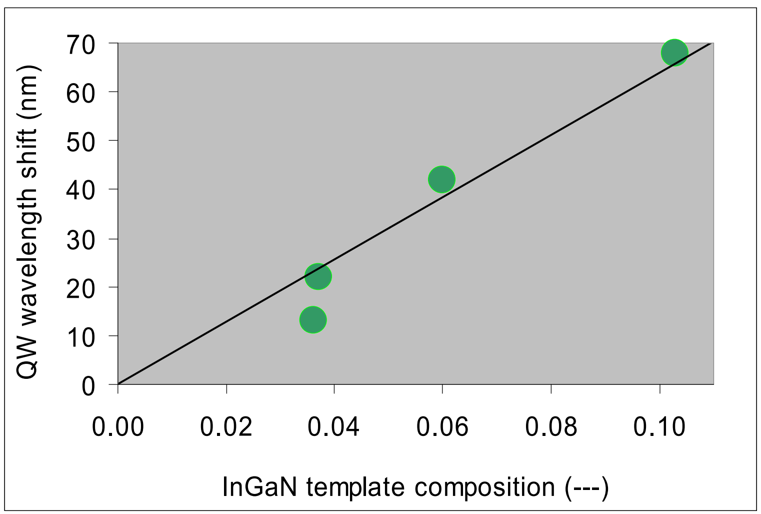
# Task 3: Progress-to-Date

| growth run # | GaN template, $\lambda_{QW}$ (nm) | InGaN template, $\lambda_{QW}$ (nm) | $\Delta\lambda_{QW}$ (nm) | InGaN template, $x$ (---) | InGaN QWs $\Delta x_{QW}$ (---) |
|---|---|---|---|---|---|
| dnz01166 | 431 | 444 | 13 | 0.036 | 0.023 |
| dnz01299 | 442 | 466 | 22 | 0.037 | 0.039 |
| dnz01254 | --- | 479 | 42 | 0.060 | 0.075 |
| dnz01376 | 463 | 531 | 68 | 0.103 | 0.122 |

- **QW emission shifts to longer wavelength on strain-relaxed InGaN templates**
- **This implies that In-content in QW increases with In-content in the strain-relaxed InGaN template**
- **Red-shift increases w/ template In-content**




**Conclusions:**

- **Fundamental premise of the project is confirmed.**
- **Emission of 531 nm exceeds 1st year milestone (505 nm)**

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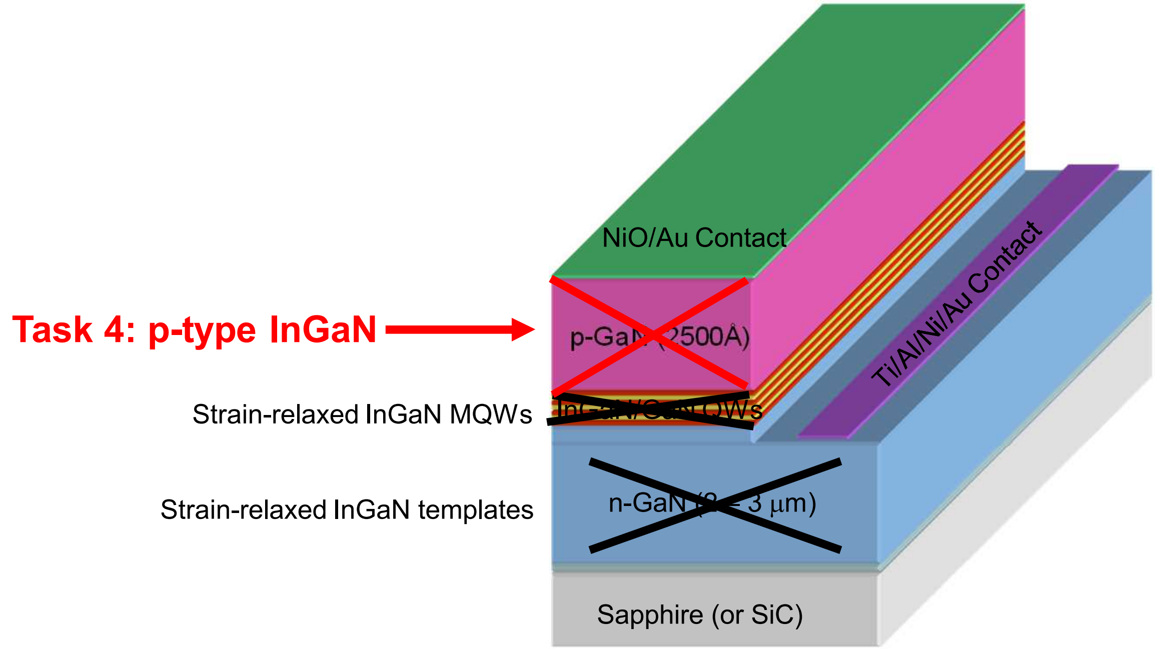
# Task 4: Development of P-type InGaN Materials, Heterostructures, and Thermal-Activation Processes

- **Goal:** produce a thermally compatible p-type InGaN epilayer process suitable for integration into deep-green p-n junction structures



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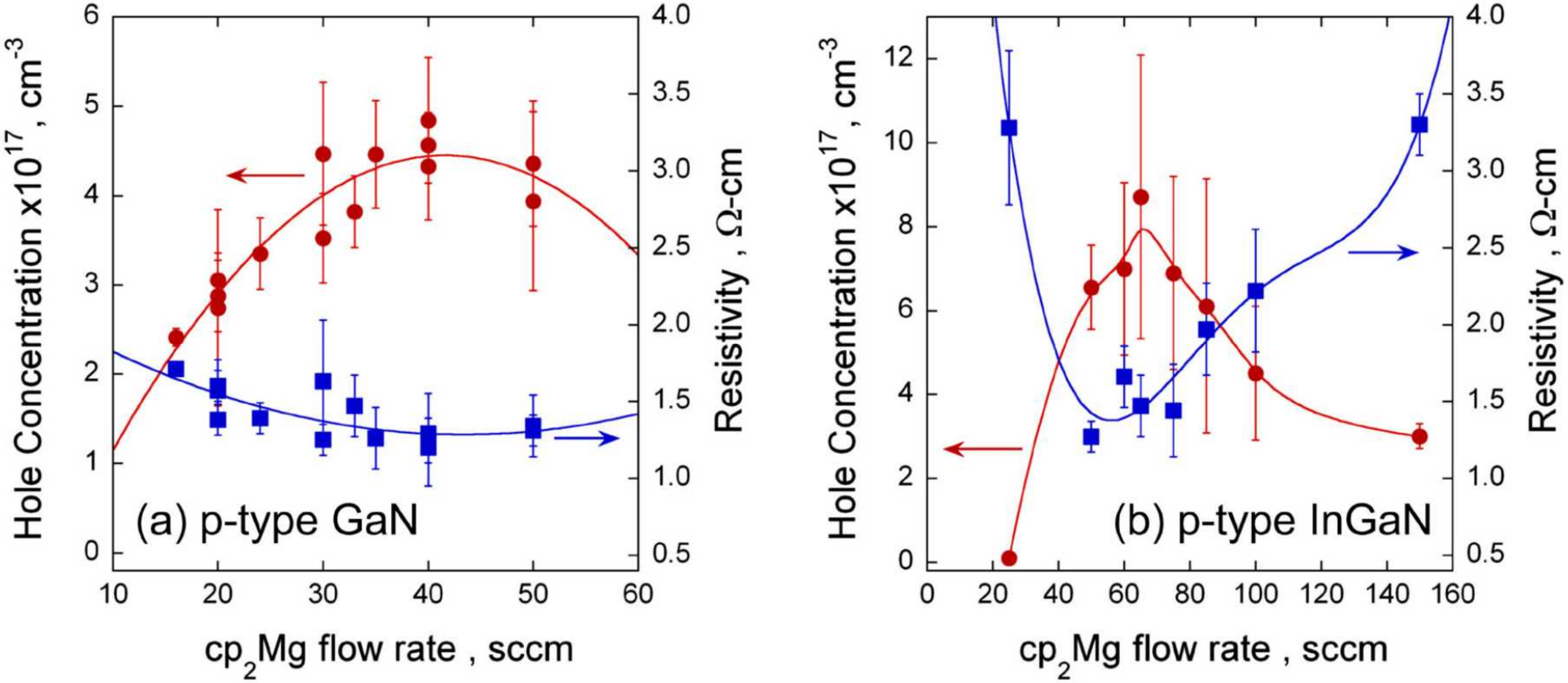
# Task 4: Progress-to-Date




- Growth of p-type InGaN (x=0.05) at 830°C in $N_2$ / $NH_3$ flow (no $H_2$):
  - fully activated dopants after growth and brief anneal at 750°C in $N_2$
  - hole concentration ~2X higher than in p-type GaN (left graph)
  - resistivity is comparable in the p-InGaN and p-GaN layers (perhaps due to poorer material quality in the InGaN)

- Year 2 Milestone: we are about halfway to achieving the 24 month milestone of $1.5 \times 10^{18}$ cm$^{-3}$ hole concentration

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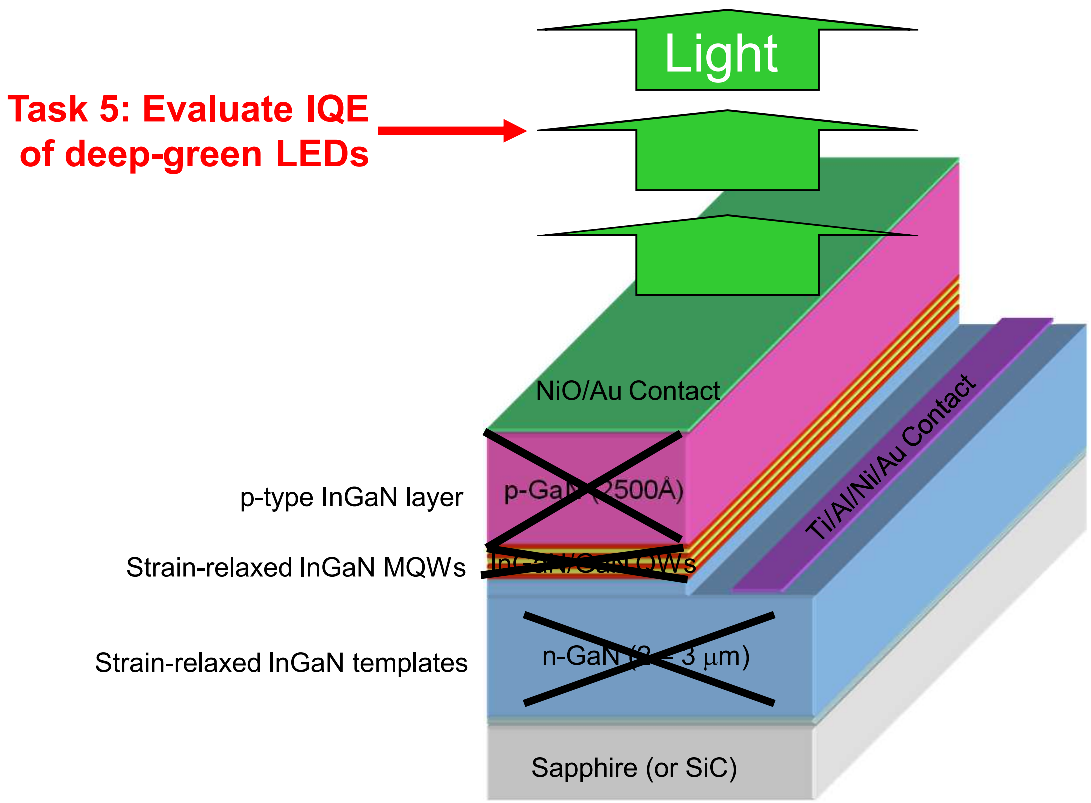
# Task 5: Evaluation of the Internal Quantum Efficiency of Deep-Green Emitters

- **Goal:** Demonstrate Internal Quantum Efficiencies (IQEs) that will significantly advance the state-of-the-art for deep-green LEDs
- **Status:** work in beginning this year



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