InGaN/GaN quantum wells by Molecular Beam Epitaxy at ICAP

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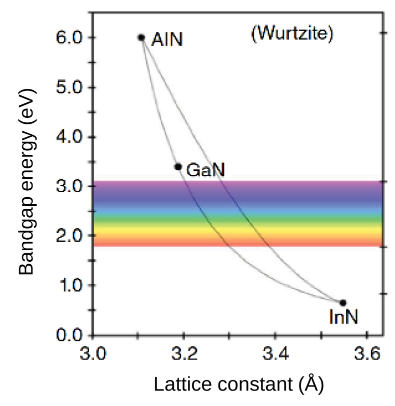
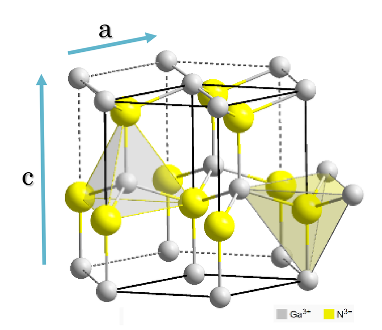
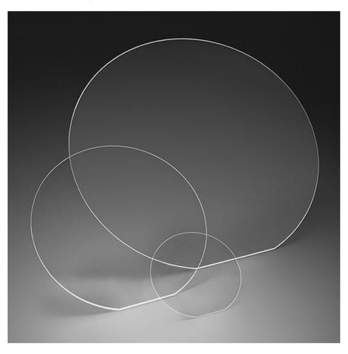
Introduction

The III-Nitride family

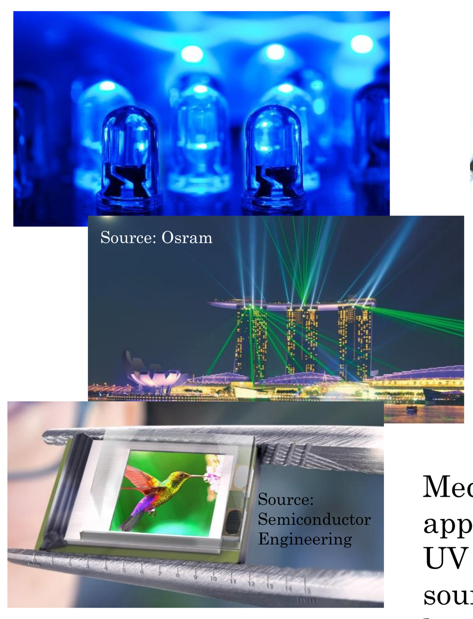
- Direct, wide bandgap semiconductors
  - High electro-optical efficiency
  - High breakdown field
- Composition-tunable properties
  - Lattice constant
  - Bandgap energy
  - Polarization
- High durability
  - Radiation hardness
  - Mechanical hardness
  - Chemical stability



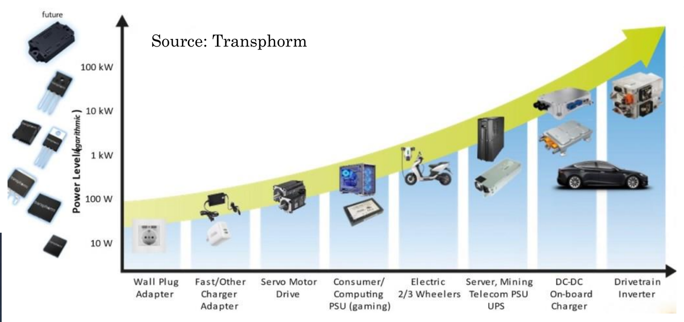




III-Nitride applications



Energy-efficient lighting – LEDs, lasers, micro-LED displays



High-frequency power electronics – data centers, automotive, fast chargers

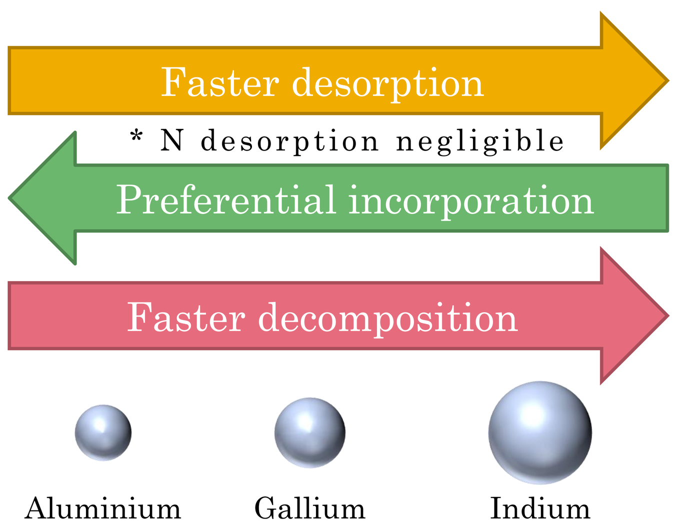
High-efficiency PV

Medical applications, UV light sources and lasers, UV and IR detectors

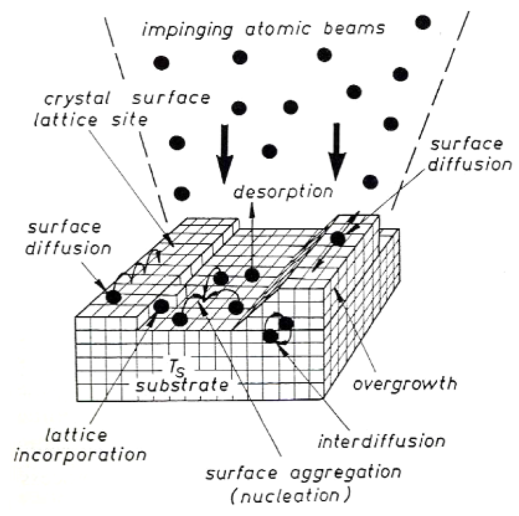
Space applications (comms, detectors, hard radiation)

High-frequency communications

Molecular Beam Epitaxy (MBE) of III-Nitrides



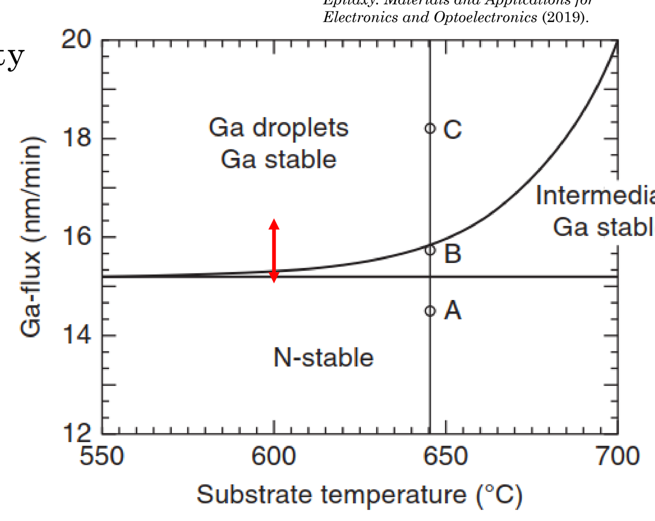
Conditions	Excess III	N-rich
Adatom surface mobility	High	Low



Herman & Sitter, *Molecular Beam Epitaxy, fundamental and current status*, Springer-Verlag Berlin Heidelberg New York, 1989.

H. Asahi and Y. Horikoshi, *Molecular Beam Epitaxy: Materials and Applications for Electronics and Optoelectronics* (2019).

- Growth regimes determine crystal quality
- Challenges with InN
  - Weak In–N bond
  - InN decomposition ~450°C
  - Preferential incorporation of Ga
    - Presence of Ga stabilizes InN
  - Long In residence time at InGaN growth temperatures
  - Phase separation



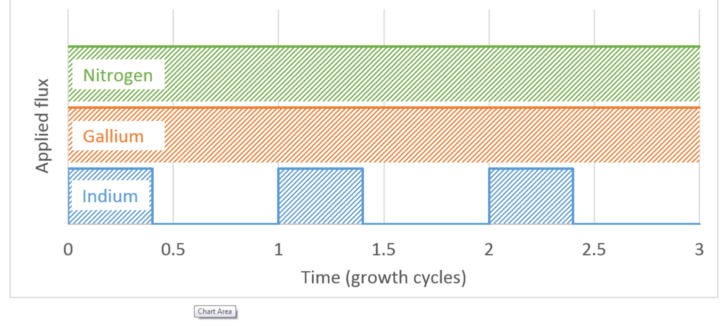
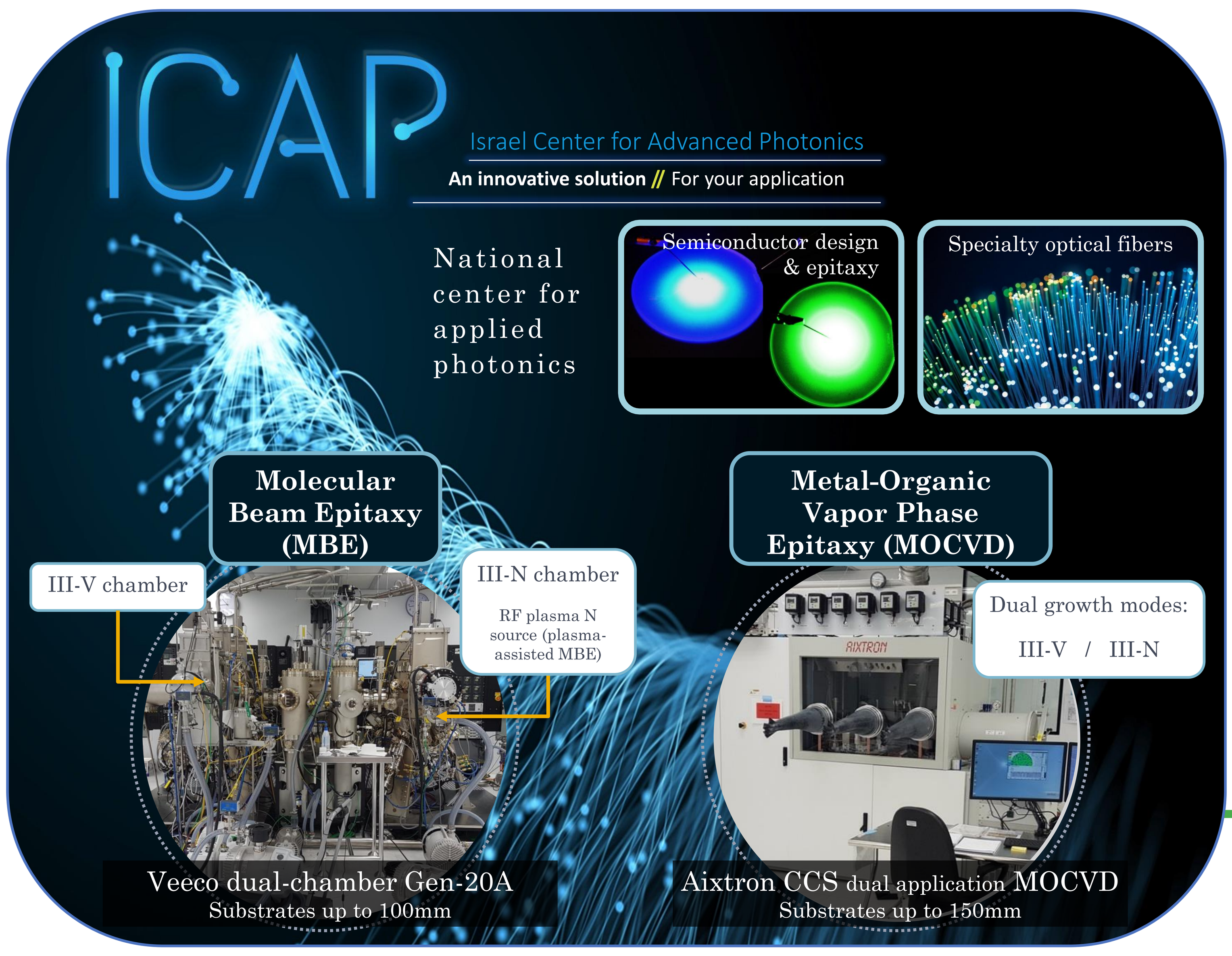


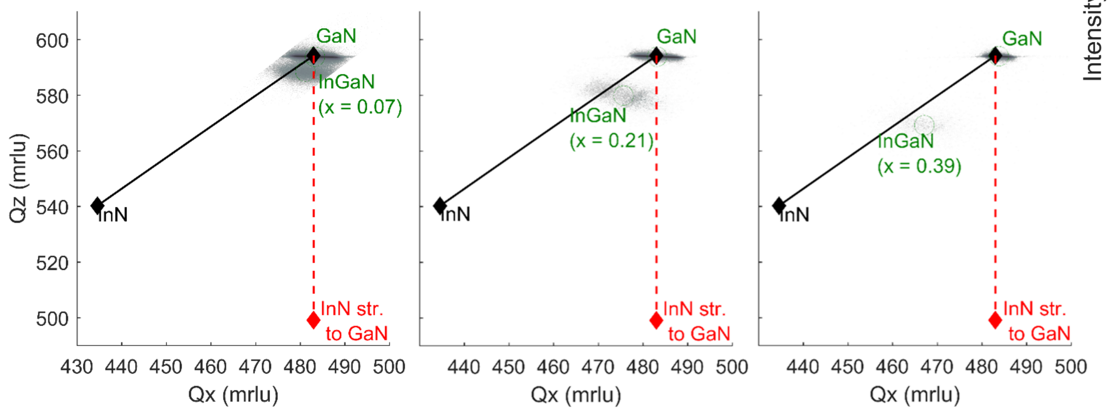
Figure 2. Flux sequence for SME InGaN (3 cycles shown). In this example the metal-rich (In+Ga+N) interval is applied for the first 40% of each cycle.

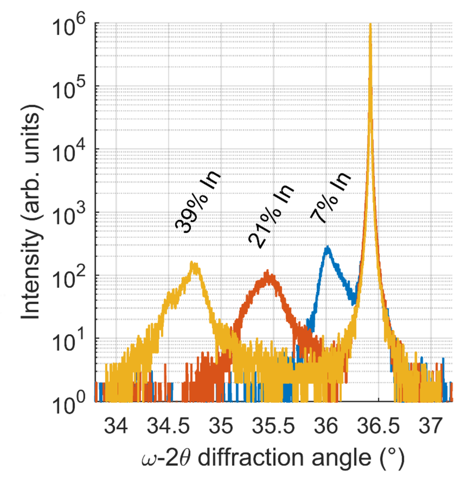
- Solution: Modulate fluxes during growth
  - "Shuttle" between regimes
  - Eliminate droplets periodically
- Flux conditions:
  - $\varphi(Ga)/\varphi(N) < 1$
  - $[\varphi(Ga)+\varphi(In)]/\varphi(N) > 1$



InGaN using shutter modulation

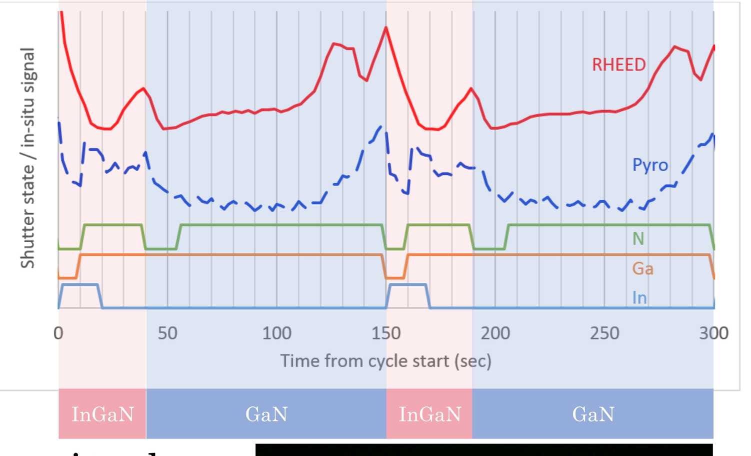
- ω-2θ (0 0 0 4)
  - No phase separation evident in peaks
  - Relaxation leads to asymmetric peaks
- RSM (1 1 -2 4)
  - x(In)↑ ⇒ Increasing relaxation
  - x(In)↑ ⇒ Fainter signal



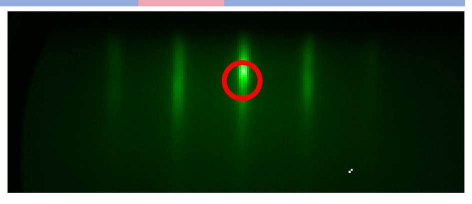


InGaN/GaN QWs using shutter modulation

- Principles of modulation:
  - $\varphi(Ga)/\varphi(N) < 1$
    - Room for In
  - $[\varphi(Ga)+\varphi(In)]/\varphi(N) > 1$
    - Excess In for metal-rich
  - InGaN QW: In > In+Ga+N > Ga+N
    - Excess In at end
  - GaN QB: Ga > Ga+N
    - Ga-only time finely tuned



- Surface conditions monitored in-situ by:
  - RHEED
  - Apparent pyrometer temperature



Doping dynamics

- Preliminary metal step → start metal-rich

$[Si]$ – Si concentration
n_{Si} – amount of Si
Ga puddle volume = 1
r – puddle vol. change rate
t – time
$Si_{\searrow}$ – Si arriving
Si_c – Si incorporated
τ – characteristic Si residence time

$$[Si] = \frac{n_{Si}}{1+rt} \qquad \frac{dn_{Si}}{dt} = Si_{\searrow} - Si_c = Si_{\searrow} - \frac{1}{\tau}\cdot\frac{n_{Si}}{1+rt}$$

- Constant volume (steady-state growth) $r = 0$:

$$\frac{d[Si]}{dt} = 0 \Rightarrow [Si]_{t\gg\tau} = \tau \cdot Si_{\searrow}$$

- SME = gradually shrinking metal layer $r < 0$: slight perturbation
- Initial transient dependent on τ

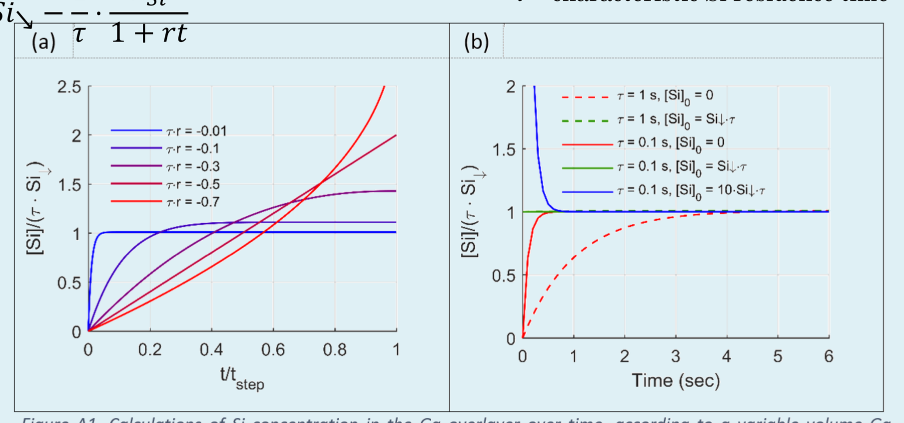
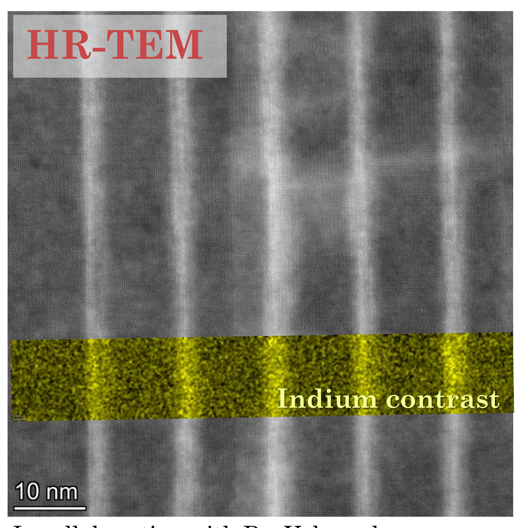


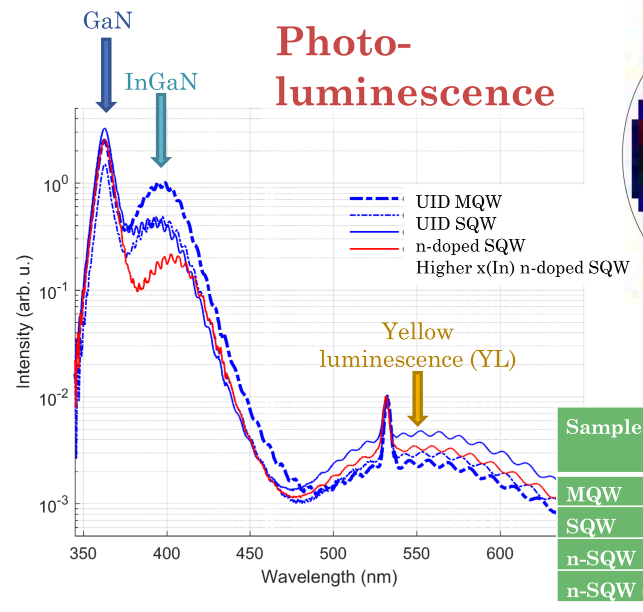
Figure A1. Calculations of Si concentration in the Ga overlayer over time, according to a variable volume Ga puddle model: (a) Development over the course of a growth step with $r = -1/t_{step}$, $Si_{\searrow} = 0.1/t_{step}$, $[Si]_0 = 0$, and various values of τ. (b) Initial transient in [Si] at the beginning of a 95-sec growth step, at the end of which the Ga puddle is completely consumed, with τ = 1 sec (dashed lines) or 0.1 sec (solid lines), and with $[Si]_0 = 0$ (red lines), $[Si]_0 = \tau\cdot Si_{\searrow}$ (green lines) and $[Si]_0 = 10\cdot\tau\cdot Si_{\searrow}$ (blue line).

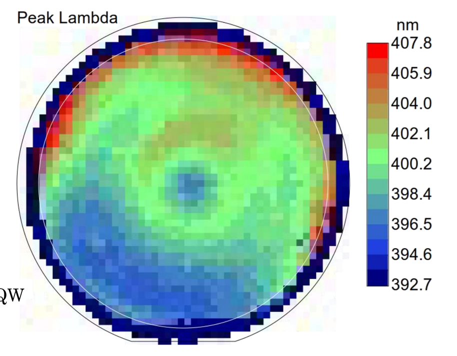
Characterization



In collaboration with Dr. Yehonadav Beckenstein, Technion

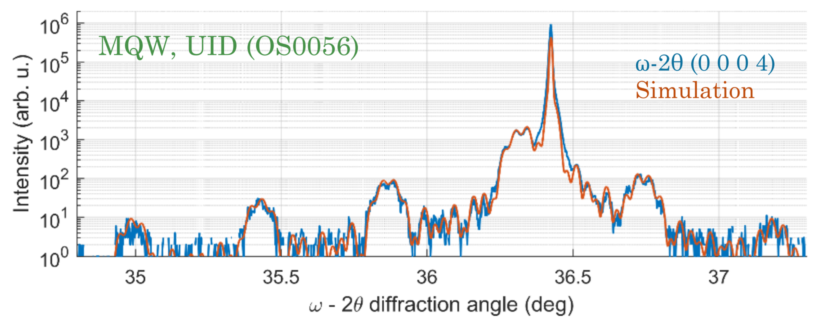
Photo-luminescence

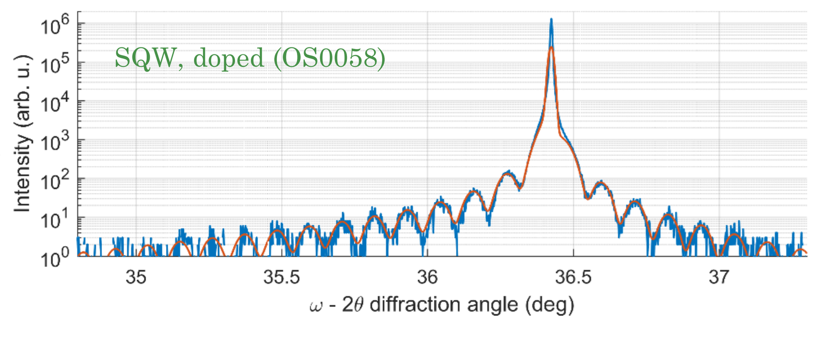




Sample	Avg. λ (nm)	St. dev (nm)	Median λ (nm)	% area
MQW	400.2	2.52	400.3	92
SQW	395.9	1.37	395.6	84
n-SQW	392.6	1.85	392.5	76
n-SQW (In+)	404.1	1.97	403.7	76

X-Ray diffraction





Summary

- Growth of MQWs and SQWs with precise structures, sharp interfaces
- General-purpose shutter-modulated growth techniques, based on RHEED monitoring
- Doping included based on analysis, taking advantage of modulation scheme
- Repeatable, uniform PL emission but broad peaks