Reinterpreting the GaN/InGaN MQW Blue LED as a Multi-State Logic Element
A Technical Note for Prof. Shuji Nakamura

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Abstract

Nakamura's pioneering GaN/InGaN multi-quantum-well (MQW) blue LED demonstrated that internal polarization fields, carrier localization, and quantum-confined Stark effects (QCSE) are not side effects but defining mechanisms of GaN optoelectronics.
This note proposes that these same mechanisms support **three electrically addressable internal regimes**—dark, excitonic, and radiative—that become a *multi-state logic element* when a control terminal is added.
Recent (2024–2026) three-terminal GaN devices show that gate modulation of MQW internal fields is already experimentally viable.
This work reframes the GaN/InGaN MQW LED, not as a quantum device, but as a **room-temperature multi-state logic component** derived directly from the physics Nakamura uncovered.

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1. Direct Foundations in Nakamura's Work

This proposal relies entirely on physical mechanisms demonstrated explicitly in Nakamura's published work:

1.1 Polarization Fields and Tilted Band Structures

As described in:

- **Nakamura, "GaN growth and device developments," MRS Bulletin (1997)**
- **Nakamura et al., "High-Brightness InGaN/AlGaN Double-Heterostructure Blue-Green-Light-Emitting Diodes," Jpn. J. Appl. Phys. (1994)**

Strong piezoelectric and spontaneous polarization generate large internal fields and tilted potential profiles in the wells.
These fields split operating regimes cleanly and enable electric-field-controlled states.

1.2 Carrier Localization in InGaN Wells

From:

- **Nakamura et al., “InGaN/GaN MQW structure and localization,” Appl. Phys. Lett. (1995)**

InGaN’s inherent indium fluctuation induces *localized excitonic states* that are *stable at room temperature*.
These localized states form a natural “middle state” between dark and radiative operation.

1.3 QCSE and Bias-Dependent Radiative Recombination

Discussed in:

- **Nakamura & Fasol, “The Blue Laser Diode,” Springer (1997)**
- **Nakamura, Nobel Lecture (2014)**

Bias changes internal fields, which changes wavefunction overlap, which changes recombination efficiency.
This provides a natural **bias-selectable regime structure**.

These three facts define the three internal operating states.
Without building anything speculative—only reinterpret what is already demonstrated.

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2. The Three Internal Regimes of the GaN/InGaN MQW LED

State 0 — Dark / No Injection

- Shallow forward bias
- Insufficient carrier density
- Polarization field dominates
- Essentially zero recombination

State 1 — Excitonic / QCSE-Dominated Regime (Middle State)

Directly tied to Nakamura’s observations:

- Strong QCSE tilts bands
- Wavefunction overlap reduced
- Localized exciton pockets form
- Radiative efficiency suppressed, but not zero

- Signatures observed in
  "InGaN MQW luminescence" (Nakamura 1994–1997)
  and "Carrier localization effects" papers

This is a distinct, bias-determined state with measurable spectral and temporal characteristics.

State 2 — Radiative Blue Emission

- Higher forward bias
- Carriers fill the localized wells
- Wavefunction overlap increases
- High radiative recombination
- The operating regime responsible for the blue LED revolution

These states already exist; they are not hypothetical.
The only question is: *can we control which state the device occupies?*
Recent research suggests: *yes*.

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3. Adding a Gate Terminal: Proven Feasible in 2024–2026 Work

New three-terminal GaN devices show that a gate electrode can control internal QCSE fields:

- **2024 (USTC)**: MOS-gated GaN LED controlling injection and emission without altering drive current.
- **2025 (Wuhan University)**: Three-terminal LED functioning simultaneously as emitter and photodetector.
- **2025–2026**: GaN Light-Emitting Transistor (LET) architectures with gate-modulated collector current and light output.

These devices demonstrate:

1. Internal electric fields in MQWs **can be externally modulated**.
2. Carrier localization and radiative efficiency **can be shifted** between distinct regimes.

Thus, adding a gate to the original InGaN MQW LED is not a conceptual leap—
it is an extension of existing experimental methods.

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4. Proposal: MQW Blue LED as a Multi-State Logic Element

Core Hypothesis

A GaN/InGaN MQW LED with an added gate terminal can act as a controllable 3-state logic device by selecting among:
(0) dark,
(1) excitonic QCSE-dominated, and
(2) radiative emission regimes.

Not a quantum bit.
Not a qutrit.
But a **three-state transistor-like element** that:

- operates at room temperature
- uses mechanisms Nakamura discovered
- scales using existing microLED fabrication lines
- is fundamentally stable due to internal polarization fields

Logic Behaviors

- **Dark state = 0** (no carriers)
- **Excitonic/field-tilted = 1** (localized, suppressed emission)
- **Radiative = 2** (high overlap, bright blue)

This is a genuine **multi-state device**, not binary.

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5. Why Nakamura's Structure Is Uniquely Suited

1. GaN's giant polarization fields create sharply defined regime boundaries.
2. InGaN carrier localization produces natural intermediate states.
3. High radiative efficiency creates a clear optical signature.
4. GaN operates at high temperature, high frequency, and high power.

5. MicroLED pixel densities (~6800 PPI in 2026) demonstrate extreme scalability.

This combination is unique to the GaN/InGaN MQW system and *does not appear in Si, Ge, GaAs, or other III-Vs*.

Nakamura's discovery is not just a light source.
It may be a foundational computing element.

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6. Testable Pathway (Minimal Requirements)

To validate the hypothesis, a lab need only test:

1. **Gate-voltage control of internal fields** (QCSE shift)
2. **Differential conductance changes** across regimes
3. **Electroluminescence spectra** as a function of gate bias
4. **Transient exciton dynamics** in the "middle state"
5. **Array behavior** in a tiled microLED structure

All tests are routine for GaN research groups and do not require new equipment.

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7. Conclusion

This note does not claim quantum functionality, nor does it claim invention.
It simply identifies that the physical mechanisms Nakamura discovered—
polarization fields, QCSE, carrier localization, and bias-dependent recombination—
form a natural three-state system.

With a control terminal, the GaN/InGaN MQW LED becomes:

- a room-temperature multi-state logic element
- based on Nobel-recognized physics
- already manufacturable
- already scalable
- already stable

This proposal is submitted with respect and admiration for the work that made it possible, and with hopes of a collaboration.