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# Enhanced Light Extraction from GaInN Light-Emitting Diodes using Micro-Patterned Graded-Refractive-Index Coatings

Frank W. Mont[a], Arthur J. Fischer[b] , Mary H. Crawford[b], David J. Poxson[a], Sameer Chhajed[a], Ahmed Noemaun[a], Jong Kyu Kim[a] and E. Fred Schubert[a]

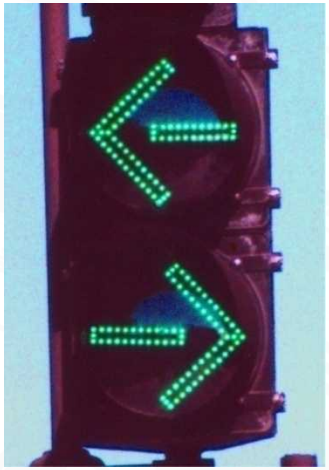
[a] The Future Chips Constellation, Rensselaer Polytechnic Institute
[b] Semiconductor Materials and Device Sciences, Sandia National Laboratories

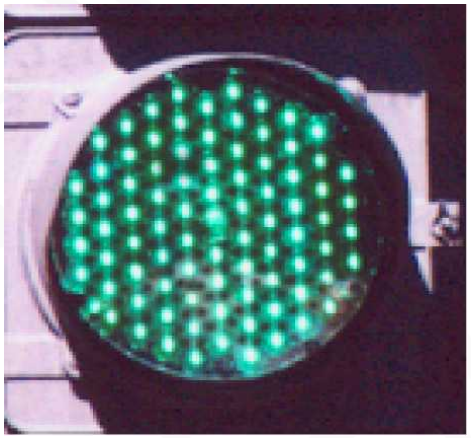
## Outline

- Introduction
- Motivation for graded-refractive-index coatings
- Graded-refractive-index fabrication methods
- Co-sputtered LED overview
- Light-extraction efficiency enhancement results
- Photoresist patterning and etching
- Photoluminescence enhancement results
- Conclusions

# Light-emitting diode applications

- **Obsolete and traditional applications**

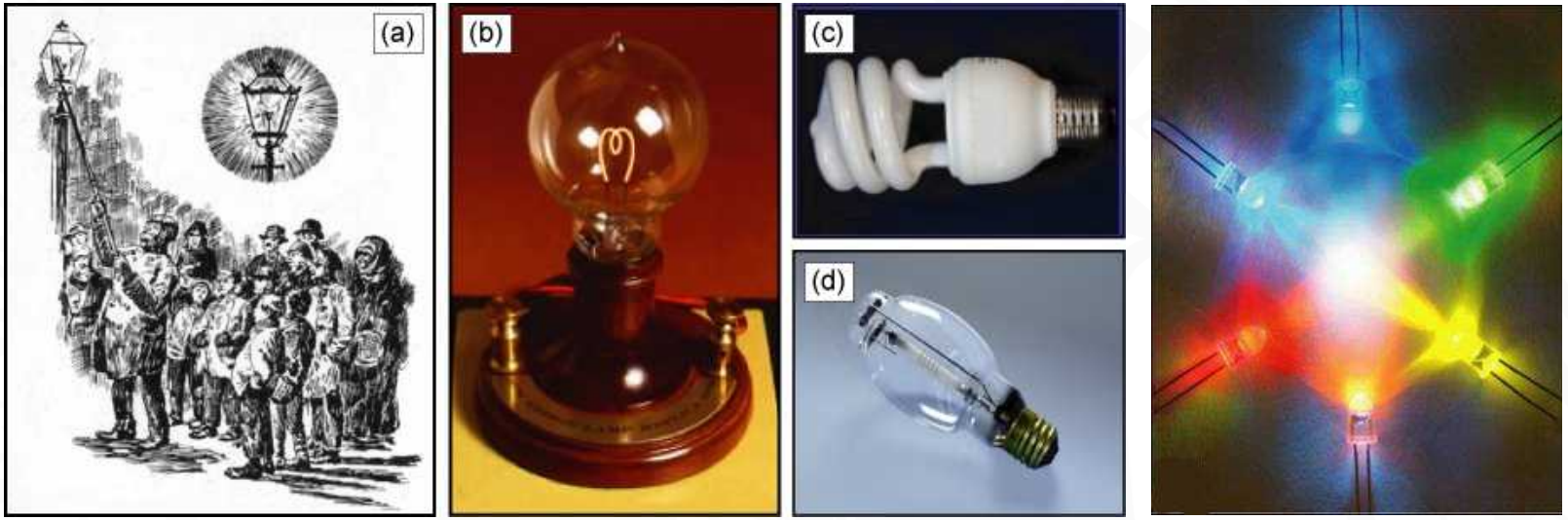





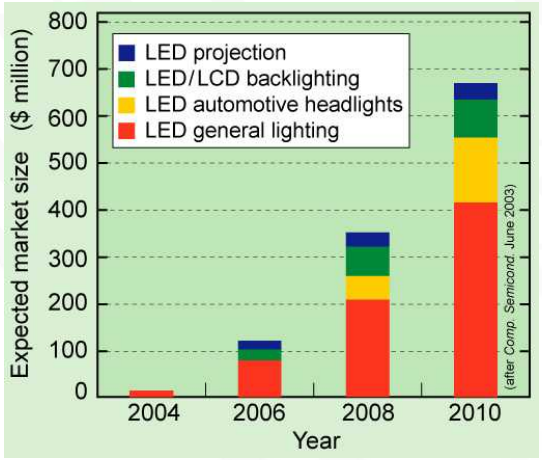
**Recent applications**

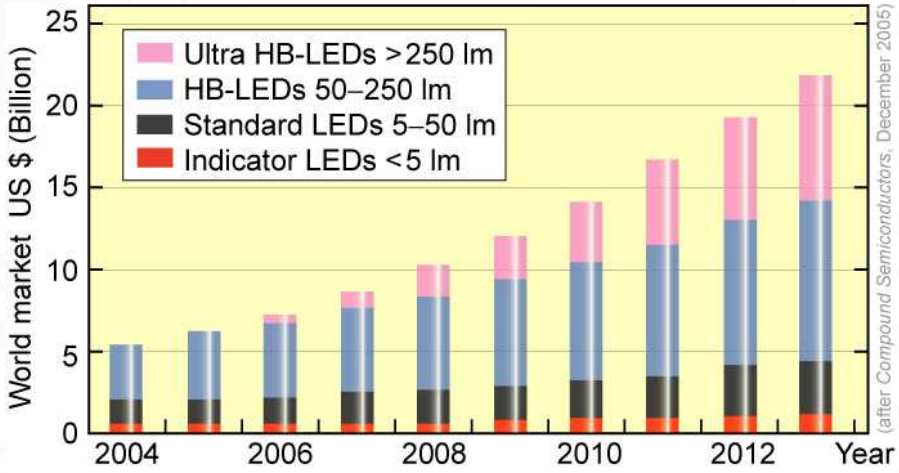

# Solid state lighting for general illumination

- **Old and new lighting technologies**

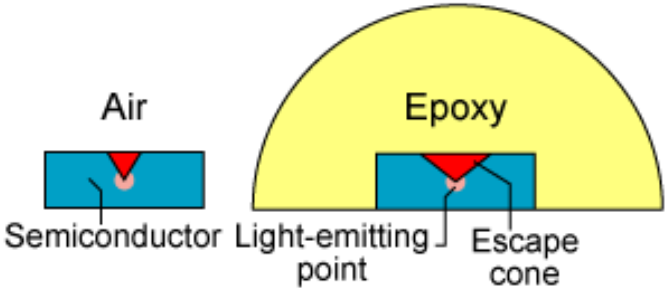



***[Schubert and Kim, SCIENCE 308, 2005]***



# Introduction: Basic LED overview



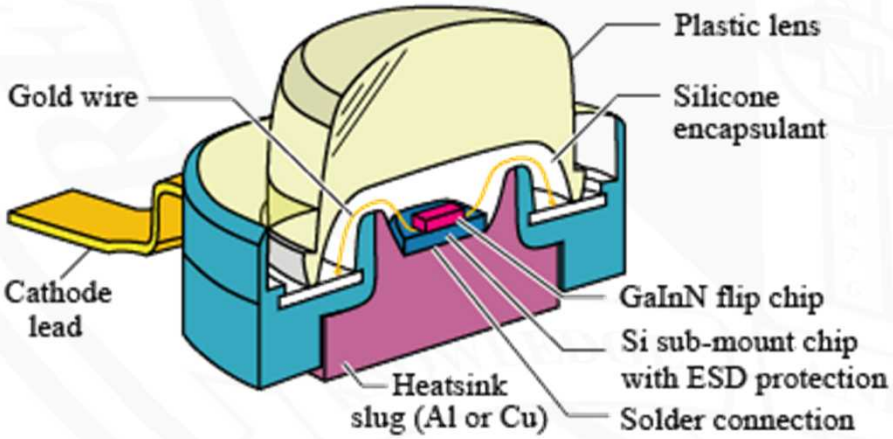
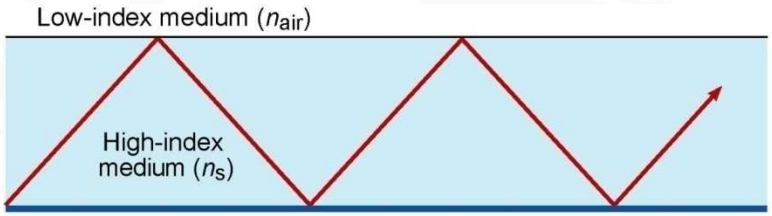




Figure reference: Lumileds

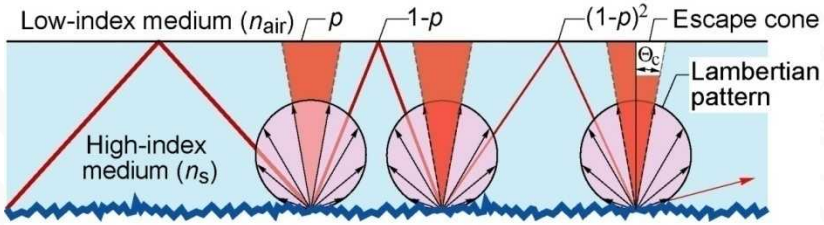
- Packaging encloses and protects the LED
- Voltage produces light in LED
- Refractive index of LEDs ($n$ = 2.5 to 3.0)
- **Escape cone** forms due to refractive index interface
- **Escape cone** allows *light at particular angles* to pass into air or encapsulant

# Introduction : Maximize LED optical output power

1. Increase light extraction efficiency
   - Surface roughening
   - Graded-refractive-index antireflection coatings
   - Micro-patterning

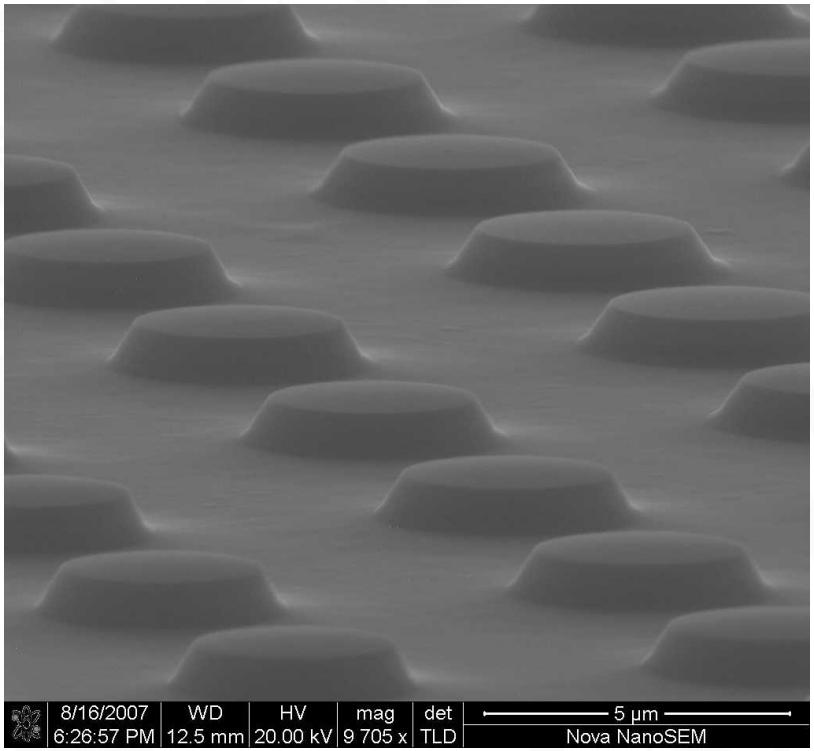



(a) Specular surface



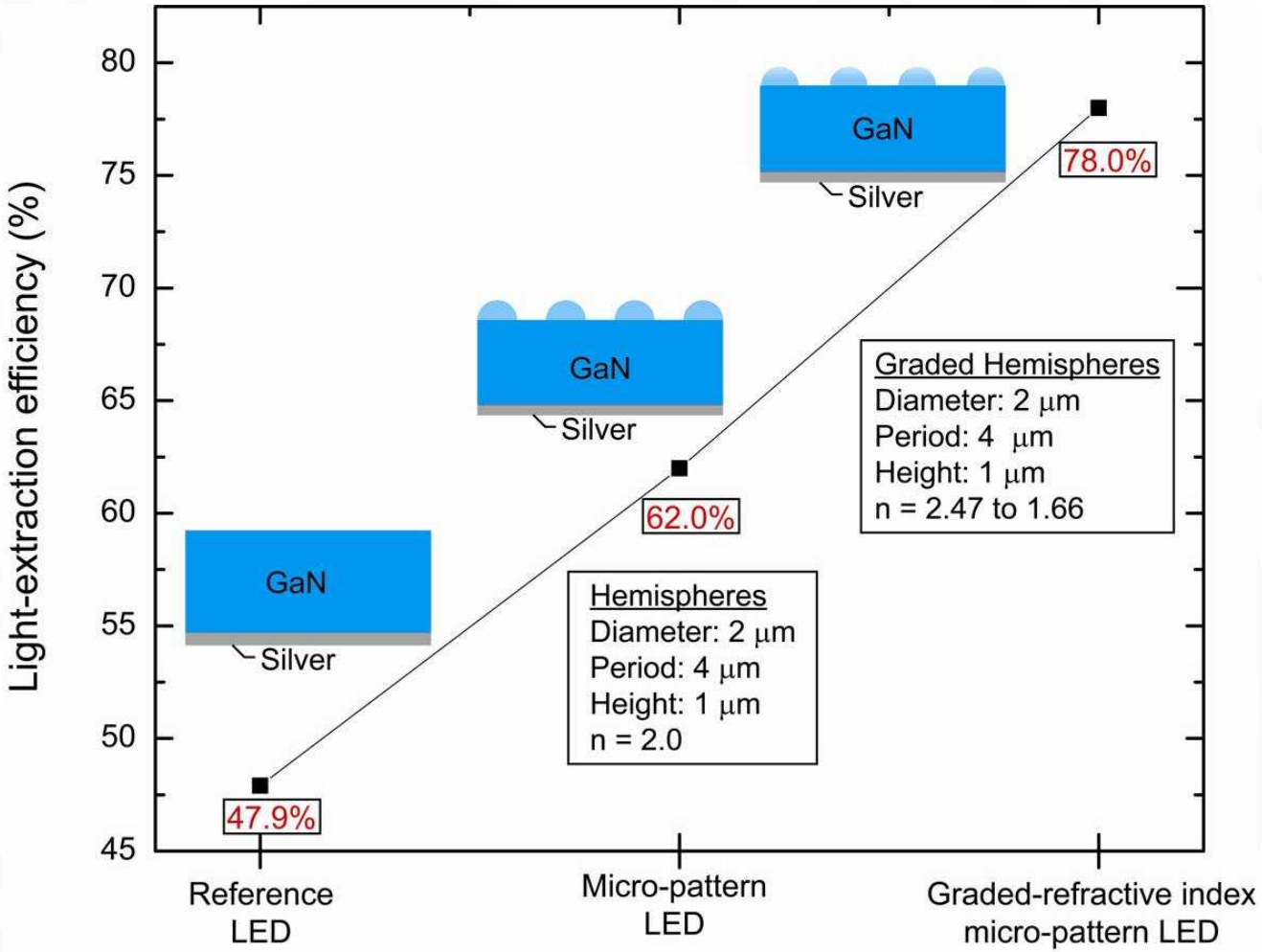

(b) Diffuse surface

Total internal reflection (TIR) light propagation of high-index medium



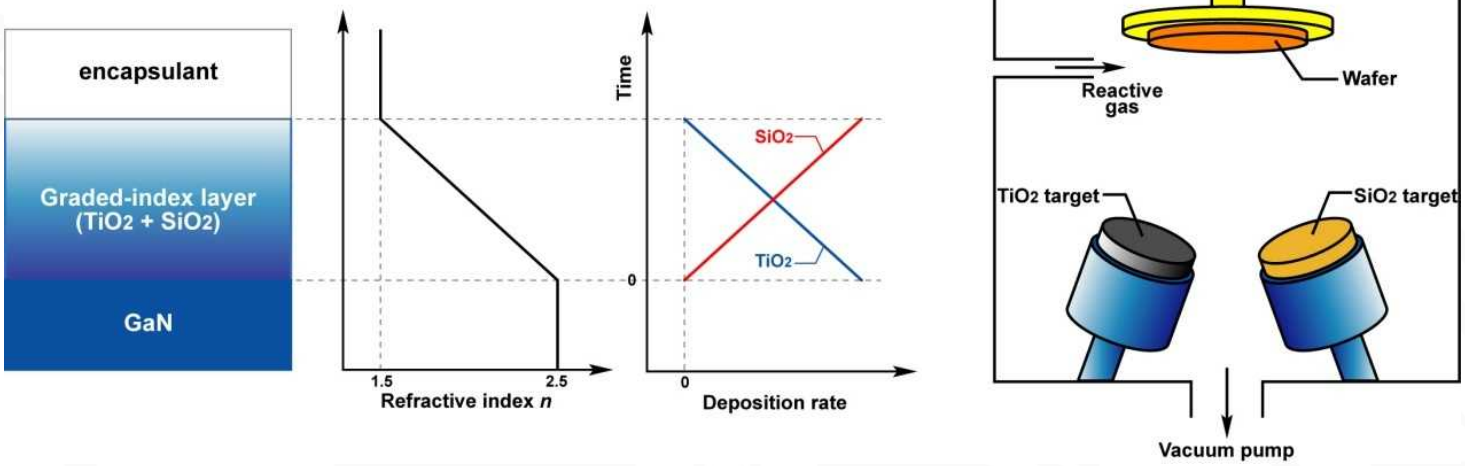

Graded index $TiO_2$-$SiO_2$ micro pillars

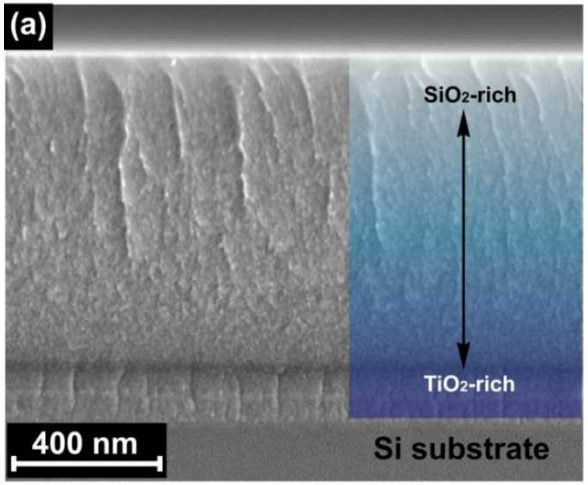
# Light-extraction-efficiency simulation

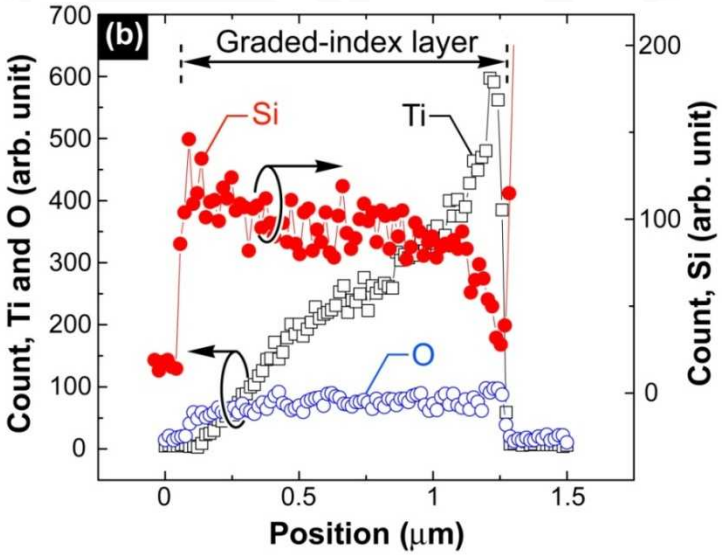



- Graded micro-pattern LED enhances light-extraction by **63%**

# Optical thin film graded refractive index methods

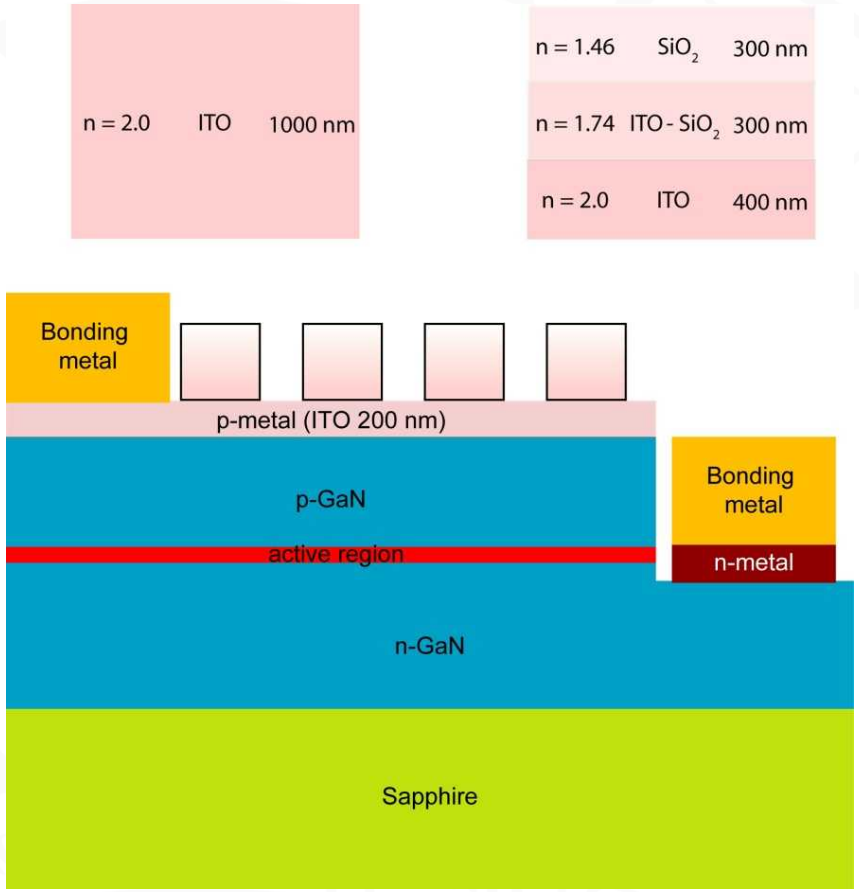


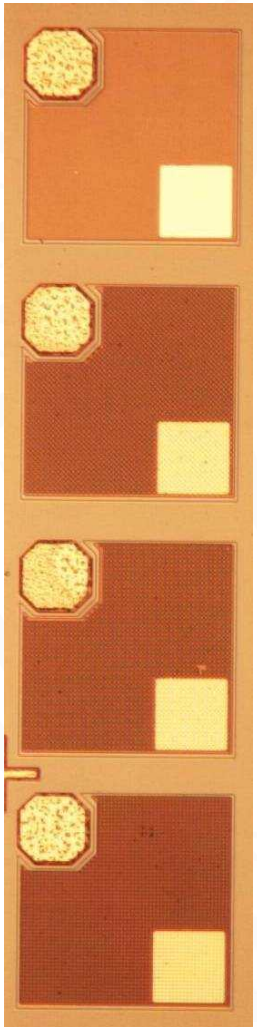

- Optical thin film with graded refractive index from 2.5 to 1.46 is possible

# Micro-patterned ITO and ITO-$SiO_2$ LED overview




- Micro-patterned ITO-$SiO_2$ coating total thickness is 1 μm
- ITO e-beam used to improve lift-off of thicker coating

# Optical micrograph of micro-pattern LED

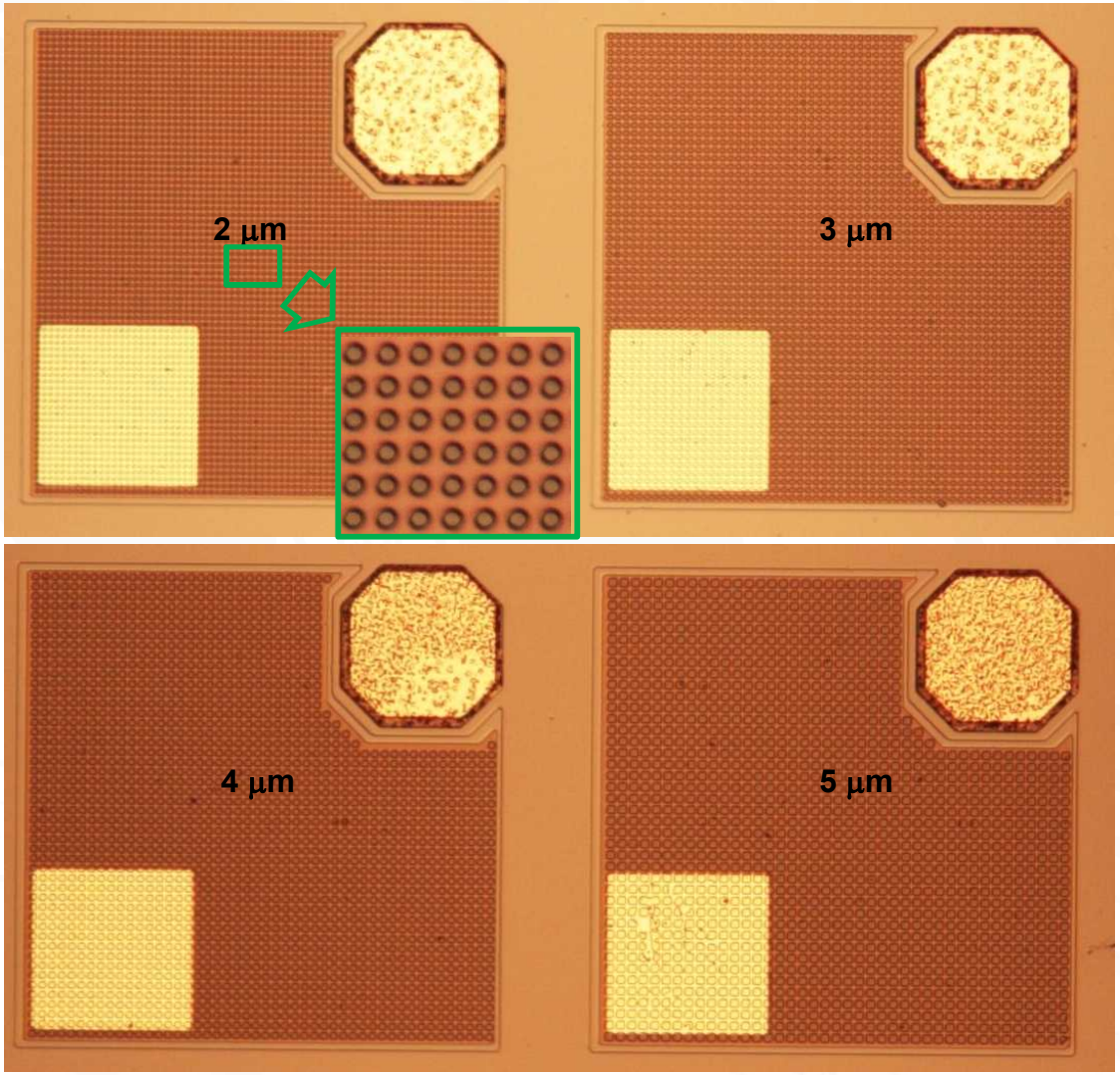


Reference:
ITO 200 nm

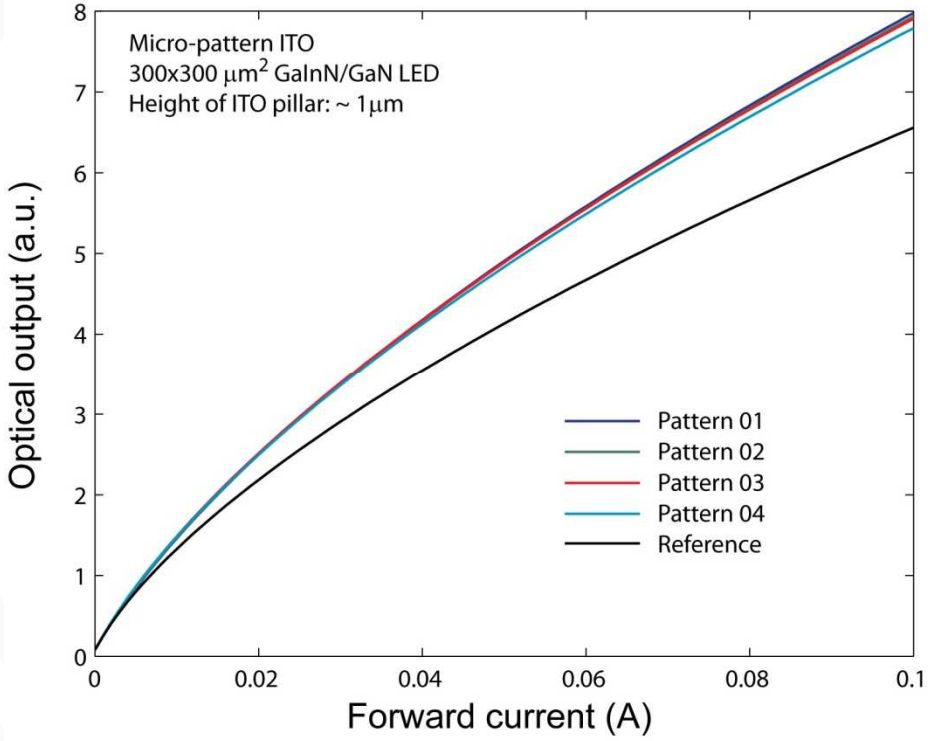
2 μm

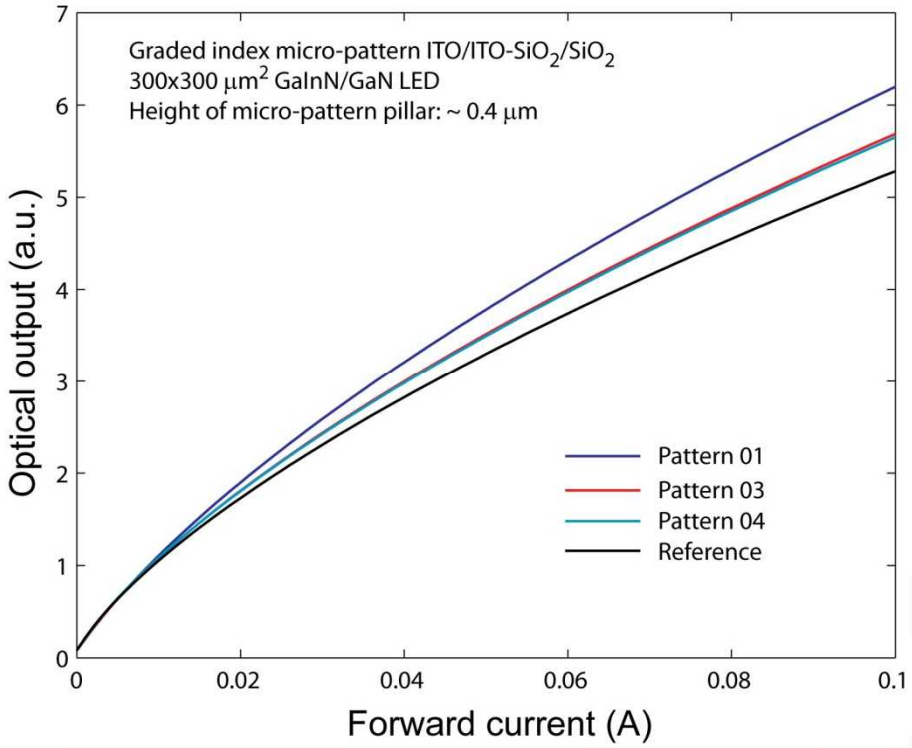
3 μm

4 μm

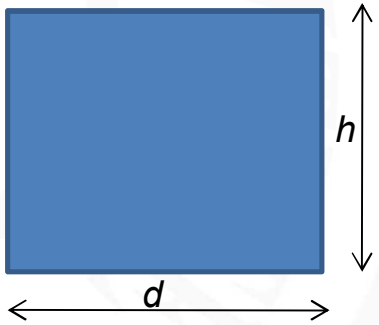


# Light-extraction efficiency enhancement results

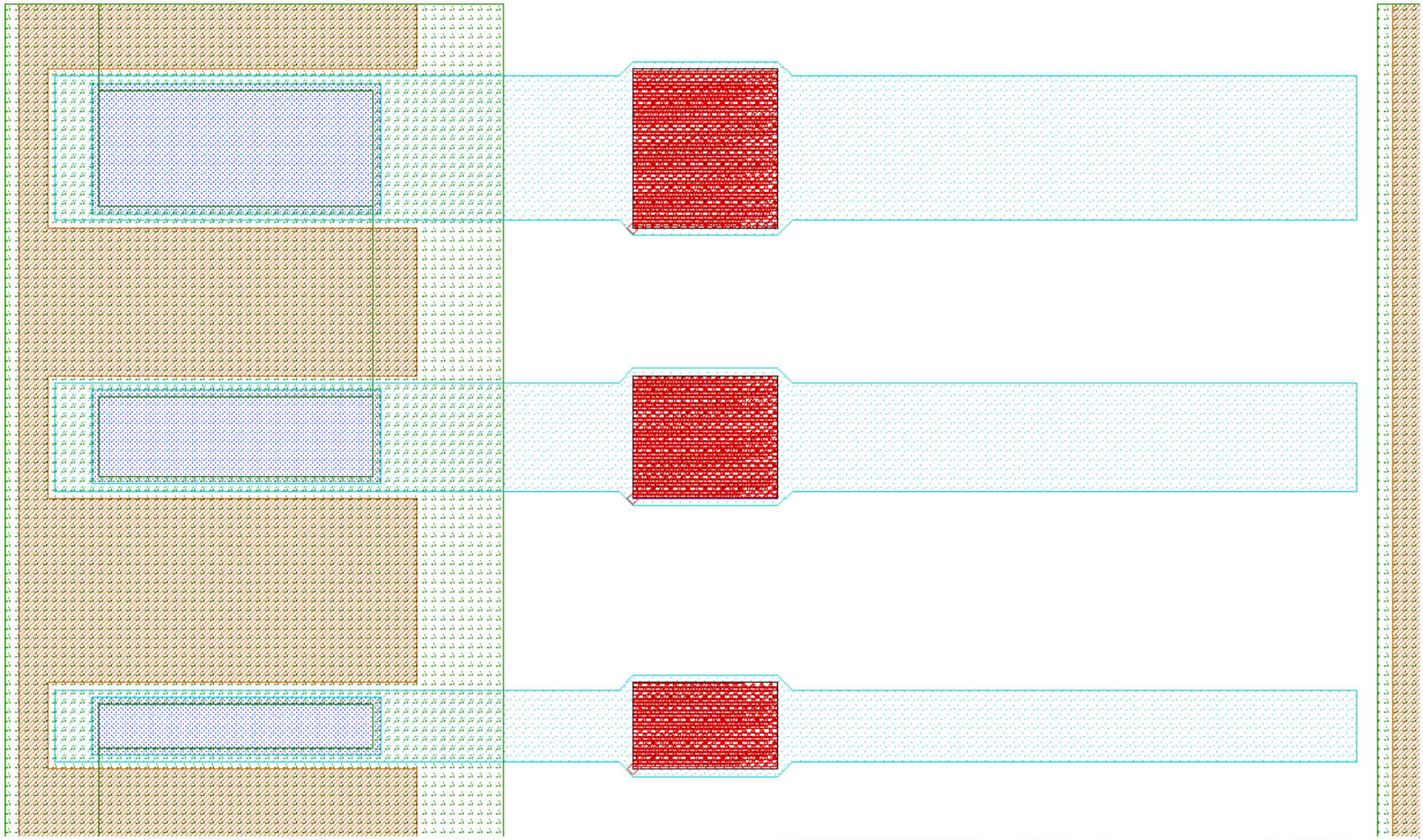


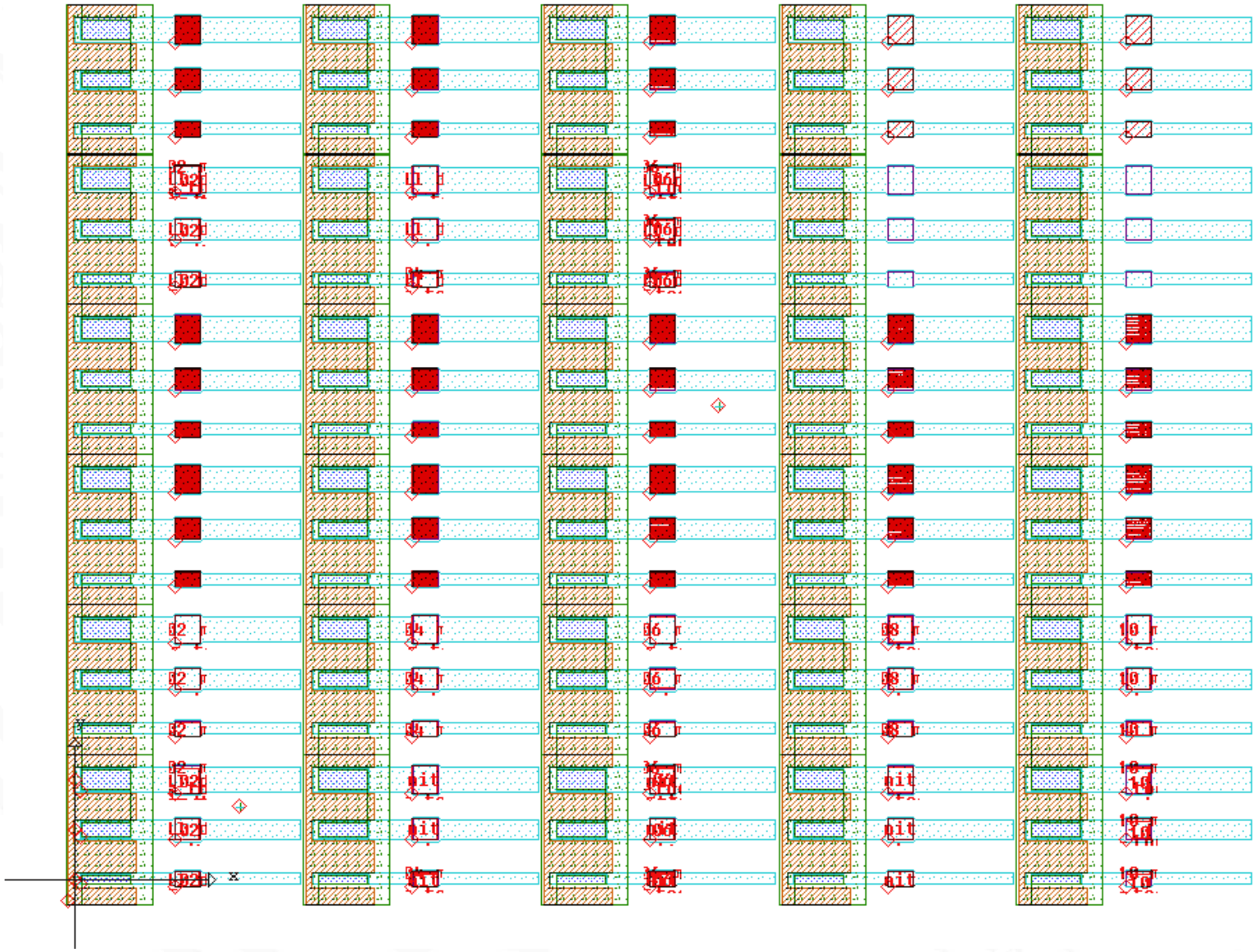




- **Improvement in light-extraction efficiency**
  - 18 to 23% for LEDs with micro-patterned ITO single layer
  - 17 to 20% for LEDs with micro-patterned GRIN ITO/ITO-$SiO_2$/$SiO_2$
  - Similar I-V characteristics
- **As *h*/*d* increases, light-extraction efficiency increases slightly**
- **Comparison of ITO and co-sputtered ITO-$SiO_2$ LED**
  - ITO-$SiO_2$ LED : Lower height and *h*/*d* (<0.2)

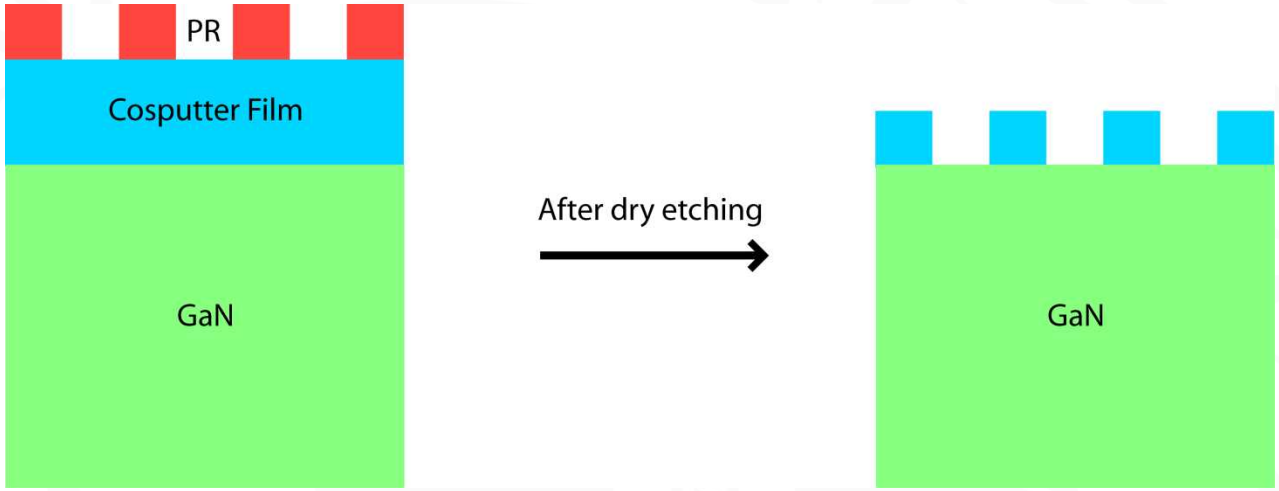


# Waveguide structure mask design



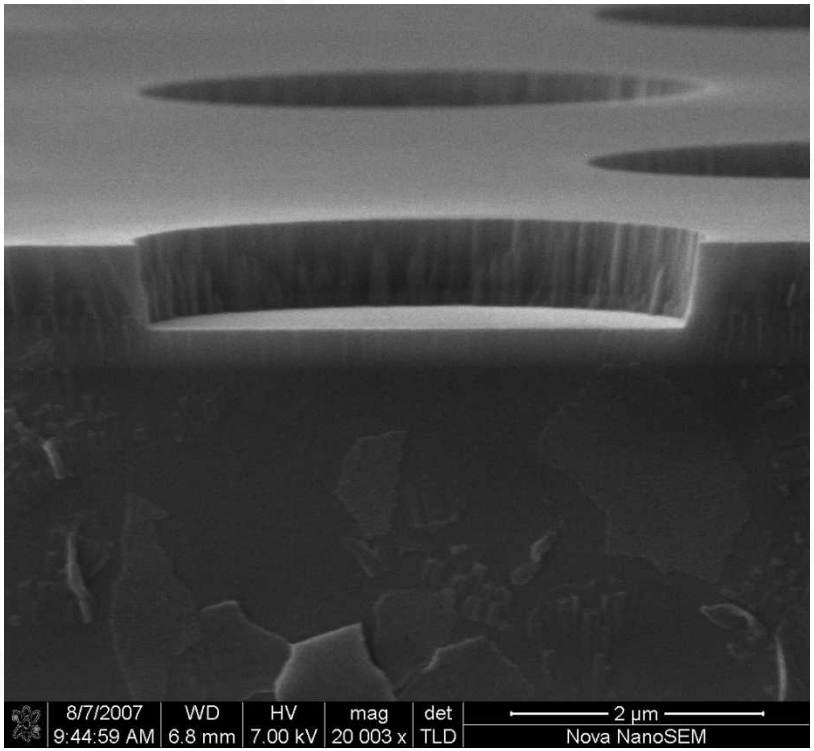


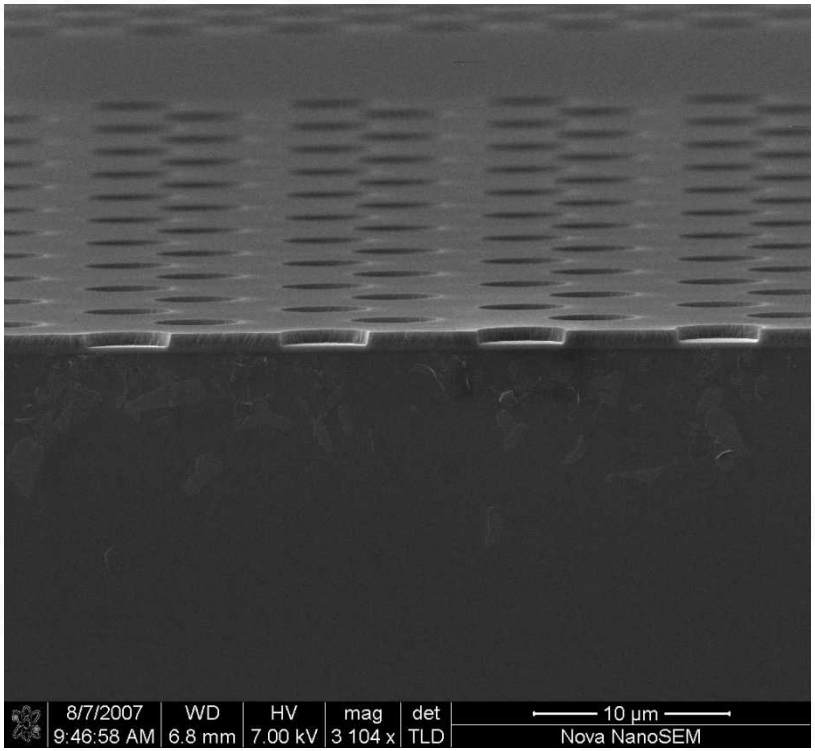
# Dry etching of AZ-4330 patterned $TiO_2$–$SiO_2$ film




| Refractive index | Material | Thickness |
|---|---|---|
| n = 1.47 | $SiO_2$ | 380 nm |
| n = 1.62 | $TiO_2$–$SiO_2$ | 218 nm |
| n = 1.91 | $TiO_2$–$SiO_2$ | 146 nm |
| n = 2.24 | $TiO_2$–$SiO_2$ | 146 nm |
| n = 2.36 | $TiO_2$ | 108 nm |

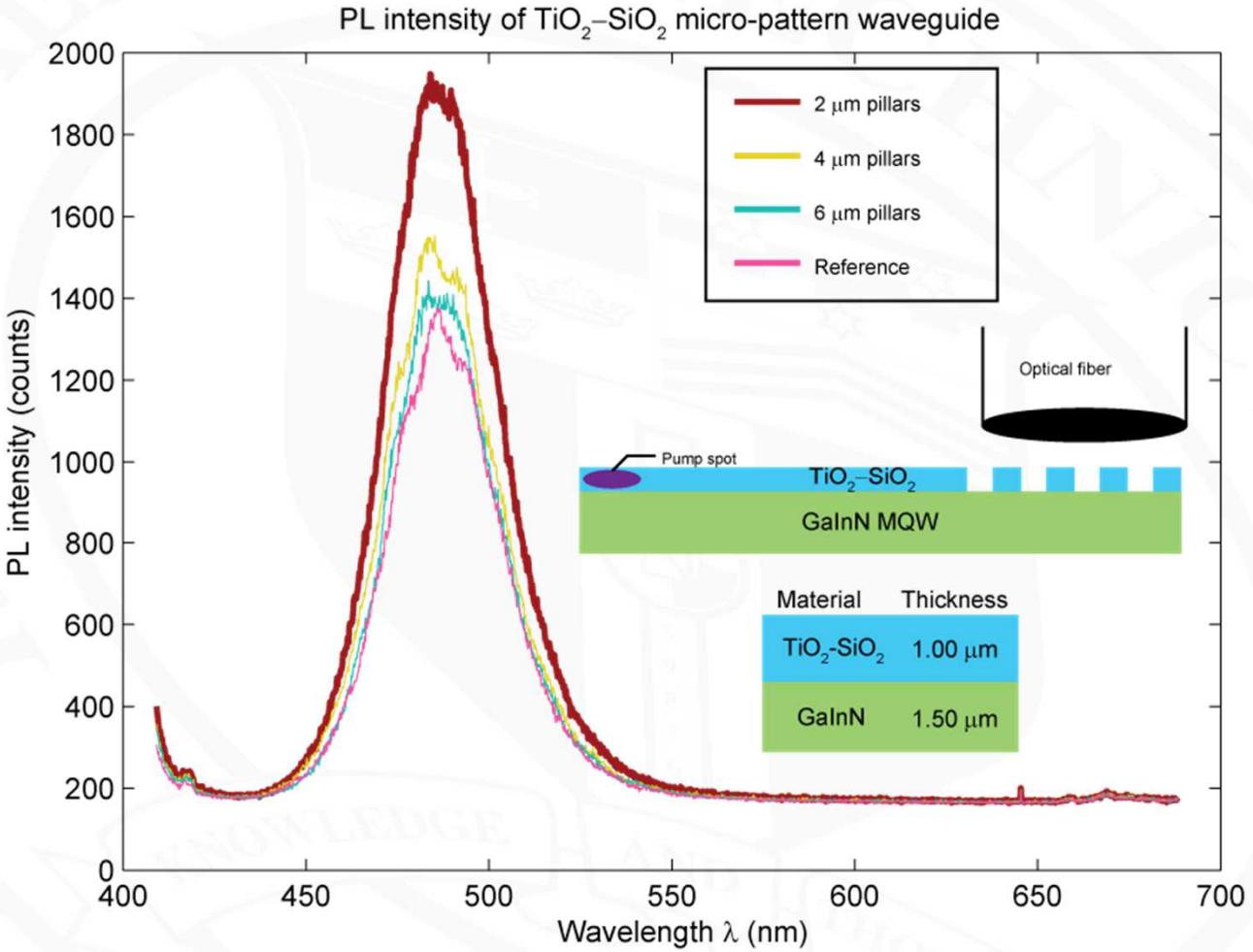
# Dry etching of AZ-4330 patterned $TiO_2$–$SiO_2$ film



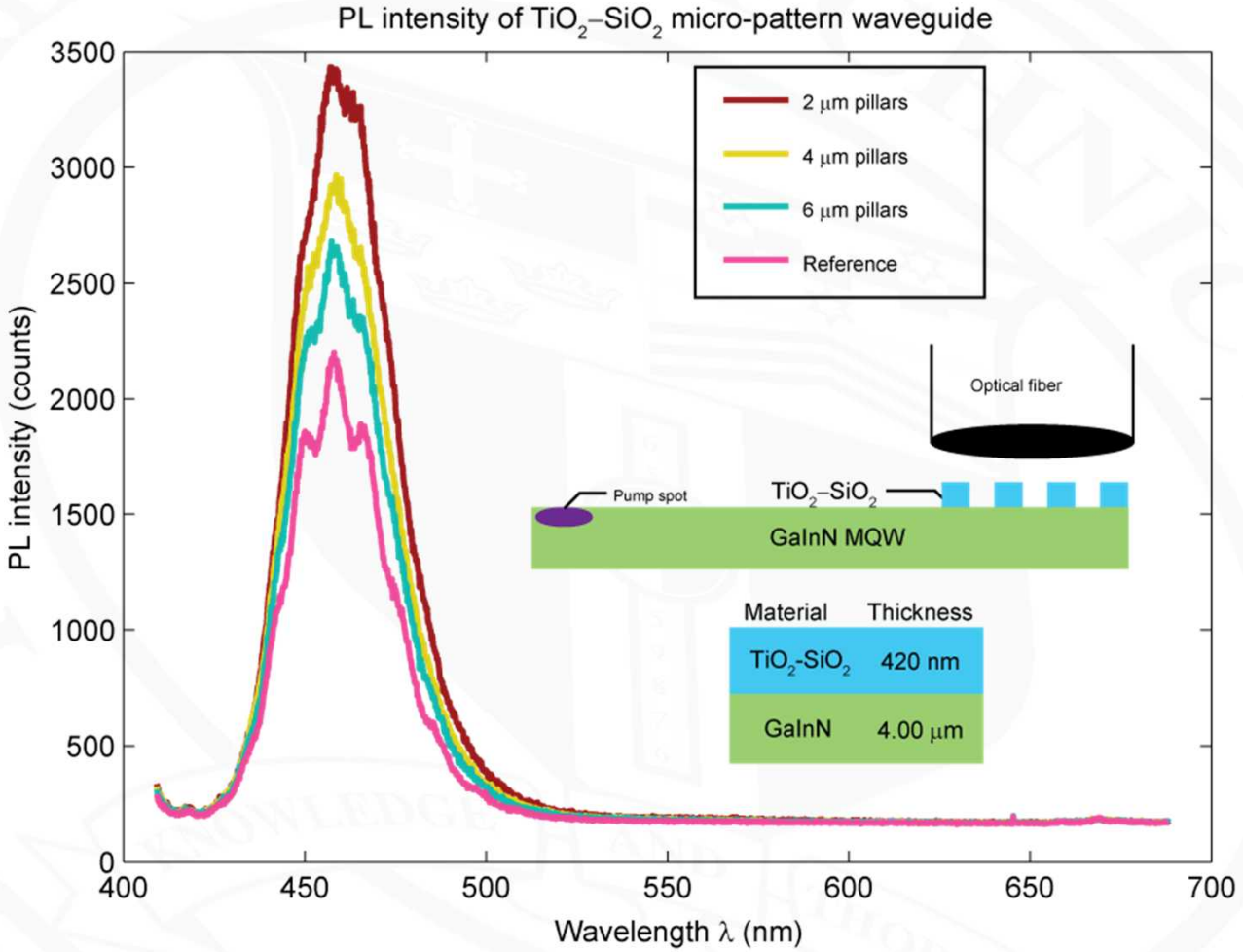

- Dry etched $TiO_2$–$SiO_2$ cosputtered film in RIE2 for 90 min. for a etch depth of 720 nm.
- Sidewalls practically vertical with surface roughness increasing with depth.

# Photoluminescence (PL) of $TiO_2$–$SiO_2$ micro-patterns




- 2 μm pillars show a **40%** higher luminescence compared to reference

# Photoluminescence (PL) of $TiO_2$–$SiO_2$ micro-patterns




- 2 μm pillars show a **58%** higher luminescence compared to reference

# Summary

- Investigated range of topics for LED light-extraction enhancement using graded-index co-sputter materials
- **Simulation light extraction efficiency enhancement of 63%** for InGaN LED with micro-pattern graded $TiO_2$-$SiO_2$ antireflection coating
- **Light extraction efficiency enhancement of 20%** for InGaN LED with micro-pattern ITO-based coating over uncoated LEDs
- **Photoluminescence enhancement** of **40%** and **58%** for GaInN waveguide using 2 μm diameter pillars of graded $TiO_2$-$SiO_2$ over planar light-extraction region
- **Future work**: Studying effects of pillar shape, thickness, surface roughness, ITO-$SiO_2$, and other factors

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