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ARPA-E Award DE-AR0000644

Glint exists to beautifully illuminate spaces, while consuming a minimum of space and resources.

Glint delivers these values with compact luminaires that integrate into the architecture and provide exceptional light utilization and visual comfort, never drawing undue attention to themselves.

DOE SSL R&D Workshop 2020
Light extraction

Andrew Kim
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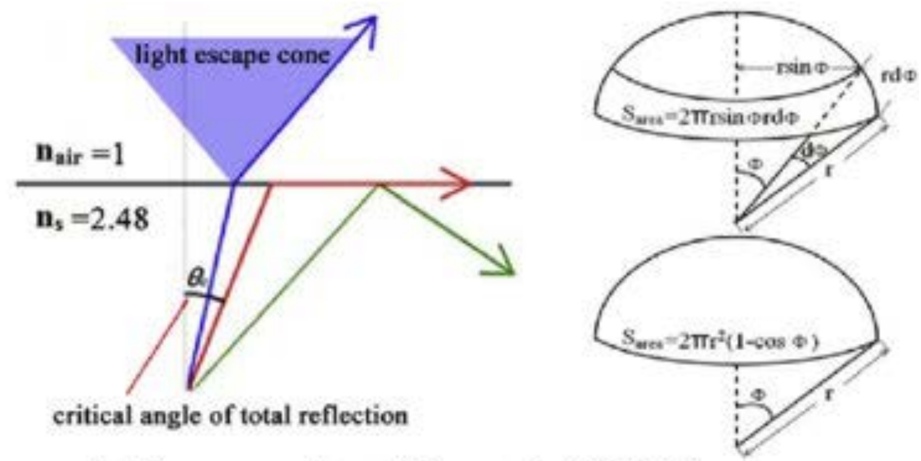
Fundamental challenge of light extraction

- Light may be trapped in a high refractive index material by total internal reflection
  - GaAs ~ 3.6
  - GaP ~ 3.3
  - GaN ~ 2.4
  - Escape probability ~$1/n^2$ (Lambertian to air)
- Light may be lost to absorption

- Strategies to increase light extraction
  - Reduce total internal reflection
  - Reduce absorption
  - Reduce reflection



$$n_s \cdot \sin\theta_c = n_{air} \cdot \sin \pi/2 \qquad \theta_c = 23.78°$$

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Some known light extraction technologies

- Reduce total internal reflection
  - Geometric: size, mesas, shaping, etc – vary incident angles
  - Scattering: patterned, roughening, etc – scatter for multi-pass extraction
  - Emission: cavity tuning, photonic crystal, etc – tune light into escape cones

- Reduce absorption
  - Contacts: geometry, materials, processing
  - Bragg reflector (for absorbing substrates)
  - Transparent substrates and windows
  - Epitaxial engineering

- Reduce reflection
  - Increase index of encapsulant
  - Step down or grade index of semiconductor
  - Multi-layer anti-reflective films

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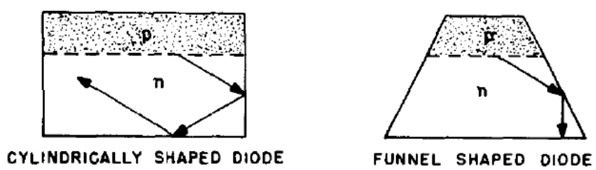
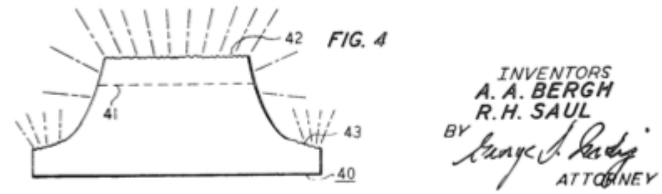
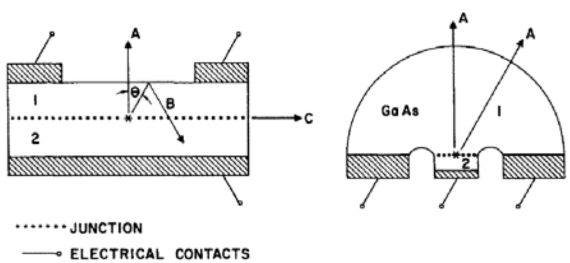
Early demonstrations



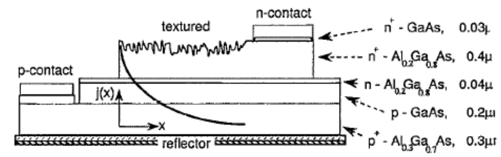
Carr *et al* (APL 3, 173, 1963)
shaped chip



Bergh *et al* (US3739217, 1969)
shaped and textured chip



Franklin *et al* (JAP 35, 1153, 1964)
domed chip and contact engineering



Schnitzer et al (APL 63, 2174, 1993)
textured thin-film

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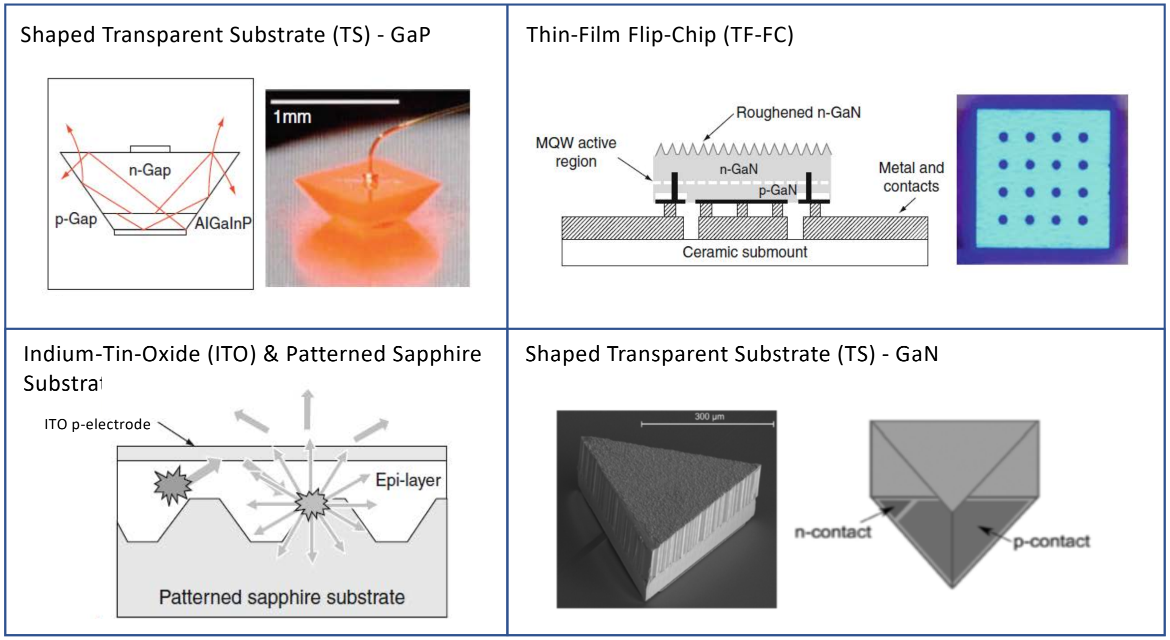
Production approaches

- Mix of different technologies in today's commercial LEDs

- New and refined ideas
- Manufacturable processes
- Materials and process developments
- Epitaxial development

Figure courtesy of Dr Mike Krames, Arkesso LLC



Krames, *Handbook of Visual Display Technology* © Springer-Verlag Berlin Heidelberg 2012
Hurni *et al.*, Applied Physics Letters 106, 031101 (2015)

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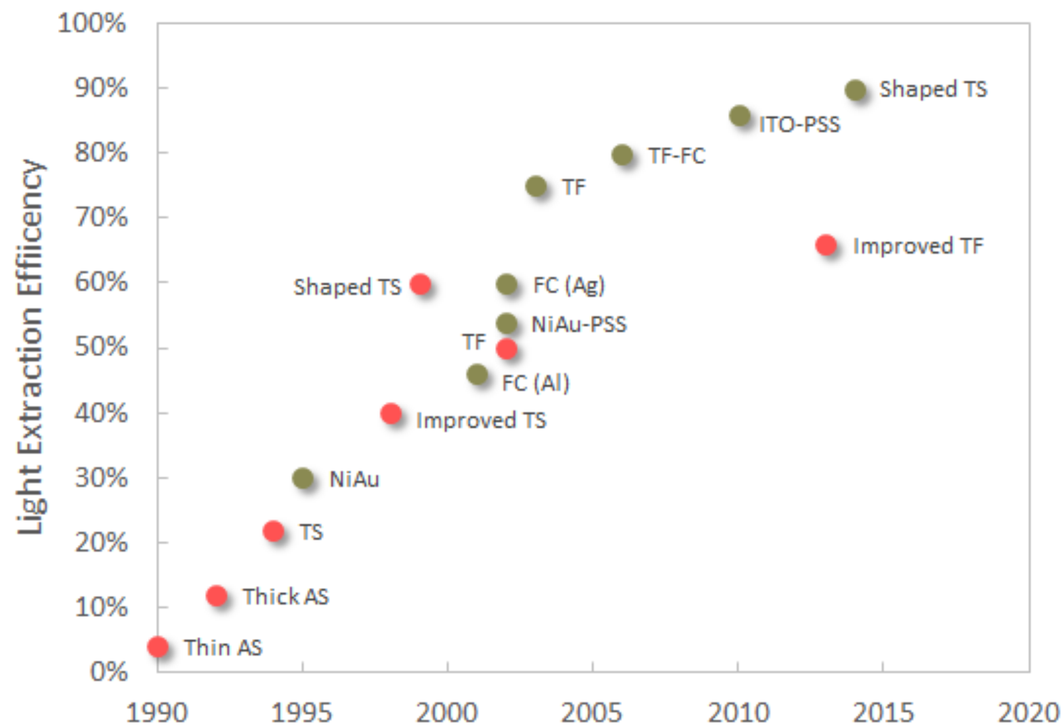
Slide courtesy of Dr Mike Krames, Arkesso LLC

Progress in light extraction efficiency

- For GaN, nearing theoretical limits
- For AlInGaP, high refractive index and internal losses remain a challenge

AS	absorbing substrate
TS	transparent substrate
NiAu	nickel-gold
Al	aluminum
Ag	silver
FC	flip-chip
TF	thin-film
ITO	indium-tin-oxide
PSS	patterned sapphire substrate



M R Krames, "Light Emitting Diode Materials and Devices," Ch. 7 in *Materials for Solid State Lighting and Displays*, A Kitai, ed. (2016); extraction into silicone *n* ~ 1.5

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So what's next?

- The industry continues to develop
  - At the die level, further refinement of extraction efficiency, cost, and quality
  - At the package level (out of scope of talk & time), continuing extensive activity in phosphor integration, encapsulation, and optics

- There is additional value to provide at the LED level
  - Luminous efficiency has been the driving performance metric, but is not the only important metric
  - Smaller, high luminance sources
  - Improved spatial and angular uniformity (of intensity and color)?
  - Optimization of light emission pattern?

- Untapped potential at the luminaire level
  - More constraints, especially on geometry and cost (due to size)

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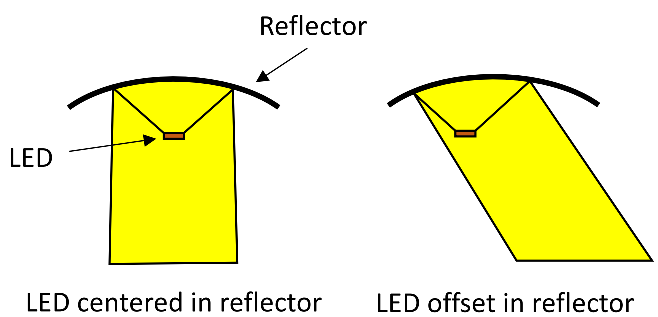
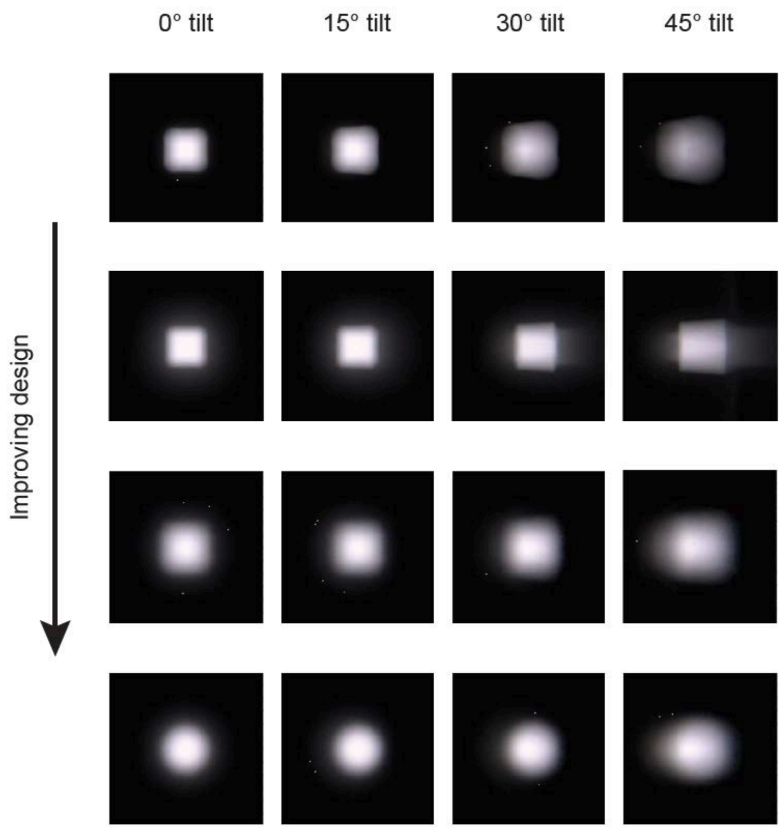
Light Shift^{TM}

- Moving LED off optical axis of collimator tilts beam…
  …but generally distorts and dims the beam

- Our innovative optics work closely with individual LEDs
  - Optics move millimeters *in-plane* to tilt beam >40°
  - Maintain brightness, shape, and uniformity
  - High collimation and low glare
  - Demanding of emitters: small, high luminance, narrow emission angle cone, uniform





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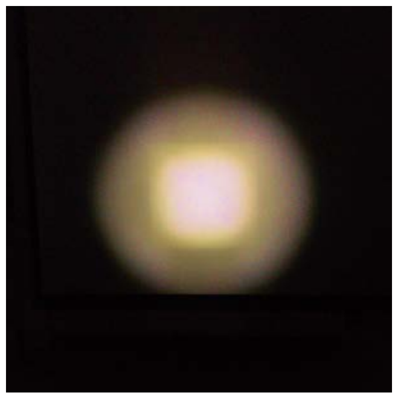
LED uniformity

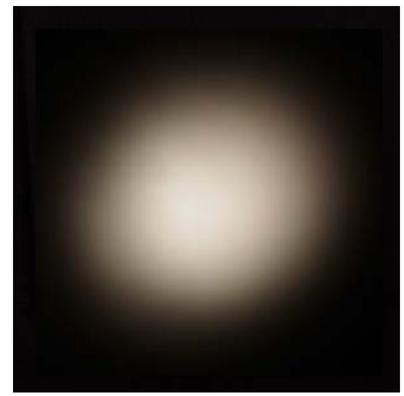
- LEDs optimized for raw efficiency might not be optimized for directional lighting applications

TFFC white LED



CSP white LED

Miracle occurs,
Funded by DOE



Glint Hero prototype

10-20 pts color variation to field angle

1 pt color variation to field angle

- Can be largely addressed in optics, but at the cost of complexity, size, efficiency, and glare

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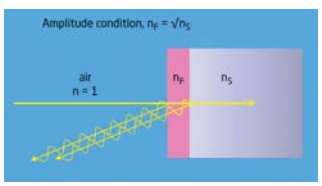
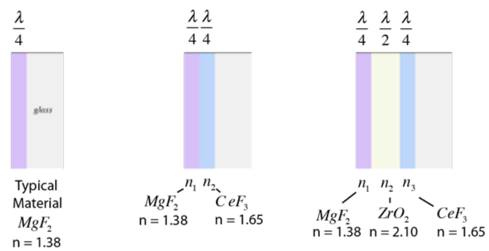
Peripheral vision = threat vision

Anti-reflective surfaces

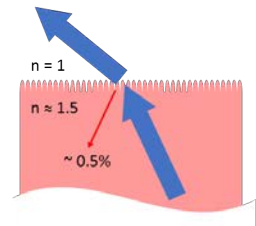
- At the luminaire level, there are many opportunities, but more constraints
  - Cost of working at a larger size scale, with fewer monolithic process options
  - Shape and texture of optics constrained by beam control requirements
  - Anti-reflective surfaces are the most universal opportunity

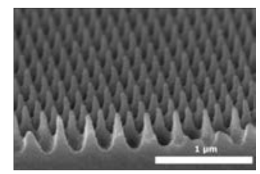


Simple index coating



Multilayer dielectric film





Graded index structures

(moth's eye anti-reflective nanostructures)

- Value proposition: Benefit / Cost
  - Anti-reflective materials not currently used in general lighting
  - Dichroic filters for MR16 IR bulbs @ $2 retail
  - Glint Hero – exquisite glare control
  - Anti-reflective nanostructures (ARN) can be produced roll-to-roll or imprinted by various means

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Scope of potential anti-reflective applications

System **Primary optics** **Emitter**

← Area increases (cost, processes, etc)

→ Operating temperature increases

→ Materials compatibility challenges increase

← Environmental exposure increases (durability, fouling, etc)

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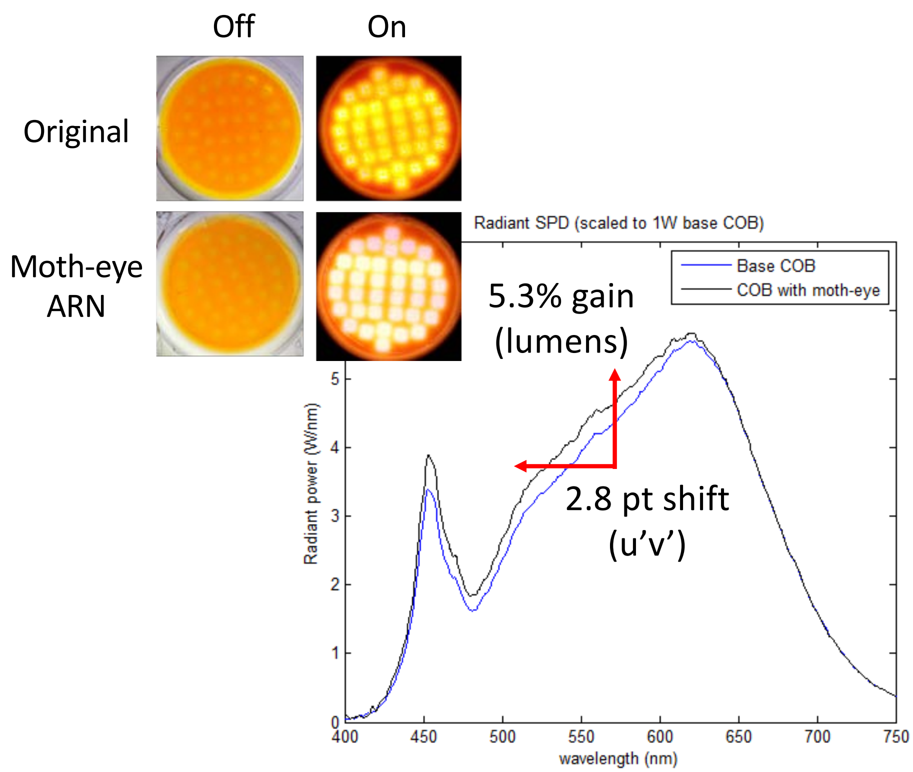
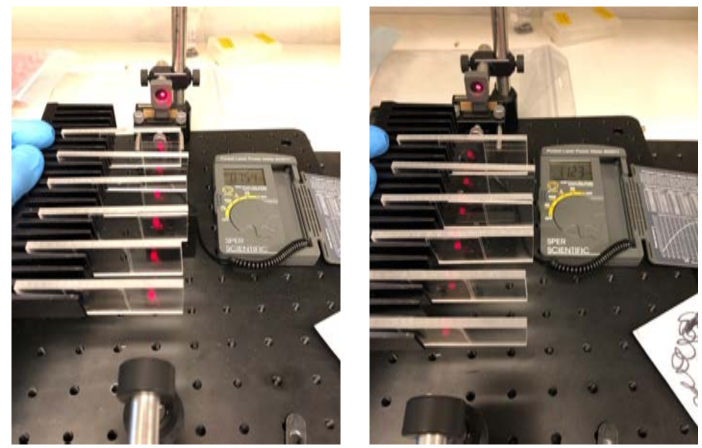
Demonstration

ARN integration on COB



ARN integration on optics



- 6 pieces of PMMA
- 12 Air-PMMA interfaces
- **62% transmission uncoated**
- **92% transmission with ARN film**

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Demonstration

ARN integration in track light

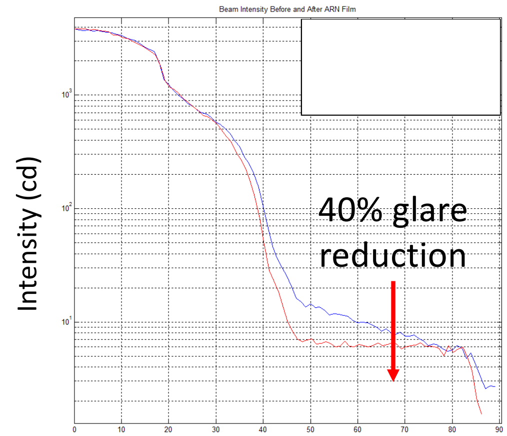
- 35° adjustable track fixture

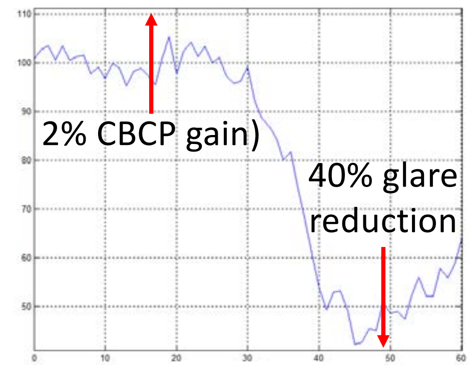
- ARN applied to front cover
  - Gain of 0.3% flux, 2% CBCP
  - 40% reduction in high-angle glare

- More light is where it should be (higher CBCP, lower glare)
- What glare figures of merit capture this kind of improvement well?

- Small raw flux gains due to low absorption

- We are mapping different luminaire types to identify biggest opportunities for flux and glare gains





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Concluding thoughts

- Light extraction at the die (and package) level have made incredible strides, especially for GaN
- There are LED performance metrics beyond raw efficacy that impact system-level performance, especially in directional lighting
- Anti-reflective surfaces have clear benefits at the luminaire level for extraction and glare, but need further study to see where they are practical in cost, process, compatibility, and reliability
- DOE Snapshots have repeatedly noted the slow progress of downlight efficacy, DLC is raising the threshold for Interior Directional – Standard from 65 Lm/W to 80 Lm/W, more efficient means of light control are important

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