Materials and Technology for Energy Efficient Lighting

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Australia

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University of Technology, Sydney

Architect Frank Gehry

UTS BUSINESS FACULTY

UTS ENGINEERING FACULTY

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UTS, Faculty of Science

UTS Centre for:
Materials and Technology for Energy Efficiency

AIM: To develop innovative, clean and inexpensive energy-saving technologies using advanced materials

Materials & Technology for Energy Efficiency

Solid State Lighting

Electro-Chemical Energy Storage

Daylighting Physics

MAU & SEMLAB New Platform Technology

Advanced Photovoltaics

Computational Modelling

Plasmonics

Materials & Technology for Energy Efficiency

Solid State Lighting

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Computational Modelling

Plasmonics

Electro-Chemical Energy Storage

Prof Guoxiu Wang

Electro-Chemical Energy Storage Prof X Wang

Clean Energy Technologies

Advanced battery technologies for cars & smart electricity grid applications.

Rechargeable Li batteries, Li-air & Li-S batteries

Supercapacitor technology for high power applications

High surface area carbonaceous & tailored mesopore electrode materials

Hydrogen production and hydrogen storage

H production biomass & photocatalytic H_2O splitting, high capacity H storage materials

Hydrogen fed fuel-cell technologies

NanoPt catalysts for O reduction + H oxidation, polymer membrane proton conduction

Bio-fuel cell technology for biomedical application

Improvement of efficiency and lifetime of bio-fuel cells for implantation

Powertrain for electric car and hybrid electric car

Novel architecture design of electric vehicles (EVs)

Fundamental research on graphene

Large-scale synthesis of graphene material & applications for energy storage

Types of Electric Vehicles (EVs)

Hybrid

Ford Escape HEV

Plug-in Hybrid

Toyota Prius PHEV conversion

Battery Only

Tesla Roadster BEV

Fuel Cell

Honda FCX hydrogen FCV

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Computational Modelling
Prof Mike Ford

UTS Materials Computational Capabilities

Atomistic

Density functional theory (DFT) calculations of nano-structures, band structure, defect energies, thermodynamics

Density Matrix **- divide and conquer**

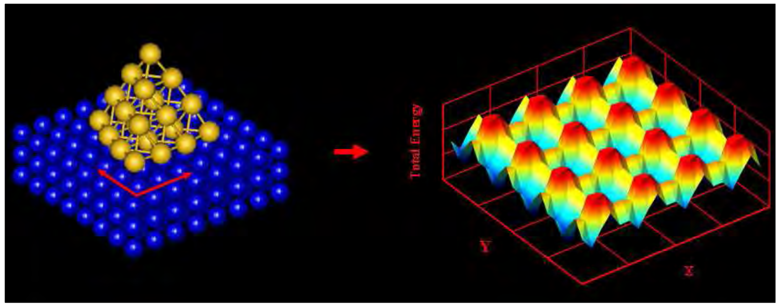
DFT for very large numbers of atoms (millions !)

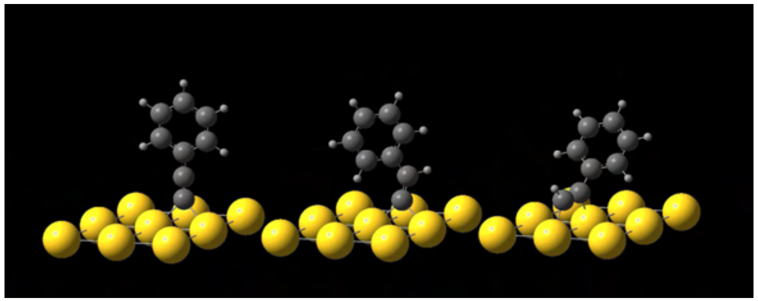
Time-Dependent DFT

Optical properties from first principles - band structure of entire nanoparticles and nanowires

Continuum or classical electromagnetism

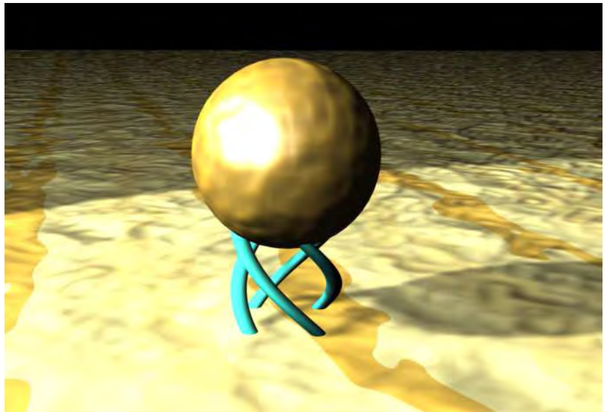
DDA, T-matrix, FDTD, nanostructure calculations





Computational Modelling

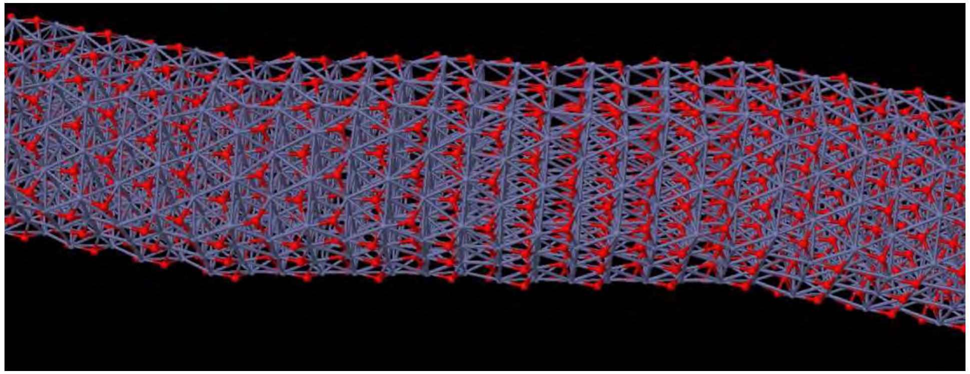
Nanoparticles



Courtesy of David Cortie

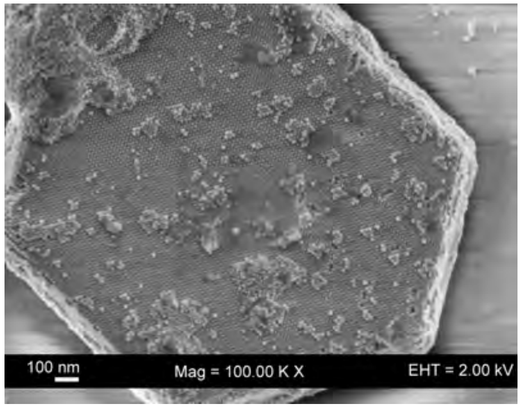
- structural, electronic & optical
- 10 nm = 10,000s of atoms

ZnO Nanowires



- Light emission / role of defects
- Transport properties
- Effect of strain

Macroscopic gold colloidal crystals



Harris, Ford et al Nanotechnology **18** (2007) 365301

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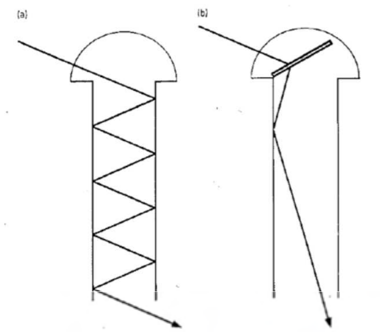
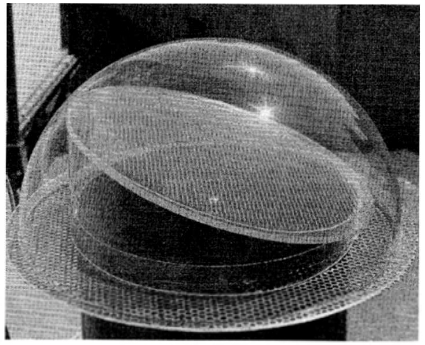
Daylighting Physics
Prof Geoff Smith

Daylighting Physics - Prof G Smith

Efficient Daylight Harvesting and Transport
Optical and Materials Physics

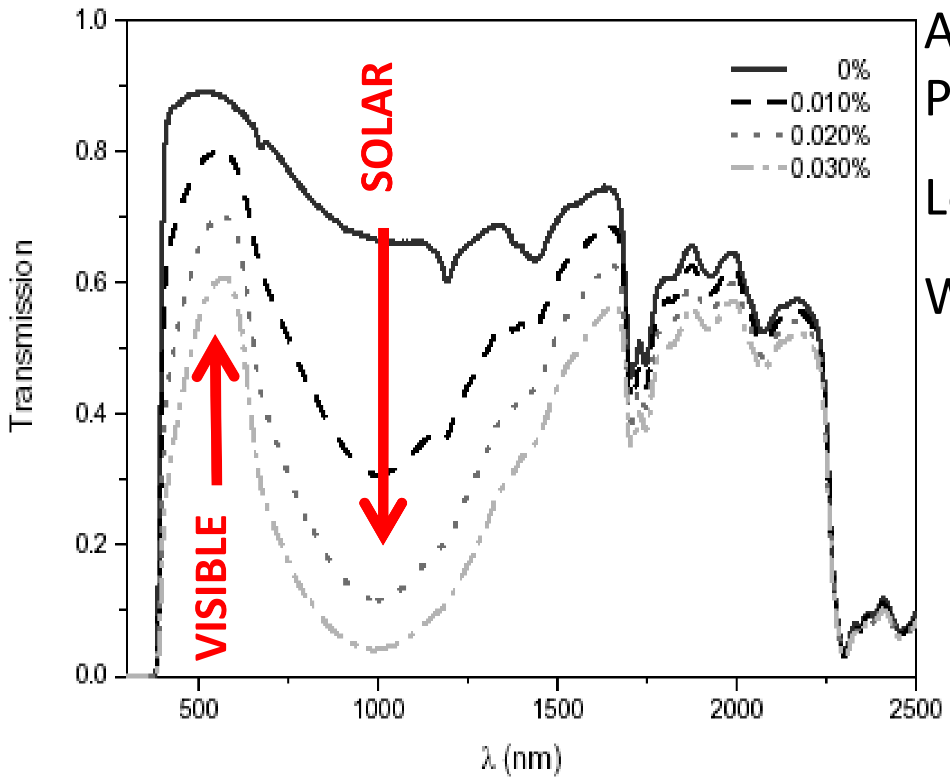




Solar Tubes

Optimum Daylight Transmission
Roofing for Sydney Olympic Stadium

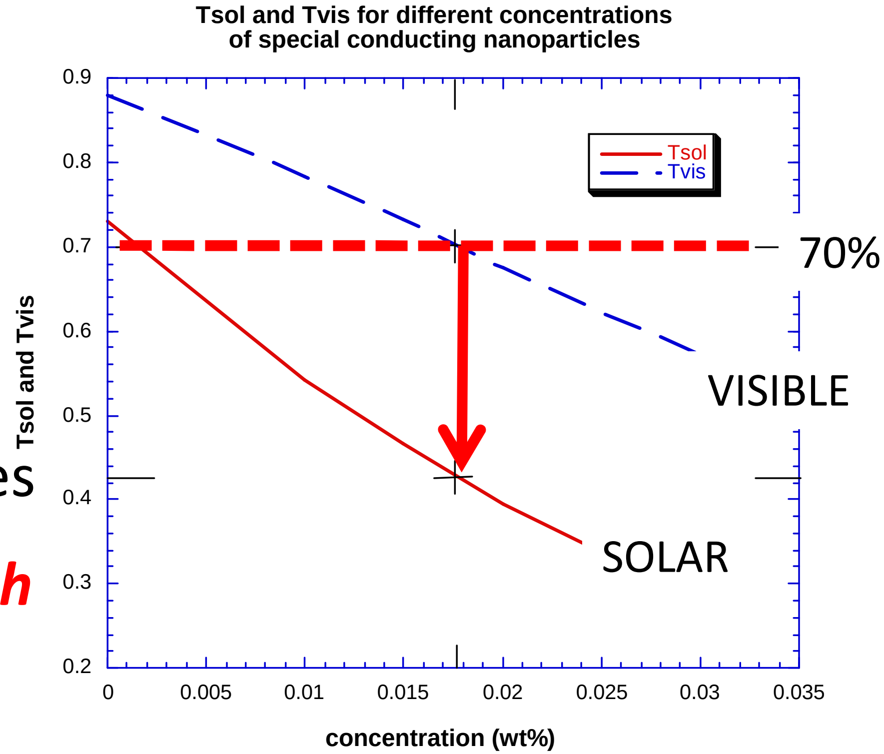
Laminated glazing with LaB_6 nanoparticles in PVB layer



Addition of LaB6 Nanoparticles in 0.7 mm PVB foil between two sheets of glass

Low Solar with High Visible Transmittance

Windows & Car Windscreen Tvis > 70 %



Addition 0.017wt% LaB6 nanoparticles

50% reduction in solar radiation with 20% reduction in visible light

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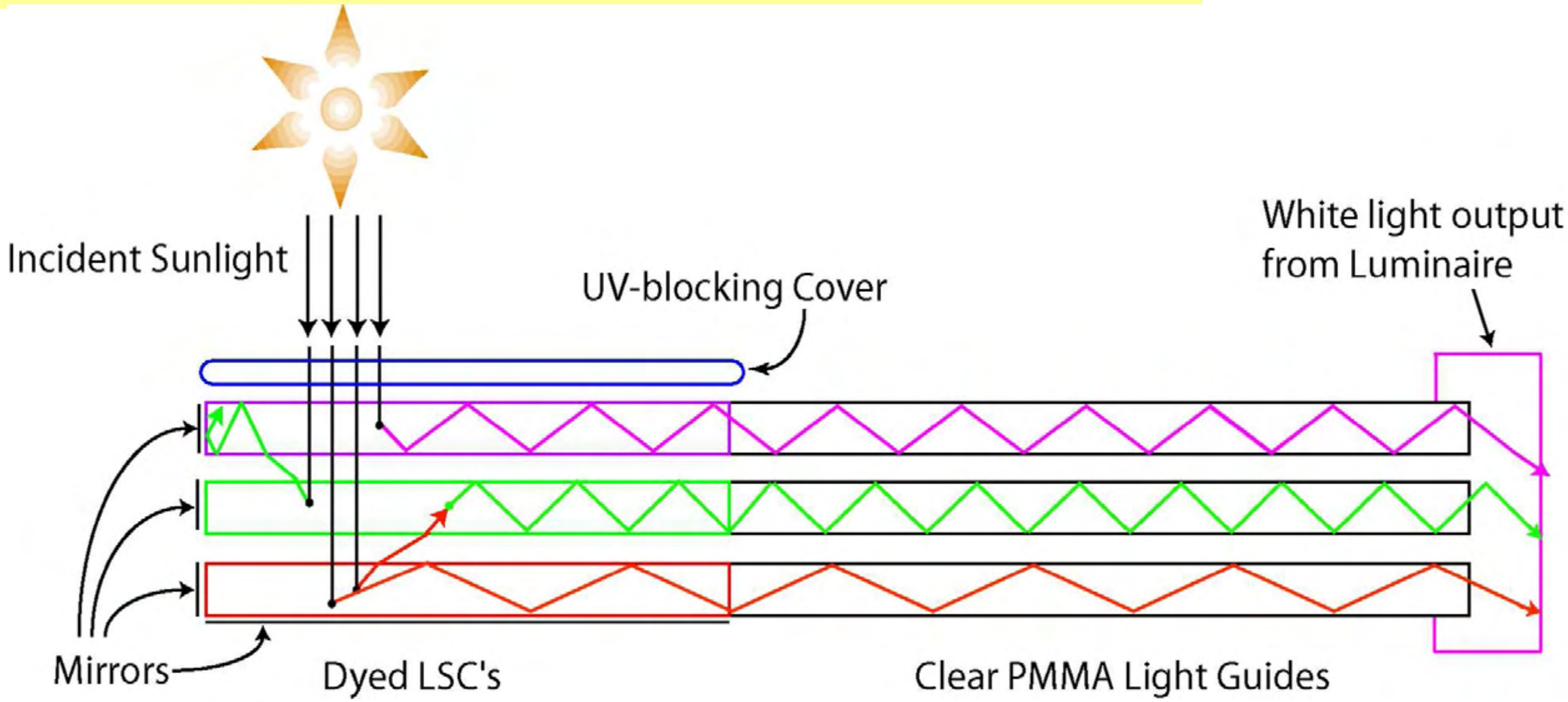
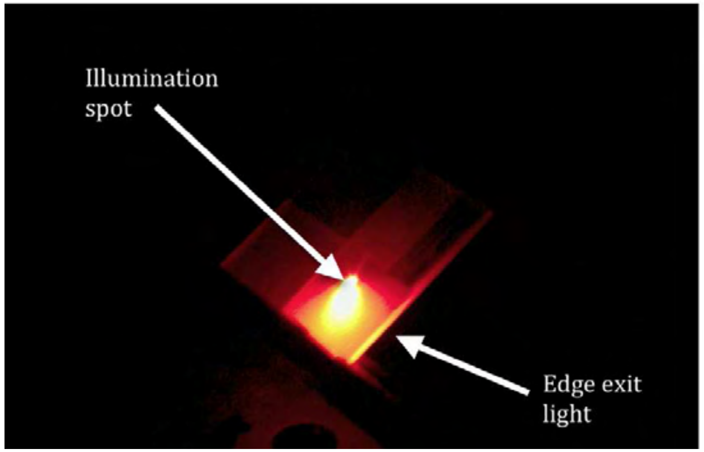
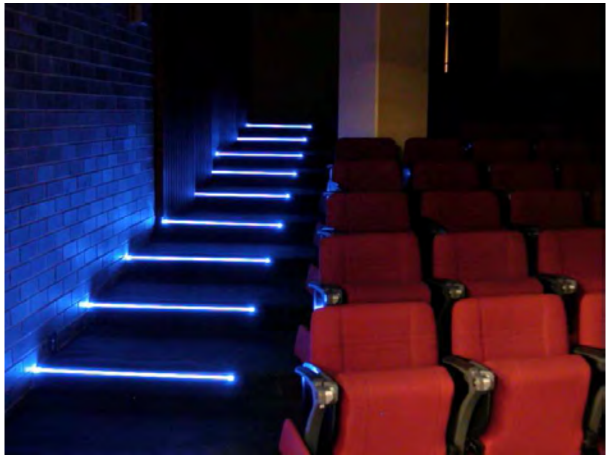
Fluorescent solar concentrators

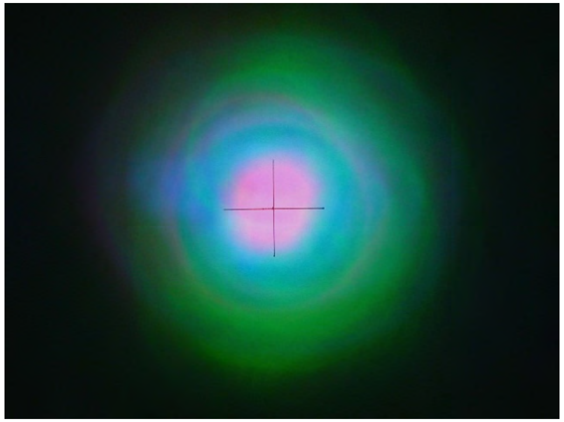


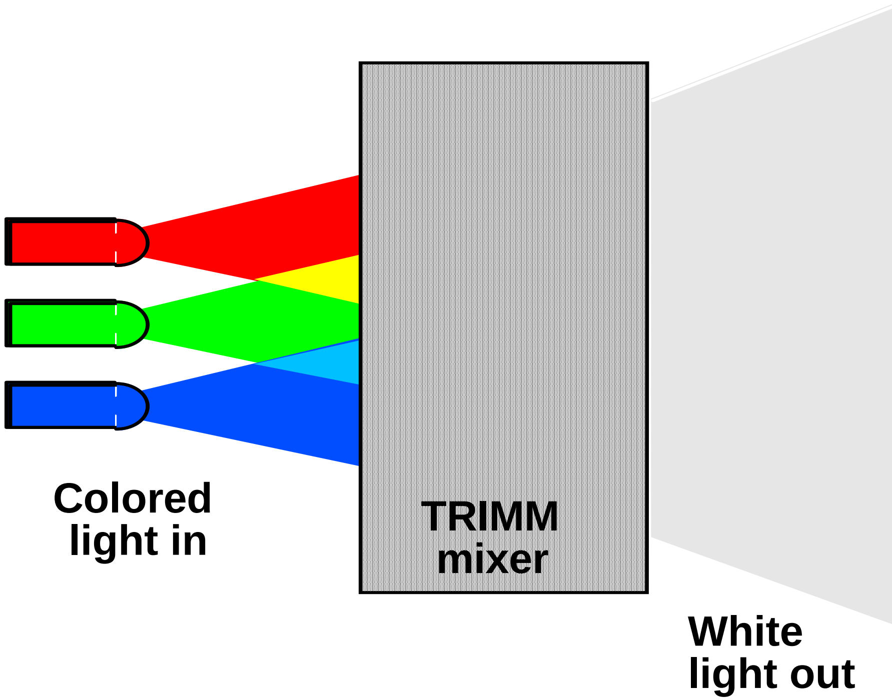




Beam White Light from LEDs

Transparent Refractive Index Matched Micro-particles





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SEMLAB
New Materials Research
Platform Technology
Prof Milos Toth

SEMLAB - Prof M Toth

5 year Collaborative Research Program
Between UTS and FEI Company, Oregon, USA

Enable real-time nano-scale imaging and correlative analysis of dynamic processes in a reactive gas environment

Completely new approach to materials research

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SEMLAB

Simplified schematic of an *in-situ* environmental cell reaction chamber in a Scanning Electron Microscope

Observation at 1 nm resolution

Heat to 1200°C

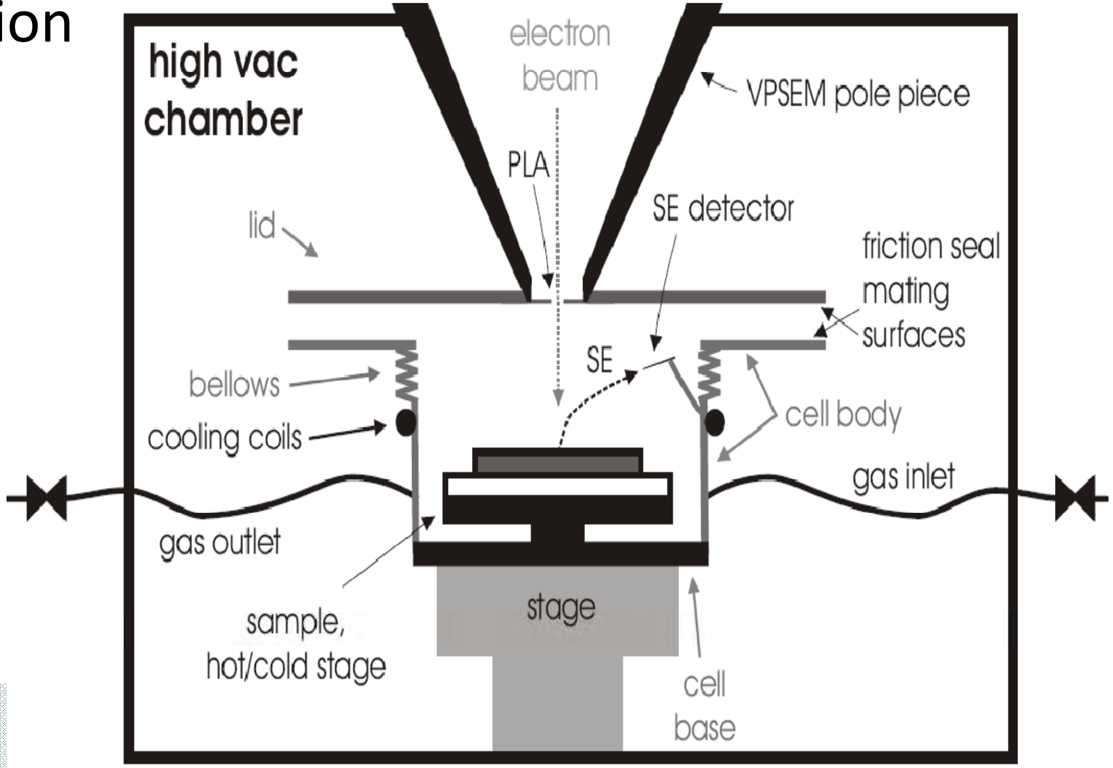
Cool to -200°C

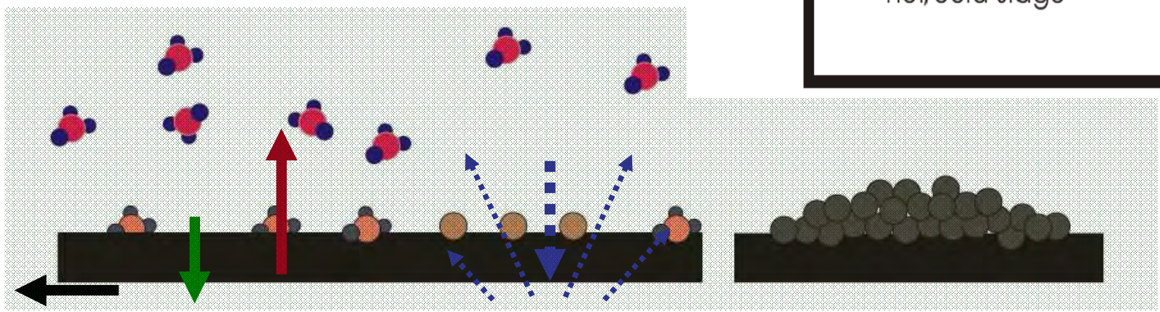
Any gas environment

In-situ chemical analysis

Nanoscale Deposition

Nanoscale Etching





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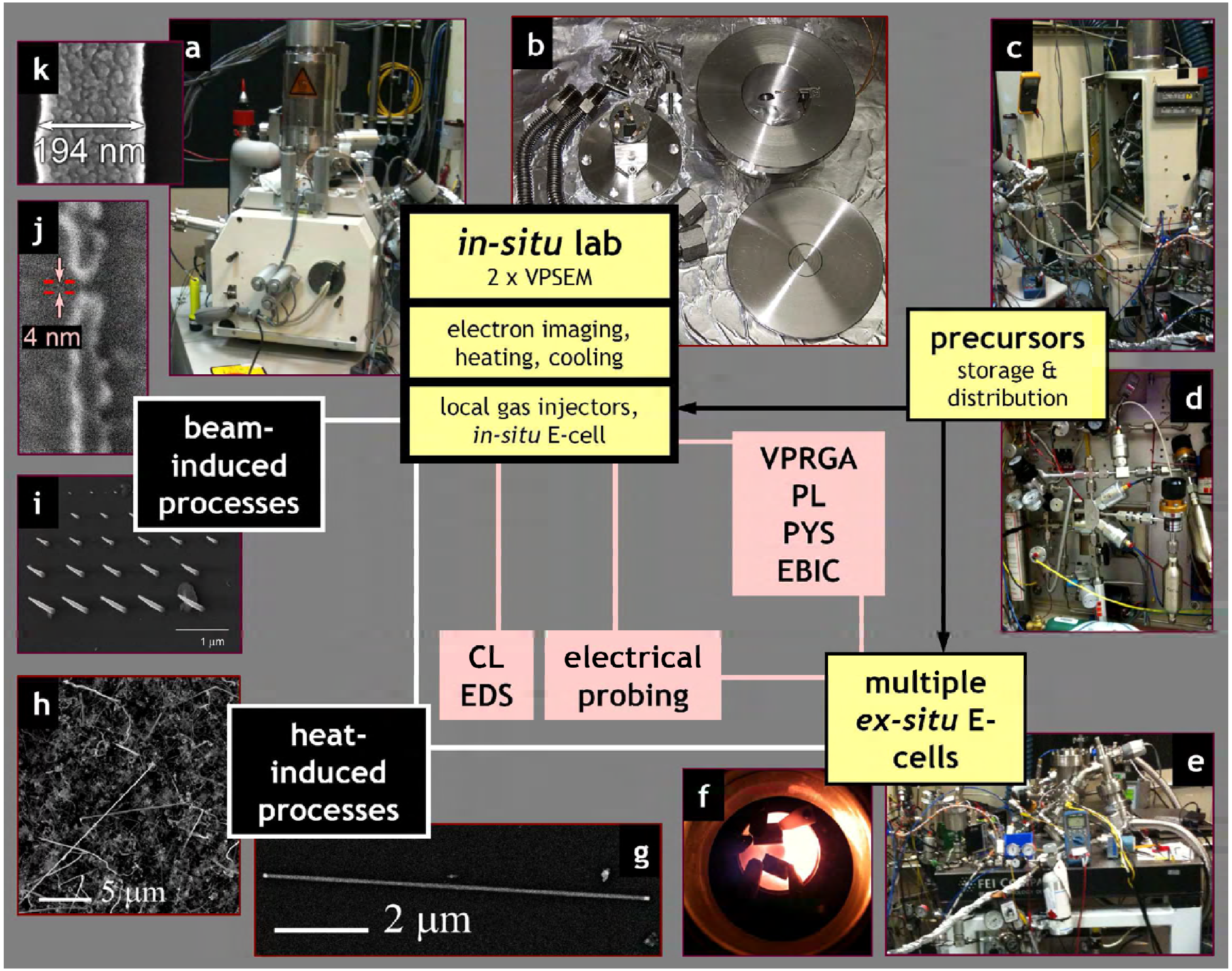
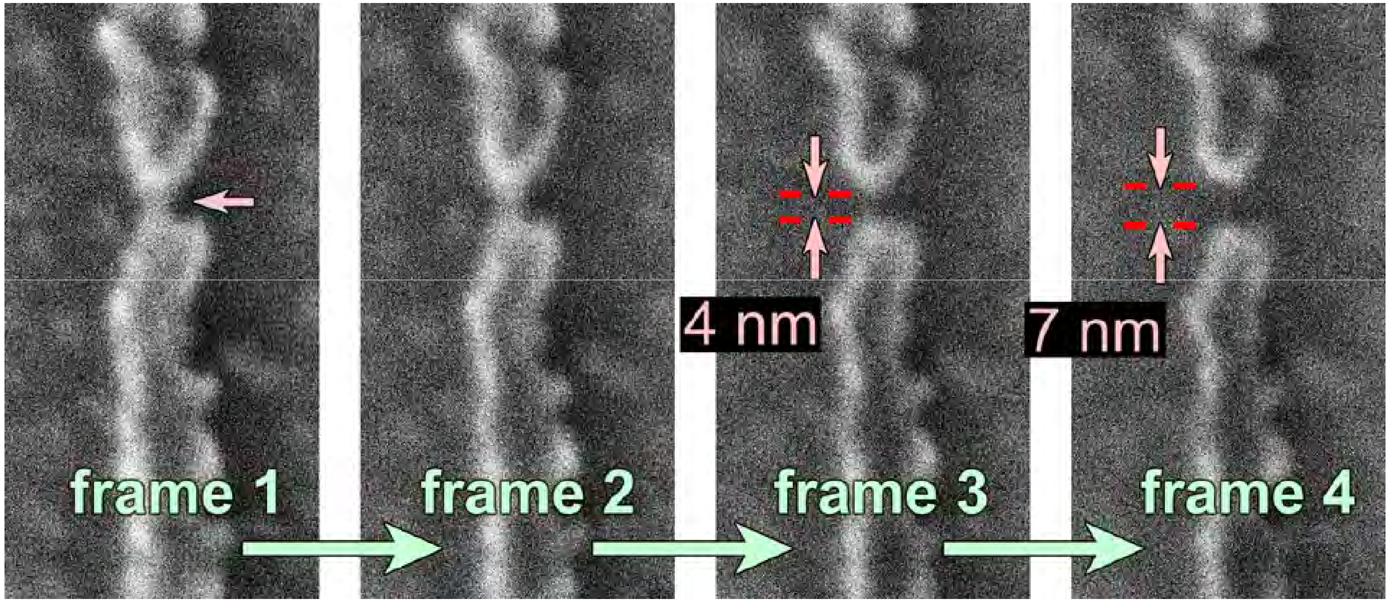
UTS-FEI SEMLAB Research Capabilities



High Spatial Resolution
Electron Beam Induced Deposition & Etching



Toth, Lobo, Knowles & Phillips, Nano Letters 7, 525 (2007)

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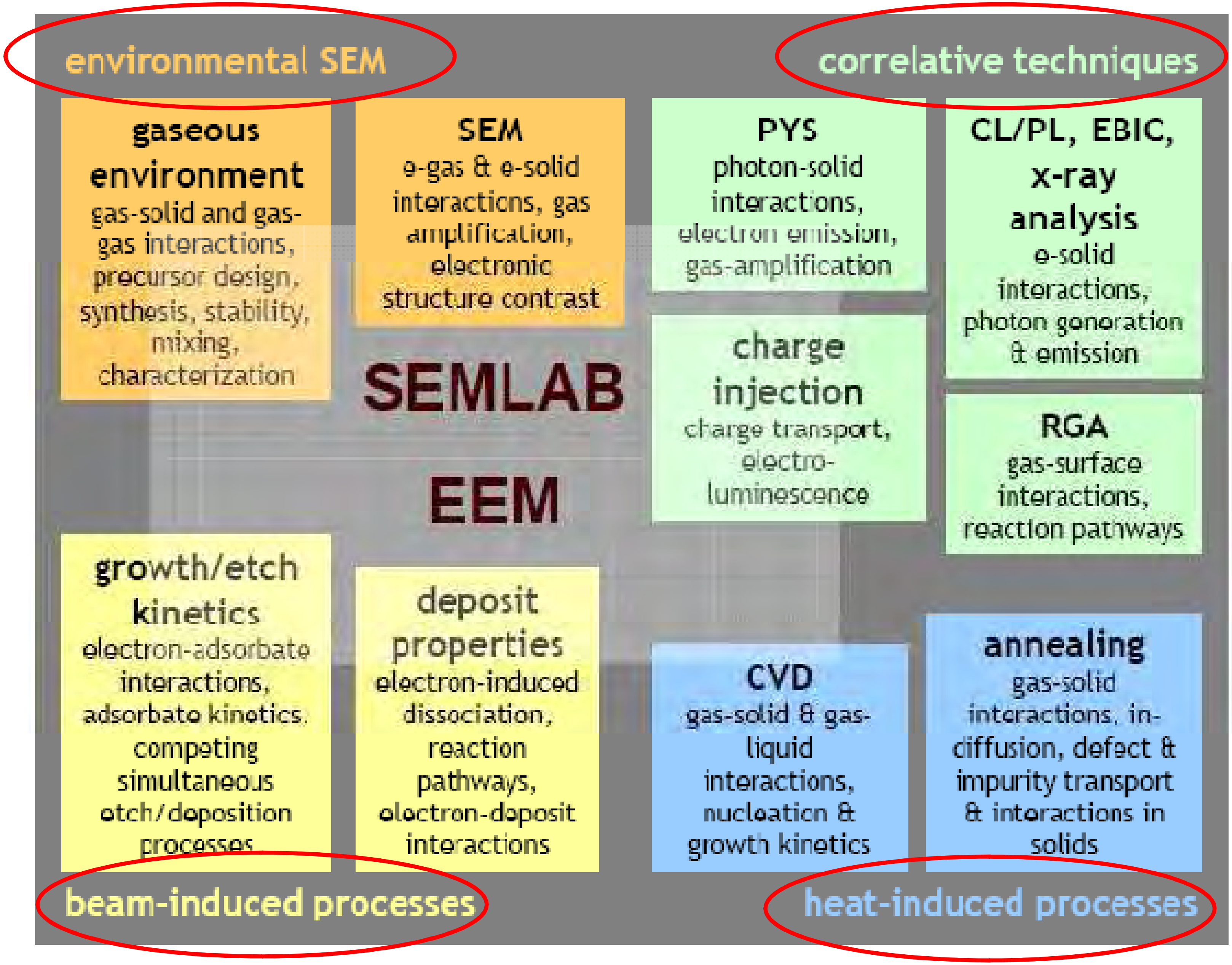

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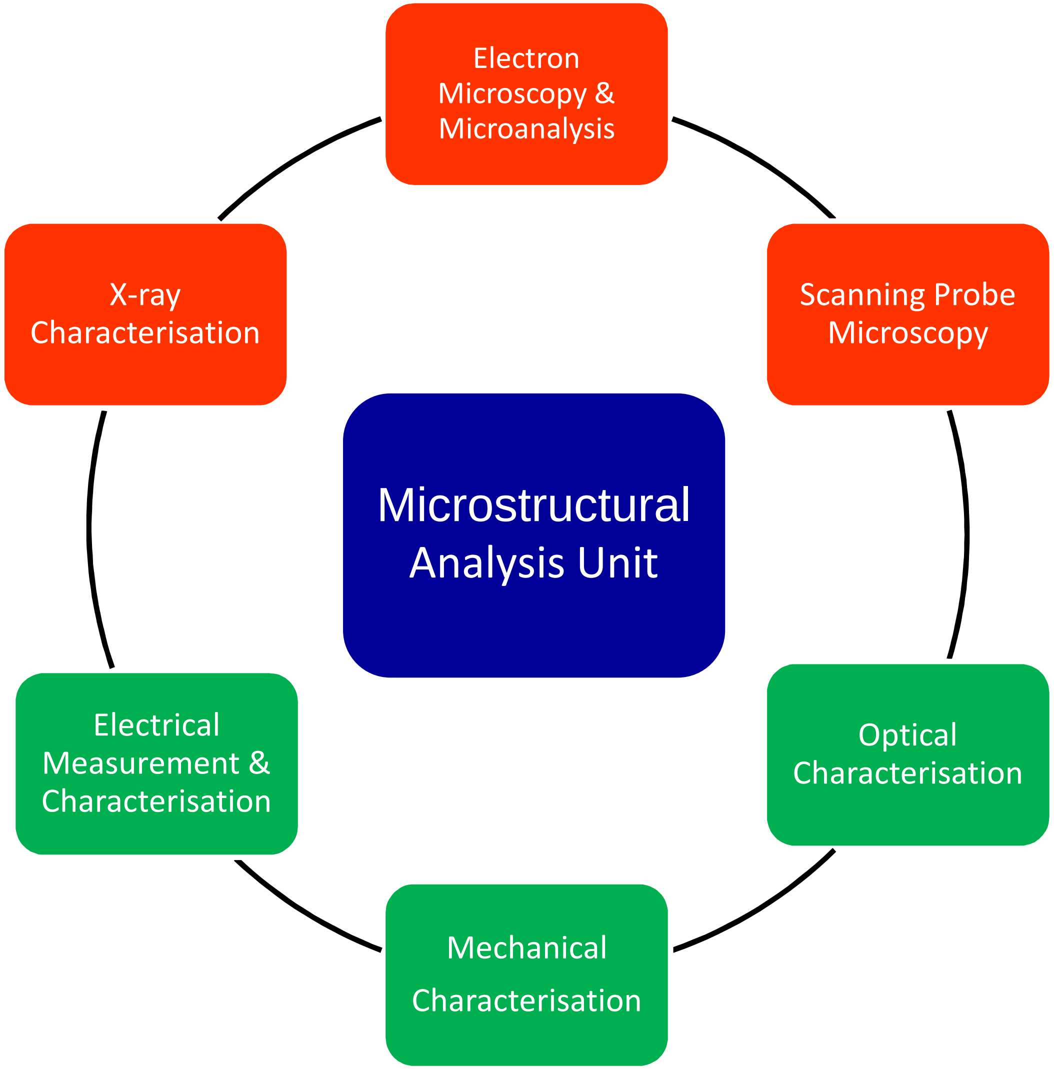
Microstructural Analysis Unit
Prof Matthew Phillips

Microstructural Analysis Unit



Microstructural Analysis Unit

Director
Prof Matthew Phillips

Professional Officer-Operations
Ms Katie McBean

Professional Officers
Mr Mark Berkahn
Dr Norman Booth
Mr Jim Franklin
Mr Geoff McCredie
Dr Ric Wuhrer

Available MAU Research Equipment

http://www.science.uts.edu.au/centres/mau

Scanning Electron Microscopes (SEM) & X-ray EDS

- Zeiss Supra 55VP SEM with RAITH E-beam Lithography System & HKL EBSD
- FEI XL30 ESEM
- FEI Quanta 200 ESEM with Gatan MONOCL3 System
- JEOL 35CF SEM
- FEI Sirion FEG ESEM
- JEOL 35C SEM

SEM Accessories

- Kleindiek Micromanipulators

Scanning Probe Microscopes (SPM)

- Digital Instruments Dimension™ 3100 AFM and Bioscope
- Digital Instruments Multimode SPM
- Nanonics Near Field Scanning Optical Microscope (NSOM)
- Nanosurf Easyscan STM

X-ray Diffraction (XRD)

- Siemens D5000 Diffractometer

Spectroscopy

- Varian Cary Eclipse Fluorescence Spectrometer
- Perkin Elmer LS50 Luminescence Spectrometer
- Gatan MONOCL3 Cathodoluminescence System
- Perkin Elmer Lambda 950 UV/VIS/NIR Spectrometer
- Varian Cary 5E UV/VIS/NIR Spectrometer
- Ocean Optics SD2000 Diode Array Spectrometer
- J-Y Instruments Phase Modulated Ellipsometer
- X-ray Photoelectron Spectroscopy (XPS)

Thin Film Coating Chambers

- Edwards EO6 Deposition System
- Denton DV502 Turbo Deposition System
- Dynavac CE12-14s Evaporation System
- Shannon E-beam Evaporation System

Sample Preparation and Processing

- Polishers
- Diamond saw
- Spin coater

Microstructural Analysis Unit

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Solid State Lighting
Prof Matthew Phillips

Lighting essential for enhancing societies'

- **productivity & prosperity**
- **health & well-being**
- **safety and security at night**

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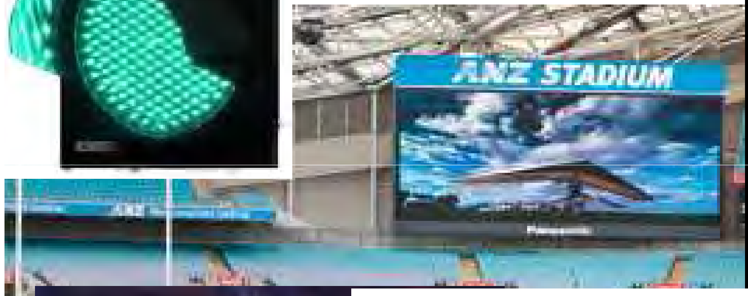
Green Lighting Revolution

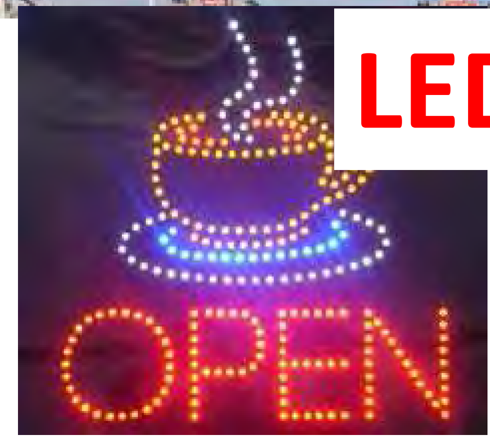
INEXPENSIVE, CLEAN & EFFICIENT LIGHTING

SOLID STATE LIGHTS

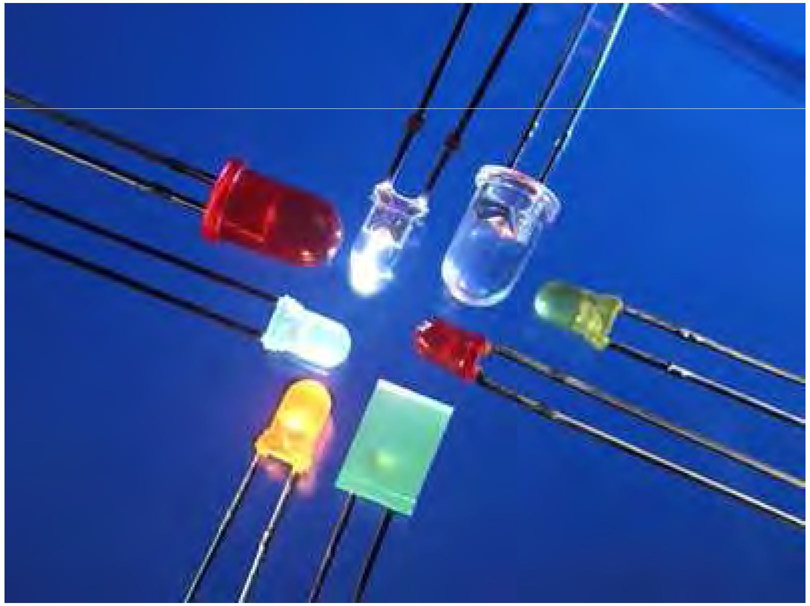
THE REVOLUTION HAS BEGUN!

LEDs are Everywhere





What is a
Light Emitting Diode
Solid State Light Source ?



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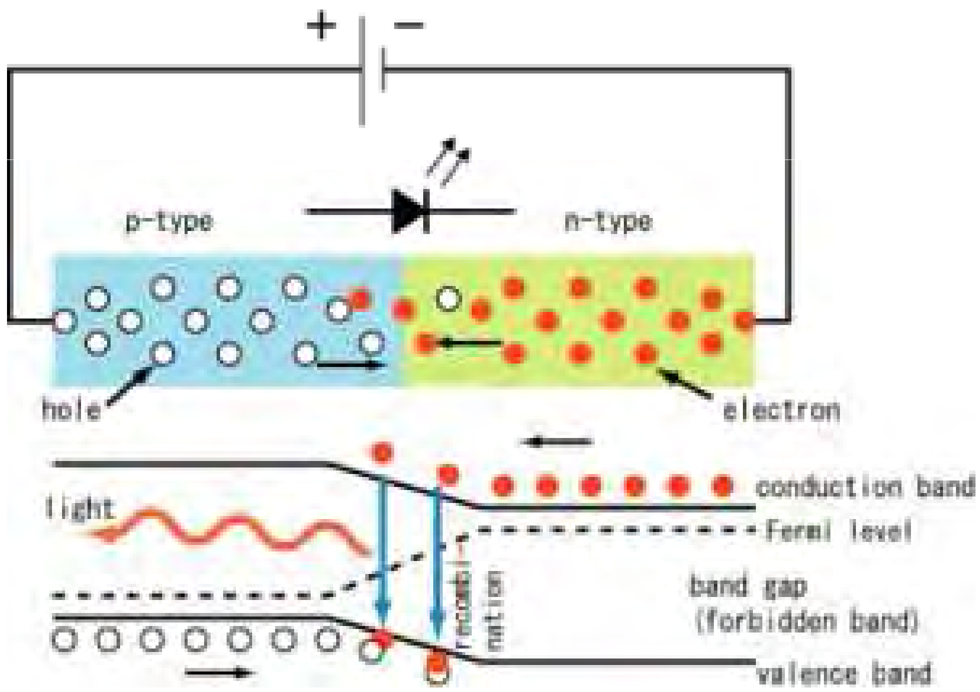
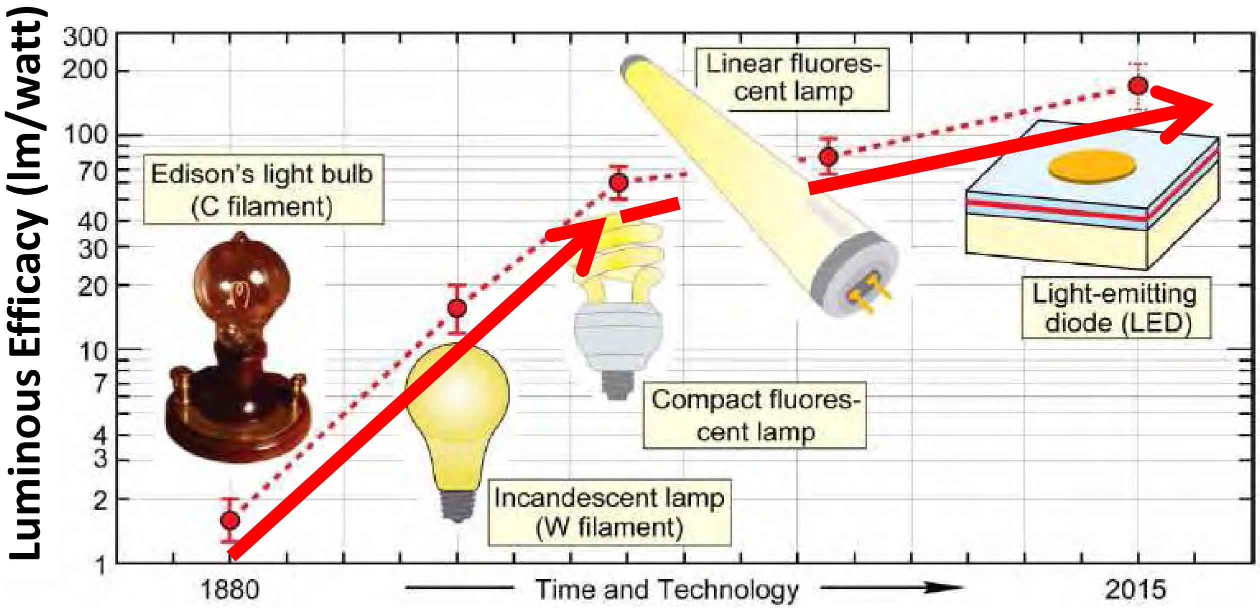
The Light Emitting Diode (LED)

Semiconductor device that converts electricity into light

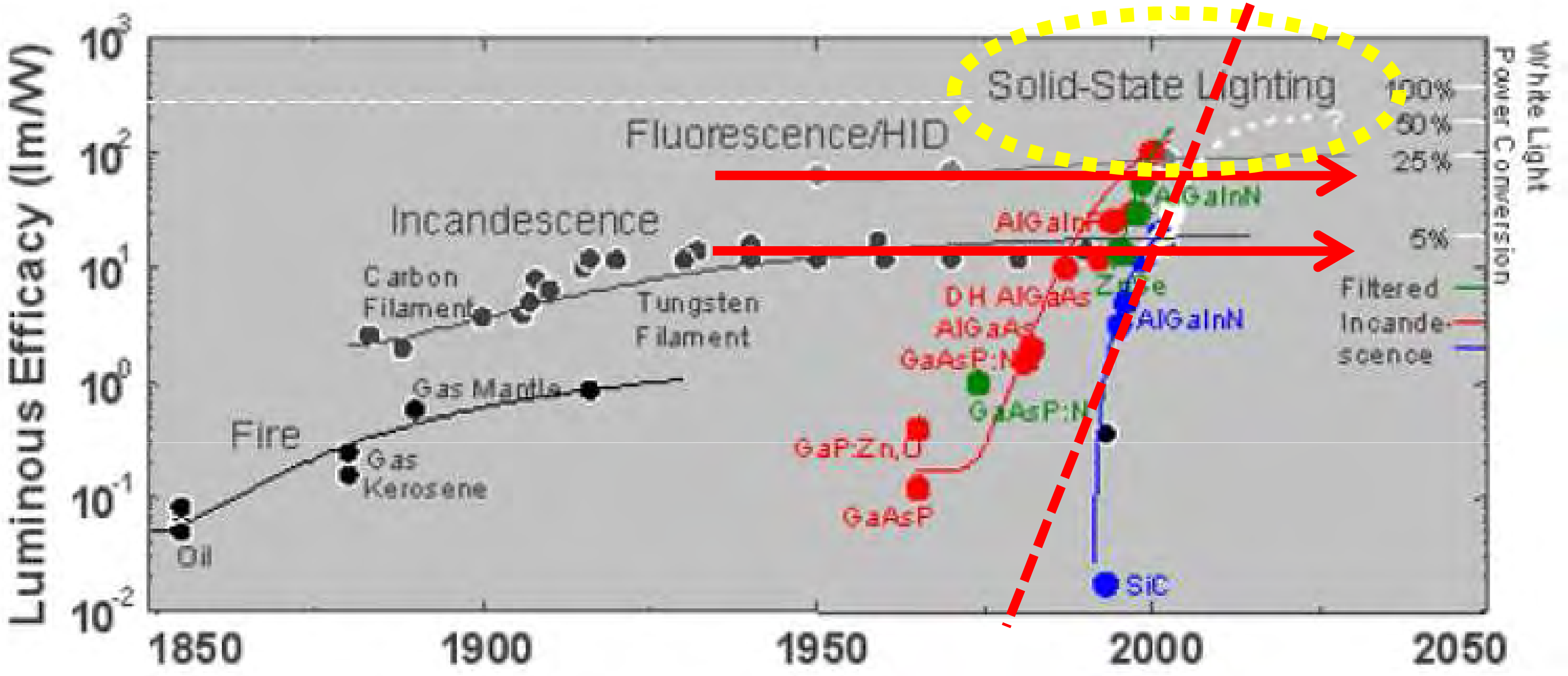
LED consists of a junction between n-type and p-type semiconductor layers



Luminous Efficacy (lm/W)



Evolution of Efficient Lighting



Incandescent	Linear Fluorescent	Compact Fluorescent	LED (commercial)	LED (lab)	LED (theory)
15 lm/W	90 lm/W	50 lm/W	130 lm/W	200 lm/W	350 lm/W

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Measuring
Light Source Performance

LUMENS PER WATT

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Lumen per Watt?

A Lumen is a measure of light output

30 cm

1 lumen = amount of <u>visible light</u> ~ 30 cm from a candle

A Watt is a measure of electrical energy = voltage x current

Lumen per Watt (efficacy) =

amount of <u>visible light</u> out for each Watt of energy used

Incandescent Light Bulb

Efficacy = 16 lumen per watt

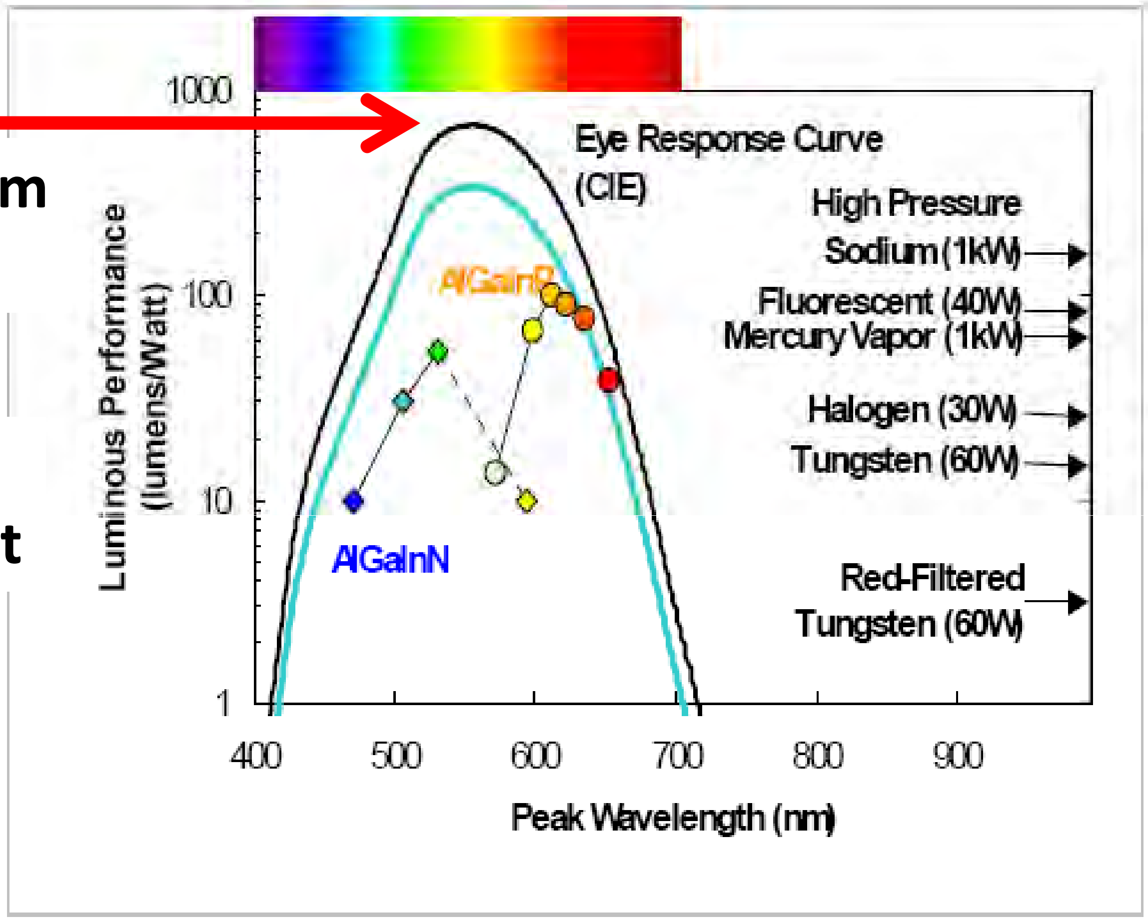
100W bulb produces 1600 lumen
60 W bulb produces 960 lumen

100W = 130 Candles

Theoretical Maximum Efficacy (lumen/Watt)

MAX at 555nm
683 lm/Watt

MAX white
~325 lm/Watt



Conversion efficiency from electrical to optical power combined with conversion of optical power to lumen sensed by human eye

Incandescent Light Bulb is OUTLAWED in Australia from 2010

Energy Efficient Lighting Revolution has begun

Incandescent Light Bulbs Banned by Governments around the world

Argentina	complete ban by 2011
Canada	complete ban by 2012
Cuba	complete ban by 2005
United States	**100-watt bulbs in 2012 and all by 2014**
Venezuela	complete ban by 2005
Philippines	complete ban by 2010
European Union	**complete ban by 2012**
Australia	**complete ban by 2010**
China	**100-watt bulbs in 2015 and all by 2018**

WHY?

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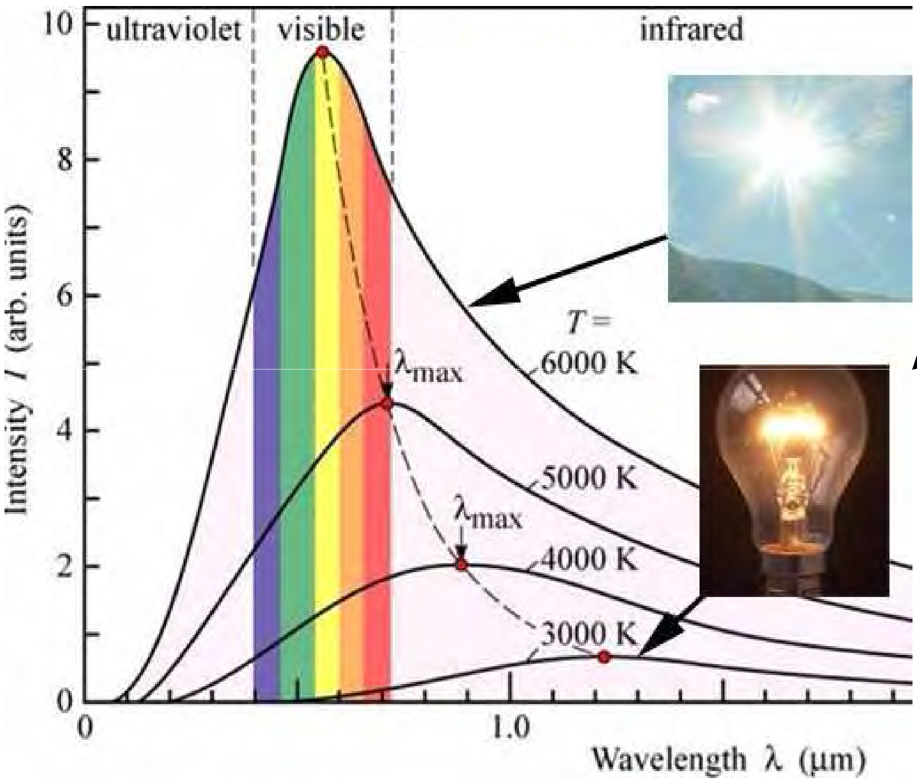
Incandescent Light Bulb - Highly Inefficient

Bulb Efficacy = 16 lm/watt



95% of Energy Lost as HEAT!

LED LAMPS already > 200 lm/watt

20% World's Electricity Used for Lighting

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Today's LED Solid State Lighting Technology is already

Ten times the **Efficacy** of Incandescent Bulbs
Twice the **Efficacy** of CFLs

Ten time the **lifetime** of Incandescent Bulbs
Five times the **lifetime** CFLs

Significant the power, cost savings and environmental benefits

Global Savings by SSL over 10 years

- ***ECONOMY*** *- Significant financial savings*

  > 1,800 trillion dollars

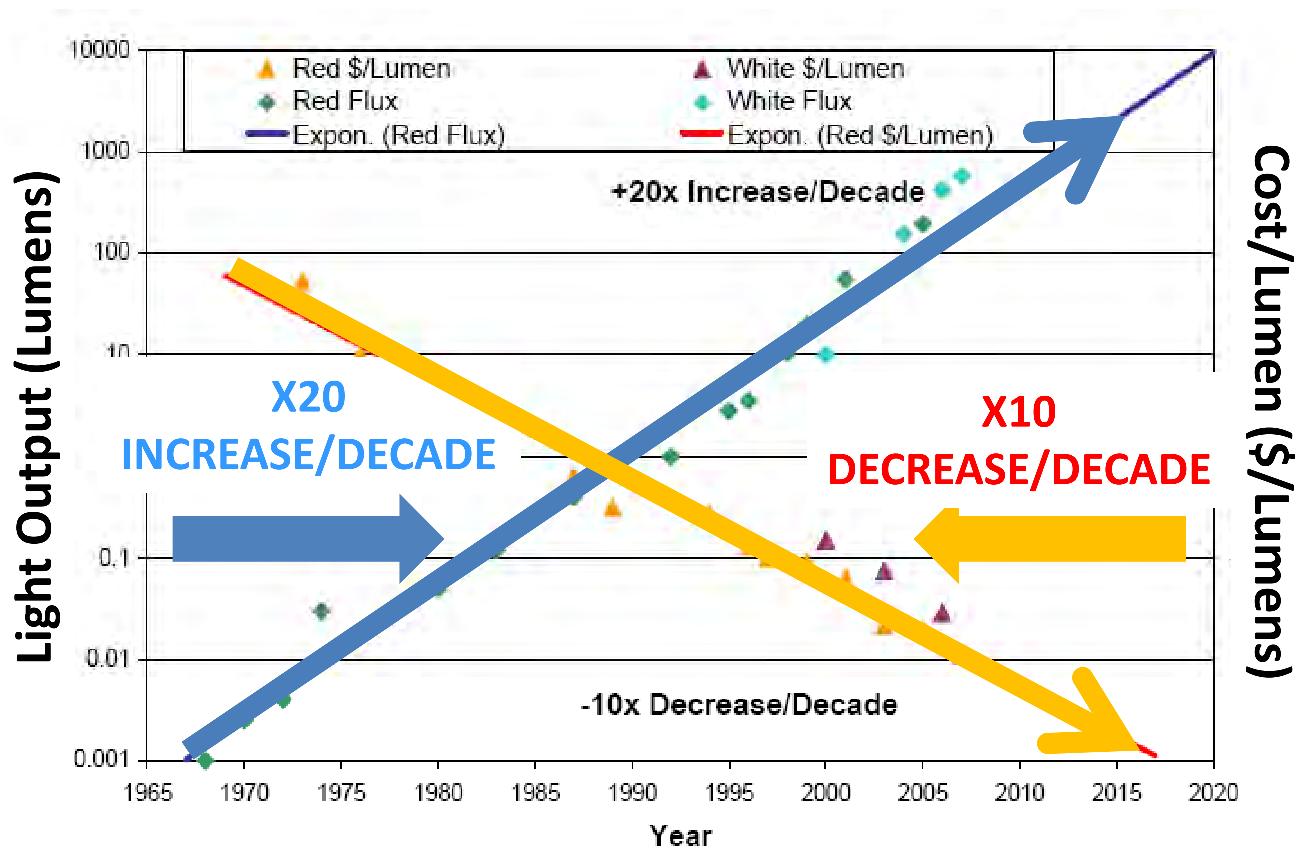
- ***ENVIRONMENT*** *- Reduced Pollution*

  > 10,000 mega-tonnes of CO_2

- ***ENERGY*** **-** *Reduced Electricity Consumption*
  - > 18,000 Terra-Whr
  - Eliminate the need for 280 power plants
  - 962.4 Million barrels crude oil

22 December 2008 / Vol. 16, No. 26 / OPTICS EXPRESS 21842

Haitz' Law



"Every 10 years the amount of light generated by an LED increases by a factor of 20, while the cost of per lumen falls by a factor of 10".

Haitz' Law suggests all lighting should become LEDs within a decade.

LEDs are the Future!

2002 USA Dept of Energy Solid State Lighting Technology Roadmap

TECHNOLOGY	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incande-scent	Fluore-scent
Luminous Efficacy (lm/W)	25	75	150	200	16	85
Lifetime (hr)	20,000	>20,000	>100,000	>100,000	1,000	10,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400
Input Power (W/lamp)	1	2.7	6.7	7.5	75	40
Lumens Cost ($/klm)	200	20	<5	<2	0.4	1.5
Lamp Cost ($/lamp)	5	<5	<5	<3	0.5	5
Color Rendering Index (CRI)	75	80	>80	>80	95	75

Cree Industries announce 208 lm/W in lab Feb 3, 2010

10 years ahead of target

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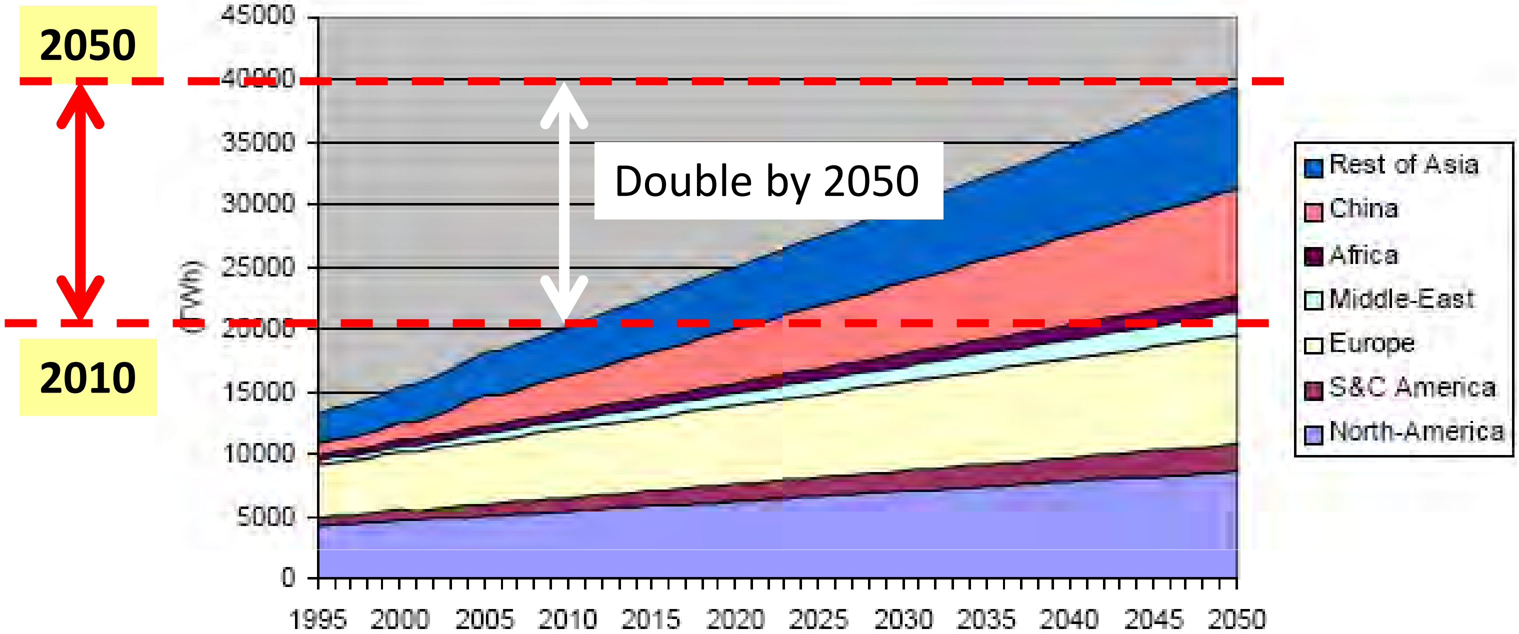
World Electricity Consumption to Double by 2050



smh.com.au The Sydney Morning Herald

Power cost to surge in three years
Clancy Yeates
March 20, 2010

Electricity prices will jump by up to 60 per cent over the three years to 2012-13

Australia ~ $0.18 kW.hr

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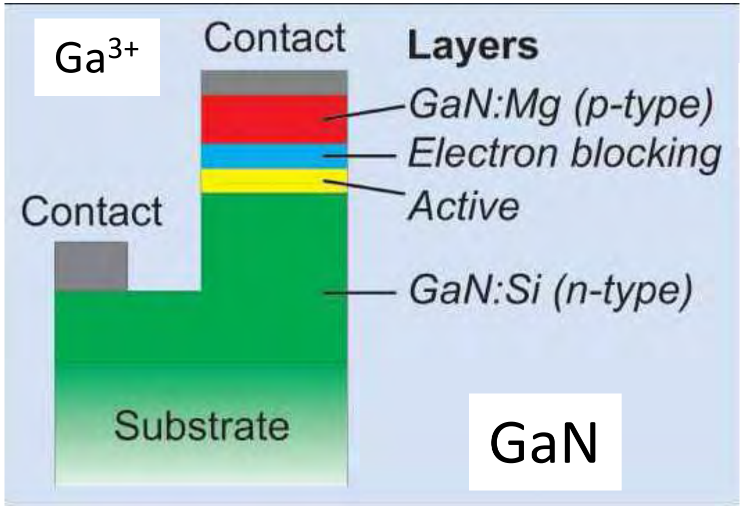
LEDs are over 30 years OLD – What's New?

Nitride & Oxide Semiconductors

$In_{(1-x)}Ga_xN$ AlN   ZnO

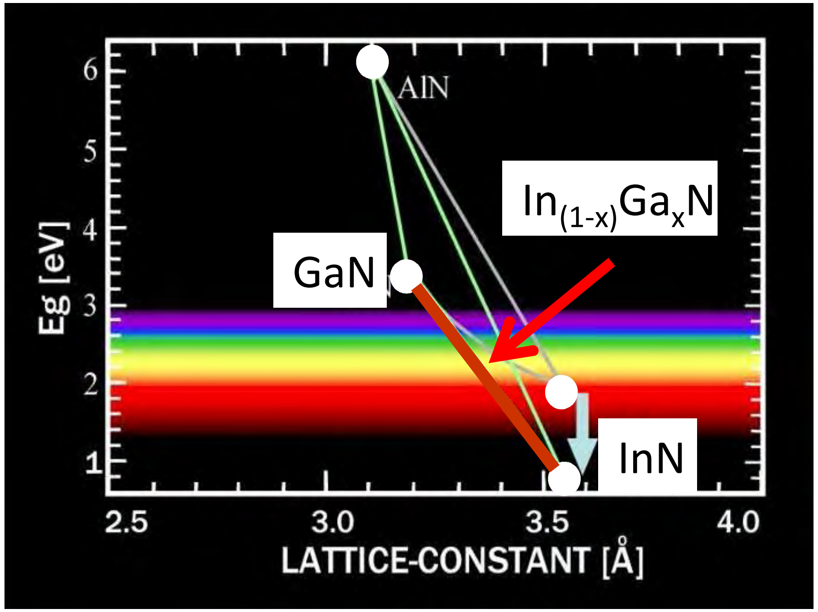
Extremely Bright
UV, Blue and Green LEDs

SO WHAT?



Mg^{2+}

Si^{4+}



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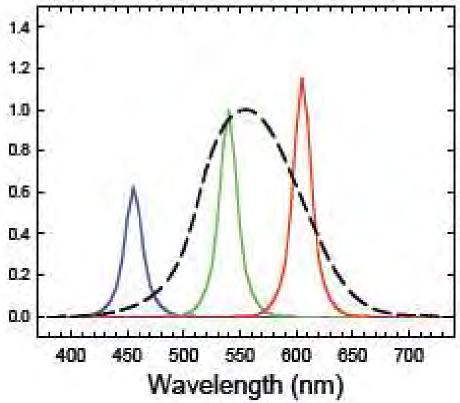
Fabrication of White Light LEDs – > 200 lumen/watt

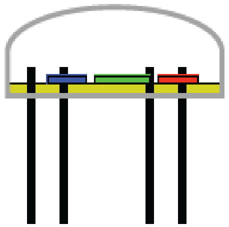
HOW?

Nitride White LEDs

Multichip RGB

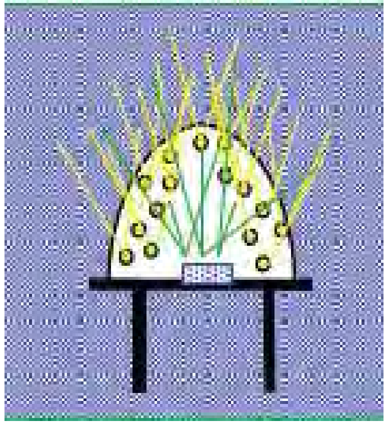


1 red(620nm) InGaInP
1 green(540nm) InGaN
1 blue(455nm) InGaN



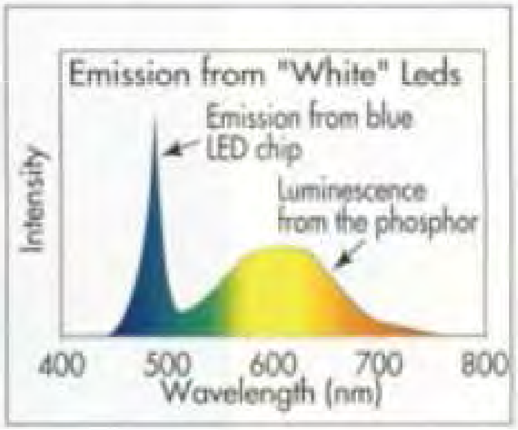
- Very high colour control
- Theoretically best efficiency
- High Cost

Single blue chip + phosphor



blue (455nm) InGaN

Ce^{3+}:YAG phosphor



- Lower colour control
- Lower efficiency (currently)
- Lower Cost

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LED LAMPS

CLEAN & EFFICIENT

ALTERNATIVE to Energy Wasting Bulbs & CFLs

SOLID STATE LIGHTING

What's the hold up?

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COST PER LUMEN

COST PER LUMEN

60 Watt Incandescent
= 900 lumen @ 15 lumen/watt

US $0.30 per kilolumen
Lifetime 1000 hrs

900 lumen CFL Equivalent
= 18 Watt @ 50 lumen/watt

US $2 per kilolumen
Lifetime 10,000hrs

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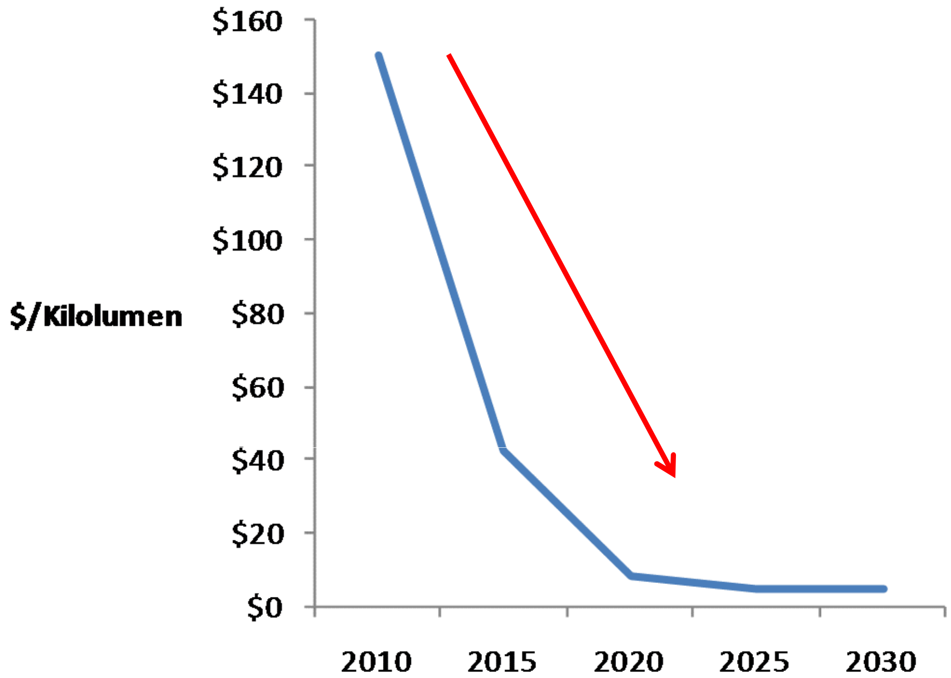
WHITE LED COST PER LUMEN

600 lumen LED 60W Equivalent
= 7 Watt @ 85 lumen/watt
life time 100,000 hours

Unit Price
US$60



US $90 per kilolumen in 2010
US $120 per kilolumen in 2006
US $350 per kilolumen in 2003

US $16 per kilolumen in 2015

Future Aim < US $3 kilolumen

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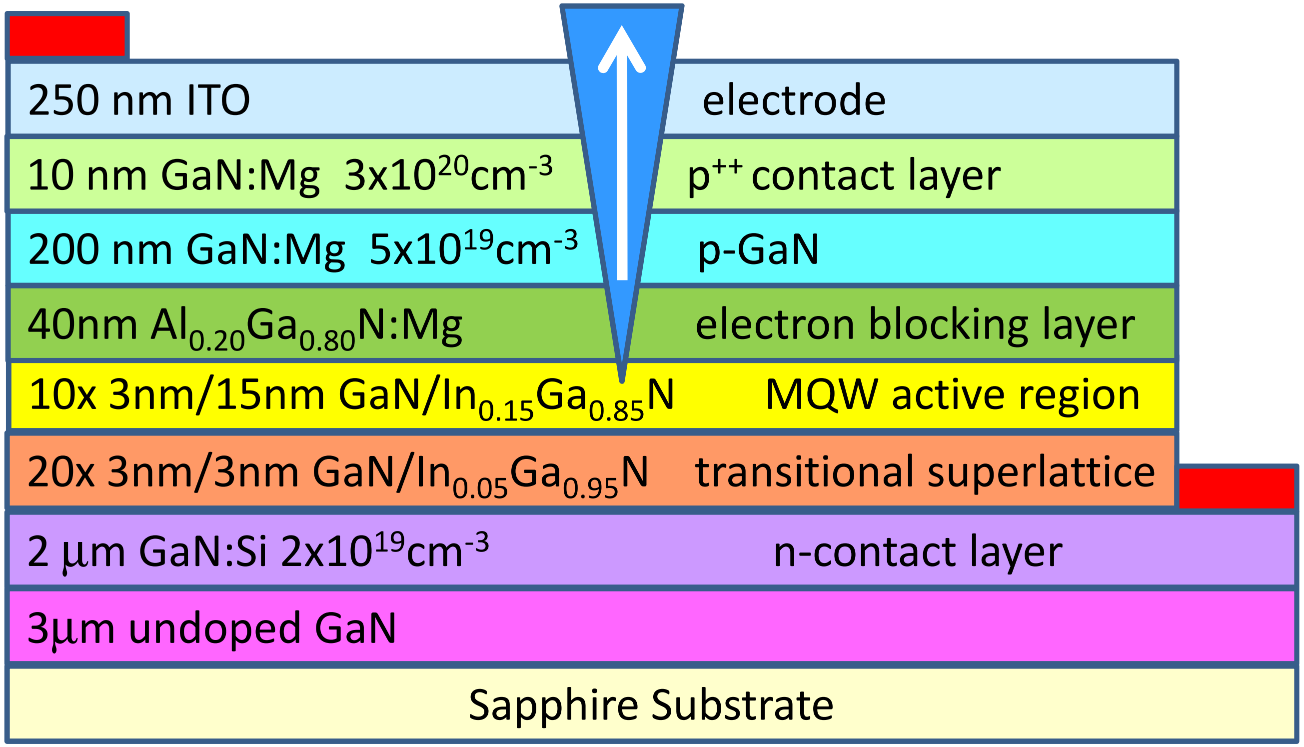
Reducing Cost per Lumen

Lower LED cost

Increase light output

Fabrication of LED devices is EXPENSIVE
Will decrease as Fabrication Improves

MOCVD Reactor



Complex man-made structures with typically 36 layers, including 20 x 3 nm quantum wells for spatial confinement of electrons & holes

Accurate control of In concentration and thickness is crucial

Increase Light output

IMPROVING LED EFFICIENCY

Current White LED Efficacy

90 lumen/watt (commercial)   208 lumen/watt (research lab)

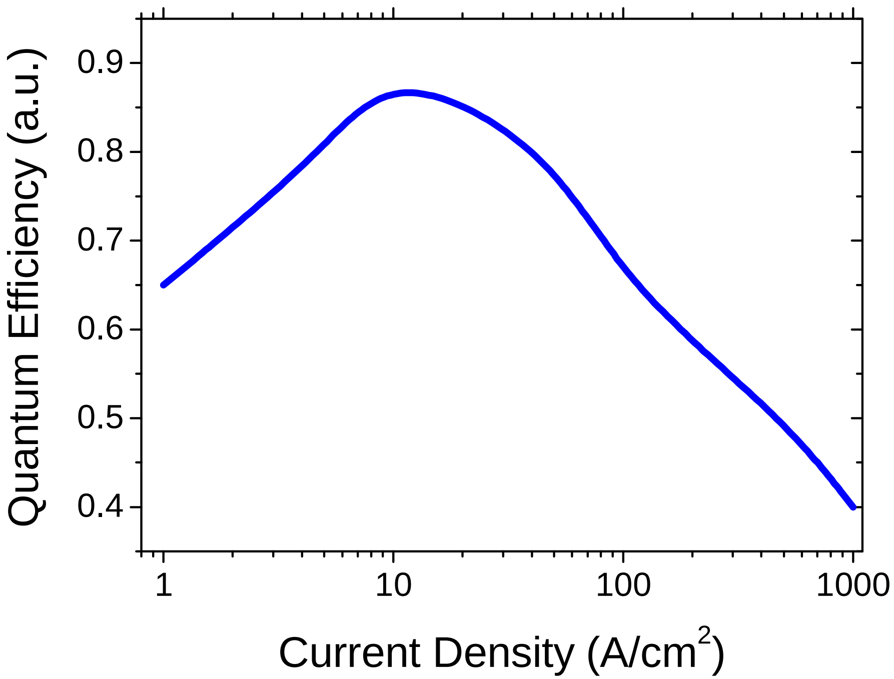
Theoretical Maximum ~325 lumen/watt

Internal Light Emission	**60% - better semiconductors**
Light Extraction	**70% - novel physics**
Phosphor Light Emission	**90% - quantum dots**
LED-Phosphor Efficiency	**80% - better matched materials**
Package Efficiency	80% - contacts & light scattering

LEDs "DARK" SECRET

Efficiency Droop

LEDs lose efficiency at higher drive currents



APRIL 2010
CREE XM LED Released

160 lumen/Watt at 350 mA

110 lumen/Watt at 2 A
(770 lumen for 7 Watts)

Resolving droop is the key challenge in SSL

What Causes Efficiency Droop?

No one knows!

What Causes Efficiency Droop?

No one knows!

Current Explanations

- Inadequate carrier confinement in MQWs
- Electron overflow due polarization fields at MQW interfaces
- Auger recombination processes due to high carrier densities
- Saturation of local bands arising from In rich & poor regions
- Poor hole transport - light generated only in top MQWs
- Efficient longitudinal optical phonon scattering - Heating
- Carrier scattering with threading dislocations

UTS and Nanjing University

Australian Technology Network of Universities
Australia/China NanoNetwork Collaboration

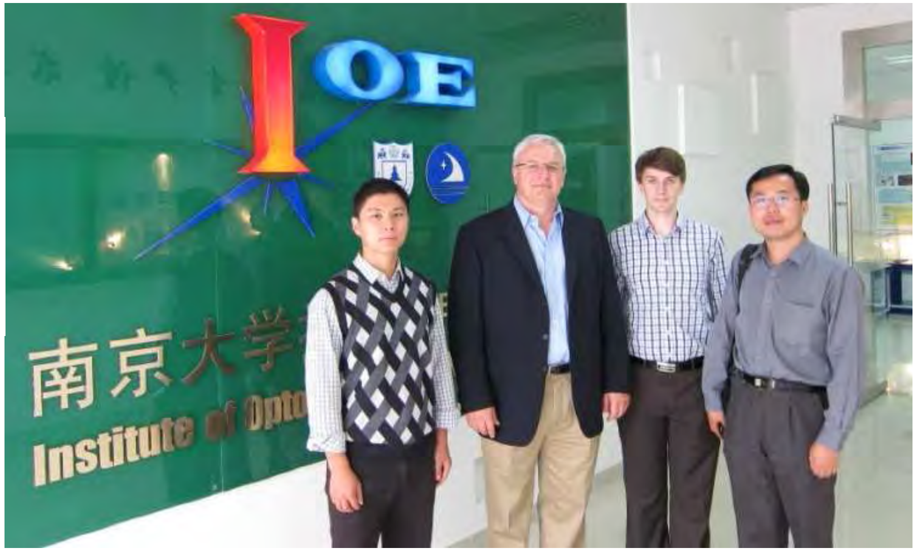
Professor Matthew Phillips UTS
Director, Microstructural Analysis Unit

Professor Chen Peng NU
Director, Institute of Optoelectronics

Joint Doctoral Research Programs

Droop in InGaN/GaN multiple quantum well structures

AUSTRALIAN TECHNOLOGY NETWORK OF UNIVERSITIES



ISTA International Strategic Technology Alliance
國際應用科技開發協作網

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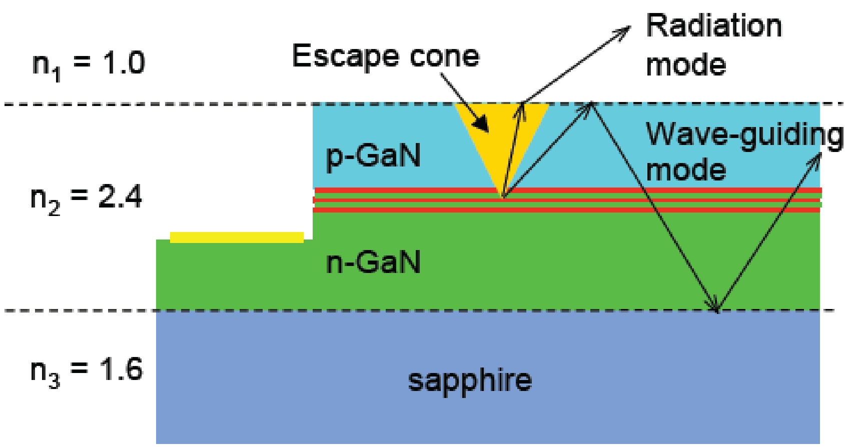
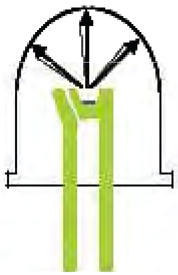
Light Extraction



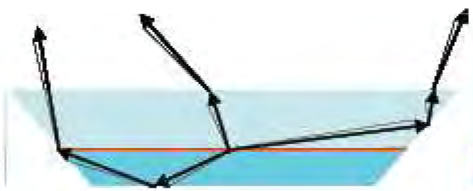
Light trapped by internal reflection

< 5% escapes

Best current efficiencies ~ 60 %

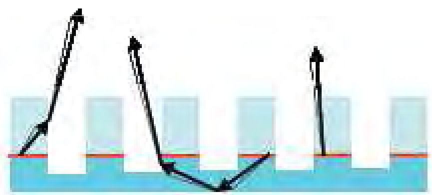


Epoxy Encapsulation & Nanoparticles



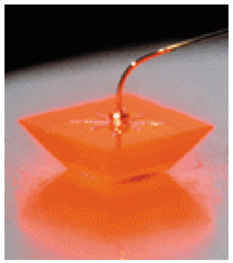
Chip Shaping

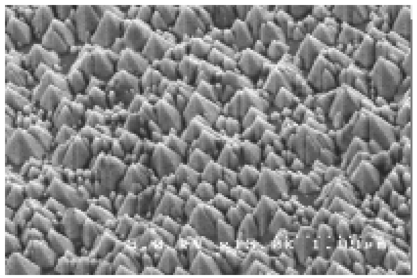
Surface Texturing & Nanowires

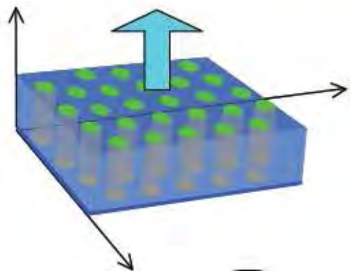


Plasmonics & Photonic Crystals

Light forward Scattering with reduced backscattering







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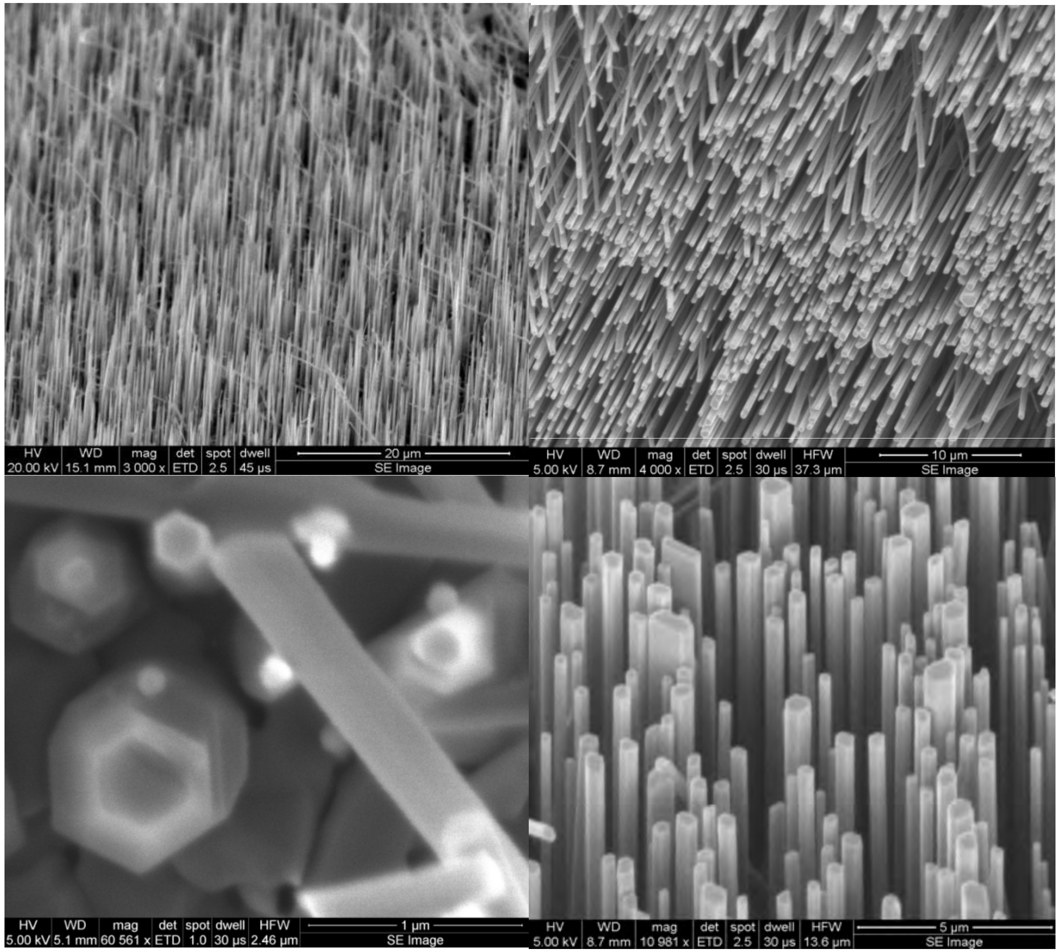
UTS Zinc Oxide Nanowires – Light Extraction



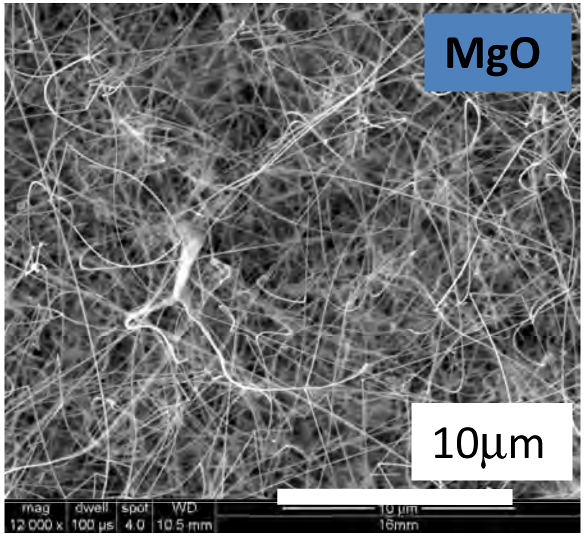
Transparent Conductive Oxide

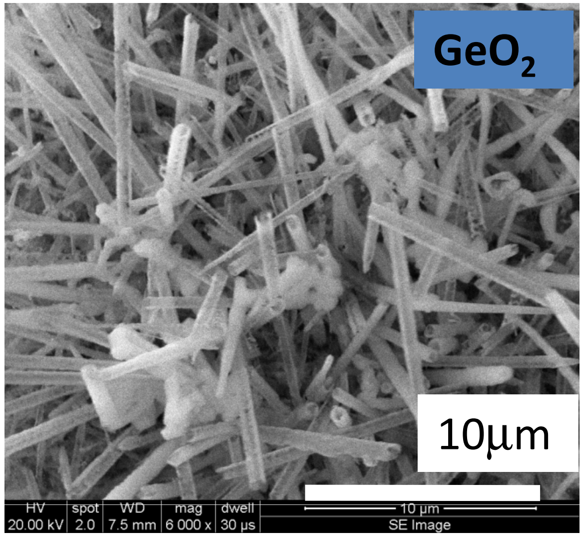
Act as Optical Waveguides

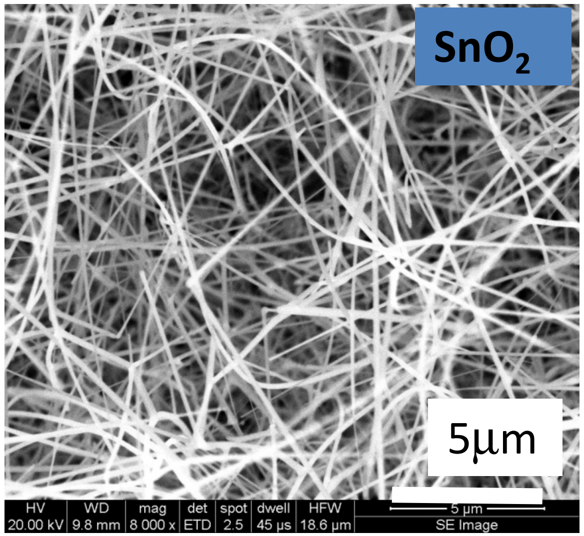
Inexpensive

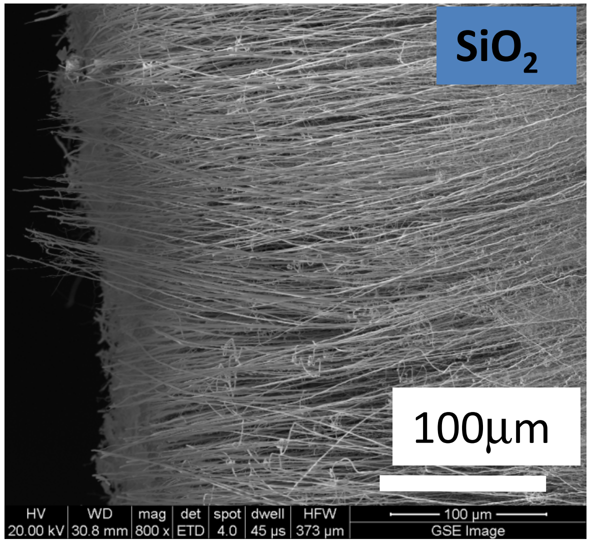
Similar Crystal Structure to GaN

Binary Oxide Nanowires – Light Extraction



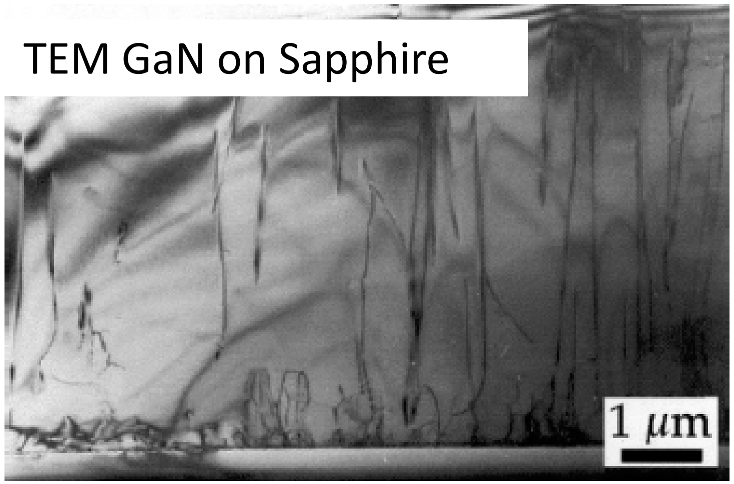




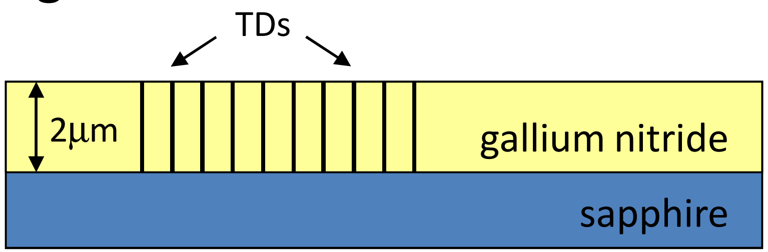


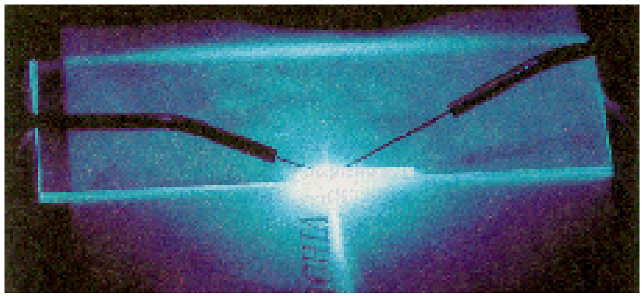
Threading Dislocations in Gallium Nitride

- High Quality GaN 2μm epilayers grown by MOCVD at ~ 900^{o}C on Al_2O_3
- Significant lattice mismatch and thermal expansion coefficients between GaN and substrate
- Very high density (10^8 - 10^{10} cm^{-2}) of TDs to relieve interface strain
- High performance LEDs despite high TD

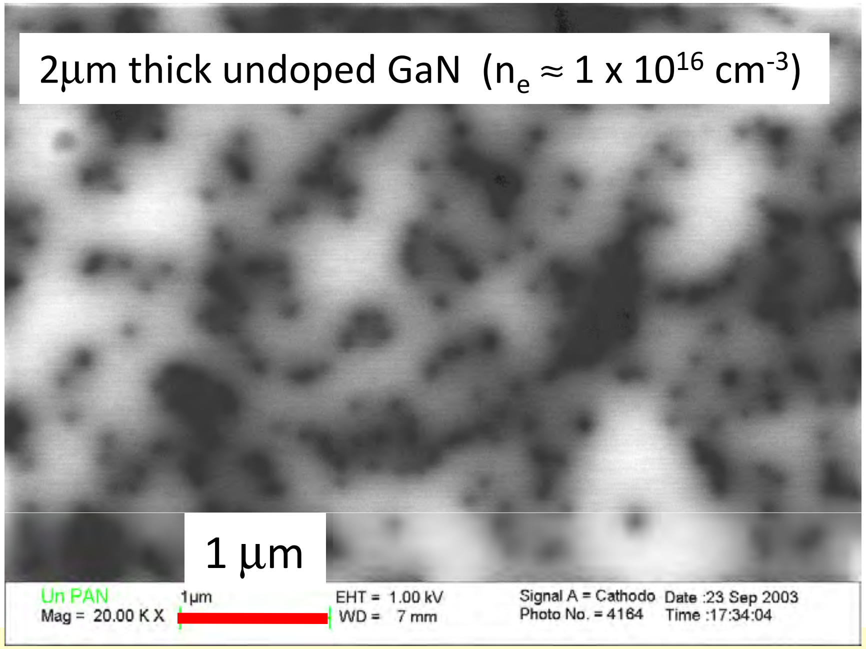


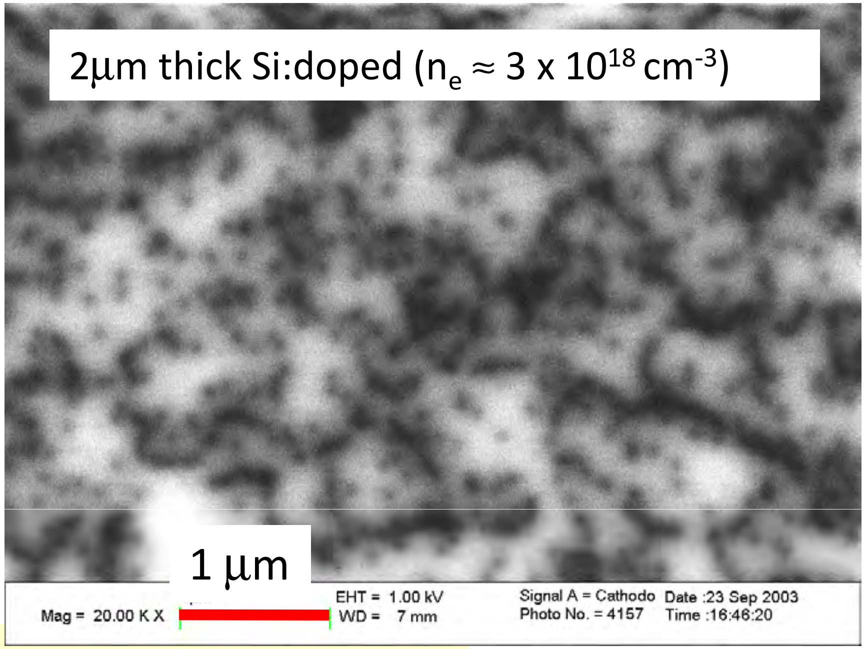
273-274 (1999) 24-32



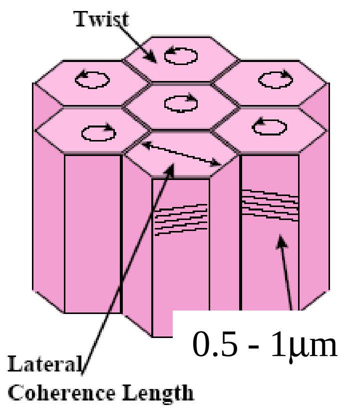


UTS Cathodoluminescence top down view of TDs in GaN





- **Threading dislocations** act as highly localized non-radiative recombination centres which **reduce light emission**
- Higher dislocation density in Si doped GaN consistent with higher strain
- Dislocations decorate GaN domain grain boundaries leaving defect free GaN patches



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SOLID STATE LIGHTING

APPLICATIONS

LED ENERGY EFFICIENCY but Wait There's More.....

Additional LED Advantages

- Durable – LED lifetime > 100,000 hrs ~ > 20 years
- Robust – shock resistant

(Light bulb ~ 1,000 hrs)

- Compact
- No radiant heat – cold emitter
- Light weight
- "instant" switch-on time
- Non-toxic – mercury free
- Excellent control over colour or whiteness

City of Sydney LED Lighting Trial

Testing 250 LED Street Lights in Circular Quay, Martin Place, Alexandria and Darlinghurst

City of Sydney

20,000 street lights – electricity cost \$3.5M uses 13 Million kWhr, produces 1300 tonnes CO_2 & maintenance cost \$5M

LED Street Lighting 50% reduction

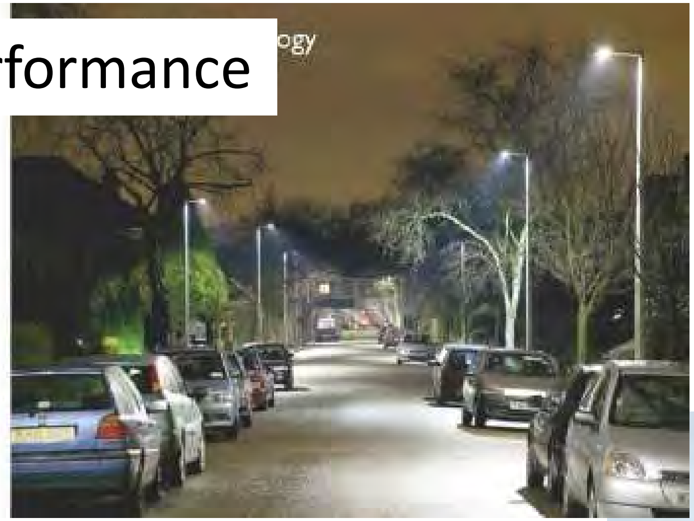
Australia Wide

2 million street lights, costs \$210 million, uses 1,035 Gigawatt hours (GWh) of electricity & produces 1.15 million tonnes of CO_2

Globally LED street lighting market estimated to grow from \$108M in 2008 to \$1 billion in 2011

LED Street Lighting

Better performance



Solar Powered

20 year
Lifetime

Future of
Solid State Lighting

Affordable, Safe and Efficient

Lighting in Developing Countries

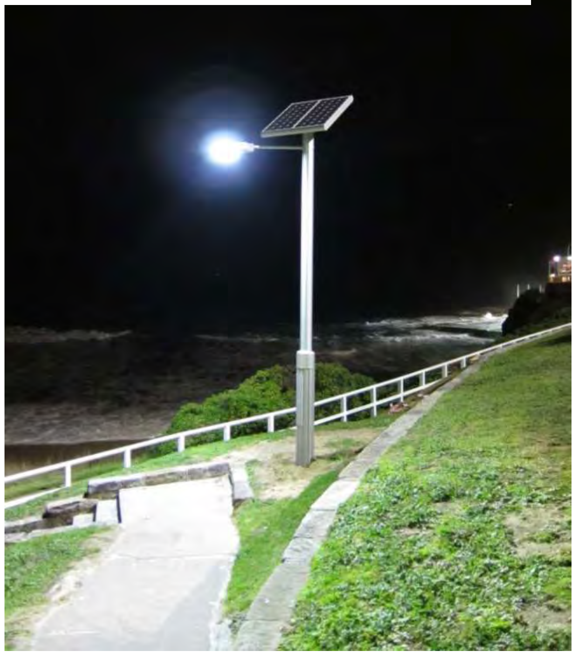
Over 2 Billion People do not have access to electric lighting

Light up the world foundation (www.lutw.org)

LED - Solar- Battery technologies perfected matched for domestic lighting off the grid

Lighting off the Electricity Grid

Sustainable Solar Powered LED Lighting



South End Bondi Beach, Sydney, Australia

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Lighting off the Electricity Grid

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Deep Ultra-Violet LEDs

UV LED application in:

- resin curing
- adhesion
- drying
- medical treatment
- chemical analysis
- photo catalysis
- water purification and sterilization.

Research Collaborators

Australian Government
Australian Research Council

BLUGLASS

FEI COMPANY™

NANJING UNIVERSITY 1902

TU berlin

UNIVERSITÉ DE SHERBROOKE

IFPAN

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

UNIVERSITY OF TECHNOLOGY SYDNEY

UTS Research Team

Thank you for your attention

<u>Collaboration</u>

Contact:

Matthew.Phillips@uts.edu.au

www.science.uts.edu.au\mau

Additional Slides

ORGANIC LIGHT EMITTING DIODES

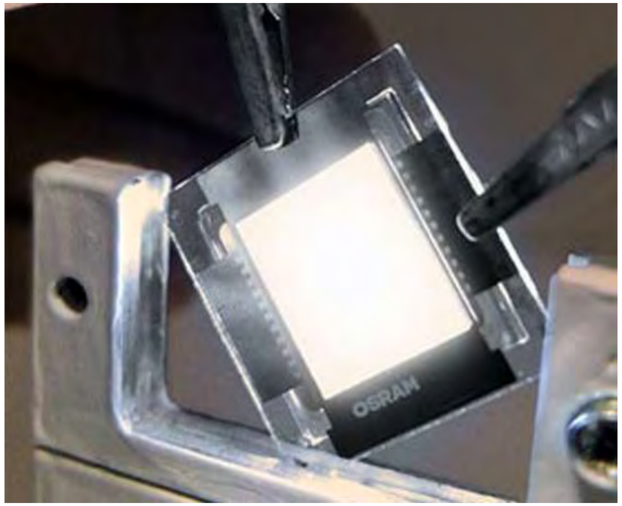
OLEDS

60 lm/watt & 10,000 hrs

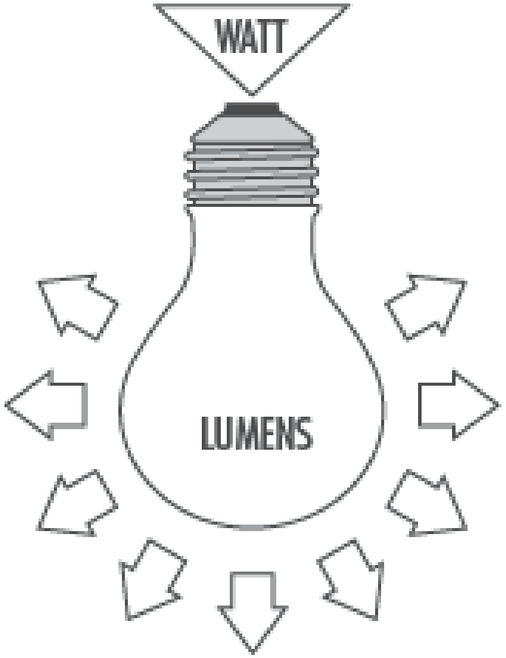
Flexible displays

Large area lighting

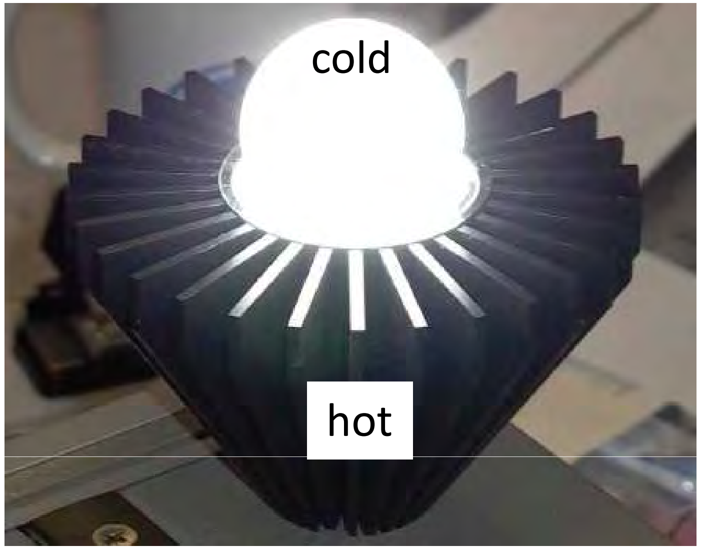
Cost $25,000 per kilo-lumen

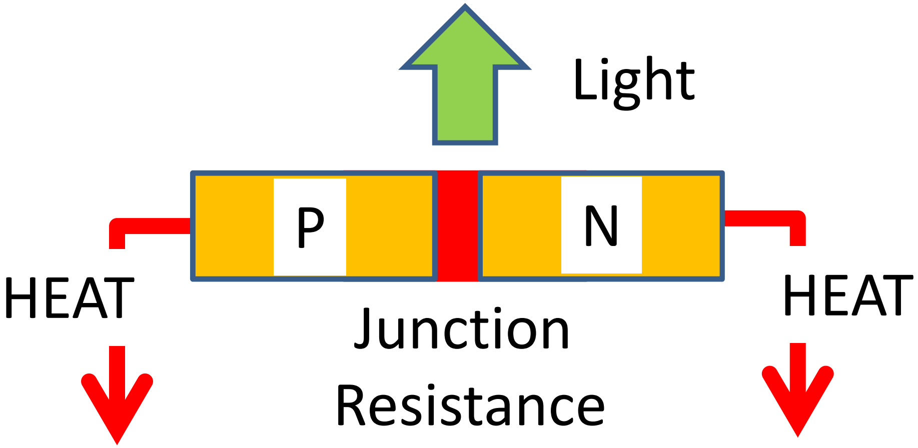


LED Heat Management



Heat Dissipation in Air





SOLID STATE LIGHTS

WHY THE BLING?

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Other Light Source Metrics

Ability of a light source to accurately reproduce colour

Colour Rendering Index (CRI)

Light Source	CRI
Sunlight	100
Incandescent Bulb	100
Fluorescent Light	60 - 85
LEDs	60 - 90
Sodium Vapour Lamp	40

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Incandescent Bulb

CRI 100

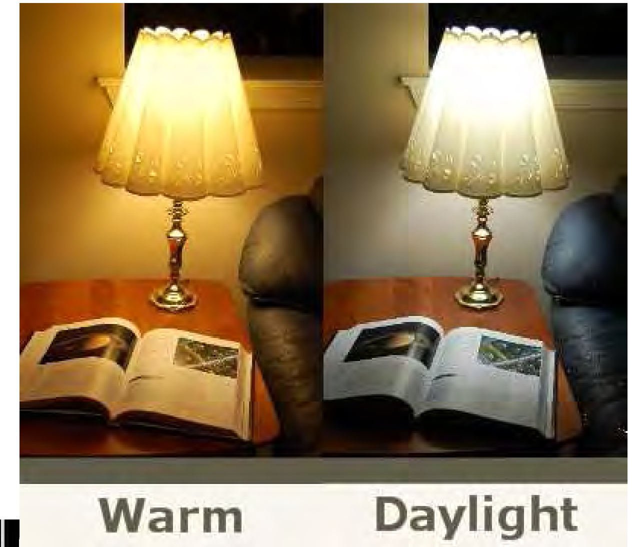
Sodium Vapour Street Light

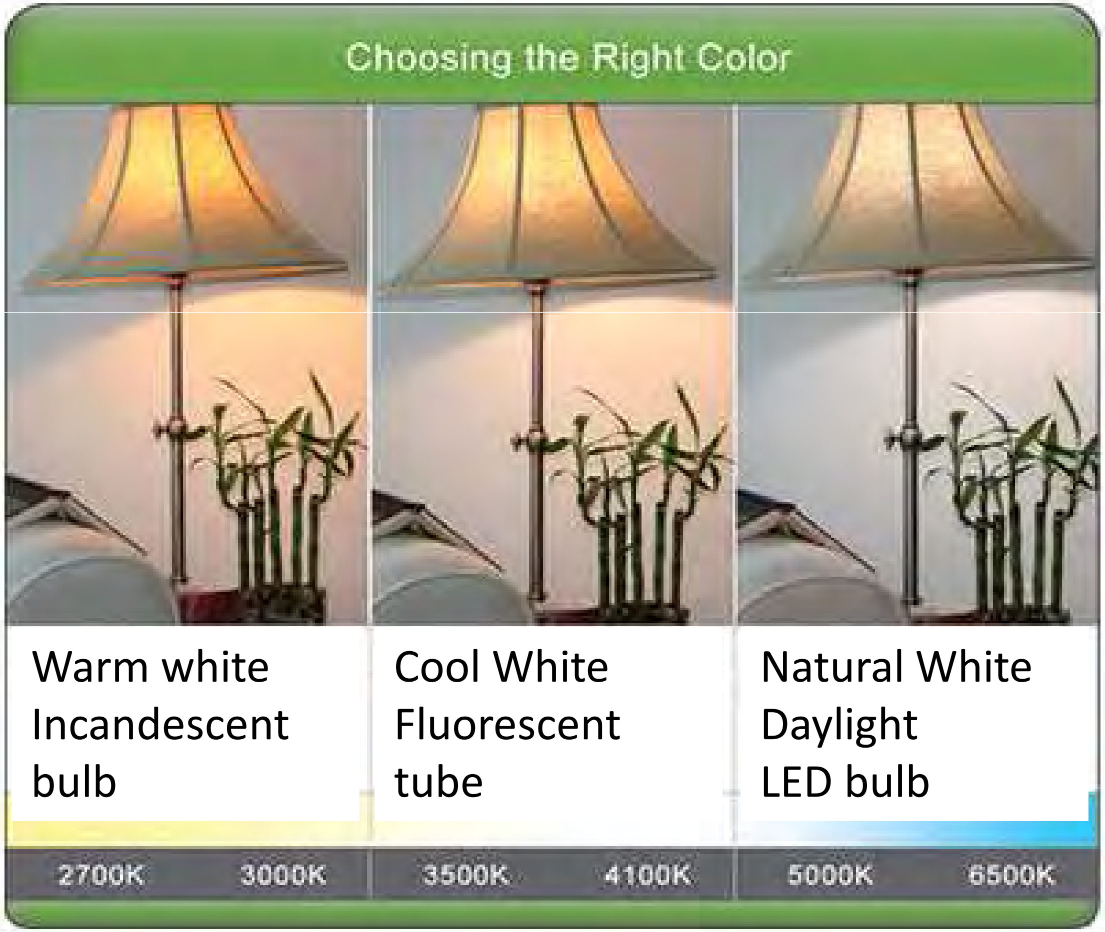
CRI 40

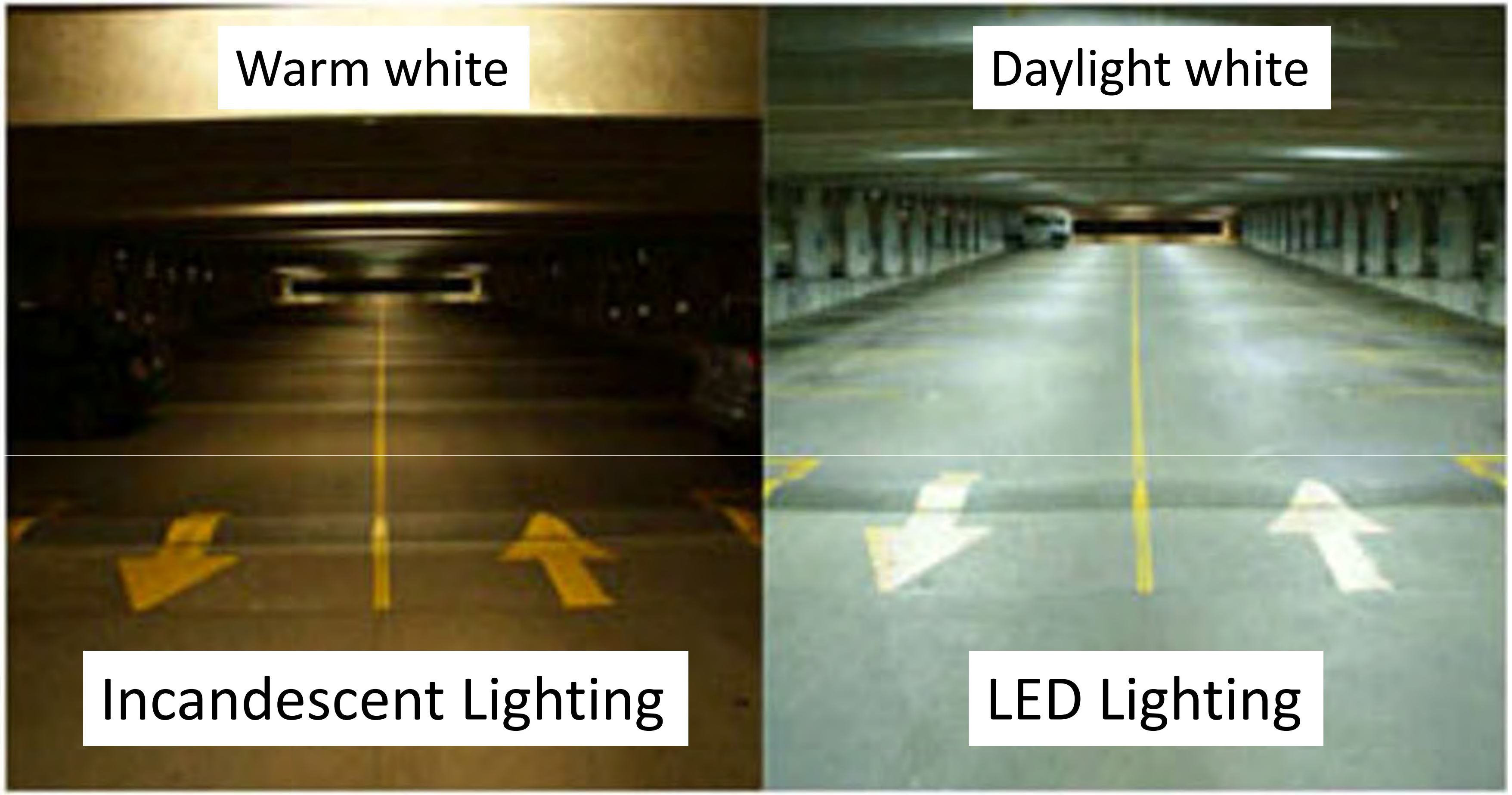
Other Light Source Metrics

Colour Temperature (K)

Measure of the colour of white light source






Warm white
Daylight white
Incandescent Lighting
LED Lighting

Serious Issues with Compact Fluorescent Lighting

CFL “Green” Technology????

Compact Fluorescence Lighting - Green?

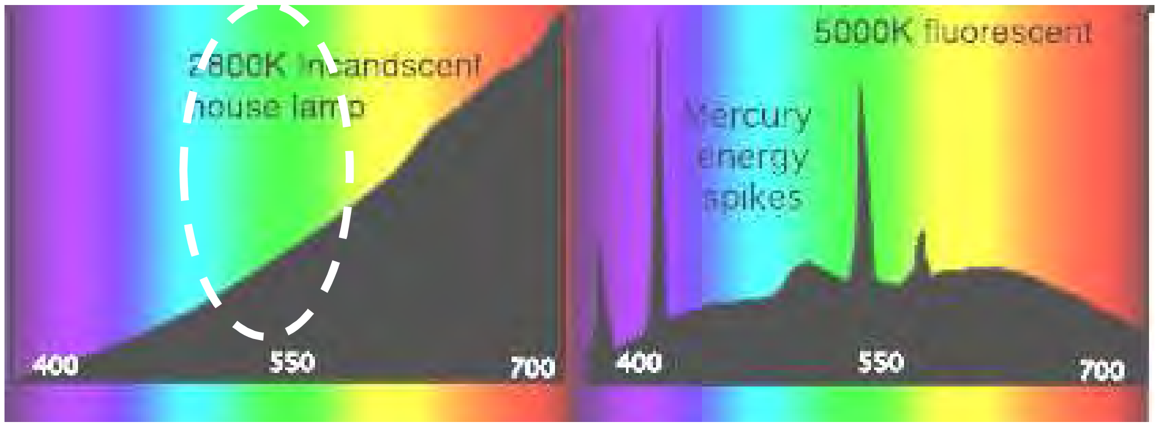
Contains 4mg of highly toxic material Mercury
- Enough to contaminate 100,000 litres of water

Fragile and break easily

Emits significant dose of UV light
– skin cancer & eye damage.

Disposal of spent CFLs produces additional environmental issues
- USA already dumps 500,000 fluoro tubes per year

Lifetime ~ 10,000 hours & Efficacy 50 lumen/watt



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U.S. Environmental Protection Agency June 2010
Cleaning Up a Broken Compact Fluorescent Light Bulb

Before Cleanup: Air Out the Room

* **Open a window and leave the room for 15 minutes or more**

* Shut off the air conditioning system

Cleanup Steps for Hard Surfaces

*Carefully scoop up glass pieces and powder and **place them in a glass jar with metal lid**

*Wipe the area clean with damp paper towels or disposable wet wipes. Place towels in the glass jar or plastic bag.

*Do not use a vacuum or broom to clean up the broken bulb on hard surfaces.

•**Cleanup Steps for Clothing, Bedding and Other Soft Materials**

* If clothing or bedding materials come in direct contact with broken glass or CFL powder from inside the bulb that may stick to the fabric, **the clothing or bedding should be thrown away.** Do not wash such clothing or bedding because mercury fragments in the clothing may **contaminate the machine and/or pollute sewage.**

Disposal of Cleanup Materials

* **Check with your local government** about disposal requirements as some do not allow such trash disposal. Instead take broken and unbroken CFL bulbs to a local recycling center.

Future Cleaning of Carpeting or Rug: Air Out the Room During and After Vacuuming

*The **next several times you vacuum**, shut off air conditioning system and open a window.

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LED Applications

LED Traffic Lights

80% of traffic lights are now LED- based

LEDs are 10 x more efficient than bulbs

Cost saving $600 / year per intersection

Lifetime > 12 years no maintenance costs

Payback time 1 year

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SOS Print + Media, Alexandria

Replaced 484 Fluorescent Tubes with LED Tube™ Lights

Savings:

$25,184 each year on electricity

149 tonnes of CO_2 emissions per year

Plus savings on maintenance costs

Return on investment in less than 2 years!

www.spectrumlighting.com.au

LED Brake Lights

High brightness – no colour filters

Highly Directional & long lifetime

Robust – impact resistant

No catastrophic failure – dimmer or one out in LED array

Instant on (100ns) old Globes ~250 ms

- 8 metres less stopping distance at 120 km/hr

Multiplier Effects – CFL (50 lm/Watt)

Average house in Australia
has 20 light fittings

X

7 million homes in Australia

140 million light bulbs

Total Savings in Australia to 2020

30 terraWatt.hr & $4,500 million dollars

$28 million tonnes of CO_2
= 500,000 cars or one coal power station

New Building Design

500,000 Cree LEDS

Water Cube National Aquatic Centre

Peace Bridge USA

Beijing Olympic Games

260,000 Cree LEDS

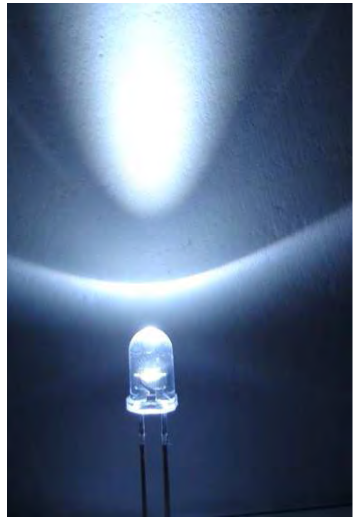
Bird’s Nest National Stadium

Motivation

90%
energy lost
as HEAT

15 lm/watt

Replacement with
energy efficient LEDs



150 lm/watt

10% reduction in global electricity usage = 2 x 10^{12} kW.hr/yr

Energy, Environmental & Economic Savings

$$$

>$120 billion

eliminate
~ 250 megatons
of green house

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Evolution of Lighting

Fire – Torches
Prehistoric times

Oil Lamps
7000 BC to present

Gas Lamps
From 1700

Spermaceti Candles
From 1700

Arc Lamp
From 1800

Kerosene Lamp
From 1800

Carbon Filament
Incandescent Bulbs
1880

Tungsten Filament
Incandescent Bulbs
1910 > 1000hrs

Fluorescent tube
From 1940s

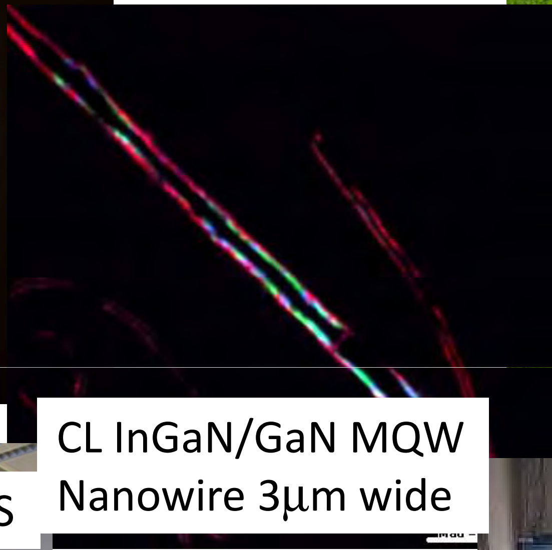
Tungsten-Halogen
1970s whiter light

Compact Fluorescent Tube
From 1980s

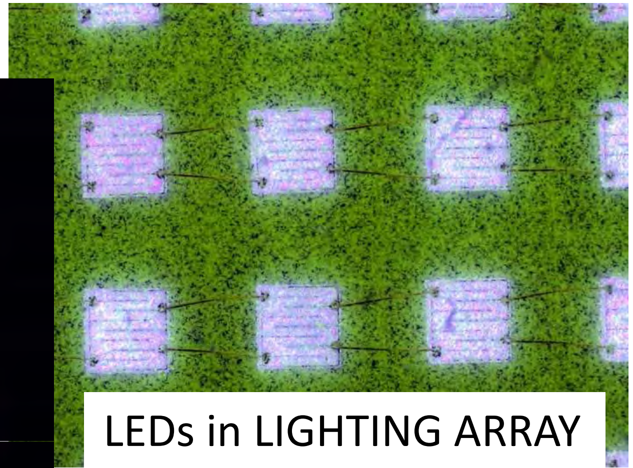
Solid State LED Light
From 2010

Development of Ultra-High-Brightness InGaN/GaN-based Quantum Well LEDs

LED LIGHTING ARRAY

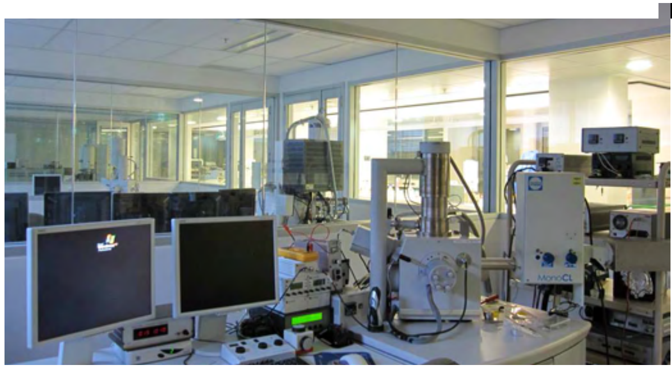


CL InGaN/GaN MQW Nanowire 3μm wide



LEDs in LIGHTING ARRAY

Advanced Characterisation UTS



Microstructural Analysis Unit UTS

Fabrication NU

AIXTRON MOCVD NANJING UNI

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