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Senior Editor
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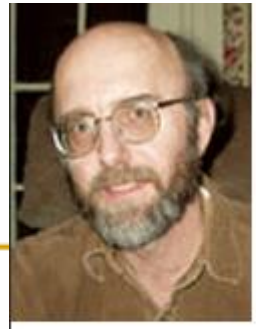

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Fundamentals of Photonics:

Deep UV LEDs: Technology and Applications

Jeff Hecht

Contributing Editor, *Laser Focus World*

Author: *Understanding Lasers*

Overview

- The Ultraviolet spectrum
- UV Sources
  - Lamps
  - Lasers
  - LEDs
- UV applications
  - Germicidal and sterilization
  - Spectroscopic and instrumentation
  - Fluorescence sources
- Emerging developments

Ultraviolet Spectrum

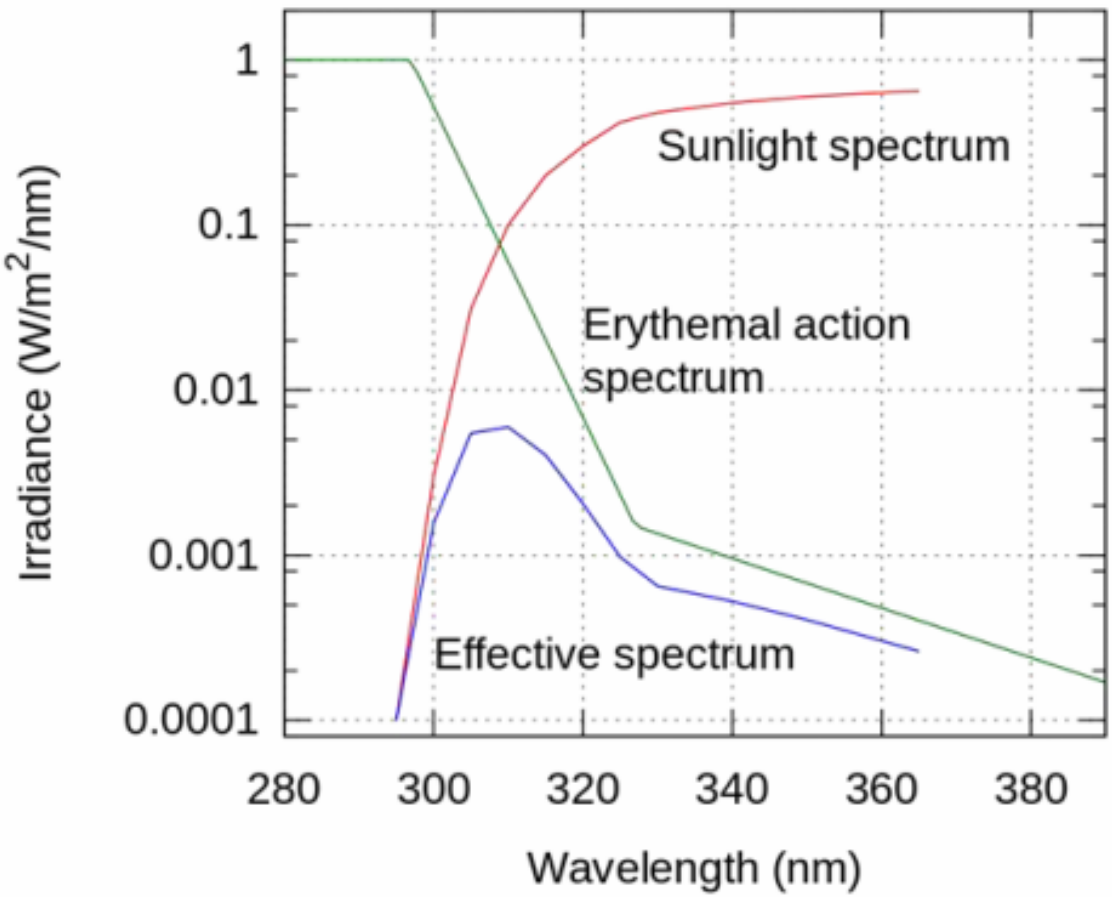
Name	Abbrev	Wavelength	Photon energy	Notes
Ultraviolet	UV	400 – 100 nm	3.10 – 12.4 eV	
Ultraviolet A	UVA	400 – 315 nm	3.10 – 3.94 eV	black light
Ultraviolet B	UVB	315 – 280 nm	3.94 – 4.43 eV	ozone absorbs
Ultraviolet C (Deep UV)	UVC	280 – 100 nm	4.43 – 12.4 eV	germicidal, oxygen absorbs
Near Ultraviolet	NUV	400 – 300 nm	3.10 – 4.13 eV	visible to birds, insects and fish
Middle Ultraviolet	MUV	300 – 200 nm	4.13 – 6.20 eV	Some germicidal
Far Ultraviolet	FUV	200 – 100 nm	6.20 – 10.16 eV	Vacuum UV
Extreme UV	EUV	100 -- 10 nm	12.4 – 124 eV	Soft X rays

Adapted from Wikipedia

UV health/medical effects

- Arise from photon energy
- Health benefits
  - Production of vitamin D
    - UVB moderate exposure
  - Treatment of psoriasis other skin conditions
- Tissue damage from overexposure
  - UVB – suntan to sunburn
  - UVB – some DNA damage, carcinogenic, mutagenic
  - UVC – More severe effects, more DNA damage
    - Germicidal effect
  - UVA, B, C damage skin (collagen), eye

Sunlight effect on skin



Wikipedia art

Deep UV, oxygen, and ozone

- Stratospheric ozone absorbs UVB, UVC
- Oxygen (O_2) absorption strongest <200 nm
- Ozone production
  - UVC <240 nm splits O_2 molecules generating energetic O atoms which form O_3
  - 240-320 nm produces stable atomic oxygen
  - Mercury vapor line at 184 nm produces O_3
  - High voltage discharges produce ozone
  - Ozone can aid cleaning

Major Deep UV sources

- Gas discharge lamps
  - Low-pressure mercury lamps
    - Germicidal 254 nm
    - Germicidal 184 and 254 nm
    - Variant on fluorescent bulbs
  - Pulsed Xenon lamps 190-330 nm
  - Xenon excimer lamps 172 nm
  - Other excimer lamps
  - Deuterium 180-330 nm
- Gas lasers
  - Excimer lasers
    - ArF 193 nm, KrF 248 nm
  - Nitrogen lasers
- Diode lasers >360 nm
- LEDs down to 240 nm

Deep UV Source Costs

- $100 Xe-Hg or Hg
- $300-$400 Deuterium lamps
- LED 1-W 280 nm
  - $166-$200
- http://www.laserfocusworld.com/articles/2014/04/uv-disinfection-leds-versus-lamps.html

Wikipedia

Deep UV lamps

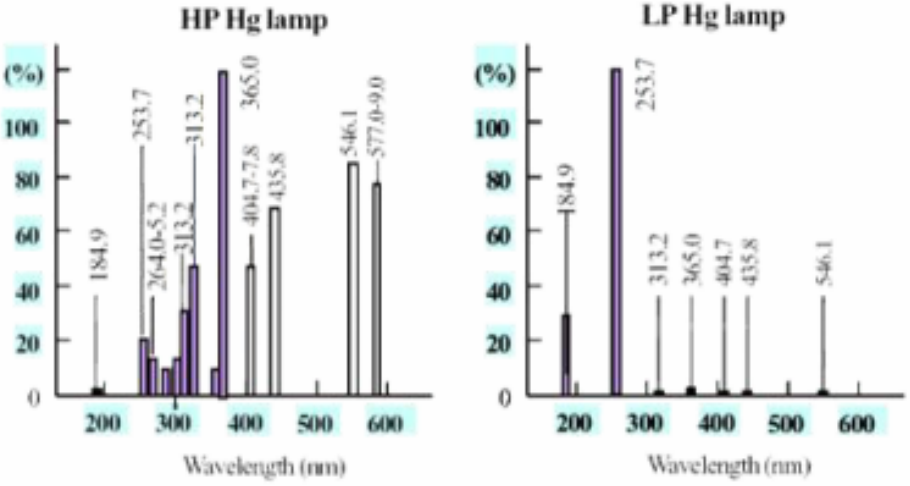
Type	Wavelength (nm)	Power input	Effic.	Price	Life (hrs.)
Xenon excimer	172	8-40 W	~40%	Expensive	2500
Mercury	254	5-160 W	~40%	~ $100	to 10,000
Mercury	184, 254	5-160 W	~40%	~ $100	to 10,000
Deuterium	190-330	30 W		few hundred $	~ 2000
Xenon flash	300-400	pulsed			
Mercury-Xenon	184-400	50-500 W			1000-3000

Mercury lamps

- Electric discharge in mercury vapor
- Like fluorescent bulbs
  - Without phosphors
- Tube filters light
- Low pressure emits only 184 and 254 nm
- 184 nm line
  - Produces ozone
  - Synthetic quartz tube
  - transmits 184 nm
- Prices ~ $80-$300
- Life ~ 10k-17k hours
  - Power drops 20%

Wikipedia

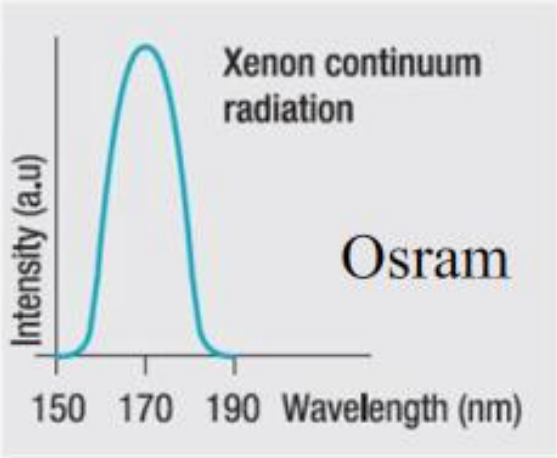
Wavelength (nm)	Color
184.45	ultraviolet (UVC)
253.7	ultraviolet (UVC)
365.4	ultraviolet (UVA)
404.7	violet
435.8	blue
546.1	green
578.2	yellow-orange

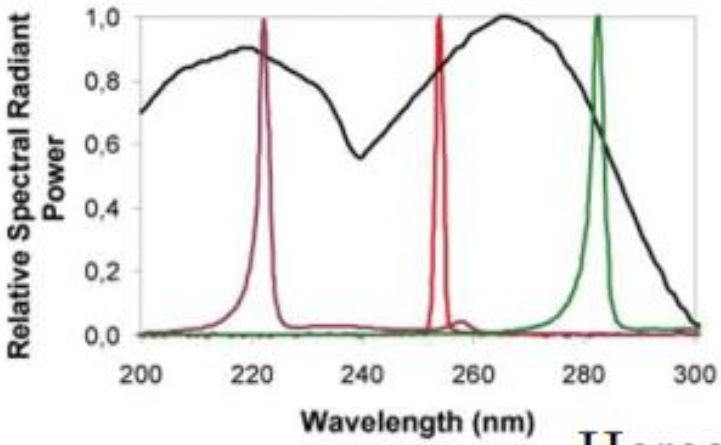


Crystec

Excimer lamps

- Xe_2* 172 nm
- XeBr* 282 nm
- KrCl* 222 nm
- Many other lines
- Not lasers, but similarly pulsed
- Not as efficient as mercury
- But no mercury





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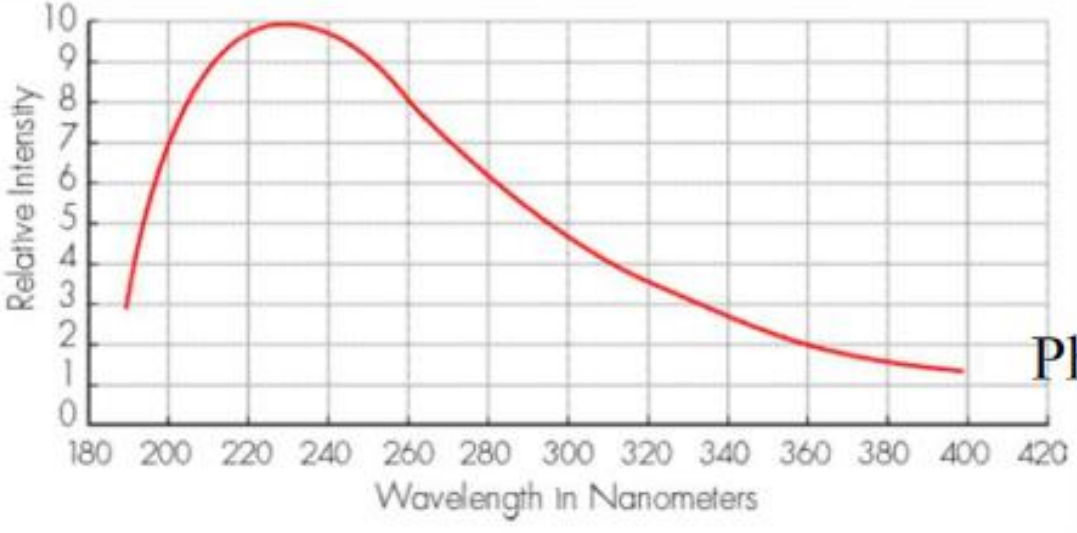
Deuterium lamps

- Broadband across UVC and UVB 190-330 nm
- 300-500 V to ignite discharge
- Operates at 100-200 V

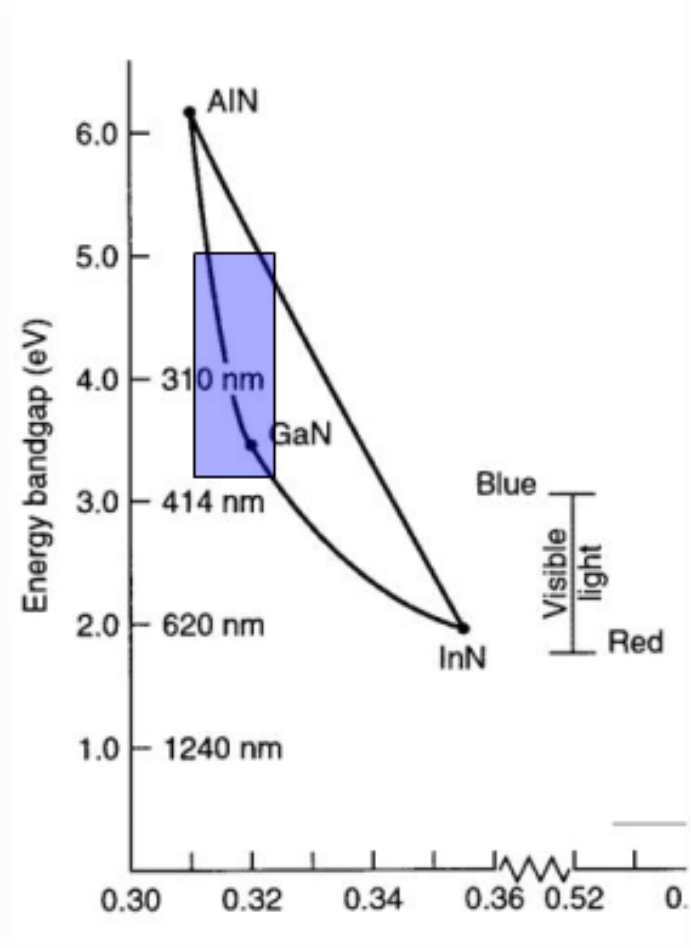
Wikipedia art



Photron data

UV LEDs and diode lasers

- III-V LEDs
  - AlGaN on GaN, SiC, AlN, sapphire
  - Modified blue diodes
  - GaN ~ 370 nm
  - GaAlN to 240 nm
  - Room-T operation
  - DC 6-30 V
- III-V diode lasers
  - Shortest 336 nm (Yoshida et al., APL 93, 241106)
  - Optical pumping shorter

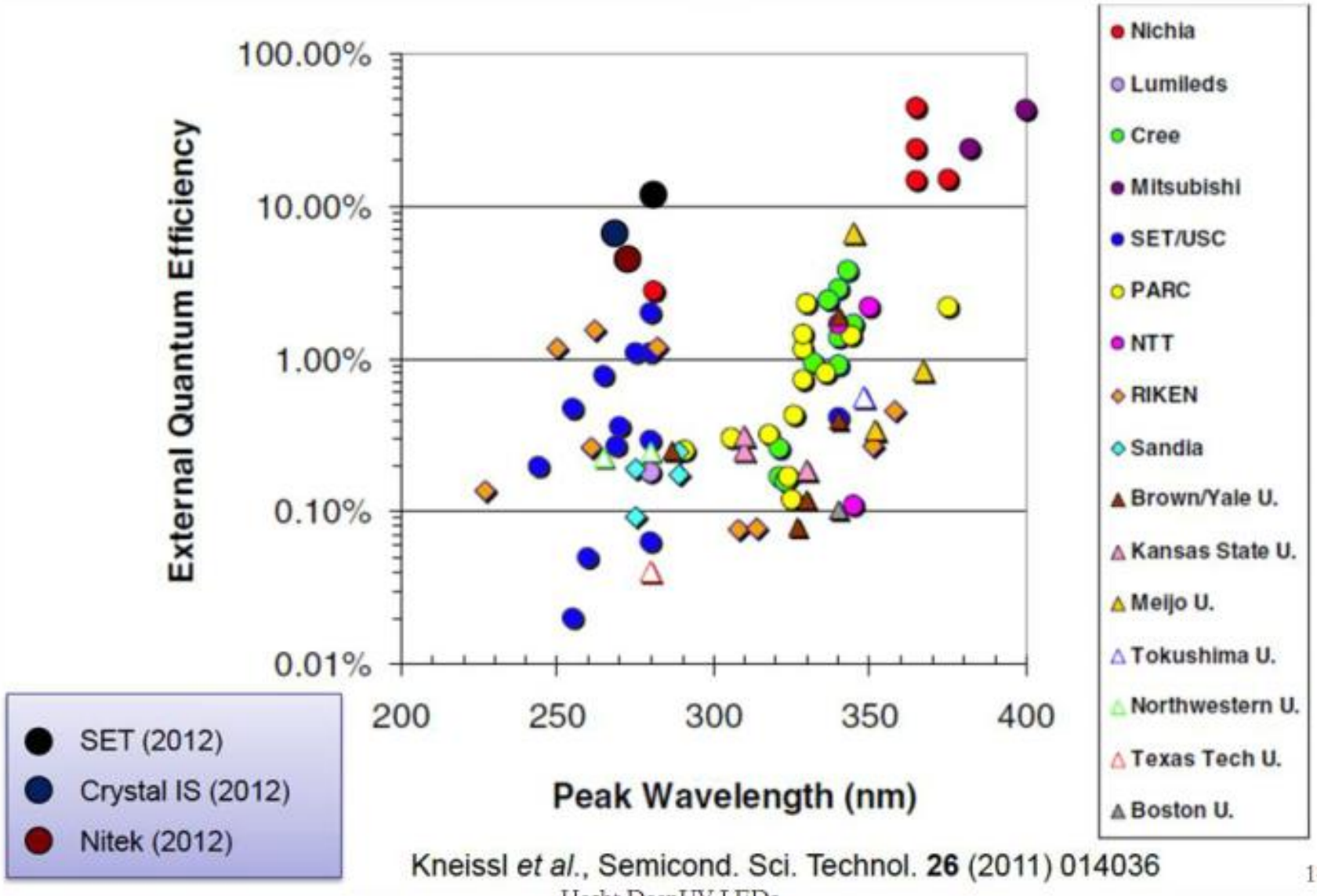


LED UV Wavelength ranges

- Commercial (GaAlN)
  - ~240-380 nm
  - More power at longer wavelengths
  - To 20% efficiency
- UV-C (240-280 nm)
  - ~1-W @280 nm
    - lowest $166-$200
  - Prices ~2X @245 nm
- Research
  - AlN – 210 nm (6 eV)
    - Close to end of range
  - BN – 215 nm
  - Diamond – 235 nm
- DARPA demoed
  - 270-280 nm
    - 7% wall-plug efficiency
    - 150 mW pulsed
    - 70 mW CW
    - >5000 hour lifetime

UV LED efficiency

from Michael Wraback,
US Army Research Laboratory



Kneissl *et al.*, Semicond. Sci. Technol. **26** (2011) 014036

Deep UV LED development

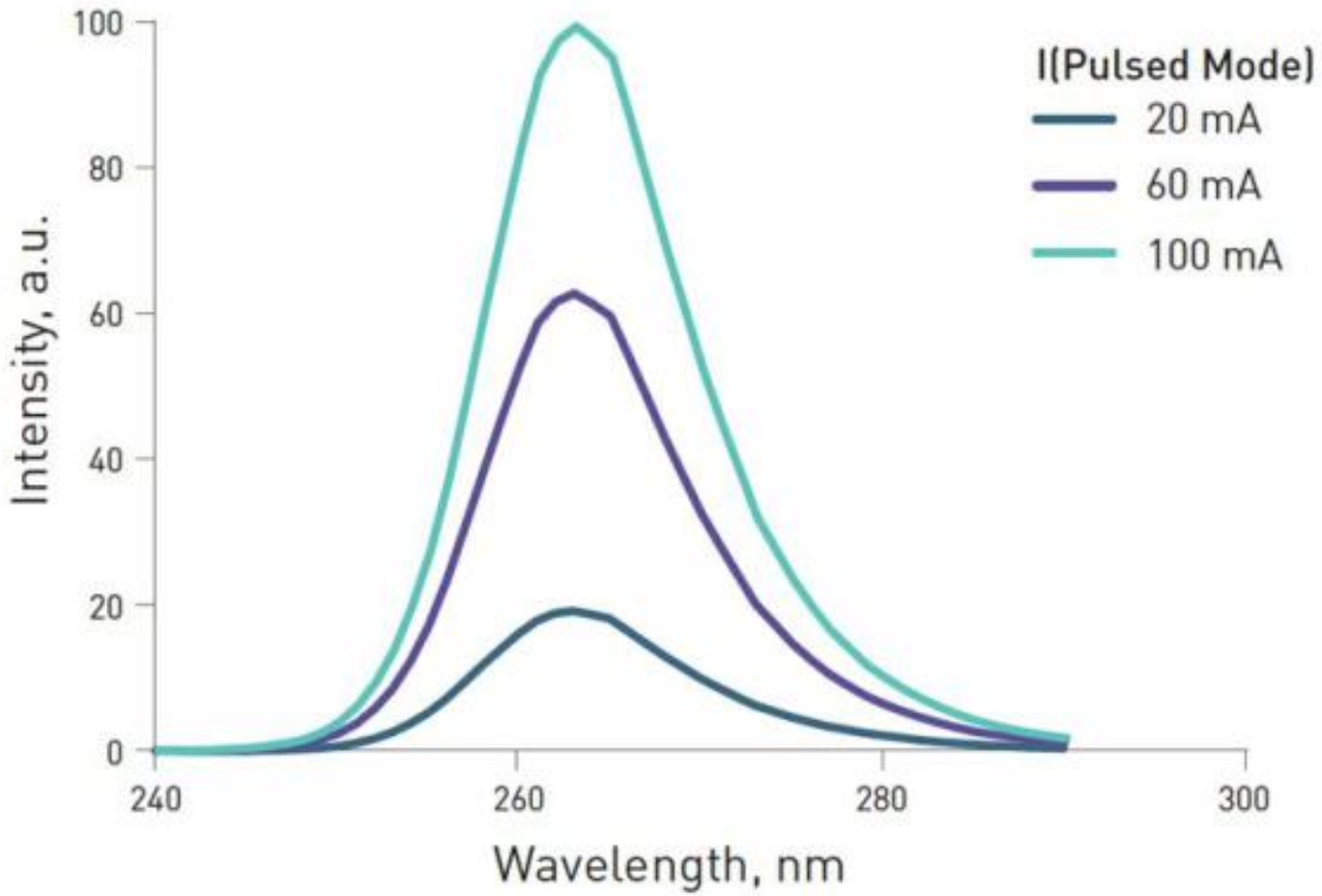
- 275 nm UV LEDs on sapphire
- 7 mW @ 100 mA
- Phys. Status Solidi C 11, No. 3–4, 798 (2014)
- Asif et al, U of South Carolina

- 270 nm UV LEDs
- Over 60 mW CW
- 67 mW @ 300 mA
  - External QE 4.9%
  - Wall-plug eff 2.5%
  - AlN substrate
- *Appl. Phys. Express 6 (Mar 2013) 032101*
- *Crystal IS/Army Research Lab*
- Up from 20 mW CW @260 nm CLEO 12

Packaging variations

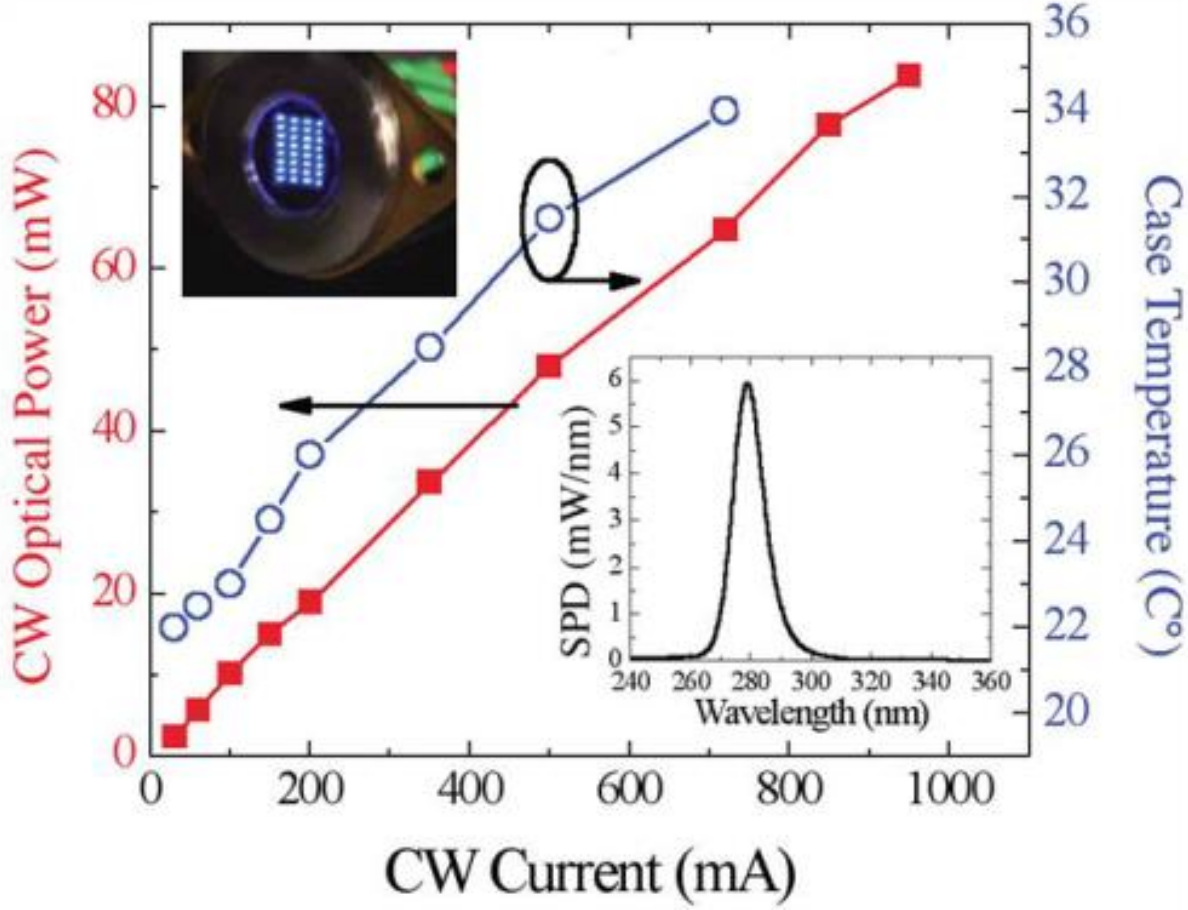
- Surface mount devices
- Ball lens in TO-39 can
- Flat-top cans – quartz
- Arrays in cans
- High-power heat-sinked cans with lens
- Bare wafers
- Customized
- 5 or 10 nm bins
- Various power levels

DUV LED spectra change with current



Multi-chip UV-LED Lamp

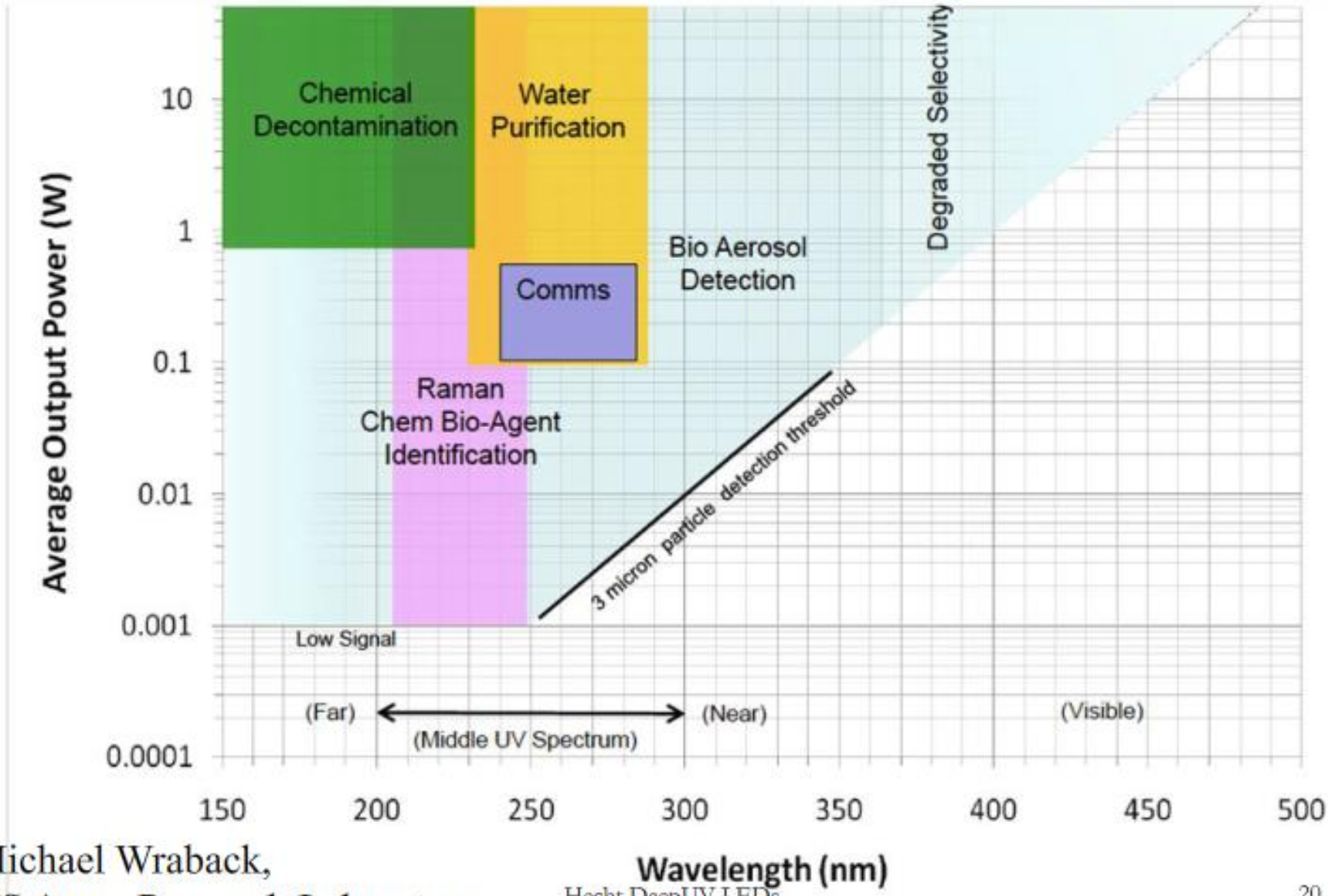
- Passive or active cooling
- >50 mW CW @280 nm
- Single device
  - 0.5-1.5 mW
  - 20 mA
- ~2% ext QE



Deep UV Applications

- UV Treatment
- Germicidal UV
  - Water sterilization
  - Air purification
  - Hospital
  - Food surface sterilization
- UV cleaning
- UV light therapy
- Food preservation
- Instrumentation
- Sensing
  - Fluorescence
  - Water quality monitors
  - Environmental quality
  - Petrochemical
  - Biomedical
  - Pathogen sensing
  - Forensics
  - Protein & DNA analysis
- Short-range communication
- UV IDs and bar codes

DARPA CMUVT program progress



Michael Wraback,
US Army Research Laboratory

UVC LEDs vs. Hg and Xe lamps

Feature	UVC LED	Hg lamp	Xe lamp
Germicidal effectiveness	+	+	+
Instant on/off	+	-	+
Small size	+	-	-
Mechanically durable	+	-	-
No high voltage required	+	-	-
Longer operating lifetime	+	-	-
Environmental hazards	+	Hg -	+
Battery operable	+	-	-
Design flexibility	+	-	-

http://www.laserfocusworld.com/articles/2014/04/uv-disinfection-leds-versus-lamps.html

Source: Crystal IS

Source comparison

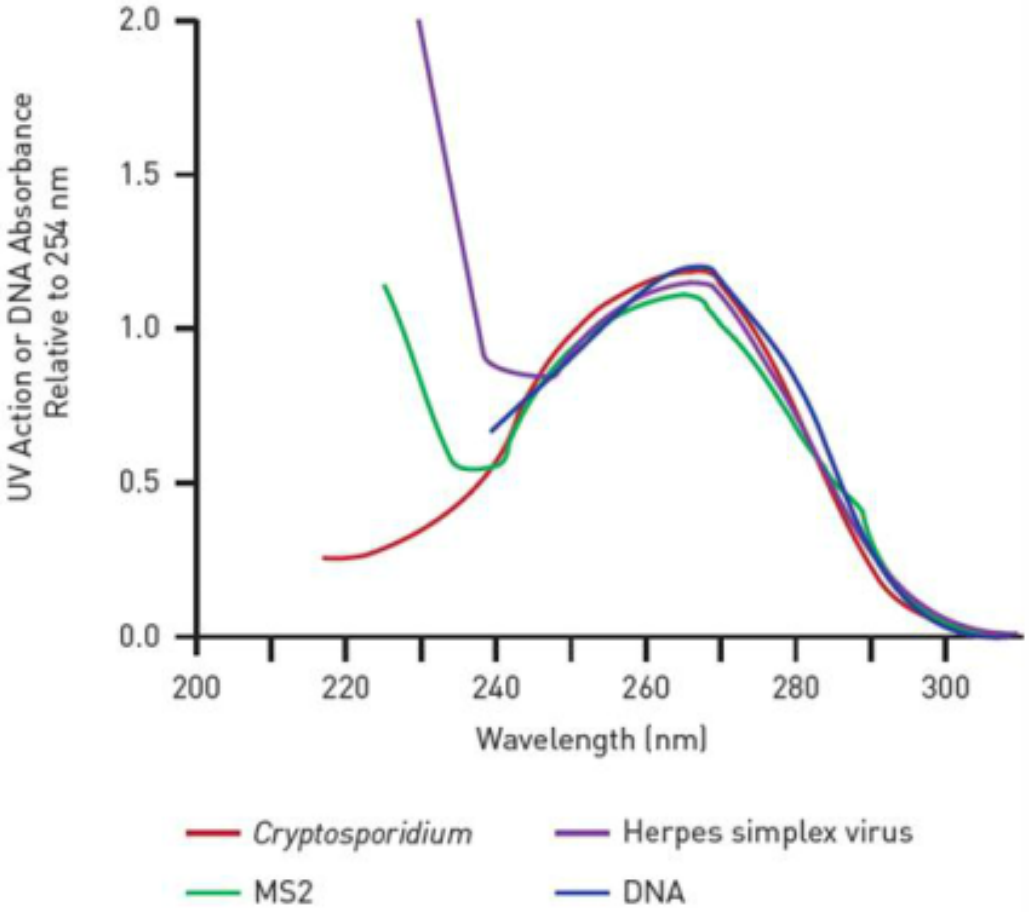
Attribute	Mercury Lamp	UV LED
Bulb Lifetime	10,000 hrs	50,000 hrs (glass lens)
Warm-up time	2 - 15 min	Instantaneous
On/Off Cycles	Lifetime Degradation	No Degradation
Flow Architecture	Cylindrical Tube	Adjustable/Versatile
Drive Circuits	Complex	Simple, Compact
Voltage	110 - 240 VAC	6 - 30 VDC
Emission Wavelength	Polychromatic Fixed	Customizable
Ruggedness	Glass Tube	Shock Resistant Semiconductor
Heavy Metals	Mercury (20 - 200 mg)	None

Deep UV disinfection

- Extremely potent against pathogens
  - *Cryptosporidium* and *Giardia* (Cl-resistant)
  - Breaks down DNA
- Reduces need for hazardous chemicals
- Reduces overall hazards
- Reduces waste, environmental impact
- Regulatory requirements for drinking water
  - Leaves no aftertaste
- BCC Research says $1.1 billion market in 2013
  - $2.1 billion projected in 2018

UV action

- DNA effect
- Kill virus
- Kills bacteria
- Peak near 260 nm
- 100 mJ/cm^2 reduces *Salmonella 99%*



Hospital pathogens – pulsed xenon

200-280 nm harsher effects
cell walls & structures

Xenex

Mobile phone sterilization

- Portable disinfection cases for mobile phones, tablets, etc.
- Internal DUV LEDs
- Recharges with mini-USB
- Turns on when closed
- 50% of healthcare workers use with patients
- Only 8% clean them
- Sensor Electronic Technology Inc.

In Duct Fixture

Inside ventilation system

UV lights for surface cleaning

- Goes beyond DNA breakup
- Wavelengths <240 nm break molecular bonds
  - 184 nm from mercury
- Cleaning aided by ozone produced by 184 nm line
- Ozone requires special precautions beyond UVC

Water sterilization

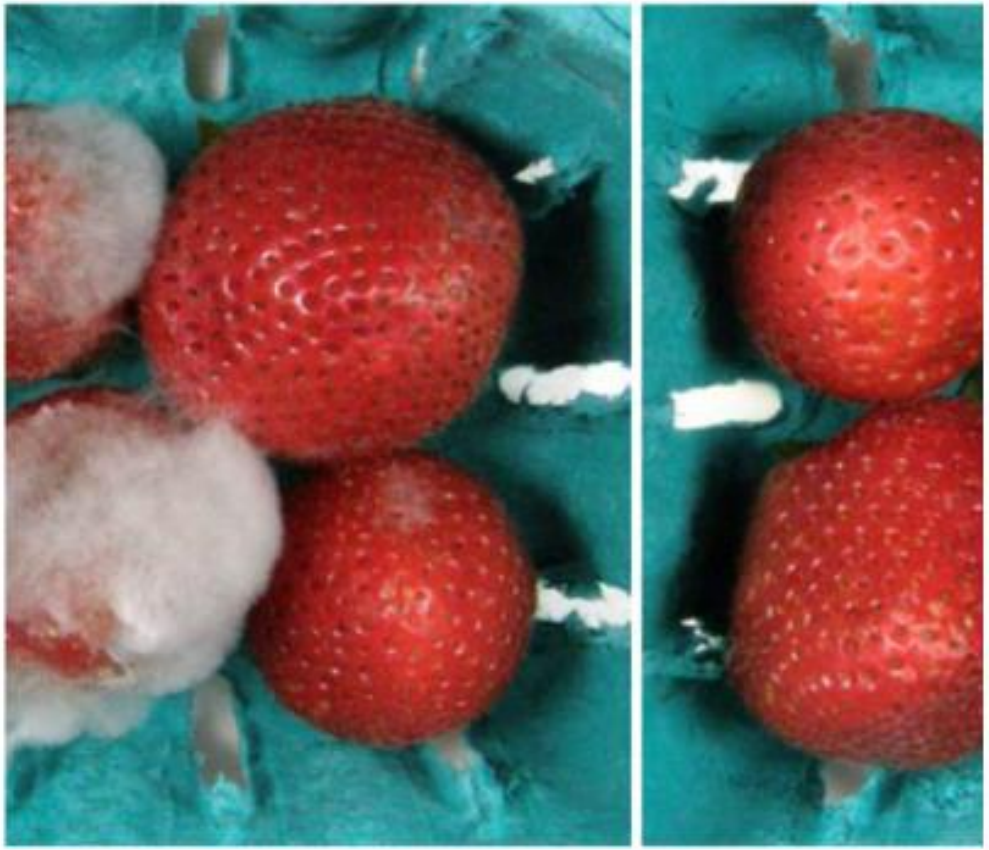
- Short contact with water
  - Sterilizes by breaking up DNA at 240-280 nm
  - Pathogens have different resistance levels to UV
- 275 nm LEDs, 0.5-2 liters per minute
  - More effective than shorter mercury wavelength for water-born pathogens
- Developing countries need simple, low power
- Point of use water purification with LEDs
  - Small home units
  - Need tens of milliwatts of UVC
  - Solar power possible
  - Multi-chip LEDs possible

UVC vs. chlorine disinfection

- No overdose possible with UVC
- No by-products or toxins
- No volatile organic compound (VOC) emissions or toxic air emissions
- Does not affect the smell, taste or minerals in the water
- Does not require storage of hazardous material
- Requires minimal space for equipment and contact chamber

Strawberry preservation

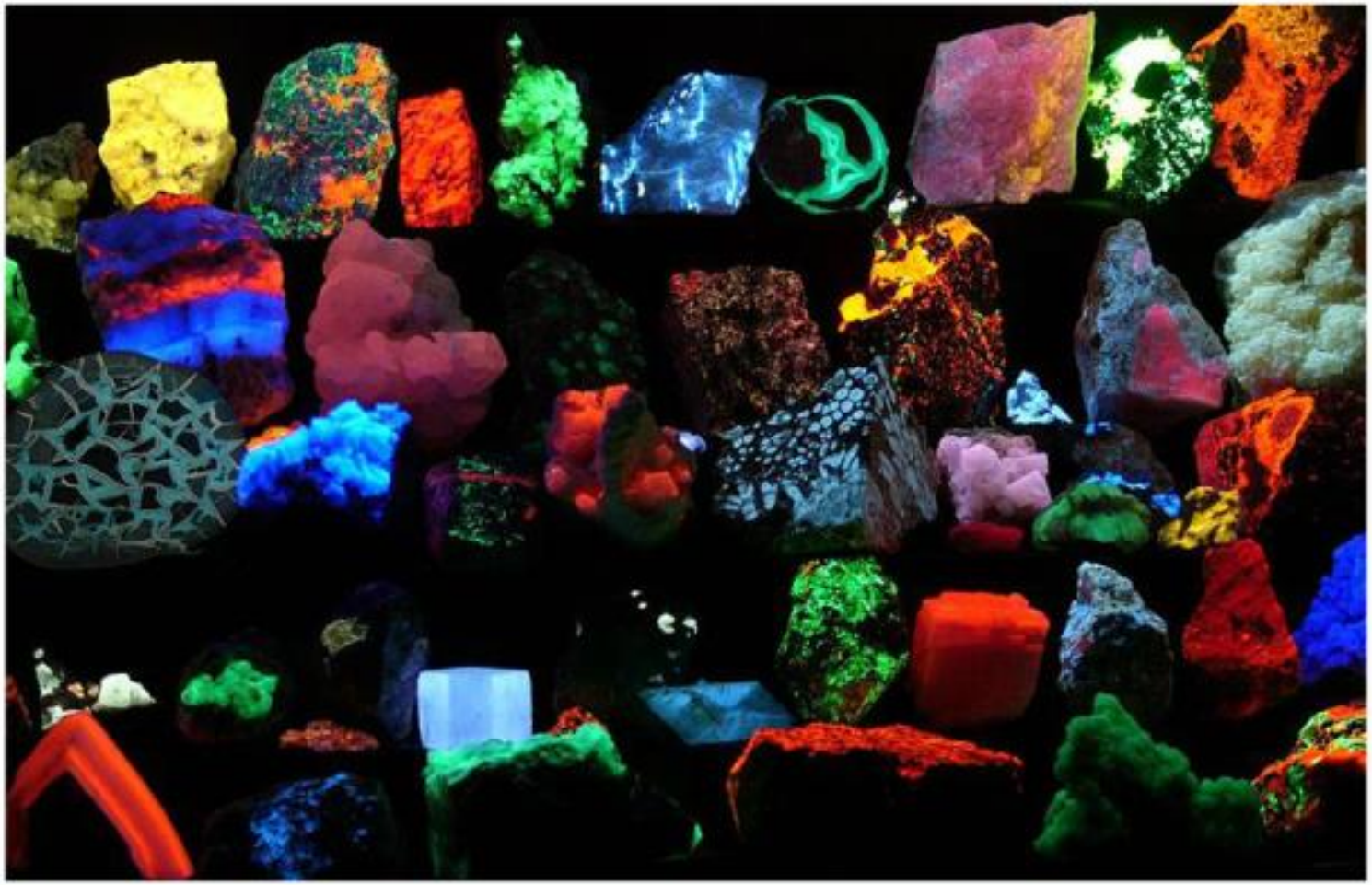
- UVB 280-305 nm
- LEDs illuminate refrigerated berries
- Prevents decay and mold
- Antioxidants remain
- UVC stops mold but not decay
- USDA tests CLEO 2013
- Doubles shelf life
  - 20 mW/m^2
- In cooled trucks



Instrumentation and measurement

- Identifying chemical and biological agents.
- Protein Analysis
- Medical Diagnostics
- Drug Discovery
- End Point Detection
- Blood Gas Analysis
- Petro-Chemical Analysis
- Gas Detection
- Bio-Threat Detection
- Real-time monitoring

Fluorescence spectroscopy



Wikipedia

WET Labs fluorimetry

- Fluorescent detector of oil in water
- Oil spills, petroleum exploration
  - Dispersant to oil ratio
- 280 nm source
  - Detection limit 36 **ppb** oil dispersed in water
  - Linear response to 300 **ppm**
  - Linear over 4 orders of magnitude
- LED advantages
  - High spectral quality and light output
  - Long life, simple drive electronics

Tests by Crystal IS

Deep UV LEDs for water quality

- Fluorescence to analyze drinking water quality
- Compared Deep UV LEDs to lasers
  - Dissolved organic compounds at low levels
  - LEDs at 265 nm, 300 nm, 335 nm, and 355 nm
  - Nd-laser harmonics at 266 and 355 nm
  - Greater than expected SNR observed with LED excitation is a good indication that a compact, less expensive LED based system might be used for detection and/or monitoring of trace organics and appropriate species in these liquids
- Sharikova and Killinger, U of South Florida
  - Laser Pulse Phenomena and Applications ed F. J. Duarte

Ozone sensor

- Tropospheric ozone is toxic gas
  - Irritates humans at 100 ppb
  - Long-term respiratory effect
  - Process monitoring
- LEDs
  - Small, inexpensive, long-lived
  - Wavelength customizable
- 255-260 nm LED

Gas Sensing with Deep-UV LEDs

- Direct modulation can chop LED output for absorption meas.
  - Avoids need for mechanical choppers
- Narrow linewidth
  - Avoids need for wavelength filters
  - Can match spectral peaks
- Continuous emission monitors of NO_2/SO_2
  - NO_2 @ 400 nm, SO_2 @280 nm, compare lines
  - Convert NO to NO_2 for measurement
  - Higashi et al, Proc. SPIE doi:10.1117/12.2036159
- 228-nm LED for monitoring NO absorption
  - In-situ combustion gas measurements ppm levels
  - Degner et al, CLEO 2012 paper JTh1L.2
- 255-260 nm LED for ozone monitoring ppb/ppm
  - Bilenko et al, CLEO 2012 paper JHt1L.1

Outlook: LEDs for deep UV applications

Attractions

- Solid-state devices
  - Compact
  - Durable
  - Low-voltage
- No mercury
- More wavelength options
- Improving technology
- Simple spectra
- Real-time monitoring

Development needs

- Improved efficiency
  - At shorter wavelengths
- More power
- Lower costs
- Encouraging precedent
  - Solid-State Lighting