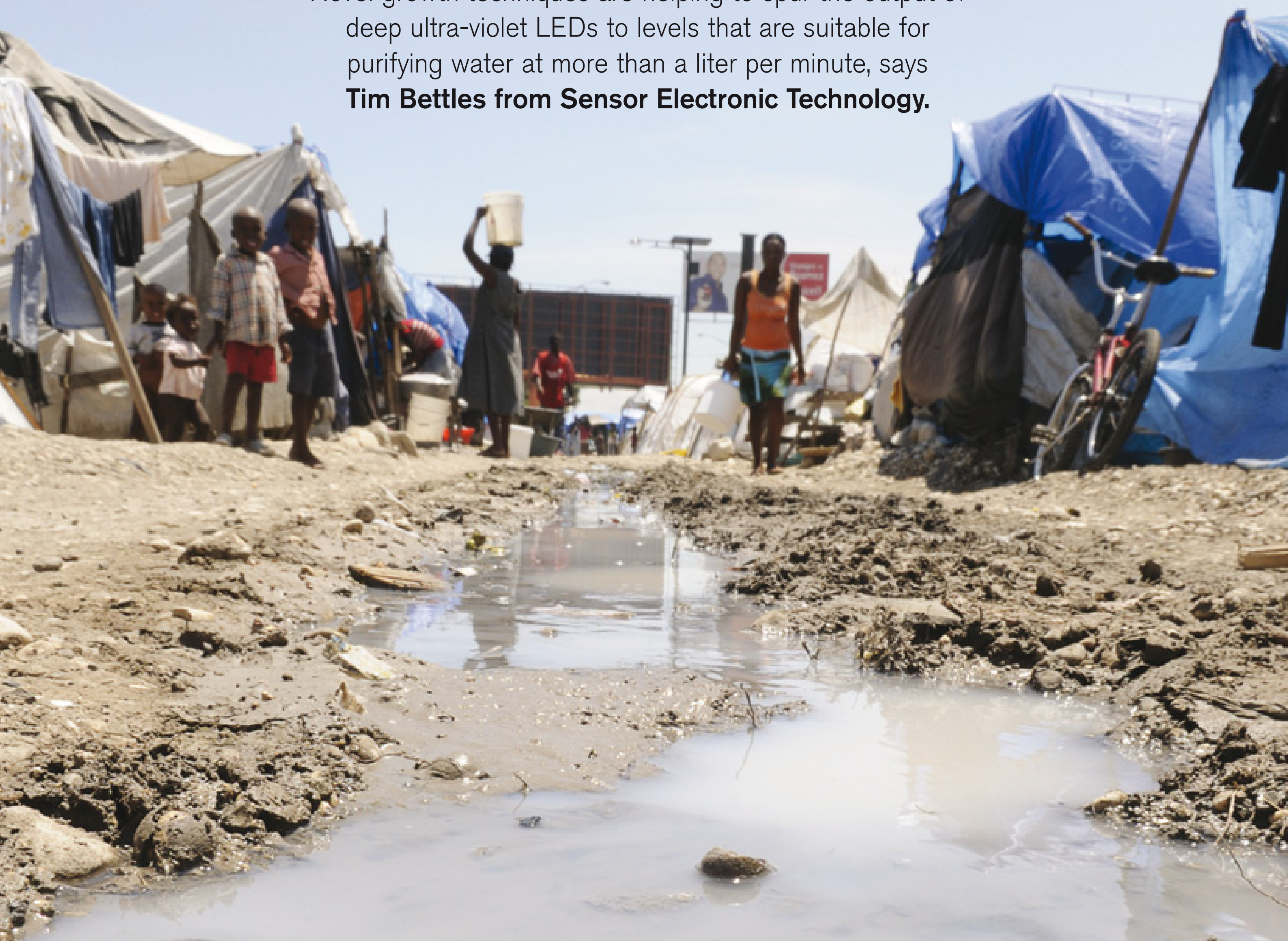
Putting deep UV LEDs to work

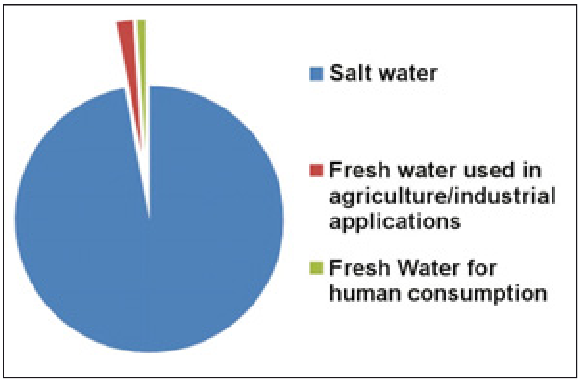
Novel growth techniques are helping to spur the output of deep ultra-violet LEDs to levels that are suitable for purifying water at more than a liter per minute, says **Tim Bettles from Sensor Electronic Technology.**



Water is in great abundance – it covers more than two-thirds of the earth. However, most of it – more than 97 percent – is of little use to humanity, because it contains salt. Only around three percent of the world's water is suitable for drinking, and in this form it is also wanted for many industrial and agricultural processes.

Due to greater global productivity and increases in population, the demand for salt-free water is on the rise. Unfortunately, in some countries this has led to a scarcity of drinkable water; according to the World Health Organization, one-fifth of the world's population does not have access to safe drinking water and two-fifths lack sanitation facilities. This lack of basic provision means that four million people die every year from waterborne diseases. The vast majority of them live in developing countries where priorities have been set by the United Nations to provide international aid for 'sustainable development'.

An example of a sustainable development program is water reuse – returning contaminated water to standards fit for human consumption. In developing countries, it is



A very small proportion of the world's water is suitable for drinking

estimated the two out of every three people do not have access to toilets or latrines and over 90 percent of wastewater is discharged back into the water system without any treatment. This practice spreads fatal, water-related diseases such as cholera, hepatitis, dengue fever and other parasitic diseases that can be attributed to many of the four million deaths and many more disabilities. Reducing these deaths by producing potable water from contaminated water is not cheap: Today a typical small community treatment system costs upwards of $5 million. So a dire need exists for a low cost-of-operation, easy-to-use, sustainable water-cleaning system.

One of the most effective methods for treating unsafe water is UV disinfection. As a physical, chemical-free disinfection process, it has much to recommend it: It is easy to use, with no danger of over dosing; unlike chemical disinfection, it requires very little contact time; it does not require storage of hazardous materials; there are no toxic by-products; and the process itself has little or no environmental impact (although the mercury based UV lamps do need to be disposed of frequently).

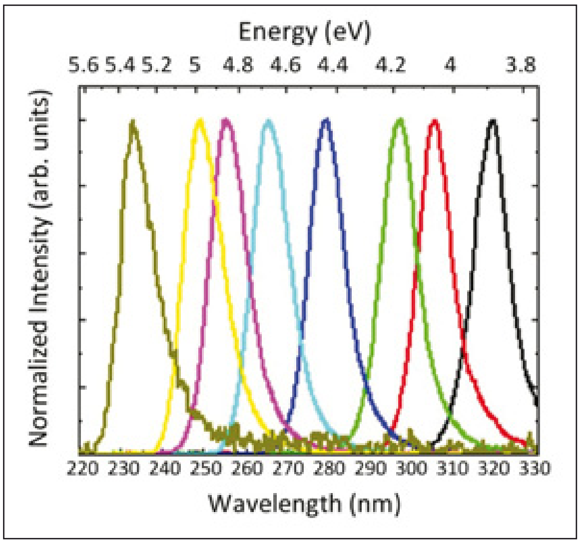


Figure 1. Normalized room-temperature electro-luminescence (EL) spectra of DUV LEDs with peak emissions at 235 nm, 250 nm, 255 nm, 265 nm, 280 nm, 295 nm, 305 nm and 320 nm

Using UV light to disinfect drinking water is well established. It's an approach that has been used for nearly one hundred years, and is recognized by many organizations around the world including the US Environmental Protection Agency (EPA). Wavelengthsranging from 240 nm to 280 nm can attack the DNA of micro-organisms, destroying their genetic information and preventing their reproductive capability. Without the ability to reproduce, these micro-organisms are rendered harmless when consumed by humans.

The major drawback of current UV systems is associated with their mercury lamps. These are bulky, fragile, require regular maintenance, have limited lifetime and present a disposal issue.

Recent developments in III-Nitride wide bandgap semiconductor technology demonstrate promising results to overcome these shortages of conventional UV light sources. A very attractive alternative is the AlGaN-based LED, which has peak emission wavelength shorter than 365 nm. These deep UV LEDs, or DUV LEDs, promise to enable the production of UV disinfection systems that will equip families and individuals with water purification systems that can provide a sustainable source of safe drinking water.

The UV spectrum can be sub-divided into four ranges: UV-A (320 nm – 400 nm); UV-B (290 nm – 320 nm); UV-C (200 nm – 290 nm); and vacuum UV (40 nm – 200 nm). The very longest of these wavelengths can be reached with active regions that pair GaN with InGaN, but for wavelengths of 365 nm or below, a combination of AlGaN and GaN must be employed.

At Sensor Electronic Technology, Inc. (SET), a company based in Columbia, SC, we have been pioneering the development of these UV sources. Thanks to these efforts, we were the first company to the market with a product line spanning the spectral range 240 - 355 nm (see Figure 1).

DUV LEDs are far more difficult to make than their blue and white cousins, due to issues related to strain, doping, efficiency and polarization (see "Six barriers to making UV LEDs", p.40). To overcome these challenges, we have developed two new epitaxial growth techniques: migration enhanced (ME) MOCVD and migration enhanced lateral epitaxial overgrowth (MELEO). These deposition technologies can decrease dislocation densities by orders of magnitude, which in turn enables the growth of thick, high-quality AlGaN, AlInGaN, AlInN and AlN epitaxial layers (see Figure 2). Better quality materials also offer additional benefits: a longer carrier non-radiative recombination lifetime, (see Figure2 (a)), higher efficiency and better device reliability. And further improvements in device performance are possible by employing superlattice buffers to reduce strain (see Figure 2(b)), alongside phonon band engineering approaches to negate the negative effects of the polarization fields and realize very high internal quantum efficiency.

Capturing electrons

We have also developed new quantum well configurations for deep UV LEDs that incorporate very narrow quantum wells within an wider 'energy tub'. In the example shown in figure 2(d), the bandstructure is engineered so that the difference in the energy of an electron when it enters the energy tub and when it is at the top of the quantum wells is equal to or greater than the energy of a polar optical phonon in the device material. Electrons emitting this form of phonon cool down much faster on entering the energy tub, and the chances of the carriers remaining there are high, due to the difference in composition on the p-type side of the LED. Now localized in the well, the electrons are more likely to recombine with holes to emit light.

Our efforts at refining band structure, growth methodologies and device processes have culminated in the fabrication of DUV LEDs with CW output powers in the milliwatts range and pulsed powers over 100 mW (see Figure 3). Lifetimes now exceed 5,000 hours for many DUV LED wavelengths for devices run continuously at 20 mA at room temperature without any heat sinking.

Recently, DUV LEDs have also passed space qualification – so far they have demonstrated over 26,000 hours of pulsed operation with no significant power drop or spectral shift. The qualification process was performed at Stanford University and National Security Technologies (NSTec) on our 255 nm UVTOP LEDs, with tests involving extreme radiation hardness, temperature cycling and 14g rms random mechanical vibrations.

For water disinfection applications, CW powers of tens of milliwatts or more are required. To meet this demand, we have developed and launched multi-chip LED lamps and products with powers over 100 mW at 275 nm; each

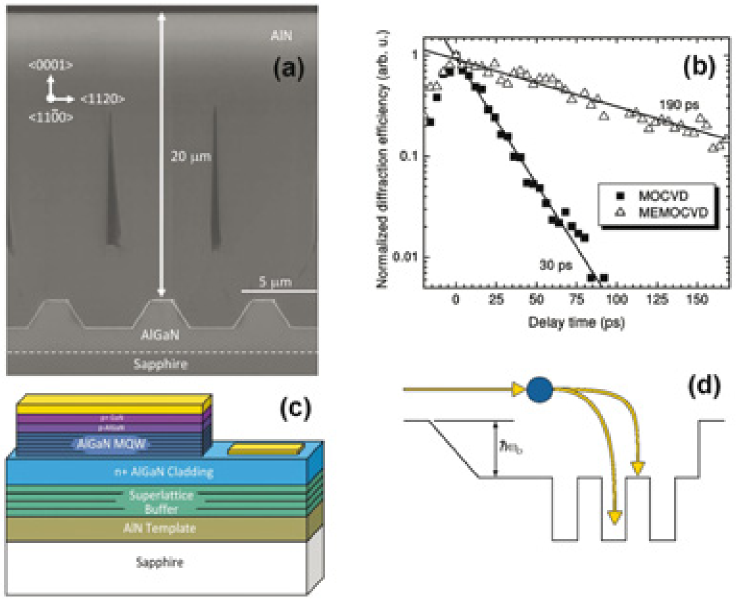


Figure 2 (a) SEM micrographs of a fully coalesced 20 µm thick AlN sample grown by MELEO (b) Light-induced transient grating (LITG) decay in MOCVD and MEMOCVD-grown AlGaN epilayers for the grating period of 7.7 µm. Carrier lifetimes were estimated by fitting the decay transients with single exponents (lines) (c) Typical deep UV LED design (d) Schematic band diagram of DUV LED for capturing electrons in the light emitting region

lamp containing as many as 100 single chips. In the same manner, DUV LEDs having different emission wavelengths are often combined together in one package to create broadband UV LEDs and multi-wavelength LEDs. Multi-wavelength DUV LEDs have up to 26 individually addressable wavelengths and can be directly coupled to an optical fiber, enabling spectroscopic and fluorometer applications.

Efforts at producing high-power single-chip LEDs are underway. Powers of 100 mW at an emission wavelength of 275 nm have been demonstrated on a 1.5 mm x 1.5 mm chip with an active area of 1 mm^2 packaged in a TO-3 metal can. The Department of Defense has a

Our efforts at refining band structure, growth methodologies and device processes have culminated in the fabrication of DUV LEDs with CW output powers in the milliwatts range and pulsed powers hitting 100 mW

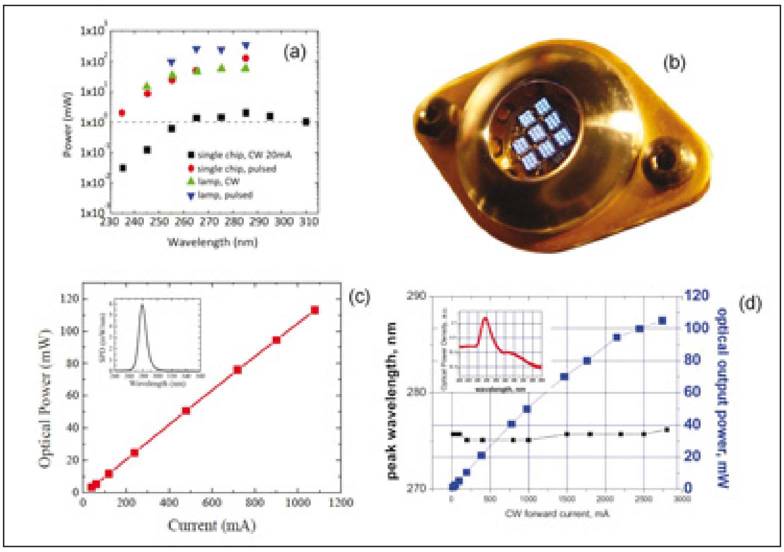


Figure 3 (a) optical power of single-chip DUV LEDs and DUV LED lamps for CW and pulsed modes (b) UVClean high power LED lamp from SET (c) SET's UVClean multi-chip lamp with over 100 mW of CW optical power at 275 nm at room temperature (d) SET's large-area single-chip LED with over 100 mW CW optical output power at 275 nm

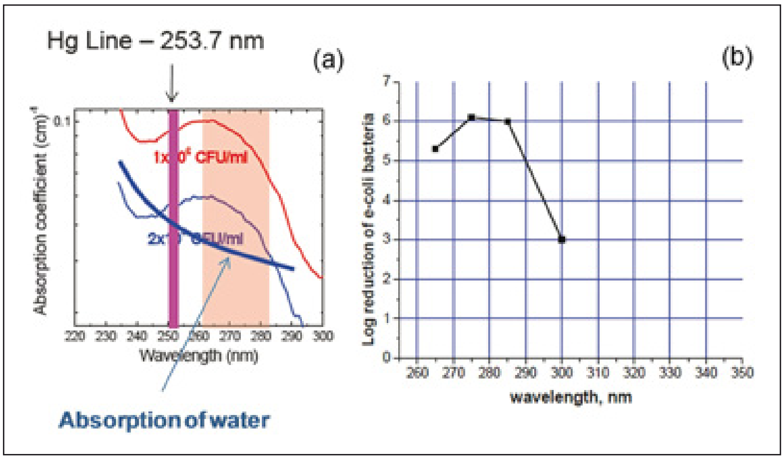


Figure 4 (a) Water shifts the most effective wavelength for water treatement (b) Optimim wavelength for disinfection of potable water has been demonstrated to be 275 nm

Six challenges to making UV LEDs

There are many challenges to overcome when fabricating UV LEDs. Six of the key ones are:

- Managing the strain to enable growth of crack-free, thick, doped AlGaN epitaxial layers. Strain is much higher in DUV LEDs than in their visible counterparts due to larger lattice mismatch between AlN/AlGaN and sapphire.
- Realizing n-type doping in AlGaN with high aluminum composition. AlGaN with more than 50 percent aluminum is required for fabrication of sub-300 nm DUV LEDs. Due to a larger donor activation energy in higher aluminum-content AlGaN, room-temperature electron concentration decreases and sheet resistance increases, leading to severe current crowding effects in the devices.
- Reducing concentration of non-radiative recombination centers in AlGaN that are responsible for low internal quantum efficiency.
- Catering for the strong polarization effects in the AlGaN-based quantum well active region of DUV LEDs. Fields resulting from polarization can pull apart injected electrons and holes, ultimately reducing the radiative recombination rate.
- Realizing a sufficiently high p-type doping of the AlGaN electron blocking or cladding layers, which is much more difficult than it is in p-GaN. Low p-doping efficiency of AlGaN is the main reason for high forward voltages and poor p-contact. Switching to lower aluminum content p-AlGaN or even a p-GaN contact layer is not necessarily beneficial, because it reduces light extraction due to strong UV light absorption in the p-contact layer.
- Obtaining reasonable light extraction efficiencies. In DUV LEDs, extraction efficiencies tend to be lower than those in InGaN-based devices, due in the main to a combination of strong absorption in p-contact layers and larger internal reflection at the AlN/sapphire interface.

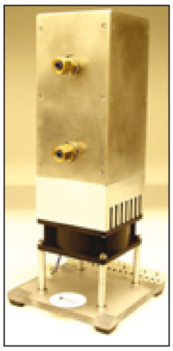
significant interest in DUV LEDs to detect and identify biological and chemical agents that may be in use by enemy forces. Current detect methods require large, heavy equipment and a great deal of power. To address these deficiencies, DARPA's (Defense Advanced Research Projects Agency) CMUVT program is targeting high performance UV semiconductor devices; 100mW LEDs operating at 250 – 275 nm with 20 percent wall-plug efficiency and 10 mW, 220 – 250 nm laser diodes. Today DUV LEDs address markets such as life sciences and scientific analysis where they are ideally suited for fluorescence and fluorescence lifetime measurements. The characteristics of DUV LEDs, including wavelength selection between 240 nm and 355 nm, switching speeds in the range of a few nanoseconds, small physical size with high power density and simplified optics and electronics present very large benefits over traditional UV light sources in the same wavelength range. This set of desirable characteristics has driven adoption of LEDs in systems for medical analysis, gas detection and monitoring and medical disinfection. However, with recent advancements in high-power LED lamp technology and the development of high-power, single-chip LEDs, development activity in many household applications has significantly increased. The resulting UV components from the DARPA CMUVT program will not only significantly improve size, weight, power and capability of chemical/biological-agent detectors, but will also allow the current development of consumer type systems to be realized in high volume markets.

Believed to be the largest market opportunity for UV LEDs, development has begun on LED-based point-of-use (POU) in-line water systems under NSF SBIR support. POU systems are designed to clean water on-demand in a small scale where it is to be (kitchen faucet, refrigerator dispenser, etc) rather than in a large centralized location. With fast turn on/off speeds, small footprint, low voltage operation and the ability to operate in cold environments, LEDs offer many advantages in this application space over traditional mercury lamps. However, mercury vapor fluorescent lamp technology is well established and for markets where size, turn on/off speeds and power requirements are not issues, it is unlikely that LEDs will replace this technology until later in their product life cycle. Instead, DUV LEDs will open new market opportunities that cannot be addressed with mercury lamps.

Previously HydroPhoton demonstrated UV LEDs in a portable on-demand water purifier which reduced the level of E-coli. by 99.99 percent in water flowing at a rate of 150 ml per minute. ("Brighter LEDs improve water purification rates", *Compound Semiconductor*, Nov 14, 2005)Thanks to the support of the National Science Foundation (NSF), this work has been continued recently with high power DUV LEDs used to disinfect higher water flows. Traditional UV disinfection systems use far shorter 253.7 nm light, as this is the wavelength attainable using mercury lamps. However, it is widely known in the field that 265 nm is the peak wavelength of absorption of DNA, and practical analysis has shown that 275 nm is the most effective wavelength for eradicating pathogens such as E-coli. in water (see Figure 4). This wavelength shift is due to the absorption of water, which increases as the wavelength becomes shorter.

Applications for Deep UV LEDs

- Protein Analysis
- Medical Diagnostics
- Drug Discovery
- End Point Detection
- Blood Gas Analysis
- Petro-Chemical Analysis
- Gas Detection
- Bio-Threat Detection
- Phototherapy
- UV Curing
- Water Disinfection
- Air Disinfection
- Surface Disinfection



SET's UVClean LED-based water purification chamber

DUV LED water disinfection systems employing 275 nm sources have been produced. The systems, which feature our 275 nm DUV LED lamps, have been tested for E-coli. and MS2 disinfection at flow rates of 0.5 to 2 liters per minute. The water purification chamber, 3-inches in diameter and 6-inches long, was tested with 34 mW of DUV LED optical power (<4.5 W of electrical power). E-coli. was now reduced by 99.99 percent in water flowing at a rate of more than 1 liter per minute. These results are encouraging, and further gains in this direction in DUV LED performance and water disinfection chamber designs will soon open up new market opportunities in point of use applications that can benefit from LED advantages.

Believed to be the largest market opportunity for UV LEDs, development has begun on LED-based point-of-use (POU) in-line water systems under NSF SBIR support. POU systems are designed to clean water on-demand in a small scale where it is to be (kitchen faucet, refrigerator dispenser, etc) rather than in a large centralized location