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UV LEDs and Their Applications

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Abstract

The purpose of this research is to design and develop a semiconductor light source emitting ultraviolet (UV) light. The final device will then be integrated into a biomedical application to assist clinicians in patient diagnosis. A light emitting diode (LED) is the specific UV source of interest, which has been the subject of major research and development over the past 20 years, with applications spanning surface disinfection to biomedical imaging. To realise the UV LED, the semiconductor structure must first be ‘grown’ which is a research area in and of itself. This project focuses specifically on taking the as-grown material of the LED and forming individual functioning devices, characterisation and then further optimisation of the growth. Challenges currently being faced include the physical constraints (electrical and optical properties) of certain materials, and extracting as much UV light as possible from the device. With 2 years left in the project, these challenges will hopefully be overcome to produce a high efficiency UV LED, integrated into a biophotonics diagnostic tool.

Keywords: semiconductor, fabrication, ultraviolet, light, biophotonics.

> *”If we knew what it was we were doing, it would not be called research, would it?”*
>
> — *Albert Einstein*

Ultraviolet Light

If you hear the term ‘UV’, you may think of the scenes in CSI-style TV shows where they use a purple-bluish light to reveal hidden bloodstains. While the science behind this is questionable (blood does not intrinsically fluoresce), the fundamental flaw in most people’s knowledge of UV light is the colour. In fact, UV light is essentially invisible to the human eye! Ultraviolet light is electromagnetic radiation that has a wavelength between 100 and 400 nanometres (nm). For reference, blue light has a wavelength of 460 nm. The shortest wavelength the human eye can detect (weakly) is around 380 nm. The whole range of UV light is broken into 3 categories: UVA (400 – 315 nm); UVB (315 – 280 nm); and UVC (280 – 100 nm). Each category has various applications and properties, but to some degree, all of these wavelength ranges are found in sunlight. The atmosphere absorbs almost all UVC light, and most UVB so the majority of the UV light that reaches the earth's surface is UVA.

Applications

Biomedical

UV light is used in a wide array of applications in both diagnostics and treatment. One novel example of how UV LEDs are used in the diagnosis of cancerous tissue is microscopy using ultraviolet surface excitation (MUSE)[4] This technique takes advantage of the shallow penetration depth of UV light in tissue. By shining a UV LED onto a tissue sample, the light is absorbed in the first few microns only. In tissue, there are molecules known as 'fluorophores', which, when excited by a wavelength specific to each fluorophore, emit light of a longer wavelength. An example of a fluorophore you may have heard of is collagen. These fluorophores in tissue are endogenous/biological fluorophores, but fluorophores can also be found in dyes.

Once excited, the fluorophore's emitted light is detected by a camera, forming a high definition, sub-cellular image with useful information for clinicians. This fast, low-resource technique has the potential to replace the conventional method which involves forming thin slices of tissue and many hours of intricate sample preparation. Similarly, fluorescence spectroscopy is another diagnostic technique in which UV LEDs can be used. Just as in MUSE, by exciting fluorophores with UV light, a special camera can detect the emission wavelengths of fluorophores and hence infer their concentrations in the tissue. This technique is in fact the application of interest for this research project, and the area that our UV LED will be used in. These fluorescence spectroscopy techniques are generally non-invasive, fast, and high resolution. *Invasive* diagnostic methods generally bring with them more risks than do non-invasive ones, so as well as potentially detecting cancerous growths in tissue, these techniques will also improve patient-care quality.

Psoriasis is a debilitating inflammatory skin disease, affecting over 100 million people worldwide. Fortunately, it can be treated with exposure to UVB light.[10] UVB LED-containing products make use of the LED's compact size, narrow wavelength, and low cost. UVB light can also be beneficial for the production of vitamin D in the body. Light therapy treatments, which use LEDs to provide the UVB light (specifically 310 nm), are available to promote the body's production of vitamin D.[7]

Tanning Beds

UVB light from the sun is responsible for sunburn as it is absorbed in the outer layers of the skin (epidermis). UVA light penetrates deeper into the skin (dermis) than UVB due to its longer wavelength. This is what triggers the process that generates melanin in the skin i.e., a tan. Tanning beds, which use UVA lamps, have become a popular means to shortcut the sun's

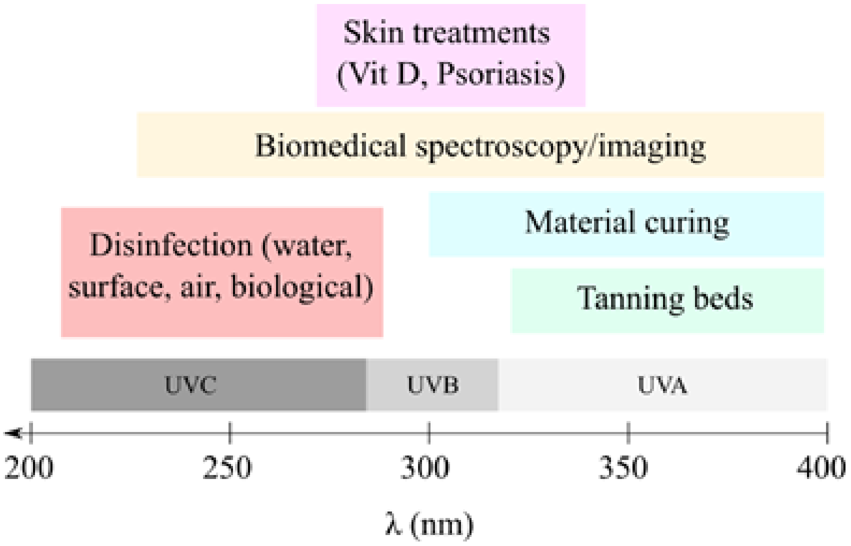

Figure 1: Illustration of some UV LED applications as a function of wavelength

UV emission. Despite significant scientific research pointing to the dangers of this intense exposure (a higher dosage than that from the sun), tanning beds are still in use today.[3] Within the dermis exists collagen and elastin (the structural elements of skin), which can be damaged by large UVA absorption. Effects such as photo-aging are common and an ocean of research has now shown the relationship between UV-induced DNA damage and skin cancer.[2]

Disinfection

The market for UVC light sources has exploded in recent years, accelerated by the COVID-19 pandemic, as well as increased reporting of antibiotic-resistance superbugs.[9] As a result, the UVC LED market is now the dominant market in UV LED manufacturing. Market analysis has predicted that “the UVC LED market could reach US$2.5 billion in 2025…”.[1] The demand from COVID-19 is due to the germicidal properties of this wavelength range. UVC light supplies enough energy to disrupt the DNA/RNA sequence, for example rendering the SARS-CoV-2 virus unable to reproduce. It has been found that 265 nm is the most effective wavelength for this process. This principle can be applied to air, surfaces, or water. Water purification applications consist of large “reactors” with a powerful UV lamp in the centre, around which the water flows. Currently, UVC LEDs are being developed to rival the currently used gas discharge lamps in power, offering benefits such as improved efficiency and easier maintenance. In Japan, a municipal drinking water facility is using a UVC LED-based water purification setup.[6] Similarly for air, large buildings are implementing UV purification units into the air conditioning systems, reducing airborne bacteria.

To summarise, the applications of UV light sources span many areas. A breakdown of various applications as a function of wavelength can be seen in Figure 1.

Semiconductor Light Sources

Up until recently, UV light sources have usually been in the form of mercury vapour lamps, which work by applying an arc through a mercury vapour to emit UV light. Mercury, however, is toxic to humans, and harmful to the environment. The Minamata Convention on Mercury,[8] which came into effect in 2017, introduced the phasing out of mercury-containing products – including a ban on mercury-containing lamps from 2020. With a whole technology now deemed obsolete for future use, an alternative is required, and this is where the UV LED comes into play.

The crucial realisation of the first blue light emitting diode (LED) in 1991 by Shuji Nakamura has ultimately led to the LED's pervasiveness in today's world.[5] Most white LEDs that we see around us are actually a blue LED with a phosphor coating to convert some fraction of that light into longer wavelengths (green, yellow, and red) to give white. Fundamentally, as the name suggests, an LED is a type of diode. This means there is a region with a high concentration of electrons, and a region with a high concentration of holes (the absence of an electron). By applying a voltage across these regions, the electrons will combine with the holes at the interface (or junction) between them, and in the process emit energy in the form of light. In order to improve the output efficiency of this process, there are usually many more layers added with individual functions to stop electrons and holes producing unwanted heat energy instead of the desired light. The LED structure is 'grown' crystallographically, layer by layer, by a process called metal-organic chemical vapour deposition (MOCVD), which allows layers around 10,000 times thinner than the diameter of a human hair to be prepared on a thick substrate, typically a disc of a crystal material like sapphire, which are called a wafer (not, unfortunately, a biscuit).

Figure 2 (a) illustrates the LED material after growth. The material system used for making LEDs in this wavelength range is known as III-Nitrides. That is, a compound with an element from group 3 in the periodic table, and nitrogen. For example, gallium nitride (GaN), aluminium nitride (AlN) and indium nitride (InN) are all examples of III-Nitrides. To adjust the wavelength of emitted light (the energy emitted by the electron-hole combination), we must choose a particular composition/mixture of these materials. This can mean forming a 'ternary' (three elements e.g., aluminium gallium nitride [AlGaN]) or even a 'quaternary' (four elements e.g., aluminium indium gallium nitride [AlInGaN]) alloy. For UV light, we generally use AlGaN. By changing the ratio of aluminium to gallium, we can fine-tune the energy of the electron-hole recombination and – because energy is related to the wavelength by $E=hc/\lambda$ where E is the energy, h is Planck's constant, c is the speed of light, and λ is the wavelength – we can therefore change the emitted wavelength.

After the material is grown on the wafer, individual LED devices must be created. This collection of processes is referred to as semiconductor fabrication. Imagine for a moment that the semiconductor wafer is an actual wafer biscuit. Often, a biscuit will have various patterns on

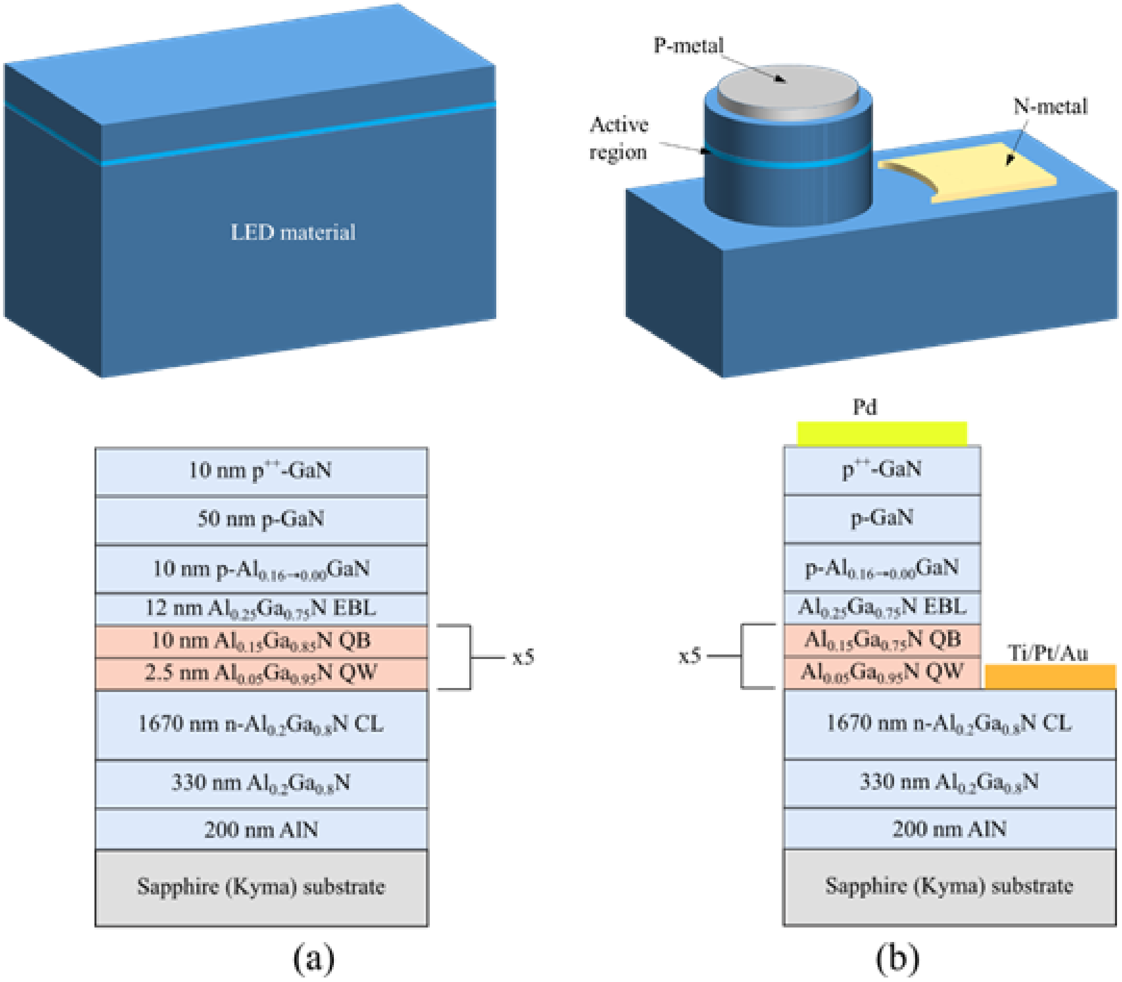

Figure 2: (a) Grown UV LED structure before fabrication. (b) Individual UV LED device after fabrication processing

it, which are usually formed by a pre-shaped mould. The desired features on a semiconductor wafer, however, are too small to use a mould. It is the role of fabrication to form extremely fine 3-D patterns (on the scale of a few micrometres, or even less) onto the semiconductor wafer.

Photolithography is the process of forming the patterns. If you have ever made the shape of a ‘bunny rabbit’ on a wall by using your hands in front of a light source, you are already on track to understanding the principle of photolithography. In practice, it works by depositing a UV-sensitive material onto the wafer and shining UV light through a patterned ‘mask’ so that only defined areas of the wafer are exposed. The exposed material is then removed chemically – leaving behind a high-resolution pattern. After photolithography, this surface can then undergo ‘etching’ in which the exposed area is bombarded with a plasma to form trenches between flat-topped mesa areas with extremely high precision. The same LED structure schematic as before – but after fabrication – can be seen in Figure 2 (b).

Compared to visible-light LEDs, UV LEDs are much more difficult to produce. This is largely due to the materials required (AlGaN) to produce the UV light. As mentioned above, crystalline layers must be grown on top of each other. If the distance between the atoms in a crystal is c, then the difference in c parameters between 2 neighbouring material layers is known as the lattice mismatch. If the lattice mismatch is large (which is inherent to III-Nitrides), faults known as dislocations are produced, which deleteriously effect the performance. Various strategies can be used to try to relax the 'strain' produced by this lattice mismatch, but it remains one of the biggest challenges in the growth of III-Nitrides. One other major challenge specific to UV LEDs is maximising the extraction of the UV light. Even standard glass absorbs UV light, so finding a material that provides both good electrical contact to the top of the structure while also reflecting the light out the bottom of the structure is difficult. There are very few materials that are reflective in the UV. Aluminium is the best performing, with a reflectivity of approximately 90% across the entire UV range.[11] Unfortunately, due to its physical properties, aluminium does not form good electrical contact to hole injector layers in III-Nitride materials. Various alternative strategies have been investigated in the literature and some are attempted for this project, including: varying the material used; or even the structure design. For my project, the goal is to design, grow and fabricate a 320 nm AlGaN-based UV LED – overcoming the aforementioned (and many other) challenges – which will then be integrated into a biomedical application.

Conclusion

I have covered the fundamentals of UV light, some examples of UV LED applications and the fundamentals of semiconductor light sources. UV light has great potential if compact, robust and non-toxic sources can be realised. The specific goal for this research project is to develop a UV LED that emits 320 nm light, and then integrate this packaged device into a fluorescent spectroscopy application. While the project is 2 years in development and significant work has been done, there are still major challenges to be overcome to realise an efficient, narrow linewidth UV LED.

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Declarations of interests

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