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MuAnalysis

Leaders in diagnostic services for microelectronics and photonics

Quantum Wells in the Seasonal Department,
The Technology of LED Christmas Lights

We present the results of a teardown and technology analysis of the now common multi-colour strings of LED's sold as Christmas lights. Interesting findings are reported and demonstrations of some advanced analysis techniques are illustrated.

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1. Samples

The samples were all Noma brand.

There was a 70 light string of coloured faceted bulb style units, a 100 light string of coloured omnidirectional point source units, and a 70 light string of white “icicle lights”.

Figure 1: Faceted, omnidirectional, and “icicle light” LED units.

2. Configuration and Assembly

On both coloured strings, the colours were arranged in repeating blocks of eight units with a consistent colour pattern. Blue and green LED units occur only once each per block, and red, orange, and yellow units occur twice per block.

Figure 2: Colour pattern of eight-unit blocks

Clearly the blue and/or green LED's are most expensive, an issue in a cost-sensitive market. Colour mix is on the "warm tone" side for most tastes. The green colour is very yellow, and the orange and yellow colours slightly brown-toned.

Series sub-strings totalling 35 or 50 LED's are connected in parallel to make 70 or 100 light strings.

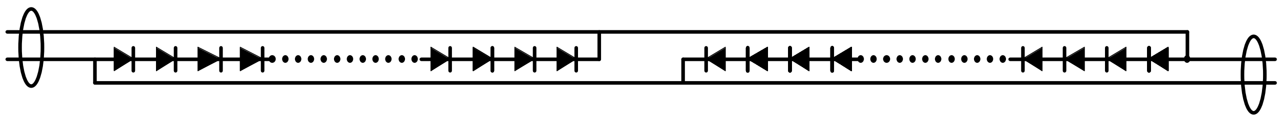


Figure 3: Schematic of strings.

In all three strings examined, power is fed through the length of the string, providing for end-to-end connection.
At the ends of each sub-string, discretes are included: Resistors in the 70 light strings, and diodes in the 100 light string

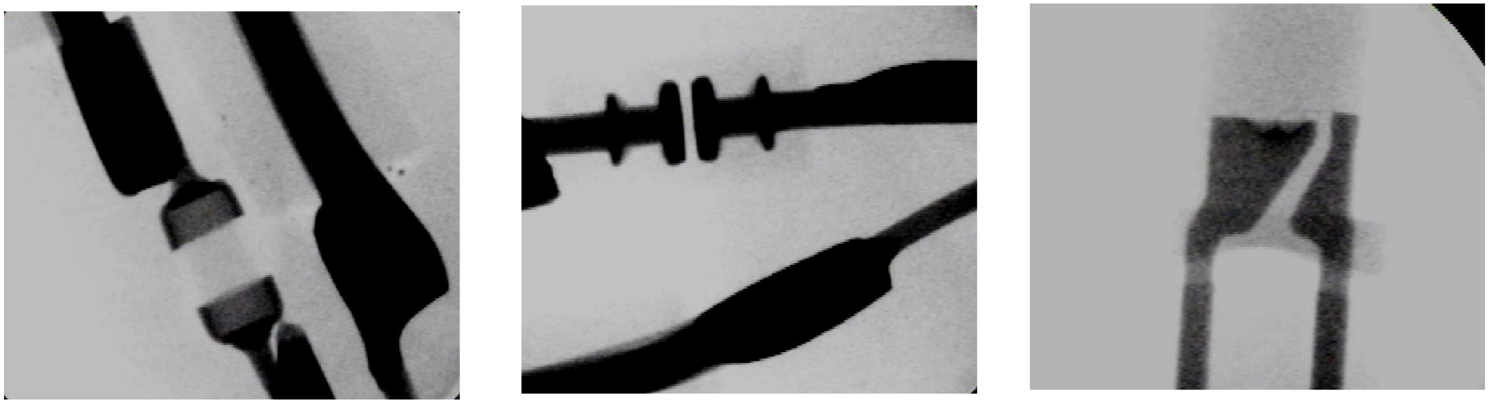


Figure 4: X-Ray images of a resistor (left) and a diode (centre) wired in series at ends, and a typical LED (right).

Each coloured diode is a commodity LED unit with a specially moulded encapsulant or added cover in different styles. Similar commodity LED lead frames were seen in all units. The encapsulant is moulded in colour on the multi-colour strings, suggesting that un-illuminated colour is an issue with the customer or some colour tuning is being done. The white LEDs on the “icicle light” string had typical commodity LED domed clear encapsulant with a clear plastic “icicle” applied over the dome.

Each individual LED was soldered (two joints each) to the stranded copper wiring harness. This must be automated or expensive. Christmas 2006 samples had lead-bearing solder and brominated plastics (RoHS violations if applicable).

The manufacturer must have very good control over polarity, as one LED wrong would render the whole substring scrap.

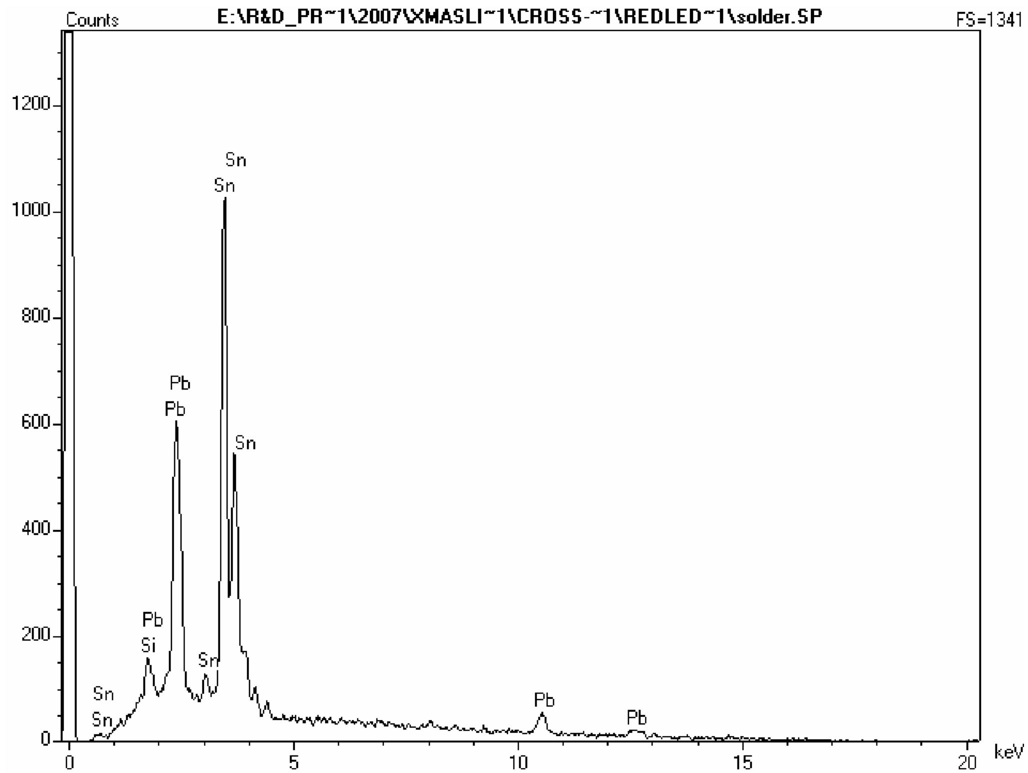
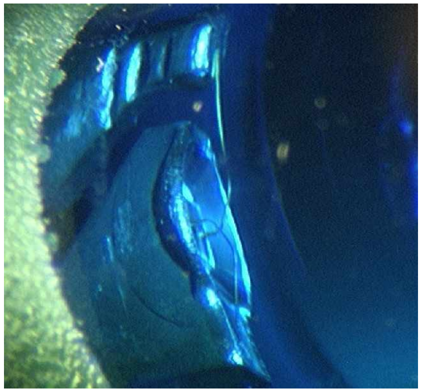


Figure 4a: EDX spectrum of the solder joint that connects the diodes to the wire harness.

3. Electrical Characteristics

With series connection, each diode must operate at a common current. These strings measured 10-20mA. Diodes must be sized to suit the current, so as expected a considerable size range seen. Typically the LED die attach to the lead frame is one terminal and there is only one bond wire required. Blue and white LED's have two bond wires, so their substrates must be high resistance.



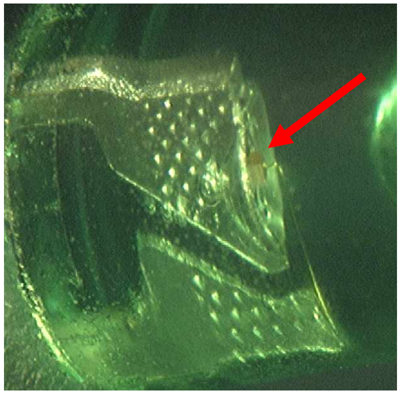


Figure 5: Blue LED (left) with large die and two bonds

Figure 6: Green LED (right) with small die and a single bond.

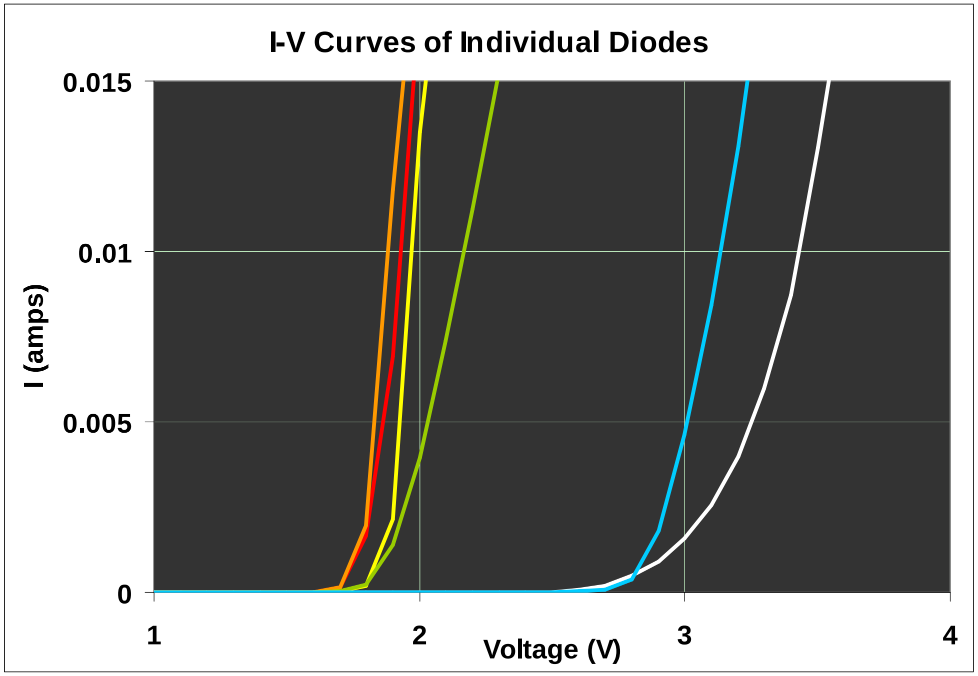


Figure 7: I-V characteristics of individual diodes.

- Red, orange, and yellow diodes are surprisingly similar
- Green seems unique but low voltage
- Blue and white have same voltage but different quality factors

4. LED Technologies

4.1 Red LED

The GaAs die is very small, indicating high apparent brightness per unit current.

The epilayer structure is very sophisticated, incorporating a superlattice for strain relief under the active area, a multilayer AlGaAsInP system active area, and a current distributing GaP cap layer. In contrast, wafer fabrication is almost trivial, with just a single patterned top contact.

There is evidence of a passivation etch-back of the die sides after singulation.

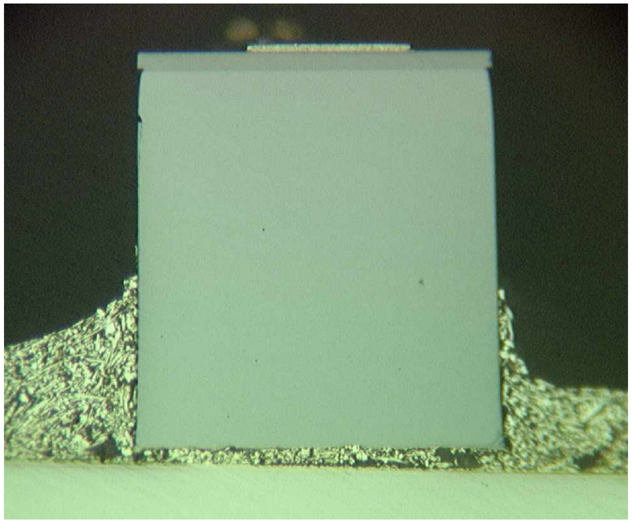


Figure 8: Optical image of a polished cross-section, showing the tall aspect ratio of the die and a single contact.

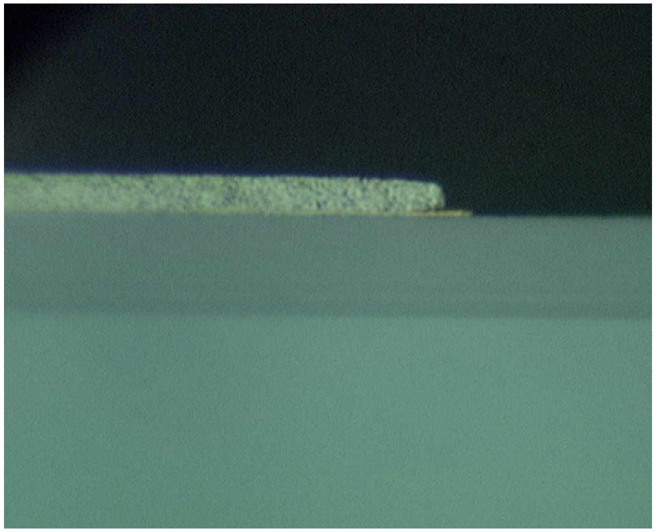


Figure 9: High magnification optical image of polished cross-section. There is only one patterning step, but the contact metallurgy is complex.

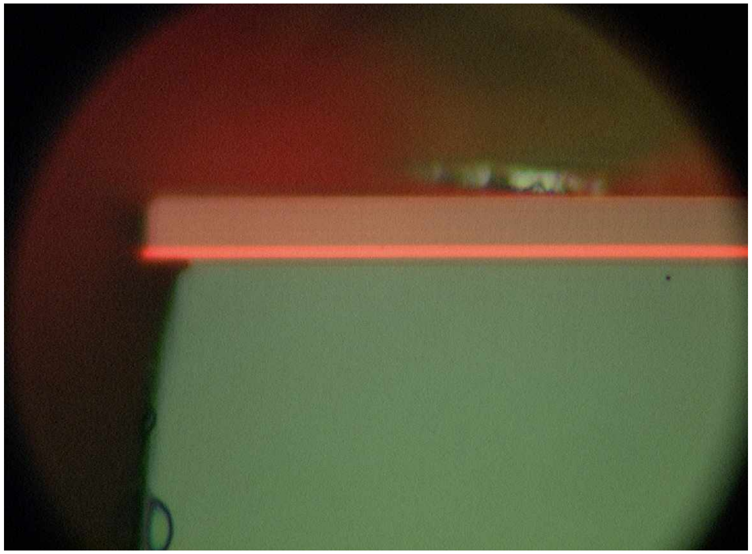


Figure 11: Emission image of a cross-section sample locates the active area. The cap and the superlattice do not emit.

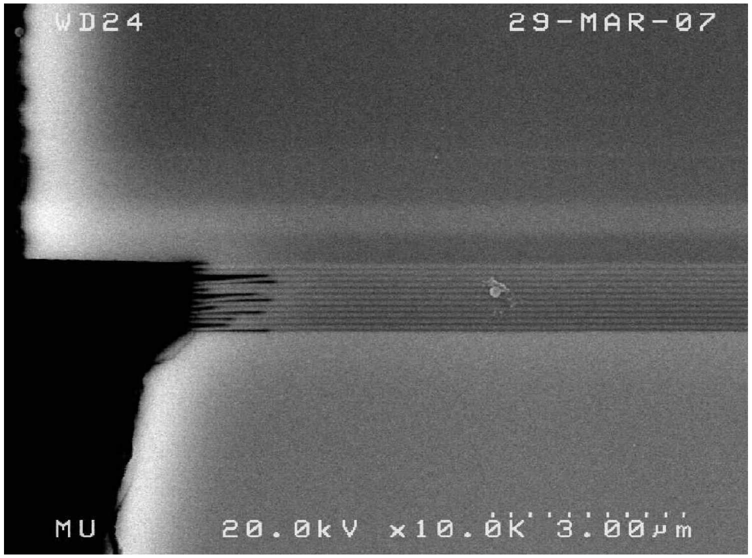


Figure 12: High magnification SEM image of the cross-section shows a superlattice, a complex active area, and evidence of a sidewall etch.

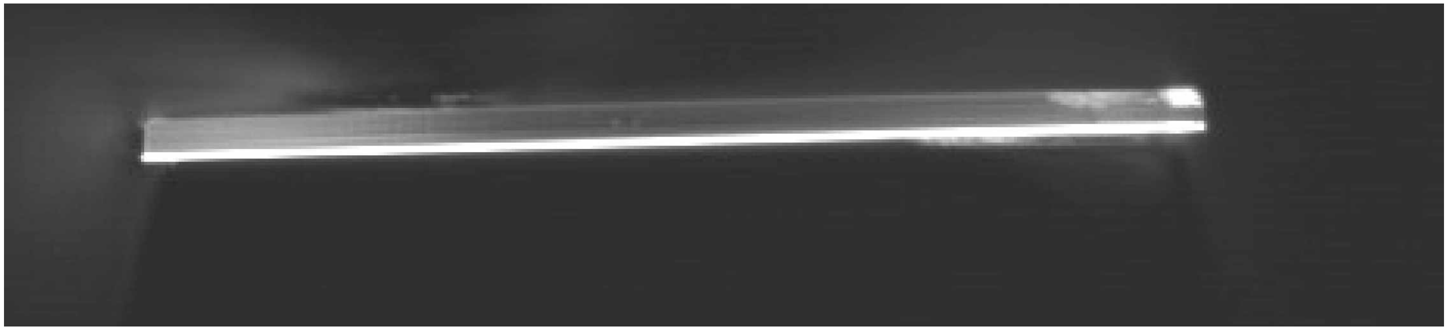


Figure 13: Optical Beam Induced Current (OBIC image) of cross-section is in this case similar to the emission image.

4.2 Orange LED

The die technology is very similar to that of the red LED, with possibly a less complex epi-layer growth. There are with fewer layers in the superlattice, and the active layers are simple or not resolved.

The die fabrication process is more complex, with a scribe channel patterned in a cap layer. The larger die suggests lower efficiency, and there is no die side etch-back.

The actual die emission colour may not be as orange as it looks, i.e. the encapsulation may be a colour filter. This could explain the muddy brown-orange apparent colour of the orange LED units.

Dark spot defects are seen in emission imaging of this device.

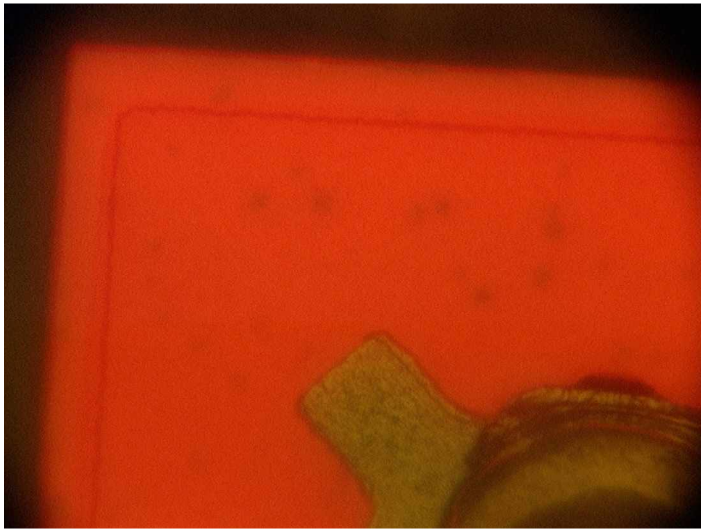


Figure 14: Plan view emission image reveals dark spot defects and complex fabrication.

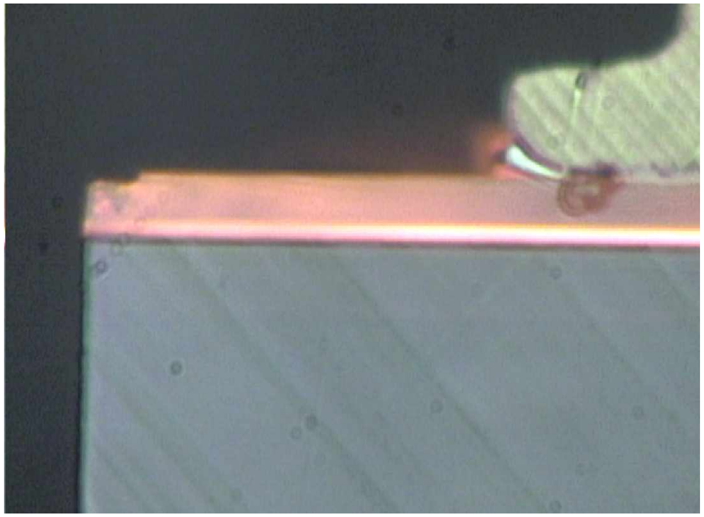


Figure 15: Cross-section emission image is very similar to that of the red LED. The superlattice is smaller and there is no evidence of a die side etch.

4.3 Yellow LED

A small die suggests good efficiency like the red LED. A die side etch-back has been performed - this process seems to go with small die.

The die technology is similar to that of the red and orange LEDs, with active layers nearing InP composition. It has the usual GaAs substrate and GaP cap for this “family” of LEDs. The Levels of epi-layer and fabrication complexity are very similar to those of the orange LED. A superlattice is seen, but is not thought to be part of the active region.

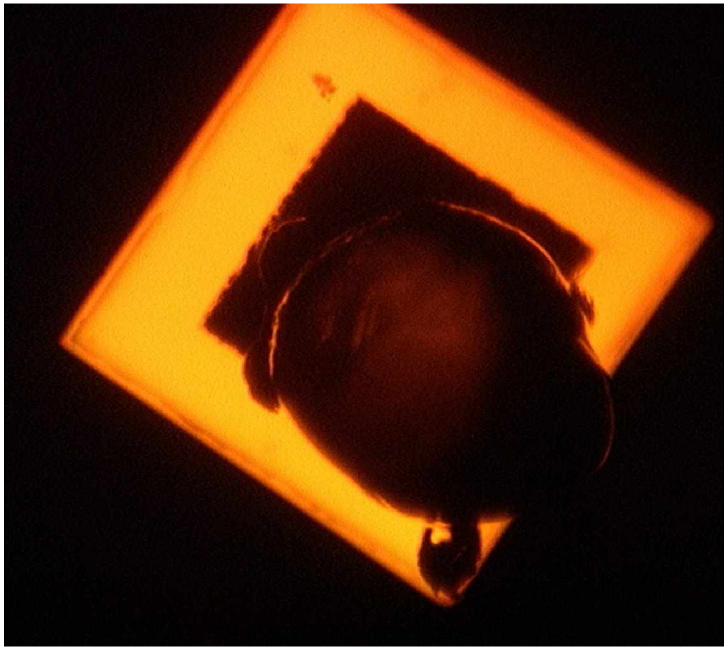


Figure 16: Emission image of the orange LED. There is a scribe lane visible.

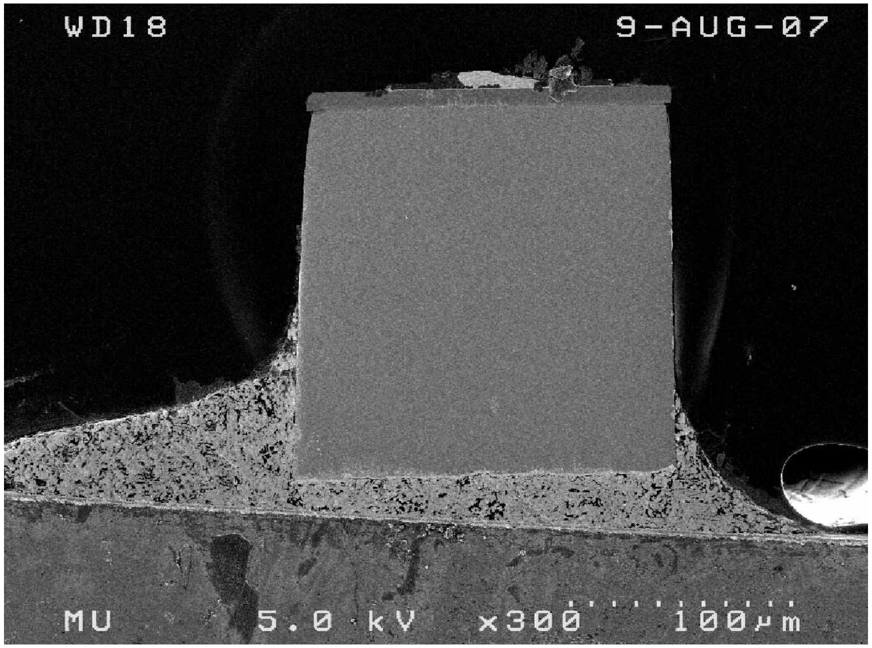


Figure 17: SEM image of a polished cross-section. The Small, and a die side etch-back is seen. Note the poor placement of the die.

4.4 Green LED

The die is small and the wafer thick, so the aspect ratio of the die is extreme. There is a single large bond pad, allowing inexpensive assembly.

The epi structure is simple or absent, the junction may be implanted or diffused. The material is GaP, with doping not known. The emission colour is yellow-green.

The die fabrication process is simple, with a single pad. The die surface is rough after pad patterning.

It appears that most of the light is emitted from the sides of the die, so the large top pad does not impact efficiency severely.

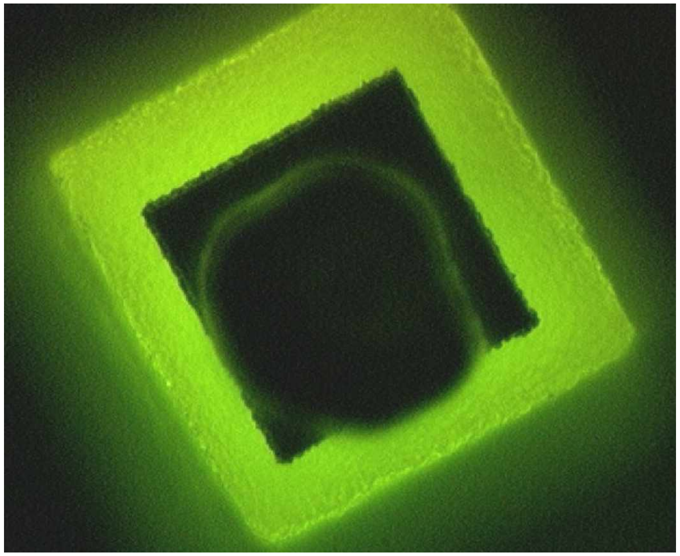


Figure 18: Plan view emission image shows rough surface, very simple structure, and a large bond pad.

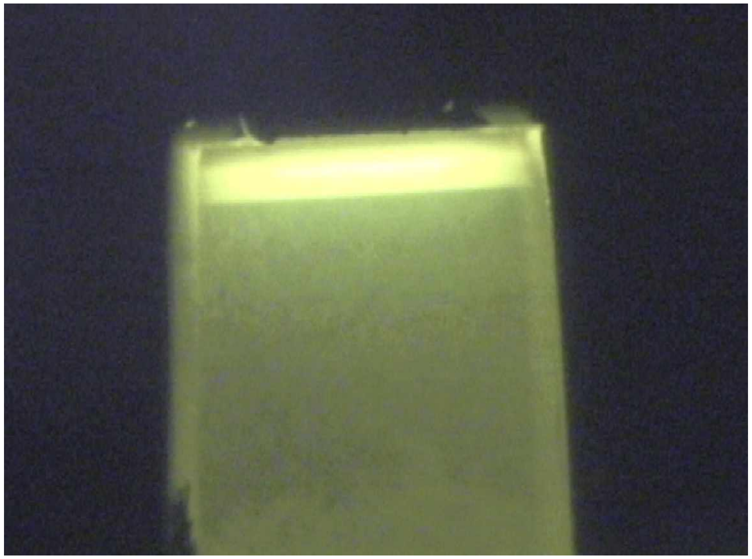


Figure 19: Cross-section emission shows buried active layer, and emission from the side of the die.

4.5 Blue LED

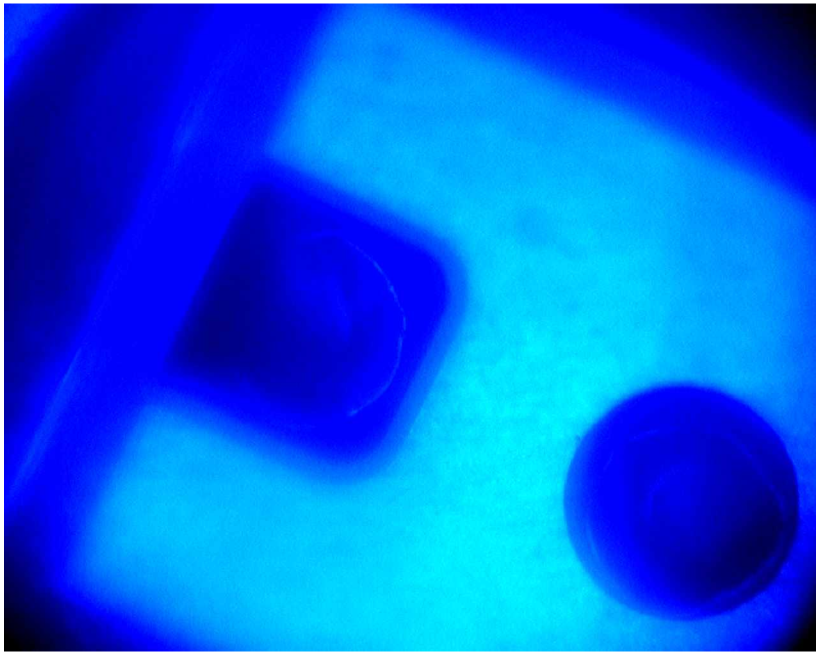


Figure 20: Emission image of a blue LED, showing two bond pads and complex structure.

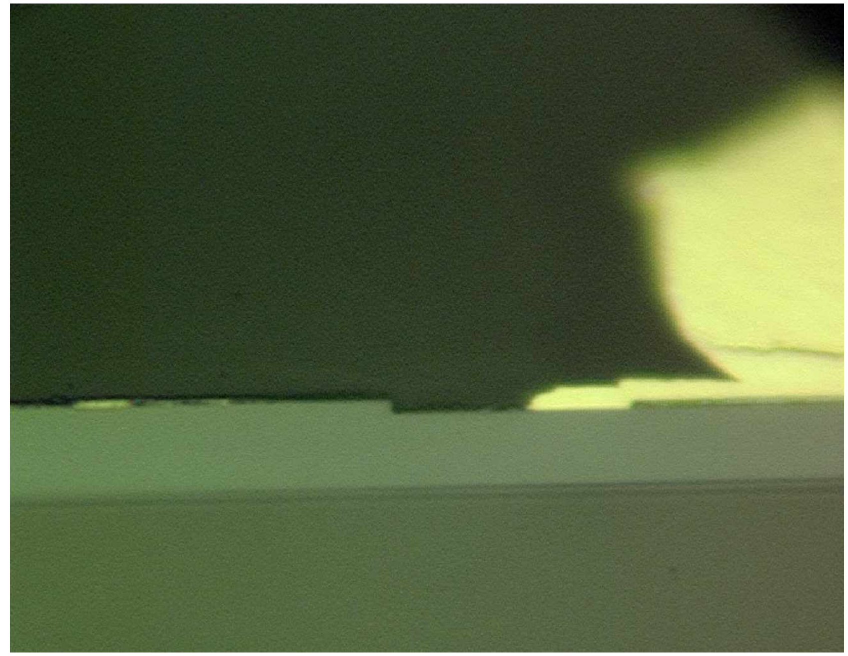


Figure 21: Optical microscopy image of polished cross-section, showing various patterned layers.

The substrate is sapphire, an insulator, which explains the two wirebonds. The active layer is GaN or possibly AlGaN/GaN.

The die fabrication process is complex, with a layer etch, a dielectric deposition and patterning., and contact metal (gold) deposition and patterning.

This is an obviously expensive diode to include in a multi-colour string, but emits a very nice colour that adds considerable appeal.

4.6 White LED

The die is of similar technology to the blue LED die, GaN on sapphire requiring two wire bonds. I-V characteristics (Figure) show the same turn-on voltage as the blue LED, but different ideality. Almost certainly the die are from different suppliers.

The cool white colour is partly fluorescence from a drop of fluorescent material over the die and partly the blue GaN emission.

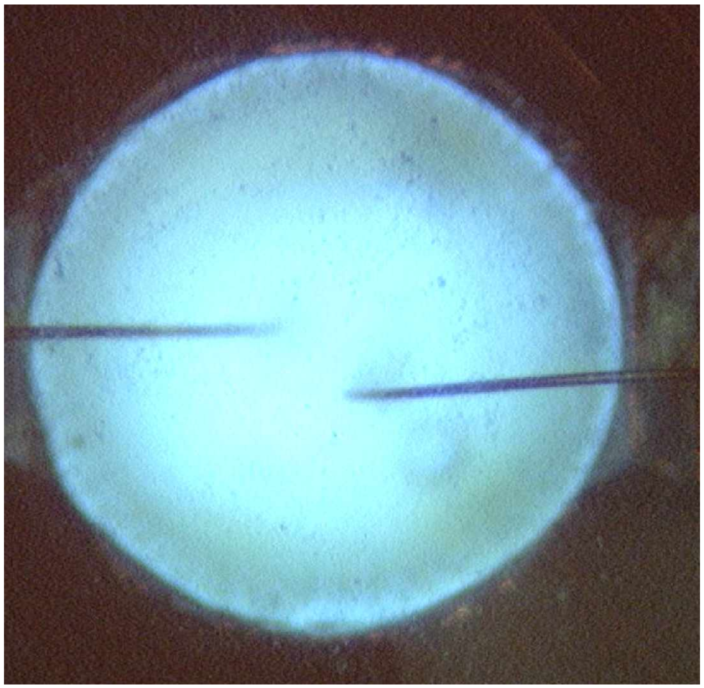


Figure 22: Emission image of a white LED. There are two bond wires, and a drop of fluorescent material encapsulating the die.

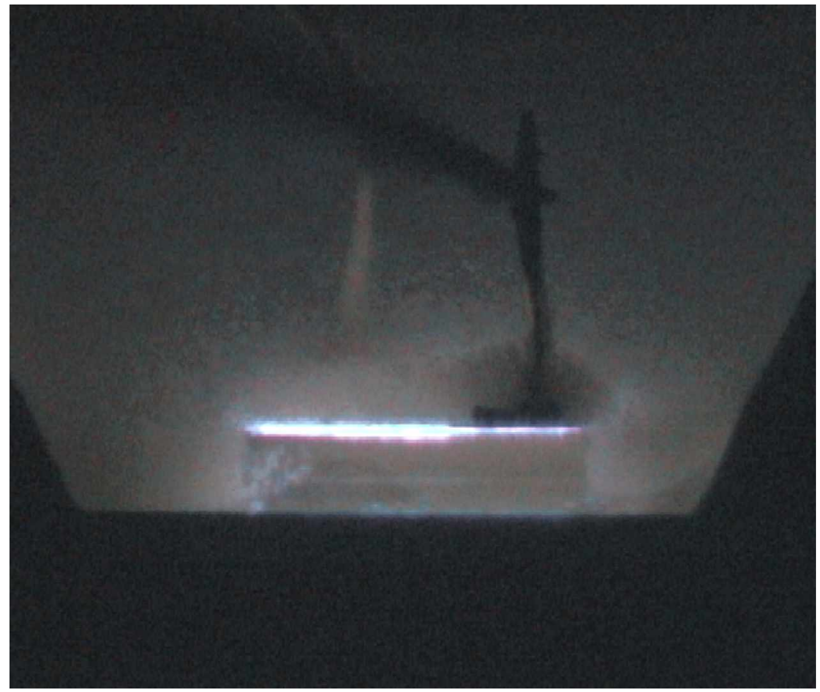


Figure 23: Emission image of cross-section sample shows that the die is transparent.

5. Raman Spectroscopy of GaN

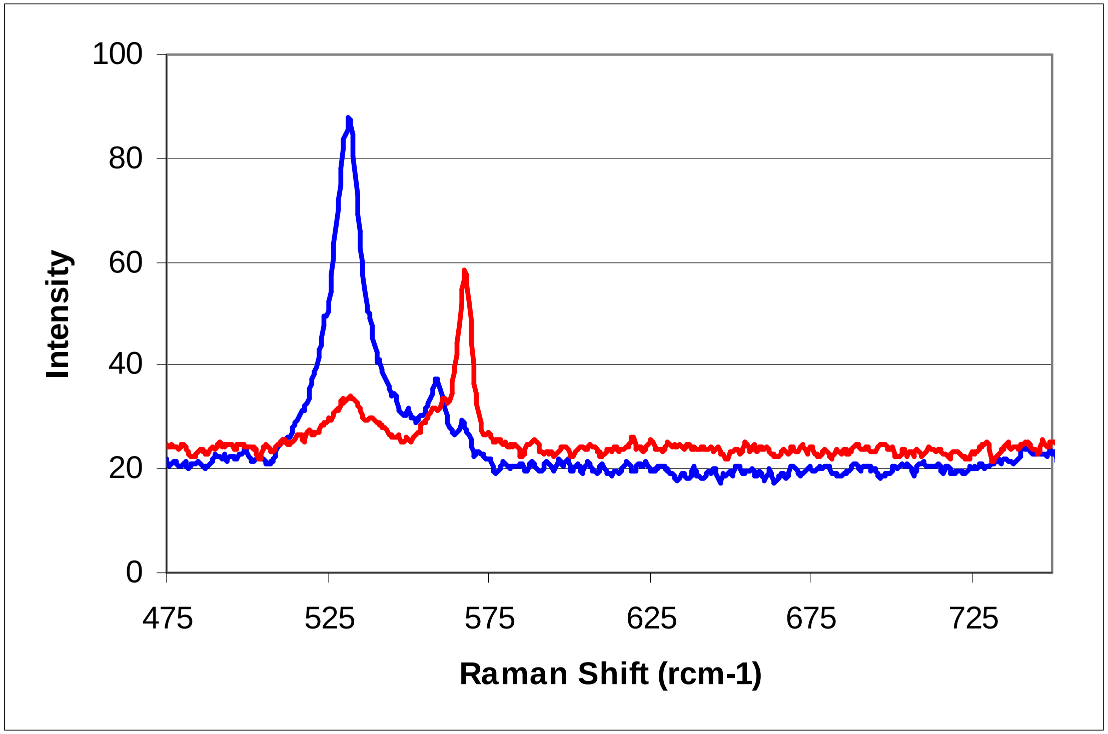


Figure 24: Raman spectra of a GaN LED in 2 polarizarion configurations.

Although Raman spectroscopy was not done in the teardown of light strings, it is a powerful tool that yields significant information on material quality. These spectra, from a different and more in-depth study of other GaN devices, are shown here to illustrate the sensitivity of the technique to crystalline orientation.

6. Fluorescent layers in white LEDs

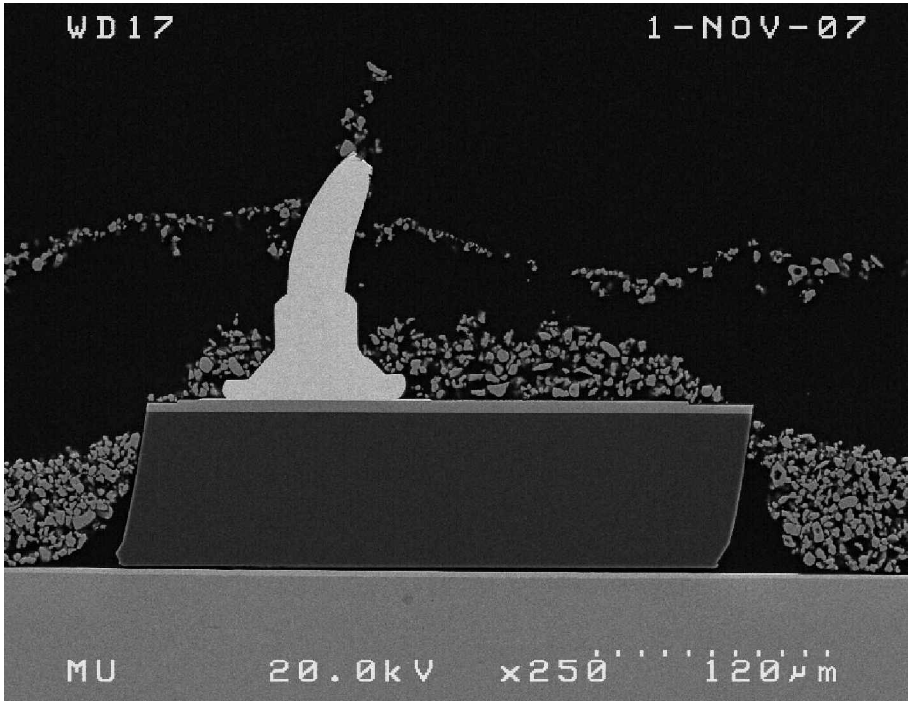


Figure 25: In the XMAS light strings, the fluorescent layer of white LEDs is an organic of uniform composition. In more expensive devices, additional materials are included. The particles seen here contain Yttrium.