Nano-Optic Augmented Micro-LED Arrays

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Abstract *A new class of nano-optic augmented micro-LED array, fabricated by mass transfer of nano-optical structures is proposed for application to polarised, colour converted and directional output for AR/VR, stereoscopic, privacy, and foldable/rollable micro-LED displays. Candidate nano-optic structures and manufacturing process steps are presented. To illustrate fabrication principles, a micro-LED array with orthogonal sparse nano-polarisers demonstrated >8:1 photoluminescence polarisation contrast ratio.*

Keywords *Micro-LED, nano-optic, micro-optic, mass transfer, laser assisted, wafer, array, nano-polariser.*

1. Introduction

The displays industry continues to present new challenges for spatial light modulator technology including near-eye and heads-up display, large area (for example pillar-to-pillar displays in automotive vehicles), flexible/rollable displays for mobile and inevitably ongoing cost-down and power reduction. To this end, improved efficiency, increased colour gamut, extended dynamic range, large area, mechanical resilience and super-high resolution remain critical requirements.

With inorganic micro-LED displays offering a future route to exceed OLED and LCD performance in most or all of these areas, the challenge for the displays industry necessitates demonstrating mass transfer onto backplanes of millions of sub 10µm structures without damage and with sub-micrometre alignment tolerances. Various mass transfer techniques have been investigated [1,2], including electrostatic forces, elastomeric stamps [3], fluidic self-assembly [4] and laser assisted transfer [5,6].

Exploiting the unique interactions between light and matter at the nanoscale, an optical nanostructure is a material or device engineered at scales typically less than 100nm to manipulate and control light in ways that are often not possible with conventional materials and micro-optics. Using properties such as resonance, diffraction, scattering effects, enhanced light absorption, transmission, or reflection, nano-optics offer promise particularly when used in combination with the small light sources provided by micro-LEDs.

Conventional approaches to micro-LED optical manipulation typically use display-scale optical films. Macroscopic optics with complex nano-optical structures and high uniformity requirements would be low yield and prohibitively expensive. In an alternative approach, some workers have investigated incorporating nano-optics such as wire-grid polarisers directly into LED wafers [7, 8] to provide polarised output devices. However, such approaches can significantly impact the yield of individual micro-LEDs.

In this paper, nano-optic augmented micro-LEDs are proposed that offer simplified optical stack manufacture with increased yield while increasing functionality.

2. Nano-optic augmented micro-LED functionality

Figure 1 is illustrative of the goals for a future optimised nano-optic augmented micro-LED pixel, with an emitter-scale stack of wafer-mastered nano-optical structures applied in sequence to an underlying micro-LED with Lambertian or quasi-Lambertian narrow-band unpolarised optical output to enhance display system performance.

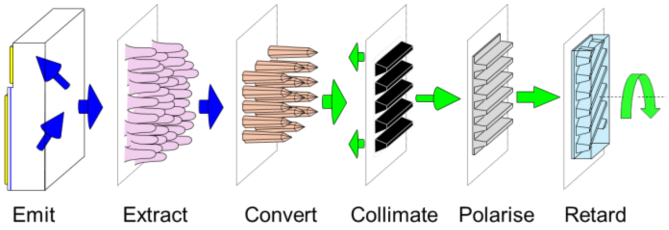

Figure 1. Nano-optic light manipulation from micro-LEDs on a pixel-by-pixel and layer-by-layer basis

Envisaged functionalities include efficient extraction of light using moth-eye or graded index structures that modify the coupling of guided light within the high index LED to the external optical environment. In a further example of coupling micro-LEDs to waveguides, such as used in AR eyewear, ultra-low index structures formed from sparse spacer columns surrounded by air can provide resilient attachment of pixels to waveguides while maintaining TIR light guiding for the coupled light.

Thin-film wavelength conversion structures such as quantum rod forests [9, 10] can enable new options for colour pixel fabrication, to mitigate yield losses from on-chip quantum rods. To improve system optical efficiency, output light collimation using diffractive, micro-louvre or micro-lens structures that direct light towards an optical exit pupil can be foreseen, with applications in efficient near-eye display and privacy display.

Further, meta-lenses can be added for collimation, deflection and light beam manipulation. Spectral and reflectance properties of micro-LEDs can be enhanced with multi-layer dichroic stacks with high layer numbers. For improved contrast nano-black materials such as Vantablack^{TM} may be applied between pixels for enhanced light absorption.

Ultra-thin polarisers and form-birefringent retardation can be applied for pixel level polarisation control, for example for stereoscopic display. In an early proof-of-principle demonstrator, nano-optics comprising wire-grid nano-polarisers are used to create pixellated polarised output for application to stereoscopic micro-LED display as will be described below.

3. Mass transfer fabrication methodology

Micro-LED wafer growth and nano-optic structure fabrication are processes that are vulnerable to defects and uniformity degradation with inherently low yield compared to the demands of defect-free displays.

Such yield losses do not enable sustainable full area utilisation of monolithic micro-LED or nano-optic growth wafers. The challenge of nano-optic augmented micro-LED displays is thus to combine these two low yield processes with selective transfer and a high yield attachment process.

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Nano-optic augmented micro-LED fabrication as described here refers to the addition of sparse arrays of nano-optic structures (i) to sparse arrays of micro-LEDs (*array-array* attachment) such as for direct view displays; or (ii) to monolithic (dense) array micro-display applications (*array-wafer* attachment) such as for AR/VR.

An example of array-array attachment is shown in Figure 2. The micro-LED array is fabricated, by GaN/AlInGaP wafer growth and mass transfer of sparse arrays of micro-LEDs onto a silicon or glass backplane with control circuitry. In parallel, nano-optic structures are fabricated most commonly by wafer-scale lithography and/or nano-imprint lithography (NIL). Defect and uniformity analysis is used to select suitable areas of nano-optic for mass transfer so that 'known good' regions from nano-optic wafer are mass transferred onto 'known good' micro-LEDs.

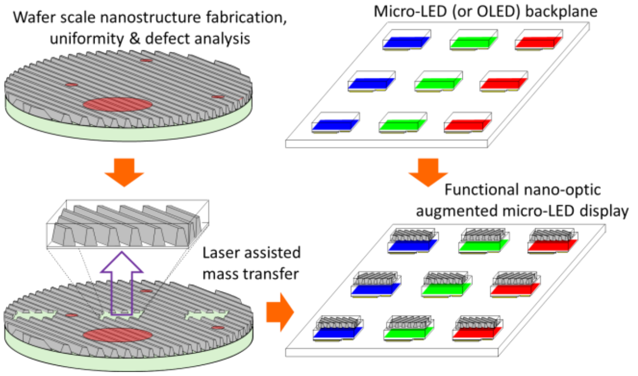

Figure 2. Wafer scale nano-optical structures are fabricated and analysed. Laser assisted mass transfer is used to transfer good regions of nano-structure onto the backplane-mounted micro-LEDs.

Nano-optic augmented micro-LEDs fabricated in this manner have distinct advantages compared to applying a single layer of nano-optic across the entirety of the micro-LED array. Uniformity variations and defects in the donor nano-optic array are not transferred, substantially increasing final display yield while the utilisation of the nano-optic donor is increased, thereby reducing the materials cost of nano-optic per display. The final device has fewer substrates, reducing thickness so that improved folding, rolling and alignment characteristics for ultra-thin display devices can be achieved. The substrate-free or minimal substrate thickness of transferred nano-structures also improves the optical coupling between the layers of the nano-optic stack, increasing efficiency. Scaling to larger display sizes does not necessitate large scale nano-optic mastering and replication so that multi-stage wafer-scale processing technologies can be used, even with relatively high defect densities, to produce displays substantially larger than the wafer diameter. Finally, for multi-stage optical manipulation of Figure 1, stack assemblies can be tested before transfer to optimise system performance, yield and uniformity.

4. Nano-optic wafer and transfer considerations

It is considered by the authors that the most promising approach for nano-optic transfer onto a micro-LED is by laser assisted mass transfer using a pattern of UV laser illumination to provide extraction from the growth wafer. Figure 3 illustrates various layers that can be considered during nano-optic wafer preparation in laser assisted mass transfer, and Table 1 shows illustrative material options for absorbing and transmissive layers when illuminated by a 248nm KrF excimer laser for a 5eV bandgap transmission threshold.

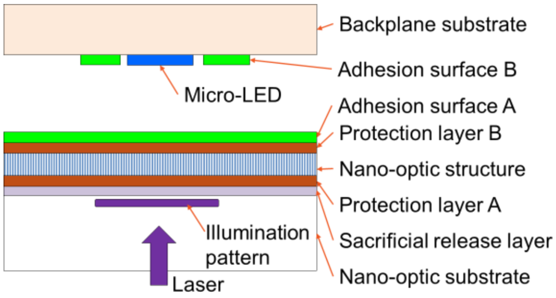

Figure 3. Nano-optic layers for laser assisted mass transfer

Table 1. Nano-optic stack material considerations

	Type	Material / (Nanostructure)	Material Bandgap (eV)	Refractive index @589nm
UV absorb @5eV	Metal	Al	4.3	1.20
	Polymer	PDMS	1.6	1.40
		polyimide	2.9	1.75
	Inorganic	Nb_2O_5	3.4	2.34
		GaN	3.4	2.40
		TiO_2	3.2	2.61
		SiC	3.26	2.65
		Si	1.12	3.98
UV transparent @5eV	Polymer	PEDOT:PSS	5.0~5.3	1.51
	Inorganic	MgF_2	>10	1.38
		SiO_2	7.5~9.7	1.46
		Al_2O_3 / sapphire	7	1.77
		Si_3N_4	6.9	2.02
		AlN	6	2.15

The UV transmissive nano-optic substrate is coated with a UV absorbing sacrificial material, for example a thin GaN layer for a dissociative release of the nano-optic structure. For direct transfer onto a micro-LED, the sacrificial layer can also serve to protect the multiple quantum well structure of the micro-LED from excessive UV illumination that may otherwise degrade its emission properties.

Optional protection layer A can provide mechanical resilience of the nano-structure during the ablative release, as well as protection during handling and attachment of the removed nano-structure and, depending on the absorption depth, can be combined with the sacrificial layer.

Similarly, sacrificial layer and protection layer A may be omitted and the nano-optic structure formed from a suitable bandgap material such that its input surface also acts as the sacrificial layer; indeed this is the case with the nano-polariser described below. In such a case, the interaction of the input laser wavefront with the nano-structure itself needs further consideration - for example, the polarisation state of the input beam can be used to tune absorption of the sacrificial region of the nano-structure.

Protection layer B also provides mechanical support and may be configured, by controlled cracking to distribute the mechanical forces on the nano-structure at release, reducing damage. Protection layers A and B can also have anti-reflection or index matching properties to enhance device efficiency.

Optional adhesive surfaces A, B provide attachment mechanisms to and around the micro-LED.

5. Nano-optic augmented micro-LED early proof-of-principle demonstration

5.1 Nano-polariser transfer

Figure 4 illustrates the optical stack of an aluminium wire-grid nano-polariser [11] on a UV transmissive substrate. Protection layer B is provided by a SiOx coating and MgF$_2$ overcoat, with total nano-stack thickness of approximately 1 µm.

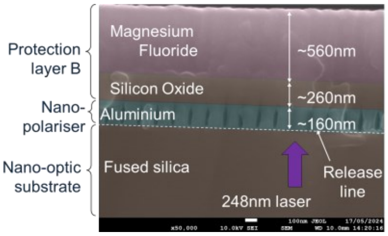

Figure 4. SEM of optical stack of wire grid polariser

Table 1 indicates that the aluminium metal has a bandgap to provide UV absorption at 248nm so for demonstration purposes the aluminium of the nano-polariser itself is used as the release material. The authors have found that by tuning process conditions, effective transfer that preserves the nanostructure with protection layer B delivered a repeatable methodology, as shown in Figures 5 & 6. Some nano-polariser degradation is evident, and an additional release layer would be expected to improve uniformity at the nano-scale.

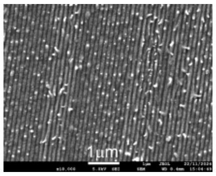

Figure 5. SEM image of nano-polariser released surface

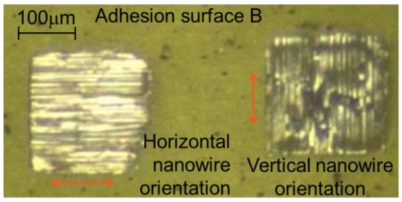

Figure 6. Transferred nano-polariser on adhesive layer B

Of note in the transfer, the nano-polariser is segmented into strips with 5~10um pitch. SEM investigations shown in Figure 7 indicate that this was due to cracking in the protection layer B and was present in the unprocessed samples, likely originating in differential thermal coefficients during processing. During laser assisted mass transfer, the cracks propagate and produce clean breaks at transfer edges.

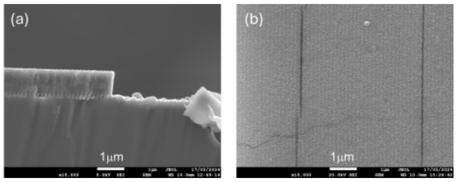

Figure 7. (a) Cross section of transferred wire grid polariser (b) Top view of cracks in protection layer that further propagate during device transfer

5.2 Polarised nano-optic augmented micro-LED demonstration fabrication

Figure 8 illustrates the various process steps to fabricate demonstration nano-optic augmented micro-LEDs.

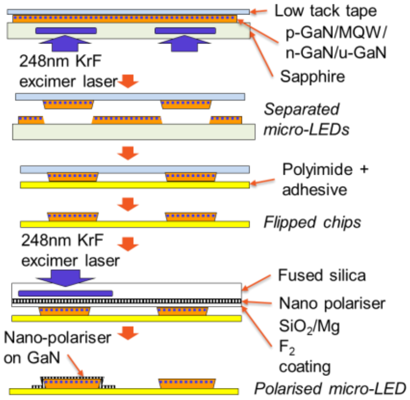

Figure 8. Demonstrator fabrication methodology

Figure 9 shows an example of polarised GaN devices aligned with an oversized nano-polariser, with adhesion surface B used to pin the nano-polariser in place around the micro-LED.

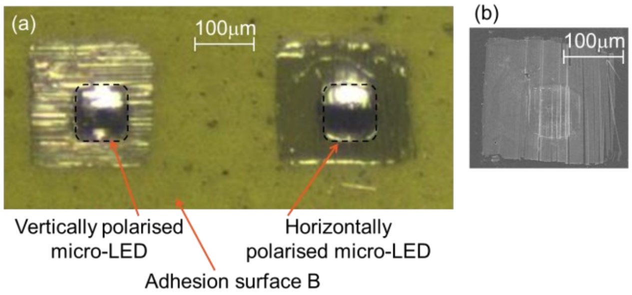

Figure 9. Nano-polariser augmented GaN LEDs (a) Photomicrograph (b) SEM image

The transferred strips enable some conformity to the ~7µm height deviations caused by the micro-LED on the substrate. With adhesion of the nano-polariser to the adhesion surface B only, this illustrated the 1D strapping effect of the bands of nano-polariser over the micro-LED. Further management of adhesion to the micro-LED surface and clean-room processing conditions would be expected to minimise the delamination artefacts visible in SEM and enhance contrast ratio.

5.3 Nano-optic augmented micro-LED array characterisation

Photoluminescent characterisation of the micro-LEDs is illustrated in Figures 10 & 11, with the output visible light analysed by rotation of a dichroic analyser. Photoluminescence output is illustrated in Figure 12.

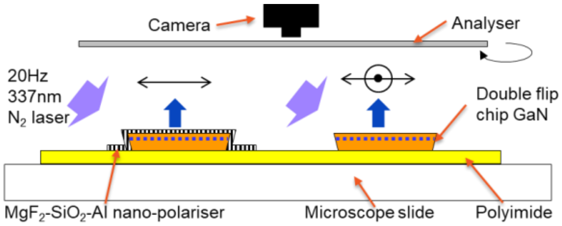

Figure 10. Polarised emission characterisation schematic

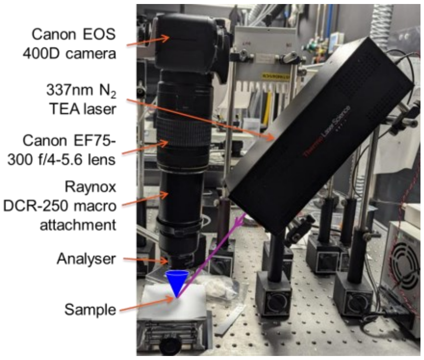

Figure 11. Polarised photoluminescence measurement apparatus

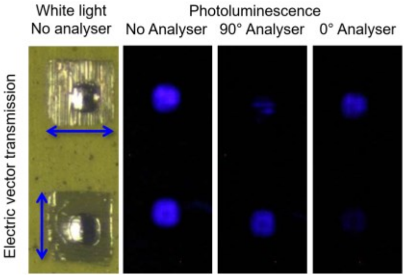

Figure 12. Analysed photoluminescent output

The underlying contrast ratio of the non-transferred nano-polariser is 30:1 and peak contrast ratio measurements of >8:1 were made from the nano-optic augmented micro-LED region as well as from the transferred polariser around the micro-LED. The observed non-uniformities of polarisation contrast ratio seen in Figure 12 corresponded well with SEM investigations of transfer integrity of the nano-polariser, for example as in Figure 9(b). Modification of transfer layers including an added sacrificial release layer and improved bonding are expected to reduce the difference between underlying and transferred element contrast ratios.

5.4 Polarisation efficiency enhancement

Improved output efficiency of polarised light using reflective polarisers is well known and this would be a significant benefit for nano-polariser augmented micro-LED. However, characterisation of recirculation efficiency is not a straightforward experimental measurement with the devices made here and is closely dependent on the details of the light recirculation stacking of the micro-LED and polariser, including the depolarisation scattering of the thin chip material, substrate reflections, retarder configurations as well as nano-polariser overlay characteristics that determine edge effects, for example as illustrated schematically in Figure 13(a).

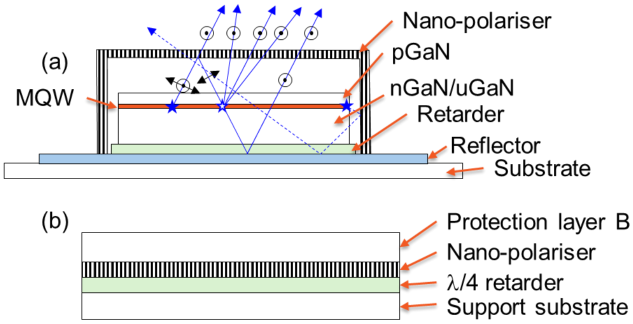

Figure 13. (a) Efficiency enhancement using scattering and polarisation state manipulation (b) alternative nano-structure stacking for reflection enhancement

Future work would evaluate suitable optical nanostructure stacks including the example of Figure 13(b) and use electroluminescent output, rather than front side photoluminescence.

6. Conclusion

Micro-LED manufacture continues to progress towards displays that are predicted to supplant incumbent LCD and OLED products. Nano-optic augmentation of micro-LED arrays offers to increase the sophistication of micro-LED display device performance through pixel level manipulation of micro-LED optical output.

Both micro-LED manufacture and nano-optic fabrication are inherently processes that are subject to defects and uniformity degradation and so are low yield processes in comparison to the demands of display defect rates. High display pixel yield can be achieved by combining selective mass transfer of micro-LEDs and nano-optics with a high yield attachment process.

As a practical example of the principles of nanostructure transfer onto micro-LEDs, an early stage technology demonstration using UV laser transferred micro-LEDs and separately transferred nanostructures has been used to demonstrate photoluminescent micro-LEDs augmented with nano-polarisers. A photoluminescent contrast ratio of >8:1 was demonstrated using a wire grid nano-polariser material with a pre-transfer contrast ratio of 30:1.

7. Acknowledgements

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