

# Laser-Based Micro/Nano-Processing Techniques for Microscale LEDs and Full-Color Displays

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Micro light-emitting diode (Micro-LED) display is an emerging display technology thanks to its high brightness, fast switching speed, and low power consumption. The commercialization of this technique is being explored by developing advanced processing techniques on an industrial scale. Recent ground-breaking advances in the manufacture of Micro-LEDs are mainly based on powerful laser micro/nano-processing techniques with the unique ability to fabricate materials, structures and devices with the advantages of non-contacting processing, high efficiency, adjustable coverage from micro- to macroscale and the compatibility with organic and inorganic materials. This paper categorizes, reviews and analyzes the main challenges and technical solutions in the Micro-LED displays by various laser manufacturing processes, covering chip dicing, geometry shaping, laser annealing, laser lift-off (LLO), laser-based Micro-LED transfer, laser-assist bonding (LAB) and laser repair. The fundamental principles of these techniques are discussed along with their basic mechanisms, followed by an exploration of the latest progress in the field. Finally, a detailed analysis of the advantages and disadvantages of these techniques is given, and the future research directions of laser techniques in Micro-LED display are discussed.

in terms of the power consumption, brightness, response speed, color saturation, display density, reliability, etc.

So far, a wide range of potential applications using Micro-LEDs have been explored, such as AR/VR,<sup>[4,16,17]</sup> high-definition TVs,<sup>[18]</sup> projectors,<sup>[19,20]</sup> smart contact lens,<sup>[21,22]</sup> smart watches,<sup>[23]</sup> automotive displays,<sup>[24]</sup> etc. Despite the great potential in these applications, the commercialization of Micro-LED displays has been hindered by many technical challenges and the prohibitive manufacturing cost.<sup>[25,26]</sup>

Micro-LED mass transfer process<sup>[9,27–35]</sup> is widely regarded as one of the biggest obstacles for Micro-LED display. Being small, ultrathin and fragile, Micro-LEDs cannot be properly manipulated using a conventional sequential pick and place method. The low transfer speed is another major factor limiting the use of a conventional die bonder (40 k/h). For commercial success and cost con-

sideration, the transfer speed must be one-order faster than surface-mount technology (SMT) techniques at least. Hence a mass transfer technique is used wherein a large number of devices from the growth wafer are released and transferred to the target substrate in a massively parallel fashion.<sup>[9]</sup> However, this is proven to be very challenging because accurately assembling millions of Micro-LEDs onto a driving circuit requires a complicated transfer and bonding process. For example, ≈25 million chips are needed for a 4 K TV display. Such a massive amount demands the high-throughput capability of the transfer method to increase the integration efficiency and cost-effectiveness. Therefore, high-throughput technologies that accurately and cost-effectively assemble microscale devices on display substrates with high yield are key enablers for Micro-LED displays.<sup>[9]</sup> To address these challenges, a variety of massive transfer technologies have been developed, such as stamp transfer,<sup>[27,28]</sup> fluid transfer,<sup>[29,36,37]</sup> electrostatic transfer,<sup>[30]</sup> magnetic transfer,<sup>[31,32]</sup> roll-to-roll,<sup>[3]</sup> etc. However, most of these techniques suffer from the poor transfer accuracy and compromised transfer yield. Therefore, although all the transfer approaches mentioned above do work in principle, their commercial viability for high yield assembly onto a silicon backplane is doubtful. Bonding for reliable interconnect of the die to the driver backplane<sup>[8,38–41]</sup> is another technical bottleneck to be solved. Although die-to-wafer bonding,<sup>[42]</sup> and wafer-to-wafer<sup>[43]</sup> bonding techniques based on low-melting

## 1. Introduction

The revolution of various display techniques has notably enriched our daily life. From smart phones and laptops to large TVs, we are living in a vivid world of exchanging visual information by using various display electronics. Meanwhile, some new applications such as VR/AR, wearables, and high-definition screens have driven the development of new display technologies. As one example, emissive displays based on micrometer sized light emitting diodes (Micro-LEDs) have emerged recently,<sup>[1–15]</sup> thanks to their incomparable advantages over conventional liquid crystal technology and OLEDs

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solders are available, these techniques suffer from serious bonding reliability issues such as misalignments, open circuits and shorting effects, due to the reduced pixel size. The third challenge lies in the defect management.<sup>[44,45]</sup> Since the transfer yield of Micro-LEDs is unlikely by 100%, inspection and repair technologies are indispensable to enhance and assure production yield. Assuming the transfer bonding yield is 99.9%, a 4K TV would have  $\approx 25\,000$  defects. Given that Micro-LED chip dies are small, how to efficiently repair and replace bad dies after identifying them is a challenging task.

Recent advance in laser-based techniques<sup>[46–55]</sup> sheds light on overcoming these challenges. Significantly different from the traditional processes, laser processes have unique advantages such as rapid processing, high material selectivity in the multi-material system, flexible and controllable processing area, noncontact interaction mode, highly-localized affected area, and remarkably high levels of controllability. Being high-power, highly directional light sources induced by stimulated emission, lasers can cause strong physical/chemical interactions with the materials (or devices) being irradiated, and result in localized heating, phase change, ablation, delamination and/or material decomposition.<sup>[56]</sup> Taking use of these effects, lasers have been widely used for a variety of Micro-LED processing such as dicing, drilling, surface texturing, thermal annealing, chip mass transfer, interconnect printing, laser lift-off (LLO), and defect repair. For instance, lasers serve as a heat source for rapid annealing, and forming ohmic contact of low contact resistance for Micro-LEDs.<sup>[57,58]</sup> Laser induced heating, ablation and decomposition are utilized for Micro-LED dicing,<sup>[59]</sup> chip shaping<sup>[60,61]</sup> and surface texturing.<sup>[62]</sup> Substrate removal by LLO is another well-established technique for making high power LEDs for general lighting<sup>[63]</sup> and are now extended for making thin film Micro-LEDs by exploiting the UV laser irradiating at the GaN/sapphire interface through a transparent sapphire substrate and laser-induced GaN decomposition under high temperature.<sup>[34]</sup> Micro-LED transfer techniques such as LLO-assisted transfer,<sup>[47,64]</sup> and laser induced forward transfer (LIFT)<sup>[52]</sup> have been also developed, which exhibited several orders of magnitude faster transfer speed than other approaches. Laser-assisted bonding<sup>[54]</sup> is another field being actively explored, which is very effective for the bonding integration of Micro-LEDs onto the backplane by applying localized heat to the solder bumps. Laser is also powerful for Micro-LED trimming and repairing, and particularly suited for selective defect management, while without affecting the adjacent working device.<sup>[52,53]</sup> More importantly, laser technology is fully scalable and can cope with the trend of smaller and smaller Micro-LED chips without costly reinvestment or process replacement. Therefore, just as commercial success of laser processing has been achieved in OLED and LCD industry,<sup>[65]</sup> undoubtedly laser-based processes will play a critical role in manufacturing Micro-LED displays. This is evidenced by the fact that many companies are investing on the development of laser-based processing equipment for large-scale Micro-LED production, such as Coherent, Toray, ASM, UniQarta, QMAT and Tesoro Scientific.<sup>[52,66,67]</sup> Significant progress in laser equipment for Micro-LED has been achieved.

Here, we present an overview of various laser processing techniques used in the manufacture of Micro-LEDs and displays (**Figure 1**), covering laser dicing, chip shaping, surface texturing, via drilling, laser annealing, laser lift-off, laser-based Micro-LED transfer printing, laser direct writing (LDW), and laser detection and repair. We begin the review by introducing the laser-material interactions, and discussing how they affect the material property. We then give a comprehensive review of various laser-based techniques used for the fabrication, substrate removal, die transfer, die bonding, and defect repair of Micro-LED. We discuss the merits and disadvantages of each processing technique, along with the relevant processing details and Micro-LED device performances. Finally, we highlight the commercial potential and provide a perspective regarding the opportunities for further progress in this field. Our review aims to motivate researchers to translate the benefits afforded by laser-relevant processing into large-scale industrial production of Micro-LED display devices.

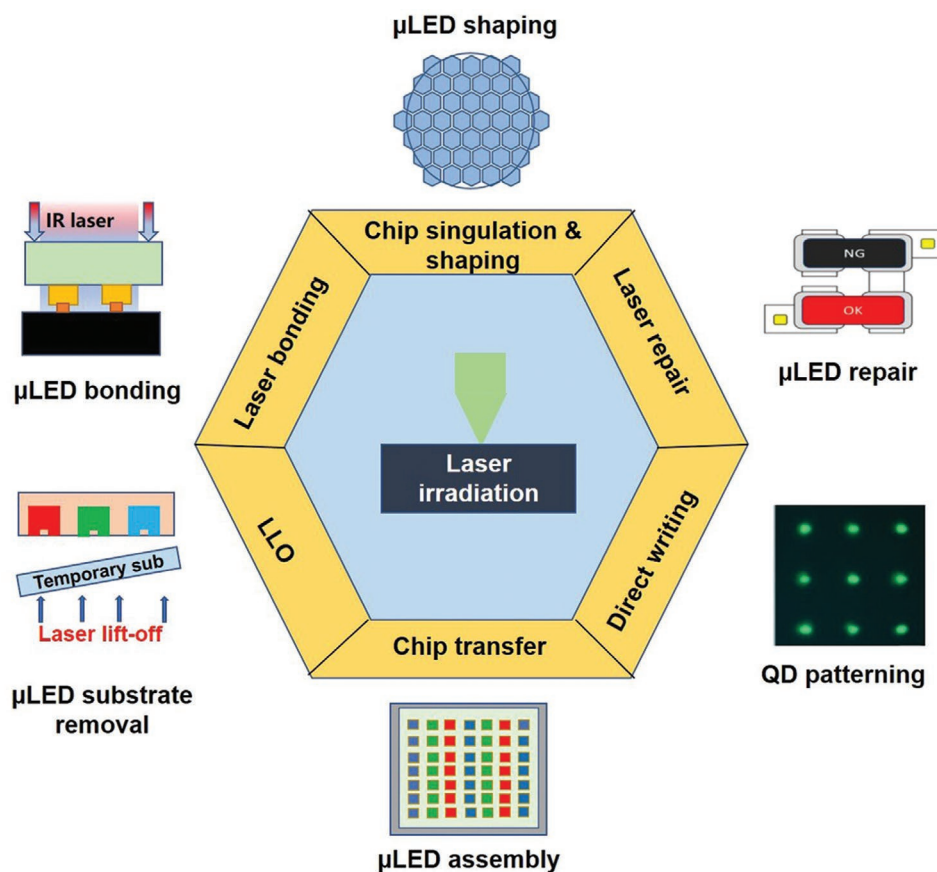
## 2. Overview of Micro-LED Displays and Laser-Material Interactions

### 2.1. Micro-LED Characteristics and Device Structures

In simple terms, Micro-LEDs (**Figure 2a**) often refer to inorganic, microscale light-emitting diodes, with a typical dimension ranging from a few microns to a few tens of microns.<sup>[68]</sup> Despite of their much smaller dimensions than conventional LEDs used for general lighting, Micro-LEDs possess many excellent properties such as high brightness, long lifetime, fast switching time, and low power consumption.<sup>[8]</sup> Consequently, Micro-LEDs are regarded as excellent light emitters for emissive, high-resolution displays. Not only is its in-plane dimension notably reduced, but also Micro-LED is much thinner in the vertical direction because the original growth substrate is commonly taken off.<sup>[47,69]</sup> It is believed substrate-free devices can remarkably improve the display contrast and suppress the sidewall emission induced by the thick substrate.

The emission wavelength of the Micro-LED is determined by the bandgap of semiconductor active layers deposited on the substrate. For example, blue and green Micro-LEDs can be achieved from InGaN MQWs grown on sapphire substrates, whose bandgap can be tuned by controlling the indium composition in the MQWs. Red Micro-LEDs, on the other hand, are commonly made from AlGaInP MQWs grown on GaAs substrates.<sup>[59,70–72]</sup> The well-established epitaxy technique for Micro-LEDs is mainly based on MOCVD, although other techniques such as MBE,<sup>[73]</sup> and PLD are also available but commercial success is not achieved. Since the epitaxy technique is adapted from those for conventional large size LED, technical obstacles for Micro-LED epitaxy are relatively limited, but both the wavelength deviation and the epitaxy defect density across the wafer must be minimized.

Similar to conventional large-size LEDs, there are three different Micro-LED device structures, including top-emitting chip, flip-chip and vertical chip.<sup>[74]</sup> Currently, flip-chip Micro-LEDs are used most frequently, primarily because they are easier for bonding and integration onto the driver backplane,



**Figure 1.** Various laser-based processing techniques for Micro-LED and displays. Lasers are used for multiple purposes, including chip shaping, defect repair, substrate removal, chip bonding, chip mass transfer, QD patterning, etc.

and they have higher efficiency than the top-emitting counterparts.<sup>[9]</sup> Vertical chips<sup>[64]</sup> are also very efficient, but the integration of vertical chip is more complex, considering two electrodes face oppositely.

## 2.2. RGB Micro-LED Display Architecture

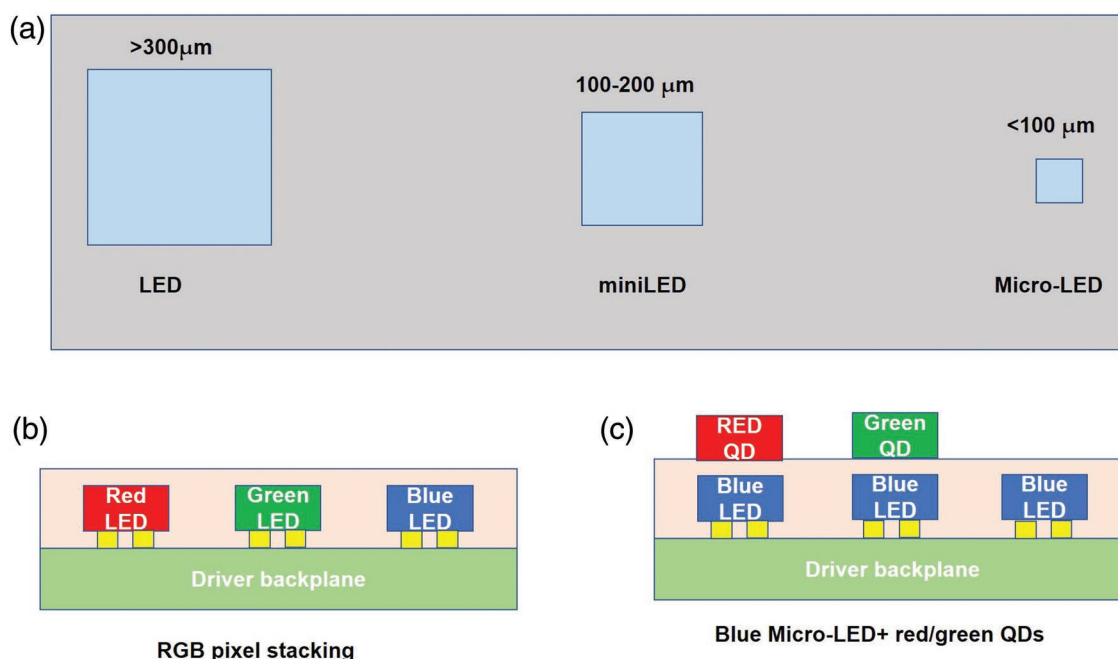
Although monochromatic displays can be made from Micro-LEDs emitting at the same wavelength, full-color Micro-LED displays are more desired because of the wider application prospects. So far there are two major display architectures<sup>[9,75]</sup> that have been proposed, as schematically shown in Figure 2b,c. Each configuration has its merits and disadvantages. The first configuration (Figure 2b) is based on the stacking of discrete RGB Micro-LED chips onto the driver backplane.<sup>[9]</sup> Through independent control of each unit containing RGB pixels, various mixed emission colors can be realized by controlling the driver current of each pixel. This configuration is the preferred display architecture, and many display panel makers are using this configuration. The major technical challenges of developing Micro-LED displays in this configuration, however, lies in the mass transfer of the RGB Micro-LEDs emitting at different wavelengths from the source wafers, and bonding them to the backplane, since the process relies critically on the transfer rate, alignment accuracy, bonding strength and reliability of all three types of

Micro-LEDs emitting at blue, green and red wavelengths. The defect management is another major issue to be addressed.

Alternatively, full color display can be enabled by using a blue-emitting Micro-LED array with integrated green and red color converters<sup>[75–77]</sup> (Figure 2c). In the latter configuration, mass-transfer of individual Micro-LEDs is not necessarily required. Instead, wafer bonding is commonly used to integrate all blue-emitting pixels on the driver backplane simultaneously, which can simplify the Micro-LED process. Green and blue quantum dots (QDs) are then patterned and integrated onto blue emitters. Through down converting of the blue emission to green and red, a full-color display can be also enabled. While this concept does work, it also faces some technical obstacles. For example, the low QD conversion efficiency<sup>[76–79]</sup> may seriously compromise the display performance, in particular the power consumption. There is also no mature, cost-effective method to produce thick enough QD patterns of ultrahigh resolution, and integrate them reliably onto the ultrasmall Micro-LEDs. Finally, the lifetime and reliability issue of QD/Micro-LED hybrid devices are major limiting factors remaining to be overcome.

## 2.3. Basics of Laser Interactions with Materials

In this section, we have a brief introduction of the various physical processes that the laser beam can interact with materials, in



**Figure 2.** a) Dimension comparison among a conventional large-size LED, a miniLED, and a Micro-LED; Micro-LED display architectures based on b) RGB pixel stacking, and c) a blue Micro-LED array with integrated green and red quantum dots (QDs).

order to understand the capabilities of laser processing. Laser is produced by the transition of atoms (or molecules, ions, etc.) as well as spontaneous emission, just like other luminescence in nature. But unlike the ordinary light sources, lasers can travel as a very narrow beam and the property of high spatial and temporal coherence makes it highly directional so that it has extremely high energy density and laser brightness.<sup>[56]</sup> With such high optical power density, lasers make possible to deposit, remove and modify almost any material property through strong laser–material interactions.<sup>[80]</sup> When a laser beam is incident on the surface of a material, various phenomena can occur, including reflection, refraction, absorption, scattering and transmission. The laser energy absorbed by the material during laser–material interaction is converted into heat accumulated in the material. Depending on the magnitude of the temperature rise, various effects such as heating, melting, vaporization, ablation and plasma formation can be induced. These effects constitute the basis of several laser materials-processing techniques, as schematically show in **Figure 3**.<sup>[80]</sup> The extent of these effects primarily depends on the laser characteristics such as laser intensity, laser wavelength, pulse duration time and angle of incidence, as well as the materials parameters including absorptivity, thermal conductivity, specific heat, etc.

Among these parameters, the absorption coefficient of the material is one of the most important parameters affecting the laser–material interactions. According to the Beer–Lambert law,<sup>[81]</sup> the absorption of laser radiation in the material is generally expressed by the equation:

$$I(z) = I_0 e^{-\alpha z} \quad (1)$$

where  $I_0$  is the incident intensity,  $I(z)$  is the intensity at depth  $z$ , and  $\alpha$  is the absorption coefficient. The absorption coefficient

$\alpha$  directly determines the penetration depth, which is given by  $h = \frac{1}{\alpha}$ . Stronger absorption materials lead to shallower penetration depth.

Laser irradiation wavelength is another important parameter, which is directly correlated with the absorption coefficient  $\alpha$ , and can be expressed as:<sup>[82]</sup>

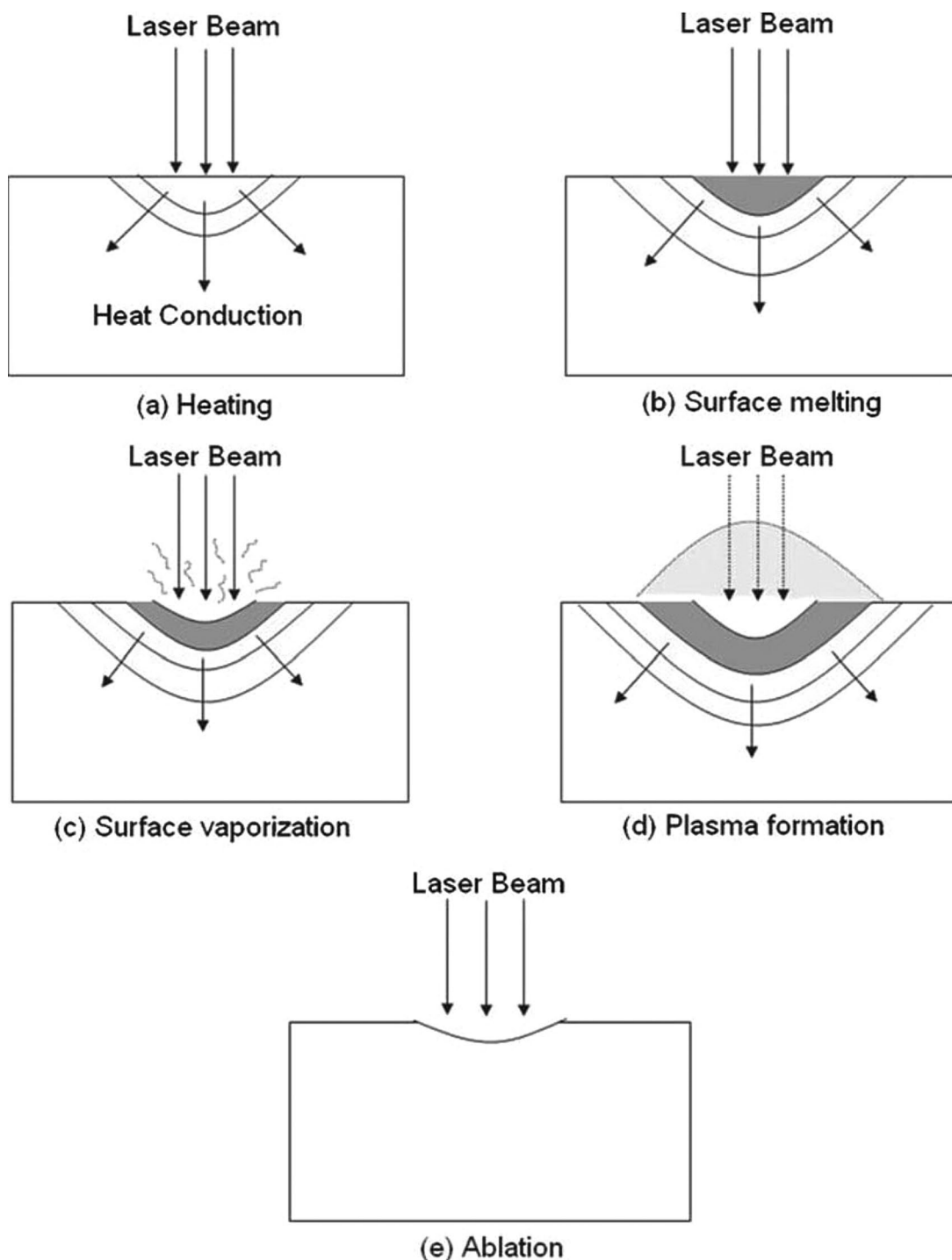
$$\alpha = 4\pi k_e / \lambda \quad (2)$$

where  $k_e$  is the extinction coefficient. To minimize laser induced damage to the adjacent layer, the penetration depth  $h$  should be as small as possible. Therefore, UV short wavelength lasers are more powerful to achieve smaller irradiation depth than those lasers in the long wavelength region.

Other parameters such as laser pulse width, laser irradiation time, and thermal conductivity of the materials also affect the laser–material interactions.<sup>[83]</sup> Higher thermal diffusivity leads to a sharper temperature–depth gradient in the materials. Lasers with short pulse widths are very helpful for material processing where localized heating is strictly required, in order to avoid thermal damage to temperature-sensitive materials. Laser peak intensity, on the other hand, can be modulated to accurately control the peak temperatures at the interface, which may find applications in interfacial modifications or the decomposition of interface materials.

### 3. Laser Processing Techniques for Micro-LEDs

Laser processing techniques have been widely applied in the last 20 years in semiconductor industry, in particular for wafer dicing, and TFT production for LCD and OLED display.<sup>[84]</sup>



**Figure 3.** Various laser–material interactions. Reproduced with permission.<sup>[80]</sup> Copyright 2008, Springer Nature.

A major advantage of laser processing relies on the ability to directly structure matter at different scales and to prepare novel materials with unique physical and chemical properties. It is also a contact-free approach that makes it possible to work in an inert or reactive environment.<sup>[85]</sup>

Micro-LED is an emerging display technology, which has many advantages compared with existing display techniques such as

LCD and OLED displays. However, the manufacture of Micro-LEDs is proven to be challenging. Many different laser processes have been developed to meet the need of fabricating next-generation Micro-LED display panels, such as LED geometry shaping, chip singulation, chip transfer, substrate removal, QD patterning, defect repair, etc. In the following, we give a detailed review of these laser-based processes for Micro-LED displays.

### 3.1. Chip Singulation

Laser dicing has been well established for conventional large-size LED singulation. Laser dicing uses laser technology to dice the wafer by delivering focused laser beams onto the wafer, and generating a spot of high localized temperature to remove the dicing lane area between the chips. The laser induced temperature is so high, such that the area under the laser spot is ablated or vaporized. The laser can also be focused to deliver this heat into the bulk of the wafer, this method is called “stealth” laser dicing. For this approach, the heat from the laser creates voids within the dicing lane. These weakened regions then act like a perforation and tear apart when the wafer is expanded. Laser dicing has the advantage for higher cutting speed, smaller kerf width, better dimension control, accurate ablation depth control and lower damage to the die, compared with conventional mechanical saw dicing. An extra benefit of laser dicing is the reduced amount of stress imparted on the die.

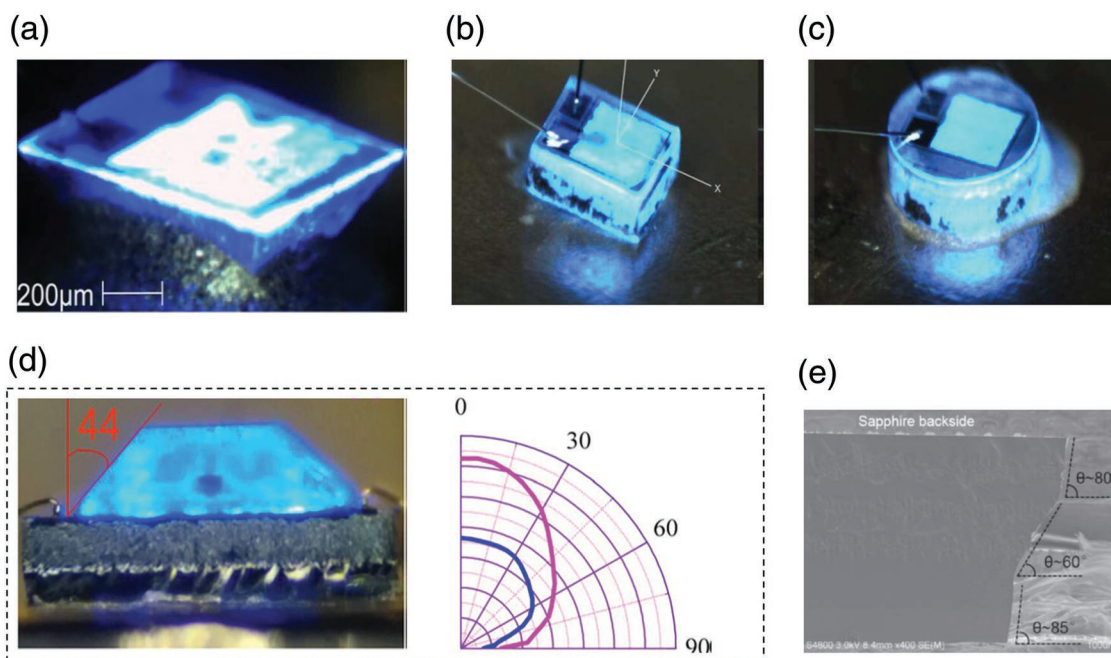
In the case of Micro-LED laser dicing,<sup>[59]</sup> however, a few extra factors must be considered. First, the Micro-LED chip dimension is commonly in the order of a few tens of microns or even less. Therefore, the dicing-induced damage to the sidewall must be minimized, as well as the shape distortion and dimension variation. Choosing the right laser with medium irradiation intensity and ultrashort pulse width may play a critical role for minimizing the laser-induced damage and dimension variation. Second, dicing street width must be as small as possible, in order to increase the die numbers per wafer, and control the dicing cost. The conventional dicing limits the street width of LED chips to 80–100  $\mu\text{m}$ . While this is fine for large-sized

LEDs for general lighting, it is not economic for singulating Micro-LEDs with reduced dimension. Therefore, for Micro-LED dicing, the laser spot size must be significantly reduced. Finally, the high cost of ownership of a laser dicing system and its low material removal rate makes laser dicing more competitive for ultrathin wafers.

### 3.2. Chip Shaping, Surface Texturing, and Via Drilling

#### 3.2.1. Chip Shaping

LEDs are emissive light sources which can find applications for general lighting and displays. However, common LEDs with a rectangular geometry suffer from limited light efficiency, due to the large refractive index contrast between the semiconductor and ambient medium. According to Snell's law, the critical angle of total reflection on the interface of nitrides to air is only  $24^\circ$ . Consequently, for those LEDs grown on sapphire substrates, a significant amount of the light will be trapped as a guided mode, with 66% trapped in the GaN, and 22% trapped in the sapphire substrates. Geometry shaping is an effective means to alleviate this issue.<sup>[60]</sup> Laser micromachining, compared with other techniques, is a versatile and flexible method for micro-machining and precision manufacturing of miniature components with various geometry shapes. **Figure 4a–d** shows examples of LEDs with various geometries defined by laser machining, including reverse pyramid, cubic, cylinder and truncated pyramid.<sup>[60,61,86]</sup> Sapphire sidewall shaping<sup>[87]</sup> was also effective for enhanced efficiency (Figure 4e). Some of these shapes are virtually impossible to be achieved by other



**Figure 4.** Laser-micromachined LEDs with different geometries. a) Inverted pyramid. Reproduced with permission.<sup>[60]</sup> Copyright 2009, IEEE. b) Cube. Reproduced with permission.<sup>[86]</sup> Copyright 2009, The Optical Society. c) Cylinder. Reproduced with permission.<sup>[86]</sup> Copyright 2009, The Optical Society. d) Truncated pyramid. Reproduced with permission.<sup>[61]</sup> Copyright 2013, AIP Publishing. e) A LED with multiple shaped sidewalls. Reproduced with permission.<sup>[87]</sup> Copyright 2017, IOP Publishing.

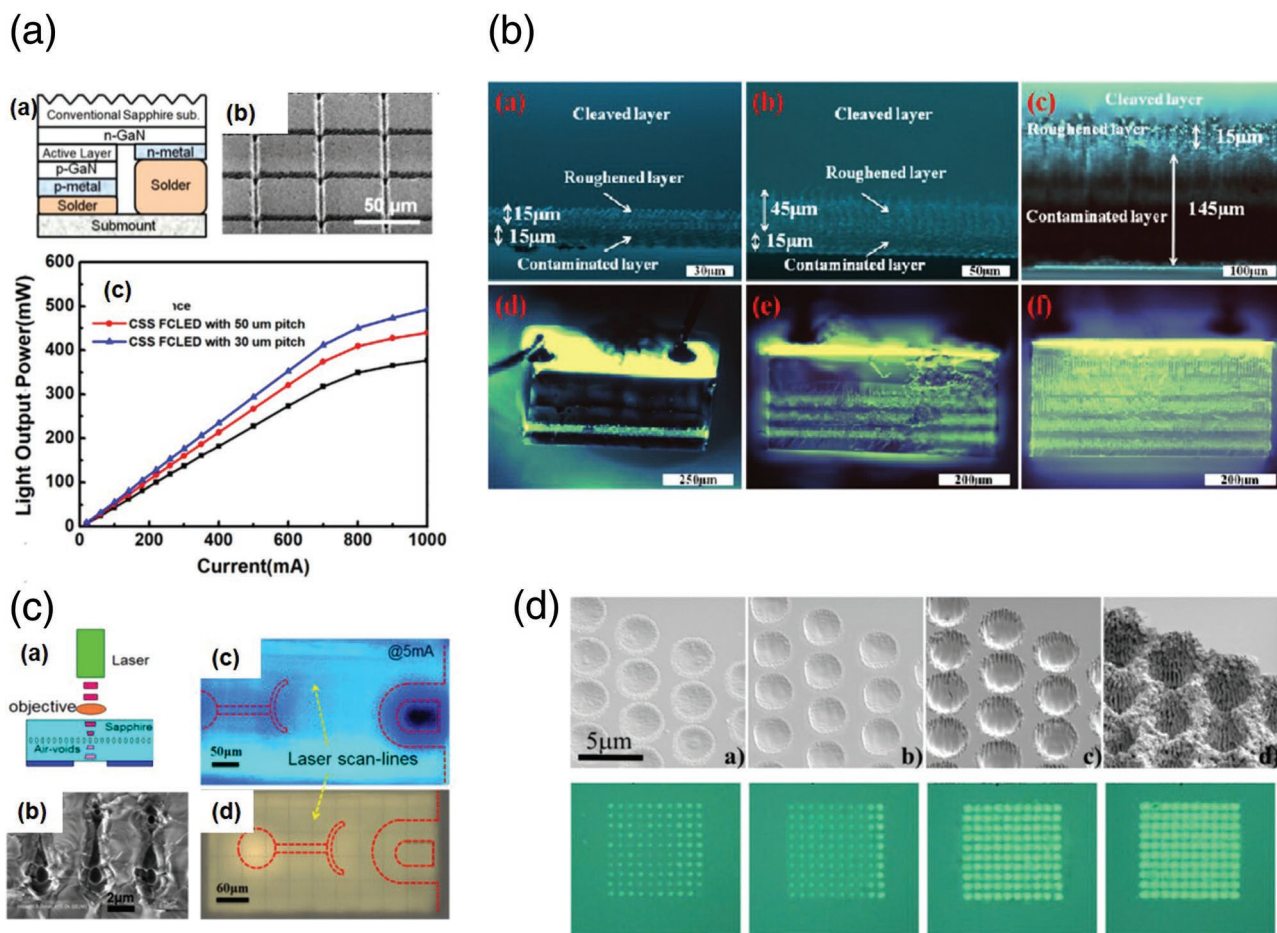
techniques. In all cases, LED devices shows improved light extraction, compared with conventional rectangle shaped LEDs. The actual degree of the brightness improvement is highly dependent on the geometry and the sidewall angle. The beam profile of these LEDs can be also notably altered, depending on specific geometry and sidewall angle.<sup>[61]</sup>

### 3.2.2. Surface Texturing

Surface or sidewall texturing is an alternative technique for improving light extraction. Ku et al.<sup>[62]</sup> demonstrated the mesh-patterned sapphire with 30  $\mu\text{m}$  pitch via nanosecond pulsed laser scribing could significantly improve the light extraction of the flip-chip LED by 28.7%, compared with the counterpart with flat sapphire (Figure 5a). Zhang et al.<sup>[88]</sup> reported a multiple laser stealth dicing (multi-LSD) method to form multiple texture patterns on the sapphire sidewall using a picosecond (ps) laser (Figure 5b). As a result, the light extraction efficiency (LEE) of InGaN-based light-emitting diodes (LEDs) was improved by 11.2%, compared with single stealth-diced LEDs.

The enhanced LOP is due to the increased side emission from the large-area roughened sidewalls of the sapphire substrates fabricated in the multi-LSD process. The same group<sup>[89]</sup> also reported the use of stealth dicing to form dumbbell-like air-void array inside the sapphire substrate using a picosecond (ps) pulse laser, leading to 24.7% improvement of the light output power, which was explained by the strong light scattering at the air-void array/sapphire interface (Figure 5c). The formation of dumbbell-like air-void array was attributed to the local heating effect around the laser focus. Jelமாக et al.<sup>[90]</sup> found the light extraction of a flip-chip LED can be enhanced up to 40% by forming micro-hole arrays on the sapphire substrate via femtosecond laser pulse irradiation (Figure 5d).

A detailed summary of the light extraction efficiency (LEE) improvements for different laser-defined sidewall angles, LED geometries, and surface texturing patterns is given in Table 1. Despite the improved brightness of large size LEDs, whether these laser-based methods can be extended to roughen Micro-LEDs, remains to be clarified. Micro-LEDs would be more sensitive to laser-induced damage, simply because of the much smaller junction area.



**Figure 5.** Various LEDs with textured surface or textured sidewalls. a) Flip-chip LEDs with mesh-patterned sapphire with 30  $\mu\text{m}$  pitch via nanosecond pulsed laser scribing. Reproduced with permission.<sup>[62]</sup> Copyright 2019, Elsevier. b) LEDs with multiple texture patterns on the sapphire sidewall by stealth dicing using a picosecond laser. Reproduced with permission.<sup>[88]</sup> Copyright 2012, The Optical Society. c) LEDs with dumbbell-like air-void array inside the sapphire substrate formed by stealth dicing. Reproduced with permission.<sup>[89]</sup> Copyright 2013, The Optical Society. d) LEDs with patterned microhole sapphire substrate via femtosecond laser pulse irradiation. Reproduced with permission.<sup>[90]</sup> Copyright 2015, IOP Publishing.

**Table 1.** Summary of the LEE improvements for different LED geometry, sidewall angle, and surface textures defined by laser processing.

Processing category	LED geometry/texture pattern	Sidewall angle	LEE improvement	Reference
Geometry shaping by laser processing	Reverse pyramid	−50°	85.2%	[60]
	Cuboid	90°	18.3%	[86]
	Cylinder	90°	14.22%	[61]
	Truncated pyramid	44°	46%	[87]
Surface texturing by laser processing	Mesh-patterned sapphire	/	28.7%	[62]
	Textured pattern on the sapphire sidewall	/	11.2%	[88]
	Dumbbell-like air–void array	/	24.7%	[89]
	Patterned micro-hole array on the sapphire substrate	/	Up to 40%	[90]

### 3.2.3. Via Drilling

Pulsed laser is also powerful for drilling microscale via holes, which are required for a number of reasons. Via holes have found commercial application in 3D packaging, where high density conductive micro-vias must be formed in the interposer to connect traces and pads on the top and bottom surfaces.<sup>[91]</sup> While deep dry etching is well established to form via holes in silicon, laser drilling is a preferred technique for forming via holes on hard substrates such as sapphire, and glass, because of the higher throughput. Likewise, via holes formed by laser drilling can find many applications in extending LED functionality and performance.<sup>[92]</sup>

For instance, Lee et al.<sup>[92]</sup> reported the formation of via holes on the sapphire substrate by laser drilling, leading to the efficiency improvement of the UV LEDs by 19% (Figure 6a). Wu et al.<sup>[93]</sup> demonstrated a novel LED device with an n-contact formed at the sapphire backside by depositing n-metals through the laser-drilled micro via holes (as shown in Figure 6b). With this modification, the device becomes surface-mountable and thus facilitates the integration of LED onto the package. The additional benefit is the 17.4% improved luminous efficiency, due to the decreased n-junction area and increased effective p-junction emission area (Figure 6b-i), compared with the reference LED (Figure 6b-ii). Via holes are also important structures for interconnection of the various components between different layers for LED display applications.<sup>[94,95]</sup> For example, Verplancke et al.<sup>[94]</sup> demonstrated a stretchable 64 × 45 RGB LED display prototype by assembling a RGB LED matrix onto the circuit using pick-and-place techniques, followed by interconnecting the anodes and cathodes between different layers through screen printing isotropic conductive adhesives into laser drilled via holes (Figure 6c). Phung et al. used a similar strategy based on via holes to fabricate a LED matrix display on multilayer flexible printed circuit board.<sup>[95]</sup> These works clearly demonstrate that well-defined via holes can be fabricated by using lasers technology. Nevertheless, ensuring the via bottom is clean and the chip is not thermally damaged are important considerations for via hole processing based on laser drilling.

### 3.3. Laser Annealing

Laser annealing refers to the technique of annealing materials or devices using a focused laser beam. As an example, laser annealing induces the crystallization of amorphous

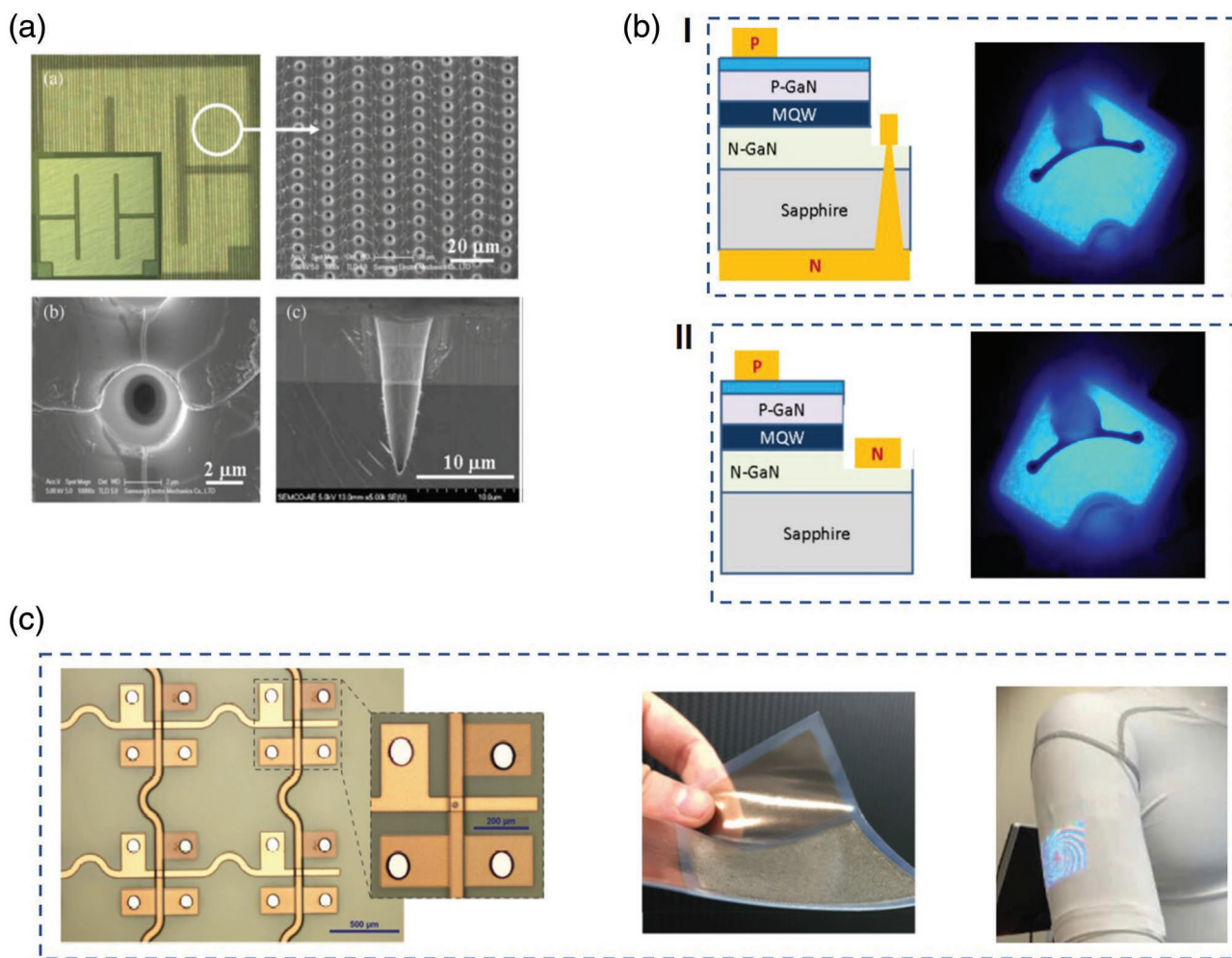
silicon films without heating substrates to a high temperature, resulting in the forming of low-temperature polycrystalline silicon (LTPS) films with high carrier mobilities.<sup>[65]</sup> It should be emphasized that laser annealing has been used for the large-volume production of low-temperature polycrystalline silicon (LTPS) TFTs for LCD and OLED displays. However, we will not discuss this area of study since it has been covered by a number of articles. Instead, we concentrate on reviewing the potential of this technique for inorganic LEDs and displays.

In the case of III-nitride LEDs, laser annealing has been mainly employed to form good electrical contacts with low contact resistance.<sup>[57,58,96,97]</sup> The formation of very low-resistance ohmic contacts is essential for the further improvement of the electrical and optical performance of such devices, because a large voltage drop across the GaN/contact interface leads to poor device reliability. Jang et al.<sup>[96]</sup> demonstrated the laser irradiation was effective for decreasing both p-contact and n-contact resistance (Figure 7a). For n-type GaN, laser annealing using a pulsed KrF excimer laser resulted in forming an ohmic contact with low specific contact resistivity of  $1.7 \times 10^{-6} \Omega \text{ cm}^2$ . The mechanism of the low n-contact resistance was explained by the formed N vacancies, which lead to form a degenerated GaN layer near the surface. In the case of p-type GaN, the laser irradiation increased both the acceptor concentration and the activation efficiency of Mg dopants, which in turn decreased the p-contact resistance to  $3.6 \times 10^{-4} \Omega \text{ cm}^2$ . More recently, M. Mikulics et al.<sup>[57]</sup> developed a laser-micro-annealing (LMA) technology for the precise local conditioning of nano-LEDs (Figure 7b). The experimental data confirm the reduction of the defect layer depth from 17 to 5 nm determined by the LMA process. Consequently, both the *I*–*V* and EL performance of the devices are significantly improved, compared with the reference sample without laser annealing.

Unlike other techniques, laser-based annealing has one distinct advantage for selective irradiation. Therefore, forming localized contact without affecting other areas is possible. Despite these progresses, laser annealing is regarded as a more expensive process, imposing practical limitations for massive formation of good electrical contacts, compared with the conventional thermal annealing process.

### 3.4. Substrate Removal

For GaN-based LEDs grown on sapphires, there are a few reasons to take off the growth substrate. First of all, sapphire is



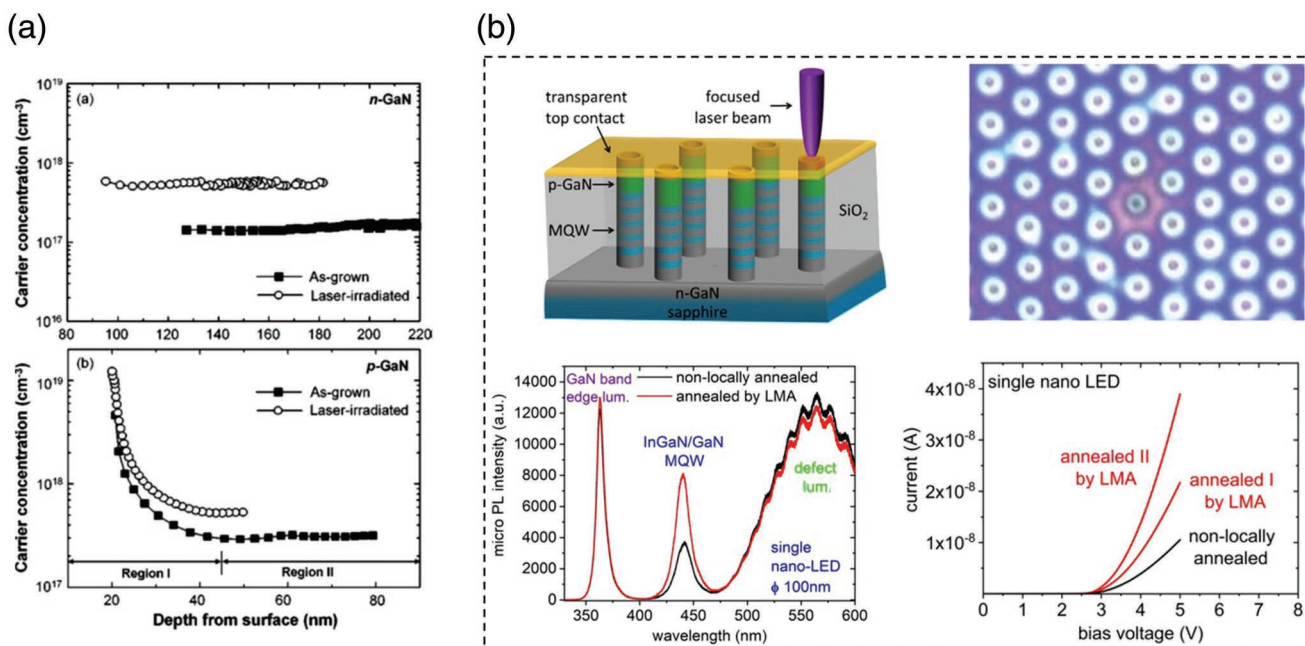
**Figure 6.** a) UV LEDs with drill v-shaped holes in the sapphire. Reproduced with permission.<sup>[92]</sup> Copyright 2010, IEEE. b) A novel LED device with n-contact formed at the sapphire backside by depositing n-metals through the laser-drilled micro via holes (top image). For comparison, the configuration of a reference LED without via drilling is also included (bottom image). Reproduced with permission.<sup>[93]</sup> Copyright 2011, Trans Tech Publications. c) A stretchable 64 × 45 RGB LED display prototype formed by interconnecting electrodes through screen printing isotropic conductive adhesives into laser drilled via holes. Reproduced with permission.<sup>[94]</sup> Copyright 2016, Society for Information Display, published by Wiley.

not thermally conductive enough, and thus restricting the LED performance at high current injection. Second, due to the large infraction index difference between sapphire and air, a large quantity of light will be trapped inside a sapphire, leading to limited light extraction.<sup>[60]</sup> Third, a thick sapphire will induce strong side-wall emission, which causes undesirable optical crosstalk effects for display.<sup>[98–100]</sup> This is particularly true for Micro-LED based display, where the substrate for Micro-LEDs must be removed.

LLO is a well-established technique for substrate release.<sup>[63]</sup> As schematically shown in **Figure 8a**, LLO exploits the difference in absorption of the laser light between the substrate and the semiconductor layer to release the substrate. In the case of GaN LEDs formed on a sapphire substrate, GaN has a band gap  $E_g$  of  $\approx 3.3$  eV, whereas the band gap energy of sapphire is  $\approx 9.9$  eV. So, a laser beam with the photon energy larger than the GaN  $E_g$  but smaller than the sapphire  $E_g$  will be transparent for the sapphire. This is the reason why short UV lasers, such as 248 nm krypton fluoride (KrF) laser and 266 nm yttrium aluminum garnet (YAG):Nd lasers, and 355 nm diode-pumped

solid-state (DPSS) lasers are chosen for GaN LLO. Laser irradiation results in intensive heating at the GaN/sapphire, which leads to the decomposition of the GaN near to the GaN/sapphire interface into Ga droplets and nitrogen gas. Consequently, the GaN LEDs can be released from the substrate.

Considering the device performance, there has been growing interest in integrating LEDs on other substrates. Laser lift-off (LLO) provides a well-established route for this substrate replacement process due to its high-efficiency, non-contacting and damage-free operating mode, the area of coverage for large-scale, and high compatibility of conventional LED process.<sup>[34]</sup> Hence, laser lift-off techniques, in conjunction with wafer temporary bonding processes, can be used to integrate GaN with other dissimilar materials and eliminate the sapphire substrate constraint. For instance, for the GaN LED chips on sapphire, laser lift-off (LLO) is the most simple and efficient method to destroy the interfacial connection of  $\text{Al}_2\text{O}_3$  and GaN layer (AlN layer may also exist to optimize the epitaxial growth), to transfer other substrate.<sup>[101]</sup> **Figure 8b** shows an

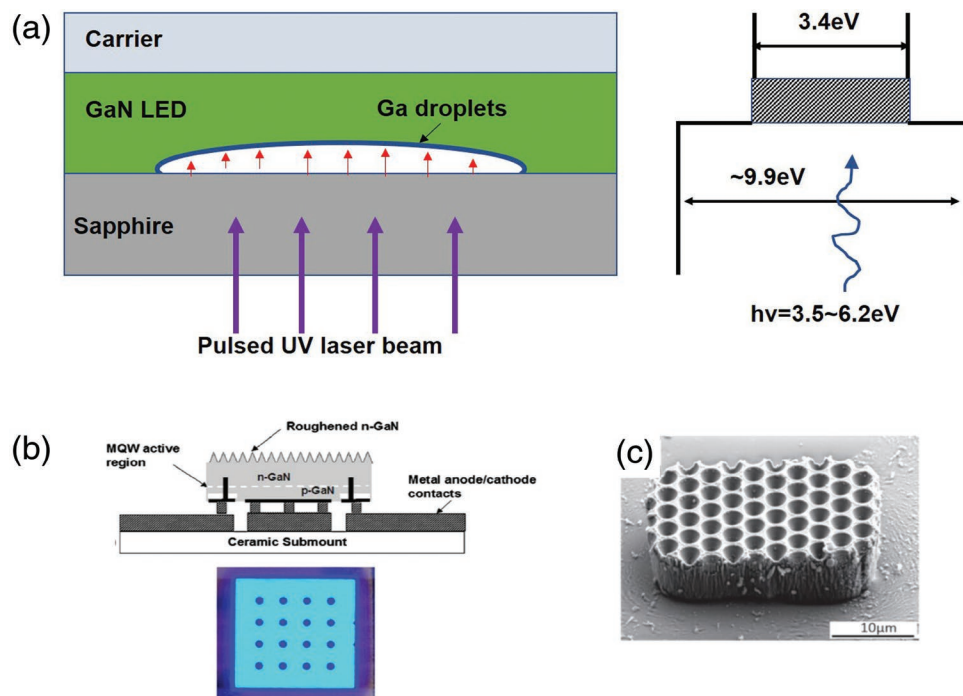


**Figure 7.** a) Decreased p-contact and n-contact resistance by laser irradiation. Reproduced with permission.<sup>[66]</sup> Copyright 2003, AIP Publishing. b) Precise local conditioning of nano-LEDs by laser-micro-annealing (LMA). Reproduced with permission.<sup>[57]</sup> Copyright 2021, AIP Publishing.

example of resulting thin-film LEDs integrated onto a ceramic submount developed by Philips for general lighting, which showed improved brightness and heat dissipation capability.<sup>[63]</sup> In addition, the laser beam geometry on the wafer during the LLO process can be adapted to the actual wafer diameter, which

can meet the needs of different wafer size processing and mass production.

Nevertheless, successful LLO depends on the optimization of various laser processing parameters to avoid the occurrence of defects, such as laser wavelength, laser beam size,



**Figure 8.** a) Schematic of the LLO process along with the bond diagram of the GaN/sapphire interface. b) A large-sized thin-film LED for general lighting formed by LLO. Reproduced with permission.<sup>[63]</sup> Copyright 2006, AIP Publishing. c) A Micro-LED with the sapphire removed by LLO. Reproduced with permission.<sup>[69]</sup> Copyright 2022, IOP Publishing.

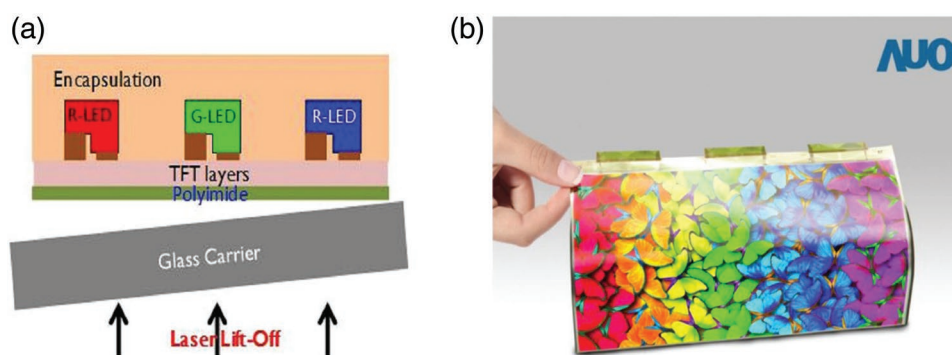
peak intensity and pulse width.<sup>[102]</sup> It has been found that the laser scanning speed could alter the structural quality of the GaN films.<sup>[103]</sup> The adhesion strength between GaN and sapphire substrate is closely related to the energy density of UV laser irradiation.<sup>[104]</sup> J. Xu et al.<sup>[105]</sup> researched the energy density of the incident laser beam which was varied between 200 and 5000 mJ cm<sup>-2</sup> by using a silica convex lens having the focal length of 40 cm. In this work, the initial laser radiation with the energy density of 200 mJ cm<sup>-2</sup> did not result in any change on the sample. After the laser energy density reached ≈400 mJ cm<sup>-2</sup>, GaN films were successfully separated from sapphire substrates. However, laser radiation with high energy density (5000 mJ cm<sup>-2</sup>, for example) will result in cracked GaN films, because the decomposition is usually accompanied by generating vapor pressure, which can be high enough to crack the original GaN film. Different UV lasers have been used for LLO of GaN thin films from sapphire substrates, such as Nd:yttrium aluminum garnet (YAG) lasers,<sup>[106]</sup> and KrF pulsed excimer laser (248 nm).<sup>[107]</sup> The feasibility of the LLO process has also been explored for fabricating free-standing InGaN-MQW LEDs,<sup>[108]</sup> vertical-structure blue LEDs,<sup>[109]</sup> blue LEDs on Si<sup>[110,111]</sup> and LEDs on copper<sup>[101,112–114]</sup> all of which exhibited good device performance, indicating appropriate LLO process did not cause obvious damage to the LED. In the case of Micro-LED LLO (Figure 8c), the care that should be taken is that the laser beam size and pulsed laser intensity should be reduced in order to ensure a high lift-off success rate.<sup>[42,69]</sup> Suitable strategies for beam-shaping, beam-scanning, and beam profile control are also important factors for further improving the Micro-LED LLO performance. As an example, Coherent<sup>[115]</sup> developed a commercial UVblade LLO system for fast Micro-LED LLO. Two different beam scanning strategies were used in the system, including the line-beam scanning, and raster scanning methods. In the case of full-wafer LLO, line-beam scanning mode is preferred, which are favorable for maximizing the LLO throughput. The line beam is shaped into a uniform top-hat profile, which can cover the entire wafer, and ensure that the entire process area is exposed to the same optimum fluence. Alternatively, a raster scanning process, combined with a smaller beam size was adopted for LLO. In this case, fast LLO of a full wafer can be achieved by multiple sequential scans of the rectangle-shaped laser beam with a top-hat profile, besides

selective LLO of a specific localized area from the wafer. With these innovations, the system exhibited very high throughput (the processing time is only a few seconds for a 4" wafer) and uniform processing capability of the Micro-LED LLO. However, in the case of the raster scan approach, it demands the controlled stitching of the individual shots in the scan direction as well as the stitching between the scans. The gap in the stitching area should also be minimized.

For flexible display, there is also the need of temporary substrate removal by LLO.<sup>[55,116]</sup> For example, AU Optronics Corp reported a 9.4-inch 228 PPI flexible Micro-LED display on a polyimide (PI) film, where the glass carrier was taken off by LLO.<sup>[55]</sup> The temporary glass substrate was introduced to act as a handling carrier to form PI film and IGZO TFTs, followed by assembling RGB Micro-LEDs (Figure 9a). Once the fabrication is finished, LLO was conducted to release the glass substrate, resulting in a flexible Micro-LED display formed on the soft PI film (Figure 9b). The release mechanism is based on the interfacial decomposition and gas evaporation of the PI film when it is subject to intensive laser-induced heat. Sun et al. demonstrated an 8-inch flexible miniLED display based on a similar LLO process.<sup>[116]</sup>

### 3.5. Chip Mass Transfer

The development of techniques that can transfer LED chips from the growth substrate to another substrate is of great importance, which is driven by a few primary considerations.<sup>[117,118]</sup> The first driving force is to improve the LED optical performance and thermal stability. This is particularly true for general lighting, where high-power LEDs must be used. To meet these needs, high-power thin-film GaN LEDs transferred to Si or Copper have been developed, which show improved brightness and thermal stability.<sup>[63]</sup> The second driving force is toward developing high-resolution Micro-LED display, for which millions of Micro-LEDs must be assembled onto a driving backplane. In the latter case, a variety of Micro-LED transfer techniques have been developed, including polydimethylsiloxane (PDMS) stamp transfer,<sup>[5,27,118,119]</sup> electrostatic transfer,<sup>[120]</sup> fluid assembly,<sup>[121,122]</sup> laser-based transfer,<sup>[46,48–50]</sup> magnet-assisted transfer,<sup>[123]</sup> roll-to-roll,<sup>[121]</sup> tape transfer,<sup>[124,125]</sup>



**Figure 9.** a) Schematic drawing of the LLO process used for releasing the temporary glass carrier. b) The resulting 9.4-inch 228PPI flexible Micro-LED display device on a polyimide film after the LLO process shown in (a). Reproduced with permission.<sup>[55]</sup> Copyright 2021, Society for Information Display, published by Wiley.

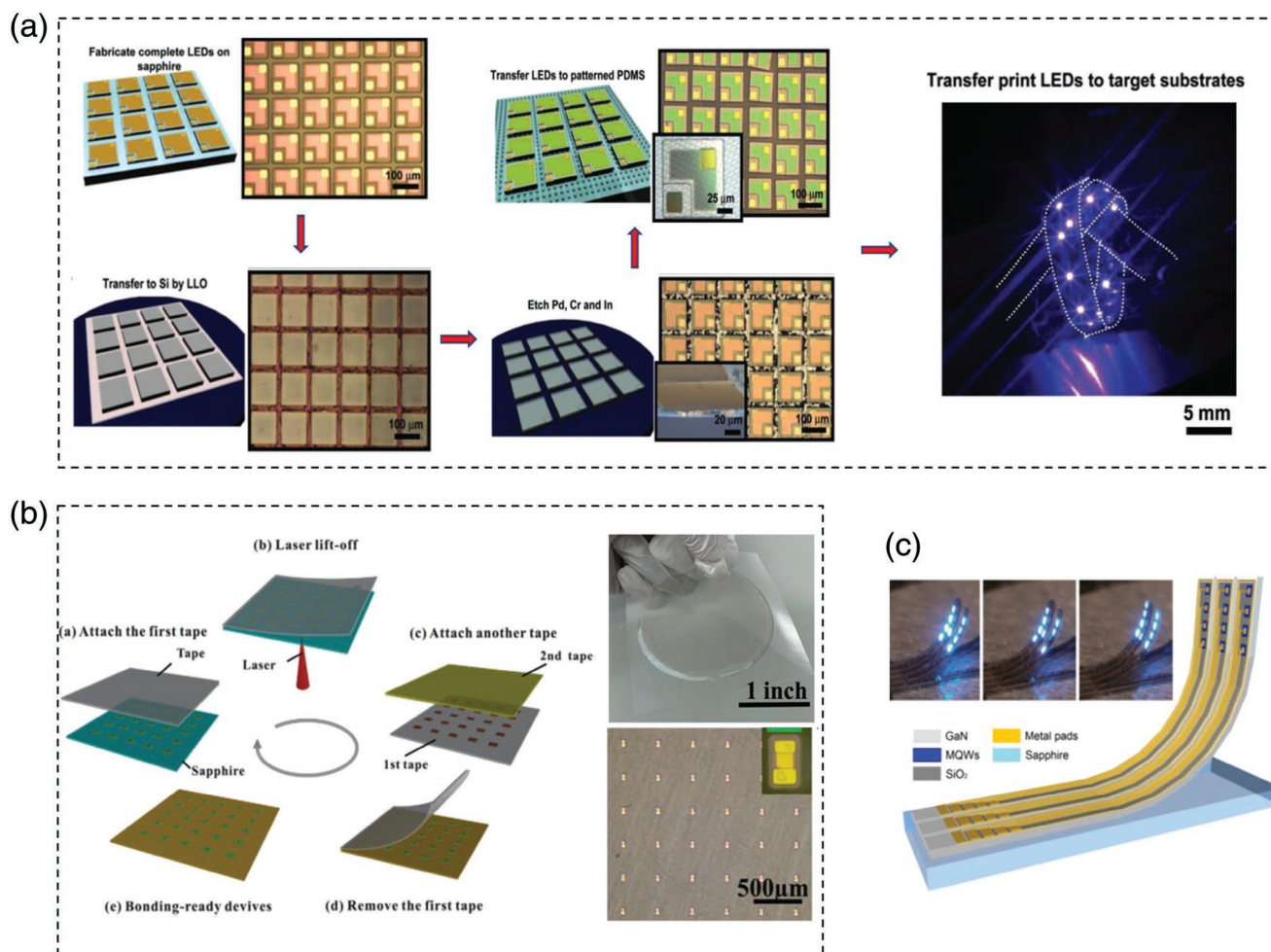
etc. Among these methods, laser-based transfer techniques have attracted intensive research interest, primarily because laser techniques have some distinct advantage such as high transfer speed, high yield, good selectivity, and the prospect for industrial production. Here we give a comprehensive overview of the laser-related transfer printing techniques developed recently, which are critical for the future industrialization of Micro-LED display.

### 3.5.1. Micro-LED Transfer by LLO

As discussed earlier, LLO can be used to release the sapphire substrate where Micro-LEDs are formed. By exploiting this capability of LLO, Micro-LEDs can be transferred to various substrates. To assist the Micro-LED transfer, Micro-LEDs are usually bonded onto a handling carrier.<sup>[64,125–127]</sup> LLO was then conducted to release the sapphire substrate. With this strategy, tiny, efficient and ultrathin  $\mu$ -LEDs transferred to a handling carrier can be obtained, which can be further transferred to

other substrates.<sup>[128]</sup> Although various methods were proposed, they can be classified into two categories.

The first type of methods is based on LLO in combination with the wafer bonding of Micro-LEDs onto a rigid substrate. This bonding is most frequently a temporary bonding but sometimes it is a permanent bonding. A temporary bonded carrier can serve as an intermediate handler, which allows multiple transfers, and can be removed eventually. For instance, Kim et al.<sup>[129]</sup> developed a protocol to transfer GaN Micro-LEDs to a rigid Si carrier by combining wafer bonding, LLO, and transfer printing (Figure 10a). First of all, Micro-LEDs were predefined on the growth substrate. Pd–In was then used to bond the pre-patterned Micro-LED array to a temporary Si carrier. Afterward, LLO was conducted to remove the sapphire substrate, followed by undercutting the Micro-LEDs by wet etching. Finally, these Micro-LEDs were picked up using a PDMS stamp and transferred to the final substrate to build a flexible display device. G. Ezhilarasu et al.<sup>[30]</sup> propose a wafer-level Micro-LED transfer and assembly process based on LLO and adhesive bonding, which can potentially attain >99% transfer yields. Instead of



**Figure 10.** a) A protocol of transferring GaN Micro-LEDs to a rigid Si carrier by combining wafer bonding, LLO, and transfer printing. Reproduced with permission.<sup>[129]</sup> Copyright 2012, Wiley-VCH. b) A tape-assisted LLO method for fabricating thin-film Micro-LED arrays transferred to a soft tape carrier. Reproduced with permission.<sup>[47]</sup> Copyright 2020, Wiley-VCH. c) Free-standing Micro-LED stripes formed by LLO without using a handling carrier. Reproduced with permission.<sup>[130]</sup> Copyright 2016, American Chemical Society.

In–Pd metal bonding, a thermoplastic, laser-debondable polyimide-based adhesive (HD3007) is used to attach the Micro-LED to a temporary glass carrier, followed by the LLO process. This method exhibited the capability for selective assembly of the Micro-LED device on the final substrate, since the adhesive can be patterned lithographically.<sup>[42]</sup> However, these methods are relatively complex, with multiple processes involved, such as wafer bonding, LLO, transfer printing and debonding. It is known that wafer bonding is a complex, costly process which requires the expensive bonding and debonding tools, and not all regular users can access them.

The second type of methods exploits soft, adhesive carriers to assist the LLO transfer.<sup>[51,127]</sup> For example, Z. Pan et al.<sup>[47]</sup> presented a novel process which used a UV tape to serve as a handling carrier for wafer-level LLO of Micro-LEDs (Figure 10b). The UV tape can be simply imprinted onto the Micro-LED wafer using a roller or a film applicator, without using the complex wafer bonding process. After LLO, a second tape was introduced, in order to flip over the Micro-LEDs for a subsequent process. The method allows for the fast fabrication of thin-film Micro-LEDs on the tape with extremely high transfer yield ( $\approx 99.8\%$ ) and small displacement error ( $< 0.5 \mu\text{m}$ ). One distinct advantage of this method is the capability for programmable LLO of Micro-LED in a wafer level by using a shadow mask. Consequently, this method significantly simplifies the transfer process and reduces the cost, indicating its potential for wafer-scale production. Although thermal release tapes<sup>[51]</sup> have been also used to assist the LLO transfer, the transfer accuracy after LLO is compromised, due to the volume expansion of the polymer microsphere embedded in the tape, which induces the position shift of the Micro-LED chip. Given LLO is able to take off the rigid sapphire substrate, a wide range of flexible LED display devices can be enabled.<sup>[42,47,51,131]</sup>

In rare cases, no handling carrier was used for LLO.<sup>[130]</sup> As an example, Choi et al.<sup>[130]</sup> used this concept to develop free-standing, naturally bended Micro-LED stripes for curved displays (Figure 10c). Specifically, individual Micro-LED strips are first patterned on the sapphire substrate. Selective-area LLO was then conducted to release the major part of each Micro-LED stripe, but only the far end of the stripe was not released. Due to the strain relaxation, these Micro-LED stripes are spontaneously bended, enabling the demonstration of a flexible display in an unusual manner. However, this method is not suited if the Micro-LEDs need to be transferred multiple times. In another example,<sup>[12]</sup> the Micro-LED array was bonded

permanently onto the TFT circuit. The sapphire substrate was then removed by LLO, leaving a thin-film Micro-LED array integrated with the TFT backplane.

As shown above, laser lift-off techniques potentially offer many advantages such as a short processing time, wafer-level processing, and selective LLO capability. However, successful LLO depends on a number of factors. There is evidence that Micro-LED chips may be damaged if the LLO pulsed energy is excessively high. The LLO quality were not only impacted by the adhesive bonding material, but also strongly correlated with LED dimensions, laser parameters, bonding methods, handling carriers, etc.<sup>[132]</sup> A detailed summary of various methods used for Micro-LED transfer and different parameters that may affect the LLO performances can be found in **Table 2**.

### 3.5.2. Micro-LED Transfer by LIFT

So far, the above LLO techniques are based on laser ablation and decomposition of the absorption layers inside the functional chip to assist the chip transfer, which however, may cause thermal damage to the chips. To address this problem, UniQarta<sup>[52]</sup> developed a method called LIFT technology to pursuit high-volume placement of structures or devices with tiny feature sizes for electronics manufacturing. The transfer mechanism is schematically shown in **Figure 11a**. A dynamic release layer (DRL) material is coated on a transparent glass carrier. Devices to be transferred are then placed on the DRL. When a laser pulse irradiates through the glass substrate and is absorbed by the DRL, laser–material interaction occurs and causes a phase change of the DRL, which turns a small amount of DRL materials into gas, and drives the release of the LED chips to the receiver (Figure 11a).

The LIFT technique has the advantage of fast die transfer and release. Marinov et al.<sup>[52]</sup> demonstrated that, by using LIFT techniques, a transfer speed of 100M units/h can be obtained. Notably, this method also exhibited the outstanding selective transfer capability by controlling the laser irradiation pattern. Different from LLO technology, LIFT is a technique based on the ablation of adhesive, for which the required laser intensity is 5–20 times lower than that of III–V semiconductors. This high efficiency means that high output can be achieved with low laser power. In addition, the transfer speed can be further enhanced by using a multiple beam scanning strategy. Specifically, an array of laser beams was formed by using diffractive

**Table 2.** Summary of various LLO-based Micro-LED transfer methods with different handling carriers and bonding methods.

Laser type	Pulse energy	Pulse width	Handling carrier	Bonding method	Lift-off area	Reference
248 nm KrF laser			PET	Wafer bonding (Ti/Au/AuSn/Au)	20 mm × 20 mm	[126]
248 nm KrF laser	900 mJ cm <sup>-2</sup>	5 ns	Si	Wafer bonding (Cr/Pd)		[129]
266 nm Nd:YAG laser			/	/	11.3 × 0.46 mm <sup>2</sup>	[130]
266 nm DPSS laser	>600 mJ cm <sup>-2</sup>	10 ns	Glass	Adhesive bonding using polyimide	4-inch	[30]
266 nm DPSS laser	300 mJ cm <sup>-2</sup>	5 ns	UV tape	Adhesive bonding using UV tape	2-inch wafer	[47]
266 nm DPSS laser	<600 mJ cm <sup>-2</sup>		Glass	Adhesive bonding using polyimide	12 mm × 10 mm	[42]
266 nm DPSS laser			Acrylate adhesive tape	Adhesive bonding		[132]
248 nm KrF	>950 mJ cm <sup>-2</sup>	20 ns	Glass	PDMS glue bonding	14 × 14 array	[69]

optics, and projected onto the sample simultaneously, as schematically shown in Figure 11b. this leads to parallel transfers of multiple arrays at the same time. Being a unique contactless technology, LIFT exhibited the potential for large-scale, parallel assembly.<sup>[133,134]</sup> Nevertheless, for successful LIFT, the devices must be temporarily placed on the intermediate DRL. This means LIFT techniques cannot be used alone to transfer Micro-LEDs directly from the growth substrate to the receiver. Another disadvantage is the compromised placement accuracy caused by the ablative laser process, in which a relatively low-density gas pushes a higher density object. These effects can be alleviated by controlling the release velocity.<sup>[133,135]</sup>

### 3.5.3. Laser-Assisted Stamp Transfer

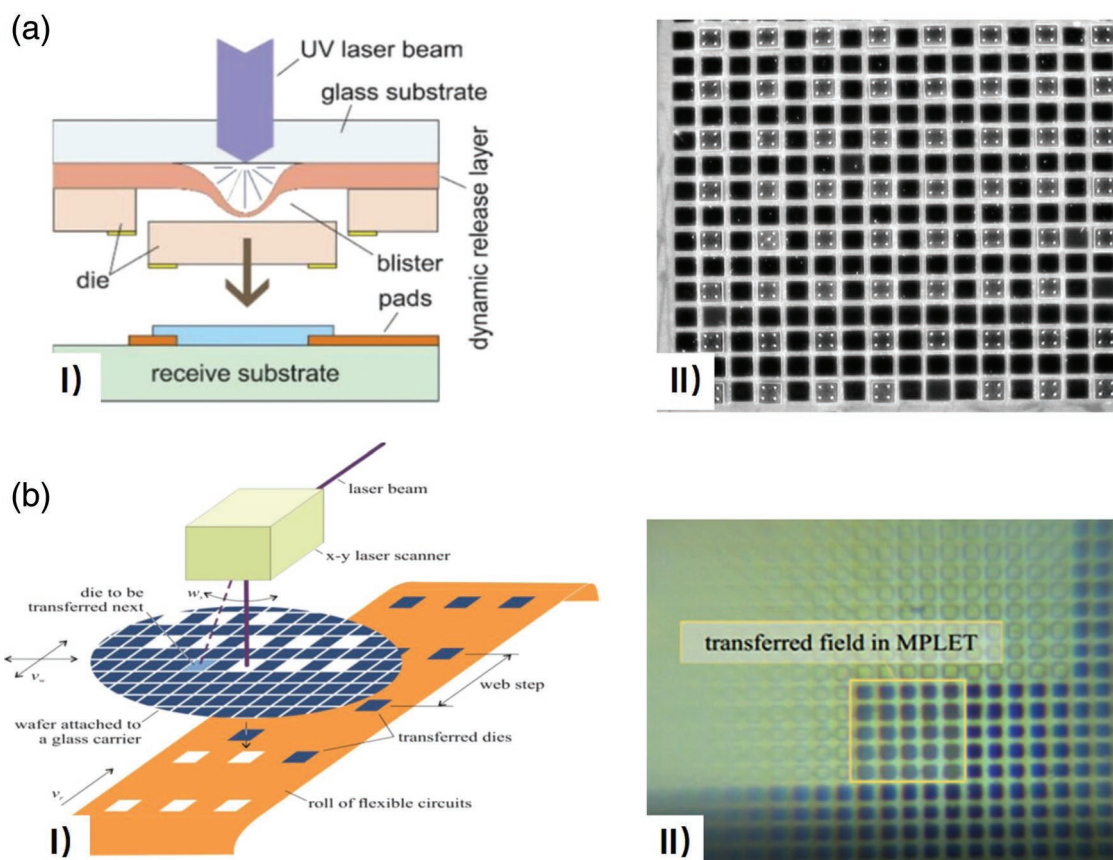
Stamp transfer printing techniques<sup>[27,46,118,119,136]</sup> have been well established for micro-part assembly. The adhesion of the stamp can be controlled, which determine the pickup and release of the micro-object. However, conventional stamp transfer has some disadvantages. First, during the transfer process, the device must be physically contacted with the stamp. Therefore, potential surface contamination of the device can be induced. Second, the stamp can be deformed during the contact printing process, which will cause placement displacement.<sup>[137,138]</sup>

Modified non-contact stamp transfer methods in combination with laser irradiation have therefore been developed, which exhibit improved transfer printing performance.

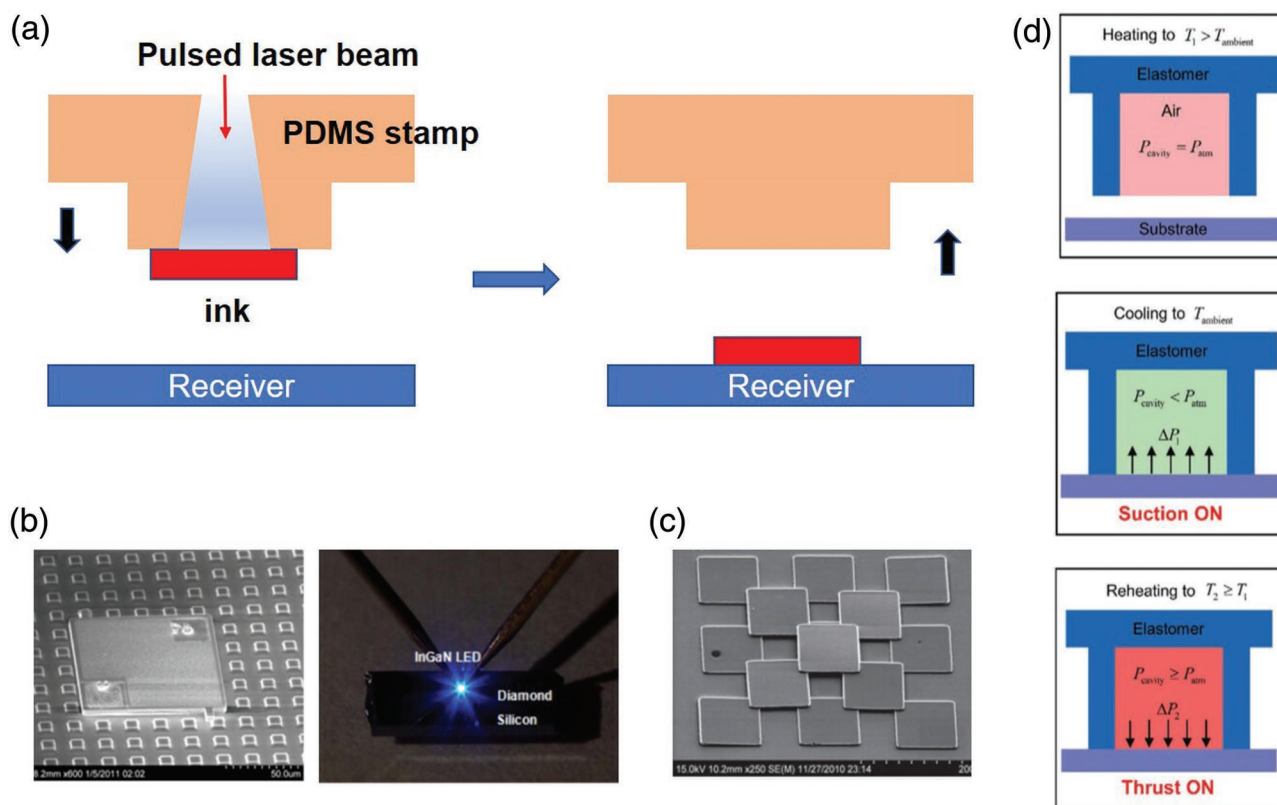
**Laser Assisted PDMS-stamp Transfer:**<sup>[139–141]</sup> Saeidpourazar et al.<sup>[140]</sup> proposed a laser-assisted PDMS stamp transfer method operated in a non-contact mode (Figure 12a). An adhesive PDMS stamp was used to pick up the ink. The stamp was then subject to pulsed laser beam irradiation from the top. Because thermal responses between the PDMS stamp and the ink are different, the ink can be released from the stamp to the receiver in a contactless manner, due to the small gap between the ink and the receiver. Using this technique, they have demonstrated the transfer printing of Micro-LEDs and complex 3D-stacked micro-chips (Figure 12b,c).

More recently, Luo et al.<sup>[141]</sup> reported an improved method by using a laser driven PDMS stamp with patterned air cavities (Figure 12d). The laser heating the air cavity can induce large change of the pressure between the cavity and the air. Therefore, the adhesion of the stamp can be simply tuned by laser heating, enabling the ink pick-up or release.

**Laser Assisted SMP-Stamp Transfer:** Instead of the PDMS stamp, Eisenhaure et al.<sup>[136]</sup> proposed the use of a stamp made from composite carbon black shape memory polymer (CBSMP) in combination with localized laser heating to achieve the selective transfer printing of the inks (Figure 13). The carbon



**Figure 11.** a) The schematic diagram of UniQarta's laser transfer process (Left). Optical image of selectively transferred  $50\ \mu\text{m} \times 50\ \mu\text{m}$  Micro-LED array (Right). b) A schematic illustrating the LIFT based on using a multiple beam scanning strategy (Left). Snapshot of the multiple Micro-LEDs transferred simultaneously (Right). Adapted with permission.<sup>[52]</sup> Copyright 2018, Society for Information Display, published by Wiley.



**Figure 12.** a) Sketch of the laser-driven non-contact PDMS printing. Printed Micro-LED (b) and 3D microstructures (c) using the method shown in (a). Images in (a), (b) and (c): Reproduced with permission.<sup>[140]</sup> Copyright 2012, IEEE. d) A modified laser-driven non-contact printing based on a PDMS stamp with an air cavity. Reproduced with permission.<sup>[141]</sup> Copyright 2021, Wiley-VCH.

black shape memory polymer (CBSMP) presented an excellent shape and adhesion response to heating in a relatively low temperature window (60–120 °C), thereby exhibiting the adhesion switching from “off” state to “on” state, or vice versa (Figure 13a). Consequently, inks can be picked up or released in a programmable manner (Figure 13b). Compared with the laser-driven PDMS printing, the current technique notably reduced the heating temperature, which can thus avoid the thermal induced damage to the inks.

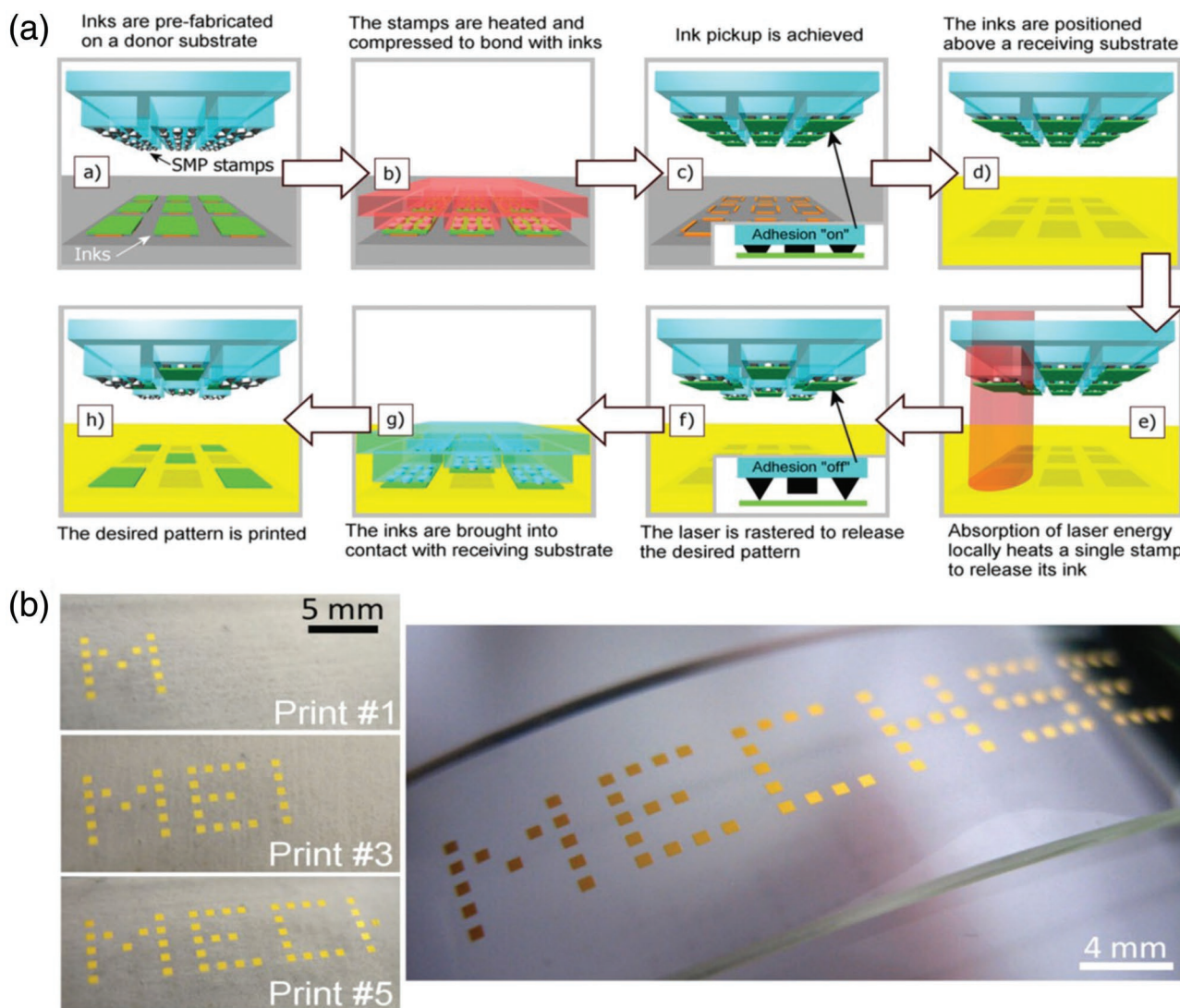
**Laser-Assisted Tape Transfer.** The above methods used elastic stamps to pick up and release inks. However, the fabrication of such stamps is tedious, with complex lithography and molding technologies involved. To overcome this limit, cheap adhesive tapes<sup>[50,142]</sup> used as the stamps have been proposed, in conjunction of localized laser heating, to achieve the pick-up and release of the inks onto various receivers. For example, Wang et al.<sup>[142]</sup> demonstrated the use of laser irradiation to generate localized heat in a commercial thermal release tape (Figure 14). Because microspheres in the tape are thermally responsive, higher temperature leads to volume expansions of the microspheres, and thus a notable adhesion decrease in the laser irradiation region. Consequently, inks in the heated region can be released from the tape, while inks in other areas are not. This means the inks can be transferred in a programmable manner. Using this strategy, selective printed SAW sensors (Figure 14b) and Micro-LEDs are demonstrated (Figure 14c). The printed Micro-LEDs were then used to fabricate a flexible Micro-LED

display (Figure 14d). However, because of the volume expansion, this method imposes limitations for transfer accuracy—only inks of hundreds of microns which can be transferred. In a separate paper, Jung et al.<sup>[50]</sup> reported a similar strategy, but they used a UV tape combined with laser heating for selective printing of mini-LEDs. Despite these achievements, excessive laser heating can induce high temperature in the ink surface, which may cause thermal shock to the devices.

A detailed performance comparison of these laser-based transfer techniques for Micro-LEDs is summarized in Table 3. It is clearly seen that each method has its own advantages and limitations. For example, LIFT exhibits the highest transfer speed, but the transfer accuracy is compromised, due to the non-contact transfer mechanism. Laser-assisted tape transfer, on the other hand, is less expensive, but the transfer speed is slower. By contrast, the tape-assisted LLO transfer technique exhibits both high transfer speed and high transfer accuracy.

### 3.6. Laser-Assisted Bonding (LAB)

Not only is chip transfer important for displays, but also the subsequent bonding and integration are critical, in order to achieve reliable electrical interconnection with the driver backplane. Solder-bump/thermal compression bonding,<sup>[63,143,144]</sup> and anisotropic conductive film (ACF) bonding<sup>[145,146]</sup> have been well established for conventional semiconductor devices

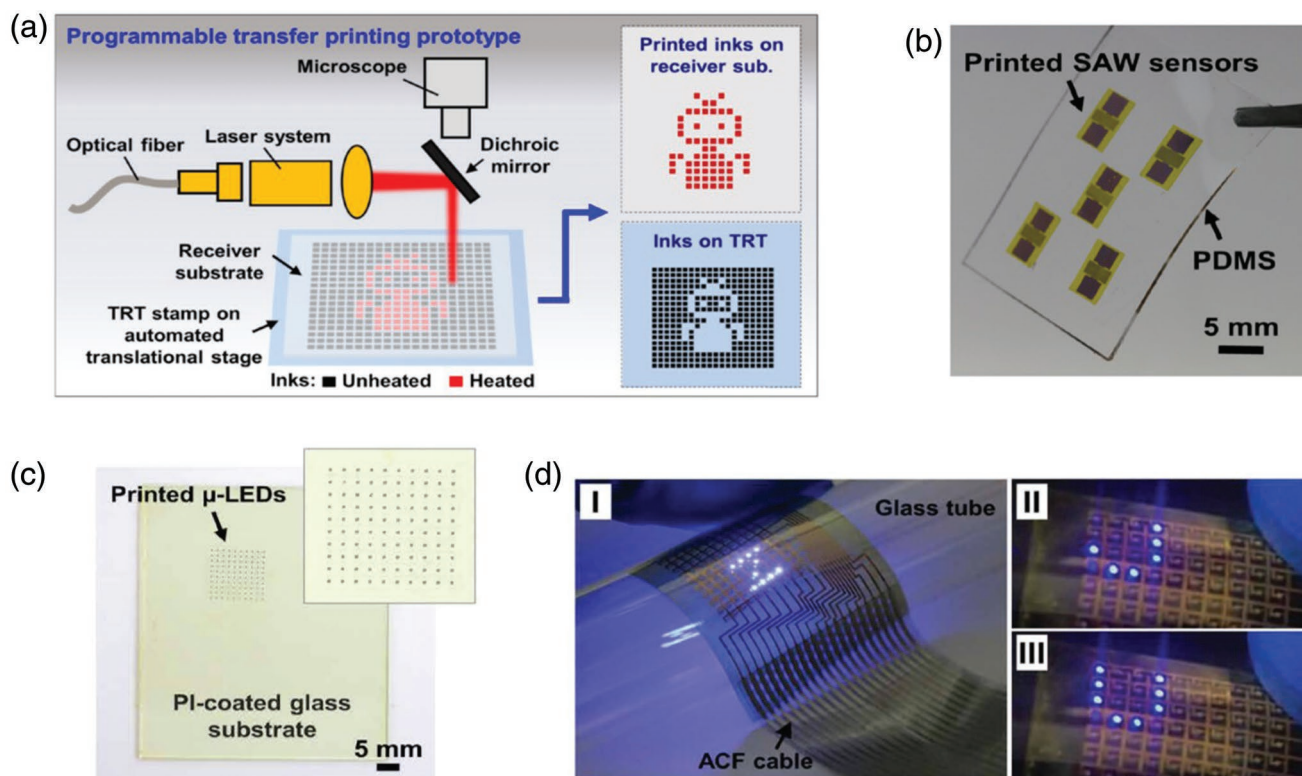


**Figure 13.** Laser assisted SMP-stamp transfer method. a) Transfer mechanism and b) selectively printed inks on a flexible PET substrate. Reproduced with permission.<sup>[136]</sup> Copyright 2016, Wiley-VCH.

with a relatively large die size. However, in the case of bonding fine-pitch Micro-LEDs<sup>[8,12,38,40,147–149]</sup> whose dimension are significantly reduced, these methods face serious technical challenges, such as the difficulty for accurate registration, and the bonding non-uniformity issues. The long-time heating and soldering reflow over a large bonding area cause serious thermal stress, and the wafer warpage. The solder bumps used for common flip-chip bonding may not have the consistent heights. Both effects can cause serious bonding non-uniformity across the bonding area. Bump-to-trace shorting issues were significantly increased with decreasing the pitch and pixel size. ACF bonding, on the other hand, may cause high contact resistance or open circuits for Micro-LED bonding. The polymer particles in the ACF have dimensions comparable to Micro-LEDs, implies that only limited quantity of particles can be used for bonding Micro-LEDs. Furthermore, ACF bonding is not repairable. By contrast, laser-assisted bonding (LAB)<sup>[150]</sup> has the advantages for selective bonding, localized heating and very

fast temperature control, making it suitable for fine-pitch Mini/Micro-LED bonding.<sup>[54,151]</sup>

Joo et al.<sup>[54]</sup> developed a LAB process to integrate Micro-LEDs onto the driver board, which is schematically shown in **Figure 15a**. A Micro-LED interposer held by a vacuumed bonding head was aligned to the receiving substrate, where the bonding pads were coated with anisotropic solder paste (ASP). IR laser beam was then applied to the bonder head. As the laser power transmitted through the interposer, it got absorbed by the solder interconnections, which then melted within a very short time (less than 1 s). Retracting the bonding head led to the integration of Micro-LED to the receiving substrate. Using this method, a  $20 \times 20$  Micro-LED array was successfully integrated onto the driver board (**Figure 15b**). The PMMA balls in the ASP served as a spacer, and a Sn58Bi solder joint was formed between the  $\mu$ LED electrode and the substrate pad. The bonding strength can be significantly improved by the epoxy in ASP, which acts as an underfill between the  $\mu$ LED



**Figure 14.** Laser-assisted tape transfer method. a) Working principle, b) printed SAW sensors, c) selectively printed Micro-LEDs, and d) a flexible display device made from printed Micro-LEDs shown in (c). Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>).<sup>[142]</sup>

and the substrate (Figure 15c). All pixels are functional, indicating the laser-assisted bonding technique is promising for Micro-LED integration (Figure 15d). The LAB technique offers many potential advantages. First of all, the laser induced heat is localized and the temperature can be applied selectively in the interconnection areas. Thus, the warpage of the substrate can be minimized, since thermal stress is only generated in the laser irradiation area. Furthermore, LAB shows good compatibility for the bonding on flexible substrates.<sup>[152]</sup> Nevertheless, the bonding efficiency of LAB needs to be improved, in order to meet the requirement for bonding large quantity of LED dies

for a display panel. The laser beam must be very uniform across the bonding area. Otherwise, bonding failures may be induced.

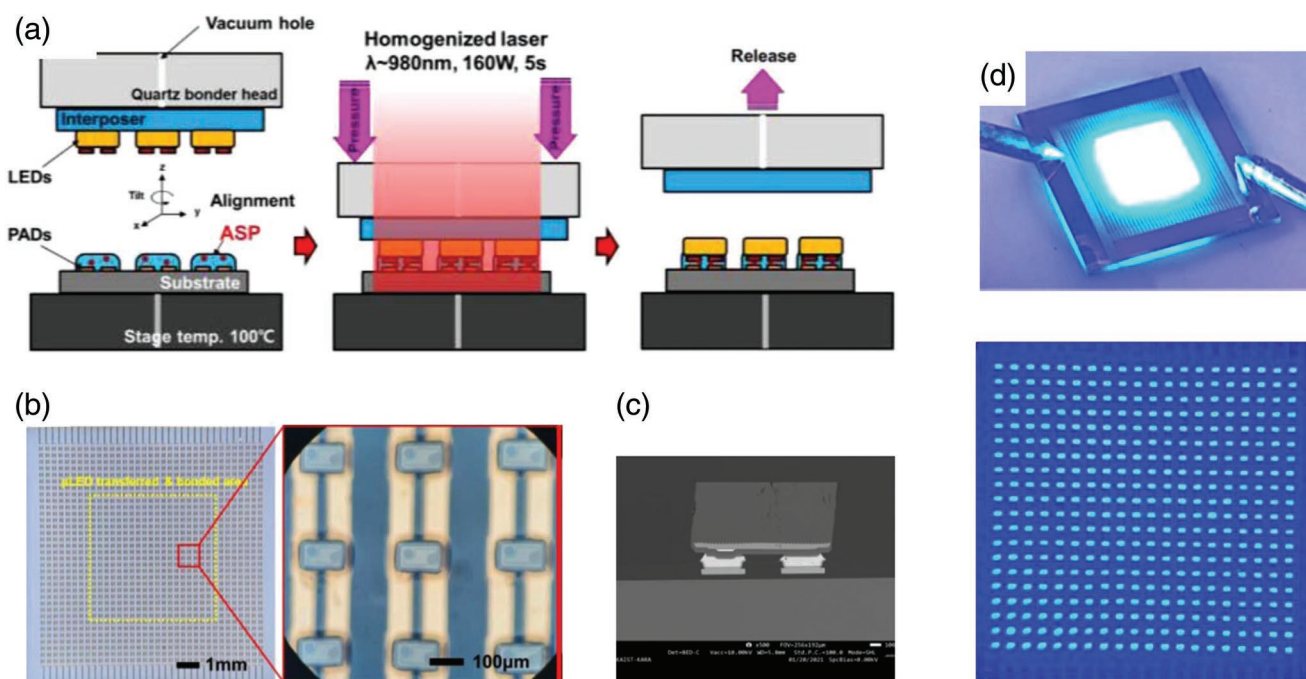
### 3.7. Laser-Based Writing Techniques

#### 3.7.1. QD Writing

As mentioned earlier (Figure 2c), full color Micro-LED can be achieved by integrating green and red QDs onto a blue-emitting Micro-LED array.<sup>[6,40,75,153,154]</sup> This route eliminates the problem

**Table 3.** Performance comparison of various laser-based Micro-LED mass transfer techniques.

Laser transfer category	Detailed working mechanism	Placement accuracy	Transfer efficiency	Transfer yield	Cost	Reference
LLO-based transfer	Tape was used as a temporary substrate for Micro-LED LLO and transfer	High (+/-0.5 $\mu\text{m}$ )	Fast (30 s per wafer)	High (99.8%)	Medium	[47]
	Multiple processes were used for Micro-LED transfer, including Wafer bonding, LLO, and PDMS transfer	Medium	Low	Medium	High	[129]
Laser induced forward transfer	A DRL layer with Micro-LEDs was subjected to pulsed laser irradiation and turned into gas, which released the Micro-LEDs	Medium (+/-1.5 $\mu\text{m}$ )	Fast (up to 100 KK/h)	High	Medium	[52]
Laser-assisted stamp transfer	A PDMS stamp combined with a pulsed laser was used to release and transfer Micro-LED	Medium	Medium	Medium	Medium	[140,141]
	A SMP-stamp combined with a pulsed laser was used to release and transfer Micro-LEDs	Medium	Medium	Medium	High	[136]
	An adhesive tape combined with a pulsed laser was used to release and transfer Micro-LEDs	Low	Medium	Medium	Low	[142]



**Figure 15.** Laser-assisted bonding. a) Working mechanism, b) laser bonded Micro-LED array, c) cross-sectional SEM image of the bonded Micro-LED onto the circuit using solder bumps, and d) optical image of the device switched on. Reproduced with permission.<sup>[54]</sup> Copyright 2021, IEEE.

of Micro-LED mass-transfer, but in the meanwhile a new challenge arises—the patterning of high-resolution QDs. Some printing techniques such as ink jet printing,<sup>[154]</sup> aerosol jet printing<sup>[155]</sup> and EHD printing<sup>[156,157]</sup> do work, but cannot fully address the challenge. These methods either suffer from poor resolution or cannot achieve a QD pattern with sufficiently large thickness. The second issue is commonly overlooked, but actually the patterned QD must be thick enough to warrant strong absorption for efficient color conversion. Laser printing/writing provides an alternative means to pattern the QDs in a mask-less manner.<sup>[158–162]</sup>

Zhan et al.<sup>[159]</sup> reported a method of formed PQDs by in-situ LDW (Figure 16a). First, a precursor solution in DMF with fixed amounts of CsI, PbI<sub>2</sub>, and PMMA was spin coated onto a glass substrate to form a composite film with perovskite precursors. The film was then subject to 405 nm laser irradiation, which caused the evaporation of DMF due to heating and the crystallization of  $\gamma$ - phase PQDs. By modifying the laser irradiation pattern, various patterned PQDs can be achieved. The finest linewidth can be up to 900 nm, which is smaller than most of the existing printing techniques.

Huang et al.<sup>[161]</sup> demonstrated highly luminescent monochromic CsPbBr<sub>3</sub> QDs can be decomposed through femto-second laser irradiation and recovered by thermal annealing (Figure 16b). This process of luminescence erasing and recovery can be repeated for many cycles, without obvious degradation of the luminescent intensity. The mechanism is explained by the decomposition of CsPbBr<sub>3</sub> QDs into PbBr<sub>2</sub> and CsBr accompanied with PL quenching in the laser erasing process, while a reverse reaction leads to the formation of CsPbBr<sub>3</sub> QDs in the annealing process. Taking use of this effect, highly ordered CsPbBr<sub>3</sub> QD arrays can be fabricated.

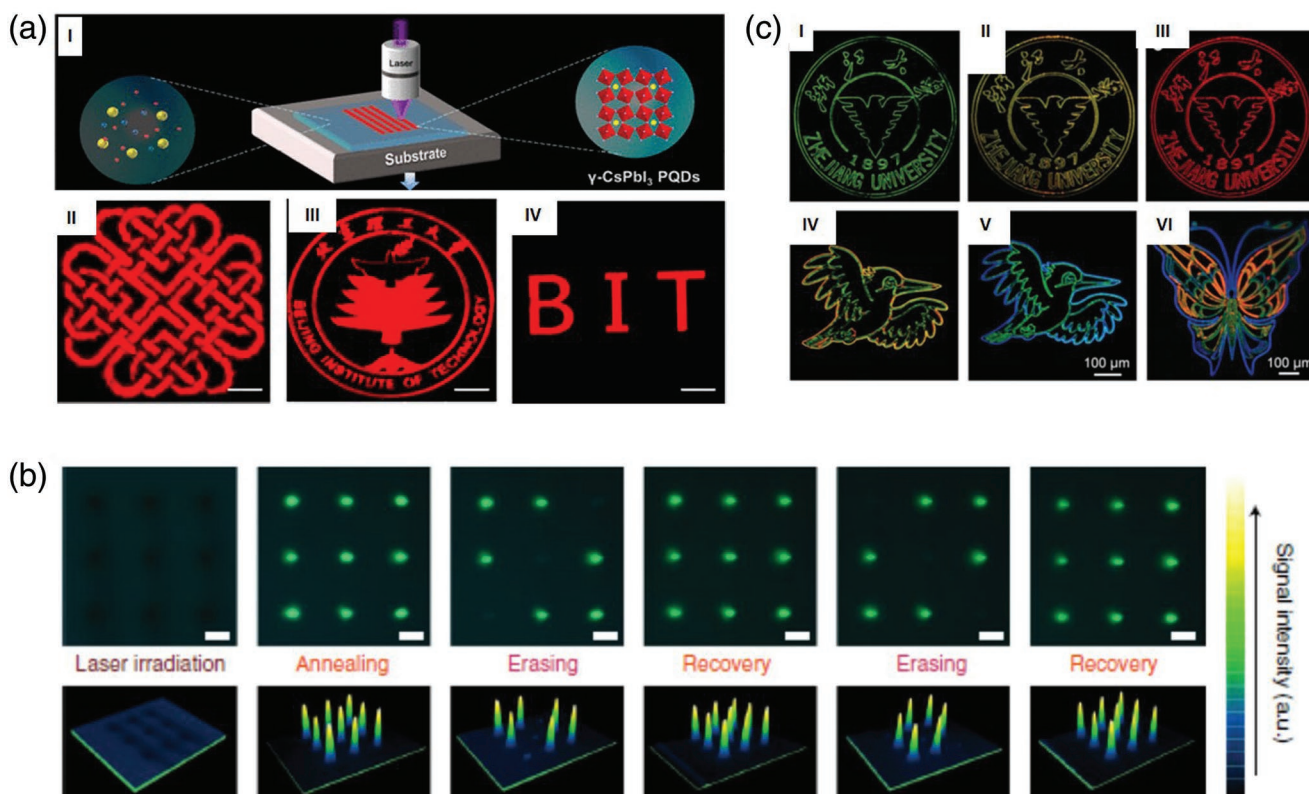
Sun et al.<sup>[162]</sup> reported a different strategy for engineering the local chemistry of perovskite NCs (PNCs) by using an ultrafast pulsed laser (Figure 16c). The ultrafast laser irradiation induces strong thermal accumulation and increases the local pressure and temperature above the liquidus of PNCs. Consequently, localized liquid nanophase separation occurs, resulting in the formation of color-tunable PNCs inside glass. Using the patterned PNCs as color converters, they have further demonstrated a full-color Micro-LED display prototype device.

As shown above, lasers provide a versatile means of directly writing PQD patterns with ultrahigh resolutions. Integrating such patterns onto Micro-LEDs may enable the demonstration of full-color Micro-LEDs, which are highly desirable for many potential applications such as AR/VR, wearables, smart glasses, etc.

### 3.7.2. Interconnect Printing

For LED packaging and advanced displays, LEDs need to be interconnected by solder bumps or metal wiring, such that the LED can be electrically addressed. Wire bonding technology is the most common chip interconnection method used throughout the electronics industry today. However, with shrinking the LED size and increasing the LED pixel density, interconnections of such ultra-small high-density LEDs are far beyond the capability of wire bonding technology.

LDW,<sup>[163–166]</sup> on the other hand, provide a unique capability for printing free-form solder bumps or interconnects with pre-design geometries in a contact-free manner. For example, Wang et al.<sup>[164]</sup> demonstrated the laser printing of high-resolution 3D metal interconnects based on laser-induced forward transfer



**Figure 16.** Laser direct writing for QD patterning. a) Laser printed PQR patterned formed by the evaporation of DMF and the crystallization of  $\gamma$ -phase PQRs due to laser induced heating. Reproduced with permission.<sup>[159]</sup> Copyright 2021, American Chemical Society. b) Rewritable CsPbBr<sub>3</sub> QD patterns via femtosecond laser irradiation. Reproduced with permission.<sup>[161]</sup> Copyright 2019, Springer Nature. c) Color-tunable PNCs inside glass formed by an ultrafast pulsed laser. Reproduced with permission.<sup>[162]</sup> Copyright 2022, The American Association for the Advancement of Science.

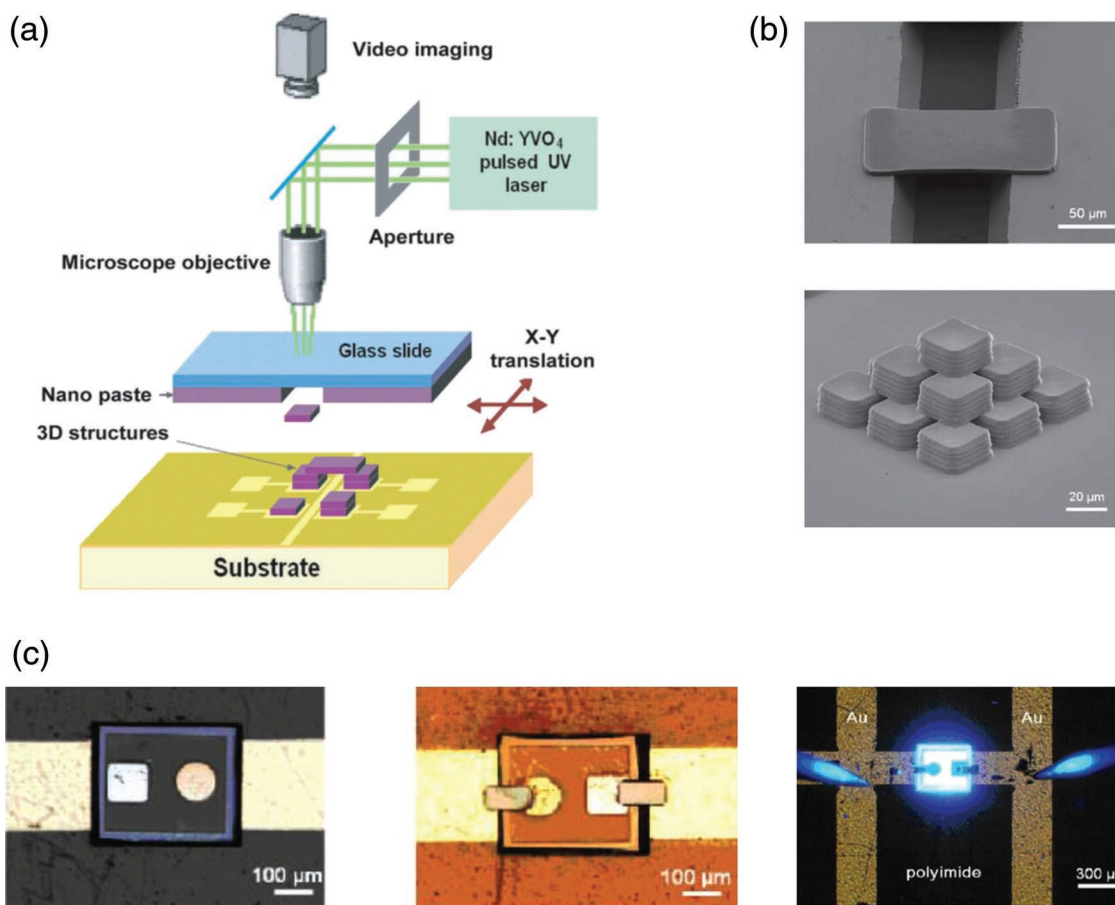
(LIFT) of high concentration silver nano-paste for interconnecting LEDs (Figure 17). Specifically, silver nano-pastes are coated on a glass carrier. Pulsed laser was irradiated from the top of the carrier, which led to the deposition of a small amount of the silver nanopaste onto the receiver in a non-contact manner (Figure 17a). The feasibility of this LDW method is verified by printing different shapes and 3D interconnect structures (Figure 17b). Interconnection of a LED with printed silver interconnects on polyimide has been also demonstrated (Figure 17c), indicating this technique does compatibly well with dissimilar materials and flexible substrates at low processing temperatures.

### 3.8. Laser Inspection and Defect Repair

In a Micro-LED display made from miniaturized RGB chips, some defective pixels can be generated during chip assembly. Consequently, defect management is required to screen out and replace defective LED chips.<sup>[28,52,167,168]</sup> Techniques that can detect those defective pixels in a short time thus becomes critical. Optical detection based on non-contact, micro-pulsed laser scanning technology has emerged to fulfil this purpose.<sup>[44,168]</sup> Photoluminescence (PL) occurs if a semiconductor (e.g., Micro-LED) has been excited by a high energy focused laser beam, due to the radiative transition from the conduction band to the

valence band (Figure 18a). Given that the excitation energy of the laser should be higher than the expected emission energy, UV lasers are the preferred laser sources for defect detection of LEDs emitting at visible wavelengths. Scanning the pulsed laser beam leads us to achieve the photoluminescence for each Micro-LED. The resulting spectra for all pixels are analyzed, yielding information about the defective pixels with lower PL signal. Figure 18b shows an exemplar picture of the PL map collected from the Micro-LED arrays based on the laser scanning technology, where 4 defective pixels show a much lower PL intensity.<sup>[44]</sup> Laser-based PL inspection is a fast, non-destructive method for deflection detection, which has achieved partial commercial success. However, PL based methods alone are not possible for the detection of defective pixels with poor electrical performance arising from electrical shorting<sup>[45,168]</sup> (Figure 18c). Therefore, EL-based methods<sup>[169,170]</sup> for deflection screening are more desirable, which however, are still under development.

After identifying the defective pixels, the next critical task is to remove them, and replace them using functional pixels. Laser trimming<sup>[52,53]</sup> and re-bonding appear to be the promising route to achieve this goal, although stamp transfer method,<sup>[44]</sup> and redundant pixel design have been also proposed.<sup>[28,171]</sup> A possible laser-based repair process is schematically shown in Figure 18d. The initial process is to locate the positions of the defect pixels and remove all of them by laser trimming process. A separate process is then used to assemble the Micro-LEDs on



**Figure 17.** Laser direct writing of metallic interconnect. a) Sketch of the printing setup. b) Printed 2D and 3D structures. c) Printed interconnects for a LED. Reproduced with permission.<sup>[164]</sup> Copyright 2010, Wiley-VCH.

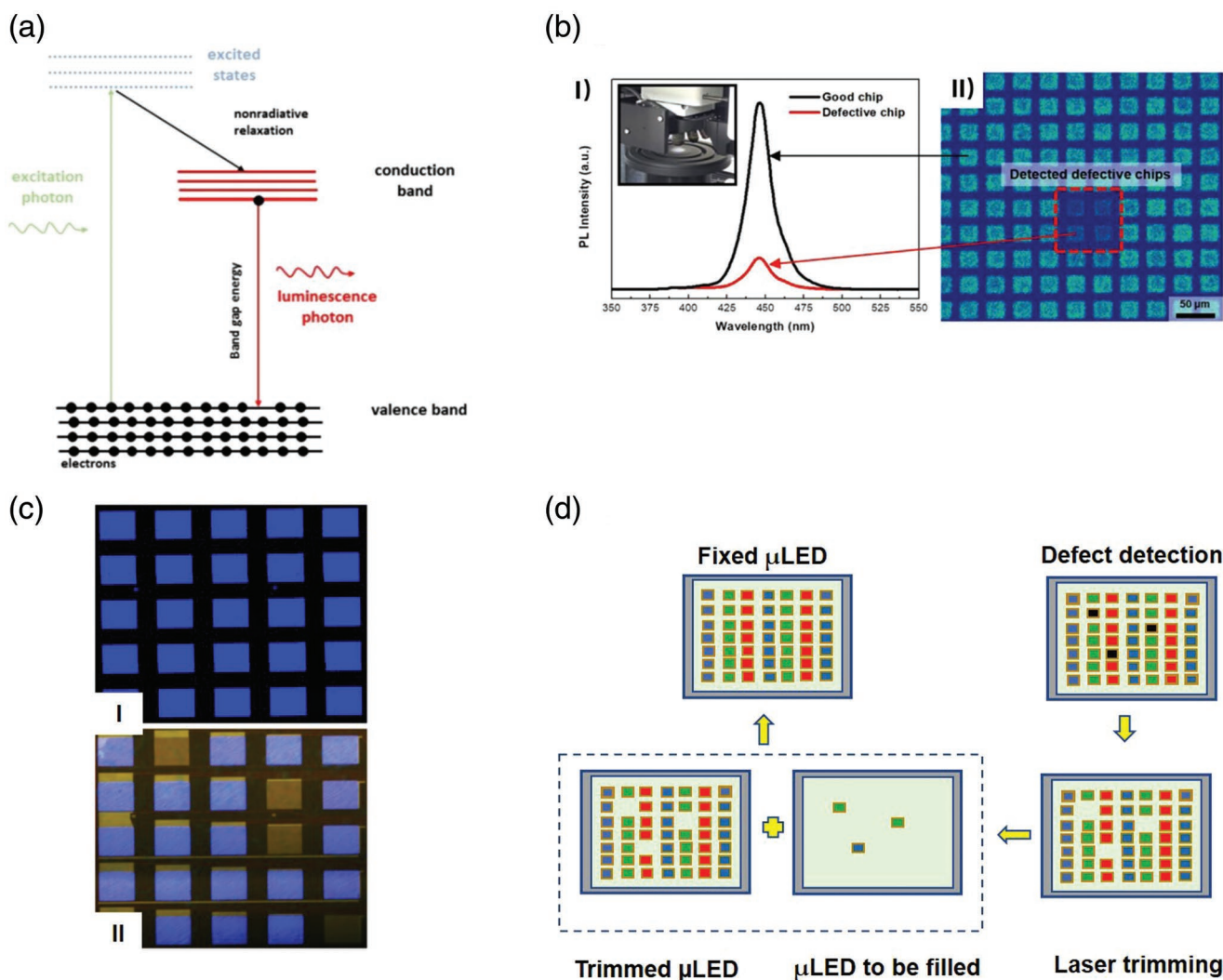
a temporary carrier according to the positions of the bad dies. These Micro-LEDs on the temporary carrier aim to refill the regions in the trimmed array. This leads to a fully fixed Micro-LED array without defects. Defect management is one of the biggest challenges for Micro-LED display. At the moment, there are no mature solutions which can meet the need of industrial repair. Several companies such as Uniqata and Toray are developing laser-based defect repair tools. However, major challenges remain for enhancing the repair efficiency and reducing the repair cost.

#### 4. Conclusions and Outlook

Micro-LED has many advantages compared with current LCD and OLED displays, leading to a wide range of applications and huge markets. Overall, Micro-LED technologies are progressing at a fast pace. Nevertheless, multiple manufacturing and technology issues still need to be solved before consumer-level Micro-LED display products can enter in the market. From the viewpoint of industrial production, efficient yield management and repair strategies are critical to enable Micro-LED displays, as well as high-throughput transfer methods. To address these problems, various laser-based techniques with impressive capabilities in fabricating Micro-LED display have

been developed. In this review, the recent research advances in these laser-based techniques for Micro-LED display were overviewed. Both the working principles and the related progresses of a wide range of laser techniques were discussed, such as chip singulation, geometry shaping, surface texturing, laser annealing, LLO, laser-assisted chip transfer, laser-assisted bonding and defect management. The advantages and limitations of these laser processing techniques are also summarized, along with their commercial potential. Despite the great progress in the development of these laser techniques for Micro-LEDs, great efforts for technical improvements are still needed before these laser-based techniques are feasible for large volume production of consumer Micro-LED display panels.

First of all, there is a great need of the further improvement in LLO quality and yield, such that ultrathin Micro-LEDs chips without substrate can be manufactured on an industrial scale. LLO exhibited the potential for achieving this goal. However, the LLO yield must be further improved. Currently it is easy to achieve a 99.9% yield, but it is difficult to obtain 99.99% or an even higher yield of the Micro-LED chip, due to the technical obstacle in accurate control of the beam uniformity across the total scanning area. Technical innovations for stable beam spot and beam profile control, therefore, are important factors for further improvement of the LLO technology. Furthermore, to



**Figure 18.** a) Principle of the photoluminescence (PL) excited by a laser source. b) An example of the defects detected by the PL measurement based on a pulsed laser. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>).<sup>[44]</sup> c) Comparison between PL and EL measurements of the same Micro-LED array. The images clearly show some pixels are not functional electrically but they are working optically. Reproduced with permission.<sup>[168]</sup> Copyright 2021, Society for Information Display, published by Wiley. d) Sketch of the laser-based Micro-LED repair method.

enhance the transfer speed, faster laser scanning methods are highly desired.

Second, further improvements in the Micro-LED transfer throughput, yield, and accuracy are in highly demand. LIFT appears to be a promising method, which indeed exhibited the capability for high-speed Micro-LED transfer of 100 KK/h. The ink placement accuracy, however, needs to be further improved, in order to meet the need of volume production. Furthermore, the laser ablation induced residuals from the ablated sacrificial layer may cause contaminations on the device surface, which should be minimized. Techniques based on laser induced reversible adhesion switching, rather than laser ablation, may provide a good solution to overcome the above limitations. Innovative strategies for controlling the pulsed beam intensity and beam shape, and designing new light-responsive sacrificial materials with low residuals, are also important considerations in developing commercially feasible LIFT tools. In addition, since LIFT cannot release the device from the growth substrate

directly, it is therefore practical to combine multiple laser processing techniques, for instance both LLO and LIFT, into one laser system.

Finally, an improved laser-based defect repair strategy is required. Sequential laser trimming and re-bonding do work, but the low repair efficiency is a major limiting factor from the viewpoint of cost considerations. Parallel pixel repair strategy using multiple programmable laser beams, may be one right direction to be worth investigating in the future. Undoubtedly, Laser techniques will play a determinative role in large-scale production of Micro-LED display if it can be commercialized.

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## Conflict of Interest

The authors declare no conflict of interest.

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