Micro-LED Technologies and Applications

Light-emitting diodes (LEDs) offer extraordinary luminance, efficiency, and color quality, but to date are largely used in displays as backlights or packaged pixel elements in large-area LED billboard displays. Building high-performance emissive displays in a smaller form factor requires a new micro-LED technology separate from what is used for large LED billboards. Several approaches have been proposed to isolate micro-LED elements and integrate these micro-LEDs into active-matrix arrays. Technologies that use micro-LEDs offer the potential for significantly increased luminance and efficiency, unlocking new possibilities in high dynamic range, augmented/mixed reality, projection, and non-display light-engine applications.

by Vincent W. Lee, Nancy Twu, and Ioannis Kymissis

THE luminance and power efficiency of a light source are the key factors for determining suitable applications. Light-emitting diodes (LEDs) offer very high luminance levels, greater than 50,000,000 cd/m^2, giving them a proven ability to perform in high-ambient display applications. LEDs also offer some of the highest efficiencies for converting electrical power to optical power. Depending on the material system, an energy conversion of over 60% can be achieved. Due to these benefits and the small solid-state form factor, emissive LEDs can become a solution for display applications of all sizes.

In today's display applications, LEDs are most commonly used as the illumination source for liquid-crystal displays (LCDs) of practically all sizes, including 100-in. TVs to 0.5-in. microdisplays. Individually packaged LEDs are also used as the direct pixel element in large-area billboard displays, which are currently the only format of directly emissive LED displays. What remains underexploited is the use of LEDs as individual pixel elements in all other smaller display formats.

In large-area displays, discrete packaged LED pixels, each containing a red, green, and blue LED chip in the package, form the active elements in emissive video walls. Emissive video walls are attractive for stadium and advertising applications given the high luminance (excellent viewability under bright ambient light conditions) and energy efficiency of LEDs. Although the size of each packaged LED pixel is relatively large, full-resolution displays are easily achieved in these large-area applications. Building smaller displays with packaged LEDs is more difficult. When using the smallest available packaged LED pixels (approximately 0.75 mm), 70 in. is the current minimum achievable size for a FHD-resolution (1920 × 1080) full-color display. When using packaged LED pixels, displays smaller than 70 in. can be produced, albeit with lower resolution.

New applications such as high-dynamic-range (HDR) television and augmented reality are demanding the same high-performance specifications as that of large-area displays, but at dimensions that are difficult to scale for fully packaged LEDs. For example, TV displays require a peak luminance of 10,000 cd/m^2 for future HDR content, and microdisplays need to reach 100,000 cd/m^2 to support the luminance needs of augmented-reality and mixed-reality (AR/MR) glasses. These requirements are easily satisfied by LEDs, which can have luminances up to 50,000,000 cd/m^2. Like other emissive displays, an emissive LED display offers the luminance and efficiency of the pixel source without the typical loss associated with light selection and modulation elements (polarizers, color filters, *etc*). Emissive LED arrays therefore have a huge luminance advantage

High-luminance emissive FHD-resolution LED displays smaller than 70 in. cannot be made from packaged LED pixels, and thus require the development of new manufacturing techniques and technologies. Specifically, these smaller display formats require fabrication and use smaller LED elements or "micro-LEDs." Loosely defined, micro-LEDs are

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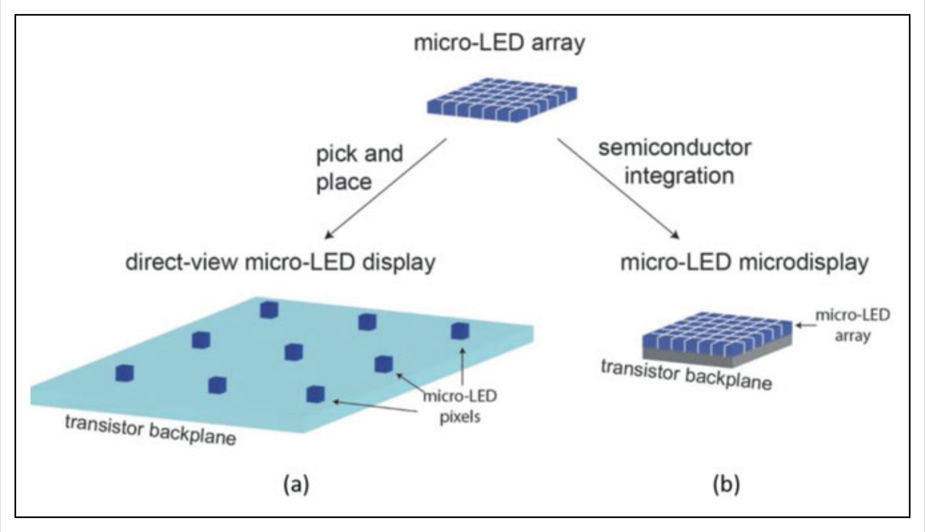

Fig. 1: Shown are two approaches used to build micro-LED displays. Both methods start with a micro-LED array but use either (a) a pick-and-place technology for direct-view displays or (b) semiconductor integration for microdisplays.

devices in which the LED emission area per pixel is below 50 × 50 µm, or 0.0025 mm^2. An array of micro-LEDs makes up a micro-LED display, which ranges in size from fractions of an inch up to 70 in.

Micro-LED displays take advantage of the exceptional luminance of LEDs by spreading the generated photons over a larger area than the area occupied by the micro-LEDs themselves, either by distributing the LED elements spatially or by dispersing light optically. This is illustrated in Fig. 1. There are wide differences between these two technologies, despite confusing nomenclature that refers to both as "micro-LED." The former technology, shown in Fig. 1(a), distributes LED elements spatially and can be used to build displays ranging from 3 to 70 in. In this article, these are referred to as "direct-view micro-LED displays." The latter technology, shown in Fig. 1(b), disperses light optically and is used to build displays < 2 in., which are referred to as "micro-LED microdisplays."

In direct-view micro-LED displays, micro-LEDs are fabricated with a small pixel pitch, separated into individual dice, and transferred to an active-matrix backplane using pick-and-place methods. This allows for the development of an LED display in which the active LED area occupies only a small fraction of the total area. The area expansion allows for direct viewability of high-luminance micro-LEDs (up to a full 50,000,000 cd/m^2 per LED) because the micro-LEDs are spatially separated, resulting in a lower apparent luminance per pixel. The area unoccupied by micro-LEDs is available for a black matrix and integration of interconnection electronics. With larger current-distribution buses available, this approach allows for passive-matrix display development and integration and also lends itself to active-matrix approaches using large-area electronics.

Micro-LED microdisplays use semiconductor integration techniques to combine an array of small pixel-pitch micro-LEDs with a transistor back plate, which are then integrated with an optical system such as projection lenses or see-through glasses. Because the < 20-µm pixel pitch of micro-LEDs for microdisplays is even smaller than that of direct-view displays, the scaling of micro-LEDs for microdisplays requires full integration at the wafer-fabrication level. There are several strategies to perform the semiconductor integration between micro-LEDs and transistors, including pixel-to-transistor bonding, LED epitaxial transfer to silicon CMOS, and integration with thin-film-transistors (TFTs).

Because of fundamental differences in technology approaches and display sizes, micro-LEDs for direct-view displays and micro-LEDs for microdisplays target different markets. Together they offer the promise of replacing all displays now and in the future with the most efficient and highest-luminance systems possible.

Direct-View Micro-LED Displays Using Pick-and-Place Technologies

Today, stadium and large street displays use fully packaged surface-mounted LEDs in a

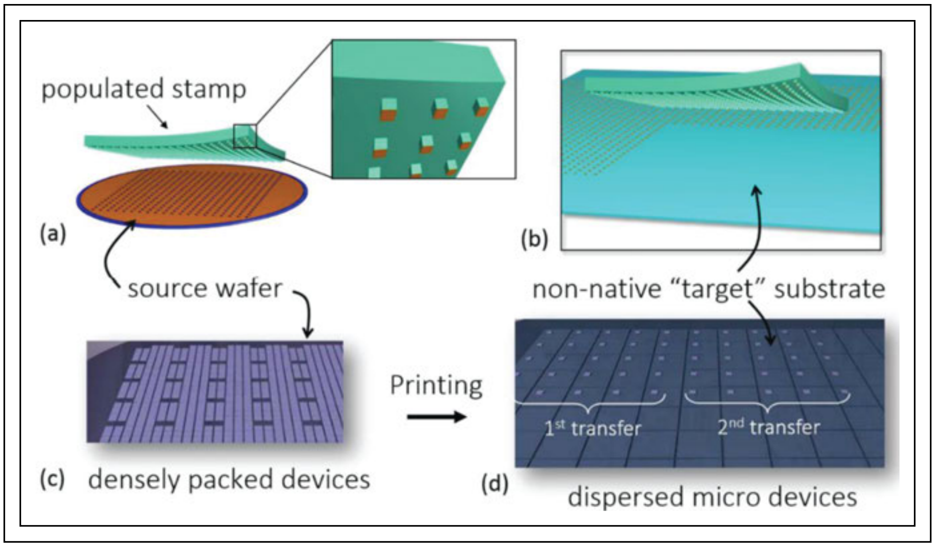

Fig. 2: In (a) and (c), selected individual chips are picked from a wafer using an elastomer stamp. In (b) and (d), the stamp is then moved to a non-native "target" substrate where the devices are placed, typically in a sparse array. Multiple devices are picked and placed in each transfer, and multiple transfers are used to complete a final display.[1]

tiled format. With reductions in packaged LED sizes, large-area tiled displays have scaled to smaller sizes and higher resolution displays, as small as 70 in. with FHD resolution. Direct-view micro-LED technologies are the natural extension of efforts to further shrink stadium-sized LED displays for new applications. Instead of using packaged LEDs, direct-view micro-LED technologies use smaller unpackaged LED dies and pick-and-place techniques to build emissive LED displays in the 3–70-in. size range. The resulting direct-view micro-LED displays show increased luminance and improved color gamut for HDR displays, provide different form factors for wearable and flexible displays, and address the push for ever-increasing power efficiency in these applications.

Several academic groups and companies have demonstrated pick-and-place approaches for transferring LED dies to a substrate board and connecting the elements to each other. All of these techniques begin with fabrication of densely packed small-pitch micro-LEDs. The micro-LEDs are then separated into individual dies, transferred to a secondary substrate, and physically spread out to a large pitch via proprietary pick-and-place processes. The choice of secondary substrate depends on the specific application and resolution. Applications such as flat-panel displays use a secondary glass substrate with active-drive transistors, while wearables such as watches and wristbands can use a flexible secondary substrate.

While several pick-and-place methods are being developed, few are publicly disclosed in detail. One paper by Bower *et al*. from X-Celeprint highlights some key aspects of pick-and-place processes.[1] Figures 2(a) and 2(c) show an array of densely packed devices (micro-LEDs) from which a subset of devices is sparsely picked up by an elastomer stamp. This stamp is moved to a secondary substrate, shown in Figs. 2(b) and 2(d), placing the devices in a dispersed array. The stamp can pick up many micro-LED devices at one time to lower the number of transfers needed to populate a full display.

Figure 3 shows X-Celeprint's process for transferring a small-pitch (~20 µm) micro-LED array to a larger pitch (~200 µm) on a glass substrate.[2] The micro-LEDs have a sacrificial release layer that is engineered into the LED epitaxial growth and later undercut to release the micro-LEDs from the growth substrate [Fig. 3(b)]. The micro-LEDs are then picked up by the elastomer stamp and transferred to a glass substrate with some pre-defined metal lines [Fig. 3(c)]. A second metal layer is then deposited [Fig. 3(d)] to electrically connect the transferred micro-LEDs to the glass substrate. By using this transfer process, X-Celeprint demonstrates a 100 × 100 color passive-matrix display [Fig. 3(e)]. Active-matrix formats can also be achieved by transferring the micro-LEDs to a secondary substrate with indium gallium zinc oxide (IGZO) or low-temperature polysilicon (LTPS) transistors.

Sony's micro-LED technology, initially demonstrated at CES in 2012, was recently released. Based on available technical data,

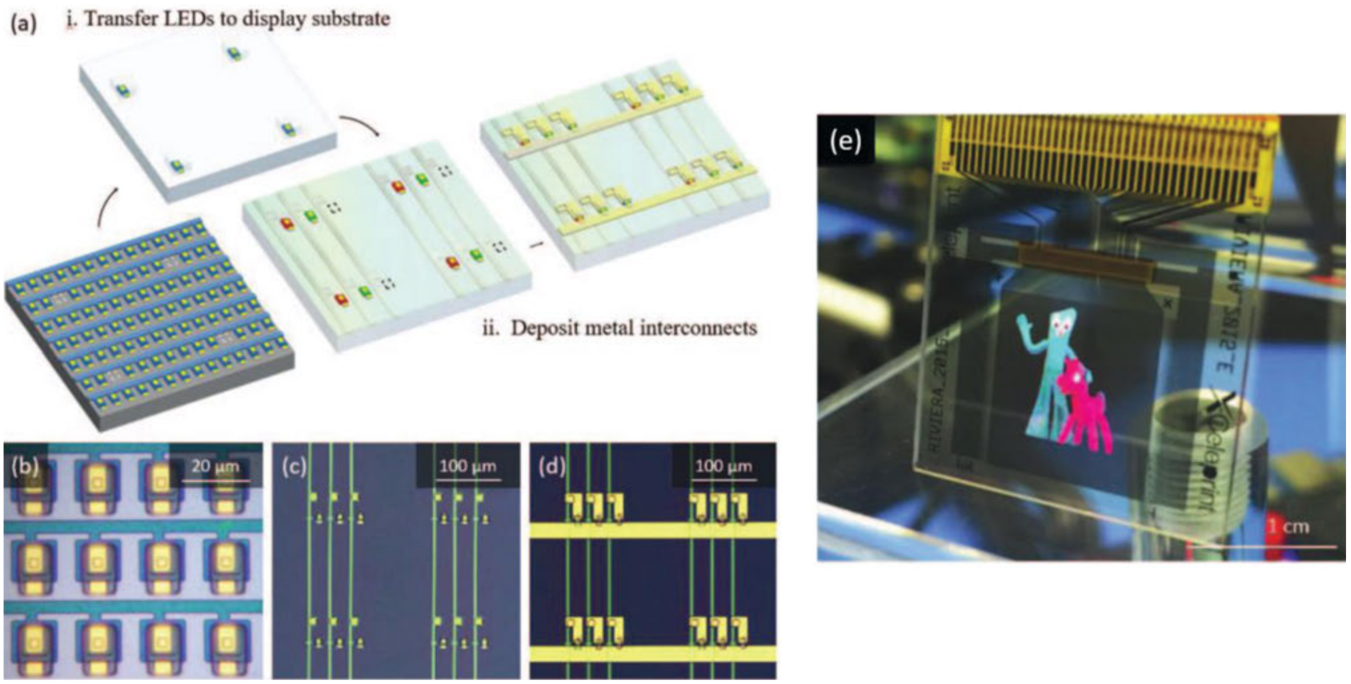

Fig. 3: *Image (a) shows the pick-and-place process of micro-LEDs to a secondary substrate. Image (b) is a micrograph of ready-to-transfer micro-LEDs on a source wafer with an undercut etch of the sacrificial layer. The LED size is approximately 10 x 10 µm. Images (c) and (d) are micrographs of transferred micro-LEDs and deposited metal layer for interconnection between micro-LEDs and a secondary substrate, respectively. Image (e) shows a full-color passive-matrix micro-LED display.*[2]

micro-LEDs approximately 50 × 50 µm in size are placed on a 320 RGB × 360 tile.[3] Much like conventional stadium displays, these micro-LED based tiles are then further arrayed to form the FHD display. Not much is known about the pick-and-place method or the backplanes used in Sony's demonstrations. Two other companies in the space are InfiniLED and LuxVue. InfiniLED's micro-LED technology uses a unique parabolic micro-LED structure for light collimation and light extraction [Fig. 4(a)].[4] This type of shaping allows for control of the micro-LED emission angle and potential improvements to the overall efficiency of the display. LuxVue, recently acquired by Apple, uses a MEMS-based pick-and-place process for micro-LEDs.

For pick-and-place technologies, the manufacturing challenges are similar across all of the techniques. The primary challenge is pixel transfer yield, as modern displays require nearly zero dead pixels across a FHD screen. To reach the needed pixel yields, some groups have proposed transferring redundant micro-LEDs,[4] as shown in Fig. 4(b), or performing individual pixel repair transfers for dead pixels.[2] These workarounds will add to either the base material cost or manufacturing time to build a display, reducing scalability. In addition, each pick-and-place process requires careful engineering of the LED materials, sometimes even custom LED epitaxy, to ensure that the electrical and optical performances are not affected throughout the fabrication process (LED ohmic contacts, undercut etch of the micro-LEDs, transfer of pixels, *etc*).

Micro-LED Microdisplays Using Semiconductor Integration Technologies

For microdisplays with a panel diagonal < 2 in., pick-and-place technologies cannot scale to the smaller pixel pitch required for FHD displays. Microdisplays < 2 in. using passive-matrix schemes also cannot achieve sufficient resolution or luminance, even though small pixel pitches have been demonstrated.[5,6] Building bright high-resolution < 2 in. microdisplays requires direct integration of micro-LED arrays with arrays of transistors that provide active-matrix switching. There are several transistor technologies and approaches to building the integrated active-transistor matrix. At a high level, these technologies can be sorted into the three categories as shown in Fig. 5: (a) chip-level

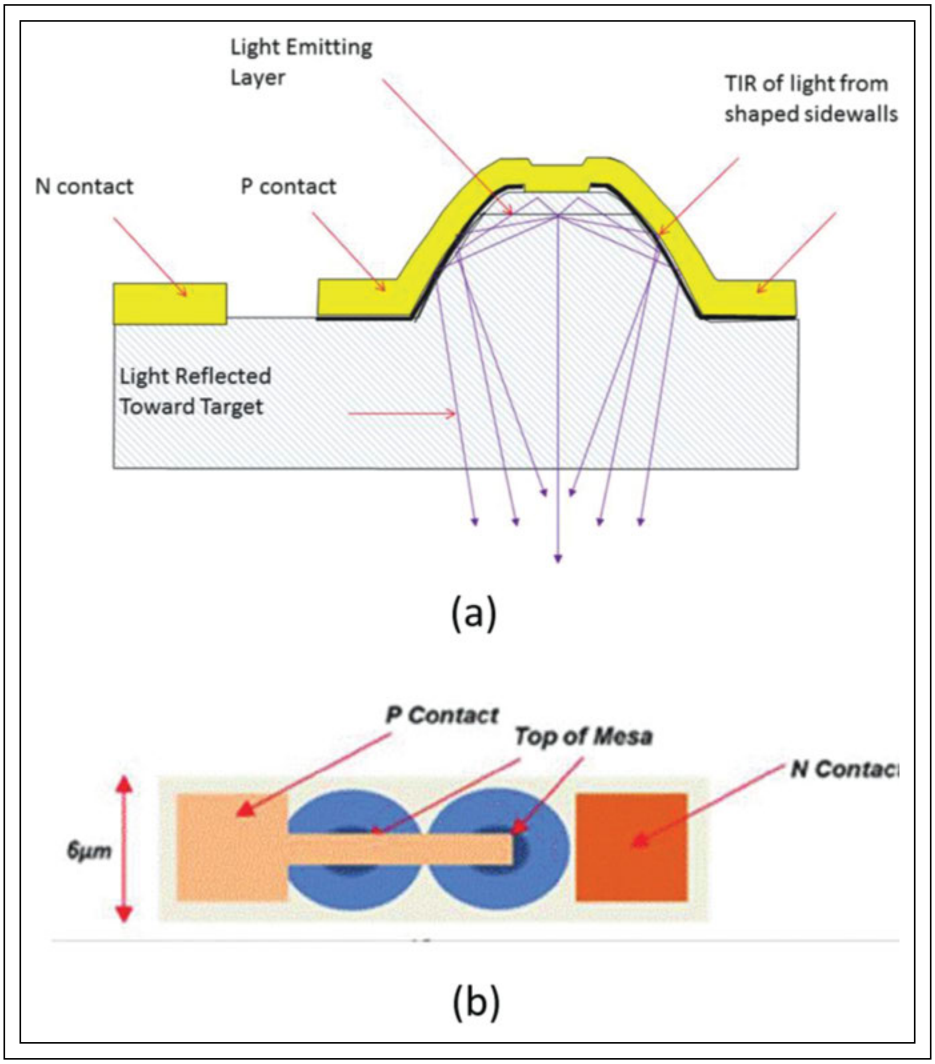

Fig. 4: *The top image (a) shows a micro-LED schematic with reflective sidewalls and a curved shape for light collimation and extraction. The lower image (b) demonstrates a top-view design of a twin micro-LED emitter for redundancy and improvement of micro-LED yield.*[4]

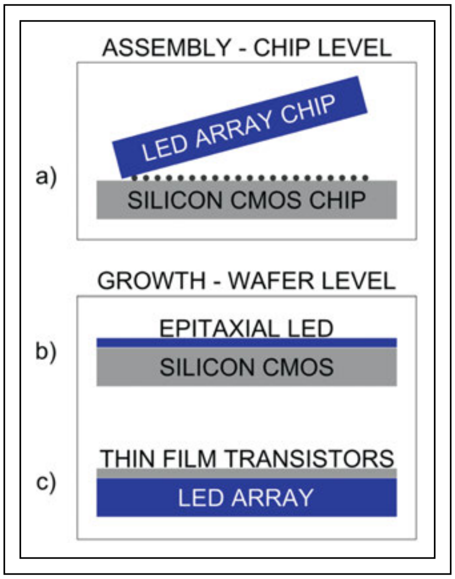

Fig. 5: *Shown are three approaches to the integration of silicon transistors and micro-LED arrays for microdisplays: (a) chip-level hybridization of foundry CMOS chip with micro-LED arrays; (b) wafer-level transfer of LED epitaxial layers to CMOS wafer; and (c) wafer-level fabrication of TFTs directly on micro-LED arrays.*[7]

micro-LED pixel–to–CMOS-transistor bonding, (b) LED epitaxial transfer to silicon CMOS, and (c) micro-LED array integration with TFTs.

Under first consideration is chip-level micro-LED pixel–to–CMOS-transistor bonding, a process also known as flip-chip bonding. Because of the ubiquity of foundry CMOS processes, many technologies in this category start with a completed silicon chip and work within back-end processes to add functionality, namely, chip-level assembly of micro-LED arrays as shown in Fig. 5(a). The LED arrays are fabricated by lithographic patterning of contacts and mesa etches. Bump bonds are then fabricated either on the silicon CMOS chip or on the micro-LED array. Next, the micro-LED arrays are die separated and bump bonded to the silicon CMOS chip. This fabrication flow offers researchers the advantage of using the highest-performing transistors, demonstrated by researchers at the University of Strathclyde,[8] the Hong Kong University of Science and Technology,[9] the Industrial Technology Research Institute,[10] and mLED.[11] Devices fabricated by mLED with conventional flip-chip bonding have been hybridized and demonstrated up to nHD (640 × 360) resolution with a pixel pitch as low as 20 µm.

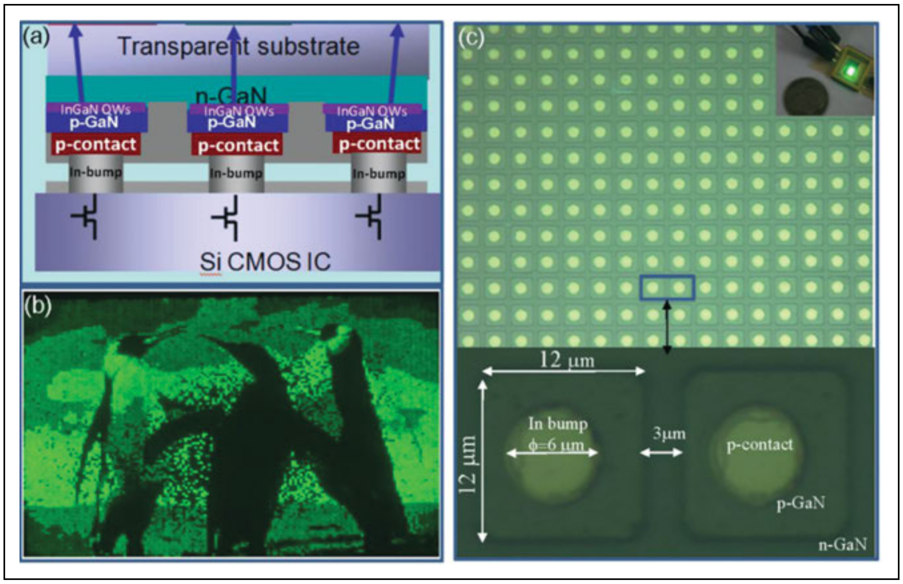

Fig. 6: *Image (a) shows a cross-section schematic of a silicon CMOS IC flip-chip bonded with a micro-LED array using indium bump bonds. An image of a monochrome microdisplay appears in (b) and a micrograph of a micro-LED array with indium bonds prior to flip-chip bonding is shown in (c).*[12]

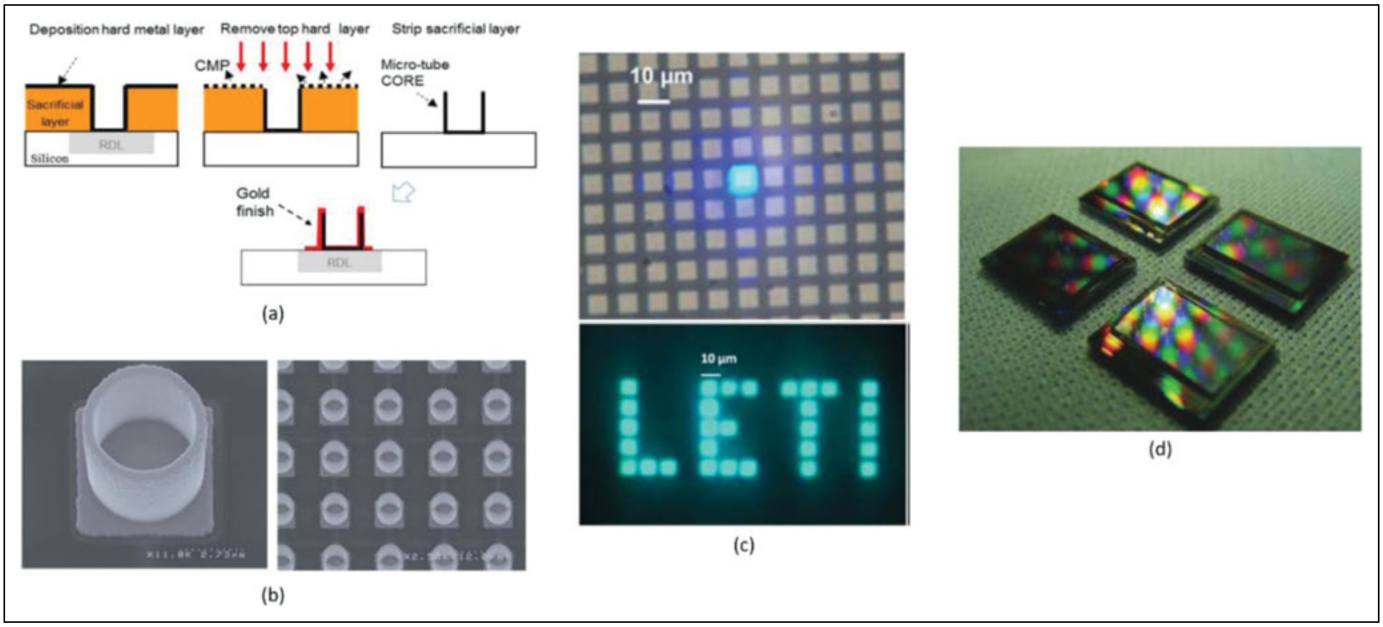

Fig. 7: *Image (a) shows a schematic cross section of the micro-tube fabrication process. Image (b) shows a scanning electron micrograph of micro-tubes fabricated on a CMOS wafer. In (c) and (d), micrographs and a photograph of flip-chip bonded micro-LED arrays with a 10-µm pixel pitch are shown.*[13,14]

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