Paper 59-3 has been designated as a Distinguished Paper at Display Week 2018. The full-length version of this paper appears in a Special Section of the *Journal of the Society for Information Display (JSID)* devoted to Display Week 2018 Distinguished Papers. This Special Section will be freely accessible until December 31, 2018 via:

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Authors that wish to refer to this work are advised to cite the full-length version by referring to its DOI:

https://doi.org/10.1002/jsid.649

Wafer Scale Hybrid Monolithic Integration of Si-based IC and III-V Epilayers - a Mass Manufacturable Approach for Active Matrix micro-LED Displays

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Abstract

JBD has developed its unique wafer-level mass manufacturable approach of monolithic hybrid integration of compound semiconductor functional device arrays on Si ICs, which enables the fabrication of hybrid chips with large device array and ultra-fine pitch of a few micrometers. Red, green and blue active matrix micro-LED (AMμLED) micro displays of VGA format with 1270ppi pixel resolution and 256 grayscales were successfully fabricated using JBD's monolithic hybrid integration technology. Further integration of a micro-reflector array on the micro-LED array significantly improves the emission directionality of the AMμLED micro display, resulting in an ultra-high brightness of $3x10^6$ nits for green AMμLED micro displays. The resultant monochromatic micro-LED micro displays exhibit improved device performance compared to other micro display technologies and have great potentials in applications such as portable projectors and near-to-eye projection for augmented reality (AR). More importantly, the wafer-scale monolithic hybrid integration technology offers a clear path for large volume, low cost mass production of hybrid opto-electronic integrated circuit (OEIC) chips.

Author Keywords

Micro-LEDs, Hybrid monolithic integration, Micro-display

1. Background

Since its invention in the late 1950s, silicon based integrated circuits (IC) have enjoyed sustained rapid advancement. With their unsurpassed capabilities in logic operation, signal processing, and data storage, silicon based ICs are now used in virtually all electronic equipment and have revolutionized the human society. Computers, mobile phones, and other home appliances are now inextricable parts of human life, made possible by the small size and low cost of ICs.

However, limited by its physical properties, many functional devices cannot be achieved on Si. For example, Si is an indirect bandgap semiconductor with a bandgap energy of 1.12eV, which makes it unsuitable for light emitting devices, as well as photodectectors in the UV and IR wavelength ranges. While compound semiconductors such as GaAs, InP, GaN, and GaSb are best suited for the fabrication of light emitting devices and photodetectors [1] [2] [3], [4]. Fusion of the high-performance of IC and the light emission/detection capability of compound semiconductor devices will offer great opportunities for light-based technologies and products [5], [6], [7], [8]. However, due to the vast difference in their material properties and fabrication processes, the integration of compound semiconductor devices with Si based ICs is extremely challenging.

In the past few decades, significant research and development efforts have been devoted to search for effective hybrid integration of compound semiconductor and Si based ICs. With limited success, the hybrid integration technologies as of today are still mainly constrained to the PCB level for discrete devices and chip level for large arrays [9], [10], [11].

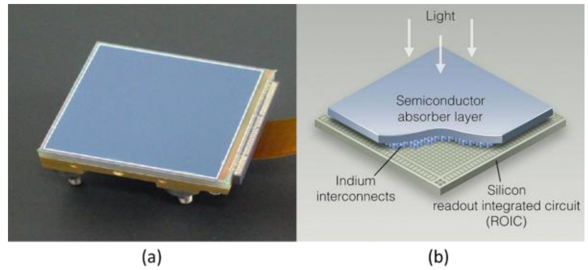

Figure 1: (a) A photo of an infrared focal-plane array detector chip made by Teledye Imaging Sensors for astronomy and space applications [5]; (b) A schematic illustration of the architecture of the hybrid integrated infrared focal-plane array detector chip [6].

Recently, the emerging applications of augmented reality (AR) raise urgent call for new display technologies. The miniaturized displays that can be accommodated to those market applications need to meet stringent technical requirements that cannot be satisfied by current display technologies such as LCD or OLED. Inorganic micro-LED micro displays [11], [12], [13] are viewed as one of the most promising solutions and has gained considerable traction in recent years. As a self-emissive display technology, micro-LED micro displays are more compact in size, fast in response time and can provide higher contrast ratio and energy efficiency compared with LCD and LCoS technologies. Meanwhile, compared to OLED micro displays which are also self-emissive, micro-LED micro displays excel in the higher luminance and reliability. To mass produce the micro-LED micro displays that meet the market need, large-volume, low-cost production method must be developed for the hybridization of micro-LED arrays with Si driver ICs. Although flip-chip technology has been used by various groups [11], [12], [13], [14] for the successful demonstration of AMμLED micro displays, the inherent drawbacks of flip-chip technology make it unsuitable for low cost mass production of fine pitch AMμLED micro displays.

Flip-Chip Technology: Flip-chip technology is the most widely used technique for the hybrid integration of Si-based pixel driver/readout IC and compound semiconductor functional device arrays. Fig. 2 shows a schematic illustration of the flip-chip process [15]. In this approach, Si-based pixel driver/readout ICs and compound semiconductor functional device arrays are designed having identical geometric layouts and fabricated separately on their own substrates. After the wafer-scale fabrication, individual chips containing the functional device arrays are separated from the wafer and bonded to the Si ICs in a high precision alignment bonding equipment using an array of solder bumps to electrically join the pixel driver/readout circuit array and the functional device array.

 ISSN 0097-996X/18/4702-0786-$1.00

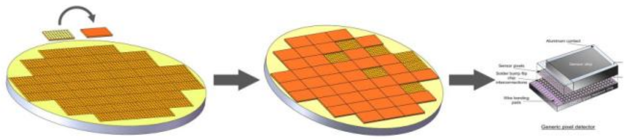

Figure 2: Schematics of flip-chip process.

With the flip-chip technology, hybrid integration of large-scale functional device arrays on Si ICs is made possible, which enables many advanced device applications such as UV and IR focal plane array chips for imaging applications [1], [4] as well as the AMμLED micro displays emerged recently for advanced display applications [11]. However, the inherent drawbacks associated with flip-chip technology limit the performance and the cost of hybrid chips produced by this method. First of all, flip-chip is a chip-level process that requires precise alignment, which makes it a low through-put hence high-cost process. The cost of making hybrid chips with flip-chip process increases substantially as the pixel size of device arrays shrinks. Secondly, the compound semiconductor growth substrate typically remains after the hybrid integration; therefore, transparent substrates are essential [12], [14]. In addition, the thermal mismatch between the compound semiconductor substrate and Si substrate introduces build-in stress in the hybrid chips, which may cause manufacture yield loss and long-term reliability issues. Furthermore, limited by the existing manufacturing equipment capability and the flip-chip process itself, the size of the pixel is usually larger than 50 μm. Even though the industry is working diligently to achieve a pixel size as small as 20 μm, there is no foreseeable clear path to bring it down to less than 10 μm pixel size at a reasonable cost.

2. Monolithic Hybrid Integration Technology

To overcome the issues associated with the flip-chip technology and address the market demand for high performance micro-LED micro displays, JBD has developed its unique monolithic hybrid integration technology. The technology fully utilizes the well-established infrastructure, equipment sets, and semiconductor processes developed by the Si-based IC industry. Wafer-level monolithic hybrid integration of compound semiconductor device arrays on Si based ICs has been realized for producing high resolution, high brightness AMμLED micro displays, making it suitable for large-volume and low-cost mass production of highly integrated functional hybrid chips.

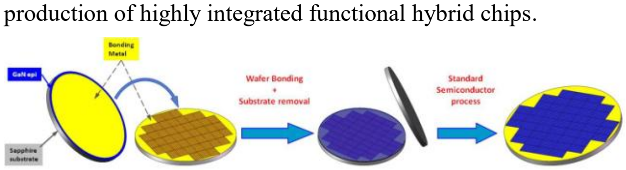

Figure 3: JBD's wafer-level monolithic hybrid integration technology.

The general process of the monolithic hybrid integration technology is schematically illustrated in Fig. 3. Instead of flip-chip bonding a pre-fabricated array of functional devices, compound semiconductor epitaxial layers are transferred onto the Si IC wafer through wafer bonding and substrate removal process. Such wafer-level blank epi transfer eliminates the need of precise alignment as required by the flip-chip technology, therefore making it a high throughput wafer-scale fabrication process. With this process, JBD has successfully demonstrated the transfer of various functional compound semiconductor epitaxial layers, including GaN, GaAs or InP epitaxial layers, onto the Si IC wafers. The resulted epi-on-IC templates are subsequently processed with the standard semiconductor device fabrication processes to produce monolithic hybrid opto-electronic integrated circuit (OEIC) chips with different functionalities. With the high-precision photolithography equipment and process well established in the semiconductor industry, compound semiconductor functional device arrays can be fabricated on top of the pixel driver/readout circuit arrays with sub-micron alignment accuracy. This in turn enables fine pitch device arrays with pixel size as small as a few microns.

3. Active Matrix LED micro displays

Using JBD's monolithic hybrid integration technology, we have successfully demonstrated a mass manufacturable approach for the fabrication of high-performance monochromatic active matrix micro-LED (AMμLED) micro displays.

In the demonstration, the CMOS active matrix backplane used for fabricating the micro-LED micro display contains an array of pixel driver circuits with a display resolution of 640×480 and a pixel pitch of 20μm. Commercially available LED epitaxy wafers were used for the fabrication of the AMμLED micro displays. Different material systems are used for different emission colors: InGaN/GaN based materials are used for the green/blue LEDs and AlInGaP/GaAs based materials are used for the red LEDs. The fabrication process has been presented in a different paper and will not be illustrated in detail here.

As shown in Fig. 4, we have demonstrated ultra-high-brightness red, green, and blue AMμLED micro display panels of VGA format with a pixel pitch of 20μm and a pixel resolution of 1270 ppi. The brightness of the green AMμLED micro display well exceeds $5x10^5$ cd/m^2, when the driving current density reaches 50A/cm, representing an improvement of over 500-times compared to the existing self-emissive micro displays.

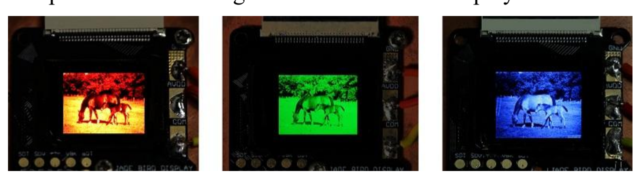

Figure 4: Photos of packaged red, green, and blue AMLED micro displays showing pictures when the control and image signals were fed into the devices.

Ultra-high pixel density of 5000+ ppi has also been demonstrated using JBD's monolithic hybrid integration approach with optimized fabrication processes. To our best knowledge, this represents the highest resolution reported for AMμLED micro displays. With further optimization of the device design and fabrication process, it is believed that the pixel pitch of the AMμLED micro displays can be reduced further, reaching a pixel density higher than 10,000 ppi which is very difficult to achieve for other hybrid integration technologies.

4. AMμLED with directional emission

The ultra-high brightness and the self-emissive nature make AMμLED micro displays the promising candidates for compact, high-brightness projection applications. However, limited by the large divergent angle of the light emission from the micro LED, the optical efficiency for the AMµLED-based projection is inherently low. Even in a projection system with a large aperture of F/1.0, only <10% of light from the micro-LED display can be collected and projected.

Unlike the flip-chip approach, AMµLED micro displays made with JBD's monolithic hybrid integration technology does not have the growth substrate covering the micro-LED arrays, which enables further integration of micro-optics arrays on top of the micro-LED arrays to reduce the divergence of the emitted light and enhance the light projection efficiency. Previously we have demonstrated reduction in the divergence angle of the AMµLED micro display using micro-lens array, in which each micro-LED has one micro-lens integrated on top [19]. An optical spacer is usually formed between the micro-LEDs and micro-lens to control the optical focus of the micro-lens. However, with the constraint of the pixel pitch size and the intrinsic optical properties of the micro-lens, only the small-angle light (typically < +/- 45 degrees) from the micro LED can be effectively converged, leaving the large-angle light, which carries the significantly larger amount of power, being wasted or coupled to the adjacent micro lens to cause optical crosstalk.

An alternative approach employs a micro-reflector array to reduce the divergence angle of the micro-LED with minimal power wasting and zero inter-pixel crosstalk. In this configuration, each micro-LED pixel is integrated with a cup-shape micro-reflector, which can effectively reflect the large-angle light into small angles, leading to a higher optical converging efficiency compared with the micro-lens approach.

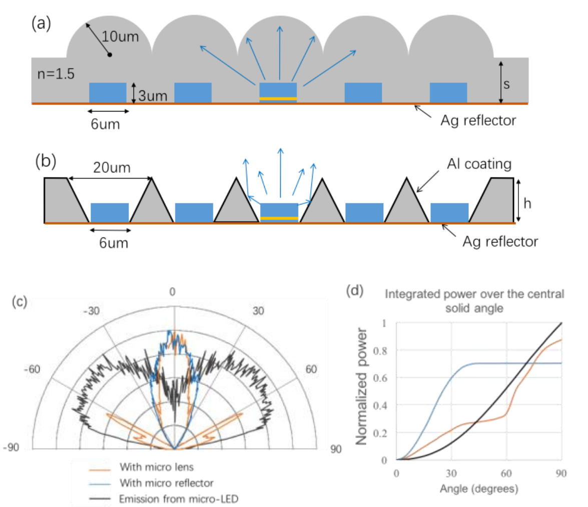

Figure 5: Cross section of 5x5 micro-LED array with (a) the micro-lens array and (b) the micro-reflector array. The simulation results for (c) angular distribution of light and (b) integrated power over central solid angle.

Ray-Tracing Simulation: 3D non-sequential ray tracing simulation (Zemax OpticStudio) is employed to study the divergence angle of light from micro-LED micro display with and without the presence of the micro reflectors or the micro-lenses. In the simulation, we consider a 5x5 micro-LED array with a period of 20 µm, placed on a planar silver reflector. The cylindrical micro-LED has a diameter of 6 µm and a height of 3 µm. A volume cylindrical source with 100nm thickness is placed inside of the central LED to model the light emission from the quantum well region. The wavelength of light is 460nm. The refractive index of the mesa is 2.5. Fig. 5a and 5b show the corresponding micro-LED array with micro lenses and micro reflectors integrated respectively. The micro reflector features straight sidewall coated with aluminum.

The effect of the reflector height h and the spacer thickness s on the divergence angle is studied. For illustration purpose, Fig.5c shows the resulted angular light distribution for h=16 µm and s=10 µm. Both the micro-reflector and micro-lens are effective in suppressing the divergence angle from the micro-LED, but a significant optical crosstalk is observed with the micro-lens configuration. Fig. 5d shows the integrated power of the far field light over the central solid angle, where the power is normalized to the total output power from the micro LED. The micro reflector is generally 2~3 times more efficient than the micro-lens configuration in terms of optical convergence.

Experimental Demonstration: Monolithic integration of Al-coated micro-reflector array has been successfully demonstrated on our VGA-format AMµLED micro display, as shown in Fig. 6a. The emission field distribution is measured and compared with the micro-lens-integrated AMµLED micro display prepared separately. The measurement result, as shown in Fig. 6b is consistent with the ray-tracing simulation in Fig. 5. With the improved emission directionality, the brightness of green AMµLED micro displays is enhanced by a factor of 6 to > 3×10^6 cd/m^2 in the normal direction. Further reduction of the divergence angle and enhancement of the brightness is possible by optimizing the dimensions of the micro reflector and the micro lens, such as reducing the bottom diameter and increasing the top diameter of the reflector, adjusting the thickness of the spacer below the micro lens, etc.

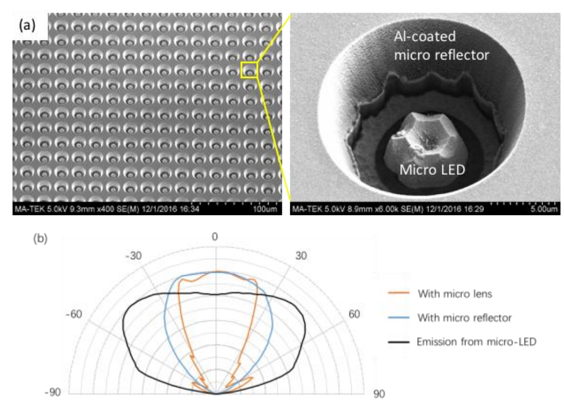

Figure 6: SEM of AMµLED micro display with monolithically integrated micro-reflectors; (b) the angular distribution of AMLED emission with/without micro-lens/micro-reflector.

5. Potential Applications

With the improved directionality of emission, the ultra-high brightness red, green, and blue AMµLED micro display panels can be used to produce a full-color 3-LED light engine for projection application [18]. Using an external optics such as a trichroic prism, full-color images can be generated by combining the monochromatic images from the red, green and blue micro-LED micro display panels. The image produced by the light engine can be further enlarged and projected by projection optics. Based on the concept, a full-color projector of

VGA resolution was demonstrated as shown in Fig. 7. Since the AMμLED micro display panels are self-emissive, compared to the traditional 3-LCD or DLP light engines, no external backlight unit is needed for the 3-LED light engine, making it more compact and energy efficient for portable projector applications.

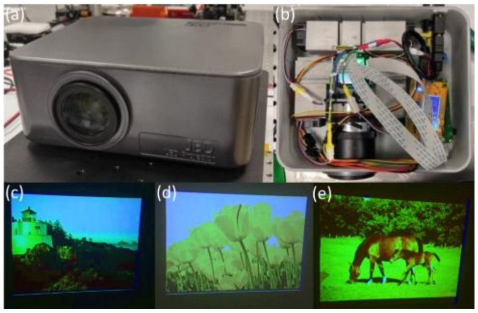

Figure 7: (a) A projector based on 3-LED light engine; (b) Inner structure of the 3-LED projector; (c), (d), and (e) Full color images projected by the 3-LED projector.

For AR applications, AMμLED micro displays made with JBD's monolithic hybrid integration technology provide not only high brightness and high contrast, which is necessary for outdoor operation with strong ambient light background, but also high resolution to achieve large field of view (FOV) for the AR system without sacrificing the image quality and system compactness. In addition, AMμLED micro displays have the advantages of high efficiency, low power consumption, and high reliability compared to other display technologies. Along with the capability of achieving resolution higher than 10,000 ppi, AMμLED micro displays hold great promise for AR applications.

6. Conclusion

In summary, a wafer-level mass manufacturable approach of monolithic hybrid integration of compound semiconductor functional device arrays on Si ICs is demonstrated, which enables the fabrication of hybrid chips with large device array and ultra-fine pitch of a few microns. Monochromatic red, green, and blue AMμLED micro displays with high resolution and high brightness were successfully fabricated on 4-inch CMOS driver IC wafers with the capability to scale up readily when larger epi-wafers are adopted. With further integration of micro-reflector array on the micro-LED array, the light emission directionality is improved significantly, resulting in a brightness of higher than 3×10^6 cd/m^2 in the normal direction for the green AMμLED micro display, representing thousands of times improvement compared to the OLED micro displays. The significant performance improvement over other micro display technologies makes the AMμLED micro displays highly desirable for applications including augmented reality (AR) and portable projectors. Most importantly, the demonstrated manufacturing approach utilizes standard semiconductor equipment and processes and can be easily accommodated to the existing semiconductor fabrication infrastructure, making the large-volume and low-cost production of such hybrid OEIC chips possible.

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