Monolithic integration of full-color micro-LED display using MoS_2 TFTs

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ABSTRACT

We report a novel 2D semiconductor-on-compound-semiconductor fabrication method that is compatible with a batch microfabrication process. A thin film of molybdenum disulfide (MoS_2), one of the representative TMDCs, was directly synthesised on a gallium-nitride (GaN)-based epitaxial wafer and formed as the TFT array. Subsequently, the MoS_2 TFT was monolithically integrated with micro-LED devices to produce an active-matrix micro-LED display. In addition, we demonstrate a simple approach to yield red and green colours through the printing of quantum dots on a blue micro-LED, which allows for the scalable fabrication of full-colour micro-LED displays[1].

1 Introduction

Micro-light-emitting-diode (micro-LED) displays have attracted much attention as the next generation display because of various advantages such as low power consumption, quick response, and high luminous efficiency, which enable the fabrication of highly reliable displays[2-4]. The most widely used method to fabricate an active-matrix micro-LED display is to transfer the micro-LED chips onto a circuit board with a backplane[4]. This method involves epitaxial growth of LED wafer, patterning, etching, lift-off, and physical bonding of the micro-LED chips formed on different wafers that act as the sources of red, green, and blue colours. It works well with large-area displays with low resolution but has limitations when utilised in the fabrication of micro-LED displays for high-resolution and high-speed operation. Such challenges include difficulties in the alignment and bonding of the electrical interconnects of the micro-LED chips with the backplane circuitry and a low production yield due to separate implementation of the three-colour chips. Intensive research has been done to overcome these issues. For example, to enhance both the accuracy of the alignment and the transfer speed, the roller stamp with the directional microstructure and an overlay-aligned roll-transfer printing method have been developed[3,5,6]. To improve the bonding between LED chips and backplane circuit, a fluidic-assisted method based on a low melting point solder alloy for self-assembly of LED chips has been reported. Despite the various efforts, practical implementation of such approaches involves many significant engineering challenges.

We present two alternative approaches: (1) direct growth of a two-dimensional (2D) semiconducting material, MoS_2, on a GaN epitaxial wafer for blue LEDs and (2) printing of quantum dots (QDs), which are used as a colour-conversion layer, on GaN micro-LEDs for realising a full-colour display. The former process allows for the monolithic integration of the MoS_2 thin film transistor (TFT) arrays on the top layer with the micro-LEDs on the bottom layer in a manner that bypasses the need for transfer, alignment, and bonding of micro-LED chips. It can increase the pixel density with high aperture ratio, which is essential for ultra-high-resolution displays for various applications, such as augmented reality (*AR*) and virtual reality (*VR*). Furthermore, the heterogeneous integration approach enables the fabrication of a wafer scale electronic system that consists of diverse materials with specific function using foundry-compatible fabrication processes. The latter QDs printing process enables the fabrication of a full-colour display through a high-throughput printing method. This approach avoids the complex transfer process of RGB sub-pixels from three different epitaxial wafers.

2 Experiment

MoS_2 thin film was grown via MOCVD system[7,8]. GaN/Si and GaN/sapphire substrates with 100 nm-thick HDP-CVD grown SiO_2 was prepared. Molybdenum hexacarbonyl (MHC, Alfa Aesar, 13057) and dimethyl sulfide anhydrous (DMS, Sigma Aldrich, 274380) are used as precursors for Mo and S respectively. After the synthesis of bilayer MoS_2 thin film on GaN wafer, the MoS_2 was patterned via reactive ion etching (RIE) method using CHF_3 and O_2 plasma. The HDP-CVD SiO_2 was also used as passivation layer between the TFTs and micro-LEDs and hence, it was patterned and etched in buffered oxide etchant (BOE) for metal electrodes connection. P-type ohmic contact metals (Ni/Au: 10/30 nm) were defined on the p-GaN via holes on the SiO_2. Source-drain electrodes with W/L of 45um/10um (Cr/Au: 3/50 nm) for TFTs were patterned using photolithography, and the source electrodes and p-type contact metals are connected to each other. Mesa of the micro-LED was defined using Inductively Coupled Plasma (ICP) RIE and n-type contact metals (Cr/Au: 3/50 nm) were patterned on the n-GaN surface. The average diameter of the oleic-acid-capped red and green QDs (CdSe/ZnS) is 9.3 ± 0.5 nm and 6.2 ± 0.5 nm, respectively. QDs dispersed in toluene is mechanically stirred using a magnetic bar to evaporate the solvent at room temperature. Then, cyclopentanone (Sigma Aldrich), which is the main solvent of SU-8, is chosen to disperse the QDs in an ultrasonic bath. After confirming no significant aggregation of QDs, transparent photoresist, SU-8 is added in the solution with a concentration of 30 wt% and stirred at 200 RPM overnight at ambient environment.

3 Results & Discussion

Fig. 1a presents a schematic illustration of the stages in the fabrication of a full-colour micro-LED display. The process began with the growth of a bilayer MoS_2 thin film (thickness ~1.4 nm) on the 4-inch GaN epitaxial wafer coated with an insulating SiO_2 buffer layer via metal-organic chemical vapour deposition (MOCVD) carried out at 580 °C. Next, MoS_2-based TFTs (top layer) and GaN-based micro-LEDs (bottom layer) were monolithically interconnected after a patterning process. Then, for the implementation of a full-colour display, red and green QDs mixed with a transparent photoresist (SU-8) were printed on the micro-LED chips through a standard photolithography process.

Transmission electron microscopy (TEM) analysis showed the formation of a uniform MoS_2 bilayer film on the GaN wafers coated with a protective SiO_2 buffer layer (Fig. 1b). The number of layer and the quality of MoS_2 film were confirmed using atomic force microscope (AFM), The MoS_2 film has well-stitched grain boundaries which can improve the electrical properties and stability. The high-temperature growth (over 750 °C) can cause thermal damage to the multi-quantum well of the GaN wafer. To avoid such damage, the MoS_2 film was grown at 580 °C. The Raman and PL spectra measured at room temperature proved that the MoS_2 film successfully grew on the GaN wafer (Fig. 1c, d).

The uniformity of the MoS_2 film grown on GaN epitaxial wafers enables the batch fabrication of an active-matrix micro-LED display. Fig. 2a shows 16 sets of 16 × 16 array of top emission micro-LEDs formed on GaN/Si substrate and 100 × 100 array of bottom emission micro-LEDs on GaN/sapphire substrate (inset). The drain electrode of the TFT with W/L of 45 μm/10 μm, respectively, for the case of a GaN/Si substrate was connected to the anode of the micro-LED (inset of Fig. 2b). The MoS_2 TFTs in the integrated device exhibited μ_{FE} of 12.3 ± 2.6 cm^2/Vs, an on-off ratio of 10^9 ± 10, a subthreshold swing of 0.8 ± 0.2 V/dec, and V_{TH} of 2.4 ± 1.2 V (Fig. 2b). In particular, the V_{TH} of the TFT indicates that the micro-LEDs exhibit the normally-off operation when zero gate voltage is applied. This behaviour is important for the low power consumption of display circuits. Furthermore, the output (I_d-V_d) characteristics of the MoS_2 TFT show that the drain current value reaches 0.4 mA at the gate voltage of 10 V with ohmic behaviour (Fig. 2c). Histograms of the μ_{FE} and V_{TH} of the MoS_2 transistors array show uniform values with averages of 11.2 cm^2/Vs and 1.1 V, respectively (Fig. 2d). These results indicate that the MoS_2 transistors are suitable for the reliable production of large-area micro-LED displays.

Finally, the electrical properties of the MoS_2-TFT-integrated micro-LED pixels were examined. The micro-LEDs on the silicon (the size: 180 μm × 100 μm) and the sapphire substrates (the size: 90 μm × 90 μm) began to turn on at V_{GS} and V_{DD} values over 0~2 V, which is comparable to the turn-on voltage of typical LED chips (Fig. 2e, f). It was also driven from the off-state to the on-state at a fixed V_{DD} of +6 V by repeating the gate-pulse bias between +8, and 0 V, which showed a uniform and fast switching response at 60 Hz without any delay (Fig. 2g). The brightness of each pixel unit was clearly controlled by the modulating gate voltage at a fixed V_{DD}. The micro-LEDs were at the off state when V_g was below 0~2 V and the light intensity of the pixel unit increased with increasing V_g, which indicates outstanding gate controllability (Fig. 2h). In particular, the bottom emission micro-LEDs fabricated on sapphire substrates achieved the emission area ratio of ~ 100% due to transparency of substrate. These results indicate that the monolithically integrated device can be utilised in micro-LED displays.

For system level operations, data lines, gate lines, and ground (GND) lines are connected to the drain electrode, gate electrode, and n-pad of the LED, respectively. The fabricated micro-LED was electrically connected to an external driving circuit using a flexible printed circuit board and driven at a 60 Hz refresh rate (V_g = 0 V for off state and 8 V for on state). Five alphabetic characters, ‘M’, ‘I’, ‘C’, ‘R’, and ‘O’ were encoded in the driving circuits and displayed through top emission with a high yield and uniformity (Fig. 3a, b). In addition, micro-LED display on a sapphire substrate which enables bottom emission, was operated in a similar manner to demonstrate a large area display with a relatively high resolution of 100 pixels per inch (ppi) (Fig. 3c-e). The production yield of the micro-LED pixels is about 92%; one row of the display did not function because of disconnection in the interconnect, which can be solved by the optimized process. To further demonstrate a high-resolution display with 508 ppi, micro-LEDs with small size of 10 μm × 10 μm were integrated with MoS_2 TFTs of W/L = 20 μm / 2 μm, which exhibited stable operation (Fig. 3f-h).

Furthermore, to realise the RGB-full-colour display, CdSe/ZnS green and red colloidal quantum dots (QD) were mixed with a transparent photoresist and were patterned by a standard photolithography process. The absorption and PL spectra of the optimised QD conversion layers showed excellent characteristics as a colour converter for the display with external quantum efficiency (EQE) of 27.76% and 26.30% for green and red QD, respectively. Both red and green QDs showed high absorption at 450 nm, which is emitted by the GaN-based blue micro-LEDs. Therefore, they can be excited by the blue micro-LEDs and emit red and green colour at 640 nm and 530 nm, respectively. As shown in Fig. 3i, the display operated steadily without any optical crosstalk and presented three different colours, red, green, and blue. Electroluminescence spectra of the resulting micro-LEDs show that the red, green, and blue pixels exhibit peak wavelengths of 643, 538, and 454 nm, respectively. The blue colour could be slightly observed along with the red and green pixels. This phenomenon can be overcome by further improvement in the design/engineering of the micro-LEDs. To confirm the colour gamut of the display, its CIE chromaticity was investigated. The colour coverage of the active matrix full-colour micro-LED display reached 110% of the National Television Standard Committee (NTSC) specification in the CIE 1931 colour space.

4 Conclusions

We developed a full-colour active-matrix micro-LED display using the MoS_2-on-GaN epitaxial wafer and QDs. The new fabrication method allowed for the monolithic integration of MoS_2 as an active component to drive the full-colour display of the micro-LEDs. Moreover, this approach would provide opportunities for heterogeneously integrated optoelectronic devices that need to incorporate semiconductor materials. The incorporation of materials such as III-V compound semiconductor, Si, and 2D materials in such devices may find application in not only the active matrix displays but also optical and biological sensors that require an assembly of dissimilar semiconductors.

References

[1] S. Hwangbo *et al.*, "Wafer-scale monolithic integration of full-colour micro-LED display using MoS_2 transistor", Nature Nanotechnology, **17**, 500 (2022)

[2] H. Zhang & J. A. Rogers, "Recent advances in flexible inorganic light emitting diodes: From materials design to integrated optoelectronic platforms", Adv. Opt. Mater. **7**, 1800936, (2019).

[3] H. Kim *et al*. "Unusual strategies for using indium gallium nitride grown on silicon (111) for solid-state lighting", Proc. Natl Acad. Sci. USA **108**, 10072-10077, (2011).

[4] D. Peng *et al*. "Design and fabrication of fine-pitch pixelated-addressed micro-LED arrays on printed circuit board for display and communication applications", IEEE J. Electron. Devices Soc. **5**, 90-94, (2017).

[5] M. Choi *et al*. "Stretchable active matrix inorganic light-emitting diode display enabled by overlay-aligned roll-transfer printing", Adv. Funct. Mater. **27**, 1606005, (2017).

[6] Y. Lee et al, "Morphable 3D Structure for Stretchable Display", Materials Today, 53, 51 (2022)

[7] S. M. Shinde *et al*. "Surface-functionalization-mediated direct transfer of molybdenum disulfide for large-area flexible devices". Adv. Funct. Mater. **28**, 1706231, (2018).

[8] M. Choi *et al*. "Flexible active-matrix organic light-emitting diode display enabled by MoS_2 thin-film transistor", Sci. Adv. **4**, 8721, (2018).

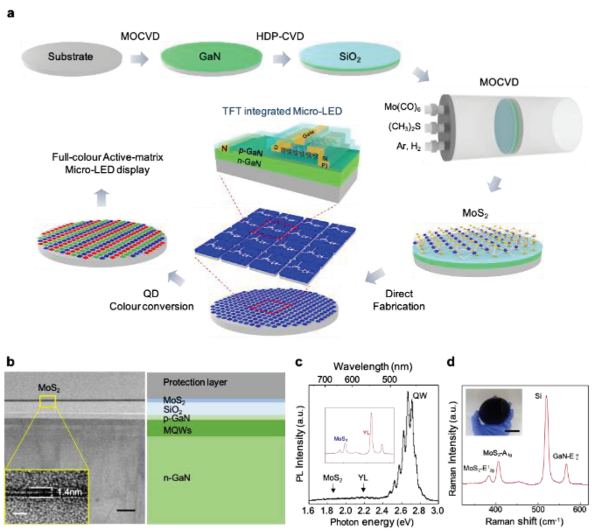

Fig. 1 Monolithic integration of MoS_2 transistor and GaN-based full-colour micro-LED display.

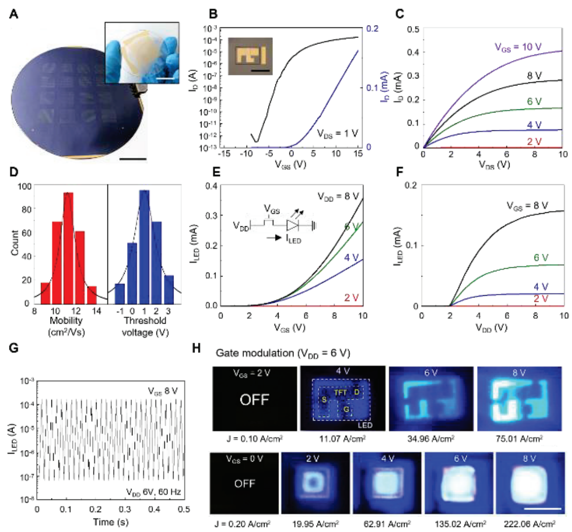

Fig. 2 Batch fabrication of MoS_2-TFT-integrated micro-LEDs and their electrical properties.

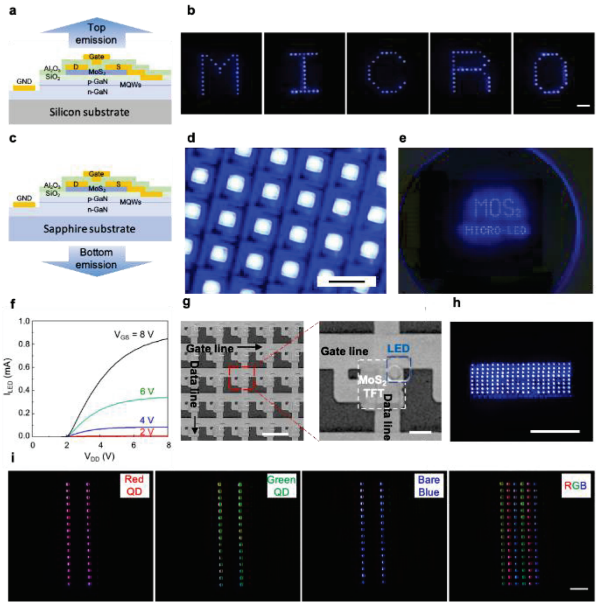

Fig. 3 The operation of full colour active-matrix micro-LED display using MoS_2 TFT and QD