Three-dimensional Monolithic Micro-LED Display Driven by Atomically Thin Transistor Matrix

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ABSTRACT

Two-dimensional materials are promising candidates for future electronics due to unmatched device performance at atomic limit and low-temperature heterogeneous integration. Here, we show the integration of large-area MoS_2 thin-film transistors (TFTs) with nitride micro light-emitting diodes (LEDs) through a BEOL process and demonstrate high-resolution displays at 1270 PPI.

1 Introduction

Recently, nitride micro-LED with remarkable features of extreme brightness, low power consumption and quick response enable many novel applications such as augmented and virtual reality (AR/VR), visible-light communication and biomedical probes.[1] [2] [3] The fabrication of active matrix micro-LED display is usually mass transfer, and it still face challenges of resolution, yield, and cost.[4] Monolithic three-dimensional (3D) integration of the high-performance thin-film transistor (TFT) backplane is urgent needed. Being van der Waals materials, 2D semiconductors such as MoS_2 can be transferred to arbitrary substrates under room-temperature and non-vacuum conditions. This facilitates back end of line (BEOL) integration with mainstream semiconductor technologies.[5]

In addition, 2D materials can be synthesized in wafer-scale by chemical vapor deposition with mobility greater than 100 cm^2/Vs, which is much higher than amorphous TFT materials. The atomically thin channel also guarantees low leakage current at stand-by.[6] To meet the future demands for the human - machine interface, individual pixels need to be of micrometre size and have unapparelled brightness. The most competitive TFT channel materials are IGZO and LTPS. However, typical mobility of IGZO is only ~10 $cm^2V^{-1}s^{-1}$, which is about an order of magnitude lower than MoS_2.[7] LTPS requires high-temperature laser annealing and ion implantation, which is undesirable for a BEOL process.[8] Compared to these existing TFT technologies, MoS_2 not only offers advantages in driving capability, low-power consumption and low-temperature integration, but it also enables new forms of flexible and transparent displays.

2 Experiment

The GaN-based micro-LEDs proposed here were fabricated using commercial GaN-based epitaxial structure grown by metal-organic chemical vapor deposition(MOCVD). Indium content in InGaN multi-quantum wells for blue and green light emission was 13% and 21%, respectively. The circular micro-LED mesa was fabricated by photolithography and dry etching using Cl_2/BCl_3 plasma. Next, the micro-LED chips were spin coated with ~1.3 μm SOG (IC1-1000, FUTURREX) and baked at 200° C for 30 min, followed by 20nm Al_2O_3 deposited using atom layer deposition(ALD) as passivation layer. Next, backgate electrodes and gate lines was patterned and 20 nm Al_2O_3 was deposited as gate dielectric. Next, the vertical via holes were etched by reactive ion etching (RIE) using CF_4 plasma. We developed Au-assisted transfer and fabrication method to integrate MoS_2 TFTs. The MoS_2 was dry-delaminated and transferred to prepatterned chip using PDMS/PMMA/Au stamp. Next, the unnecessary Au/MoS_2 was patterned and etched. The TFT and micro-LED were interconnected through via hole to form 1T-1D cell. In the final step, we opened the MoS_2 channel region by wet etching a gap on the Au film. The 3D schematic structure image of the micro-LED display driven by MoS_2 TFT is shown in Fig.1.

Fig. 2 shows the cross-sectional SEM of a 1T-1D cell. All the functional layers including GaN-based MQW (blue), SOG (green), interconnection and electrode metal (yellow) and MoS_2 channel (red) are clearly visible.

3 Results and Discussions

3.1 Performance of MoS_2 TFT and one transistor one micro-LED (1T1D)

Fig. 3 present transfer and output characteristics of a typical MoS_2 device with 1 μm channel length (L) and 10 μm channel width (W). The transistor exhibits n-type behavior with V_{th} of 0.2 V, SS of ~240 mV/dec, I_{on} of 210 μA/μm and nearly hysteresis-free.

Fig.4(a) show the optical micrograph of the 1T1D pixel (V_g denotes the gate voltage of the MoS_2 TFT and V_{data} denotes the bias voltage of the 1T1D). Fig.4(b) shows the gate-tunable operation points of the 1T1D (the interception points of the LED and TFT). At the on state of the TFT, the voltage drop on the transistor was only 0.57 V, corresponding to 14.3% of the total power consumption. The electrical properties of the 1T1D are shown in Fig.5, for $V_{dd} = V_{data} = V_g = 8$ V, the MoS_2 TFT was able to supply a drive current of more than 1.4 mA corresponding to a current density of ~1.1‑17.8 × 10^5 mA cm^{-2} in these micro-LEDs. Under such conditions, the blue and green micro-LEDs showed extremely bright luminance of 1.9 × 10^7 and 7.1 × 10^7 cd m^{-2}, respectively. Fig.6 shows the LED brightness simultaneously modulated by PAM and PWM schemes in the 1T1D. Each row and column correspond to a constant V_g amplitude and pulse width, respectively. Based on the 1T1D performance, we can evaluate MoS_2 TFT technology for various display applications (AR/VR glasses, vehicle display under sunlight, and even visible light communication).

Furthermore, We benchmark our MoS_2 TFTs with commercial high-performance TFT technologies (Table 1). MoS_2 TFT exhibits drive current that is more than over an order of magnitude higher and mobility that is several times higher than that of amorphous TFT materials (α-Si, IGZO). Compared with LTPS, MoS_2 TFT also shows improved mobility and drive current. Meanwhile, both V_{dd} and V_{gs} of α-Si, IGZO and LTPS is much higher than MoS_2 TFT.(Table 1)

3.2 Active matrix micro-LED Display

We fabricated fully monolithic AM displays with 20-μm pitch, corresponding to 1,270 PPI. All pixels shared a global ground with independently addressable data and gate lines, which were wire-bonded to the input/output interface of a field-programable gate array (FPGA) for AM addressing (Fig.8a). Furthermore, we demonstrate pixel images of AM addressing using our micro-LED displays. Fig.8 (c) are the images of cartoon panda corresponding to the design in Fig.8 (b).

4 Conclusions

In conclusion, we demonstrate the first fully monolithic 3D integrated 1270 PPI micro-LED displays driven by 2D MoS_2 TFT matrix. The driving capability of MoS_2 and the BEOL process show that MoS_2 TFTs are suitable for a range of micro-LED display applications. Furthermore, MoS_2 TFT is compatible with flexibility and transparency displays. We believe our work opens new possibilities for active-matrix device using 2D materials.

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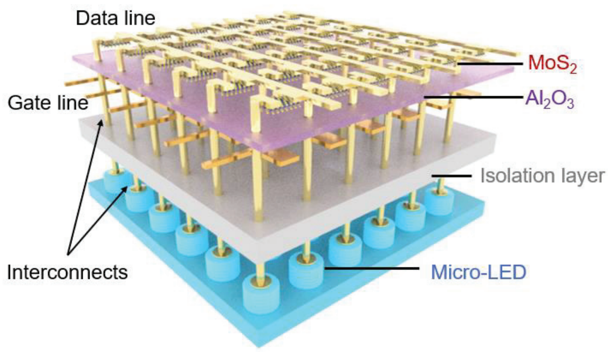

Fig1. Schematic illustration of the monolithic integration of the AM micro-LED display. Micro-LED, isolation layer, TFT matrix and interconnection are illustrated by different colors, respectively.

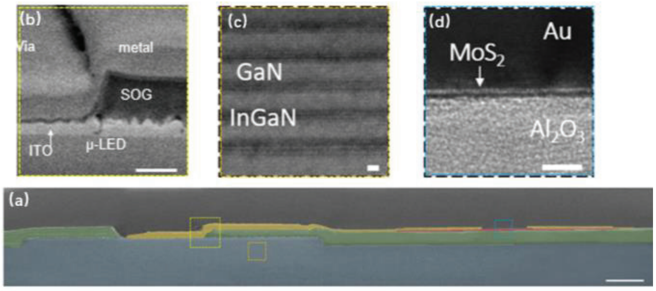

Fig2. (a) Cross-section SEM image of 1T-1D with false-color mapping. Scale bar, 1 μm. (b) Zoom-in SEM image of via holes interconnecting. Scale bar, 300 nm. (c) Cross-sectional TEM image of InGaN/GaN MQW. (d) The Au-MoS_2 contact with sharp van der Waals interface. Scale bars, 4 nm.

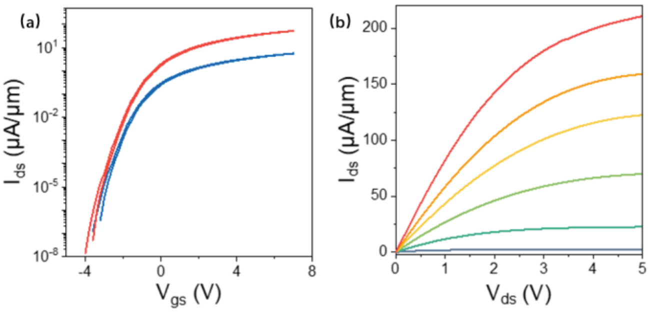

Fig3. (a) Transfer characteristics of MoS_2 TFT with W/L of 10/1μm, driven at 0.1V and 1V of V_{ds}. (b) Output characteristics of the device in (a).

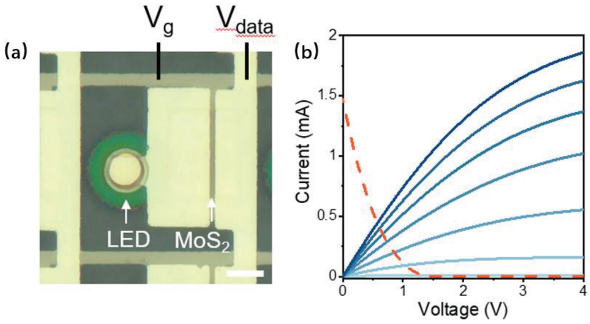

Fig4. (a) Optical micrograph of the 1T1D pixel. Scale bar, 5 μm. (b) Gate-tunable operation points of the 1T1D, which is the intersection of MoS_2 FET (blue solid lines) and micro-LED (red dashed line). W/L = 10 μm /1 μm and micro-LED diameter is 10 μm.

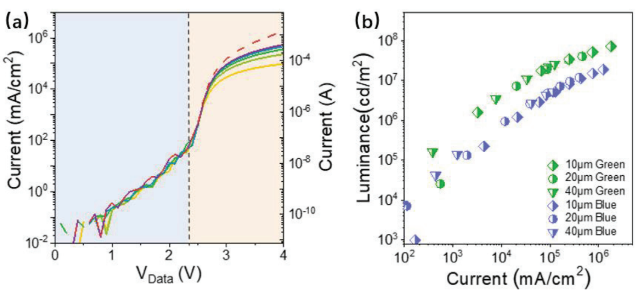

Fig5. (a) I‐V characteristics of the 1T1D under different V_{gs} (solid lines) and micro-LED only (red dashed line). (b) The luminance of 10 μm, 20 μm, 40 μm blue and green micro-LED measured on 1T-1D. Both current and luminance are normalized by the area of the micro-LEDs.

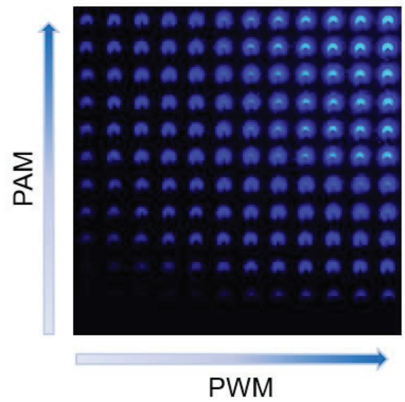

Fig6. (a) Micro-LED brightness modulated by PAM (V_{gs} sweeps from 0 to 10V) and PWM (V_{gs} sweeps from 500kHz to 10kHz) schemes in 1T-1D, achieving a 12 × 12 level of continuous brightness tuning.

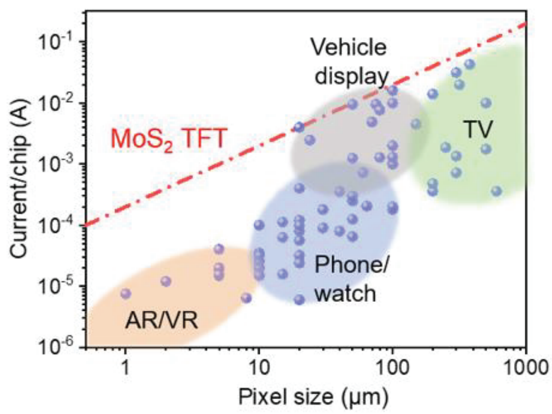

Fig7. Operating current as a function of pixel size for a wide range of LED dimensions (collected from the literature). Our MoS_2 TFT (dashed line) meet all display applications in terms of driving current.

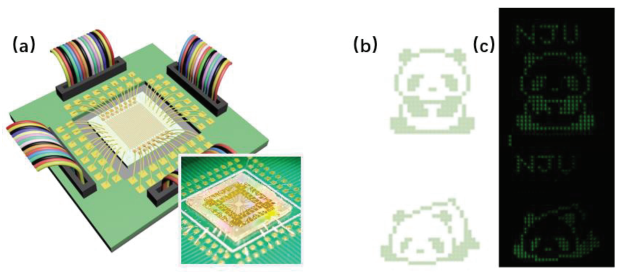

Fig8. (a) Schematic diagram and optical microscope of the AM micro-LED display wire-bonded chip. Microscopic images (c) of the cartoon panda displayed on a 1,270-PPI blue micro-LED display and corresponding design (b).

	V_{th} (V)	μ (cm^2/Vs)	I_{ON} ($\mu A/\mu m$)	I_{OFF} ($\mu A/\mu m$)	V_{GS} (V)	V_{DD} (V)
α-Si	-	~1	1-10	<1e-12	20	10
IGZO	0.5	12.3	~10	<1e-12	20	10
LTPS	2.5	64.3	~100	<1e-12	20	10
MoS_2	2.1	73	200	<1e-13	8	4

Table1. Performance comparison between MoS_2 and mainstream TFT technology. Data for α-Si, IGZO and LTPS was extracted SID Symp. Dig. Tech. 44, 771 (2013). Information Display 36, 9 (2020) and SID Symp. Dig. Tech. 49, 1268 (2018).