Supporting information

A Patterning Technology of Transfer-Free Graphene for Transparent Electrodes of Near-Ultraviolet Light-Emitting Diodes

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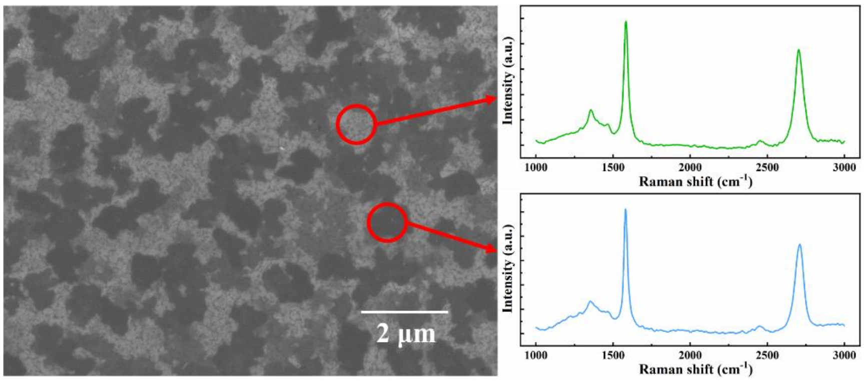

Fig.S1 Raman spectra of graphene at different locations on p-GaN.

Fig. S2 is the schematic diagram of the process flow for measuring the sheet resistance of graphene by CTLM. In order to accurately measure the sheet resistance of graphene, SiO_2 is not etched in penetrating etching, so as to avoid the contact between graphene and GaN affecting the measurement of graphene sheet resistance. Optical images of the devices and the measurement are shown in Fig. S3a. The probes are contacted on the electrodes inside and outside the “graphene rings”, and the current-voltage characteristics are measured to calculate the total resistance. Each "graphene ring" has an inner diameter of 50 μm and an outer diameter of 55, 60, 65, 70, 75, 80, 85, and 90 μm, respectively. In CTLM, the total resistance R_{T} is expressed as $R_{\mathrm{T}} = \frac{R_{\mathrm{sh}}}{2\pi}\left[\ln\left(\frac{r_n}{r_0}\right) + L_T\left(\frac{1}{r_{\mathrm{n}}} + \frac{1}{r_0}\right)\right]$, where R_{sh} is the sheet resistance of graphene, L_T is the transmission length, r_0 is the inner diameter of the "graphene ring" and r_{n} is the outer diameter. The linear fitting relationship between R_{T} and $\ln\left(\frac{r_n}{r_0}\right)$ is obtained based on the measured data, as shown in Fig. S3b. Among them, the total resistance of the device with an outer diameter of 55 μm is quite different from that of other devices, which may be due to the large influence of lithography error on the small size pattern, so it is not included here. The slope of the line is approximately equal to $\frac{R_{\mathrm{sh}}}{2\pi}$, from which R_{sh} can be calculated. When the r_{n} is equal to the r_0, the intercept is $\frac{R_{sh}L_T}{\pi r_0}$ and the L_T can be calculated from this. Furthermore, the contact resistivity ρ_c can be calculated from $L_t = \sqrt{\frac{\rho_c}{R_{sh}}}$. The sheet resistance of graphene R_{sh} is calculated as 1255 Ω sq^{-1}, and the contact resistivity between graphene and metal electrodes is calculated as 7.737 × 10^{-4} Ω cm^2. In the sheet resistance measurement, graphene covers the entire sample surface rather than patterning, and the sample size is no smaller than that of the graphene LED. This means that the growth area of graphene on the sheet resistance measurement sample is much larger than that on the graphene LED sample. However, the graphene growth conditions used in both samples were exactly the same, which resulted in poorer uniformity and quality of the graphene in the sheet resistance measurement. Therefore, the measured graphene sheet resistance should be greater than the actual sheet resistance of the graphene on the LED.

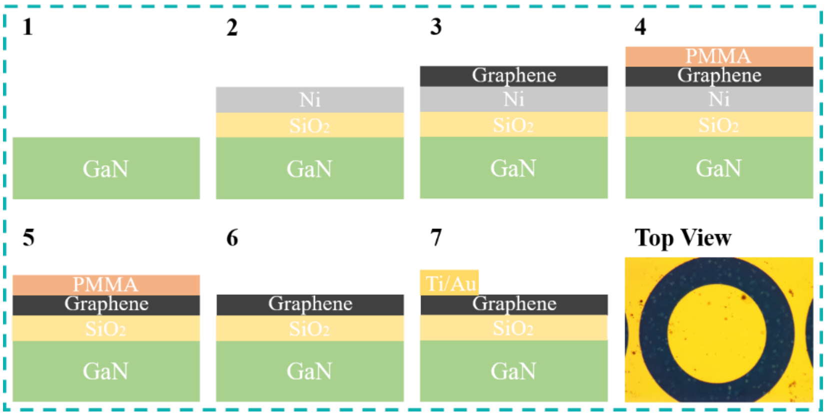

Fig. S2 Schematic diagram of the process for measuring the graphene sheet resistance by CTLM and a top view of the fabricated individual "ring" device.

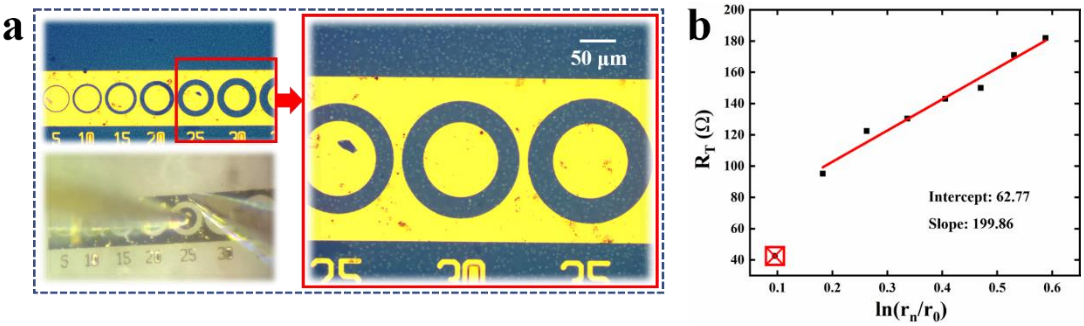

Fig. S3 Sheet resistance measurement of graphene. (a) Optical images of CTLM devices and the measurement. (b) Linear fitting of R_{T} and $\ln\left(\frac{r_n}{r_0}\right)$.

The contact resistivity between graphene and p-GaN is measured by CTLM to be approximately 0.3207 Ω cm^2. The calculation method is the same as the graphene sheet resistance calculation above.

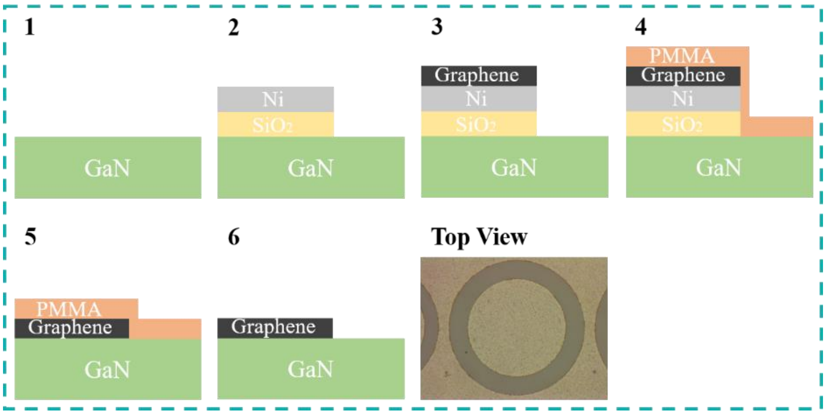

Fig. S4 Schematic diagram of the process for measuring the contact resistance between graphene and p-GaN by CTLM and a top view of the fabricated individual "ring" device.

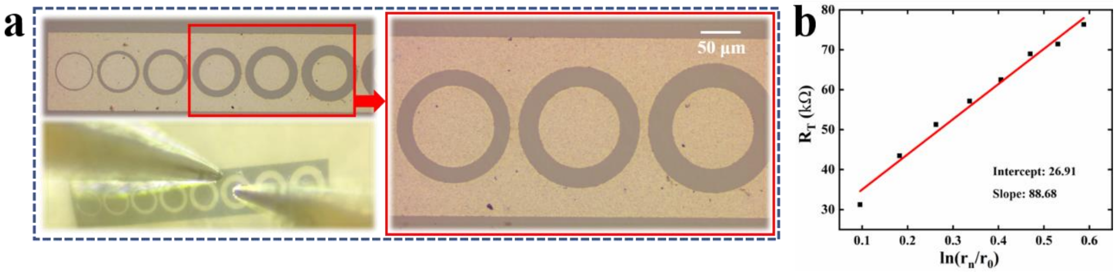

Fig. S5 Contact resistance measurement between graphene and p-GaN. (a) Optical images of CTLM devices and the measurement. (b) Linear fitting of R_T and $\ln\left(\frac{r_n}{r_0}\right)$.

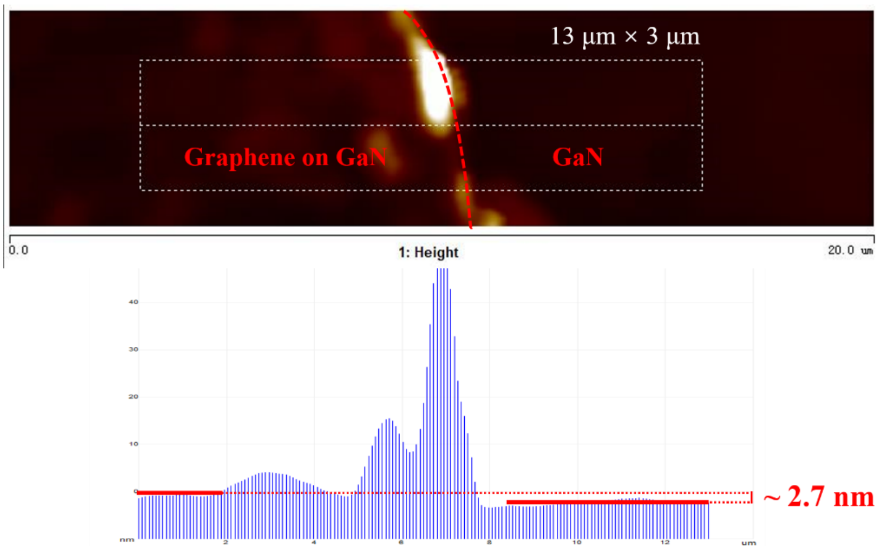

Fig. S6 AFM characterization of graphene on an LED mesa where graphene breakage resulted in partial exposure of p-GaN. The red line is the edge of the graphene on this mesa. The left side of the red line is graphene and the right side is p-GaN exposed. The blue shade represents the average height of the sample in the selected range along the direction of the long side. The bright white block to the left of the red line in the image is some unknown bump, which could be carbon accumulated at the edge of the broken graphene. The thickness of the graphene is estimated to be 2.7 nm by comparing the height difference between the bare mesa and the graphene away from the edge.

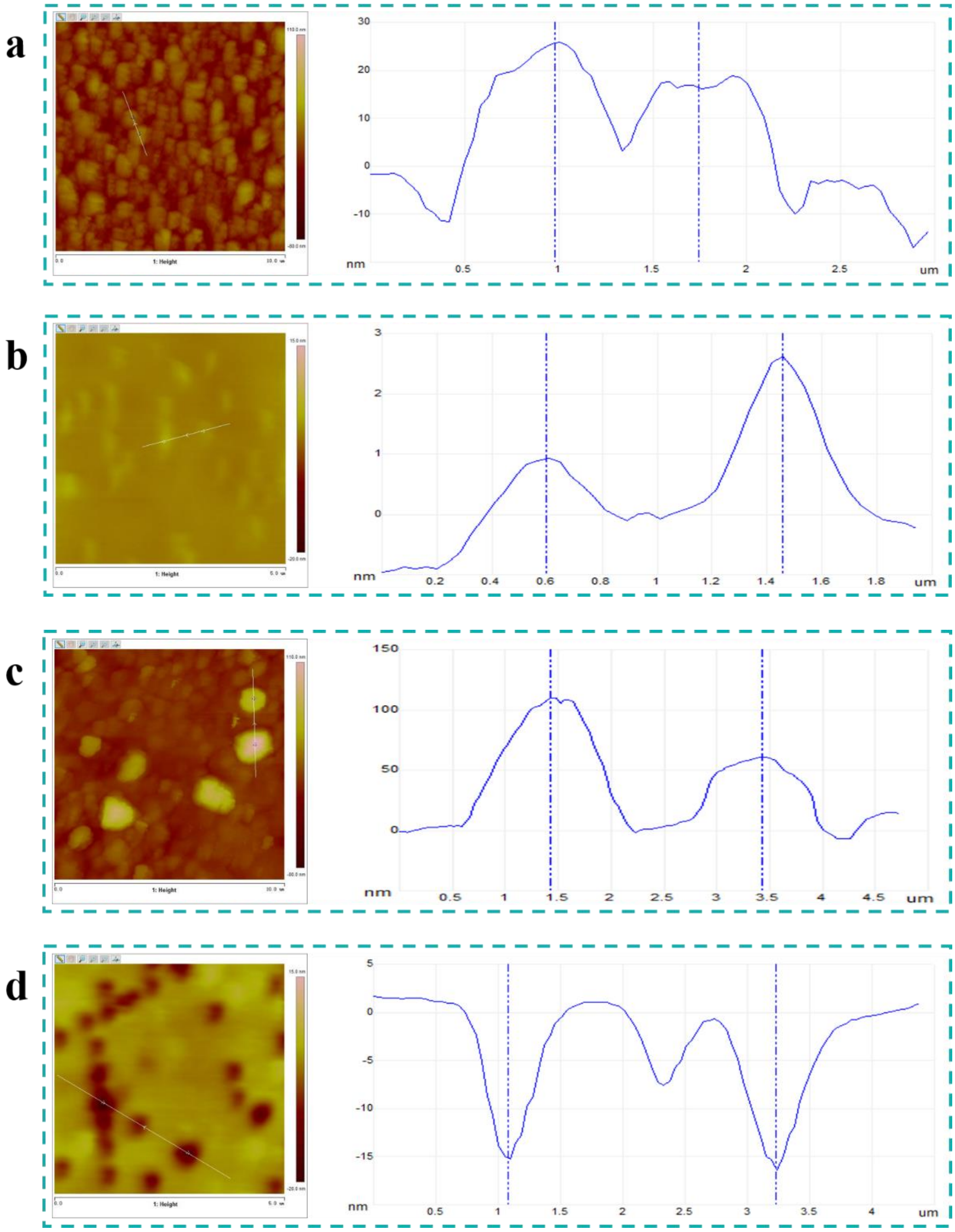

Fig. S7 Two-dimensional AFM images and the height profiles of the selected sections. (a) Sample 1. (b) Sample 2. (c) Sample 3. (d) Sample 4.