

Supporting Information

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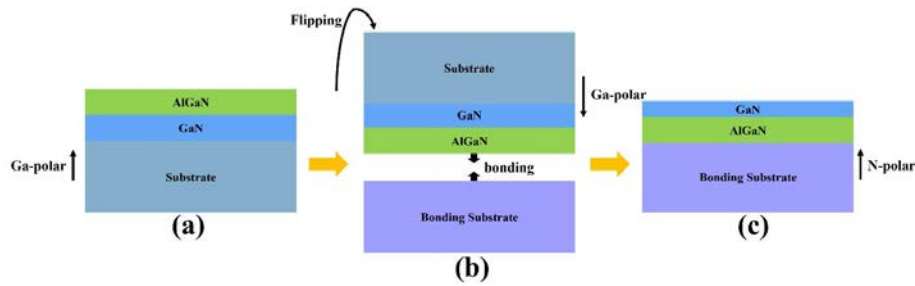
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Room-temperature terahertz emission from N-polar GaN grating-gate HEMTs

This supporting information describes the material transfer route and the THz measurement systems used for the N-polar GaN grating-gate HEMT study. The details expand the Methods section of the manuscript and provide the experimental context for the power and spectral data.

S1. Layer-transfer preparation of N-polar GaN/AlGaIn HEMTs

The N-polar GaN/AlGaIn HEMT platform was prepared by epitaxial layer transfer, following earlier N-face GaN/AlGaIn HEMT and CMP-incorporated layer-transfer work [1,2]. A Ga-polar AlGaIn/GaN HEMT stack was first grown by MOCVD on the original growth substrate. The wafer was then inverted and bonded to a Si support substrate. After bonding, the original substrate was removed by thinning, polishing and etching until the N-polar GaN surface was exposed. This route avoids direct growth of the full N-polar HEMT stack while preserving the reversed-polarization channel geometry required for surface-grating coupling.



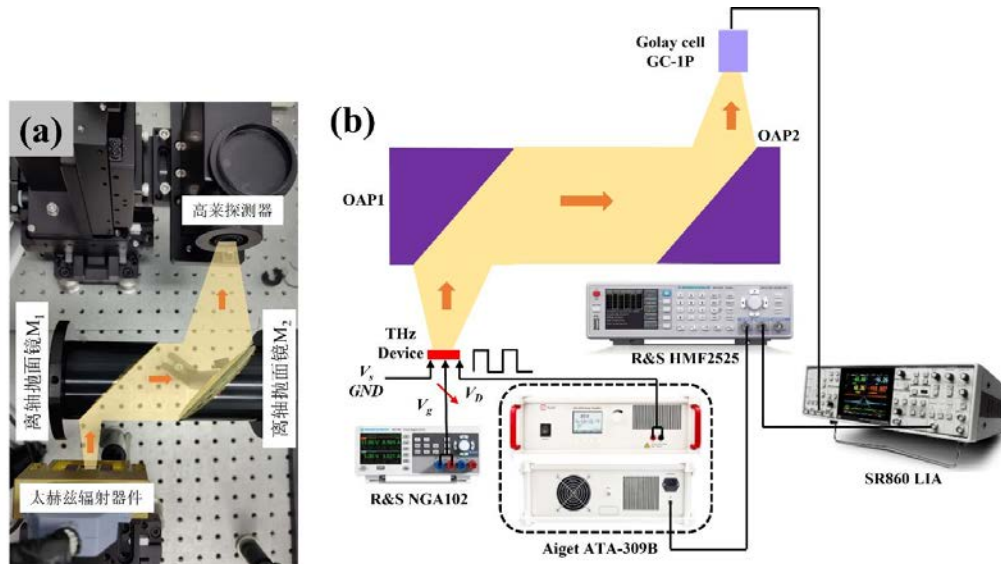
Supplementary Fig. S1 | Schematic layer-transfer process for preparing an N-polar GaN/AlGaIn HEMT platform. A Ga-polar HEMT stack is grown, bonded to a support substrate and thinned from the original substrate side to expose the N-polar GaN surface.

The final transferred stack consisted of a Si₃N₄ passivation layer, a GaN channel, an AlGaIn back-barrier, silicon-nitride diffusion-buffer layers, a Ti/Cu/Au bonding metal stack and a Si(100) support substrate. This configuration places the conducting channel close to the surface where the grating gate is patterned, while the AlGaIn layer acts as a natural back-barrier for carrier confinement.

S2. THz power measurement setup

THz power measurements were carried out at room temperature using the packaged grating-gate HEMT as an electrically driven emitter. The device package was mounted in a brass adapter for electrical access. The emitted THz radiation was collected and focused by two off-axis parabolic mirrors onto a Golay-cell detector. The detector input window was made of high-density polyethylene and covered the spectral range required for the present emitter measurements. This free-space collection strategy is consistent with electrically biased AlGaIn/GaN HEMT THz-emitter measurements reported previously [3-5].

During power measurements, the source electrode was grounded. The gate bias was supplied by a DC voltage source, while the drain electrode was driven by a square-wave signal generated by a function generator and amplified by a power amplifier. The modulation signal also provided the reference for lock-in detection, allowing the Golay-cell output to be extracted from the room-temperature thermal background. For the N-polar devices discussed in the main manuscript, the gate bias was held at 0 V, the low level of the square-wave drain signal was 0 V and the high level and duty cycle were varied. The lateral electric field was obtained by normalizing the source-drain voltage to the 600 micrometre source-drain spacing.

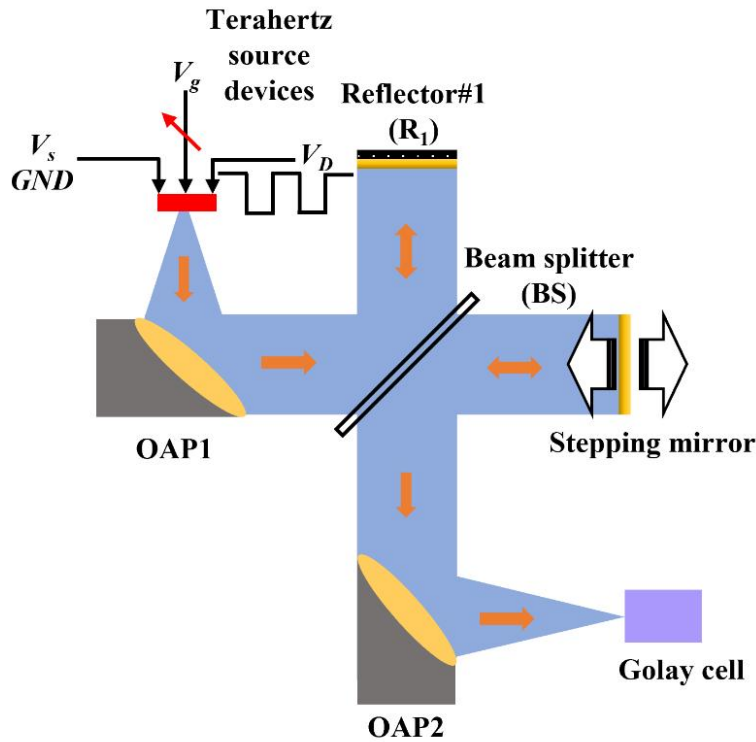


Supplementary Fig. S2 | THz power measurement setup. The optical path uses two off-axis parabolic mirrors to collect radiation from the packaged HEMT and focus it onto a Golay-cell detector. The electrical schematic shows the DC gate bias, square-wave drain excitation, power amplifier and lock-in-based readout.

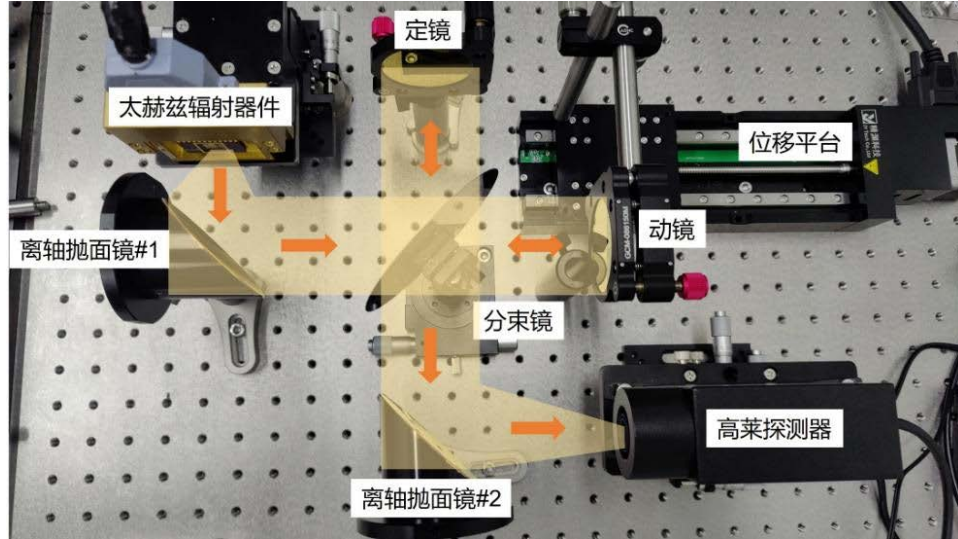
S3. Far-infrared FTIR spectral measurement setup and calibration

Emission spectra were measured using a far-infrared Fourier-transform spectroscopy setup. The system used a Michelson-type optical path with a high-resistivity Si beamsplitter, fixed and moving mirrors, off-axis parabolic collection optics and a Golay-cell detector. The moving mirror was scanned near the zero-optical-path-difference position to record the interferogram. The spectrum was then obtained by fast Fourier transformation of the measured interferometric signal, a procedure commonly used for broadband THz-emission analysis in III-nitride devices [3-5].

The device and detector electrical connections followed the THz power-measurement configuration. A 6 inch high-resistivity Si beamsplitter and 4 inch coated mirrors were used in the spectrometer. To reduce errors from stage vibration, signal acquisition was delayed after each stage movement. The lock-in amplifier integration time was set to 3 s, and the resulting spectral resolution was approximately 0.375 THz.

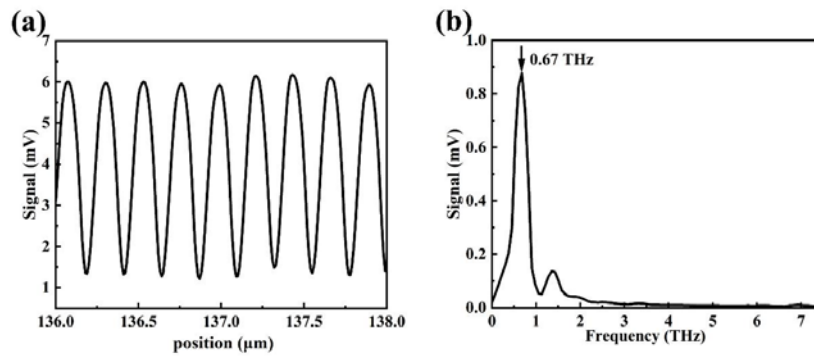


Supplementary Fig. S3 | Schematic of the far-infrared Fourier-transform spectroscopy system used for room-temperature THz emission spectra. The setup records an interferogram by changing the optical path difference and then retrieves the frequency-domain spectrum by Fourier transformation.



Supplementary Fig. S4 | Photograph of the far-infrared FTIR spectral measurement system, showing the THz emitter position, fixed mirror, moving mirror, beamsplitter, off-axis parabolic mirrors, translation stage and Golay-cell detector.

The spectral setup was checked using a commercial 660 GHz frequency-doubled source. The measured interferogram showed a clear oscillatory signal, and the Fourier-transformed spectrum displayed a dominant peak at 0.67 THz. This calibration verified that the interferometric system could resolve the expected sub-terahertz reference signal before measuring the electrically pumped HEMT spectra.



Supplementary Fig. S5 | Calibration of the FTIR spectral setup using a 660 GHz frequency-doubled source. (a) Measured interferogram as a function of moving-mirror position. (b) Fourier-transformed spectrum showing a peak at 0.67 THz.

References

[1] Chung J W, Piner E L, Palacios T. N-face GaN/AlGaIn HEMTs fabricated through layer transfer technology. IEEE Electron Device Lett 30(2), 113-116 (2009).

- [2] Guo B H, Yu G H, Zhang L, et al. High-performance N-polar GaN/AlGa_N metal-insulator-semiconductor high-electron-mobility transistors with low surface roughness enabled by chemical-mechanical-polishing-incorporated layer transfer technology. *Crystals* 14(3), 253 (2024).
- [3] Jakstas V, Grigelionis I, Janonis V, et al. Electrically driven terahertz radiation of 2DEG plasmons in AlGa_N/Ga_N structures at 110 K temperature. *Appl Phys Lett* 110(20), 202101 (2017).
- [4] Shalygin V A, Moldavskaya M D, Vinnichenko M Y, et al. Selective terahertz emission due to electrically excited 2D plasmons in AlGa_N/Ga_N heterostructure. *J Appl Phys* 126(18), 183104 (2019).
- [5] Lisauskas A, Ramer A, Burakevic M, et al. Terahertz emission from biased AlGa_N/Ga_N high-electron-mobility transistors. *J Appl Phys* 125(15), 151614 (2019).