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Al-rich AlGa_N multichannel transistors with degenerate semiconductor electrodes

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Abstract

Ultrawide-bandgap (UWBG) Al-rich AlGa_N multichannel high-electron-mobility transistors (HEMTs) are promising components for high-power, high-frequency electronics, but their device-level potential is limited by difficulties in forming low-resistance ohmic contacts to 2D electron gases (2DEGs) buried in Al-rich AlGa_N superlattices. Here, we demonstrate undoped AlN/Al_{0.6}Ga_{0.4}N/AlN multichannel trigate HEMTs where vertically stacked polarization-induced 2DEG channels are accessed from etched sidewalls by epitaxially regrown highly degenerate n⁺⁺-Ga_N (d-Ga_N) semiconductor electrodes formed via pulsed sputter deposition. The regrown d-Ga_N acts as an intermediate semiconductor electrode that mitigates the metal–channel injection mismatch while providing 3D access to the buried channels. The devices achieve annealing-free contact resistance of below 1 Ω·mm, breakdown voltages exceeding 3 kV with average breakdown fields reaching 3.8 MV/cm, and power figures of merit approaching 3.2 GW/cm². These results demonstrate that the regrown highly degenerate semiconductor electrodes are a practical route to low-loss access in UWBG multichannel transistor platforms.

Ultrawide-bandgap (UWBG) semiconductors, or materials whose bandgaps (E_g) exceed that of GaN (≈ 3.4 eV), are being actively explored as next-generation platforms for high-voltage, high-frequency power electronics¹. As GaN- and SiC-based devices are increasingly deployed in commercial systems ranging from data centers to automotive inverters, attention is shifting toward UWBG materials, such as diamond, β -Ga₂O₃, BN, Al-rich Al_xGa_{1-x}N ($x \gtrsim 0.5$), and α -Al₂O₃, which can support higher critical electric fields (E_{crit}), higher operating temperatures, and improved power-handling figures of merit (FOMs)². Among UWBG materials, Al-rich AlGaN stands out as a continuous evolution of the wurtzite III-nitride system, from GaN³; it combines a tunable bandgap that can be increased to approximately 6.1 eV at the AlN limit, with the potential to sustain a high E_{crit} through scaling between E_{crit} and E_g ⁴. From a materials–physics standpoint, Al-rich AlGaN can leverage the strong spontaneous and piezoelectric polarizations of the III-nitride system, together with AlN-based back-barrier designs, to simultaneously support high-density polarization-induced 2D electron gas (2DEG) channels and large breakdown fields, offering—in principle—a more favorable Johnson FOM (JFOM) than GaN-based platforms during high-voltage, high-temperature operation⁵. Consistent with these expectations, researchers have used Al-rich AlGaN single-channel transistors to fabricate lateral high-electron-mobility transistors (HEMTs) with kilovolt-class breakdown voltages (BV), average breakdown fields on the order of 5–6 MV/cm, and JFOM values approaching the terahertz-volt regime, together with stable operation at elevated temperatures on AlN, Si, and sapphire substrates⁶⁻²⁵. Therefore, with its fundamental material properties and record single-channel

device performance, Al-rich AlGa_N is emerging as a leading lateral UWBG nitride platform for high-voltage power transistors.

Beyond material-level considerations, multichannel transistor architectures developed on GaN-based platforms effectively reduce channel and access resistance at a given BV^{26-31} . However, when extended to the UWBG regime, the device-level performance of such transistors is often limited by carrier injection and access. Directly extending this established multichannel concept to Al-rich AlGa_N channels is therefore not straightforward. In the UWBG regime, low-resistance ohmic injection into Al-rich AlGa_N is intrinsically difficult because of the large energetic separation between the Fermi level of the metal injector and the quantized Al-rich AlGa_N channel states; additionally, the UWBG side has a limited ability to sustain donor densities sufficient for compressing the depletion width into a tunneling-assisted injection regime. In addition, polarization-induced 2DEGs are buried and vertically distributed in Al-rich AlGa_N multichannel superlattices, so planar surface contacts cannot provide a continuous low-loss access path that couples to all channels in parallel. Consequently, the device-level trade-off between BV and specific on-resistance ($R_{on,sp}$) in Al-rich AlGa_N platforms is often governed not by the intrinsic channel transport properties themselves but by contact and access limitations. This underscores the necessity of a contact concept that can simultaneously address buried-channel access and the UWBG injection bottleneck. An alternative contact concept that simultaneously addresses energetic alignment and 3D channel access is required to overcome these coupled injections and access limitations inherent in UWBG Al-rich AlGa_N platforms. Unlike conventional metal electrodes, whose Fermi levels are fixed by their work functions, a degenerately doped GaN

(d-GaN) electrode provides a tunable quasi-metallic electron reservoir whose Fermi level can be elevated well above that of metals, enabling it to function as an effective intermediate injector to Al-rich AlGa_N channels.

In this work, we implement undoped lateral AlN/Al_{0.6}Ga_{0.4}N multichannel HEMTs in which vertically stacked polarization-induced 2DEG channels are accessed from etched sidewalls by epitaxially regrown, highly degenerate n⁺⁺-Ga_N (d-GaN) electrodes formed via pulsed sputter deposition (PSD). The regrown d-GaN electrode decouples electron injection between the metal and the Al-rich AlGa_N channels by partitioning the energetic separation between the metal Fermi level and the quantized channel states into two sequential interfaces. In this scheme, the interface between the metal and the regrown d-GaN operates in a tunneling-favorable regime. The remaining energetic separation at the d-GaN/AlGa_N interface can be systematically reduced by engineering the Fermi level position of the intermediate d-GaN electrode; this drives the interface toward the tunneling-assisted injection regime and enables efficient injection into the buried polarization-induced channels. The feasibility of realizing low-resistivity d-GaN via PSD and its application to sidewall-accessed source–drain contacts in Al-rich AlGa_N HEMTs have been established^{6-7,32}. Building on this foundation, we design AlN/Al_{0.6}Ga_{0.4}N multichannel HEMTs with PSD-regrown d-GaN semiconductor electrodes for operations where contact and access resistances remain subdominant in $R_{\text{on,sp}}$ so that the BV – $R_{\text{on,sp}}$ trade-off is governed primarily by the Al-rich multichannel platform rather than extrinsic limitations.

Results

Device architecture and injection framework

Figure 1a illustrates a 3D degenerate semiconductor injector structure implemented on an Al-rich AlN/Al_{0.6}Ga_{0.4}N multichannel platform using a regrown d-GaN electrode. All epitaxial growth processes were performed using a PSD apparatus. The devices were based on vertically stacked AlN/Al_{0.6}Ga_{0.4}N superlattices with multiple polarization-induced conduction channels. These Al-rich multichannel heterostructures were formed on Al-polar AlN/sapphire templates and patterned into fin-shaped mesas to define 3D channel geometries. Then, d-GaN electrodes were selectively formed on the exposed sidewalls in the source and drain regions, providing lateral access to the vertically distributed channels. The top surface and both sidewalls of the fin were wrapped in a Ni/Au trigate for 3D electrostatic control, and Ti/Al/Ti/Au metallization was used to form the source and drain terminals on the regrown electrodes. Further fabrication details are provided in Methods.

Figure 1b shows a simulated 1D band diagram and the carrier density profile of an undoped AlN/Al_{0.6}Ga_{0.4}N multichannel stack at zero bias, obtained from self-consistent Schrödinger–Poisson calculations. Polarization-induced 2DEGs formed on the AlGaN side of each AlN/Al_{0.6}Ga_{0.4}N interface, giving rise to multiple vertically distributed conduction channels. The AlN and Al_{0.6}Ga_{0.4}N layer thicknesses were chosen to maximize the thickness-normalized sheet electron density (Fig. S1) and were kept identical for all N_{ch} . Cross-sectional transmission electron microscopy (TEM) analysis of the multilayer stack (Fig. 1c)

reveals well-defined AlN/Al_{0.6}Ga_{0.4}N interfaces with a preserved periodic multilayer structure, verifying the structural formation of the Al-rich multichannel platform.

Lateral access to the vertically distributed channels was established by selectively regrowing d-GaN electrodes on the etched sidewalls of the AlN/Al_{0.6}Ga_{0.4}N multichannel stacks in the source and drain regions. Figure 1d shows a cross-sectional TEM image of the regrown sidewall contact region. The regrown d-GaN maintains single-crystal continuity up to the interface and directly contacts the Al_{0.6}Ga_{0.4}N sidewall without an observable amorphous or heavily reacted interlayer within the measurement resolution. It thus provides a direct semiconductor/semiconductor interface on which the injection barrier is governed primarily by the relative Fermi level positions.

Carrier injection across the regrown contact is described using an energy-based framework that explicitly partitions the total energetic injection penalty between the conventional metal (Ti) and the AlGa_N channel states into two sequential contributions (Fig. 1e): $\Delta E_{F,\text{total}} = \Delta E_{F,1} + \Delta E_{F,2}$. $\Delta E_{F,1}$ is the contribution associated with carrier injection across the metal to the d-GaN junction, and $\Delta E_{F,2}$ is the residual energetic separation between the d-GaN electrode and the AlGa_N channel states. The metal/d-GaN interface operates in the tunneling-dominated regime, thereby providing a structurally ohmic injection condition that is effectively independent of $\Delta E_{F,1}$. Accordingly, the following analysis focuses on $\Delta E_{F,2}$, or the energy separation between the Fermi level of the d-GaN electrode and the quantized polarization-induced 2DEG states in AlGa_N, after correcting the GaN Fermi level for high-density effects, specifically the Burstein–Moss shift (BMS) and bandgap renormalization

(BGR)³³⁻³⁴. Figure 1f provides a quantitative map of specific contact resistivity (ρ_C) at 300 K within a field-emission-dominated transport model (see Supplementary Discussion for model details) as a function of the effective barrier height (ϕ_B) and the tunneling parameter ($E_{00}/(k_B T)$). This representation provides a unified 2D energetic space for evaluating carrier transport across the interfaces between the metal and the degenerate semiconductor and between the degenerate semiconductor and AlGaIn. The metal/d-GaN junction is mapped primarily in the tunneling-favorable regime ($E_{00}/(k_B T) \gtrsim 5$), where the depletion width is strongly compressed by the degenerate intermediate electrode, allowing large effective barrier heights to be accommodated. The regrown d-GaN/AlGaIn interface falls into the tunneling-unfavorable regime ($E_{00}/(k_B T) \lesssim 4$), where efficient carrier injection requires a minimized effective barrier height. Accordingly, ρ_C variations are governed predominantly by the residual energetic separation at the electrode/AlGaIn interface, i.e., $\Delta E_{F,2}$, not the metal-side injection condition.

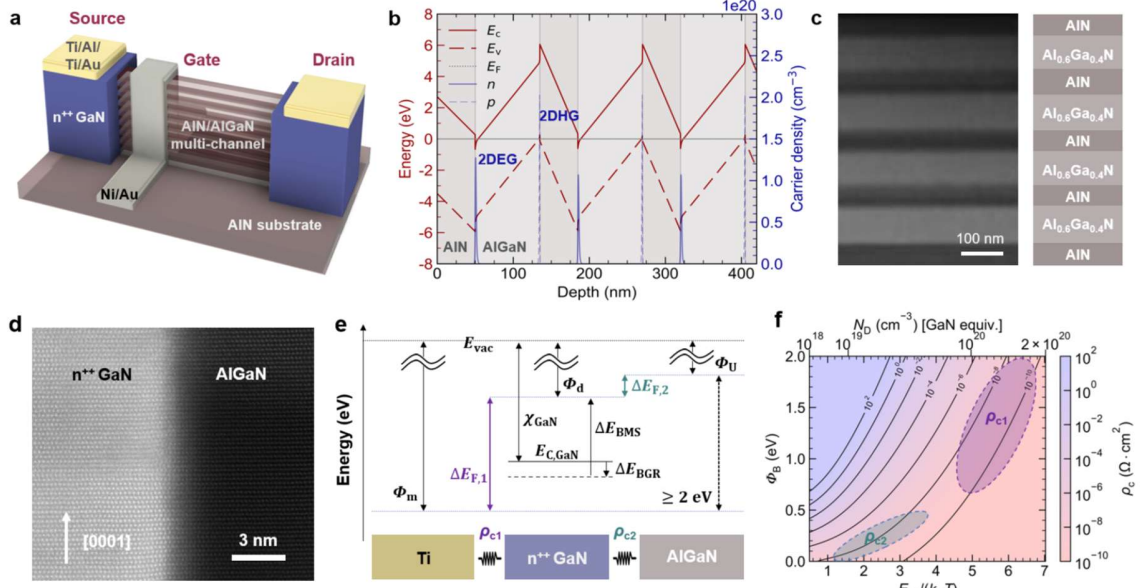


Fig. 1 | AlN/Al_{0.6}Ga_{0.4}N multichannel HEMT platform and two-step injection structure enabled by regrown semiconductor electrodes. **a**. Schematic diagram of AlN/Al_{0.6}Ga_{0.4}N multichannel trigate HEMT with selectively regrown d-GaN semiconductor electrodes on etched sidewalls and Ti/Al/Ti/Au source-drain metallization. **b**. Self-consistent Schrödinger-Poisson band diagram and carrier density profile at zero bias for representative multichannel stack, showing polarization-induced 2DEG channels and simulated 2DHG accumulation at lower interfaces. **c**. Cross-sectional TEM image of periodic AlN/Al_{0.6}Ga_{0.4}N multilayer stack, showing well-defined, abrupt heterointerfaces. **d**. Cross-sectional TEM image of selectively regrown d-GaN/AlGa_{0.4}N sidewall heterointerface, showing single-crystalline contrast up to junction without observable amorphous or heavily reacted interlayer within measurement resolution. **e**. Energetic partitioning of effective metal-channel injection mismatch into two sequential contributions, $\Delta E_{F, \text{total}} = \Delta E_{F,1} + \Delta E_{F,2}$, corresponding to metal/d-GaN and d-GaN/AlGa_{0.4}N junctions, respectively. $\Delta E_{F,2}$ is defined after accounting for the carrier density-dependent shifts of the electrode Fermi level, specifically BMS and BGR. The schematic energy references ϕ_d and ϕ_U indicate the lower and upper bounds, respectively, used for energy partitioning in this diagram; they are not considered independently defined physical quantities. **f**. Calculated ρ_c at 300 K as function of effective ϕ_B and $E_{00}/(k_B T)$, shown as color map with iso- ρ_c contours. The upper axis indicates the GaN-equivalent N_D corresponding to E_{00} . The shaded regions labeled ρ_{c1} and ρ_{c2} highlight the parameter ranges relevant to the metal/electrode and electrode/AlGa_{0.4}N junctions, respectively, and are used to contextualize the contact resistance analysis.

Structural and electrical characterization of AlN/Al_{0.6}Ga_{0.4}N multichannel stacks

The crystalline quality of the AlN/Al_{0.6}Ga_{0.4}N multichannel structures was evaluated through X-ray diffraction (XRD) and atomic force microscopy (AFM). Symmetric $2\theta/\omega$ scans for representative two- and eight-channel stacks (Fig. 2a) and the corresponding scans for other N_{ch} (Fig. S1) show pronounced superlattice fringes that are well reproduced by kinematical simulations using an AlGa_{0.4}N channel composition of approximately 60% Al. Reciprocal-space maps (RSMs) around the 10–15 reflection (Fig. 2b) indicate that the in-plane peak positions of AlN and AlGa_{0.4}N coincide within the experimental resolution for all stacks, including the thickest structure (eight channels). The X-ray rocking curves of the AlN 0002 and 10–12 reflections are comparable to those of the underlying AlN template (Fig. S2), indicating that the crystalline quality is preserved across the multichannel stacks. AFM images of the eight-channel structure (Fig. 2c) exhibit a step-and-terrace surface morphology over $2 \times 2 \mu\text{m}^2$ scan areas, with root-mean-square roughness values of approximately 0.1–0.15 nm and no observable pits or cracks in the scanned regions. Thus, the PSD-grown AlN/AlGa_{0.4}N multichannel stacks maintain a high crystalline quality and surface flatness even at large N_{ch} , in line with previously reported PSD AlN/AlGa_{0.4}N multichannel growth characteristics³⁵, providing a reliable structural basis for subsequent electrical characterization.

Room-temperature Hall-effect measurements in a van der Pauw geometry were performed on cloverleaf test structures (Fig. S3) for stacks with $N_{ch} = 1\text{--}8$ (Fig. 2d) for the

electrical validation of the multichannel design. The measured sheet carrier density (n_{sh}) increases systematically with N_{ch} , reaching $n_{\text{sh}} = 1.6 \times 10^{14} \text{ cm}^{-2}$ for the eight-channel stack, whereas sheet resistance (R_{sh}) decreases correspondingly to $R_{\text{sh}} \approx 9.5 \times 10^2 \text{ } \Omega/\text{sq}$ at $N_{\text{ch}} = 8$. These trends are consistent with the intended parallel contribution of the vertically stacked polarization-induced channels. Planar-gate capacitance–voltage (C – V) measurements were performed on the AlN/Al_{0.6}Ga_{0.4}N two-channel stack to further confirm the spatial distribution of carriers (Fig. 2e). The C – V characteristics exhibit two distinct depletion steps as the gate voltage is swept; depth profiling yields two electron density peaks separated by approximately 130–140 nm, with sheet densities on the order of $2 \times 10^{13} \text{ cm}^{-2}$ per channel. These results confirm the presence of multiple vertically separated conduction channels and serve as an electrical validation of the multichannel platform before device fabrication.

Figure 2f shows the drain current (I_{DS})–gate voltage (V_{GS}) characteristics and transconductance (g_{m}) of a planar top-gate test transistor fabricated on the same AlN/Al_{0.6}Ga_{0.4}N eight-channel stack, measured at a drain bias of $V_{\text{DS}} = 40 \text{ V}$. The I_{DS} – V_{GS} relationship exhibits a staircase-like evolution with the gate voltage, and the corresponding g_{m} – V_{GS} curve displays eight well-resolved peaks over the same voltage range. These features are consistent with the stepwise electrostatic modulation of the vertically stacked channels within a single device and provide direct device-level evidence that the individual channels remain electrostatically addressable in the multichannel platform.

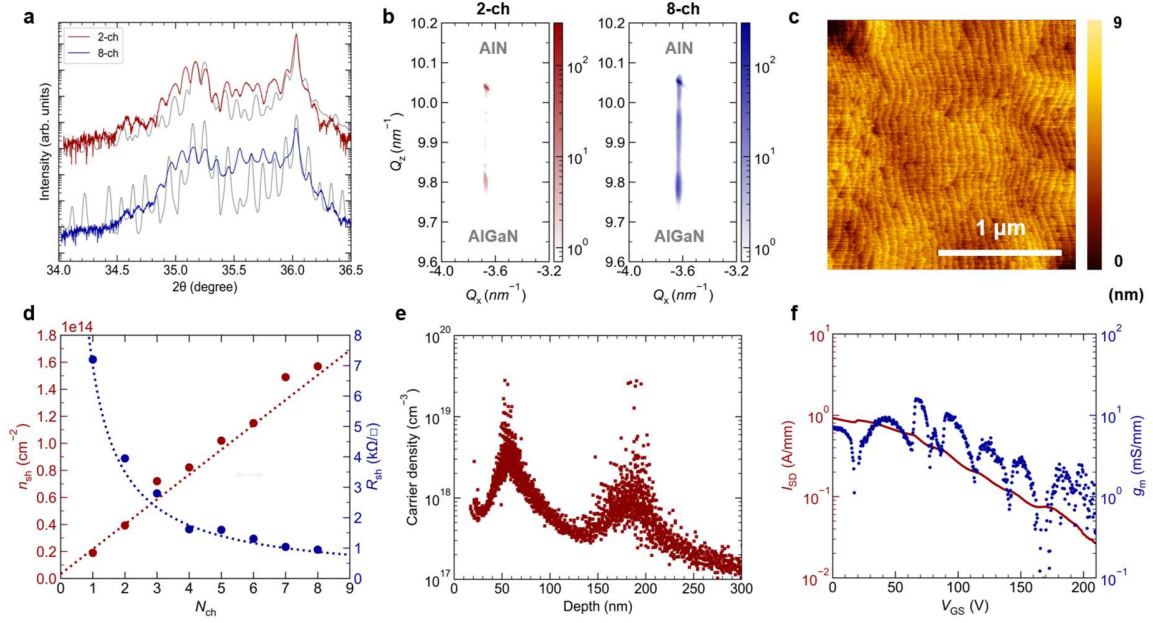


Fig. 2 | Structural and electrical characterization of AlN/Al_{0.6}Ga_{0.4}N multichannel stacks. a. Symmetric XRD 2θ/ω scans for two- and eight-channel stacks, with corresponding kinematic simulations. **b.** RSMs around 10–15 reflection for two- and eight-channel stacks. **c.** AFM image of eight-channel stack (2 × 2 μm²). **d.** Room-temperature Hall-effect measurements for stacks with $N_{ch} = 1-8$, showing sheet carrier density n_{sh} and sheet resistance R_{sh} as functions of N_{ch} . **e.** Planar-gate $C-V$ measurement for two-channel stack, showing two depletion steps associated with vertically separated channels. **f.** $I_{DS}-V_{GS}$ and g_m-V_{GS} characteristics of planar top-gate test transistor fabricated on eight-channel stack, measured at $V_{DS} = 40$ V.

Contact properties of PSD-regrown d-GaN electrodes

After validating that the AlN/Al_{0.6}Ga_{0.4}N multichannel stacks accommodate multiple vertically separated conduction channels that remain electrostatically addressable at the device-level under planar-gate operation, we experimentally examined whether the intrinsic carrier injection behavior in the multichannel system is governed by the energetic framework in Fig. 1e. Transfer length method (TLM) measurements were performed to quantify the total contact resistance and its constituent contributions. Figure 3a shows the current–voltage characteristics of Ti/Al/Ti/Au contacts formed on the regrown d-GaN,

exhibiting a linear behavior without postmetallization annealing. The extracted total resistance (R_{TLM}) scales approximately linearly with the TLM spacing (L_{TLM}) (Fig. 3b), allowing the width-normalized single-contact resistance (R_{C}) and R_{sh} to be determined. Here, R_{C} is considered an effective contact metric encompassing the metal/d-GaN interface and the d-GaN/AlGaIn junction at the regrown sidewall. For the AlN/Al_{0.6}Ga_{0.4}N eight-channel stack, the extracted values are $R_{\text{C}} = 0.83 \text{ } \Omega \cdot \text{mm}$ and $R_{\text{sh}} = 9.6 \times 10^2 \text{ } \Omega/\text{sq}$, consistent with the Hall-effect measurement results for the same multichannel structure. These measurements establish a quantitative basis for separating the contact-related contributions from the intrinsic multichannel resistance and for organizing the following analysis of contact scaling and injection mechanisms.

Figure 3c places these contact resistance values in context by benchmarking the width-normalized contact resistance R_{C} as a function of the Al composition of previously reported and the current Al-rich AlGaIn channel HEMTs. The data are grouped into those of undoped multichannel HEMTs, undoped single-channel HEMTs, and Si-doped single-channel HEMTs. “Undoped” means no donor doping is intentionally introduced into the AlGaIn channel or barrier layers; this condition differs from the highly degenerate carrier density of the regrown d-GaN semiconductor electrodes used for source–drain access in the present devices. The Si-doped single-channel class, involving heavily doped AlGaIn access layers, is the reference category. Around Al compositions of approximately 60%, previously reported undoped AlGaIn single-channel HEMTs typically exhibit R_{C} values of several tens to several hundreds of ohm-millimeters. By contrast, the proposed undoped AlN/Al_{0.6}Ga_{0.4}N multichannel devices show R_{C} values below $1 \text{ } \Omega \cdot \text{mm}$ for the eight-channel stack. The arrows

in Fig. 3c highlight the single- and eight-channel devices in the present work, illustrating the evolution of the measured R_C as N_{ch} is increased on a common $\text{Al} \approx 0.6$ platform.

The energetic injection framework in Fig. 1e is connected to the measured contact resistance in the present devices ($N_{\text{ch}} = 1\text{--}8$) by decomposing the width-normalized single-contact resistance as

$$R_C = R_1 + R_{\text{deg}} + R_2.$$

Here, R_1 and R_2 correspond to the two sequential injection contributions defined in Fig. 1e: R_1 represents the metal-to-d-GaN injection component ($\Delta E_{\text{F},1}$), whereas R_2 captures the residual injection-related resistance associated with carrier transfer from the d-GaN electrode to the AlGaIn channel states ($\Delta E_{\text{F},2}$). R_{deg} accounts for the access and current-spreading resistance within the d-GaN electrode between the metal pad and the regrown sidewall junction. R_1 is expected to vary only weakly with N_{ch} because the same metallization scheme and regrown-electrode geometry are used across devices with different channel counts. Electrode-only test structures (Fig. S4) yield $R_1 = 0.05\text{--}0.12 \text{ } \Omega \cdot \text{mm}$, corresponding to $\rho_{\text{C1}} = 0.4\text{--}1.0 \times 10^{-6} \text{ } \Omega \cdot \text{cm}^2$, and geometry-based estimates using the Hall data indicate $R_{\text{deg}} \approx 0.01 \text{ } \Omega \cdot \text{mm}$; both figures remain small under the present device geometry. Consequently, the systematic reduction in R_C with the increase in N_{ch} is primarily reflected in R_2 . We therefore organize R_2 on a common basis using the Fermi level separation $\Delta E_{\text{F},2}$ at the regrown d-GaN/AlGaIn junction. $\Delta E_{\text{F},2}$ is obtained by combining the Schrödinger–Poisson calculations for the AlGaIn channel states with the carrier density-dependent Fermi level of the degenerate d-GaN electrode, including high-density corrections (BMS and BGR) (Fig. 3d). Plotted as a

function of $\Delta E_{F,2}$, the extracted R_2 values from devices with PSD-regrown electrodes collapse into a single trend (Fig. 3e).

Figure 3f summarizes how the injection-physics-limited contact properties translate to the device-level $R_{\text{on,sp}}$ of the AlN/Al_{0.6}Ga_{0.4}N eight-channel HEMTs as a function of the spacing L_{TLM} between two regrown electrodes. The measured $R_{\text{on,sp}}$ increases approximately linearly with L_{TLM} . The channel contribution R_{ch} , estimated from the measured sheet resistance R_{sh} and the device geometry, enables baseline scaling with L_{TLM} . Guide curves were constructed by adding constant offsets of $2 R_{\text{C}}$ to R_{ch} and then overlaid for three representative electrode electron concentrations (n_1 – n_3 , corresponding to 1×10^{20} – $3 \times 10^{20} \text{ cm}^{-3}$) using the contact resistance components extracted in the preceding analysis. The experimental data lie close to the guide curve corresponding to the highest electrode carrier density, indicating that the contact-related contributions remain small over the investigated spacing range. Under these conditions, the measured $R_{\text{on,sp}}$ is governed primarily by the AlN/Al_{0.6}Ga_{0.4}N multichannel stack rather than contact or access resistance, providing a consistent basis for the subsequent breakdown and benchmarking analysis.

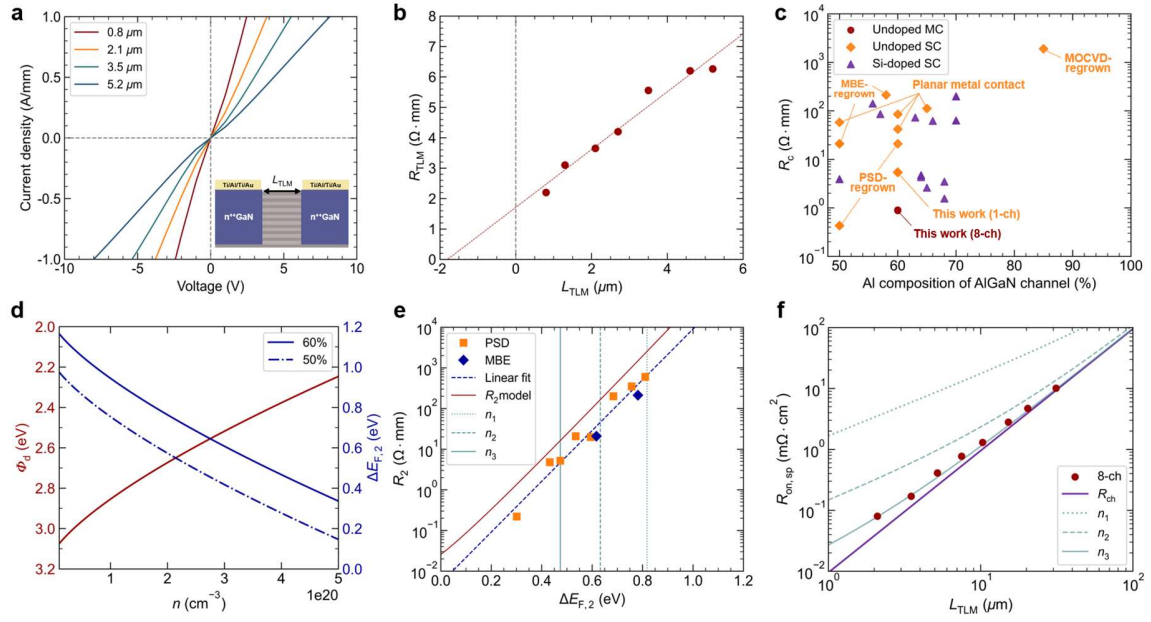


Fig. 3 | Electrical properties of PSD-regrown d-GaN electrodes. **a.** Current density–voltage (J – V) characteristics of Ti/Al/Ti/Au contacts formed on PSD-regrown d-GaN electrodes, confirming linear, annealing-free ohmic behavior. **b.** TLM characteristics of AlN/Al_{0.6}Ga_{0.4}N eight-channel stack with PSD-regrown d-GaN electrodes, used to extract total contact resistance R_C . **c.** Benchmark of R_C versus Al composition in AlGaIn channel for Al-rich AlGaIn HEMTs, comparing previously reported and current undoped multichannel HEMTs, undoped single-channel HEMTs, and Si-doped single-channel HEMTs. The arrows highlight the single- and eight-channel devices reported here and illustrate the R_C reduction enabled by the multichannel architecture at Al $\approx$ 0.6. **d.** Calculated dependence of effective work function ϕ_m and Fermi level separation $\Delta E_{F,2}$ on electron concentration (n) in regrown d-GaN electrode, including corrections for high-density effects (BMS and BGR). **e.** Dominant injection-related resistance component R_2 as function of $\Delta E_{F,2}$ for undoped single-channel HEMTs with regrown d-GaN electrodes. The orange squares and purple diamonds denote PSD-regrown and MBE-regrown electrodes, respectively, and the dashed vertical lines indicate representative $\Delta E_{F,2}$ values corresponding to electrode electron concentrations n_1 – n_3 . **f.** $R_{on,sp}$ of AlN/Al_{0.6}Ga_{0.4}N eight-channel HEMTs as function of L_{TLM} , shown with extracted channel-only resistance R_{ch} and model curves including finite $2R_C = 2(R_1 + R_{deg} + R_2)$ for n_1 – n_3 .

Electrical performance and breakdown characteristics of multichannel trigate HEMTs

Device performance was evaluated using undoped trigate HEMTs based on the PSD-prepared AlN/Al_{0.6}Ga_{0.4}N multichannel structures under operating conditions where the contact-related contributions were modest relative to channel resistance, as established in the preceding contact analysis. The devices were fabricated on fin-shaped multichannel mesas laterally contacted by PSD-regrown d-GaN electrodes, and a Ni/Au gate wrapping the top surface and both sidewalls provided 3D electrostatic control. Within this trigate framework, the nominal fin width L_w , defined by a lithographic hard mask, served as the primary geometric switch for tuning the sidewall depletion strength and therefore the threshold and transconductance responses; the effective electrical width could be smaller than L_w because of etch and sidewall-profile effects. As for transfer characteristics as a function of L_w (Supplementary Fig. S5), the pinch-off voltage shifts monotonically toward less negative V_{GS} as L_w reduces, consistent with the stronger sidewall depletion in narrower fins. The corresponding transconductance response g_m is plotted in Fig. 4a as a function of V_{GS} for devices 1, 2, 3, and 4, which had nominal L_w values of 200, 400, 600, and 800 nm, respectively. As L_w decreases, g_m becomes sharper and more strongly peaked, indicating enhanced electrostatic coupling to the vertically stacked channels. In particular, the $L_w = 200$ nm device exhibits a single pronounced g_m peak, contrary to the multipeak response observed in the planar top-gate test structures on the same multichannel stack. This peak establishes the transition from sequentially activated 2D subchannels to a single 3D-coupled

conduction fin synchronously modulated by the gate field. With an increase in L_w , the g_m peaks broaden and weaken, reflecting a reduction in the influence of sidewall gating on deeper channels as the fin widens. The following discussion focuses on seven-channel trigate HEMTs with $L_w = 200$ nm as representative devices that balance current drive, gate controllability, and process robustness in this Al-rich multichannel platform.

Figure 4b plots the output $I_{DS} - V_{DS}$ characteristics of a representative seven-channel trigate HEMT with $L_w = 200$ nm (device 1). The device delivers a maximum drain current ($I_{D,max}$) exceeding 400 mA/mm at $V_{GS} = +3$ V while maintaining a deep pinch-off at a negative gate bias, indicating a wide, well-controlled gate voltage swing. The corresponding three-terminal off-state breakdown characteristics are summarized in Fig. 4c, where BV is plotted as a function of the gate-drain distance L_{GD} for the AlN/Al_{0.6}Ga_{0.4}N multichannel trigate HEMTs and the reference GaN multichannel device in this work. The underlying off-state $I_{DS} - V_{DS}$ characteristics for each device are shown in Fig. S6. For the Al-rich AlGaN multichannel devices, BV scales approximately linearly with L_{GD} , yielding an average breakdown electric field BV/L_{GD} on the order of 3.8 MV/cm, whereas the GaN multichannel reference exhibits a substantially smaller slope of about 1.3 MV/cm. In the short- L_{GD} regime, the Al-rich multichannel trigate HEMTs reach $BV/L_{GD} = 4\text{--}5$ MV/cm, consistent with the high-lateral-field capability of this undoped Al-rich multichannel platform.

These breakdown fields are placed in a broader context in Fig. 4d, which benchmarks the breakdown electric field BV/L_{GD} as a function of the Al compositions of previously reported and the current lateral GaN- and AlGaN channel HEMTs^{6-9,11-13,18-20,36,42-}

⁴⁹. The data are grouped into four classes according to channel material and multiplicity (AlGa_N multichannel, AlGa_N single-channel, Ga_N multichannel, and Ga_N single-channel HEMTs). Within this dataset, most Ga_N single-channel and Ga_N multichannel entries fall below approximately 2 MV/cm, forming a low-field cluster. Previously reported AlGa_N multichannel HEMTs with low Al compositions similarly populate the low-field region, whereas Al-rich AlGa_N single-channel HEMTs with Al contents of around 60% exhibit high-field data points approaching ~6 MV/cm in the short- L_{GD} regime⁶. On the same composition axis, this work's AlN/Al_{0.6}Ga_{0.4}N multichannel trigate HEMTs reach breakdown electric fields of around 5 MV/cm in the short- L_{GD} regime (Fig. 4d). Thus, an undoped AlN/Al_{0.6}Ga_{0.4}N multichannel architecture can preserve the high lateral breakdown fields characteristic of high-performance Al-rich AlGa_N channel devices while enabling sidewall-accessed multichannel conduction.

Figure 4e summarizes the trade-off between BV and $R_{on,sp}$ for the same set of Ga_N- and AlGa_N channel HEMTs and overlays contours of the power FOM (PFOM) = $BV^2/R_{on,sp}$ ^{14,26,50-54}. The PFOM is used here as a compact static benchmarking metric; it does not capture dynamic on-resistance, switching loss, self-heating, or radio frequency (RF) power performance. Previously reported undoped or Si-doped AlGa_N channel HEMTs based on single-channel platforms largely cluster in the sub-GW/cm² PFOM regime. By contrast, the undoped AlN/Al_{0.6}Ga_{0.4}N multichannel HEMTs in this study shift toward lower $R_{on,sp}$ at kilovolt-class BV , reaching multi-GW/cm² PFOM values.

As for the Al-rich AlGa_N channel subset, Fig. 4f plots BV versus $I_{D,\max}$ and overlays contours of the estimated saturated RF output power per unit width $P_{\text{sat}} \approx I_{D,\max} \times (BV - V_{\text{knee}})/8$, where the knee voltage V_{knee} is extracted from the output $I_{DS}-V_{DS}$ characteristics, following a previously published definition^{7-12,14-16,36}. P_{sat} contours are used here as static heuristic visualization based on DC output characteristics, not as reported RF measurements. In this representation, Si-doped AlGa_N single-channel HEMTs can reach large $I_{D,\max}$ but often require extended L_{GD} to reach kilovolt-class BV . Undoped AlGa_N single-channel HEMTs can sustain high breakdown electric fields but are frequently limited in $I_{D,\max}$ by their large contact resistance. The undoped AlN/Al_{0.6}Ga_{0.4}N multichannel trigate HEMTs in this work occupy a high BV , high- $I_{D,\max}$ region at Al contents of around 60%, placing the representative devices on higher P_{sat} contours than most previously reported undoped and Si-doped AlGa_N single-channel HEMTs with comparable Al compositions. These simultaneous enhancements in PFOM and P_{sat} mean the present devices retain the high lateral breakdown fields of the Al-rich AlN/Al_{0.6}Ga_{0.4}N multichannel platform while suppressing on-resistance through stacked multichannel conduction and 3D d-GaN injection.

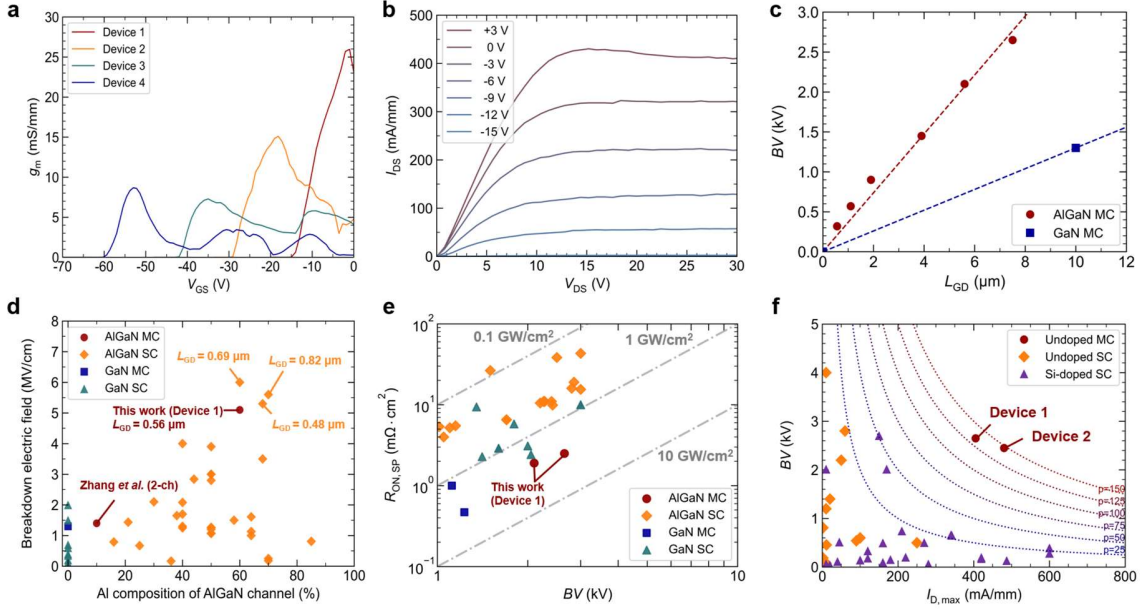


Fig. 4 | Device performance and breakdown characteristics of AlN/Al_{0.6}Ga_{0.4}N multichannel trigate HEMTs. **a.** $g_m - V_{GS}$ characteristics of seven-channel trigate HEMTs as function of nominal fin width L_w (devices 1–4: 200–800 nm). **b.** Output $I_{DS} - V_{DS}$ characteristics of representative $L_w = 200$ nm device (device 1) measured at room-temperature for V_{GS} from -15 V to $+3$ V, showing $I_{D,max}$ exceeding 400 mA/mm at $V_{GS} = +3$ V. **c.** Off-state BV as function of gate–drain distance L_{GD} for AlN/Al_{0.6}Ga_{0.4}N multichannel trigate HEMTs (red circles) and GaN multichannel reference device (blue square), with dashed lines indicating linear fits used to estimate average breakdown field. **d.** Breakdown field BV/L_{GD} as function of Al composition for previously reported and current lateral GaN- and AlGaIn channel HEMTs, grouped by channel material and multiplicity. **e.** $BV - R_{on,sp}$ map for same dataset with PFOM = $BV^2/R_{on,sp}$ contours, highlighting multi-GW/cm²-class PFOM region reached by undoped AlN/Al_{0.6}Ga_{0.4}N multichannel HEMTs for devices with $L_{GD} = 5.6, 7.5$ μm . **f.** $BV - I_{D,max}$ map with overlaid P_{sat} contours estimated from $P_{sat} \approx I_{D,max} \times (BV - V_{knee}) / 8$, comparing operating points of present multichannel devices with those of prior AlGaIn channel HEMTs.

Conclusions

We establish a UWBG device architecture that simultaneously achieves a high BV and low specific on-resistance by integrating an undoped AlN/Al_{0.6}Ga_{0.4}N multichannel platform, a 3D d-GaN injection structure, and trigate electrostatic confinement. The AlN/Al_{0.6}Ga_{0.4}N multichannel platform provides vertically stacked polarization-induced

2DEG channels that remain electrically active up to $N_{\text{ch}} = 8$, yielding a total sheet electron density of $1.6 \times 10^{14} \text{ cm}^{-2}$ and a sheet resistance of $945 \text{ } \Omega/\text{sq}$. The 3D d-GaN injection structure, implemented using sidewall-accessed PSD-regrown d-GaN electrodes, achieves annealing-free contact resistance of below $1 \text{ } \Omega \cdot \text{mm}$, rendering ohmic losses secondary to the channel resistance at the present device dimensions. The trigate electrostatic confinement transforms the stacked multichannel platform into a 3D-coupled conduction fin, enabling synchronized modulation of the vertically stacked channels and stable high-field operation, leading to an Al-rich multichannel trigate HEMT architecture with BV exceeding 3 kV, average breakdown fields reaching 3.8 MV/cm, and PFOMs approaching 3.2 GW/cm^2 .

The developed 3D d-GaN injection structure is defined by the dual role of the regrown d-GaN semiconductor electrodes. First, the ultrahigh electron density of the degenerate electrode confines most of the interfacial band bending within an ultrathin metal/d-GaN depletion region, thereby consuming most of the effective injection barrier and enabling tunneling-favorable injection without postmetallization annealing. Second, the intermediate electrode Fermi level lies energetically close to the Al-rich AlGaN channel states, reducing the remaining effective injection barrier at the intermediate electrode/AlGaN junction and enabling a transition from thermionic-field emission (TFE) to quasi-ohmic coupling to buried polarization-induced channels. Within this framework, the dominant injection-related resistance component can be organized using the residual Fermi level separation $\Delta E_{\text{F},2}$ at the intermediate electrode/AlGaN interface. This constitutes a compact design basis for engineering the intermediate electrode Fermi level to suppress injection-related ohmic losses and thus preserve a low $R_{\text{on,sp}}$ in UWBG multichannel HEMTs. After

the dominant resistance contribution shifts from injection-limited contact to channel transport, further scaling is governed by increasing the effective channel conductivity via stacked multichannel conduction while preserving the high-lateral-field capability of the Al-rich channel platform, together with fin-gate scaling toward high-frequency operation. Broadly, in UWBG transistor platforms, the feasibility of degenerate doping is a fundamental material criterion for achieving low on-resistance, low losses, and quasi-ohmic 3D-regrown access to buried conduction channels that are poorly coupled to conventional metal electrodes.

Methods

Multichannel epitaxy and d-GaN regrowth

AlN/Al_{0.6}Ga_{0.4}N multichannel heterostructures were epitaxially grown via PSD on Al-polar AlN/sapphire templates using pulsed group-III sputtering cathodes in a growth chamber. Each period consisted of 55 nm AlN / 85 nm Al_{0.6}Ga_{0.4}N, yielding a period thickness of 140 nm (Fig. S1). The number of periods N_{ch} was varied from one to eight. The AlN and Al_{0.6}Ga_{0.4}N growth conditions were identical to those in previous studies⁶⁻⁷. Following multichannel epitaxy, fin-shaped mesas were defined via inductively coupled plasma–reactive ion etching using Cl₂-based plasma to expose the sidewalls of the AlN/Al_{0.6}Ga_{0.4}N stacks for the subsequent formation of degenerate semiconductor electrodes. Then, d-GaN electrodes were formed on the exposed sidewalls in the source and drain regions through PSD regrowth using a lift-off process. The electron concentration of the regrown GaN was approximately 10^{20}cm^{-3} , as estimated via Hall-effect measurements on reference

van der Pauw patterns fabricated on the same wafer. The relationship between the Si doping concentration and electron concentration under similar growth conditions was previously calibrated via SIMS for heavily Si-doped GaN on GaN (0001); the regrown layers in the present study follow the same trend³².

Device fabrication

The devices were fabricated using the process flow schematically illustrated in Fig. S7. Fin-shaped device structures were formed via dry etching to define the channel width and expose the AlN/Al_{0.6}Ga_{0.4}N sidewalls for subsequent gate formation and the selective formation of degenerate semiconductor electrodes. The fin width was adjusted through the lateral trimming of a metal hard mask. After selective d-GaN formation, a conformal trigate was formed by depositing gate metal on the top surface and sidewalls of the fins. The gate length was defined via lithography and lift-off, and all compared devices had a gate length of 1 μm . Ti/Al/Ti/Au metal contacts were deposited on the regrown d-GaN electrodes via electron-beam evaporation to form the source and drain contacts. Postmetallization annealing was not performed. Device dimensions were verified through scanning electron microscopy.

Schrödinger–Poisson simulation

Self-consistent Schrödinger–Poisson simulations were performed using a commercial device simulation package (FETIS 3.5, STR) to analyze the band structure and carrier distribution in the undoped AlN/Al_{0.6}Ga_{0.4}N multichannel heterostructures. These simulations were performed in one dimension along the growth direction, assuming laterally

uniform material properties within each layer. The AlN, Al_{0.6}Ga_{0.4}N, and GaN material parameters were obtained from previous literature on III-nitride heterostructures^{1,3-4,24,33,46}. Polarization-induced bound charges at the AlN/Al_{0.6}Ga_{0.4}N interfaces were included in the simulations using spontaneous and piezoelectric polarization values for wurtzite III-nitrides. No intentional background doping was assumed in the AlN/Al_{0.6}Ga_{0.4}N channel layers, consistent with nominally undoped epitaxial designs. The electrostatic boundary conditions were chosen such that the Fermi level was determined by the structure charge neutrality, and the calculations were iterated self-consistently until both the electrostatic potential and carrier density converged. The calculated conduction band profiles and electron density distributions were used to extract the sheet electron density associated with each polarization-induced 2DEG channel. For the multichannel stacks, the same bilayer design was assumed for all channel counts, with the total thickness increased accordingly. In the analysis of carrier injection at the regrown d-GaN/AlGaN junction, the carrier density-dependent Fermi level of the degenerate d-GaN electrode was evaluated within the same simulation framework, assuming a parabolic conduction band and Fermi–Dirac statistics. High-density effects, specifically BMS and BGR, were included in the simulations following standard treatments reported in the literature. The resulting Fermi level position was combined with the simulated AlGaN channel states to define the effective Fermi level separation $\Delta E_{F,2}$, which was used as an organizing parameter for contact resistance analysis.

Electrical characterization

Electrical measurements were performed on-wafer using a semiconductor parameter analyzer and a probe station under ambient conditions. Contact resistance was evaluated using TLM structures incorporating the same selectively regrown d-GaN electrodes and Ti/Al/Ti/Au metallization scheme as those of the transistor devices. The width-normalized contact resistance R_C and transfer length L_T were extracted from linear fits of the total resistance as a function of contact spacing. No postmetallization annealing was applied before electrical characterization. For the multichannel devices, $R_{on,sp}$ was extracted from the linear region of the output characteristics at a low drain bias, with the gate voltage set well above the threshold voltage. Breakdown characteristics were measured under off-state conditions by sweeping the drain voltage at a fixed gate bias below the threshold. A current compliance limit was applied to prevent catastrophic device failure during measurement. BV was defined as the drain voltage at which I_{DS} reached the compliance current. The discussed contact resistance trends were interpreted using a TFE framework following the Yu model. The carrier injection characteristics and the effective Fermi level separation $\Delta E_{F,2}$ were evaluated using a commercial device simulation package (FETIS 3.5, STR) and served as an organizing framework for interpreting the experimental data, not as a source of quantitative prediction. Further details about the contact resistance analysis and the analytical formulation are provided in Supplementary Discussion.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Competing interests

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