RF Operation of AlN/Al$_{0.25}$Ga$_{0.75}$ / AlN HEMTs with $f_\mathrm{T}/f_\mathrm{max}$ of 67/166 GHz

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1. AlGaN Channel HEMTs
2. T-gated $Al_{0.25}Ga_{0.75}N$ QW HEMT
3. Conclusion
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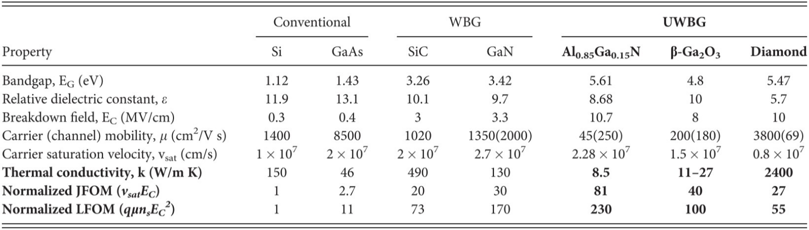
AlGaN: UWBG Semiconductor

An effective approach to enhance RF power module performance is the improve the breakdown voltage because it directly contributes to the power density of the device.



	Conventional		WBG		**UWBG**		
Property	Si	GaAs	SiC	GaN	**$Al_{0.85}Ga_{0.15}N$**	**β-Ga_2O_3**	**Diamond**
Bandgap, E_G (eV)	1.12	1.43	3.26	3.42	5.61	4.8	5.47
Relative dielectric constant, ε	11.9	13.1	10.1	9.7	8.68	10	5.7
Breakdown field, E_C (MV/cm)	0.3	0.4	3	3.3	10.7	8	10
Carrier (channel) mobility, μ (cm^2/V s)	1400	8500	1020	1350(2000)	45(250)	200(180)	3800(69)
Carrier saturation velocity, v_{sat} (cm/s)	1×10^7	2×10^7	2×10^7	2.7×10^7	2.28×10^7	1.5×10^7	0.8×10^7
Thermal conductivity, k (W/m K)	150	46	490	130	**8.5**	**11–27**	**2400**
Normalized JFOM ($v_{sat}E_C$)	1	2.7	20	30	**81**	**40**	**27**
Normalized LFOM ($q\mu n_s E_C^2$)	1	11	73	170	**230**	**100**	**55**

Figure 1: Material properties and figures of merit for conventional, WBG, and UWBG semiconductors[1].

AlN/AlGaN has an about twice the bandgap of GaN, and its electron saturation velocity is almost the same as that of GaN.

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[1] S. Choi, S. Graham, S. Chowdhury, *et al.*, "A perspective on the electro-thermal co-design of ultra-wide bandgap lateral devices," *Applied Physics Letters*, vol. 119, no. 17, 2021.

AlGaN HEMTs: Next-Gen High-Power RF Device

AlGaN HEMT is first designed by Advanced Technology Research and Development Center, Mitsubishi Electric Corporation in 2007.

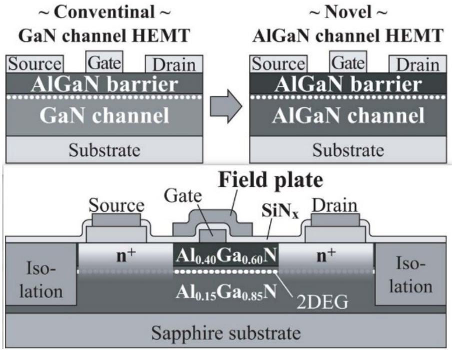

Figure 2: Concepts and schematic structure of AlGaN HEMTs[2].

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[2] T. Nanjo, A. Imai, Y. Suzuki, *et al.*, “Algan channel hemt with extremely high breakdown voltage,” *IEEE transactions on electron devices*, vol. 60, no. 3, pp. 1046–1053, 2013.

Limitations of Study on AlGaN HEMTs

JFOM is for the perforamnce of high-speed devices,

$$\mathrm{JFOM} = f_T V_{\mathrm{DS,max}} = \frac{E_{\mathrm{crit}} v_s}{2\pi}$$

- While maximize the Al content can improve the breakdown voltage for superior RF performance, the low-field mobilities and carrier densities in the AlGaN channel decrease, and make it difficult to make ohmic contacts.
- Although long-channel devices designed for power switching applications are developing rapidly, there are limited reports of their RF performance.

RF Performance of Current AlGaN HEMTs

- Record $f_\mathrm{T}/f_\mathrm{max}$ of $40/58\,\mathrm{GHz}$ is reported for $\mathrm{Al_{0.75}Ga_{0.25}}$ / $\mathrm{Al_{0.6}Ga_{0.4}}$ HEMTs.
- Highest power density is $2.7\,\mathrm{W/mm^{-1}}$ at $10\,\mathrm{GHz}$ albeit at a low PAE of 4% for a microchannel $\mathrm{Al_{0.65}Ga_{0.35}}$ / $\mathrm{Al_{0.4}Ga_{0.6}}$ HFET.

- Record $f_\mathrm{T}/f_\mathrm{max}$ of $454/444\,\mathrm{GHz}$ is reported for AlN/GaN/AlGaN HEMTs.
- High-speed graded-channel AlGaN/GaN HEMTs with PAE $> 70\%$ at 30 GHz at $2.1\,\mathrm{W/mm}$.

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This Work

- This study reports a highly scaled T-gated $Al_{0.25}Ga_{0.75}N$ quantum well channel HEMT (QW HEMT) for improved RF performance.
- The devices with simultaneously high $I_D^{max}(> 900\,\text{mA}\,\text{mm}^{-1})$ with low $R_{on} = 6.5$■mm, high average breakdown field strength $(> 2\,\text{MV}\,\text{cm}^{-1})$ and record high $f_T / f_{max} = 67/166\,\text{GHz}$ for AlGaN channel HEMTs.
- The work demonstrates high average breakdown voltage without any field plate technique, which could potentially provide cost advantages for high-voltage RF applications.

T-gated AlN/Al$_{0.25}$Ga$_{0.75}$ / AlN HEMTs

With soldered corner indium contacts to the 2DEG at the top AlN/AlGaN interface, a charge density and electron mobility of $3.05\mathrm{e}13\,\mathrm{cm}^{-2}$ and $45\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ were measured, respectively.

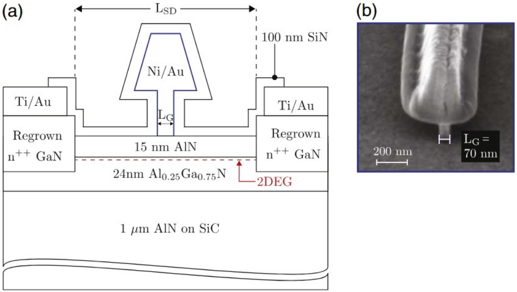

Figure 3: (a) Cross-sectional representation of the fully processed AlN/Al$_{0.25}$Ga$_{0.75}$/AlN HEMTs with a T-shaped gate. (b) SEM image of a 70 nm T-shaped gate cross section.

DC Characteristics

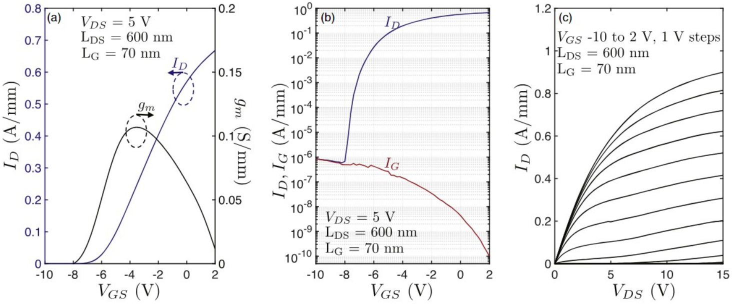

Figure 4: DC characteristics of the AlN/Al$_{0.25}$Ga$_{0.75}$/AlN HEMTs. The linear (a) and log (b) scale transfer characteristics, showing a peak transconductance of 0.11 S/mm and an on/off ratio exceeding 6 orders. (c) Output characteristics demonstrating a maximum drain current of 0.9 A^{-1} mm at a gate voltage of 2 V.

Pulsed I-V Characteristics

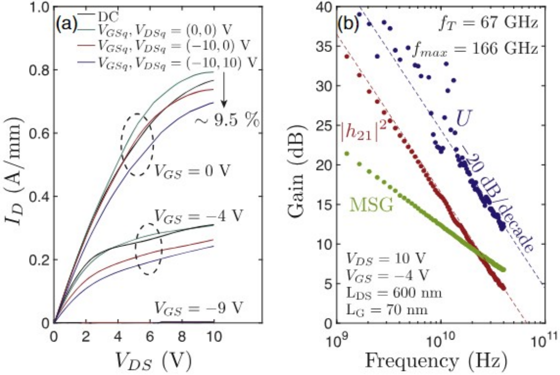

Figure 5: (a) Pulsed $I_D V_D$ measured with a 500 ns pulsed with 0.05% duty cycle at different biasing conditions. Maximum current collapse of 10% and moderate knee walkout were observed. (b) Small signal characteristics of a HEMT with $L_G = 70$ nm, with an extrapolated $f_T/f_{max} = 67/166$GHz at a gate and drain bias of -4 V and 10 V.

Breakdown Characteristics

A breakdown voltage of 59 V was measured for a HEMT with a 260 nm gate-drain distance, which corresponds to an average breakdown field exceeding $2\,\mathrm{MVcm}^{-1}$.

All measured HEMTs show $E_{\mathrm{avg}} > 1\,\mathrm{MVcm}^{-1}$.

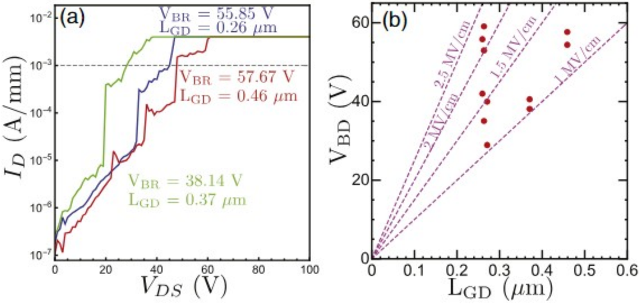

Figure 6: Breakdown characteristics for three HEMTs with $L_{\mathrm{GD}} = 0.26, 0.37$, and $0.46\,\mu\mathrm{m}$ at a gate bias of -10 V. (b) Scaling of breakdown voltage as a function of L_{GD}.

RF Performance

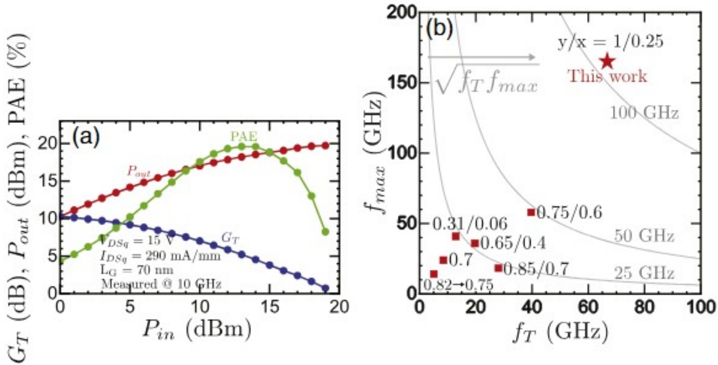

Figure 7: (a) RF power sweep at 10 GHz at $V_{\mathrm{Dsq}}/V_{\mathrm{GSq}} = 15/-3$ V, showing a peak PAE of 20% and maximum output power density of 2 W mm^{-1}. (b) Benchmark comparing $f_{\mathrm{T}}/f_{\mathrm{max}}$ of AlGaN channel HEMTs reported in the literature with this work. y/x indicates the Al composition in the top barrier/channel layer (Al$_y$Ga$_{1-y}$N / Al$_x$Ga$_{1-x}$N).

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Conclusion

- Highly scaled T-gated $Al_{0.25}Ga_{0.75}N$ quantum well channel HEMTs were demonstrated.
- The devices show a maximum drain current over $900\,\mathrm{mA\,mm^{-1}}$, a peak transconductance of $0.11\,\mathrm{S\,mm^{-1}}$, and a record high $f_\mathrm{T}/f_\mathrm{max} = 67/166\,\mathrm{GHz}$.
- Devices with $L_\mathrm{GD} = 270\,\mathrm{nm}$ exhibited an average breakdown field exceeding $2\,\mathrm{MV\,cm^{-1}}$ and a maximum output power density of $2\,\mathrm{W\,mm^{-1}}$ with a 20% PAE in the X-band.
- This initial set of data suggests that AlGaN channel transistors can achieve a comparable level of gain at high frequencies to GaN channel transistors despite the lower electron mobility.

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Phonon Database Development

If we could build the phonon database of common semiconductors, the thermal simulations of newly developed transistors can be easily conducted.

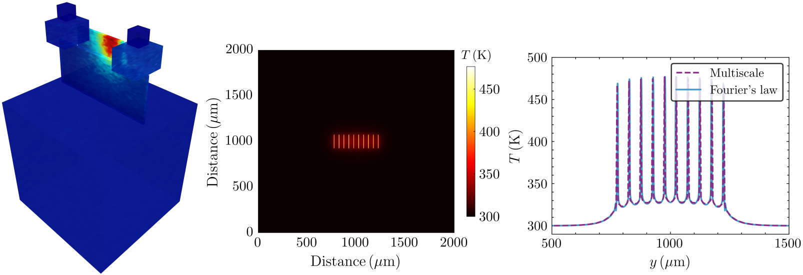

Figure 8: TDA-predicted temperature distributions of a 22 nm FinFET and multifinger β-Ga_2O_3 MOSFETs.

Thank You!