Can GaN HEMT speed reach 1 THz?

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DARPA NEXT program
Outline

• General trend in high speed HEMTs
• What determines the speed?
• Analysis of example high speed GaN HEMTs
• Summary
III-V HEMT: record $f_T$ vs. time

For >20 years, record $f_T$ obtained on InGaAs-channel HEMTs

Jesus del Alamo, MIT (2011) Workshop on High Performance Narrow-Bandgap HEMT
InAs HEMTs: the path to THz electronics?

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Record $f_T$ III-V HEMTs: megatrends

Over time: $L_g \downarrow$, $\ln_x \text{Ga}_{1-x}\text{As}$ channel $x_{\ln\text{As}} \uparrow$

Jesus del Alamo, MIT (2011) Workshop on High Performance Narrow-Bandgap HEMT
InAs HEMTs: the path to THz electronics?
Record $f_T$ III-V HEMTs: megatrends

Over time: $t_{\text{ch}} \downarrow$, $t_{\text{ins}} \downarrow$

Jesus del Alamo, MIT (2011) Workshop on High Performance Narrow-Bandgap HEMT
InAs HEMTs: the path to THz electronics?
Demonstrated high-speed GaN HEMTs to date

- InAlGaN
  - $t_{\text{Barrier}} \sim 10 \text{ nm}$
  - UND, EDL'12

- AlN/GaN
  - $t_{\text{Barrier}} \sim 4-5 \text{ nm}$
  - HRL, IEDM'11

- InAlN/AlN
  - $t_{\text{Barrier}} \sim 8-10 \text{ nm}$
  - UND, EDL'12

- InAlN/GaN
  - $t_{\text{Barrier}} \sim 8-10 \text{ nm}$
  - UND, EDL'12

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IWN 2012
Sapporo
Outline

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HEMT $f_T$

- $f_T$ measures unity current gain cut off frequency
- For long gate HEMTs, the transit time calculated by $L_g/v_e = C_{gs}/g_m$ is reasonable.
- But, for short gate HEMTs, we must take into account of other effects: fringing capacitance, short channel effects.

\[
\tau = \frac{1}{2\pi f_T} = \frac{C_{gs} + C_{gd}}{g_m} + C_{gd}(R_s + R_d) + \frac{g_{ds}(C_{gs} + C_{gd})(R_s + R_d)}{g_m} = \tau_{int} + \tau_{par}
\]

\[
C_{gs} + C_{gd} = \left(C_{gs,\text{int}} + C_{gd,\text{int}}\right) + \left(C_{gs,\text{ext}} + C_{gd,\text{ext}}\right)
\]

\[
\tau_{int} = \frac{C_{gs,\text{int}} + C_{gd,\text{int}}}{g_m}
\]

\[
= \frac{L_g}{v_e}
\]

\[
\tau_{par} = \frac{g_{ds}(C_{gs} + C_{gd})(R_s + R_d)}{g_m}
\]

Q: when $L_g \rightarrow 0$, $f_T \rightarrow$ THz?

T-gate head $\rightarrow 0$, $f_T \rightarrow$ THz?

Perfect ohmic contacts

Perfect electrostatic control

$\Rightarrow$ no short channel effects

Huili (Grace) Xing (hxing@nd.edu)
Ultimate speed limits in HEMTs: $C_{\text{fringing}}$

To be submitted to TED
Bo Song et al. (UND)
Ultimate speed limits in HEMTs: $C_{\text{fringing}}$

- HRL GaN 20-nm HEMT (IEDM'11)
  - Total delay at $L_g = 20 \rightarrow 0$
  - 0.5 THz

- Teledyne InAs 40-nm HEMT
  - Total delay at $L_g = 40 \rightarrow 0$
  - 2 THz

### Solution: high $g_{m,\text{int}}$!

<table>
<thead>
<tr>
<th>Material</th>
<th>$(C_{gs,\text{par}} + C_{gd,\text{par}}) / g_{m,\text{int}}$</th>
<th>$C_{gd} \times R_{en}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN (HRL)</td>
<td>0.35 ps</td>
<td>0.04 ps</td>
</tr>
<tr>
<td>InGaAs (Teledyne/MIT)</td>
<td>0.09 ps</td>
<td>0.02 ps</td>
</tr>
</tbody>
</table>

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Huili Grace Xing
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Outline

• General trend in high speed HEMTs

• What determines the speed?

• Analysis of example high speed GaN HEMTs
  – Structures with enhanced electrostatic control (SCE ↓)
  – Ohmic contacts (parasitic charging time ↓)
  – Ultrathin surface passivation (gate length extension ↓)
  – Mobility matters

• Summary
**AIN/GaN/AlN HEMTs – analog to SiO$_2$/Si/SiO$_2$ FETs**

Important for high power and high speed

- High $n_s$, mobility and saturation velocity
- Thin barrier, short gate length, large barrier height
- High thermal conductivity and breakdown field

Ultra-scaled WBG semiconductor-based devices (e.g. $L_g < 50$ nm, $C_g > 1.6$ $\mu$F/cm$^2$ – corresponding to ~ 5 nm thick AlN, ~ 1.6 S/mm assuming 1e7 cm/s)

(From Jesus del Alamo)
Quantum Well GaN HEMTs

AlN/GaN/AlN Ultrathin Body

Ballistic Transport

AlN/GaN HEMT

$R_s=R_d=0$

$T=300K$

$V_g-V_T=0.5V$

$g_{m,int} \sim 3 \text{ S/mm}$

$R_s=R_d=0.1 \text{ Ohm*mm}$

$V_D$ (V)

$I_D/W$ (mA/micron)

$I_D$ (A/mm)

$V_{ds} = +3 \sim -4 \text{ V}$

$0.68 \text{ A/mm}$

$0.6$ $0.4$ $0.2$ $0.0$

$V_{ds}$ (V)

$0.0$ $5$ $10$ $15$

D. Jena and Guowang Li et al. (UND) EDL 2012

Huili Grace Xing

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Ohmic contact challenge

- Contact resistance ($R_C$) a function of AlN thickness
- Pre-metallization etch developed for $R_C$ reduction
- $R_C = 0.5$ ohm-mm demonstrated on 5.5 nm AlN barrier
Control regrowth (45 nm n+GaN):

- Sheet charge $\sim 2 \times 10^{15} \text{ cm}^2$
- Mobility $\sim 52 \text{ cm}^2/\text{Vs}$
- $R_{sh} \sim 58 \text{ Ohm/sq}$
- Planar regrowth of high quality
- Lateral regrowth interface needs to be further characterized

Thickness measured by a-step

Jia Guo et al. (UND) PSS(a) 2011

Huili (Grace) Xing (hxing@nd.edu)
Structural quality of regrown contacts

MBE regrowth of S/D successful: high structural quality (gapless, invisible interface). Non-alloyed $R_c$ to regrown InN $< 0.02$ ohm-mm. $R_c$ to 2DEG $\sim 0.05$ ohm-mm. Either PECVD SiO$_2$ or ALD Al$_2$O$_3$ regrowth mask results in no damage to 2DEG.

Status:

Plans:

Improve regrowth repeatability from run to run

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Regrown contacts with n+GaN/2DEG $R_c \sim 0.05$ ohm-mm

1. Regrowth interface resistance $\sim 0.05$ ohm-mm
2. Total $R_c \sim 0.27$ ohm-mm, dominated by metal/n+GaN resistance ($\sim 0.15$ ohm-mm).
3. We have also demonstrated metal/n+InGaN $R_c < 0.02$ ohm-mm.
Regrown contacts for WBG

Reported contact resistance by regrowth

\begin{align*}
R_c (\text{ohm-mm}) &= \frac{h}{e^2} \sqrt{\frac{2\pi}{n_s}} \\
\end{align*}

Wide bandgap semiconductors
- Afford high \( n_s \).
- Trap density may also be low at the regrowth interface
- Difficult alloyed contacts, but easy regrowth contacts

Jia Guo et al. (UND) EDL 2012

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Thin surface passivation

NiCT Cat-CVD SiN (e.g. 2006 EDL)
Imec MOCVD SiN (e.g. 2011 EDL)
Ulm Thermal oxide InAlN (e.g. 2010 EDL)

MIT ALD oxides (e.g. 2011 EDL)
UND - DFP Plasma oxide (e.g. 2011 EDL)

Necessary to keep parasitics low
HEMTs with Dielectric-Free Passivation (DFP)

<table>
<thead>
<tr>
<th></th>
<th>Before DFP</th>
<th>After DFP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{sh}$ ($\Omega$/sq)</td>
<td>$n_s$ (x 10^{13} cm^{-2})</td>
</tr>
<tr>
<td>InAlN_313</td>
<td>290</td>
<td>1.62</td>
</tr>
<tr>
<td>InAlGaN_310</td>
<td>227</td>
<td>1.45</td>
</tr>
</tbody>
</table>

With DFP in the access region only:

- Mobility decreases slightly
- Carrier concentration increases
- Sheet resistance decreases
- $g_m$ increases slightly
- $f_t$ increases from 125 GHz to 210-220 GHz

Huili (Grace) Xing (hxing@nd.edu)  Ronghua Wang et al. (UND) EDL 2011
Dielectric-Free Passivation (DFP): I. InAlN

All delay components dropped.

$L_{g,\text{eff}} > 120$ nm prior to DFP

R. Wang et al. IEEE EDL, vol. 32, no. 8, 2011

Ronghua Wang et al. (UND) EDL 2011

Huili (Grace) Xing (hxing@nd.edu)
Dielectric-Free Passivation (DFP): II. InAlGaN

**Submitted to EDL, 2011**

Little dispersion observed in HEMTs with DFP

Other attributes of DFP:
1. Air stable
2. Little parasitic capacitance
3. Large signal performance yet to be tested.
Dielectric free passivation (DFP) HEMTs: I

**Before DFP** | **After DFP**
--- | ---
$R_{sh}$ ($\Omega$/sq) | $n_s$ ($x 10^{13}$ cm$^{-2}$) | $\mu$ (cm$^2$/V.s) | $R_{sh}$ ($\Omega$/sq) | $n_s$ ($x 10^{13}$ cm$^{-2}$) | $\mu$ (cm$^2$/V.s)
--- | --- | --- | --- | --- | ---
InAlN | 290 | 1.62 | 1330 | 257 | 1.86 | 1300
InAlGaN | 227 | 1.45 | 1900 | 190 | 1.83 | 1790

R. Wang et al., (UND) IEEE EDL 2011

Huili (Grace) Xing (hxing@nd.edu)
After device processing,

- the surface Fermi level is pinned at a deep level, probably related with oxidation and N-vacancies.
- the barrier surface become lossy \(\Rightarrow\) dispersion, high \(L_{g,\text{eff}}\)
- DFP can effectively mitigate these issues.
Quaternary Barrier $\text{In}_{0.13}\text{Al}_{0.83}\text{Ga}_{0.04}\text{N}$ HEMTs with $f_T/f_{\text{max}}$ of 230/300 GHz

Ronghua Wang, Huili Grace Xing et al. University of Notre Dame

Highest mobility (up to 1920 cm$^2$/V·s) and modest 2DEG density in InN-containing barrier HEMTs

Effective velocity of $1.44 \times 10^7$ cm/s, comparable to that of ultra-scaled AlN HEMTs, owing to the high channel mobility

Record high $\sqrt{f_T f_{\text{max}}}$ in InAl(Ga)N HEMTs.

Ronghua Wang, ED7-2, 11:15 am, IWN’12

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• Near ideal Gate profile has been attempted.
• Higher injection velocity thus higher $g_m$ is desired.
• Ways to inject with higher velocity? Hot-electron injection, InGaN channel …

Summary
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GaN research
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TFET research
Sponsored
SRC/NRI

Graphene/2D research
Sponsored
NSF
SRC/NRI

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High conductivity window: 2-5 nm AlN
Best metrics: $n_s = 2 \times 10^{13} \text{ cm}^{-2}$ with $u = 1900 \text{ cm}^2/\text{Vs}$
Y. Cao et al, 2011, JCG

Ongoing work on AlN/GaN/AlN

I. Smorchkova et al, 2000, APL
Y. Cao et al, 2007, APL
Y. Cao et al, 2008, APL

Huili (Grace) Xing (hxing@nd.edu)
UND HEMTs with $f_t > 370$ GHz

Model parameters

- $g_m$ (mS/mm): 864
- $g_{ds}$ (mS/mm): 192
- $C_{gs}$ (fF/mm): 272
- $C_{ed}$ (fF/mm): 30
- $R_s$ (ohm.mm): 0.43
- $R_d$ (ohm.mm): 0.37
- $R_e$ (ohm.mm): 183
- $R_l$ (ohm.mm): 19
- $f_t$ (GHz): 373
- $f_{max}$ (GHz): 28

Huili (Grace) Xing (hxing@nd.edu)
Yuanzheng Yue et al, (UND) EDL 2012