$f_T = 688 \text{ GHz and } f_{\text{max}} = 800 \text{ GHz in }$

$L_g = 40 \text{ nm } \text{In}_{0.7}\text{Ga}_{0.3}\text{As MHEMTs}$

$\text{with } g_{m_{\text{max}}} > 2.7 \text{ mS/\mu m}$

D.-H. Kim, B. Brar and *J. A. del Alamo,

Teledyne Scientific Company, *MIT

IEDM
December-6th, 2011
III-V HEMT: record $f_T$ vs. time

Current record: $f_t=660$ GHz
Leuther IPRM 2011
(Fraunhofer Inst.)

Well balanced devices:
$f_t=644$ GHz, $f_{max}=680$ GHz
at same bias point
Kim EDL 2010
(MIT)

For >20 years, record $f_T$ obtained on InGaAs-channel HEMTs. InGaAs-channel HEMTs offers record balanced $f_T$ and $f_{max}$. 
Strategy to improve $f_T$

• In typical HEMTs:
  – $R_{ON}$: 350 ~ 450 Ω-μm
  – T-Gate: Stem height = ~ 150 nm

Kim, EDL 2008
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Device Technology

- SiO$_2$ assisted T-gate
  → $L_g = 40$ nm
  → Gate-stem > 250 nm

- Two-step recess (InP = 6 nm)

- Pt (3 nm)/Ti/Pt/Au Schottky

- QW: 10 nm In$_{0.7}$Ga$_{0.3}$As
  → $\mu_{n,\text{Hall}} > 10,000$ cm$^2$/V·s

- *In$_{0.52}$Al$_{0.48}$As/In$_{0.7}$Al$_{0.3}$As spacer

- **Dual Si $\delta$-doping

TEM Images

- Mo-based S/D with 2 $\mu$m
- Gate Stem > 250 nm
- $L_g = 40$ nm, $L_{\text{side}} = 100$ nm
- $t_{\text{ins}} = \sim 4$ nm
DC of \( L_g = 40 \text{ nm} \) InGaAs MHEMTs

- Output characteristics -

- Maximum \( I_D > 1 \text{ mA/\mu m} \)
- \( R_{ON} = 280 \text{ \Omega/\mu m} \)

- \( g_m \) characteristics -

- \( g_m > 2 \text{ mS/\mu m} @ V_{DS} = 0.3 \text{ V} \)
- \( g_{m_{\text{max}}} = 2.75 \text{ mS/\mu m} @ V_{DS} = 0.8 \text{ V} \)
Subthreshold characteristics

- $L_g = 40$ nm -

- $V_T = 0.02$ V @ $V_{DS} = 0.5$ V

- $S = 100$ mV/dec., DIBL = 105 mV/V

- $g_{m\_max}$ scalability -

As $L_g \downarrow$, $g_m$ saturates.
\[ f_T \& f_{\text{max}}: L_g = 40 \text{ nm}, \ W_g = 2 \times 20 \ \mu m \]

Calibration: LRRM, De-embedding: OPEN/SHORT

- \( \frac{V_{GS}}{V_{DS}} = 0.4/0.35 \text{ V} \) -

- \( f_T = 602 \text{ GHz} \)

- \( f_T = 688 \text{ GHz} \)

- \( \frac{V_{GS}}{V_{DS}} = 0.4/0.6 \text{ V} \) -

- \( f_T \) already approaches to 600 GHz @ \( V_{DS} = 0.35 \text{ V} \).
- **Record** \( f_T = 688 \text{ GHz} \) @ \( V_{DS} = 0.6 \text{ V} \).
Gummel technique for $f_T$ extraction

In one-pole system:

$$h_{21}(f) = \frac{h_{21}(DC)}{1 + jf \frac{h_{21}(DC)}{f_T}}$$

Then:

$$Im\left[\frac{1}{h_{21}(f)}\right] = \frac{f}{f_T}$$

Slope gives $f_T$

$$\frac{1}{slope} = f_T = 690 \text{ GHz}$$

Gummel, Proc IEEE 1969
Different measurement system for $f_T$ extraction

$1 / \text{slope} = f_T$

$= 690 \text{ GHz}$

$691 \text{ GHz}$

- 8510C @TSC: 1 $\sim$ 50 GHz
- PNA @UCSB: 1 $\sim$ 67 GHz
Small-signal model for $f_T$ extraction

- Excellent agreement, modeled $f_T = 680$ GHz
  $f_{max} = 800$ GHz
**Summary on $f_T$ measurements**

Measurements in two different test benches:

<table>
<thead>
<tr>
<th>$f_T$ [GHz]</th>
<th>$f_T$ from $H_{21}$</th>
<th>$f_T$ from Gummel’s approach</th>
<th>$f_T$ from Small-signal model</th>
<th>$f_{\text{max}}$ [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8510C @TSC</strong></td>
<td>688</td>
<td>690</td>
<td>680</td>
<td>800</td>
</tr>
<tr>
<td><strong>PNA @UCSB</strong></td>
<td>688</td>
<td>691</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All measurements at same bias point: $V_{\text{GS}}=0.4$ V, $V_{\text{DS}}=0.6$ V
Balance in $f_T$ and $f_{\text{max}}$

$300 \leq 600 \leq 700 = f_{\text{avg}} = \sqrt{f_T f_{\text{max}}}$

→ Record $f_T$ FET
→ Best-balanced $f_T$ and $f_{\text{max}}$ transistor

Lai, IEDM08
Kim, IEDM10
Urteaga, DRC11

TSC/MIT (This work)
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Analytical $f_T$ Model

- First-order $f_T$ expression for HEMT:

$$f_T = \frac{1}{2\pi} \frac{g_{mi}}{C_{gs} + C_{gd} + g_{mi}(R_S + R_D)[C_{gd} + (C_{gs} + C_{gd})\frac{g_{oi}}{g_{mi}}]}$$
• Capacitance components [fF/mm]:

\[ C_{gs} = C_{gsi} + C_{gsext} \]

\[ = C_{gsi\_areal} \times L_g + C_{gsext} \]  

\[ C_{gd} = C_{gdi} + C_{gdext} \]

\[ = C_{gdi\_areal} \times L_g + C_{gdext} \]  

[ fF/\mu m^2 ]

[ fF/\mu m^2 ]
Delay time analysis

- Delay time:
\[ \tau = \frac{1}{2\pi f_T} = \tau_t + \tau_{ext} + \tau_{par} \]

- Components of delay time:

Intrinsic delay (transit time)
\[ \tau_t = \frac{C_{g_{si}} + C_{g_{di}}}{g_{mi}} = \frac{(C_{g_{si\_areal}} + C_{g_{di\_areal}}) L_g}{g_{mi}} = \frac{L_g}{v_e} \]

Extrinsic delay
\[ \tau_{ext} = \frac{C_{g_{sext}} + C_{g_{dext}}}{g_{mi}} \]

Parasitic delay
\[ \tau_{par} = (R_S + R_D)[C_{gd} + (C_{gs} + C_{gd}) \frac{g_{oi}}{g_{mi}}] \]
L_g-dependent model parameters

- Linearly proportional to L_g
- C gs_ext > C gd_ext
  \[ |V_{gs}| < |V_{gd}| \]

As L_g ↓,
- g mi saturates at L_g = ~ 60 nm
- g oi continues to increase
  \[ \rightarrow g_{mi}/g_{oi} \downarrow \]
Delay components of $L_g=40 \text{ nm InGaAs MHEMT}$

Delay time from $f_t$: $\sim 231 \text{ fs}$
- Intrinsic delay: $\sim 81 \text{ fs}$
- Extrinsic delay: $\sim 99 \text{ fs}$
- Parasitic delay: $\sim 50 \text{ fs}$
- Unaccounted: $\sim 9 \text{ fs}$

- Least significant, yields $v_e = 5 \times 10^7 \text{ cm/s}$
  - Most significant

![Pie chart showing delay components]

- $\tau_{\text{accounted}}$: $2\%$
- $\tau_{\text{ext}}$: $42\%$
- $\tau_{\text{Transit}}$: $34\%$
- $\tau_{\text{par}}$: $22\%$
Scaling of delay components

$\tau_{\text{transit}}$ and $\tau_{\text{par}}$ do not scale, become dominant for $L_g < \sim 60$ nm.
Options to improve $f_T$

- **Intrinsic delay:**
  \[ \tau_t = \frac{C_{gsi} + C_{gdi}}{g_{mi}} = \frac{L_g}{v_e} \]
  $L_g \downarrow$ (without degrading $g_{mi}$), $v_e \uparrow \rightarrow$ channel engineering

- **Extrinsic delay:**
  \[ \tau_{ext} = \frac{C_{gsext} + C_{gdext}}{g_{mi}} \]
  $C_{gsext}, C_{gdext} \downarrow$, or alternatively $g_{mi} \uparrow$ (harmonious scaling)

- **Parasitic delay:**
  \[ \tau_{par} = (R_S + R_D) \left[ C_{gd} + (C_{gs} + C_{gd}) \frac{g_{oi}}{g_{mi}} \right] \]
  $R_S + R_D \downarrow$, increase electrostatic integrity: $g_{oi}/g_{mi} \downarrow$
VDS = 0.6 V

30% reduction in all the parasitics

Modeled ft

Model Projection

VDS = 0.6 V

f_T = 1 THz is feasible at Lg = ~ 25 nm.
Summary

40-nm $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ MHEMTs on GaAs substrate

- $R_{\text{ON}} = 280 \ \Omega \cdot \mu\text{m}$, $g_{m,\text{max}} > 2.7 \ \text{mS/}\mu\text{m}$ @ $V_{\text{DS}} = 0.8 \ \text{V}$
- $S = 100 \ \text{mV/dec.}$, DIBL = 105 mV/V
- Measured $f_T = 688 \ \text{GHz}$ (Record in any FET)
- $f_T/f_{\text{max}} = 688/800 \ \text{GHz}$ (Best-balanced transistor)

Analytical $f_T$ Model

- Excellent description of $f_T$ behavior in III-V HEMTs
- Guidance to improve $f_T$ beyond 1 THz