6.012 - Microelectronic Devices and Circuits
Lecture 26 - Beyond Si; Beyond 6.012 - Outline

• Announcements
  HKN Evaluation - Do before final so you're still in a good mood.
  Final - Monday, May 19, 9:00 am to Noon, Johnson Ice Rink
  Covering all the course; closed book; 4 problems

• Review - Intrinsic Limits; Sub-threshold Design
  Subthreshold design: choosing $V_{DD}$ for minimum energy per operation
  Intrinsic high frequency limit: $\omega_T$ or $f_T$

• Devices we have known - Where are they now:
  MOSFETs: 45 nm Si, III-V high electron mobility transistors
  BJT: InP based double heterojunction bipolar transistors
  LEDs: white lighting; laser diodes
  Solar cells: multi-junction, multi-material concentrator cells

• Life after 6.012
  Is it possible? ("Where does one head after taking the header?")
Sub-threshold Circuit Design: Minimizing Energy per Operation in CMOS Logic

The energy per operation, $E_{\text{pop}}$, assuming $|V_T| = 0.4 \text{ V}$, $n = 2$, and $A = 50^*$ is plotted below. Note the minimum for $V_{\text{DD}}$ a bit below $V_T^{**}$:

* Plotted for $A = 100$ in Lecture 25.

** The results are quite sensitive in detail to the values of $n$, $A$, and $V_T$. Thanks to Naveen Verma for sub-threshold circuit discussions.
Sub-threshold Circuit Design: Minimizing Energy per Operation, cont.

Reducing $V_{DD}$ reduces the charging/discharging currents rapidly and increases the cycle time significantly, so $E_{\text{min}}$ operation is low speed.

For many remote and monitoring sensor application this is just fine.
High frequency metric, $f_T$: unity gain point of the short-circuit current gain, $\beta_{sc}(j\omega)$

\[
\log |\beta_{sc}|
\]

Low frequency value:
- $\beta_{sc}$ for BJT
- $= \infty$ for MOSFET

Unity gain point, $\omega_t$

Unity gain point, $\omega_t$, $\omega_z$, $\log \omega$

\[
\omega_t \approx \begin{cases} 
\frac{g_m}{C_{gs}} = 3\mu_{Ch} \left( V_{GS} - V_T \right) / 2L^2 = 3\mu_{Ch} \sqrt{V_T} / 2L & \text{MOSFET, no vel. sat.} \\
\frac{g_m}{C_{gs}} = W_s \frac{s_{sat}C_{ox}^*}{W L C_{ax}} = s_{sat} / L & \text{MOSFET, w. vel. sat.} \\
\frac{g_m}{(C_{\pi} + C_{\mu})} \Rightarrow \lim_{I_C \to \infty} \approx 2D_{min,B} / W_B^2 & \text{BJT, large } I_C
\end{cases}
\]

\[
= \frac{1}{\tau_{tr}}
\]
Evolution of SI-MOSFET technology

45 nm Node 2007
32 nm Node 2009
22 nm Node 2011
15 nm Node 2013

30 nm Length (Production ramp up)
20 nm Length (Development)
15 nm Length (Research)
10 nm Length (Research)

Beyond Si (but on Si!)

III-V Device
Prototype (Research)

Epi III-V

C-nanotube
Prototype (Research)

Nanowire
Prototype (Research)

15 nm node: last Si CMOS generation?

Adapted from Robert Chau, Intel

Clif Fonstad, 5/15/08
Foil courtesy of Prof. Tomas Palacios
Lecture 26 - Slide 5
High Hole Mobility in Strained SiGe-Channel MOSFETs

- change the channel material to SiGe or Ge: increased hole mobility
- hole mobility is 10x higher for strained-Ge-channel p-MOSFETs, compared to standard Si p-MOSFET technology (strained Ge channel can be grown on a Si substrate)
Si Strain Engineering Today

- Many 90-nm technologies are employing some kind of process-induced ("local") stress to increase current drive
- Enhancements associated with strain-induced mobility improvement and reduction in series resistance (for SiGe S/D)

Recessed SiGe S/D p-MOSFET

T. Ghani, et al., IEDM 2003 (Intel)

Dual-Stress Liner (Si₃N₄)

H.S. Yang, et al., IEDM 2004 (IBM)

Foil courtesy of Prof. Judy Hoyt
**Pushing \( f_T \) to 1 THz and beyond:** Even more than in IC scaling, other semiconductors are important if the fastest \( f_T \) and highest speed electronics are the goals.
**Bipolar Junction Transistors:** basic operation and modeling...

... how the base-emitter voltage, $v_{BE}$, controls the collector current, $i_C$
**Heterojunction Bipolar Transistors**: higher mobility materials, graded base to create drift field, different $E_g$ to tailor injection

*Work of Prof. Milton Feng and students at University of Illinois*
Heterojunction Bipolar Transistors, cont: $f_T = 685$ GHz @ R.T.

Notice that performance above 50-100 GHz is extrapolated using the theoretical frequency dependence to get $f_T$ and $f_{max}$ values. This is accepted practice because the instrumentation needed does not exist.
**Uniqueness:** thin channel containing pure InAs layer to enhance scalability and electron transport ($\mu_e \sim 13,000\ cm^2/Vs$ at 300K)

628 GHz: the highest $f_T$ ever reported on any FET in any material system!
High frequency metrics above 100 GHz: extrapolation to $f_T$, $f_{\text{max}}$

In Dec 2007 at IEDM, Richard Lia and co-workers from Northrup Grumman reported InGaAs HEMTs with $f_{\text{max}}$ between 1.1 and 1.2 THz that they had used to make amplifiers with 15 dB gain at 340 GHz (21 dB at 285 GHz). This is the first report of $f_T$ or $f_{\text{max}} > 1$ THz.

Transistor $f_T$'s

Data comparing the $f_T$'s of different types of transistors as a function of their breakdown voltages, which is a reflection of power-handling capability.

Figure courtesy of Professor Rajeev Ram
When \( L_g = 90 \, \text{nm} \):

\[ f_T = 163 \, \text{GHz} \]

(demonstrated)

If \( L_g = 20 \, \text{nm} \):

\[ f_T > 500 \, \text{GHz} \]

(in development)

If we make \( L_g = 20 \, \text{nm} \):

\[ \tau_{\text{total}} = \frac{1}{2\pi f_{T,\text{int}}} \sim 120 \, \text{fs} < \tau_{\text{scattering}} \]

Ballistic transport expected: \( v_e \sim 7 \times 10^7 \, \text{cm/s} \Rightarrow f_T \)

\( v_e > 2 \times 10^8 \, \text{cm/s in InN} \)

Ultra-scaled GaN HEMTs
Gallium Nitride for microelectronic applications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Unit</th>
<th>Silicon</th>
<th>Gallium arsenide (AlGaAs/InGaAs)</th>
<th>Indium phosphide (InAlAs/InGaAs)*</th>
<th>Silicon carbide</th>
<th>Gallium nitride (AlGaN/GaN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap</td>
<td>eV</td>
<td>1.1</td>
<td>1.42</td>
<td>1.35</td>
<td>3.26</td>
<td>3.49</td>
</tr>
<tr>
<td>Electron mobility at 300 K</td>
<td>cm²/Vs</td>
<td>1500</td>
<td>8500</td>
<td>5400</td>
<td>700</td>
<td>1000-2000</td>
</tr>
<tr>
<td>Saturated (peak) electron velocity</td>
<td>X10⁷ cm/s</td>
<td>1.0</td>
<td>1.3</td>
<td>1.0</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Critical breakdown field</td>
<td>MV/cm</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Applications of GaN (Today)

- Wireless Base Stations: RF Power Transistors
- Power Conditioning: Mixed Signal GaN/Si Integration
- Automotive Electronics: High Temperature Electronics
- Power Transmission Lines: High Voltage Electronics
- Flame Sensors: UV Detectors
- DVD Information Storage: Blue Laser Diodes
- Solid-State White Lighting: Blue/UV LEDs
- Wireless Broadband Access: High Frequency MMICs
- Pressure Sensors: MEMS
- Heat Sensors: Pyro-Electric Detectors

www.nitronex.com

Nitride-based transistors have many properties that make them very interesting alternative for future microelectronic applications
Mixing technologies and materials on a Si platform: other routes to keeping performance on the Si roadmap; optoelectronic integration

Coaxial coupling: research at MIT

Evanescent vertical coupling: work at UCSB and Intel

Grating coupling: specific to VCSELs

Source: Dirk Taillaert, INTEC, University of Gent
Solar Cells: Illumination shifts diode curve downward
Electrical power is produced in 4th quadrant

The total current: 
\[ i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M) \]
\[ = I_S(e^{qv_{AB}/kT} - 1) - AqM(1 - a) \]

The illumination shifts the ideal diode curve vertically down.
**Solar Cells:** A single band-gap diode misses much of the solar energy spectrum

Photons with energy, $h\nu$, less than $E_g$ are not absorbed, and that part of the spectrum is lost.

Photons with energy, $h\nu$, more than $E_g$ are absorbed but all their energy above $E_g$ is lost to the crystal lattice as the electrons and holes "relax" to the bottom of their the lowest energy states. This limits Si solar cell efficiency to ~ 20%.

The solution: Stack (layer) several solar cells with differing band-gaps so each optimally absorbs the optimum range of photons.
Solar Cells: Multi-junction solar cells InGaP/GaAs/Ge

Multi-junction cells exceed 50% conversion efficiency.
They are costly so are used in sun tracking concentrator systems.
Solar Cells: Multi-junction solar cells InGaP/GaAs/Ge, cont.
Life after 6.012 - "I've taken the header, so…where can I head?"

- **Physics**
  - 6.719: Nano electronics (see also 6.701; similar but "U")
  - 6.728: Applied quantum and statistical physics
  - 6.729: Molecular electronics
  - 6.730: Physics for solid-state applications
  - 6.732: Physics of solids
  - 6.763: Applied superconductivity

- **Devices**
  - 6.720J: Integrated microelectronic devices
  - 6.731: Semiconductor optoelectronics
  - 6.772: Compound semiconductor devices
  - 6.777J: Design and fabrication of MEMS
  - 6.789: Organic optoelectronics

* alternate years
Life after 6.012 - cont.

- **Processing**
  - 6.152J: Microelectronics processing technology \( U(F,S) \)
  - 6.774: Physics of fabrication: front-end proc. \( H \ G(F*) \)
  - 6.776: High speed communications circuits \( H \ G(S*) \)
  - 6.778J: Materials and processes for MEMS \( H \ G(S) \)
  - 6.780J: Control of manufacturing processes \( H \ G(S*) \)
  - 6.781J: Sub-micron and nanometer technology \( H \ G(S) \)

- **Analog circuits**
  - 6.301: Solid-state circuits \( G(F) \)
  - 6.302: Feedback systems \( G(S) \)
  - 6.331: Advanced circuit techniques \( H \ G(F*) \)
  - 6.334: Power electronics \( H \ G(S) \)
  - 6.376: Low power analog VLSI \( H \ G(F) \)
  - 6.775: Design of analog MOS LSI \( H \ G(S) \)

- **Digital circuits**
  - 6.374: Analysis and design of digital ICs \( H \ G(F) \)
  - 6.375: Complex Digital Systems Design \( H \ G(S) \)

* alternate years
• The current state-of-the-art

Very small and blazingly fast

L_{\text{min}} = 1.0 \text{ mm}
→ 0.75 \text{ mm}
→ 0.5 \text{ mm}
→ 0.35 \text{ mm}
→ 0.25 \text{ mm}
→ 0.18 \text{ mm}
→ 0.13 \text{ mm}
→ 0.09 \text{ mm}
→ 0.065 \text{ mm}
→ 0.045 \text{ mm}
→ 0.035 \text{ mm}
→ 0.025 \text{ mm}

(and getting smaller and going faster every day)

The world of semiconductor electronics encompasses far more than Si µP's and RAM, but it all benefits from the technology advances these major Si applications fund.

We're in this region now.

We're in this region now.

• Life after 6.012

Yes, there is life after 6.012.

→ Physics
→ Devices
→ Processing
→ Analog circuits
→ Digital circuits

You now have "6.012 Inside" and many worlds are open to you. Go for it! And good fortune!!
Thank-you to our TA's:
Diana Cheng
Shaya Famenini
Khoa Minh Nguyen

and to our recitations instructors:
Prof. Dimitri Antoniadis
Prof. Tomas Palacios

Good fortune on the final.
Best wishes for the summer, and for your lives and careers beyond 6.012 and MIT.