Future progress of electronics, Moore’s Law

Nanoscale MOSFETs: short-channel effects and contacts

Two types of FETs developed at Rutgers:
  - single-crystal organic FETs (OFETs)
  - transition metal dichalcogenide FETs

Moore’s Law

Gordon Moore

the # of transistors in a dense integrated circuit doubles ~ every two years

Global semiconductor sales annually.

Data: https://en.wikipedia.org/wiki/Transistor_count
The source and drain contacts are heavily doped $n$-type ($N_D \sim 10^{26} m^{-3}$), the channel region is \textit{undoped}.

Intel’s 10 nm technology: 
- fin pitch 34 nm,
- fin height 53 nm.
State-of-the-Art FinFETs (cont’d)

Reduced heat dissipation

Faster operation
Extreme ultraviolet lithography?

Fundamental Limitations?
Desirable FET Characteristics

- Small $V_T$ and $V_{ON} - V_{OFF}$
- Absence of gate leakage
- ON/OFF current ratio $> 10^4$
- Well-defined saturation regime
- Fast switching $\tau \sim R_{tot} C_{eff}$

minimization of the dynamic energy dissipation

The energy dissipation per switching $\propto C_{eff} V_{GS}^2$.

minimization of the static energy dissipation in the OFF regime
Challenges of Further Downscaling

- tunneling of carriers through the thin gate oxide;

- tunneling of carriers from source to drain, and from drain to the body of the FET;

- precise control of the density and location of dopant atoms in the FET channel and source/drain region. The required high channel doping to control short channel effects degrades carrier mobility, lowers the drain current, and increases tunneling across the junction;

- voltage-related effects such as subthreshold swing, built-in voltage and minimum logic voltage swing;

- hot carriers that degrade device reliability;

- etc., etc.
Contact Resistance

Electronics (especially Nano-Electronics) is all about contacts of different materials. In many instances, materials themselves are somewhat secondary to the device performance. For this reason the “molecular electronics” will probably never work.

The accumulation layer resistance $R_{ac}$ represents the resistance in the gate-to-source or gate-to-drain overlap regions where carriers remain confined to the surface. The spreading resistance $R_{sp}$ is associated with carriers spreading from the surface under the overlaps uniformly into the entire depth of the junction. The sheet resistance $R_{sh}$ is related to the uniform transport of carriers through the source or drain region. Finally, the contact resistance $R_{co}$ is present at the interface between the source or drain and the metal contact lines.


What are the fundamental limitations on the contact resistance?
FinFET Dimensions

Samsung’s 14 nm and 16 nm FinFETs

<table>
<thead>
<tr>
<th>Feature</th>
<th>Samsung 14 nm</th>
<th>Intel 14 nm</th>
<th>TSMC 16 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fin pitch (nm)</td>
<td>48</td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td>1/3 fin pitch</td>
<td>16</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>Gate length</td>
<td>~30</td>
<td>~24</td>
<td>~33</td>
</tr>
<tr>
<td>Contacted gate pitch (nm)</td>
<td>78</td>
<td>70</td>
<td>88</td>
</tr>
<tr>
<td>Minimum metal pitch (nm)</td>
<td>67</td>
<td>52</td>
<td>70</td>
</tr>
<tr>
<td>6T SRAM cell area (μm²)</td>
<td>0.08</td>
<td>0.059</td>
<td>0.074</td>
</tr>
</tbody>
</table>

The “pitch” size is not the size of the transistor!
**Problem.** Consider a 2D conductor. By lithography, you make a constriction with a width of \( W = 30 \text{nm} \). What should be the range of electron concentrations in the 2D conductor in order to have only one conduction channel in this constriction?

\[
\frac{\pi}{W} < k_F < \frac{2\pi}{W}
\]
Number of Transverse Modes in FinFETs

*Landauer:* the contact resistance cannot be less than \( \frac{\hbar}{2e^2} \) (# of 1D conduction channels)

Boltzmann statistics:

\[
\lambda_{dB} = \frac{\hbar}{m^* v}
\]

\[v \approx \sqrt{\frac{3k_B T}{m^*}} \sim (m^* = 0.2m_e, T = 300K) \sim 2.5 \times 10^5 m/s\]

\[
\lambda_{dB} = \frac{\hbar}{m^* v} = \frac{\hbar}{\sqrt{2m^* k_B T}} = (m^* = 0.2m_e, T = 300K) \sim 2nm
\]

F-D statistics: \( \lambda_{dB} \sim \lambda_F \) at \( n_{2D} \sim 10^{17} m^{-2} \)

The number of transverse modes in a 30nm-tall FinFET (note that the modes are on the “surface” of the fin):

\[
\frac{60nm}{(\lambda_{dB}/2)^2} \sim 60 \quad \text{- still a multi-mode system}
\]

The contact resistance cannot be less than \( \frac{12.6k\Omega}{60} \sim 200\Omega \) !

(this number is consistent with accepted value \( \sim 20\Omega \cdot \mu m \) for Si MOSFETs)
**Contact Resistance (cont’d)**

This estimate is irrelevant at low $n_{2D}$.

To get this estimate, consider a degenerate 2D Fermi system with the number of conduction channels

$$N_c = \frac{2W}{\lambda_F} = \frac{W k_F}{\pi} \quad k_F = \sqrt{2\pi n_{2D}}$$

$$R_{\text{cont}}^\text{min} = \frac{h}{2e^2} \frac{\pi}{W k_F} \quad R_{\text{cont}}^\text{min} W = \frac{h}{2e^2} \frac{\pi}{k_F} = \frac{h}{e^2} \frac{\sqrt{\pi}}{8n_{2D}}$$

This estimate is irrelevant at low $n_{2D}$.

However, the electrons are non-degenerate at low $n_{2D}$, and $\lambda_F$ must be replaced with the thermal $\lambda_{dB}$, which is smaller than $\lambda_F$ at low $n_{2D}$ and doesn’t depend on $n_{2D}$:

$$\lambda_{dB} = \frac{\hbar}{m^* v} = \frac{\hbar}{\sqrt{2m^* k_B T}} = (m^* = 0.2m_e, T = 300K) \sim 2.5 \text{nm}$$

$$R_{\text{cont}}^\text{min} = \frac{h}{2e^2} \frac{\lambda_{dB}}{2W} \quad R_{\text{cont}}^\text{min} W \approx 0.25 \times 26 k\Omega \times 2.5 \times 10^{-9} m \approx 16 \Omega \cdot \mu m$$

Thus, the contact resistance for Si MOSFETs ($\sim 20 \Omega \cdot \mu m$ at $n_{2D} \sim 10^{17} m^{-2}$) cannot be further reduced (fundamental limitation!).
Energy Dissipation: Dynamic (Classical) Effects

If a transistor switches at a $1 \text{GHz}$ rate, it dissipates $1 \times 10^{-5} \text{W}$. $10^6$ MOSFETs switching at $1 \text{GHz}$ rate dissipate $10\text{W}$! There are $10^9$ MOSFETs in latest Intel chips, but not all of them switch simultaneously.

The time constant for a FinFET with $R_{cont} = 200\Omega$:

$$\tau > C^* R_{cont} = 50 \times 10^{-15}F \cdot 200 = 1\text{ps}$$

$$f = \frac{1}{2\pi\tau} < 10^{11}\text{Hz} = 100\text{GHz}$$

(reported up to $500\text{GHz}$)

Energy dissipation due to capacitor charging/discharging per one switching:

$$\delta E = \frac{1}{2} C^* V_{GS}^2 \approx 50 \times 10^{-15}F \times 0.5^2 \approx 1 \times 10^{-14}\text{W}$$

FinFET gate capacitance.
Reduction of all dimensions requires reduction of the gate dielectric thickness (to reduce parasitic capacitances). However, the gate dielectric cannot be too thin, otherwise the current flows between the gate and the channel due to quantum tunneling \( \Rightarrow \) excessive energy dissipation.

\[
P_T = \sum (P_D, P_{ST})
\]

\( P_D \approx fCV^2 \) - the \textit{dynamic} energy dissipation due to charging/discharging of all capacitors.

\( P_{ST} \) - the \textit{static} energy dissipation due to the leakage currents.

Use of high-\( k \) dielectrics (e.g. \( HfO_2 \)) helps to increase oxide thickness (without decreasing \( n_{2D} \)) and to block tunneling.
Multiple Facets of Tunneling

A. Asenov et al., Journal of Computational Electronics 1, 503 (2002)
Strong \( E_{DS} \) results in degradation of the subthreshold characteristics and, eventually, in elimination of the OFF regime - the gate has no control over the current. Two tunneling effects: the source-drain tunneling (punchthrough effect) and the \( VB – CB \) tunneling. This becomes an issue at channel lengths below 5nm.

\[
I \propto e^{-\frac{\sqrt{2m^*}}{\hbar^2}(U(x) - \varepsilon)}
\]
For nano-FETs the $E$ field in the channel approaches $10^6 V/m$ and the high-field effects become prominent. Because of scattering by optical phonons (large DoS), carrier velocities eventually cease to increase with increasing $V_{DS}$ and saturates at a value of $\sim 10^5 m/s$ (the same order of mag. as $\sqrt{\frac{2kBT}{m^*}}$ for $m^* = 0.2m_e, T = 300K$).

In the long-channel devices, $I_{DS}$ saturation corresponds to the channel pinch-off. In the short-channel devices, $I_{DS}$ saturates when the carrier velocity does.

Time-of-flight $\frac{20nm}{10^5 m/s} = 0.2ps$
- Electric Field Effect
- MOSFETs: band structure, depletion and inversion
- Long-channel MOSFETs

- Two types of FETs developed at Rutgers:
  - single-crystal organic FETs (OFETs)
  - transition metal dichalcogenide FETs
Single-Crystal Organic FETs

conjugated polymers and small-molecule organic semiconductors

weak van der Waals bonding

narrow ($\sim 0.1$ $eV$) bandwidth

low mobility of carriers, 
$\mu \sim 0.1 - 10$ $cm^2/Vs$

Si, Ge, GaAs

strong covalent bonding

large ($\sim 10$ $eV$) bandwidth

high mobility of electrons and holes, 
$\mu \sim 100 - 1000$ $cm^2/Vs$

Wanted: flexibility + reasonably high $\mu$
Hendrik Schön received his Ph.D. from the University of Konstanz in 1997, and was hired as a post-doc by Bell Labs. In 2001 he was listed as an author on an average of one newly published research paper **every eight days**!

2001-2002: eight papers in Science, seven papers in Nature (!!!!)

Findings included realization of ultra-high mobility of charge carriers in organic semiconductors, high-$T_c$ superconductivity in organic compounds, lasing from organic transistors, etc.
Jan Hendrik Schön, 31
Nanotechnologies
Lucent Technologies Bell Labs

Hendrik Schön is reinventing the transistor at the place it was born. He and his Bell Labs coworkers have produced single-molecule transistors whose electrical performance is comparable to that of today’s best silicon devices but which are hundreds of times smaller. Making such molecular transistors, which could lead to ultrafast, ultrasmall computers, has been a goal of researchers for years; Schön’s clever design established Bell Labs as a leader in the race. But Schön is not interested in simply reinventing the transistor. He wants to change the very materials that form microelectronics, replacing inorganic semiconductors with organic molecules. Schön has made an organic high-temperature superconductor, renewing hopes that superconductors could have widespread electronic applications. He also helped devise the first electrically driven organic laser, which could mean cheaper optoelectronic devices. The soft-spoken Schön recalls being “very surprised” by how well his molecular transistors worked. But it won’t be a surprise if Schön helps transform microelectronics.

On a fast track to Nobel prize...
Sept. 2002: REPORT OF THE INVESTIGATION COMMITTEE ON THE POSSIBILITY OF SCIENTIFIC MISCONDUCT IN THE WORK OF HENDRIK SCHÖN AND COAUTHORS
Withdrew journal papers [edit]

On October 31, 2002, Science withdrew eight papers written by Schön.[14]


On December 20, 2002, Physical Review withdrew six papers written by Schönh.[15][16]


On May 2, 2003, Science withdrew another paper written by Schönh.[21]


On March 20, 2003, Advanced Materials withdrew two papers written by Schönh.[22]


On March 5, 2003, Nature withdrew seven papers written by Schönh.[23]

In June 2004 the University of Konstanz issued a press release stating that Schön's doctoral degree had been revoked due to "dishonorable conduct". Schön sued the university, and in 2010 a court ruled in his favor (no evidence that Schön had committed misconduct while at the university). However, the university appealed, and in 2011 the Administrative Court of Baden-Württemberg ruled that the university was within its rights to rescind the degree.
These results have been recognized by Scientific American as one of the major contributions to the development of flexible electronics in 2005.

**Mobility** – up to 20 cm²/Vs, 10 times greater than in the best organic TFTs and α-Si:H MOSFETs, is *independent* of $V_{GS}$ (i.e. $n$) and $V_{DS}$ (i.e. $E$) - in contrast to the polymer and α-Si:H TFTs. Most importantly, this is the intrinsic (not trap-limited) $\mu$.

**On/off ratio** – up to $10^7$

**Sub-threshold slope** – 10 times better than in organic TFTs and α-Si:H MOSFETs.

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Intrinsic (not limited by defects) mobility

FETs Based on *Layered* Inorganic Semiconductors

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**inorganic**

- strong covalent/ionic bonds (high mobility, lots of surface states)

**organics**

- weak van der Waals bonds (low mobility, few surface states)

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Transition Metal Dichalcogenides - $MX_2$, where $M$ stands for a transition metal and $X$ - for Se, S or Te.

Layered semiconducting TMDs – an ideal FET material, “the best of both worlds”:
- covalent/ionic bonding within the layers \(\equiv\) high mobility,
- + weak van der Waals interlayer bonding \(\equiv\) no dangling bonds, low $V_T$

\[ \mu_p (WSe_2, 300K) \sim 500 \ cm^2/\text{Vs} \]
- even better than the RT mobility of electrons in commercial Si MOSFETs

TMD-based FETs

Channel length scaling

\[ L^* = \sqrt{t_{ch} t_{ox} (\varepsilon_{ch}/\varepsilon_{ox})} \]

where \( t_{ch} \) is the semiconductor (channel) thickness, \( t_{ox} \) is the gate dielectric thickness, and \( \varepsilon_{ch} \) and \( \varepsilon_{ox} \) are the semiconductor and gate insulator dielectric constants, respectively.

\[ L^* (\varepsilon_{ch} = 11, \varepsilon_{ox} = 4, t_{ox} \approx t_{ch} \approx 4nm) \approx 8nm \]

Advantages of monolayer FETs: reduction of short-channel effects.
“Monolayer” transistors:

- are capable of RF operation
- cannot compete yet with high-performance III-V and Si RF transistors.

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Midterm II: Low-dim. structures, Landau levels, classical and quantum Hall effect, Law of Mass Action in Semiconductors, MOSFETs.