Nanotechnology in Nanoelectronics Development

Jin-Woo Han and Meyya Meyyappan
NASA Ames Research Center
Moffett Field, California, USA
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Electronic Revolution from Transistors
Evolution of Electronics

Abacus →

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Vacuum Tube →

Vacuum Triode (1906)

Junction Transistor (1948)

Pentium (1995)

Transistor →

Integrated Circuit

Pascal calculator (1670)

Babbage engine (1830)

Eniac (1946) 17,000 Tubes

Tradic (1954) 800 Transistors

IBM (1983)

Roman Analog (1500)

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Back to the Past for Better Future

For low-standby power (~2007)
By MEMS technology

Nano-Electro-Mechanical Switch

For high mobility channel (~2004)
By ALD technology

For low gate delay
By MG technology (~1990’)

Relay
1849
- Babbage Engine
- 8000 relays/5 tons
- Short lifetime

Vacuum Tube
Late 19th Century
- Expensive
- Bulky
- Fragile
- Energy hungry

1st Transistor
1947 (William Shockely)
- Ge material
- Instable

1st IC
1959 (Robert Noyce)
- Si material
- SiO₂ dielectric
- Al gate

Now
- Si substrate
- SiO₂ dielectric
- Poly-Si gate

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Operation Mechanism of Triode Devices

Vacuum Tube
- Cathode
- Grid
- Anode
- Vacuum

Transistor
- Gate
- Source
- Drain
- Silicon

Drain/Anode Current vs. Gate/Grid Voltage

- ON
- OFF

- Switch
- Amplifier
Benefit of Vacuum Channel – Speed

**Vacuum**

Ballistic Transport

\[ c = 3 \times 10^{10} \text{cm/s} \]

**Silicon crystal lattice**

Lattice Scattering

Velocity Saturation

\[ = 5 \times 10^7 \text{cm/s} \]
Benefit of Vacuum – Temperature Immunity

Crystal lattice scattering in semiconductor

Vacuum Channel is immune to high temperature.
→ Military applications
Benefit of Vacuum – Radiation Immunity

Radiation ionization in semiconductor

Vacuum Channel is immune to radiation.
→ Nuclear & space applications
Weakness of Vacuum Device - Bulky

Replacing a bad tubes ENIAC, Integration?
Weakness of Vacuum Device – Energy

[Image showing a hot cathode and quantum well]

- Hot cathode
- Quantum Well
- Electron
- Workfunction
- Energy
Evolution Scenario of Triode Devices

**Vacuum Tube**
- High gain
- High performance
- Premier audio
- Bulky, Fragile
- Expensive
- Short Lifetime
- Power consumption

**MOSFET**
- Cheap
- Integrated Circuit
- Reliable
- Low energy
- Long lifetime
- Variety applications
- Low performance
- Low breakdown

**Nano Vacuum Tube**
- CMOS process
- Cheap !!
- Long lifetime
- High power
- High performance
- Variety applications
- Premier audio

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[Diagram showing a vacuum tube with labels for Cathode, Anode, Back gate, and Vacuum ambient with dimensions <5nm and <50nm.]
What If Nanoscale Vacuum Device?

Conventional vacuum tube

Machining (millimeter scale)
→ Discrete component
→ Operation voltage > 100V
→ Thermionic emission (heater)
→ Short lifetime
→ Glass package (fragile)
→ High vacuum requirement

Nanoscale vacuum tube

Wafer process (nanometer scale)
→ Integrated vacuum circuit
→ Operation voltage <10V
→ Field emission (cold cathode)
→ Long lifetime due to heating free
→ Semiconductor package
→ Relaxed vacuum requirement
Fowler-Nordheim Tunneling

Electron tunneling through a potential barrier, rather than escaping over it.

Thermal excitation

Photo excitation

Tunneling

Surface barrier

Surface barrier bending due to applied field

Off-state

On-state

$V_G < V_{\text{turn-on}}$

$V_G > V_{\text{turn-on}}$
F-N Tunneling Equation

Field Emission Current Density

\[ J = e \int_{-\infty}^{+\infty} N(T,s)D(F,s,\phi)ds \]

\( N(T,S): \) electron density
\( D(F,s,\phi): \) tunneling probability
\( s: \) kinetic energy
\( T: \) temperature
\( F: \) applied field
\( \phi: \) work function

Fowler-Nordheim Equation

\[ J = \frac{e^3 F^2}{8\pi \hbar \phi^2(y)} \exp \left[ -\frac{8\pi(2m)^{1/2} \phi^{3/2}}{3\hbar eF} v(y) \right] \]

\( J: \) emission current density
\( e: \) electron charge
\( m: \) mass of electron
\( \phi: \) work function of the cathode
\( h: \) Planck’s constant
\( F: \) electric field at cathode
\( y: \) function of \( F \) and \( \phi \)
\( t(y), v(y): \) approximated as constants
Simplified F-N Tunneling Equation

\[ I = a V^2 \exp\left(-\frac{b}{V}\right) \quad \text{or} \quad \ln\left(\frac{I}{V^2}\right) = \ln(a) - b\left(\frac{1}{V}\right) \]

Where:

\[ a = \frac{1.56 \times 10^{-6}}{1.1\phi} \alpha \beta^2 \exp\left(\frac{10.4}{\phi^{1/2}}\right) \]

\[ b = 6.44 \times 10^7 \phi^{3/2} / \beta \]

Field Enhancement Factor

\[ \beta = F / V \]

\( F \): electric field at emitter tip

\( V \): voltage between anode and cathode

\[ \beta = \frac{2h}{r} \times \frac{1}{d} \ln\left(\frac{h}{4r}\right) - 2 \]
# Target Specifications

## Target dimension < 50 nm

<table>
<thead>
<tr>
<th>Vacuum range</th>
<th>Pressure (mbar)</th>
<th>Mean free path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient pressure</td>
<td>1013</td>
<td>68nm</td>
</tr>
<tr>
<td>Low vacuum</td>
<td>300-1</td>
<td>0.1-100um</td>
</tr>
<tr>
<td>Medium vacuum</td>
<td>1-10^{-3}</td>
<td>0.1-100mm</td>
</tr>
<tr>
<td>High vacuum</td>
<td>10^{-3}-10^{-7}</td>
<td>10cm-1km</td>
</tr>
<tr>
<td>Ultra high vacuum</td>
<td>10^{-7}-10^{-12}</td>
<td>1km-10^5km</td>
</tr>
<tr>
<td>Extremely high vacuum</td>
<td>&lt;10^{-12}</td>
<td>&gt;10^5km</td>
</tr>
</tbody>
</table>

## Target operation voltage < 5V

<table>
<thead>
<tr>
<th>Ionization Energies (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H</strong> 13.6</td>
</tr>
<tr>
<td><strong>Li</strong> 5.4</td>
</tr>
<tr>
<td><strong>Na</strong> 5.1</td>
</tr>
<tr>
<td><strong>Be</strong> 9.3</td>
</tr>
<tr>
<td><strong>B</strong> 8.3</td>
</tr>
<tr>
<td><strong>Al</strong> 6.0</td>
</tr>
<tr>
<td><strong>C</strong> 11.3</td>
</tr>
<tr>
<td><strong>Si</strong> 8.2</td>
</tr>
<tr>
<td><strong>N</strong> 14.5</td>
</tr>
<tr>
<td><strong>P</strong> 10.5</td>
</tr>
<tr>
<td><strong>O</strong> 13.6</td>
</tr>
<tr>
<td><strong>S</strong> 10.4</td>
</tr>
<tr>
<td><strong>Cl</strong> 13.0</td>
</tr>
<tr>
<td><strong>F</strong> 17.4</td>
</tr>
<tr>
<td><strong>Ne</strong> 21.6</td>
</tr>
<tr>
<td><strong>Ar</strong> 15.8</td>
</tr>
</tbody>
</table>
Summary

• Lesson learned from solid-state device history
• Pivot of historical change in device technology
• Nanoscale vacuum less than mean-free-path air
• Operation voltage less than ionization potential
• Gate-all-around structure
• Vacuum electronics may be back to the future