An Overview of Transistors

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ME 6405
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Outline

• Background
• Basics of Transistor operation
• Transistor Types
• Practical considerations
• Example Applications
• BJT vs. MOSFET for logic level circuits
• Summary
• References
Background

• Invented by Bell Laboratories in 1947.
• Revolutionized the computer industry by eliminating the need for:
  • vacuum tubes
  • mechanical switches
• Utilized in many products that we use every day such as:
  • TVs
  • Cars
  • Radios
  • Microprocessors
Background: Semiconductor Evolution

- **1900's**: Vacuum Tube invented in England, used for AC→DC rectifier.
- **1940's**: Transistor invented at Bell Labs
- **Late 1950s**: First integrated circuit at Texas Instruments.
- **1960's**: Small Scale Integration (SSI), up to 20 gates per chip.
- **Late 1960's**: Medium Scale Integration (MSI), 20-200 gates per chip.
- **1970's**: Large Scale Integration (LSI), 200-5000 gates per chip.
- **1980's**: Very Large Scale Integration (VLSI), over 5000 gates per chip.

Diagram:

1. **Silicon** (insulator)
2. **Doped Silicon** (1 P-N junction)
3. **Transistors** (multiple P-N junctions)
4. **Microprocessors** (thousands of P-N junctions)
What is a transistor?

- 3 terminal electronic semiconductor device
- Uses small input current to get large output current
- A switch or a amplifier
- Main component of microprocessor
Transistor composition

- Base material of transistor is silicon.
- Pure silicon is a insulator which restricts current flow.
- Silicon has 4 valence electrons.
Transistor composition

Two types of dopants or impurities are added to change conductivity:

**P-type** (positive): Add Group III elements, like Boron, with 3 valence electrons to create holes for charge carriers to fill.

**N-type** (negative): Add Group V elements, like Phosphorus, with 5 valence electrons to create free charge carriers.
Depletion Region

P-type (positive charge)

N-type (negative charge)
Forward Biased Example

Supplied Current flows with hole diffusion current

- Holes diffuse
- Electrons diffuse
- Supplied Current
Reverse Biased Example

Supplied Current fights against hole current
Charges can not diffuse unless supplied current flows towards n
Therefore no current flows!

Holes diffuse

Electrons diffuse

Supplied Current
Bipolar Junction Transistors (BJT)

- Three terminals in a BJT
  - Collector (C)
  - Base (B)
  - Emitter (E)

- Two Types of BJT’s
  - NPN: current flows from base to emitter
  - PNP: current flows from emitter to base
2 p-n junctions form Transistor

1. Base-emitter junction (EBJ)
2. Collector-base junction (CBJ)

<table>
<thead>
<tr>
<th>Mode</th>
<th>EBJ</th>
<th>CBJ</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut off</td>
<td>Reverse</td>
<td>Reverse</td>
<td>Open Switch</td>
</tr>
<tr>
<td>Saturation</td>
<td>Forward</td>
<td>Forward</td>
<td>Closed Switch</td>
</tr>
<tr>
<td>Active</td>
<td>Forward</td>
<td>Reverse</td>
<td>Linear Amplifier</td>
</tr>
<tr>
<td>Break Down</td>
<td>Exceeds limits</td>
<td>Overload</td>
<td></td>
</tr>
</tbody>
</table>
BJT Operation as a switch

\[ i_c = \beta i_b \]

Where \( \beta \) = gain of transistor

To reach saturation \( i_b \geq \frac{i_c}{\beta} \)
As base current increases the collector current is amplified.

\[ i_c = \beta i_b, \]

Where \( \beta \) = gain of transistor
BJT Characteristic

BJT is not an ideal switch.
Small amount of current still flows thru $V_{ce}$ junction when $I_b$ is zero.
Types of Transistors

1. Bipolar Junction Transistors (BJTs)
2. Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs)
3. Insulated Gate Bipolar Transistors (IGBTs)
4. Thyristors
5. Gate Turn-off Thyristors (GTOs)
6. Metal-Oxide Semiconductor Controlled Thyristors (MCTs)
BJTs
Bipolar Junction Transistors

N-P-N Type

P-N-P Type

\[ GAIN : \beta = \frac{i_C}{i_B} \]
Darlington Configurations

Need more current?

Overall Gain:

\[ i_C = \prod_{k} \beta_k i_B \]
MOSFETs
Metal Oxide Semiconductor Field Effect Transistors

\[ i_D \]

\[ D_{\text{drain}} \]

\[ V_{DS} \]

\[ V_{GS} \]

\[ V_{DS} = 7V \]

\[ 6V \]

\[ 5V \]

\[ 4V \]

\[ 0V \]
IGBTs
Insulated Gate Bipolar Transistors
Thyristors

A (anode)  K (cathode)  G (gate)

$V_{AK}$

$i_G$  $i_A$

Forward On-state

Breakover w/ gate current

Reverse blocking

Forward blocking

Breakover w/o gate current
Power Transistor Application: 

3φ Rectifier for DC motor control

Utility grid & transmission lines  3φ Controlled Rectifier  DC Motor
3φ Rectifier Waveforms

Uncontrolled (max) RMS voltage

Delayed angle

3 AC Source Voltages, 120° apart

Controlled RMS voltage at delay angle \( \alpha \)

\[
V_{DC}(\alpha=0°) = V_{DC,max} \\
V_{DC}(\alpha=90°) = 0 \\
V_{DC}(\alpha=180°) = -V_{DC,max}
\]

Range of controlled RMS voltage with firing delay angle 0 - 180°
GTOs
Gate Turn-off Thyristors

\[ V_{AK} \]

\[ i_A \]

\[ i_G \]

\[ G \text{ (gate)} \]

\[ K \text{ (cathode)} \]

\[ A \text{ (anode)} \]
MCTs
MOS-controlled thyristors

P-Type

N-Type

\( i_A \)

\( V_{AK} \)

Turn-on

Turn-off
Switching Characteristics

Control Signal

Voltage / Current

Power Dissipation (switching losses)

\[ E_{\text{sw}} = \frac{(V \cdot I \cdot t_{\text{switch}})}{2} \]

\[ E_{\text{on}} = V_{\text{on}} I_{\text{on}} t_{\text{on}} \]
Safe Operating Area

Idealized switching trajectory

Outside actual SOA: need protection here

Ideal SOA, fast switch times

Actual SOA (high freq)

Actual SOA (low freq / DC)

Realistic current & voltage limits while conducting

\[ \log(i_C) \]

\[ i_{C,max} \]

\[ v_{CE,max} \]

\[ \log(v_{CE}) \]
Voltage Spikes

\[
\lim_{\Delta t \to 0} V_s \approx \lim_{\Delta t \to 0} \left( V_D - L \frac{\Delta i}{\Delta t} \right) = \infty
\]
Snubber Circuits

\[ v_s(t) \]

\[ i(t) \]

RCD Snubber circuit
## Semiconductor Limitations

<table>
<thead>
<tr>
<th>Type</th>
<th>Max Frequency</th>
<th>Max Voltage</th>
<th>Max Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFETs</td>
<td>1 MHz</td>
<td>1 kV</td>
<td>200 A</td>
</tr>
<tr>
<td>IGBTs</td>
<td>80 kHz</td>
<td>2 kV</td>
<td>500 A</td>
</tr>
<tr>
<td>MCTs</td>
<td>20 kHz</td>
<td>2 kV</td>
<td>750 A</td>
</tr>
<tr>
<td>BJTs</td>
<td>10 kHz</td>
<td>1 kV</td>
<td>1 kA</td>
</tr>
<tr>
<td>GTOs</td>
<td>1 kHz</td>
<td>3 kV</td>
<td>2 kA</td>
</tr>
<tr>
<td>Thyristors</td>
<td>500 Hz</td>
<td>5 kV</td>
<td>3 kA</td>
</tr>
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</table>

Increasing frequency

Increasing power & size
Semiconductor Limitations
Typical Applications

- Current amplification
  - Audio driver applications
- Switching
  - use microcontroller to turn something on or off
When is a transistor and necessary?

- Desire to control a device with moderate to high current draw
- Microcontroller can put out 5V but typically less than 10 mA
A real world example: the airbag testing center at JCI

- A much more expensive boards (National Instruments $1000-5000+)
- Similar current limitations
System description

- Environmental chamber
- High speed cameras
- High intensity lights
- Thermal couples
- Pressure transducers
Why were transistors necessary?

- To make the system easy to use
- To minimize the heating up of the instrument panel by the high intensity lights
- Second generation airbags require deploying the two stages of the airbag approximately 10ms apart
Airbag Control Black Box
Stage 1 Fire/Trigger Circuits

Connection from Labview (DACOUT0)

Stage 1 Fire Signal (to gray relay box)

Shunt closing to ground

x4 (there are 4 of these transistors: one triggers Labview and the others trigger the 3 cameras)
Analog Output/Trigger Circuitry: DACOUT

Connections from Labview

Stage 1 NPN Transistor 1

Stage 1 NPN Transistor 2 (x4)

Stage 2 NPN Transistor

Stage 1 PNP Transistor
BJT switching circuit design

- How much current do you need?
- How much current can you supply?
BJT current multiplication considerations

- Typically desire $V_{CE}$ to be small
- $i_{BASE}$ must be large enough to cause saturation
Example Circuit

Control signal input

To +V voltage source

R1

R2

R_{LOAD}
# Experimental BJT Results

<table>
<thead>
<tr>
<th>R1 (Ohms)</th>
<th>i&lt;sub&gt;BASE&lt;/sub&gt; (mA)</th>
<th>V&lt;sub&gt;CE&lt;/sub&gt; (V)</th>
<th>V&lt;sub&gt;LOAD&lt;/sub&gt; (V)</th>
<th>i&lt;sub&gt;LOAD&lt;/sub&gt; (mA)</th>
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<tr>
<td>510</td>
<td>8.43</td>
<td>0.12</td>
<td>4.88</td>
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<tr>
<td>1020</td>
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<td>0.16</td>
<td>4.84</td>
<td>96.8</td>
<td>23.0</td>
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<tr>
<td>2200</td>
<td>1.95</td>
<td>0.22</td>
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<td>49.0</td>
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<td>4400</td>
<td>0.98</td>
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<td>4.65</td>
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<tr>
<td>10000</td>
<td>0.43</td>
<td>1.11</td>
<td>3.89</td>
<td>77.8</td>
<td>180.9</td>
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Results from using Motorola 2N2222 transistor with 
R<sub>LOAD</sub>=50Ω and 
R2=∞
## Experimental BJT Results

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<th>R1 (Ohms)</th>
<th>i\textsubscript{BASE} (mA)</th>
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The diagram illustrates the relationship between the collector current (I\textsubscript{C}) and the collector-emitter voltage (V\textsubscript{CE}) for different base currents (I\textsubscript{B}). The avalanche of the C-B junction is also shown.
Example MOSFET Circuit

$V_{DS}$ and $i_{GATE}$ are very small:

$V_{DS} \approx 0.04 \text{ V}$

$i_{GATE} < 0.01 \text{mA} \text{ (R1 is arbitrary)}$
MOSFET Circuit #2: defaults to off position

R1 ≈ 10 * R2

R1

R2

Control signal input

To +V voltage source

R\text{LOAD}

i_{\text{LOAD}}

V_{\text{LOAD}}

i_{\text{GATE}}\text{ is still very small}

V_{\text{DS}} \approx 0.2V
Experimental MOSFET Results

<table>
<thead>
<tr>
<th>R1 (Ohms)</th>
<th>V_{LOAD} (V)</th>
<th>V_{DS} (V)</th>
<th>i_{GATE} (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>4.92</td>
<td>0.04</td>
<td>0.0070</td>
</tr>
<tr>
<td>510</td>
<td>4.91</td>
<td>0.04</td>
<td>0.0004</td>
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V_{DS} and i_{GATE} are very small:

V_{DS} \approx 0.04 \text{ V}

i_{GATE} < 0.01 \text{mA (R1 is arbitrary)}
68HC11 BJT Example
68HC11 BJT Example

Control signal input

R1

R2

To +V voltage source

R_{LOAD}

Control input connection

R1

Collector-load connection

R2
68HC11 MOSFET Example
68HC11 MOSFET Example

Control input connection

Drain-load connection

To +V voltage source

Control signal input

R1

R2

LOAD

D

G

S
68HC11 Example

*Code to turn load off

ORG $1040
LDAA #%00001100
STAA $1009
LDAA #%00000000
STAA $1008
SWI
END

*Code to turn load on

ORG $1060
LDAA #%00001100
STAA $1009
LDAA #%00001100
STAA $1008
SWI
END
MOSFET vs. BJT

- BJT
  - Cheaper (≈$0.06)
  - Can be made to handle more voltage and current

- MOSFET
  - More expensive (≈$0.60)
  - Faster
  - Less power dissipated during use
  - Less current draw from MPU
  - Simpler circuit design
Summary

• A mechanical engineer can use transistors to solve practical problems with limited knowledge of electronics.

• MOSFET’s should be first choice for logic level applications.
References

TEXTS

WEBSITES
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