EEL 5245 POWER ELECTRONICS I
Lecture #4: Chapter 2
Switching Concepts and Semiconductor Overview
Objectives of Lecture

• Switch realizations
• Objective is to focus on terminal characteristics
  – Blocking capability
  – Conduction direction
• Device loss mechanisms
• Qualitative relationships between
  – On state resistance
  – Breakdown Voltage
  – Switching Time
• Survey of some commonly available commercial products
• Comparison of Switching Devices
## Switch Classifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Current Flow</th>
<th>Voltage Blocking</th>
<th>Switch implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Forward</td>
<td>Reverse</td>
<td>Diode</td>
</tr>
<tr>
<td>2</td>
<td>Forward</td>
<td>Forward</td>
<td>Transistor</td>
</tr>
<tr>
<td>3</td>
<td>Forward</td>
<td>Bi-directional</td>
<td>SCR</td>
</tr>
<tr>
<td>4</td>
<td>Bi-directional</td>
<td>Forward</td>
<td>Transistor with flyback Diode</td>
</tr>
<tr>
<td>5</td>
<td>Bi-directional</td>
<td>Bi-directional</td>
<td>Triac</td>
</tr>
</tbody>
</table>
Switch Realizations-Power Diode

- Passive means no active means of control
- Device conducts in forward direction in response to positive forward voltages
- Devices turns off with negative forward voltage

A passive switch
Single-quadrant switch:
- can conduct positive on-state current
- can block negative off-state voltage
- provided that the intended on-state and off-state operating points lie on the diode i-v characteristic, then switch can be realized using a diode
Switch Realizations-BJT/IGBT

- An active switch, controlled by terminal C
- Single-quadrant switch:
  - can conduct positive on-state current
  - can block positive off-state voltage
- provided that the intended on-state and off-state operating points lie on the transistor $i$-$v$ characteristic, then switch can be realized using a BJT or IGBT

- Active-controlled turn on and turn off
- BJT conduct in forward direction in response to control current at C
- IGBT conduct in forward direction in response to control voltage at C (wrt terminal 0)
- Devices turns off when control signal removed
Switch Realizations-MOSFET

- Active-controlled turn on and turn off
- MOSFETs conduct in forward direction in response to control voltage at C (wrt terminal 0)
- Devices turns off when control signal removed

- An active switch, controlled by terminal C
- Normally operated as single-quadrant switch:
- can conduct positive on-state current (can also conduct negative current in some circumstances)
- can block positive off-state voltage
- provided that the intended on-state and off-state operating points lie on the MOSFET i-v characteristic, then switch can be realized using a MOSFET
Switch Realizations-SPST

Buck Converter example

Switch A: transistor
Switch B: diode
Switch Realizations-BJT and Diode

\[ i_L + v_L - \]

\[ V_n \]

\[ i_1 \quad + \quad v_1 \quad - \]

\[ +v_L(t) - \]

\[ L \]

\[ i_{L}(t) \]

\[ v_2 + i_2 \]

\[ switch 1 \quad on \]

\[ switch 1 \quad off \]

\[ switch 2 \quad on \]

\[ switch 2 \quad off \]
Switch Realizations-
Anti-parallel Diode

- Usually an active switch, controlled by terminal C
- Normally operated as two-quadrant switch:
  - Can conduct positive or negative on-state current
  - Can block positive off-state voltage
- Provided that the intended on-state and the off-state operating points lie on the composite $i$-$v$ characteristic, then switch can be realized as shown
Switch Realizations - MOSFET Body Diode

Power MOSFET Characteristics

Power MOSFET, and its integral body diode

Use of external diodes to prevent conduction of body diode
Switch Realizations-
Bidirectional Voltage Blocking-SCR

- Usually an active switch, controlled by terminal C
- Normally operated as two-quadrant switch:
  - Can conduct positive or negative on-state current
  - Can block positive off-state voltage
- Provided that the intended on-state and the off-state operating points lie on the composite \( i-v \) characteristic, then switch can be realized as shown

- Thyristor family also has this \( i-v \) characteristic
  - Silicon Controller Rectifier (SCR)
  - Gate Turn Off Thyristor (GTO)
Power Diode Overview

- **Diode**
  - Minority carrier device
  - Passively controlled device
  - Controlled by external circuitry
    - Forward Bias to turn on
    - Reverse Bias to turn off
  - Relatively low on state conduction losses
  - Turn-on is to charge the depletion capacitor across the pn-junction
  - Turn-off is more complex.
Figure 2.9 Typical diode switching characteristics. (a) Switching circuit with $S$ closed at $t = t_0$. (b) Diode current.
Diode Switching Characteristics

Conventional

Example:

Assume

- Ideal switch
- D has finite $t_{rr}$
- The diode is turned off at $t = t_0$

($S$ is turned on)

$t_{rr} = t_{12} + t_{23}$

Recovery Time

Fig. 2.9

$t_{12}$: due to the minority current changes in the depletion region

$t_{23}$: due to the charges stored in the bulk of the semiconductor material
Diode Switching Characteristics
Fast Recovery Type
Types of Power Diodes

Standard recovery
• Reverse time not specified, intended for 50/60 Hz

Fast recovery and ultra-fast recovery
• Reverse recovery time and recovered charge specified
• Intended for converter applications

Schottky diode
• A majority carrier device
• Essentially no recovered charge
• Model with equilibrium I-V characteristic, in parallel with depletion region capacitance
• Restricted to low voltage (few devices can block 110V or more)
Diode Switching Characteristics
Simulation-Dbreak

- Circuit Diagram
- Graph showing current (I(D1)) vs. time
- Key points:
  - Time: 10.0us, 10.4us, 10.8us
  - Current (I(D1)): 0A, 0.5A, 1.0A
  - Breakdown voltage (V1): 5V
  - Diode (D1)
  - U2
  - Current source (I1)
  - Idc

Diagram shows the switching characteristics of a diode under simulated conditions.
Diode Switching Characteristics
Simulation-1N4002 General Purpose

![Diode Switching Characteristics Diagram](image)

- **I(D1)** values:
  - Time: 10.00us, Current: -80A
  - Time: 10.25us, Current: -40A
  - Time: 10.50us, Current: 0A
  - Time: 10.75us, Current: 40A

- **I(D1)** values (capacitive discharge):
  - Time: 10.700us, Current: -40A
  - Time: 10.800us, Current: 0A
  - Time: 10.624us, Current: -71A

- The diagram shows the switching characteristics of a 1N4002 diode under different time intervals.
Diode Switching Characteristics
Simulation-D1N4148-Fast Recovery

Time
10.0us
10.2us
10.4us
10.6us
10.8us

I(D1)
0A
0.5A
1.0A

1.0A
0.5A
0A

10.0us
10.2us
10.4us
10.6us
10.8us

Time
10.583us
10.600us
10.620us

200mA
0A
-200mA

10.583us
10.600us
10.620us

Time
## Survey of Commercial Power Diodes

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Rated Max. Voltage</th>
<th>Rated Avg. Current</th>
<th>$V_f$(typical)</th>
<th>$t_y$(max)</th>
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<tr>
<td><strong>Fast Recovery Rectifiers</strong></td>
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<td>IN3913</td>
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<td>30A</td>
<td>1.1V</td>
<td>400ns</td>
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<td>400A</td>
<td>2.2V</td>
<td>2μs</td>
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<td><strong>Ultra-fast Recovery Rectifiers</strong></td>
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<td></td>
</tr>
<tr>
<td>MUR815</td>
<td>150V</td>
<td>8A</td>
<td>0.975V</td>
<td>35ns</td>
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<tr>
<td>MUR1560</td>
<td>600V</td>
<td>15A</td>
<td>1.2V</td>
<td>60ns</td>
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<tr>
<td>RHRU100120</td>
<td>1200V</td>
<td>100A</td>
<td>2.6V</td>
<td>60ns</td>
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<td><strong>Schottky Rectifiers</strong></td>
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<td>MBR6030L</td>
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<td>60A</td>
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<td>30A</td>
<td>1.19V</td>
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</tbody>
</table>
General Comments on Power Diodes

• Inverse Relationship between Blocking voltage/Forward current and reverse recovery time/forward voltage drop
• Generally, Diode turn on fast enough to be considered ideal
• Device turn off generally considered ideal but can effect circuit operation
  – Diode turn off means negative current needed to remove stored charge
    • This charge removal is required for device turn off
    • In some instances, this negative current and delay can have an effect on circuit operation
    • Can result in inductive ringing (particularly when fast recovery used in an inductive enviornment)
• When required, series diodes add to blocking capability
Thyristors - Overview

- **Thyristors**
  - “Controlled diode”
  - In off state, can block positive forward polarity voltage and thus not conduct
  - Can be trigger into the on state by providing a short pulse of gate current provided that device is in forward blocking state
  - Once device begins to conduct, it is LATCHED on and gate current can be removed
Thyristors - SCR

- Silicon Controlled Rectifier
  - Once device begins to conduct, it is LATCHED on and gate current can be removed
  - Cannot be turned off by active control (activity at gate)
  - When current reduces and tries to go to negative, device turns off
  - External circuit must reverse bias the SCR to achieve turn off
  - After turn off, gate regains control allowing active turn on once the device is in forward blocking state
Thyristors - SCR Symbol and Terminal Characteristics

(a) Circuit symbol

Anode (A)

Cathode (K)

Forward current carrying (ON)

Forward voltage blocking (OFF)

Reverse voltage blocking

Max reverse voltage

Reverse avalanche region

Reverse blocking region

Forward blocking region

Forward breakover voltage

Latching current

Holding current

$i_g > i_g^2 > i_g^1$

$i_g^5, i_g^4, i_g^3, i_g^2, i_g^1, i_g^0$

$i_A$

$-v_{AK}$
Thyristors - SCR Simulation

![Circuit Diagram]

- **Gate**
- **Load Resistance (R_load)**
- **Supply Voltage (V_{in})**
- **SCR (2N1595)**
- **Gate Voltage (V_{gate})**
- **TD = 2ms**
- **VAMPL = 10V**
- **FREQ = 60Hz**

**Graphs:**
- **Current (I_{load})**
- **V(Gate)**

**Timeline:**
- **0s**
- **5ms**
- **10ms**
- **15ms**
<table>
<thead>
<tr>
<th>Product</th>
<th>Package</th>
<th>Circuit</th>
<th>VDRM</th>
<th>IT(RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST180C04C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>400</td>
<td>660</td>
</tr>
<tr>
<td>ST230C04C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>400</td>
<td>780</td>
</tr>
<tr>
<td>ST280C04C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>400</td>
<td>960</td>
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<tr>
<td>ST280C06C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>600</td>
<td>960</td>
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<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>600</td>
<td>1130</td>
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<td>ST230C08C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>800</td>
<td>780</td>
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<tr>
<td>ST180C08C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>800</td>
<td>660</td>
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<td>ST180C12C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>1200</td>
<td>660</td>
</tr>
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<td>ST230C12C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>1200</td>
<td>780</td>
</tr>
<tr>
<td>ST230C14C0</td>
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<td>1400</td>
<td>780</td>
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<td>ST230C16C0</td>
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<td>DISCRETE</td>
<td>1600</td>
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<td>ST180C16C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
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<td>TO-200AA (A-Puk)</td>
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<td>660</td>
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<td>ST180C20C0</td>
<td>TO-200AA (A-Puk)</td>
<td>DISCRETE</td>
<td>2000</td>
<td>660</td>
</tr>
</tbody>
</table>
General Comments on SCRs

• Used to be device of choice for high power applications
• SCR based Phase Controlled Rectifiers still common in three-phase industrial environment
• A minority carrier device
• SCR has highest blocking voltage and current carrying capabilities of all the semiconductor switches
• Large reverse recovery current
• Long carrier lifetimes allow low on state resistance but mean long turn off times
  – Switching very slow
• Newer designs rarely use SCRs unless very high power required
  – Most newer designs use MOSFETs or IGBTs
Thyristors - Triac

- **Triac**
  - “Back to back” SCR
  - Bidirectional current flow, bidirectional voltage blocking
  - Often used:
    - AC waveform chopping: dimmers, soldering stations, controlled heating elements
Thyristors - GTO

• Gate Turn Off Thyristor
  – Like SCR, once device begins to conduct, it is LATCHED on and gate current can be removed
  – Unlike SCR, GTO can be turned off with a negative gate-cathode voltage (i.e. active turn off control)
  – This negative gate current pulse can be short duration but must be large magnitude (\(\sim 0.33 \, i_A\))
  – A controlled switch like BJT/MOSFET but not suitable for inductive turn off
  – Slow switching time (\(fs\) max \(\sim 10\) kHz)
BJT - Overview

- Bipolar Junction Transistor
  - A minority carrier device
  - Current controlled
    - Requires a continuous base current to remain in on (conducting) state
    - Significant delays during turn off transition
    - On-state resistance has negative temperature characteristic so device paralleling not always straightforward
BJT Symbol and i-v Characteristics

Ideal switch characteristics

Cut-OFF (OFF-state)

Saturation (ON-state)

Active region

Increasing base current

ON-state

OFF-state
General Comments on BJT

• BJT has been replaced by MOSFET in low-voltage (<500V) applications
• BJT is being replaced by IGBT in applications at voltages above 500V
• Design trade off between on-state losses and switching times
• A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching, but lower on-resistance at high voltages
MOSFET Overview

- Metal-Oxide-Semiconductor Field Effect Transistor
  - A majority carrier device
  - Voltage controlled
    - Require continuous application of Gate to Source voltage to maintain on-state (conduction)
    - No gate current flows except during transitions to charge and discharge gate capacitance
    - Very short switching times
    - On-state resistance has positive temperature coefficient so device paralleling simple
MOSFET Symbol and i-v Characteristics

Gate(G) + \( V_{GS} \) - 

Source(S) 

Drain(D) 

\( i_D \) 

\( V_{GD} \) + 

\( V_{DS} \) - 

Ideal switch characteristics

ON-state 

OFF-state 

\( v_{DS} \) 

\( i_D \) 

\( v_{GS} \) 

Increasing 

Slope = \( \frac{1}{r_o} \)
## Survey of Commercially Available MOSFETs

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Rated Max. Voltage</th>
<th>Rated Avg. Current</th>
<th>Ron</th>
<th>Qg(typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFZ48</td>
<td>60V</td>
<td>50A</td>
<td>0.018Ω</td>
<td>110nC</td>
</tr>
<tr>
<td>IRF510</td>
<td>100V</td>
<td>5.6A</td>
<td>0.54Ω</td>
<td>8.3nC</td>
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<tr>
<td>IRF540</td>
<td>100V</td>
<td>28A</td>
<td>0.077Ω</td>
<td>72nC</td>
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<tr>
<td>APT10M25BNR</td>
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<td>75A</td>
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<td>400V</td>
<td>10A</td>
<td>0.55Ω</td>
<td>63nC</td>
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<tr>
<td>MTM15N40E</td>
<td>400V</td>
<td>15A</td>
<td>0.3Ω</td>
<td>110nC</td>
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<tr>
<td>APT5025BN</td>
<td>500V</td>
<td>23A</td>
<td>0.25Ω</td>
<td>83nC</td>
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<tr>
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<td>1000V</td>
<td>11A</td>
<td>1.0Ω</td>
<td>150nC</td>
</tr>
</tbody>
</table>
General Comments on MOSFET

- Majority carrier device: fast switching times
- Typical switching frequencies: tens and hundreds of kHz
- On state losses rise more rapidly with blocking voltage than in a comparable BJT
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low power levels (100W)
- Generally, on state resistance most significant factor when selecting device
IGBT Overview

- Insulated Gate Bipolar Transistor
  - Combination of BJT and MOSFET
    - Like MOSFET, has high impedance gate which requires small charge to turn on
    - Like BJT, small on state resistance even for devices with large blocking voltage ratings
  - Can be designed to block negative voltages like thyristors
IGBT Symbol and i-v Characteristics

**Symbol**

- Collector
- Gate
- Emitter

**Equivalent Circuit**

- G
- i1
- i2
- E

**Characteristics**

- ON-state
- OFF-state

**Ideal Switch Characteristics**

- $\text{Slope} = \frac{1}{r_o}$

**Graph**

- $i_D$ vs. $v_{DS}$
- $v_{GS}$ vs. $v_{DS}$

Increasing
# Survey of Commercially Available IGBTs

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Rated Max. Voltage</th>
<th>Rated Avg. Current</th>
<th>$V_f$ (typical)</th>
<th>$t_r$ (typical)</th>
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</thead>
<tbody>
<tr>
<td><strong>Single-Chip Devices</strong></td>
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<tr>
<td>HGTG32N60E2</td>
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<td>32A</td>
<td>2.4V</td>
<td>0.62μs</td>
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<td>1200V</td>
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<td>3.2V</td>
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<td><strong>Multiple-Chip Power Modules</strong></td>
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<td>CM400HA-12E</td>
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<td>400A</td>
<td>2.7V</td>
<td>0.3μs</td>
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<td>CM300HA-24E</td>
<td>1200V</td>
<td>300A</td>
<td>2.7V</td>
<td>0.3μs</td>
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</table>
General Comments on IGBT

- Faster than comparable BJT, Slower than a comparable MOSFET
- On state losses smaller than MOSFET and are comparable to BJT
- Turn on time can be effected by rate of change of $v_{gs}$
- Most new designs in the industrial power electronics market use IGBTs for medium power applications
Device Comparison

\( f_s \) vs. Power

As frequency increases, power decreases

As frequency increases, power decreases

Power (kW)

Frequency (Hz)
Future Trends in Device Progress

Power Devices:

- Technological Improvement:
  - Speed of switching
  - Power Rating

Diagram:

- Power vs. Frequency
- Ideal Progress