Pulsed Power Engineering: Switching Devices

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Ideal Switch

- $V = \infty$
- $I = \infty$
- Closing/opening time = 0
- $L = C = R = 0$
- Simple to control
- No delay or jitter
- Lasts forever
- Never fails
Switches

- Electromechanical
- Vacuum
- Gas
  - Spark gap
  - Thyatron
  - Ignitron
  - Plasma Opening
- Solid state
  - Diodes
    - Diode opening switch
  - Thyrsitors
    - Electrically triggered
    - Optically triggered
    - dV/dt triggered
  - Transistors
    - IGBT
    - MOSFET
Switches

- Electromechanical
  - Open frame relay
    - To very high voltages, set by size of device
    - Commercial devices to ~0.5 MV, ~50 kA
      - Ross Engineering Corp.
    - Closing time ~10’s of ms typical
      - Large jitter, ~ms typical
    - Closure usually completed by arcing
      - Poor opening switch
    - Commonly used as engineered ground
  - Vacuum relay
    - Models that can open under load are available
    - Commercial devices
      - Maximum voltage ~0.1 MV / current ~0.1 kA
      - Tyco-kilovac
      - Gigavac
Gas/Vacuum Switch Performance vs. Pressure

- Pressurized Spark Gaps: 
  - Sub-ns fall
- Krytron: 
  - 2 ns fall
- Thyratrons: 
  - 20 ns fall
- Ignitrons: 
  - 50 - 100 ns
- LMPV: 
  - 500 ns fall
- Vacuum Gaps: 
  - 100 - 500 ns fall
- Vacuum Tubes: 
  - Sub-ns fall

Vacuum Tube (Switch Tube)

- Space-charge limited current flow
  - \( V_{\text{ON}} \propto I^{2/3} \)
  - High power tubes have high dissipation
- Similar opening/closing characteristics
- Maximum voltage \(~0.15\) MV
- Maximum current \(~0.5\) kA, more typically \(< 100\) A
- HV grid drive
- Decreasing availability
- High Cost
Spark Gaps

- Closing switch
- Generally inexpensive - in simplest form: two electrodes with a gap
- Can operated from vacuum to high pressure (both sides of Paschen Curve)
- Can use almost any gas or gas mixture as a dielectric. (air, dry nitrogen, SF$_6$, CO$_2$, etc.) There are also liquid spark gaps (shock wave).
- Wide operating range
  - kV to MV
  - Amps to MA
- Time jitter ranges from $ns$ for triggered gaps to 100’s of $\mu$s (or longer) for self-breaking overvoltage gaps
  - Low jitter
    - Trigger voltage ~ switch voltage
    - High dV/dt trigger
Spark Gaps (cont.)

- Repetition rates - usually single shot but low kHz possible for burst mode
- \( L_{\text{arc}} \sim 15 \text{ nH/cm} \)
  - Rail-gap switch with multiple arc channels → lower inductance
- Lifetime limited
  - Erosion of electrodes (tungsten, copper, stainless steel, steel, brass, molybdenum, special alloys)
  - Debris across insulating surfaces
- Performance affected by temperature, pressure, electrode materials, surface condition of electrode, condition of insulators, operating conditions, etc.
- Devices are commercially available
# Commercial Spark Gap

## Triggered Spark Gap Ratings

<table>
<thead>
<tr>
<th>PerkinElmer Model No.</th>
<th>O-A Range, kV Min/Max (1,10)</th>
<th>SBV, kV</th>
<th>V_T Min Trig (kV Open Circuit)</th>
<th>Trigger Mode</th>
<th>Recommended PerkinElmer Transformer</th>
<th>Typical Delay Time* when operated in mode A (Nanoseconds)</th>
<th>Simultaneous Ratings Crowbar Service, Typical Life: 5000-20,000 Shots</th>
<th>Simultaneous Ratings Repetitive Switching, Typical Life: 1-5 Million Shots</th>
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<td>Peak currents up to 100 kA and charge transfer up to 5 coulombs are obtainable at reduced life (100-1000 shots).</td>
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### Features
- Fast switching operation
- High voltage holdoff
- Ceramic-metal construction
- No warm up period
- High current capability
- Long life
Thyratron: Low-Pressure Gas Switch

- High voltage: kV to ~ 100kV (normally ~ 30-40kV per internal gap)
- Maximum peak current 20-40 kA
- Closing switch ONLY, forward drop ~100 V
- Gas filled: 0.1-5.0 torr hydrogen or deuterium and hot cathode
  • Operate on the low pressure side of Paschen minimum
- High repetition rate: limited by recovery time after conduction of 30-100µs
- Low jitter (<1ns) with appropriate trigger
- Limited di/dt (emission limitations of hot cathode)
Thyratrons (cont.)

- Turn-on time (anode voltage fall time)
  - 20 ns typical
  - <5 ns for special tubes

- Lifetime usually limited by cathode depletion (1-2 years of continuously on operation) or loss of ability to control gas pressure (causes misfires, reduction of standoff voltage capability)

- Limited pulse duration

- Low average current rating

- Significant voltage reversal (>4 kV) during recovery can damage tube
Thyratrons

- Envelope: glass or ceramic (high power tubes)
- Anode materials: molybdenum, copper
- Grid materials: copper, molybdenum
- Cathode material: BaO, SrO, CaO coating on tungsten or barium aluminate impregnated tungsten
- Reservoir (maintains gas pressure over life of tube) is a hydride material such as titanium, tantalum, etc.
Thyratron Operation

- Three phases of thyratron operation
  - Triggering & commutation (closure)
  - Steady-state conduction
  - Recovery (opening)
- Positive polarity pulse applied to grid
- Cathode electrons flowing to grid ionize gas in K-grid gap
Thyratron Operation

- Plasma fills K-grid gap, grid-cathode breakdown
- Plasma electrons flow through grid and are accelerated to anode
- Electrons flowing to anode ionize gas in A-grid gap
Thyratron Operation (cont.)

- Dense plasma forms between grid and anode, creating a low resistance electrical connection
- Grid is pulsed to anodic potential
  • Trigger circuit must be protected from transient
- Plasma front propagates into grid-cathode gap
Thyratron Operation (cont.)

- Plasma connects to cathode, completing switch closure
- Begin steady-state conduction
- Once source energy is dissipated,
  - Current stops flowing through switch
  - Plasma cools
  - Ions/electrons recombine (~ms)
  - Switch is no longer conductive
- Recovery complete
Thyratron Trigger Circuit

Figure 3. Grid Circuit

Figure 4. Typical Grid Spike Suppression Circuits

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# Commercial Thyratron Examples

<table>
<thead>
<tr>
<th>Type</th>
<th>Peak Anode Voltage (kV)</th>
<th>Peak Anode Current (a)</th>
<th>Average Anode Current (A)</th>
<th>RMS Anode Current (A)</th>
<th>Plate Dissipation Factor (Pb x 10^3)</th>
<th>Cathode Heater V/A</th>
<th>Reservoir Heater V/A</th>
<th>Peak Forward Grid Voltage (kV)</th>
<th>Impedance of Grid Circuits (Max)</th>
<th>EIA Type &amp; Comments</th>
<th>Notes</th>
<th>Seated Height x Tube Width (inches)</th>
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<td>2.7</td>
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<td>1200</td>
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Thyratrons - Definition of Terms

TERMS USED TO CHARACTERIZE INDIVIDUAL PULSES

Peak Anode Voltage (epy): maximum positive anode voltage, with respect to the cathode.
Peak Inverse Anode Voltage (epx): maximum negative anode voltage, with respect to the cathode.
Peak Forward Anode Current (ib): maximum instantaneous positive anode current.
Peak Inverse Current (ibx): maximum instantaneous negative anode current.
Pulse Width (tp): current pulse full-width at half-maximum.
Pulse Repetition Rate (prr): average number of pulses/second.
Current Rise Time (tr): time for the forward current to rise from 10% to 90% of its peak value.
Anode Fall Time: time for the forward anode voltage to collapse from 90% to 10% of its maximum value.
Anode Delay Time (tad): time interval between triggering and commutation (commutation is defined below). The precise reference points for this interval vary with the application.
Anode Delay Time Drift (Δtad): gradual decrease in anode delay time that occurs as the thyratron warms up.
Jitter (tj): pulse-to-pulse variation in anode delay time.
Thyratrons - Definition of Terms

TIME AVERAGED QUANTITIES

DC Average Current (Ib): forward current averaged over one second.
RMS Average Current (Ip): root-mean-square current averaged over one second.
Plate Breakdown Factor (Pb): numerical factor proportional to the power dissipated at the anode, averaged over one second. Pb = epy x ib x prr.

STRUCTURAL PARTS OF THE THYRATRON

Auxiliary Grid: grid placed between the control grid and cathode in some thyratrons. A small DC current (or a larger pulsed current) applied between Auxiliary Grid and cathode can be used to control the anode delay time. (Anode delay time is defined above). Thyratrons with auxiliary grids are called Tetrode Thyratrons.
Reservoir: maintains the gas pressure in the tube at a level which depends on the reservoir heater voltage.

GENERAL TERMINOLOGY

Static (Self) Breakdown Voltage (SBV): applied voltage at which a thyratron will break down spontaneously, without being triggered.
Commutation: transition from trigger breakdown to full closure of the thyratron.
Recovery Time: time which must elapse after decay of the circuit current before anode voltage can be reapplied to the thyratron without causing self-breakdown. The maximum possible pulse repetition rate is the inverse of the recovery time.
Grid Bias: negative DC voltage which may be applied to the control grid to speed up recovery.
Ignitron

- Mercury filled switch
- Low pressure device: ~0.001 Torr @ 70º F
- High voltage, high current (kA to 100’s kA)
- Very simple device with many operational issues
  - Mounting (must be mounted vertically)
  - Vibration
  - Anode needs to be heated to keep mercury evaporated off
  - Ringing discharge affects lifetime
  - Has rep-rate limits and requires temperature control
- Operating voltage affected by tube pressure and electrode condition
- Current affected by plasma instabilities
- Jitter and turn-on delays issues

Anode material - molybdenum or graphite
Grids - graphite
Igniter - boron carbide
Plasma Opening Switch (POS)

- Initially, a high density plasma forms a low-conductivity channel (switch closed)
- Plasma conductivity is rapidly decreased, ~10 to 100 ns, opening the switch
- Opening mechanisms
  • Plasma erosion switch: plasma source is turned off, conductive particles are swept out by applied fields (plasma erodes), switch opens
  • Applied fields inhibit the flow of conductive particles (electrons) across switch
- Used primarily in effects simulators
- Voltage: >MV, Current: >MA
- Low jitter (ns)
- Switching speed varies from very fast (ns) to slow (100’s µs)
- Limited in peak power capability. High voltage requires series stacks and high peak current requires parallel arrays.
- Usually high average current capability (compared with thyratrons)
- Both closing devices and opening devices available
- Most can operate at high repetition rate
- Low cost in terms of average power rating
- Long lifetime if operated within peak ratings, but usually catastrophic failure when voltage ratings exceeded
Diode Opening Switch

- Solid state equivalent to POS
- Forward bias junction, switch closed
- Reverse bias switch, carriers swept from junction, when carriers are depleted, switch is open
- Any diode will work, but, ideally junction carrier density remains constant until all remaining carriers are swept out of gap
  • Dependent on doping profile across junction
  • Carrier crossing time (500 V, Si junction):
    ~0.5 ns
    - Electrons ~3X faster than holes
  • Drift Step Recovery Diode/Device (DSRD), approximates ideal

DSRD: (a) design and “plasma” distribution, dc bias, pulse bias, (b) “plasma” distribution at start of reverse bias
Grekhov, et.al., 2004 PMC
- Closing switch
- Solid state analogy to thyratron
- Maximum voltage:
  • Silicon: ~6.5 kV, limited by defects
  • Silicon carbide: ~20 kV, not commercially available
- Maximum current
  • RMS: ~5 kA
  • Pulsed: 10 to 100X (or more) greater (pulse length dependent)
- Low forward drop, <3 V (typical), low loss
- Simple to trigger
- All types of thyristors can be triggered by applying high dV/dt
- Generally, slow switch for pulsed power applications
Thyristors (cont.)

- Silicon Controlled Rectifier (SCR)
  - Simple, powerful, relatively inexpensive
  - Switching speed
    - Phase Control: intended for 50/60 Hz operation
    - Inverter grade: ~10 μs (typical)
  - Triggering
    - Low energy trigger switches device, will remain on as long as
      \[ I_{\text{conducted}} > I_{\text{threshold}} \]
    - Electrical
      - ~3 V
      - <mA small devices, <A largest devices
    - Optical
Thyristors (cont.)

- Closing/opening devices
  - Gate turn-off thyristor (GTO)
  - Integrated gate commutated thyristor (IGCT)
  - Limited use in pulsed power
    - Interrupting current $<<$ closing current
    - $dl/dt$ limitations
Fast Thyristors

- Higher energy trigger → faster carrier injection and faster turn on
- Reverse blocking diode thyristor (RBDT) (Break over diode, BOD)
  - Triggered by high $dV/dt \sim 10^{12} \ \text{V/s}$
  - Turn on time $< \mu s$
- Photon initiated (optical) thyristor
  - Triggered by intense optical pulse that liberates carriers throughout junction
  - Turn on time $<< \mu s$

Fig. 2. End view drawings of optical thyristor
McDonald, IPMC2006

Fig. 3. Photograph of PIMM optical thyristor

Fig. 4. Photograph of Two-Switch Electrode assembly.
Bulk Semiconductor Switches

- Bulk semiconductor materials; Si, GaAs, diamond-like carbon, can be used as a switch
- Carriers can be produced through the bulk of the material by depositing energy; photons (laser) or electron beam, to trigger the switch
- If trigger induces carrier avalanching, then can only operate as a closing switch, if not avalanching, then removal of trigger source will cause switch to open
- Not commercially available at present, but subject to ongoing investigation and development
- Potential for very high power solid state switch
Power Transistors

- Hard switch: closes and opens
- Bi-polar devices
  - Minority carrier devices
  - Conduction characterized by \( V_{CE} < 3 \text{ V (typical)} \)
  - NPN/PNP power transistors generally replaced by Insulated Gate Bipolar Transistors (IGBT)
    - Lower drive power
    - Available at higher voltage, current and power
- Field effect transistors
  - Majority carrier devices
  - Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
  - Conduction characterized by \( R_{DS-ON} \sim \Omega \)
IGBT

- Wide-spread use in power electronics → availability of high power modules
  - Voltages: 600 V, 1.2 kV, 1.7 kV, 3.3 kV, 4.5 kV, 6.5 kV
  - Currents: to ~kA average
    - Pulsed current, ~μs pulse duration, to ~10X greater
  - Configurations: single die, single switch-parallel die, chopper, bridge
IGBT Switching Characteristics

- Turn on
  - Ultra-fast (single die): as fast as ~50 ns
  - Power modules: ~0.5 μs (with sophisticated triggering)

- Turn off
  - Initial turn off is fast, ~turn on time
  - Tail: following initial turn off, a low current tail (~ A to 10’s of A) due to carrier recombination may persist for μs to 10’s of μs, full voltage across device → high dissipation

- Switching losses typically dominate device dissipation, small devices may operate to ~MHz, power modules typically operate at 10 to 50 kHz or less
IGBT Switching

- Insulated gate structure, capacitive load to trigger circuit
- Threshold (to turn on) ~5 V
- Maximum gate voltage ~30 V (higher voltage may punch through oxide)
- Typically bias gate to 10 – 15 V
  - Saturation current ($V_{CE}$ increases dramatically for $I > I_{SAT}$) $\propto V_{GE}$
  - Low $I_{SAT}$ limits fault current, protects device/system
  - $V_{CE}$ only weakly dependent on $V_{GE}$
- Optimum (fastest, lowest loss) triggering
  - 2-stage gate drive:
    - HV (50 to >100 V): initiates current flow to gate (parasitic L)
    - 2nd ary drive holds gate at 10 – 15 V
  - Bi-polar, fast turn off requires inverse pulse
  - Does not significantly reduce tail
  - Turn off slowly from fault condition, may loose control if L $dl/dt$ is too high
IGBT (cont.)

- Easily damaged by reverse voltage (>100 V)
  - Include anti-parallel diode in circuit
  - Integrated into modules

- “Traction motor” modules
  - “Single wide”: 12 chips: 8 IGBT/4 diode
  - Internal interconnections may promote oscillations between chips under fault conditions

- Exercise caution when connecting in parallel
  - Often have negative coefficient of $V_{CE}$ with temperature
  - Device carrying excess current than neighbors will get hotter, forward voltage will drop, and it will carry even more current
IGBT Reliability Considerations

- Collector-Emitter voltage, $V_{CE}$
  - Exceeding, even momentarily, will damage/destroy device
  - Usually limit nominal off-state voltage to 67% of $V_{CE}$

- Cosmic ray withstand voltage
  - Statistical probability dies will be struck by cosmic ray, if $V >$ withstand voltage, die will fail. Limits “normal” voltage across device.
  - Not always on data sheet, ask manufacturer, typically ~60% of $V_{CE}$
IGBT Reliability Considerations (cont.)

- Partial discharge rating/insulation capability
  - International standard sets minimum voltage cycle that results in 10 pC internal discharge for package rating (e.g. 3.3 kV device). Exceeding voltage will shorten device life.

- Thermal
  - Exceeding maximum die temperature will result in rapid failure of device
  - Thermal cycling
    - Die temperature variations (as device cycles on/off) fatigue bond wires
    - Manufacturer can provide data to determine impact on life for a calculated cycle
CM200HG-130H

Single IGBTMOD™
HVIGBT Module
200 Amperes/6500 Volts

Description:
Powerex IGBTMOD™ Modules are designed for use in switching applications. Each module consists of one IGBT Transistor in a reverse-connected super-fast recovery free-wheel diode. All components and interconnects are isolated from the heat sinking baseplate, offering simplified system assembly and thermal management.

Features:
- Low Drive Power
- Low VCE(sat)
- Super-Fast Recovery
## IGBT Data Sheet (cont.)

**Powerex, Inc., 200 E. Hillis Street, Youngwood, Pennsylvania 15697-1800 (724) 925-7272**

**CM200HG-130H**

*Single IGBTMOD™ HVIGBT Module*

200 Amperes/6500 Volts

### Absolute Maximum Ratings, $T_J = 25 ^\circ C$ unless otherwise specified

<table>
<thead>
<tr>
<th>Ratings</th>
<th>Symbol</th>
<th>CM200HG-130H</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junction Temperature</td>
<td>$T_J$</td>
<td>-40 to 150</td>
<td>°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>$T_{ST}$</td>
<td>-40 to 125</td>
<td>°C</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>$T_{OOP}$</td>
<td>-40 to 125</td>
<td>°C</td>
</tr>
<tr>
<td>Collector-Emitter Voltage ($V_{GE} = 0V, T_J = -40^\circ C$)</td>
<td>$V_{CES}$</td>
<td>5800</td>
<td>Volts</td>
</tr>
<tr>
<td>Collector-Emitter Voltage ($V_{GE} = 0V, T_J = +25^\circ C$)</td>
<td>$V_{CES}$</td>
<td>6300</td>
<td>Volts</td>
</tr>
<tr>
<td>Collector-Emitter Voltage ($V_{GE} = 0V, T_J = +125^\circ C$)</td>
<td>$V_{CES}$</td>
<td>6500</td>
<td>Volts</td>
</tr>
<tr>
<td>Gate-Emitter Voltage ($V_{GE} = 0V$)</td>
<td>$V_{GES}$</td>
<td>±20</td>
<td>Volts</td>
</tr>
<tr>
<td>Collector Current (DC, $T_J = 80^\circ C$)</td>
<td>$I_C$</td>
<td>200</td>
<td>Amperes</td>
</tr>
<tr>
<td>Peak Collector Current (Pulse)</td>
<td>$I_{CM}$</td>
<td>400&quot;</td>
<td>Amperes</td>
</tr>
<tr>
<td>Emitter Current&quot; (T_C = 25°C)</td>
<td>$I_E$</td>
<td>200</td>
<td>Amperes</td>
</tr>
<tr>
<td>Emitter Surge Current&quot; (Pulse)</td>
<td>$I_{EM}$</td>
<td>400&quot;</td>
<td>Amperes</td>
</tr>
<tr>
<td>Maximum Collector Dissipation (T_C = 25°C, IGBT Part, $T_J[\text{max}] = 125^\circ C$)</td>
<td>$P_C$</td>
<td>2900</td>
<td>Watts</td>
</tr>
<tr>
<td>Partial Discharge ($V_1 = 6900 \text{ Vrms, } V_2 = 5100 \text{ Vrms, 60 Hz (Acc. to IEC 1287)}$)</td>
<td>$Q_{pd}$</td>
<td>10</td>
<td>pC</td>
</tr>
<tr>
<td>Max. Mounting Torque M8 Main Terminal Screws</td>
<td>–</td>
<td>133</td>
<td>in-lb</td>
</tr>
<tr>
<td>Max. Mounting Torque M6 Mounting Screws</td>
<td>–</td>
<td>53</td>
<td>in-lb</td>
</tr>
<tr>
<td>Module Weight (Typical)</td>
<td>–</td>
<td>0.52</td>
<td>kg</td>
</tr>
<tr>
<td>Isolation Voltage (Charged Part to Baseplate, AC 60Hz 1 min.)</td>
<td>$V_{iso}$</td>
<td>10200</td>
<td>Volts</td>
</tr>
<tr>
<td>Maximum Turn-Off Switching Current</td>
<td>–</td>
<td>400</td>
<td>Amperes</td>
</tr>
<tr>
<td>($V_{CC} = 4500V, V_{GE} = ±15V, R_{G[ON]} = 720\Omega, T_J = 125^\circ C$)</td>
<td>–</td>
<td>400</td>
<td>Amperes</td>
</tr>
<tr>
<td>Short Circuit Capability, Maximum Pulse Width</td>
<td>–</td>
<td>10</td>
<td>µs</td>
</tr>
<tr>
<td>($V_{CC} = 4500V, V_{GE} = ±15V, R_{G[ON]} = 720\Omega, T_J = 125^\circ C$)</td>
<td>–</td>
<td>10</td>
<td>µs</td>
</tr>
<tr>
<td>Maximum Reverse Recovery Instantaneous Power</td>
<td>–</td>
<td>1200</td>
<td>kW</td>
</tr>
<tr>
<td>($V_{CC} = 4500V, \frac{dV}{dt} ≤ 1000A/\mu s, T_J = 125^\circ C$)</td>
<td>–</td>
<td>1200</td>
<td>kW</td>
</tr>
</tbody>
</table>
- **MOSFET**

- Fastest commercial solid state switch available
  - Intrinsic turn on/off time ~ns set by $R_{DS-ON}C_{OUTPUT}$ time constant (carrier junction crossing time much faster)
  - Effective switching time limited by input capacitance, stray packaging inductance, and $di_S/dt$ to $\geq 10$ ns

- Maximum voltage: 1200 V
  - Avalanche rated, limited excursion to $V > V_{DSS}$ will not damage device
  - Can operate at near $V_{DSS}$

- Maximum current: $\sim 0.1$ kA (higher for modules and lower voltage FETs)
  - Pulsed current limited to $\sim 4X$ average rating due to increase in $R_{DS-ON}$

- “Intrinsic” reverse body diode, acts as anti-parallel diode
  - FREDFET: improved reverse body diode, soft recovery

- Well suited for parallel operation, positive coefficient of $V_{DS}$ with temperature
MOSFET Data Sheet

N-Channel FREDFET

Power MOS 8™ is a high speed, high voltage N-channel switch-mode power MOSFET. This ‘FREDFET’ version has a drain-source (body) diode that has been optimized for high reliability in ZVS phase shifted bridge and other circuits through reduced t_{rr}, soft recovery, and high recovery dv/dt capability. Low gate charge, high gain, and a greatly reduced ratio of C_{rss}/C_{iss} result in excellent noise immunity and low switching loss. The intrinsic gate resistance and capacitance of the poly-silicon gate structure help control di/dt during switching, resulting in low EMI and reliable paralleling, even when switching at very high frequency.

FEATURES
- Fast switching with low EMI
- Low t_{rr} for high reliability
- Ultra low C_{rss} for improved noise immunity
- Low gate charge
- Avalanche energy rated
- RoHS compliant

TYPICAL APPLICATIONS
- ZVS phase shifted and other full bridge
- Half bridge
- PFC and other boost converter
- Buck converter
- Single and two switch forward
- Flyback
### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Ratings</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_D$</td>
<td>Continuous Drain Current @ $T_C = 25°C$</td>
<td>13</td>
<td>A</td>
</tr>
<tr>
<td>$I_D$</td>
<td>Continuous Drain Current @ $T_C = 100°C$</td>
<td>8</td>
<td>A</td>
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<tr>
<td>$I_{DM}$</td>
<td>Pulsed Drain Current ©</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>$V_{GS}$</td>
<td>Gate-Source Voltage</td>
<td>±30</td>
<td>V</td>
</tr>
<tr>
<td>$E_{AS}$</td>
<td>Single Pulse Avalanche Energy ©</td>
<td>1070</td>
<td>mJ</td>
</tr>
<tr>
<td>$I_{AR}$</td>
<td>Avalanche Current, Repetitive or Non-Repetitive</td>
<td>7</td>
<td>A</td>
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### Thermal and Mechanical Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Characteristic</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_D$</td>
<td>Total Power Dissipation @ $T_C = 25°C$</td>
<td>625</td>
<td></td>
<td></td>
<td>W</td>
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<tr>
<td>$R_{JAC}$</td>
<td>Junction to Case Thermal Resistance</td>
<td>0.20</td>
<td></td>
<td></td>
<td>°C/W</td>
</tr>
<tr>
<td>$R_{JCS}$</td>
<td>Case to Sink Thermal Resistance, Flat, Greased Surface</td>
<td>0.11</td>
<td></td>
<td></td>
<td>°C/W</td>
</tr>
<tr>
<td>$T_{J,STG}$</td>
<td>Operating and Storage Junction Temperature Range</td>
<td>-55</td>
<td>150</td>
<td>300</td>
<td>°C</td>
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<tr>
<td>$T_L$</td>
<td>Soldering Temperature for 10 Seconds (1.6mm from case)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$W_T$</td>
<td>Package Weight</td>
<td>0.22</td>
<td></td>
<td></td>
<td>oz</td>
</tr>
<tr>
<td>Torque</td>
<td>Mounting Torque (TO-247 Package), 6-32 or M3 screw</td>
<td>10</td>
<td></td>
<td>1.1</td>
<td>in-lbf</td>
</tr>
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Microsemi Website - http://www.microsemi.com
### Static Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{BS(DSS)} )</td>
<td>Drain-Source Breakdown Voltage</td>
<td>( V_{GS} = 0 \text{V}, I_D = 250\mu A )</td>
<td>1200</td>
<td>Typ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta V_{BS(DSS)/\Delta T_J} )</td>
<td>Breakdown Voltage Temperature Coefficient</td>
<td>Reference to 25°C, ( I_D = 250\mu A )</td>
<td>1.41</td>
<td></td>
<td></td>
<td>V/°C</td>
</tr>
<tr>
<td>( R_{DS(on)} )</td>
<td>Drain-Source On Resistance</td>
<td>( V_{GS} = 10\text{V}, I_D = 7\text{A} )</td>
<td>1.11</td>
<td></td>
<td>1.40</td>
<td>Ω</td>
</tr>
<tr>
<td>( V_{GS(th)} )</td>
<td>Gate-Source Threshold Voltage</td>
<td>( V_{GS} = V_{DS}, I_D = 1\text{mA} )</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>V</td>
</tr>
<tr>
<td>( \Delta V_{GS(th)/\Delta T_J} )</td>
<td>Threshold Voltage Temperature Coefficient</td>
<td>( V_{GS} = 1200\text{V}, T_J = 25\text{°C} )</td>
<td>-10</td>
<td></td>
<td></td>
<td>mV/°C</td>
</tr>
<tr>
<td>( I_{DSS} )</td>
<td>Zero Gate Voltage Drain Current</td>
<td>( V_{GS} = 0 \text{V}, T_J = 125\text{°C} )</td>
<td>250</td>
<td></td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>( I_{GSS} )</td>
<td>Gate-Source Leakage Current</td>
<td>( V_{GS} = +30\text{V} )</td>
<td>1000</td>
<td></td>
<td></td>
<td>µA</td>
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### Dynamic Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_{fs} )</td>
<td>Forward Transconductance</td>
<td>( V_{DS} = 50\text{V}, I_D = 7\text{A} )</td>
<td>15</td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>( C_{rs} )</td>
<td>Input Capacitance</td>
<td>( V_{GS} = 0 \text{V}, V_{DS} = 25\text{V} )</td>
<td>4755</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>( C_{rr} )</td>
<td>Reverse Transfer Capacitance</td>
<td>( f = 1\text{MHz} )</td>
<td>55</td>
<td></td>
<td></td>
<td>pF</td>
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<tr>
<td>( C_{oss} )</td>
<td>Output Capacitance</td>
<td></td>
<td>350</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>( C_{ocv} )</td>
<td>Effective Output Capacitance, Charge Related</td>
<td>( V_{GS} = 0 \text{V}, V_{DS} = 0 \text{V} \text{ to } 800\text{V} )</td>
<td>135</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>( C_{oer} )</td>
<td>Effective Output Capacitance, Energy Related</td>
<td>( V_{GS} = 0 \text{V}, V_{DS} = 0 \text{V} \text{ to } 800\text{V} )</td>
<td>70</td>
<td></td>
<td></td>
<td>pF</td>
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<tr>
<td>( Q_{t} )</td>
<td>Total Gate Charge</td>
<td>( V_{GS} = 0 \text{ to } 10\text{V}, I_D = 7\text{A} )</td>
<td>145</td>
<td></td>
<td></td>
<td>nC</td>
</tr>
<tr>
<td>( Q_{gs} )</td>
<td>Gate-Source Charge</td>
<td>( V_{DS} = 600\text{V} )</td>
<td>24</td>
<td></td>
<td></td>
<td>nC</td>
</tr>
<tr>
<td>( Q_{gd} )</td>
<td>Gate-Drain Charge</td>
<td></td>
<td>70</td>
<td></td>
<td></td>
<td>nC</td>
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<tr>
<td>( t_{d(on)} )</td>
<td>Turn-On Delay Time</td>
<td>Resistive Switching</td>
<td>26</td>
<td></td>
<td></td>
<td>ns</td>
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<tr>
<td>( t_{r} )</td>
<td>Current Rise Time</td>
<td>( V_{DD} = 800\text{V}, I_D = 7\text{A} )</td>
<td>15</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>( t_{d(off)} )</td>
<td>Turn-Off Delay Time</td>
<td>( R_G = 4.70\Ω, V_{GG} = 15\text{V} )</td>
<td>85</td>
<td></td>
<td></td>
<td>ns</td>
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<tr>
<td>( t_{f} )</td>
<td>Current Fall Time</td>
<td></td>
<td>24</td>
<td></td>
<td></td>
<td>ns</td>
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</table>
### Source-Drain Diode Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{SD}$</td>
<td>Continuous Source Current (Body Diode)</td>
<td>$I_{SD} = 7A$, $T_J = 25^\circ C$, $V_{DS} = 0V$</td>
<td>13</td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>$I_{SM}$</td>
<td>Pulsed Source Current (Body Diode)</td>
<td>$I_{SM} = 50$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{SD}$</td>
<td>Diode Forward Voltage</td>
<td>$V_{SD} = 1.0$ V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{rr}$</td>
<td>Reverse Recovery Time</td>
<td>$T_J = 25^\circ C$</td>
<td>250 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_J = 125^\circ C$</td>
<td>520 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_r$</td>
<td>Reverse Recovery Charge</td>
<td>$I_{SD} = 7A$, $di_{SD}/dt = 100A/\mu s$</td>
<td>$T_J = 25^\circ C$</td>
<td>1.12 $\mu C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{DD} = 100V$, $T_J = 125^\circ C$</td>
<td>3.03 $\mu C$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_{rr}$</td>
<td>Reverse Recovery Current</td>
<td>$T_J = 25^\circ C$</td>
<td>10 A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_J = 125^\circ C$</td>
<td>13.5 A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$dv/dt$</td>
<td>Peak Recovery $dv/dt$</td>
<td>$I_{SD} \leq 7A$, $di_{SD}/dt \leq 100A/\mu s$, $V_{DD} = 800V$, $T_J = 125^\circ C$</td>
<td>25 V/ns</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

1. Repetitive Rating: Pulse width and case temperature limited by maximum junction temperature.
2. Starting at $T_J = 25^\circ C$, $L = 43.59mH$, $R_G = 4.7\Omega$, $I_{AS} = 7A$.
3. Pulse test: Pulse Width < 380μs, duty cycle < 2%.
4. $C_{o(rs)}$ is defined as a fixed capacitance with the same stored charge as $C_{oss}$ with $V_{DS} = 67\%$ of $V_{(BVDSS)}$.
5. $C_{o(ef)}$ is defined as a fixed capacitance with the same stored energy as $C_{oss}$ with $V_{DS} = 67\%$ of $V_{(BVDSS)}$. To calculate $C_{o(ef)}$ for any value of $V_{DS}$ less than $V_{(BVDSS)}$, use this equation: $C_{o(ef)} = 2.17E-7V_{DS}^2 + 2.63E-5V_{DS} + 3.74E-11$.
6. $R_g$ is external gate resistance, not including internal gate resistance or gate driver impedance. (MIC4452)

Microsemi reserves the right to change, without notice, the specifications and information contained herein.
MOSFET Data Sheet (cont.)

Figure 9, Forward Safe Operating Area

Figure 10, Maximum Forward Safe Operating Area

Figure 11, Transient Thermal Impedance Model

Figure 12, Maximum Effective Transient Thermal Impedance Junction-to-Case vs Pulse Duration
MOSFET Model for Fast Switching

- Data sheet information
  - Drain-source breakdown voltage: $V_{DSS}$
  - Drain current
    - Continuous: $I_D$
    - Pulsed: $I_{DM}$
  - $R_{DS-ON} @ I_D$
  - Input capacitance: $C_{ISS} = C_{GD} + C_{GS}$
  - Output capacitance: $C_{OSS} = C_{DS}$
  - Reverse transfer capacitance (Miller capacitance): $C_{RSS} = C_{GD}$
- Typical values for 1 kV TO-247/264
  - $L_{D}: <1 \text{ nH}$
  - $L_{G} & L_{S}: \sim 6 \text{ nH}$
  - $C_{ISS}: \sim \text{few nF}$
  - $C_{OSS} & C_{RSS}: \sim \text{few 100 pF}$
- Input capacitance and parasitic inductance form resonant circuit
  • $\omega < 10^9$, therefore $\tau_r \sim$ few ns will excite the resonance
  • $Z \sim$ few ohm, therefore need significant gate resistance to damp

- Inductive voltage due to rising source current: $L_S \frac{dI_S}{dt}$
  • 50 A in 10 ns would induce $\sim 30$ V across source inductance
  • Inductive voltage subtracts from applied gate voltage

- Effects are internal to package
  • May not see true causes of slow MOSFET turn on
MOSFET Fast Switching

- Remediations
  - Use a bi-polar high voltage gate drive (limited by gate breakdown)
  - Use high gate drive resistance (balance with drive current requirements)
  - Use a larger number of smaller MOSFETs in parallel
  - Integrate driver into MOSFET package
    - Commercial units show little gain
    - Hybrid circuits can achieve ~1 ns risetime
Hybrid MOSFET/Driver for Ultra-Fast Switching

Hybrid schematic: totem pole driver, output MOSFET, and load

Tang & Burkhart, IPMC2008

Hybrid circuit; dual drivers on each side of PCB, MOSFET on bottom-side of PCB, load at bottom of photo
Interpretation of Hybrid MOSFET Data During Nanosecond Switching

- No switching until $V_{GS}$ exceeds threshold
- Switching is effectively complete before Miller capacitance is fully charged ($\sim 20 \text{ nC} < Q < 60 \text{ nC}$)
- Ultra-fast is unlike normal MOSFET switching
  - Switching time depends on “linear” behavior of device
  - Sensitive to
    - Transistor gain, $g_m$
    - Die temperature
    - Device-to-device variations

Gate and drain-source voltage as a function of gate charge, for a range of initial MOSFET voltage
High Power Switching with Solid State Switches

- Peak switching power of commercial devices is limited
  • Array, series/parallel, devices to increase power
  • Use alternative topologies

- Arrays
  • Parallel
    - MOSFETs well suited
    - IGBTs may present challenges
  • Series
    - Prevent overvoltage of individual elements under ALL CONDITIONS
      • Derate device operating: reduces effective device power
      • Add protection (e.g. RC snubber): reduces switching speed
- **Power Semiconductors (MOSFETs, IGBTs, Thyristors)**

- **Driver Circuits**
  - IXYS: [http://www.ixys.com/](http://www.ixys.com/)
  - Vishay: [http://www.vishay.com/company/brands/siliconix/](http://www.vishay.com/company/brands/siliconix/) (Siliconix devices)