Pulsed Power Engineering
Switching Devices

June 13-17, 2011

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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
  - Thyristors
    - Electrically triggered
    - Optically triggered
    - dV/dt triggered
  - Transistors
    - IGBT
    - MOSFET
Switches

• Electromechanical
  – Open 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
      – Maximum current ~0.1 kA
      – Tyco-kilovac
      – Gigavac
Gas/Vacuum Switch Performance vs. Pressure

Gas Pressure (Torr)

- \(10^{-8}\) - VACUUM TUBES - SUB ns FALL
- \(10^{-7}\) - VACUUM GAPS - 100 - 500 ns FALL
- \(10^{-6}\) - LMPV - 500 ns FALL
- \(10^{-5}\) - IGNITRONS 50 - 100 ns FALL
- \(10^{-2}\) - THYRATRONS - 20 ns FALL
- \(10^{-1}\) - KRYTRON - 2 ns FALL
- 1 - PRESSURIZED SPARK GAPS - SUB ns FALL

Decreasing delay and jitter
Longer recovery time

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Vacuum Tube (Switch Tube)

- Space-charge limited current flow
  - $V_{ON} \propto V^{1.5}$
  - 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, SF₆, CO₂, 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
- Repetition rates - usually single shot but low kHz possible for burst mode
- \( L_{arc} \) ~ 15 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
Spark Gaps

Spark Gaps are a family of versatile high voltage switches. They consist of three electrodes in a hemispherically spaced, pressurized ceramic envelope. Triggered Spark Gaps are generally characterized by a peak current capability of thousands to tens of thousands of amperes, delay times of tens of nanoseconds, and resistance of tens of milliohms and inductance of 5 to 30 nanohenries. They are suitable for capacitor switching applications such as transistors, electrically pumped gas lasers, medical isotope pumps, and as crowbar protection devices.

**Features**

- Fast switching operation
- High voltage hold-off
- Ceramic-metal construction
- No warm-up period
- High current capability
- Long life

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### Triggered Spark Gap Ratings

<table>
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<th>O-A Range, kV (Min/Max)</th>
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<th>Recommended Park/Emitter Transformer</th>
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**Notes**

1. Optimum operating voltage is typically 60 to 90% of SBV.
2. Operation below minimum value may result in erratic firing over time.
3. Operation at the value may result in self-firing over time.
4. Recommended minimum gap-breakdown voltage with no trigger applied.
5. Values shown contain safety factor for end-of-life requirements.
6. Park/Emitter (FM-114A) Trigger Module can be used to trigger all gaps.
7. Transformers listed are mechanically and electrically. See Park/Emitter Transformer Data Sheet.
8. These units must be operated in a liquid or gas dielectric to prevent internal flashover. GP-10 and GP-14B, above 24 kV; GP-12B and GP-14B, above 35 kV; GP-7 and GP-15B, above 40 kV.
9. Designed for high-altitude high-load conditions.
10. Other voltage ranges and mechanical configurations are available on request. For example, the GP-20B can be supplied with a 5 to 19 kV operating range by specifying GP-20B-20. The 20 would be the 50% and the 19 kV maximum would be 80% of 50% of SBV = 1446.
11. E = Stated energy in joules (J/cm²), Lb = average current in amperes, Ib = RMS current in amperes. R = total circuit resistance in ohms, P = average power in watts.
Thyratrons

- Closing switch, forward drop ~100 V
- High voltage: kV to ~ 100kV (normally ~ 30-40kV per internal gap)
- Maximum peak current 20-40 kA
- 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)
- 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.
Thyratrons are fast acting high voltage switches suitable for a variety of applications including radar, laser and scientific use.

PerkinElmer’s thyratrons are constructed of ceramic and metal for strength and long life. Over 300 thyratron types are available from PerkinElmer. The types listed in this guide are a cross section of the broad line available. We encourage inquiries for thyratrons to suit your particular application.

Features

- Wide operating voltage range
- High pulse rate capability
- Ceramic-metal construction
- High current capability
- Long life

How a Thyratron works

The operation of the device can be divided into three phases: triggering and commutation (closure), steady-state conduction, and recovery (opening), each of which is discussed below.

Triggering and Commutation

When a suitable positive triggering pulse of energy is applied to the grid, a plasma forms in the grid-cathode region from electrons. This plasma passes through the apertures of the grid structure and causes electrical breakdown in the high-voltage region between the grid and the anode. This begins the process of thyratron switching (also called commutation). The plasma that is formed between the grid and the anode diffuses back through the grid into the grid-cathode space. "Connection" of the plasma in the anode-grid space with the plasma in the cathode-grid space completes the commutation process. The commutation process is simply modeled as shown in Figure 2.

The time interval between trigger breakdown of the grid-cathode region and complete closure of the thyratron is called the anode delay time. It is typically 100-200 nanoseconds for most tube types.

During commutation, a high voltage spike appears at the grid of the thyratron. This spike happens in the time it takes for the plasma in the grid-anode space to "connect" to the plasma in the grid-cathode space. During this time, the anode is momentarily "connected" to the grid thereby causing the grid to assume a voltage nearly that of the anode’s. Although the grid spike voltage is brief in duration, usually less than 100 nanoseconds.
100 nS, it can damage the grid driver circuit unless measures are taken to suppress the spike before it enters the grid driver circuit. The location of the grid spike suppression circuit is shown in Figure 3, Grid Circuit.

Figure 4, Typical Grid Spike Suppression Circuits, shows the more common methods used to protect the grid driver circuit. In using any of these types of circuits, care must be exercised to assure that the Grid Driver Circuit pulse is not attenuated in an unacceptable manner. The values for the circuit components are dependent on the characteristics of the thyatron being driven, the
Thyratron - Operation

grid driver circuit design, and the performance required from the thyratron itself. Contact the applications engineering department at PerkinElmer to discuss the specific details of your requirement.

Conduction
Once the commutation interval has ended, a typical hydrogen thyratron will conduct with nearly constant voltage drop on the order of 100 volts regardless of the current through the tube.

Recovery
Thyratrons open (recover) via diffusion of ions to the tube inner walls and electrode surfaces, where the ions can recombine with electrons. This process takes from 30 to 150 microseconds, depending on the tube type, fill pressure, and gas (hydrogen or deuterium). The theoretical maximum pulse repetition rate is the inverse of the recovery time.

Recovery can be promoted by arranging to have a small negative DC bias voltage on the control grid when forward conduction has ceased. A bias voltage of 50 to 100 volts is usually sufficient.

Recovery can also be improved by arranging to have small negative voltage on the anode after forward conduction has ceased. In many radar circuits, a few-percent negative mismatch between a pulse-forming network and the load ensures a residual negative anode voltage. In laser circuits, classical pulse-forming networks are seldom used, so inverse anode voltage may not be easily generated. Recovery then strongly depends on the characteristics of the anode charging circuit. In general, charging schemes involving gently rising voltages (i.e., resonant charging and ramp charging) favor thyratron recovery, and therefore allow higher pulse repetition rates. Fast ramping and resistive charging put large voltages on the anode quickly, thus making recovery more difficult. The ideal charging scheme from the viewpoint of thyratron recovery is command charging, wherein voltage is applied to the thyratron only an instant before firing.
Thyratrons

Figure 3. Grid Circuit

Figure 4. Typical Grid Spike Suppression Circuits

(a) Filter
(b) Zener
(c) MOV
(d) Spark Gap
## Thyratrons

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<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 (Min)</th>
<th>Impedance of Grid Circuits (Max)</th>
<th>EIA Type &amp; Comments</th>
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<td>40</td>
<td>12000</td>
<td>3</td>
<td>55</td>
<td>100</td>
<td>6.3/28</td>
<td>500</td>
<td>250</td>
<td>3.6 x 3.5</td>
<td>2.6 x 3</td>
<td>3</td>
<td>6 x 4.5</td>
</tr>
<tr>
<td>LS-3426</td>
<td>45</td>
<td>5000</td>
<td>2</td>
<td>45</td>
<td>50</td>
<td>6.3/28</td>
<td>500</td>
<td>250</td>
<td>Two gap tetrode</td>
<td>5.75 x 3</td>
<td>3</td>
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<tr>
<td>LS-3229</td>
<td>70</td>
<td>15000</td>
<td>2</td>
<td>45</td>
<td>50</td>
<td>6.3/28</td>
<td>500</td>
<td>250</td>
<td>Two gap tetrode</td>
<td>9.5 x 4.5</td>
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<tr>
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<td>500</td>
<td>250</td>
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<td>6 x 4.5</td>
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<tr>
<td>LS-3001</td>
<td>40</td>
<td>20000</td>
<td>4</td>
<td>90</td>
<td>100</td>
<td>6.3/28</td>
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<td>250</td>
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<tr>
<td>LS-3002</td>
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<td>4</td>
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<td>250</td>
<td>Two gap tetrode</td>
<td>9.5 x 4.5</td>
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<tr>
<td>LS-3511S</td>
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<td>6</td>
<td>125</td>
<td>160</td>
<td>6.3/28</td>
<td>500</td>
<td>250</td>
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<td>9.5 x 4.5</td>
<td>3</td>
<td>6 x 4.5</td>
</tr>
<tr>
<td>LS-3511S</td>
<td>40</td>
<td>12000</td>
<td>6</td>
<td>125</td>
<td>160</td>
<td>6.3/28</td>
<td>500</td>
<td>250</td>
<td>Two gap tetrode</td>
<td>9.5 x 4.5</td>
<td>3</td>
<td>6 x 4.5</td>
</tr>
</tbody>
</table>

**Notes:**
- HY-3204: 800A @ <1uSec
- HY-53: 800A @ <1uSec
- LS-3101S: 800A @ <1uSec
- LS-3111S: 800A @ <1uSec
- LS-3426: 800A @ <1uSec
- LS-3229: 800A @ <1uSec
- LS-3202: 800A @ <1uSec
- LS-3001: 800A @ <1uSec
- LS-3002: 800A @ <1uSec
- LS-3511S: 800A @ <1uSec
- LS-3511S: 800A @ <1uSec
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.

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. \( Pb = epy \times ib \times prr \).
Thyratrons - Definition of Terms

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 girds 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.
Thyratron Tradeoffs

The diagram illustrates the tradeoffs between power density to arc, current density, pulse width, and inverse resistivity. The graph shows how power density decreases as current density increases, while pulse width decreases with increasing inverse resistivity. The lines for 5µs and 30µs pulses highlight the tradeoff between these parameters.
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

Simple ignitron

![Simple ignitron diagram](image)
Plasma Opening Switch (POS)

- Initially, a high density plasma forms a low-conductivity channel (switch closed)
- Plasma conductivity is rapidly increased, ~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
Solid-state Devices - General Observations

- 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
Thyristors

- Closing switch
- 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
- Closing/opening devices
  - Gate turn-off thyristor (GTO)
  - Integrated gate commutated thyristor (IGCT)
  - Limited use in pulsed power
Fast Thyristors

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

Fig. 2. End view drawings of optical thyristor
Fig. 3. Photograph of PIMM optical thyristor
Fig. 4. Photograph of Two-Switch Electrode assembly.

McDonald, IPMC2006
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

- 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 (cont.)

- 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:
      - HV (50 to >100 V): initiates current flow to gate (parasitic L)
      - 2\(^{nd}\) 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 \( \text{d}I/\text{d}t \) 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 $V_{CE}$

- **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 VGE(Ioff)
- Super-Fast Recovery Free-Wheel Diode
- Isolated Baseplate for Easy Heat Sinking

Specifications:
- Maximum Collector-Emitter Voltage: 6500V
- Collector-Emitter Voltage (Top-offset): 350V
- Collector Current (DC): 200A
- PeakCollector Current (Peak): 400A
- Emitter Current (IE): 100A
- Emitter Surge Current (Ie(1): 400A
- Max. Turning On Time C(M): 60ns
- Max. Turning Off Time C(M): 30ns
- Modbus Weight (Typical): 7.5lbs
- Isolation Voltage (Charged Part to Baseplate, AC 2500V 1min): 2500V
- Maximum Turn-On/Off Switching Current (VCE = 480V, VCE = 14V, Propagate: 250V, Tj = 125°C): 400A
- Maximum System Loss (VCE = 480V, VCE = 14V, Propagate: 250V, Tj = 125°C): 1200W

Outline Drawing and Circuit Diagram

Dimensions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCE</td>
<td>480V</td>
</tr>
<tr>
<td>VCE</td>
<td>14V</td>
</tr>
<tr>
<td>Tj</td>
<td>125°C</td>
</tr>
</tbody>
</table>

Powerex, Inc., 300 E. Main Street, Yancee, PA 15657-1380 (724) 325-7722

United States Pulsed Power Engineering Burkhart & Kemp
### Static Electrical Characteristics, $T_J = 25^\circ$C unless otherwise specified

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector-Emitter Current*</td>
<td>$I_{CEO}$</td>
<td>$V_{CE} = 25V, V_{BB} = 5V, T_J = 25^\circ$C</td>
<td>$-3.0$</td>
<td>$-3.0$</td>
<td>$-3.0$</td>
<td>mA</td>
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<tr>
<td>Gate-Emitter Threshold Voltage</td>
<td>$V_{GEH}$</td>
<td>$I_G = 25mA, V_{CE} = 10V$</td>
<td>$5.0$</td>
<td>$6.0$</td>
<td>$7.0$</td>
<td>Volts</td>
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<td>Gate Current</td>
<td>$I_G$</td>
<td>$V_{CE} = 5V, V_{BB} = 5V$</td>
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<td>$-8.0$</td>
<td>$-8.0$</td>
<td>$\mu$A</td>
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<td>Collector-Emitter Saturation Voltage</td>
<td>$V_{CES}$</td>
<td>$I_C = 25A, V_{BB} = 15V, T_J = 25^\circ$C</td>
<td>$-5.1$</td>
<td>$-6.0$</td>
<td>$-6.0$</td>
<td>Volts</td>
</tr>
<tr>
<td>Input Capacitance</td>
<td>$C_{iss}$</td>
<td>$V_{CE} = 15V, V_{BB} = 15V$</td>
<td>$41.0$</td>
<td>$-47$</td>
<td>$-47$</td>
<td>pF</td>
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<tr>
<td>Output Capacitance</td>
<td>$C_{oss}$</td>
<td>$I_{CEO} = 1A$</td>
<td>$2.5$</td>
<td>$-2.5$</td>
<td>$-2.5$</td>
<td>nF</td>
</tr>
<tr>
<td>Reverse Transfer Capacitance</td>
<td>$C_{rs}$</td>
<td>$T_J = 25^\circ$C</td>
<td>$0.7$</td>
<td>$0.7$</td>
<td>$0.7$</td>
<td>nF</td>
</tr>
<tr>
<td>Total Gate Charge</td>
<td>$Q_G$</td>
<td>$V_{CE} = 3000V, I_C = 200A, V_{BB} = 5V$</td>
<td>$8.0$</td>
<td>$8.0$</td>
<td>$8.0$</td>
<td>$\mu$C</td>
</tr>
<tr>
<td>Source-Collector Voltage**</td>
<td>$V_{CEO}$</td>
<td>$I_C = 200A, V_{BB} = 15V, T_J = 25^\circ$C</td>
<td>$0.5$</td>
<td>$0.5$</td>
<td>$0.5$</td>
<td>Volts</td>
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<tr>
<td>Turn-On Delay Time</td>
<td>$t_{on}$</td>
<td>$V_{CE} = 3000V, I_C = 200A$</td>
<td>$1.2$</td>
<td>$1.2$</td>
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<td>$\mu$s</td>
</tr>
<tr>
<td>Turn-On Switching Energy</td>
<td>$E_{os}$</td>
<td>$T_J = 125^\circ$C, $I_C = 400A$, Inductive Load</td>
<td>$1.5$</td>
<td>$1.5$</td>
<td>$1.5$</td>
<td>J</td>
</tr>
<tr>
<td>Turn-Off Delay Time</td>
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<td>$6.5$</td>
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<td>$\mu$s</td>
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<tr>
<td>Turn-Off Switching Energy</td>
<td>$E_{os}$</td>
<td>$T_J = 125^\circ$C, $I_C = 400A$, Inductive Load</td>
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<td>$3.5$</td>
<td>J</td>
</tr>
<tr>
<td>Reverse Recovery Time**</td>
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<td>$1.0$</td>
<td>$1.0$</td>
<td>$\mu$s</td>
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<td>Reverse Recovery Charging**</td>
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<td>$0.7$</td>
<td>$\mu$C</td>
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### Thermal Characteristics, $T_J = 25^\circ$C unless otherwise specified

<table>
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<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Resistance, Junction to Case</td>
<td>$R_{thJC}$</td>
<td>Per IGBT</td>
<td>$-42.0$</td>
<td>$-42.0$</td>
<td>$-42.0$</td>
<td>K/°C</td>
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<tr>
<td>Thermal Resistance, Junction to Case</td>
<td>$R_{thJC}$</td>
<td>Per FIBG</td>
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<td>$-65.0$</td>
<td>$-65.0$</td>
<td>K/°C</td>
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<tr>
<td>Contact/Thermal Resistance, Case to Pin</td>
<td>$R_{thCP}$</td>
<td>Per Module, Thermal Grayscale Applied</td>
<td>$-10.0$</td>
<td>$-10.0$</td>
<td>$-10.0$</td>
<td>K/°C</td>
</tr>
</tbody>
</table>

### Mechanical Characteristics, $T_J = 25^\circ$C unless otherwise specified

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<th>Symbol</th>
<th>Test Conditions</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
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<tbody>
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<td>$-400$</td>
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<td>$\mu$m</td>
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<td>$-3.0$</td>
<td>$-3.0$</td>
<td>$\Omega$</td>
<td></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 \( \frac{dI_s}{dt} \) 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 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 nH
  - $L_G$ & $L_S$: ~6 nH
  - $C_{ISS}$: ~few nF
  - $C_{OSS}$ & $C_{RSS}$: ~few 100 pF
MOSFET Fast Switching

• 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 ~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

• 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

Hybrid circuit; dual drivers on each side of PCB, MOSFET on bottom-side of PCB, load at bottom of photo

Tang & Burkhart, IPMC2008
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 ID, soft recovery, and high recovery dV/dt capability. Low gate charge, high gain, and a greatly reduced ratio of Cgs/Cd result in excellent noise immunity and low switching loss. The intrinsic gate resistance and capacitance of the poly-silicon gate structure help control dV/dt during switching, resulting in low EMI and reliable paralleling, even when switching at very high frequency.

**FEATURES**
- Fast switching with low EMI
- Low ID for high reliability
- Ultra low Cgs for improved noise immunity
- Low gate charge
- Avalanche energy rated
- RoHS compliant

**TYPICAL APPLICATIONS**
- 2S phase shifted and other full bridge
- Half bridge
- PFC and other boost converters
- String 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>IDmax</td>
<td>Continuous Drain Current @ Tj = 25°C</td>
<td>13</td>
<td>A</td>
</tr>
<tr>
<td>IDSS</td>
<td>Continuous Drain Current @ Tj = 100°C</td>
<td>8</td>
<td>A</td>
</tr>
<tr>
<td>IDPS</td>
<td>Pulsed Drain Current ≤ 100 Hz</td>
<td>50</td>
<td>A</td>
</tr>
<tr>
<td>VDS</td>
<td>Gate-Source Voltage</td>
<td>±30</td>
<td>V</td>
</tr>
<tr>
<td>IS</td>
<td>Single Pulse Avalanche Energy</td>
<td>1070</td>
<td>μJ</td>
</tr>
<tr>
<td>ATM</td>
<td>Avalanche Current, Repetitive or Non-Repetitive</td>
<td>7</td>
<td>A</td>
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</table>

### 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>PD</td>
<td>Total Power Dissipation @ Tj = 25°C</td>
<td>625</td>
<td></td>
<td></td>
<td>W</td>
</tr>
<tr>
<td>RDS(on)</td>
<td>Junction to Case Thermal Resistance</td>
<td>0.02</td>
<td></td>
<td></td>
<td>°C/W</td>
</tr>
<tr>
<td>RC(DG)</td>
<td>Case to Sink Thermal Resistance, flat, Gared Surface</td>
<td>0.11</td>
<td></td>
<td></td>
<td>°C/W</td>
</tr>
<tr>
<td>Tj(TSS)</td>
<td>Operating and Storage Junction Temperature Range</td>
<td>-55</td>
<td>150</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>TPk</td>
<td>Soldering Temperature for 10 Seconds (1.5mm from case)</td>
<td>300</td>
<td></td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>Wp</td>
<td>Package Weight</td>
<td>6.2</td>
<td></td>
<td></td>
<td>g</td>
</tr>
<tr>
<td>Torque</td>
<td>Mounting Torque (TO-247 Package), 0-32 or M3 screw</td>
<td>1.1</td>
<td></td>
<td></td>
<td>N·m</td>
</tr>
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</table>

**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>VDS(on)</td>
<td>Drain-Source Breakdown Voltage</td>
<td>VDS = 7V, VGS = 50V</td>
<td>1200</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>RDS(on)</td>
<td>Drain-Source On Resistance</td>
<td>RDS(on) = 71Ω</td>
<td>1.41</td>
<td></td>
<td></td>
<td>%Ω</td>
</tr>
<tr>
<td>VGS(th)</td>
<td>Gate-Source Voltage</td>
<td>VGS = 10V, IS = 0A</td>
<td>1.11</td>
<td>1.40</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>VGS(th)</td>
<td>Gate-Source Threshold Voltage</td>
<td>VGS = 10V, IS = 0A</td>
<td>3</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>VDS(th)</td>
<td>Threshold Voltage</td>
<td>VDS = 10V, IS = 0A</td>
<td>4</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>IZG</td>
<td>Zero Gate Voltage Drain Current</td>
<td>VGS = 100V</td>
<td>250</td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>ISAT</td>
<td>Gate-Source Leakage Current</td>
<td>VGS = 100V</td>
<td>1800</td>
<td></td>
<td></td>
<td>μA</td>
</tr>
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</table>

**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>IRF</td>
<td>Forward Transconductance</td>
<td>VDS = 50V, VGS = 7A</td>
<td>15</td>
<td></td>
<td></td>
<td>nS</td>
</tr>
<tr>
<td>Ciss</td>
<td>Input Capacitance</td>
<td>VDS = 25V, VGS = 25V</td>
<td>4765</td>
<td></td>
<td></td>
<td>nF</td>
</tr>
<tr>
<td>Ciss</td>
<td>Reverse Transfer Capacitance</td>
<td>VDS = 25V, VGS = 25V</td>
<td>50</td>
<td></td>
<td></td>
<td>nF</td>
</tr>
<tr>
<td>Ciss</td>
<td>Output Capacitance</td>
<td>VDS = 25V, VGS = 25V</td>
<td>350</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Coss</td>
<td>Effective Output Capacitance, Charge Related</td>
<td>VDS = 25V, VGS = 25V</td>
<td>135</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Coss</td>
<td>Effective Output Capacitance, Energy Related</td>
<td>VDS = 25V, VGS = 25V</td>
<td>70</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>IGt</td>
<td>Total Gate Charge</td>
<td>VGS = 0 V, IS = 7A</td>
<td>145</td>
<td></td>
<td></td>
<td>nC</td>
</tr>
<tr>
<td>IDSS</td>
<td>Gate-Source Charge</td>
<td>VGS = 0 V, IS = 7A</td>
<td>24</td>
<td></td>
<td></td>
<td>nC</td>
</tr>
<tr>
<td>IDSS</td>
<td>Gate-Drain Charge</td>
<td>VGS = 0 V, IS = 7A</td>
<td>20</td>
<td></td>
<td></td>
<td>nC</td>
</tr>
<tr>
<td>Id(t)</td>
<td>Turn-Off Delay Time</td>
<td>VDS = 100V, Tj = 7A</td>
<td>20</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>tRC</td>
<td>Current Rise Time</td>
<td>VDS = 100V, Tj = 7A</td>
<td>15</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>tDF</td>
<td>Turn-Off Time</td>
<td>VDS = 100V, Tj = 7A</td>
<td>85</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>tDS</td>
<td>Current Fall Time</td>
<td>VDS = 100V, Tj = 7A</td>
<td>24</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
</tbody>
</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>IF</td>
<td>Continuous Source Current (Body Diode)</td>
<td>VDS = 10 V, Tj = 25°C</td>
<td>13</td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>IFmax</td>
<td>Pulsed Source Current (Body Diode)</td>
<td>VDS = 100 V, Tj = 75°C</td>
<td>50</td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>V(I)</td>
<td>Diode Forward Voltage</td>
<td>VDS = 10 V, Tj = 25°C</td>
<td>1.0</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>tR</td>
<td>Recovery Time</td>
<td>VDS = 100 V, Tj = 75°C</td>
<td>100</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>tF</td>
<td>Recovery Charge</td>
<td>VDS = 100 V, Tj = 75°C</td>
<td>1.2</td>
<td></td>
<td></td>
<td>μC</td>
</tr>
<tr>
<td>tRmax</td>
<td>Recovery Current</td>
<td>VDS = 100 V, Tj = 75°C</td>
<td>250</td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>rDv</td>
<td>Peak Recovery drift</td>
<td>VDS = 75 V, Tj = 75°C</td>
<td>13.5</td>
<td></td>
<td></td>
<td>%Vμs</td>
</tr>
</tbody>
</table>

1. Repetitive Rating: Pulse width and case temperature limited by maximum junction temperature.
2. Soldering at Tj = 25°C, L = 43.5 mm, Rj = J = 7A.
3. Pulse test: Pulse Width ≤ 360μs, duty cycle ≤ 2%.
4. Ciss is defined as a fixed capacitance with the same stored energy as Ciss (Vgs = 0V, Vds = 25V). To calculate Ciss for any value of Vgs less than Vgsmax, use the equation: Ciss = Ciss(70Vgsmax) * Vgs/Vgsmax.
5. Rs is defined as a fixed capacitance with the same stored energy as Ciss (Vds = 25V, Vgs = 0V).

MOSFET Data Sheet - Microsemi Website - http://www.microsemi.com

June 13 - 17, 2011 USPAS Pulsed Power Engineering Burkhart & Kemp 39
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
Commercial Suppliers

• Semiconductors
  – Power Semiconductors (MOSFETs, IGBTs, Thyristors)
    • Powerex/Mitsubishi: http://www.pwrx.com/
    • DYNEX: http://www.dynexsemi.com/
    • ST Microelectronics: http://us.st.com/stonline/index.shtml
    • Westcode: http://www.westcode.com/
    • International Rectifier: http://www.irf.com/
    • Toshiba: http://www.toshiba.com
    • ABB: http://www.abb.com
    • IXYS/DEI: http://www.ixys.com/
  – Driver Circuits
    • IXYS/DEI: http://www.ixys.com/
    • Vishay/Siliconix: http://www.vishay.com/
    • Intersil/Elantec: http://www.intersil.com