Pulsed Power Engineering: Switching Devices

U.S. Particle Accelerator School
University of New Mexico

Craig Burkhart & Mark Kemp
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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

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

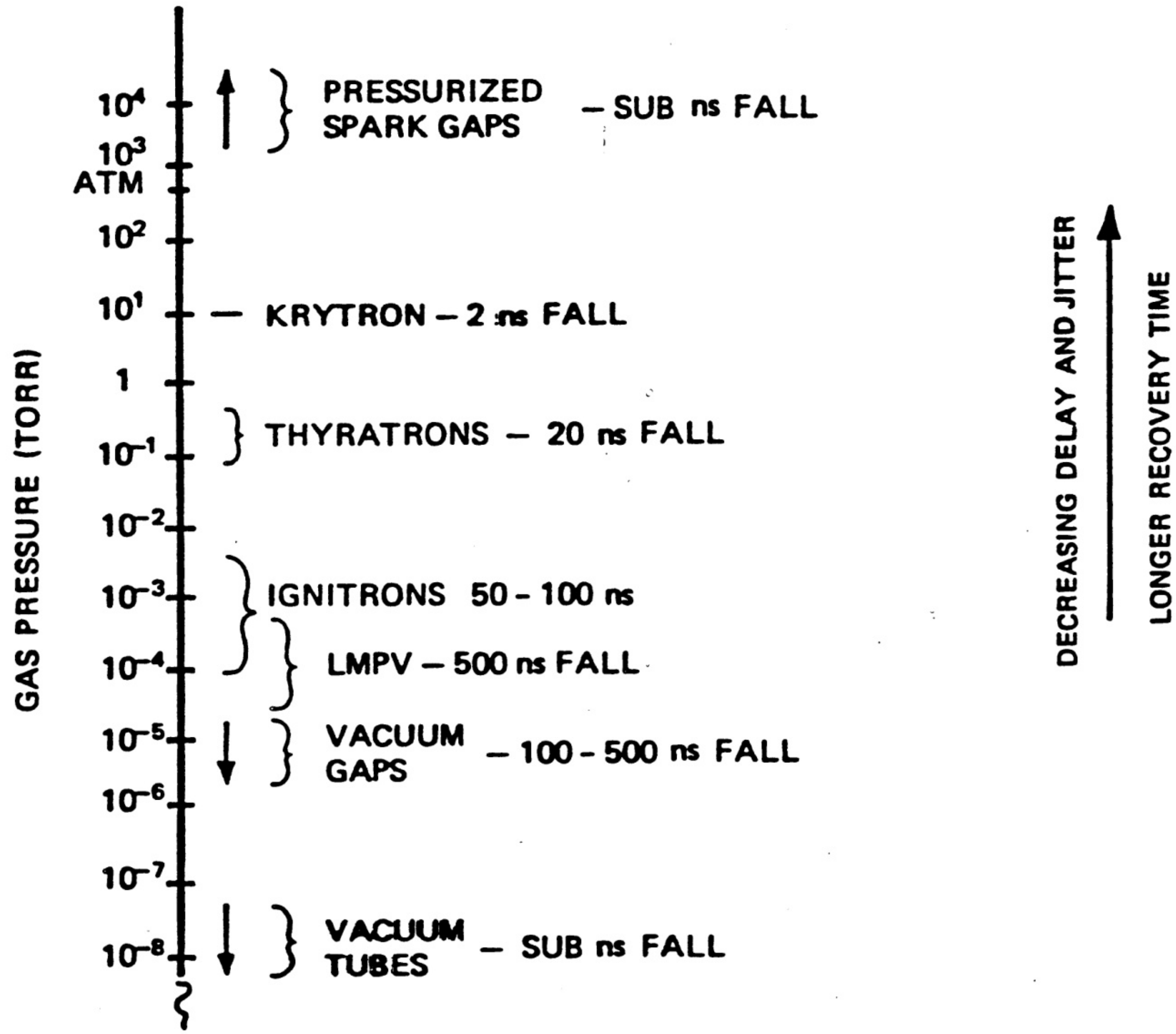
Switches

- Electromechanical
- Vacuum
- Gas
  - Spark gap
  - Thyratron
  - 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



Vacuum Tube (Switch Tube)

- Space-charge limited current flow
  - V_{ON} α $I^{2/3}$
  - 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 μs (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_{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

Commercial Spark Gap

Triggered Spark Gap Ratings

PerkinElmer Model No.	O-A Range, kV Min/Max (1,10)		SBV, kV	V_T Min Trig (kV Open Circuit	Trigger Mode	Recommended PerkinElmer Transformer	Typical Delay Time* * when operated in mode A (Nanoseconds)		Simultaneous Ratings Crowbar Service, Typical Life: 5000-20,000 Shots	Simultaneous Ratings Repetitive Switching Typical Life: 1-5 Million Shots
							At 70% SBV	At 40% SBV		
	(2)	(3)	(4)	(5)		(6, 7)			(11)	(11)
GP-89	0.7	2.1	2.6	10	C	TR-148A TR-180B	100	1000	5 kA peak 0.1 coulomb	3 millicoulombs/shot Ib = 35 mAdc Ip = 6 Aac
GP-90	1.3	3.4	4.2		C					
GP-91	4.4	10	12.5		A,C					
GP-93	8	20	25		A, C					
GP-82B	0.4	1.6	2	10	A,B	TR-148A TR-180B	30	300	7.5 kA peak 0.2 coulomb	4 millicoulombs/shot Ib = 60 mAdc Ip = 8 Aac
GP-31B	2	6	7.5		A					
GP-20B	3.5	11	14							
GP-46B	8	20	25							
GP-85	2	6	8	20	A,B	TR-1795 TR-180B TR1700	30	300	25 kA peak 0.4 coulomb	4 millicoulombs/shot Ib = 100 mAdc Ip = 10 Aac
GP-86	6	15	20		A					
GP-87	10	24	30							
GP-70	12	36	42(8)							
GP-30B	2	6	7.5	20	A,B	TR-1795 TR-1700	30	300	50 kA peak 0.5 coulomb	10 millicoulombs/shot Ib = 200 mAdc Ip = 15 Aac
GP-22B	6	15	19		A					
GP-12B	10	24	30							
GP-14B	12	36	42(8)							
GP-41B	12	36	42	20	A,B	TR-1795 TR-1700	30	300	Peak currents up to 100 kA and charge transfer up to 5 coulombs are obtainable at reduced life (100-1000 shots).	
GP-32B	20	48	60(8)		A					
GP-15B	25	60	86(8)							
GP-74B	40	100	120(8)	20	A	TR-1795 TR-1700	30	300		
GP-81B	40	100	120(9)							

Triggered Spark Gaps

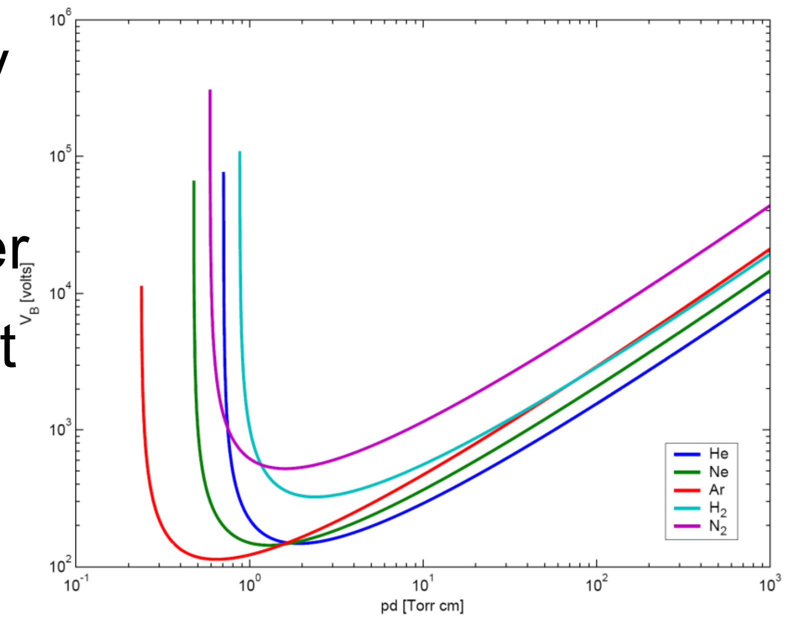
Ceramic-Metal

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)

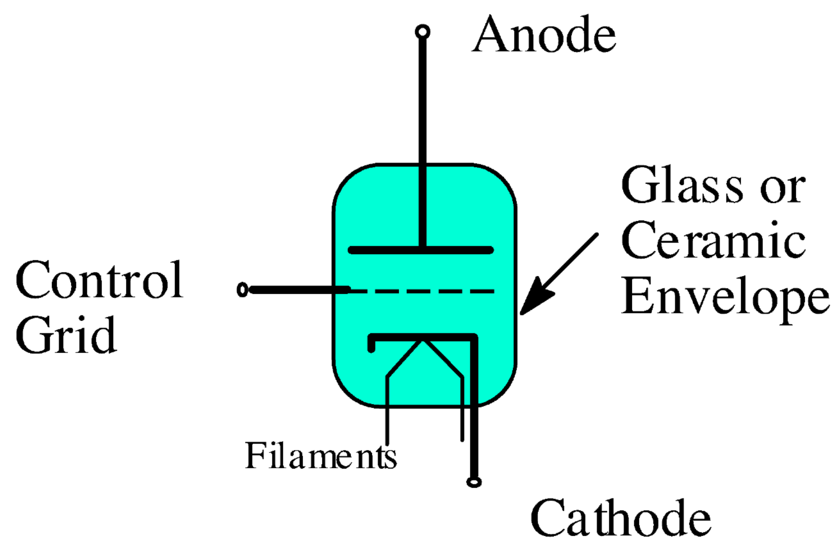


Thyratrons (cont.)

- 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

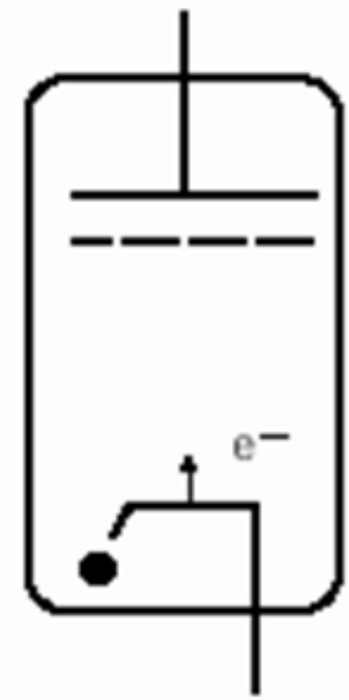
Thyratrons

- 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

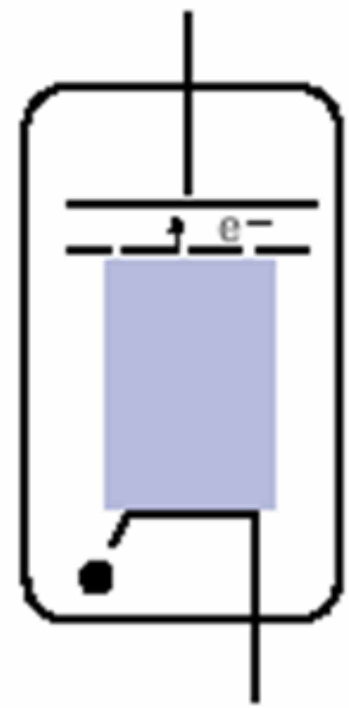
- Three phases of thyratron operation
  - Triggering & commutation (closure)
  - Steady-state conduction
  - Recovery (opening)
- Positive polarity pulse applied to grid
- Cathode electrons flowing to grid ionize gas in K-grid gap



1. Trigger pulse applied to control grid.

Thyratron Operation

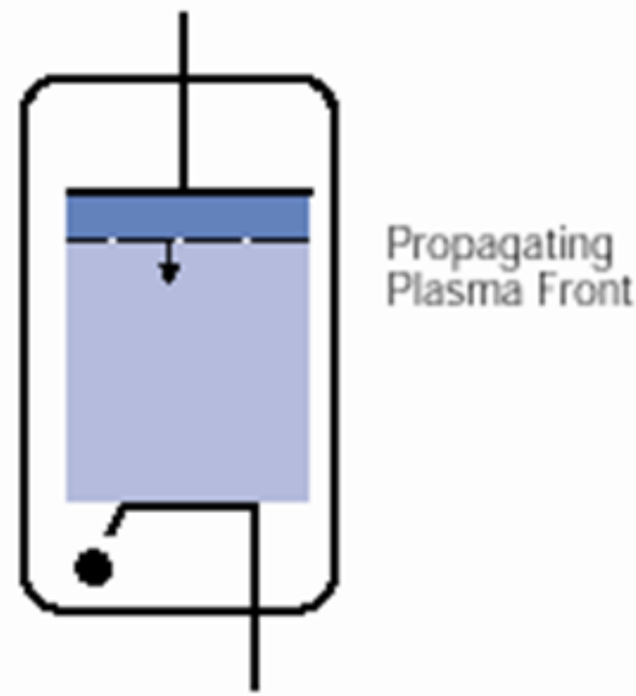
- Plasma fills K-grid gap, grid-cathode breakdown
- Plasma electrons flow through grid and are accelerated to anode
- Electrons flowing to anode ionize gas in A-grid gap



2. Grid-cathode breakdown.

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



3. Electrons from grid-cathode region create a dense plasma in the grid-anode region. The plasma front propagates toward the cathode via breakdown of gas.

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

4. Closure

Thyratron Trigger Circuit

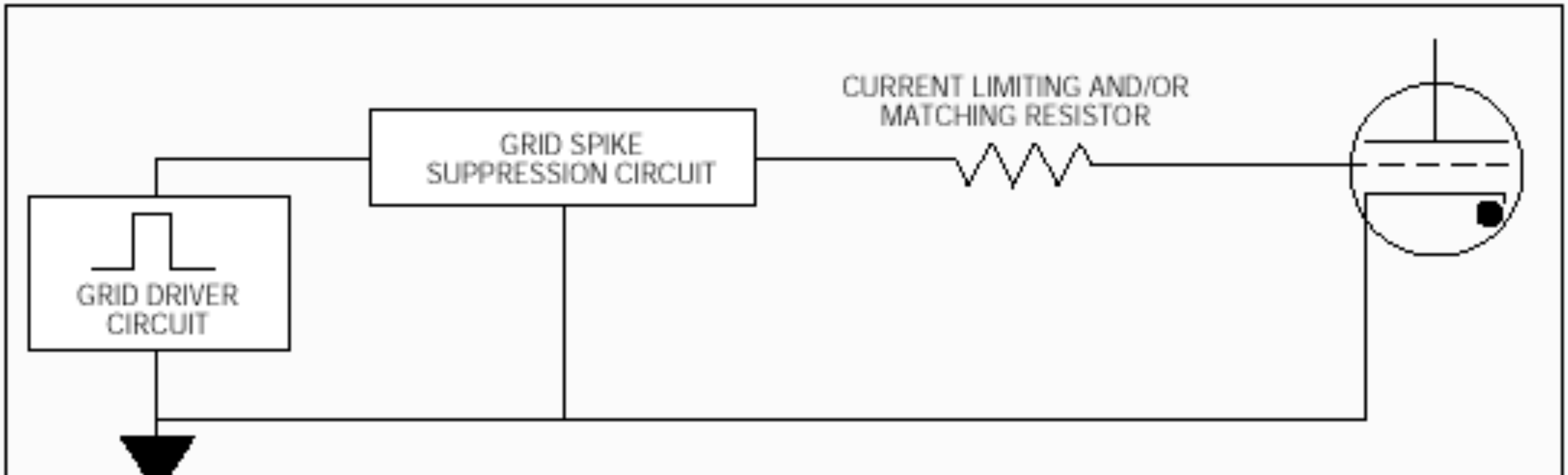


Figure 3. Grid Circuit

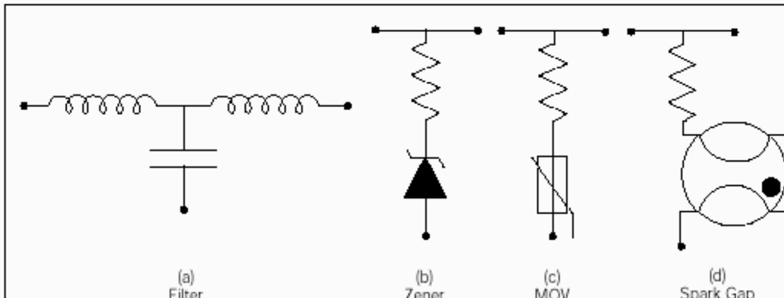


Figure 4. Typical Grid Spike Suppression Circuits

Commercial Thyratron Examples

Type	Peak Anode Voltage epy (kV)	Peak Anode Current ib (a)	Average Anode Current Ib (Adc)	RMS Anode Current Ip (Aac)	Plate Dissipation Factor Pb ($x 10^9$)	Cathode Heater V/A	Reservoir Heater V/A	Peak Forward Grid Voltage egy (Min)	Impedence of Grid Circuits g (Max)	EIA Type & Comments	Notes	Seated Height x Tube Width (Inches)
HY-2	8	100	0.1	2	2.7	6.3/3.5	Note 1	175	1200	JAN 7621	1	2.35 x 1.0
HY-6	16	350	0.5	6.5	5	6.3/7	6.3/2.5	150	1500	JAN 7782		2 x 1.4
HY-60	16	350	0.5	6.5	5	6.3/7	6.3/7	150	1500	JAN 7665A		2.4 x 1.4
HY-61	16	350	0.5	6.5	5	6.3/8.5	Note 1	150	1500		1	3.6 x 1.4
HY-10	20	500	0.5	8	10	6.3/7.5	6.3/4	200	500	JAN 7620		3.4 x 2
HY-11	18	1600	0.5	8	10	6.3/7.5	6.3/4	200	500			2.2 x 2.25
HY-1A	18	500	0.5	8	10	6.3/11	Note 1	175	500	JAN8613	1	5 x 2
HY-1102	18	1000	0.5	16	10	6.3/7.5	6.3/8	20	500		2	2 x 2
HY-3192	32	1000	2.2	47.5	50	6.3/12.5	6.3/5.5	1500	250		3	3.75 x 3.25
HY-32	32	1500	2.2	47.5	50	6.3/18	6.3/5.5	450	400		4	4 x 3.25
HY-3204	32	1500	1	25	40	6.3/18	6.3/6	450	400	ib to 10kA @ <1usec	4	3 x 6
1802	25	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	400	JAN 7322	4	4 x 3.25
HY-3002	25	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	400			4 x 3.25
HY-3003	35	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	400			4 x 3.25
HY-3004	25	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	400			4.75 x 3.25
HY-3005	35	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	400		3	4.75 x 3.25
HY-3025	28	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	250			4.25 x 3.25
HY-3189	32	5000	2.2	47.5	50	6.3/12.5	6.3/5.5	500	250			3.75 x 3
HY-5	40	5000	8	125	160	6.3/30	4.5/11	1300	100	8614		5 x 4.5
HY-53	40	5000	4	90	100	6.3/30	4.5/11	1300	100		3	5 x 4.5
LS-3101S	35	5000	2	45	50	6.3/18	6.3/6	500	250		6	5.25 x 3
LS-4101	40	12000	3	55	50	6.3/28	6.3/6	500	250		3,6	8 x 3.5
LS-4111	40	12000	3	55	100	6.3/28	6.3/6	500	250		3,5,6	8.25 x 3.5

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

SLAC

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 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

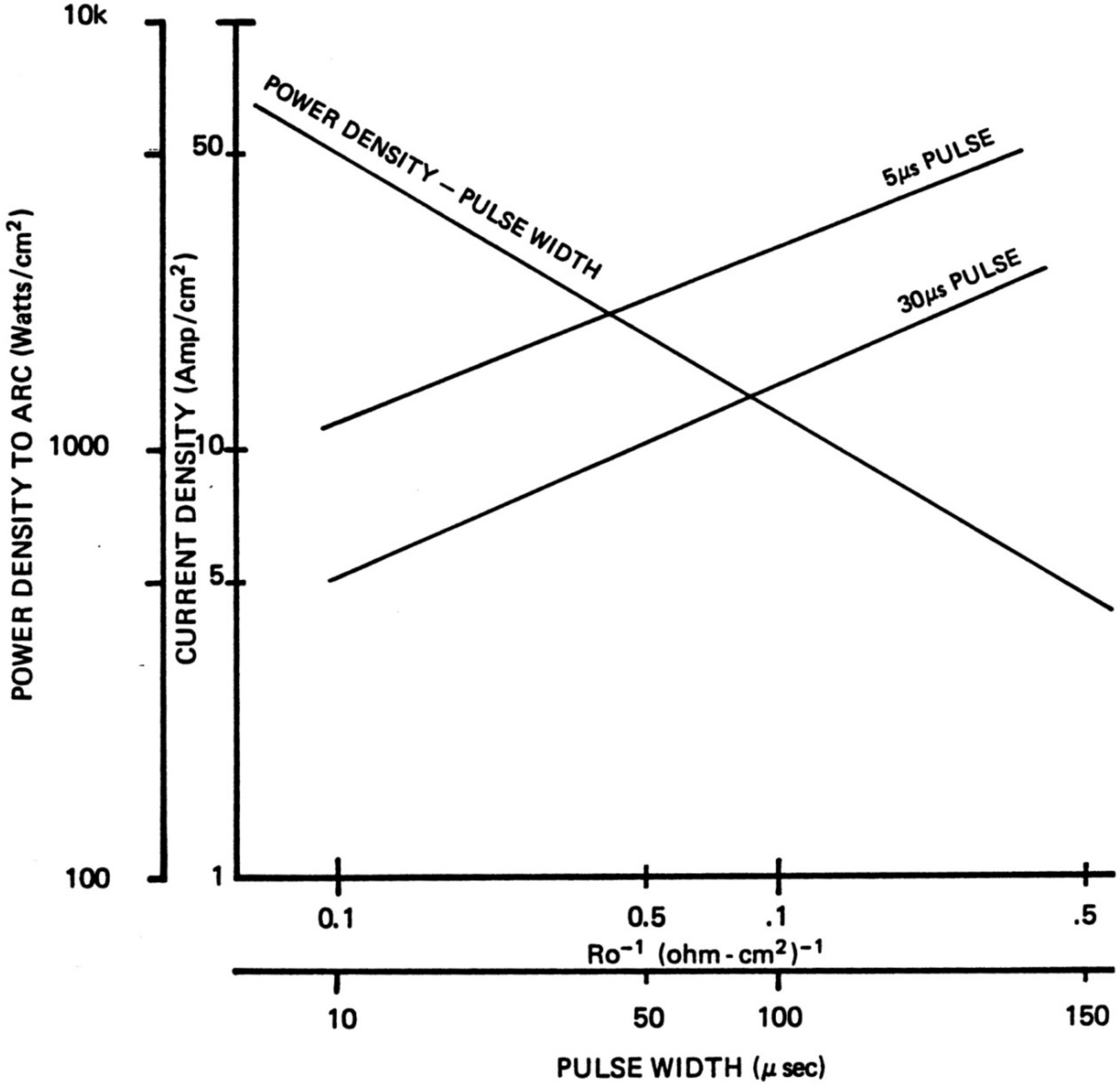
Static (Self) Breakdown Voltage (SBV): applied voltage at which a thyratron will break down spontaneously, without being triggered.

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.

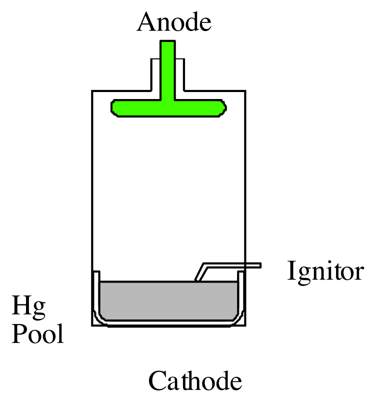
Thyratron Tradeoffs



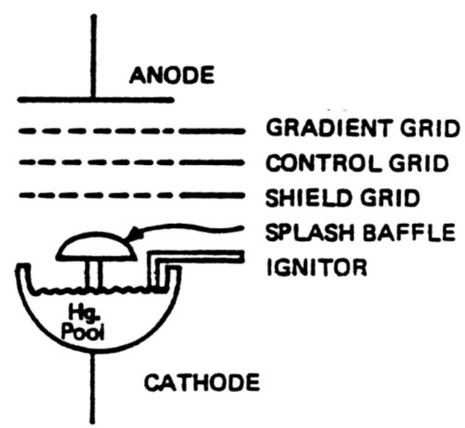
Ignitron

- 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



Plasma Opening Switch (POS)

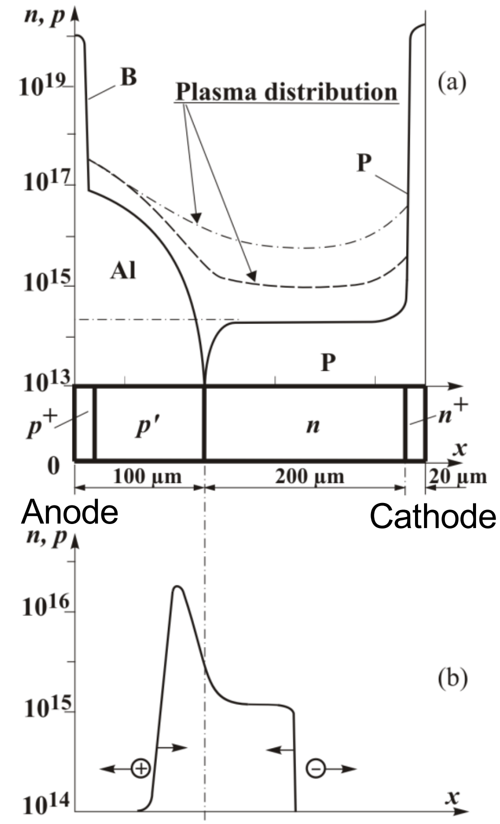
- Initially, a high density plasma forms a low-conductivity channel (switch closed)
- Plasma conductivity is rapidly decreased, ~10 to 100 ns, opening the switch
- Opening mechanisms
  - Plasma erosion switch: plasma source is turned off, conductive particles are swept out by applied fields (plasma erodes), switch opens
  - Applied fields inhibit the flow of conductive particles (electrons) across switch
- Used primarily in effects simulators
- Voltage: >MV, Current: >MA

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

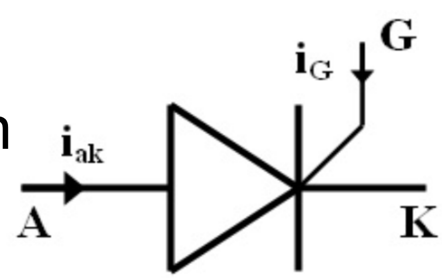


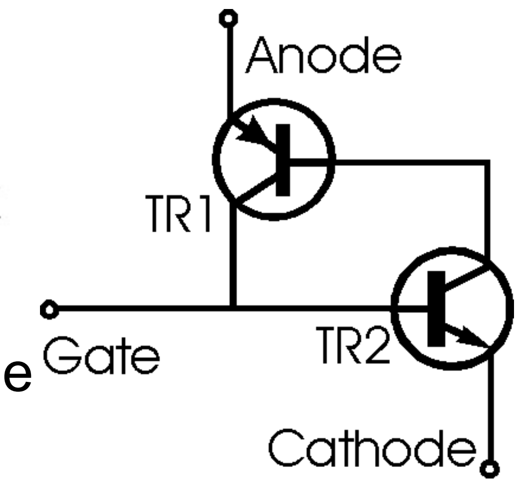
DSRD: (a) design and "plasma" distribution, ‾·‾ dc bias, ---- pulse bias, (b) "plasma" distribution at start of reverse bias

Grekhov, et.al., 2004 PMC

Thyristors

- Closing switch
- 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 $I_{conducted} > I_{threshold}$
    - 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
    - dI/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 ~ 10^{12} V/s
  - Turn on time < μs
- Photon initiated (optical) thyristor
  - Triggered by intense optical pulse that liberates carriers throughout junction
  - Turn on time << μs

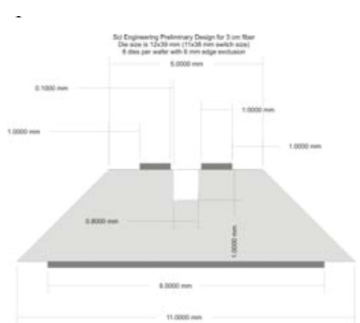


Fig. 2. End view drawings of optical thyristor

McDonald, IPMC2006

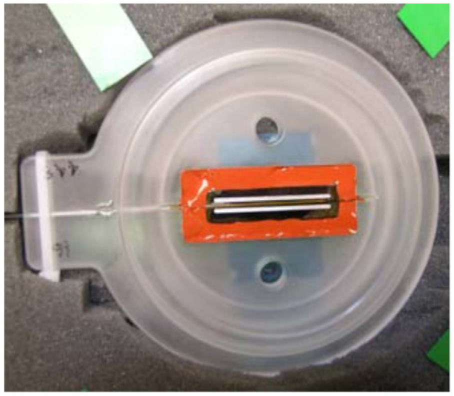


Fig. 3. Photograph of PIMM optical thyristor

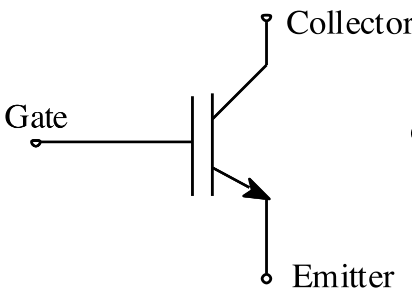
Fig. 4. Photograph of Two-Switch Electrode assembly.

Bulk Semiconductor Switches

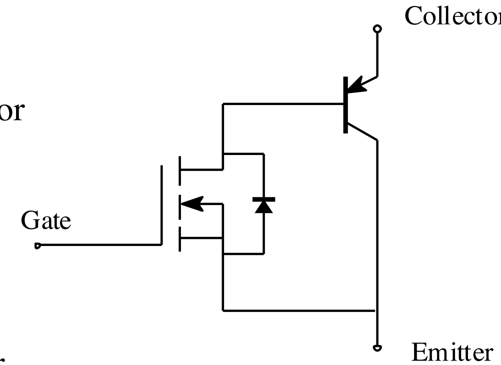
- Bulk semiconductor materials; Si, GaAs, diamond-like carbon, can be used as a switch
- Carriers can be produced through the bulk of the material by depositing energy; photons (laser) or electron beam, to trigger the switch
- If trigger induces carrier avalanching, then can only operate as a closing 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

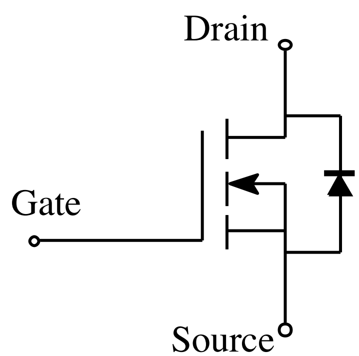
- Hard switch: closes and opens
- Bi-polar devices
  - Minority carrier devices
  - Conduction characterized by $V_{CE} < 3$ V (typical)
  - NPN/PNP power transistors generally replaced by Insulated Gate Bipolar Transistors (IGBT)
    - Lower drive power
    - Available at higher voltage, current and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



Symbol



IGBT Equivalent Circuit



Symbol (N-type)

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 $I > I_{SAT}$) α 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 dI/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

IGBT Data Sheet

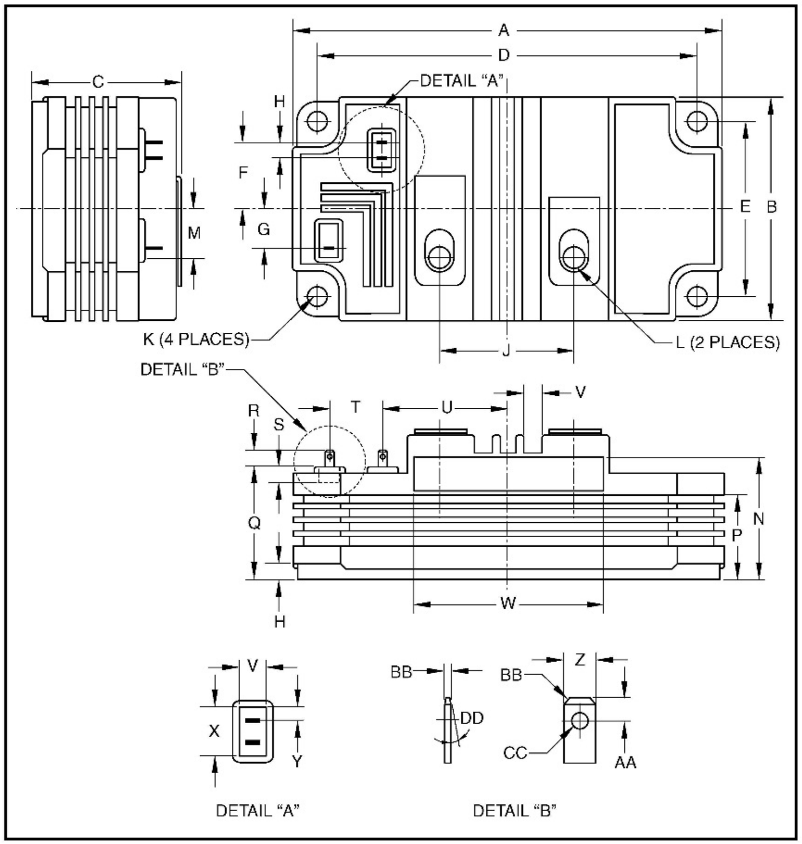
SLAC

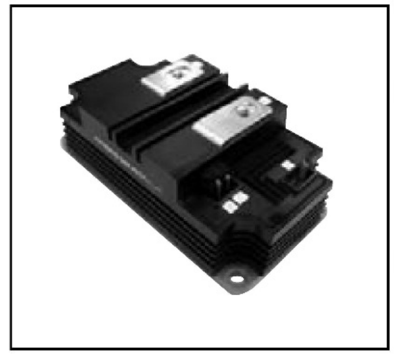
POWEREX

CM200HG-130H

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

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 $V_{CE(sat)}$
- ☐ Super-Fast Recovery

IGBT Data Sheet (cont.)

SLAC

POWEREX

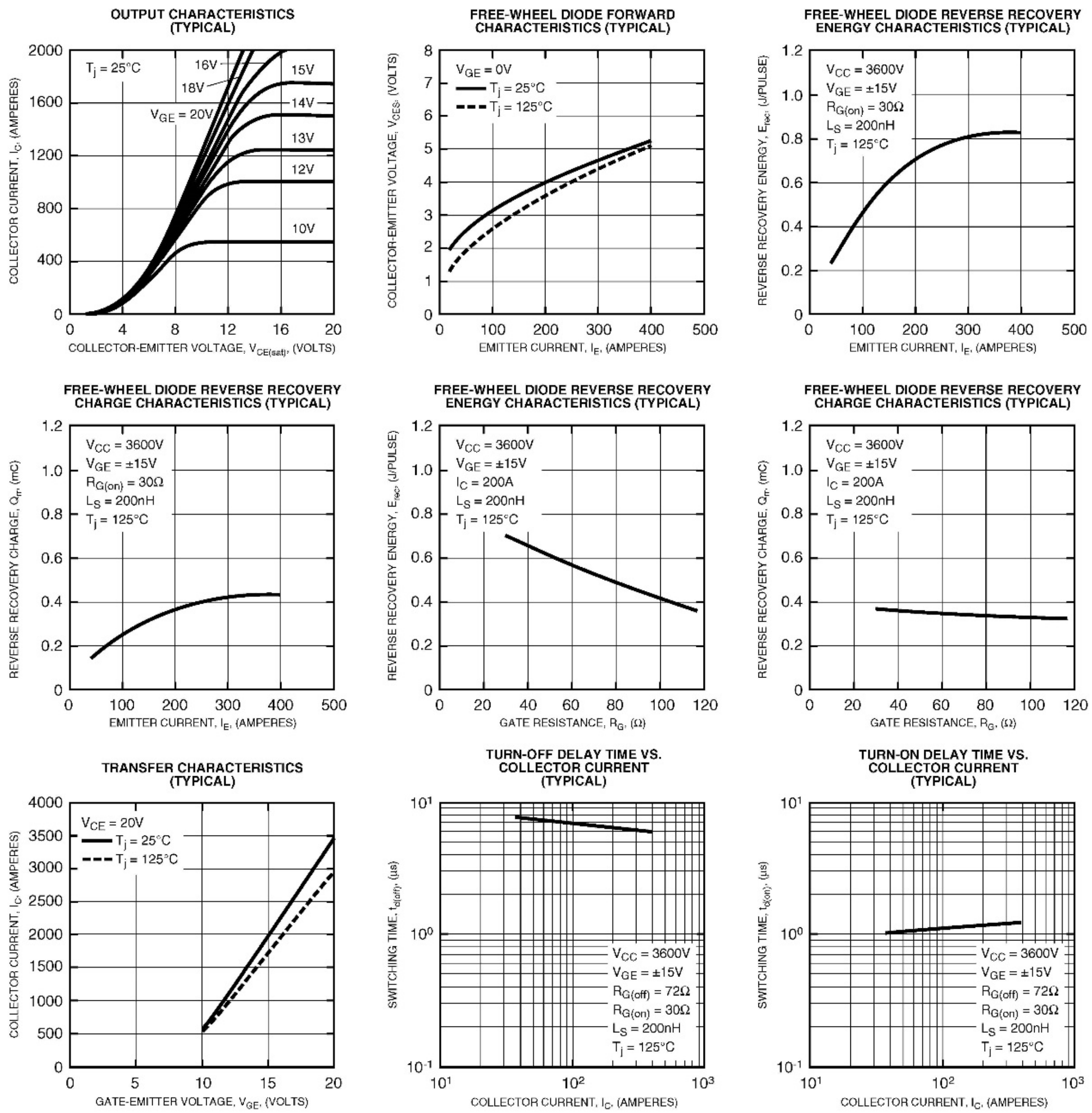
Powerex, Inc., 200 E. Hillis Street, Youngwood, Pennsylvania 15697-1800 (724) 925-7272

CM200HG-130H
Single IGBTMOD™ HVIGBT Module
200 Amperes/6500 Volts

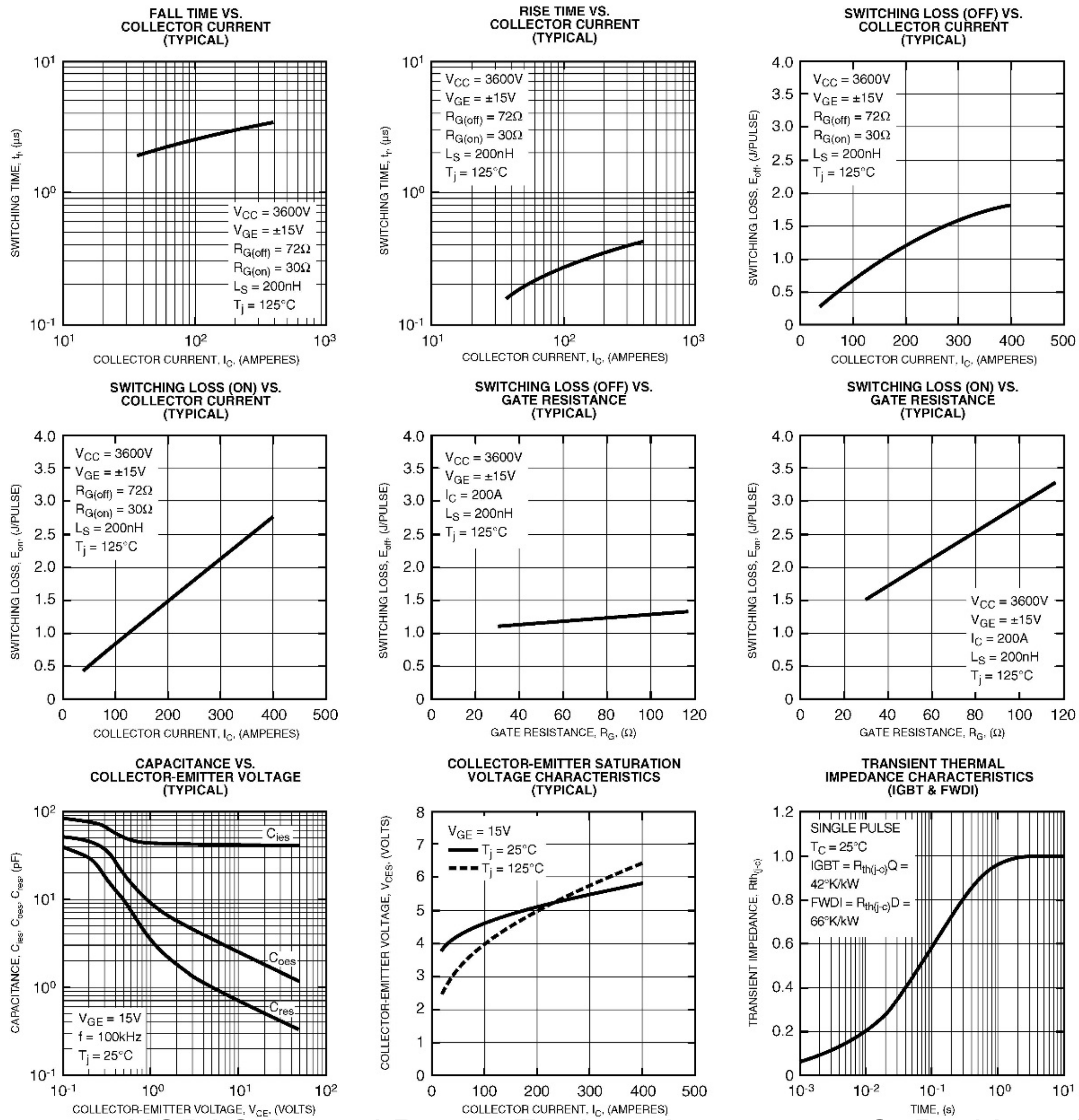
Absolute Maximum Ratings, T_j = 25 °C unless otherwise specified

Ratings	Symbol	CM200HG-130H	Units
Junction Temperature	T_j	-40 to 150	°C
Storage Temperature	T_{stg}	-40 to 125	°C
Operating Temperature	T_{opr}	-40 to 125	°C
Collector-Emitter Voltage (V_{GE} = 0V, T_j = -40°C)	V_{CES}	5800	Volts
Collector-Emitter Voltage (V_{GE} = 0V, T_j = +25°C)	V_{CES}	6300	Volts
Collector-Emitter Voltage (V_{GE} = 0V, T_j = +125°C)	V_{CES}	6500	Volts
Gate-Emitter Voltage (V_{CE} = 0V)	V_{GES}	±20	Volts
Collector Current (DC, T_c = 80°C)	I_C	200	Amperes
Peak Collector Current (Pulse)	I_{CM}	400*	Amperes
Emitter Current** (T_c = 25°C)	I_E	200	Amperes
Emitter Surge Current** (Pulse)	I_{EM}	400*	Amperes
Maximum Collector Dissipation (T_c = 25°C, IGBT Part, $T_{j(max)} \le$ 125°C)	P_C	2900	Watts
Partial Discharge (V_1 = 6900 V_{rms}, V_2 = 5100 V_{rms}, 60 Hz (Acc. to IEC 1287))	Q_{pd}	10	pC
Max. Mounting Torque M8 Main Terminal Screws	–	133	in-lb
Max. Mounting Torque M6 Mounting Screws	–	53	in-lb
Module Weight (Typical)	–	0.52	kg
Isolation Voltage (Charged Part to Baseplate, AC 60Hz 1 min.)	V_{iso}	10200	Volts
Maximum Turn-Off Switching Current ($V_{CC} \le$ 4500V, V_{GE} = ±15V, $R_{G(off)} \ge$ 72Ω, T_j = 125°C)	–	400	Amperes
Short Circuit Capability, Maximum Pulse Width ($V_{CC} \le$ 4500V, V_{GE} = ±15V, $R_{G(off)} \ge$ 72Ω, T_j = 125°C)	–	10	µs
Maximum Reverse Recovery Instantaneous Power ($V_{CC} \le$ 4500V, $di_e/dt \le$ 1000A/µs, T_j = 125°C)	–	1200	kW

IGBT Data Sheet (cont.)



IGBT Data Sheet (cont.)



MOSFET

- Fastest commercial solid state switch available
  - Intrinsic turn on/off time ~ns set by $R_{DS\text{-}ON}C_{OUTPUT}$ time constant (carrier junction crossing time much faster)
  - Effective switching time limited by input capacitance, stray packaging inductance, and dI_S/dt to ≥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: ~0.1 kA (higher for modules and lower voltage FETs)
  - Pulsed current limited to ~4X average rating due to increase in $R_{DS\text{-}ON}$
- "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

Microsemi POWER PRODUCTS GROUP

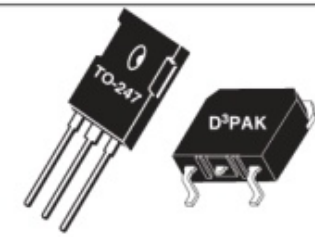
Power MOS 8™ Cooler!

APT13F120B
APT13F120S

1200V, 13A, 1.40Ω Max, t_{rr}, ≤250ns

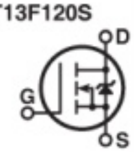
N-Channel FREDFET

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.



APT13F120B APT13F120S

Single die FREDFET



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

MOSFET Data Sheet (cont.)

SLAC

Absolute Maximum Ratings

Symbol	Parameter	Ratings	Unit
I_D	Continuous Drain Current @ $T_C = 25°C$	13	A
	Continuous Drain Current @ $T_C = 100°C$	8	
I_{DM}	Pulsed Drain Current[1]	50	
V_{GS}	Gate-Source Voltage	±30	V
E_{AS}	Single Pulse Avalanche Energy[2]	1070	mJ
I_{AR}	Avalanche Current, Repetitive or Non-Repetitive	7	A

Thermal and Mechanical Characteristics

Symbol	Characteristic	Min	Typ	Max	Unit
P_D	Total Power Dissipation @ $T_C = 25°C$			625	W
$R_{\theta JC}$	Junction to Case Thermal Resistance			0.20	°C/W
$R_{\theta CS}$	Case to Sink Thermal Resistance, Flat, Greased Surface		0.11		
T_J, T_{STG}	Operating and Storage Junction Temperature Range	-55		150	°C
T_L	Soldering Temperature for 10 Seconds (1.6mm from case)			300	
W_T	Package Weight		0.22		oz
			6.2		g
Torque	Mounting Torque (TO-247 Package), 6-32 or M3 screw			10	in·lbf
				1.1	N·m

Microsemi Website - http://www.microsemi.com

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MOSFET Data Sheet (cont.)

Static Characteristics $T_J = 25°C$ unless otherwise specified **APT13F120B_S**

Symbol	Parameter	Test Conditions		Min	Typ	Max	Unit
$V_{BR(DSS)}$	Drain-Source Breakdown Voltage	$V_{GS} = 0V$, $I_D = 250\mu A$		1200			V
$\Delta V_{BR(DSS)}/\Delta T_J$	Breakdown Voltage Temperature Coefficient	Reference to 25°C, $I_D = 250\mu A$			1.41		V/°C
$R_{DS(on)}$	Drain-Source On Resistance③	$V_{GS} = 10V$, $I_D = 7A$			1.11	1.40	Ω
$V_{GS(th)}$	Gate-Source Threshold Voltage	$V_{GS} = V_{DS}$, $I_D = 1mA$		3	4	5	V
$\Delta V_{GS(th)}/\Delta T_J$	Threshold Voltage Temperature Coefficient				-10		mV/°C
I_{DSS}	Zero Gate Voltage Drain Current	$V_{DS} = 1200V$	$T_J = 25°C$			250	μA
		$V_{GS} = 0V$	$T_J = 125°C$			1000	
I_{GSS}	Gate-Source Leakage Current	$V_{GS} = \pm 30V$				±100	nA

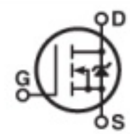
Dynamic Characteristics $T_J = 25°C$ unless otherwise specified

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
g_{fs}	Forward Transconductance	$V_{DS} = 50V$, $I_D = 7A$		15		S
C_{iss}	Input Capacitance	$V_{GS} = 0V$, $V_{DS} = 25V$ f = 1MHz		4765		pF
C_{rss}	Reverse Transfer Capacitance			55		
C_{oss}	Output Capacitance			350		
$C_{o(cr)}$ ④	Effective Output Capacitance, Charge Related	$V_{GS} = 0V$, $V_{DS} = 0V$ to 800V		135		
$C_{o(er)}$ ⑤	Effective Output Capacitance, Energy Related			70		
Q_g	Total Gate Charge	$V_{GS} = 0$ to 10V, $I_D = 7A$, $V_{DS} = 600V$		145		nC
Q_{gs}	Gate-Source Charge			24		
Q_{gd}	Gate-Drain Charge			70		
$t_{d(on)}$	Turn-On Delay Time	**Resistive Switching** $V_{DD} = 800V$, $I_D = 7A$ $R_G = 4.7\Omega$⑥, $V_{GG} = 15V$		26		ns
t_r	Current Rise Time			15		
$t_{d(off)}$	Turn-Off Delay Time			85		
t_f	Current Fall Time			24		

MOSFET Data Sheet (cont.)

SLAC

Source-Drain Diode Characteristics

Symbol	Parameter	Test Conditions		Min	Typ	Max	Unit
I_S	Continuous Source Current (Body Diode)	MOSFET symbol showing the integral reverse p-n junction diode (body diode) 				13	A
I_{SM}	Pulsed Source Current (Body Diode) ①					50	A
V_{SD}	Diode Forward Voltage	$I_{SD} = 7A$, $T_J = 25°C$, $V_{GS} = 0V$				1.0	V
t_{rr}	Reverse Recovery Time	$I_{SD} = 7A$ ③ $di_{SD}/dt = 100A/\mu s$ $V_{DD} = 100V$	$T_J = 25°C$			250	ns
			$T_J = 125°C$			520	ns
Q_{rr}	Reverse Recovery Charge		$T_J = 25°C$		1.12		µC
			$T_J = 125°C$		3.03		µC
I_{rrm}	Reverse Recovery Current		$T_J = 25°C$		10		A
			$T_J = 125°C$		13.5		A
dv/dt	Peak Recovery dv/dt	$I_{SD} \le 7A$, $di/dt \le 1000A/\mu s$, $V_{DD} = 800V$, $T_J = 125°C$				25	V/ns

① Repetitive Rating: Pulse width and case temperature limited by maximum junction temperature.

② Starting at $T_J = 25°C$, $L = 43.59mH$, $R_G = 4.7\Omega$, $I_{AS} = 7A$.

③ Pulse test: Pulse Width < 380µs, duty cycle < 2%.

④ $C_{o(cr)}$ is defined as a fixed capacitance with the same stored charge as C_{OSS} with $V_{DS} = 67\%$ of $V_{(BR)DSS}$.

⑤ $C_{o(er)}$ is defined as a fixed capacitance with the same stored energy as C_{OSS} with $V_{DS} = 67\%$ of $V_{(BR)DSS}$. To calculate $C_{o(er)}$ for any value of V_{DS} less than $V_{(BR)DSS}$, use this equation: $C_{o(er)} = -2.17E\text{-}7/V_{DS}\hat{}2 + 2.63E\text{-}8/V_{DS} + 3.74E\text{-}11$.

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.

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MOSFET Data Sheet (cont.)

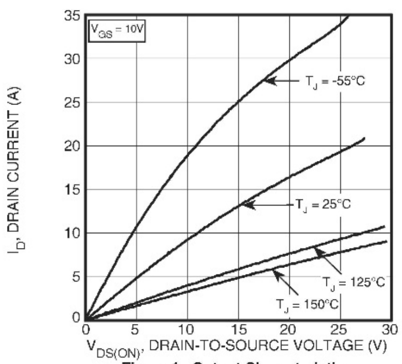


Figure 1, Output Characteristics

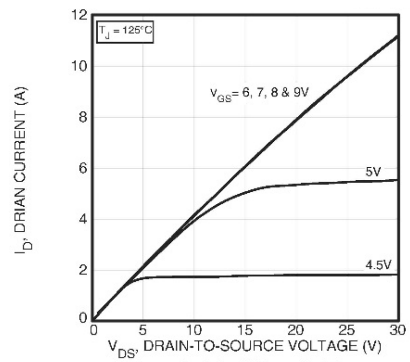


Figure 2, Output Characteristics

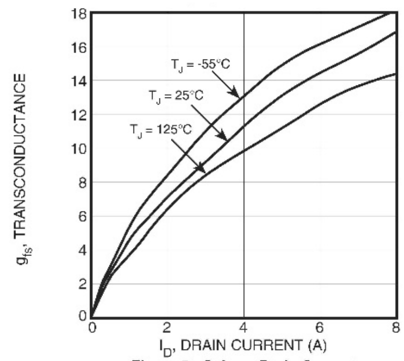


Figure 5, Gain vs Drain Current

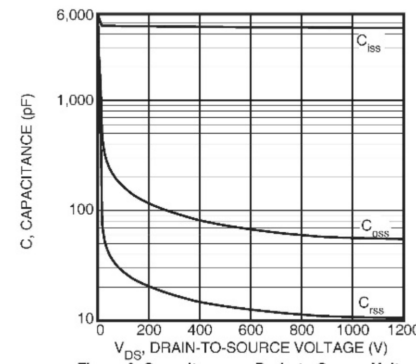


Figure 6, Capacitance vs Drain-to-Source Voltage

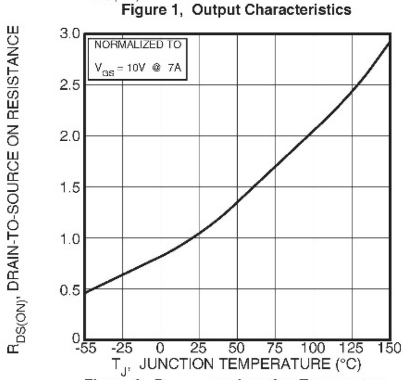


Figure 3, $R_{DS(ON)}$ vs Junction Temperature

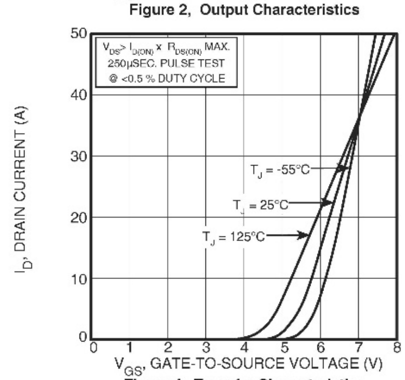


Figure 4, Transfer Characteristics

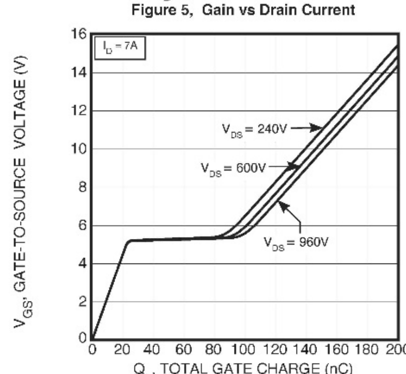


Figure 7, Gate Charge vs Gate-to-Source Voltage

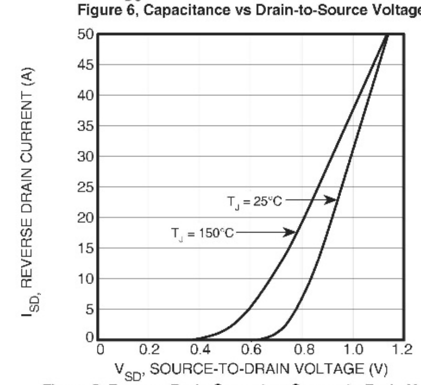


Figure 8, Reverse Drain Current vs Source-to-Drain Voltage

MOSFET Data Sheet (cont.)

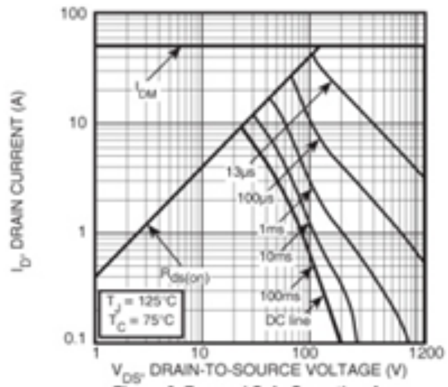


Figure 9, Forward Safe Operating Area

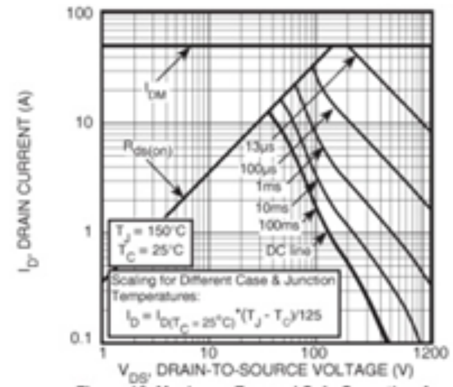


Figure 10, Maximum Forward Safe Operating Area

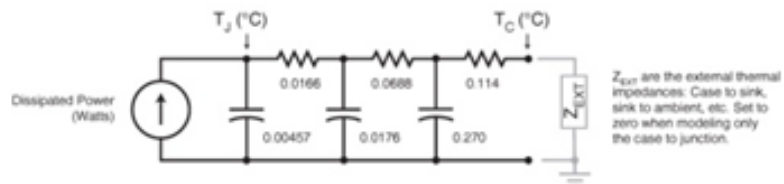


Figure 11, Transient Thermal Impedance Model

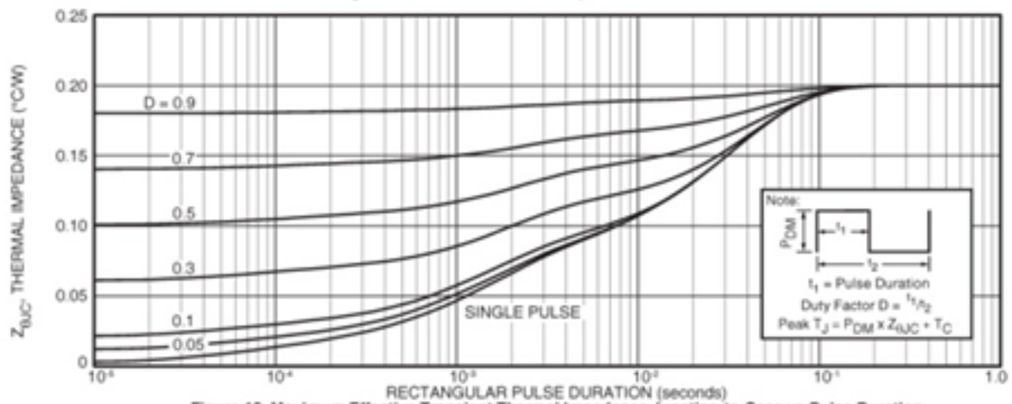
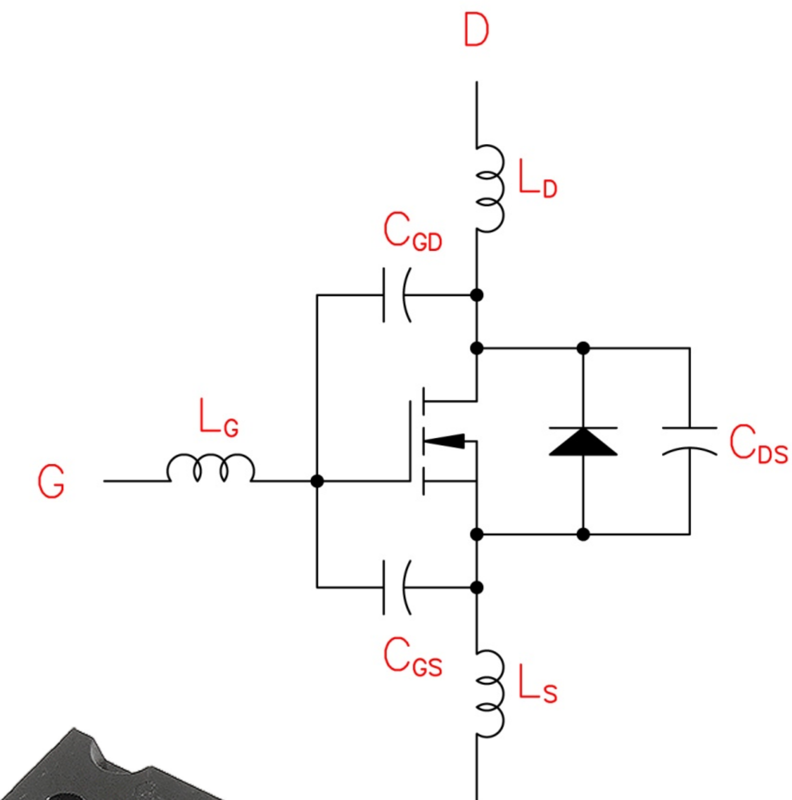


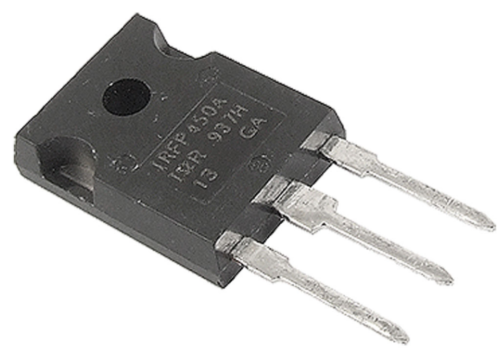
Figure 12. Maximum Effective Transient Thermal Impedance Junction-to-Case vs Pulse Duration

MOSFET Model for Fast Switching

- Data sheet information
  - Drain-source breakdown voltage: V_{DSS}
  - Drain current
    - Continuous: I_D
    - Pulsed: I_{DM}
  - $R_{DS\text{-}ON}$ @ 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



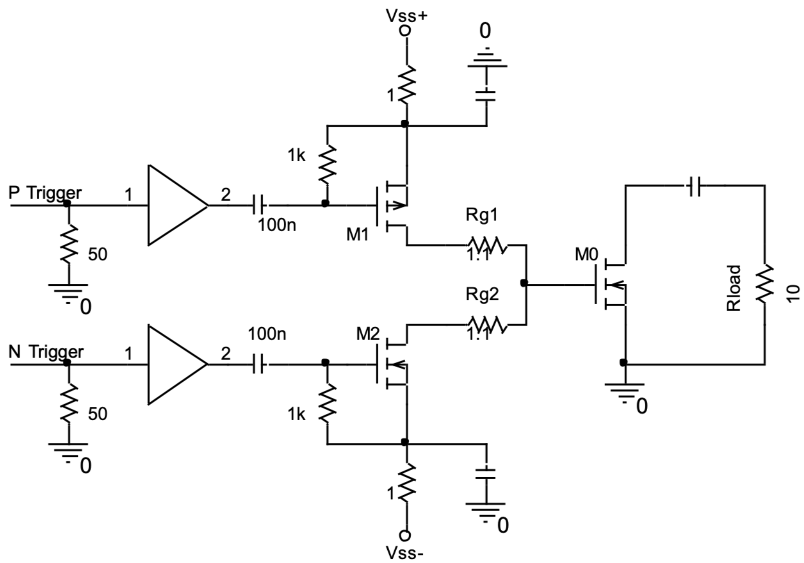
MOSFET Fast Switching

- Input capacitance and parasitic inductance form resonant circuit
  - $\omega < 10^9$, therefore $\tau_r \sim$ few ns will excite the resonance
  - Z ~ few ohm, therefore need significant gate resistance to damp
- Inductive voltage due to rising source current: $L_S dI_S/dt$
  - 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

MOSFET Fast Switching

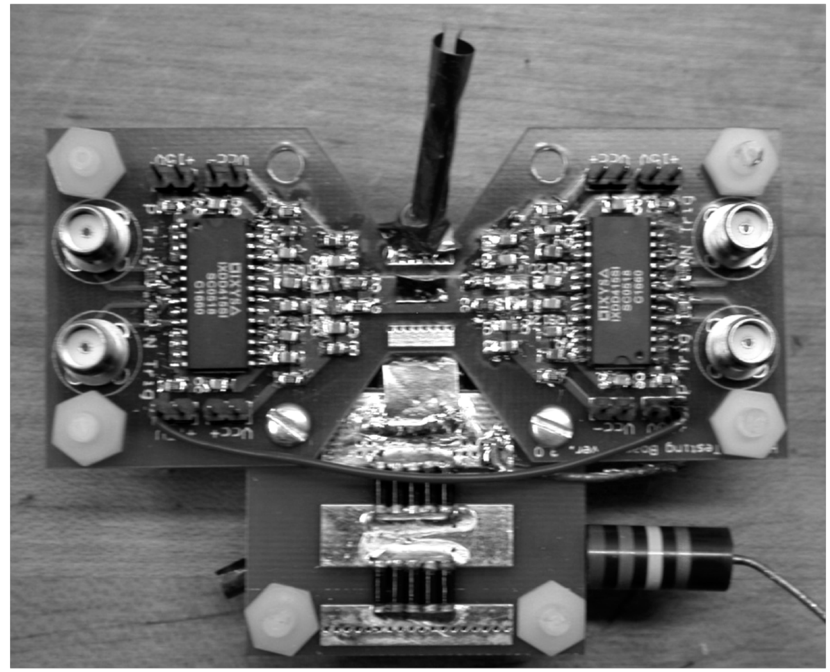
- Remediations
  - Use a bi-polar high voltage gate drive (limited by gate breakdown)
  - Use high gate drive resistance (balance with drive current requirements)
  - Use a larger number of smaller MOSFETs in parallel
  - Integrate driver into MOSFET package
    - Commercial units show little gain
 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

Hybrid MOSFET/Driver for Ultra-Fast Switching



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

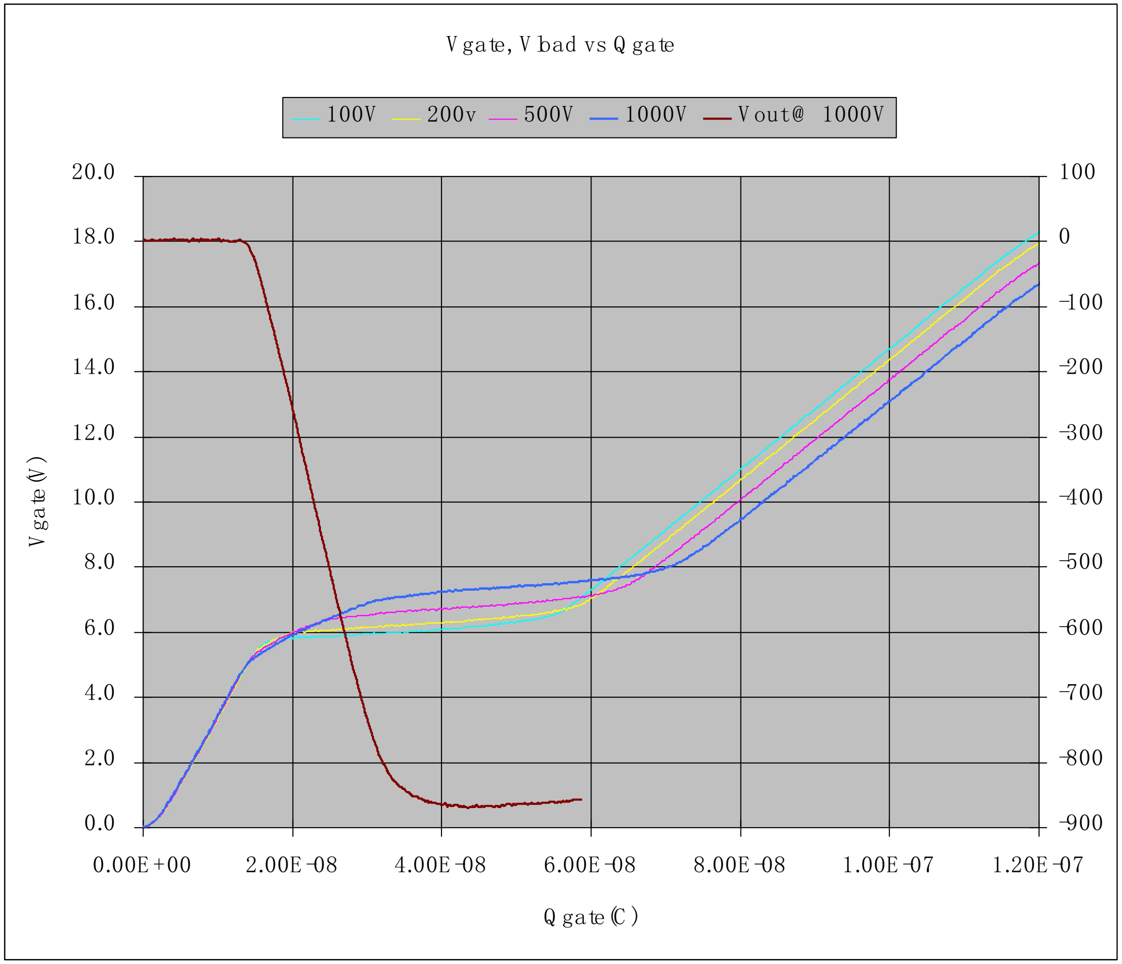
Tang & Burkhart, IPMC2008



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 (~20 nC < Q < 60 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 of Solid State Switches & Drivers

- Power Semiconductors (MOSFETs, IGBTs, Thyristors)
  - Microsemi: http://www.microsemi.com/ (APT devices)
  - Infineon: http://www.infineon.com/ (Eupec devices)
  - Powerex: http://www.pwrx.com/ (Powerex & Mitsubishi devices)
  - DYNEX: http://www.dynexsemi.com/
  - ST Microelectronics: http://www.st.com/web/en/home.html
  - Westcode: http://www.westcode.com/
  - International Rectifier: http://www.irf.com/
  - Toshiba: http://www.toshiba.com/taec/
  - ABB: http://www.abb.com/product/it/9AAC910029.aspx
  - IXYS: http://www.ixys.com/ (IXYS & DEI devices)
- Driver Circuits
  - IXYS: http://www.ixys.com/
  - Vishay: http://www.vishay.com/company/brands/siliconix/ (Siliconix devices)
  - Intersil: http://www.intersil.com/en.html (Elantec devices)