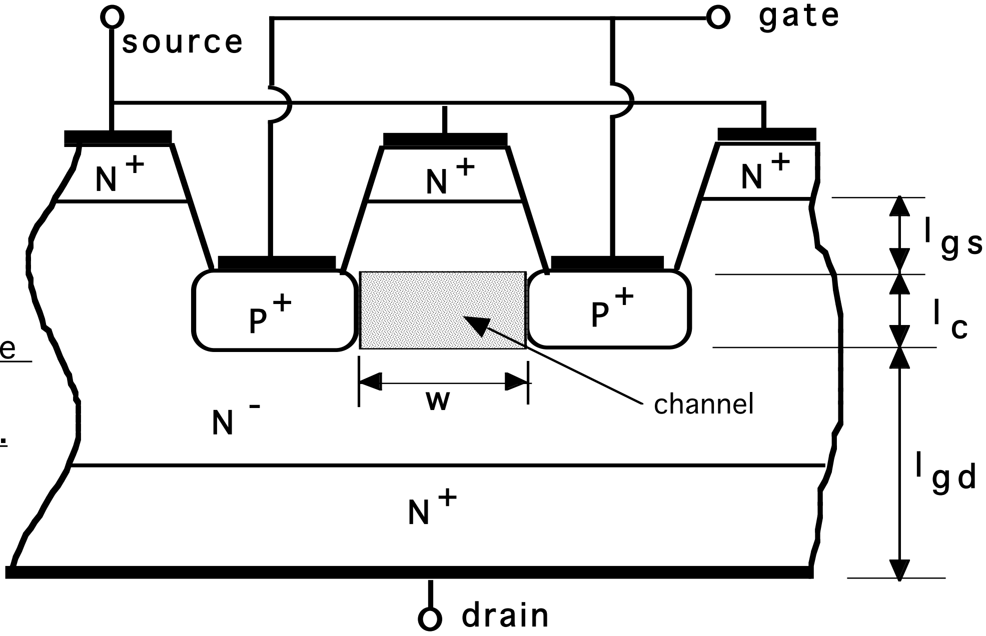
Lecture Notes

# Emerging Devices

## Outline

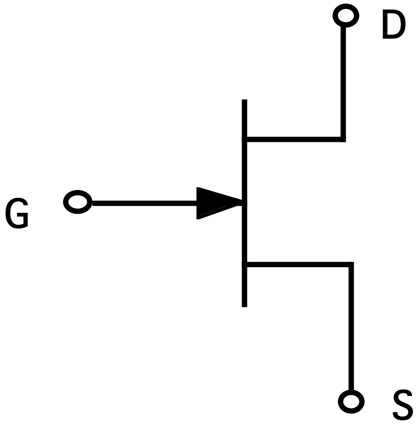
- Power JFET Devices
- Field-Controlled Thyristor
- MOS-Controlled Thyristor
- High Voltage Integrated Circuits/ Discrete Modules
- New Semiconductor Materials

# Power JFET Geometry

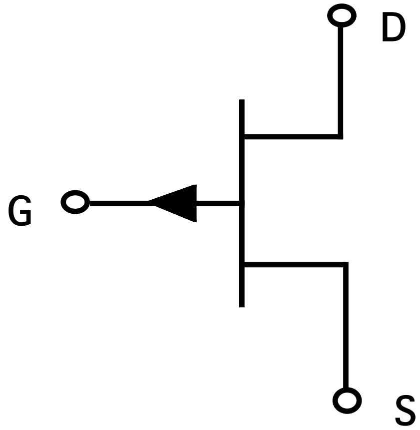


Recessed gate JFET cross-section.

N-channel JFET



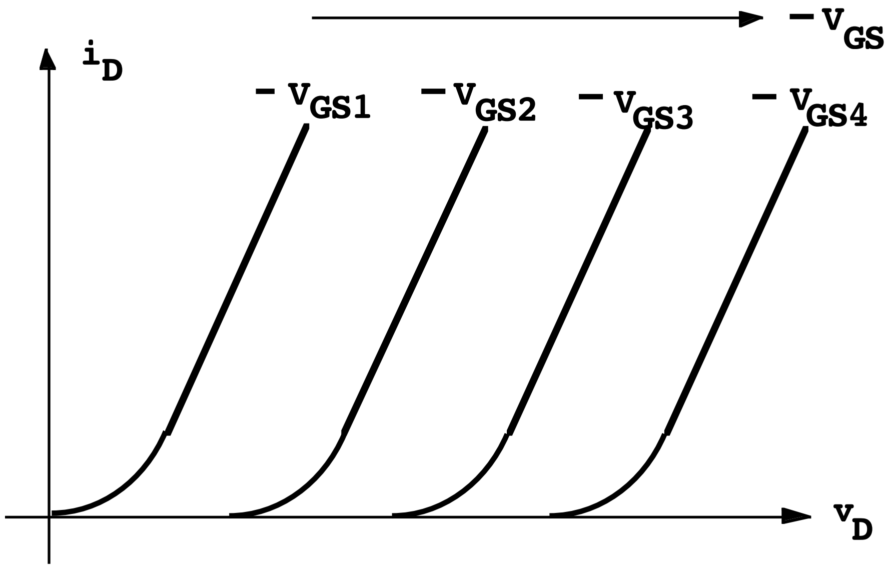
P-channel JFET



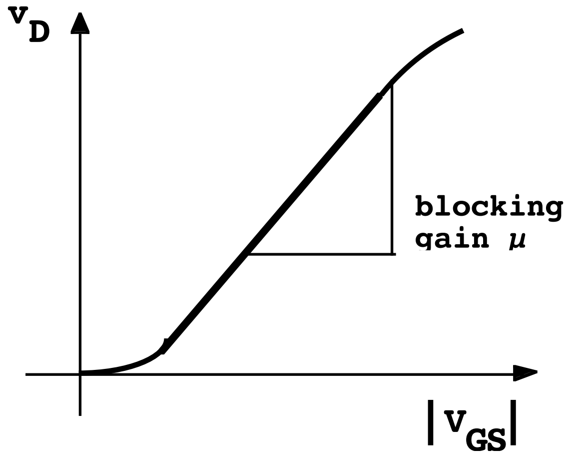
- Gate-source geometry highly interdigitated as in MOSFETs.
- Width w = $\mu$ms to a few tens of $\mu$ms ; $l_c < w$ ; $l_{gs}$ minimized.
- $l_{gd}$ set by blocking voltage considerations.

# Power JFET I-V Characteristics

Output characteristics

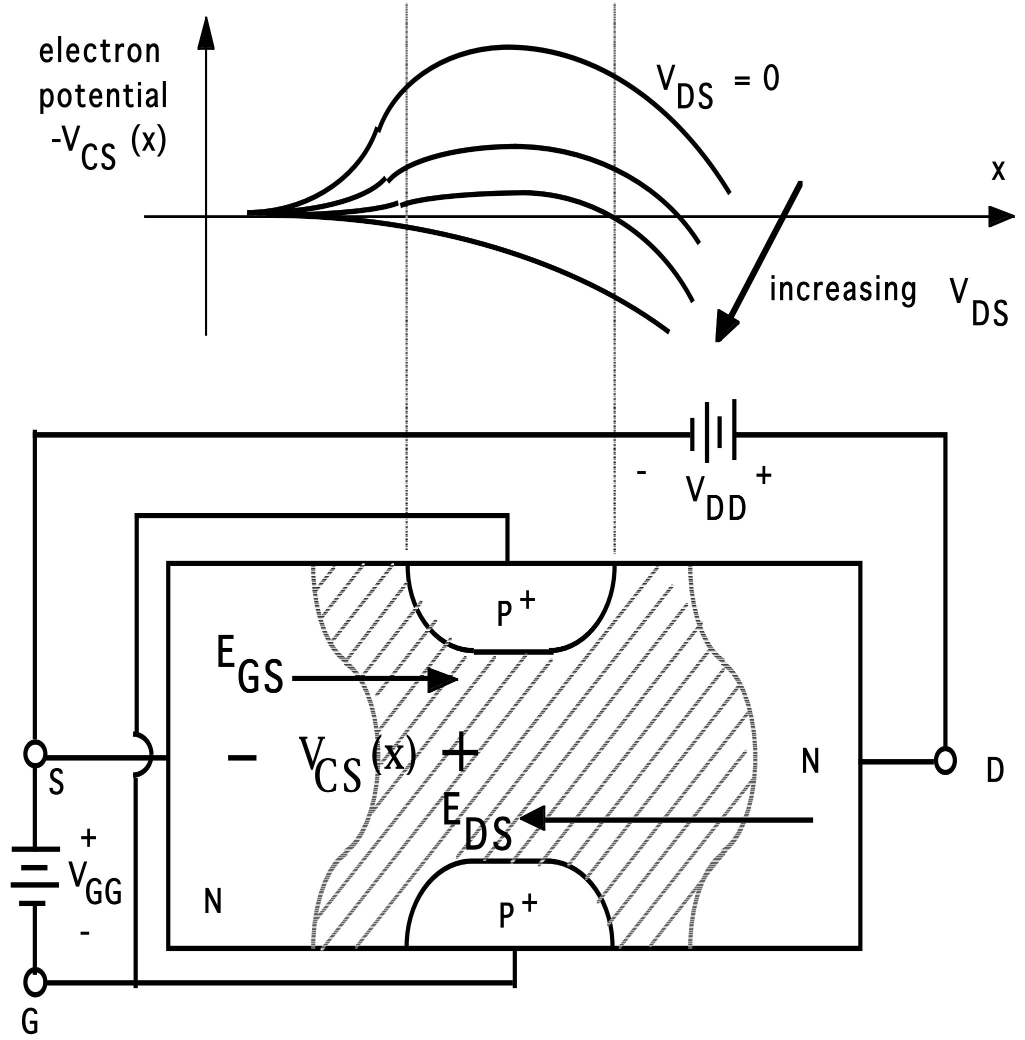


Transfer curve.



- Power JFET is a normally-on device. Substantial current flows when gate-source voltage is equal to zero.
- Opposite to BJTs, MOSFETs, and IGBTs which are normally-off devices.

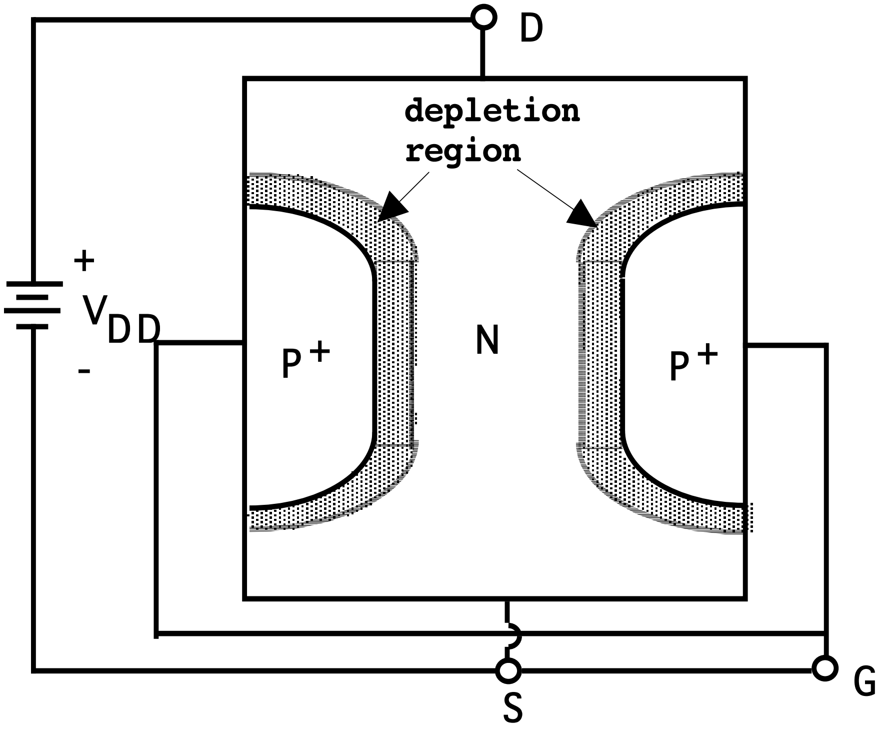
# Controlling Potential Barrier in JFETs



- $|V_{GS}| > |V_p|$ (pinchoff voltage) potential barrier to electron flow from source to drain created. No drain current can flow.
- Suppress potential barrier by increasing $V_{DS}$ at fixed $V_{GS}$. When $V_{DS} > \mu\, |V_{GS}|$ substantial drain currents flow.
- Blocking capability limited by magnitude of electric field in drift region. Longer drift regions have larger blocking voltage capability.
- Normally-off JFET created by having narrow enough channel width so that the channel is pinched off at zero gate-source voltage.

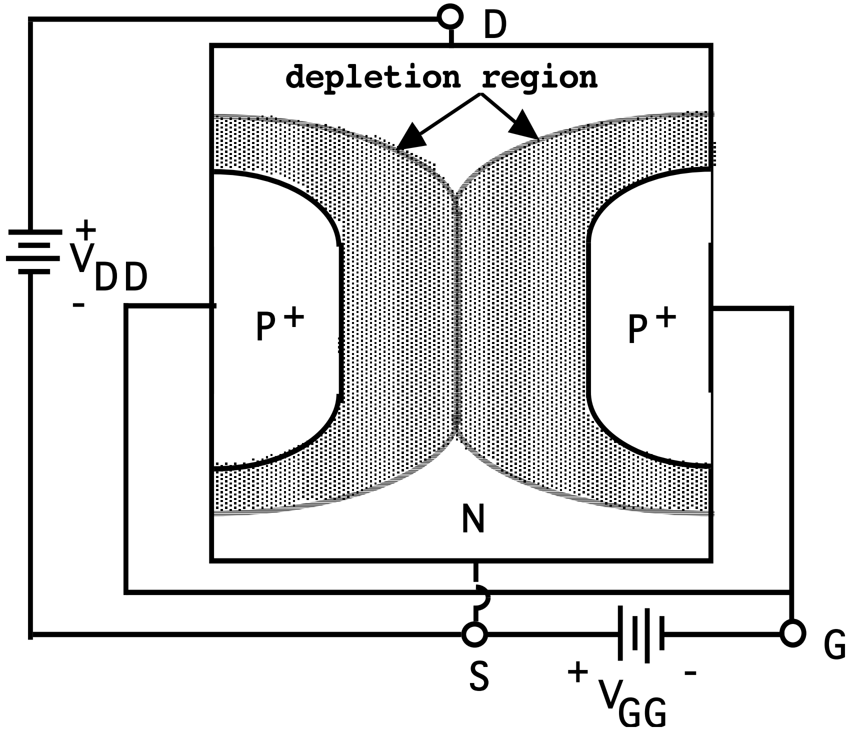
# JFET On and Off States

JFET in on-state



- **Channel open between drain and source.**

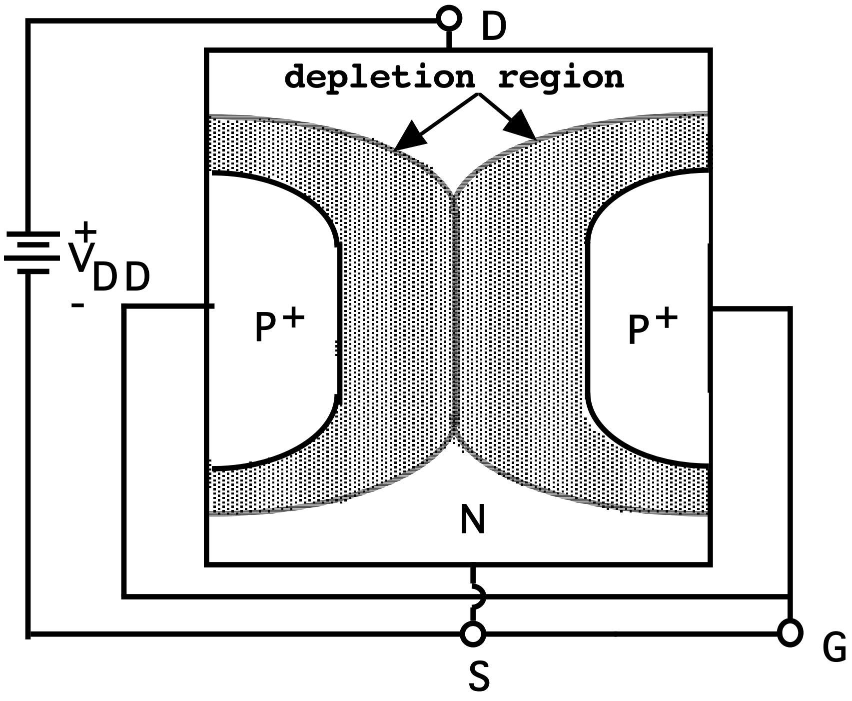
JFET in blocking state



- **Channel pinched-off (closed) between drain and source.**

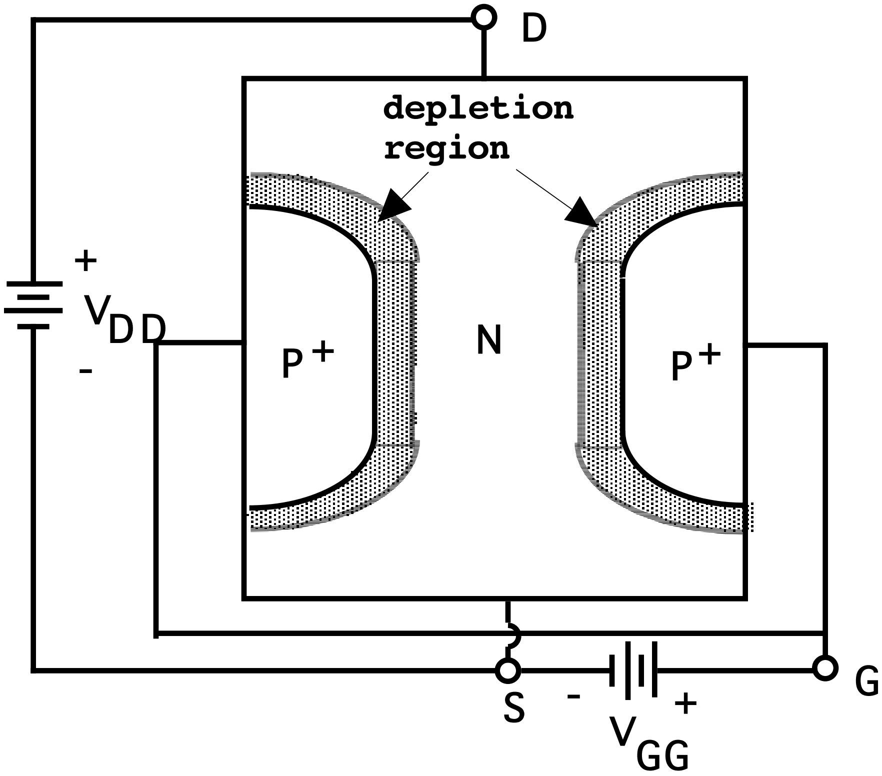
# Bipolar Static Induction Transistor (BSIT)

BSIT in blocking state



- Channel width and channel doping chosen so that at zero gate-source voltage, depletion layers of gate-channel junction pinch-off the channel.
- Narrower channel than normally-on JFET.

JFET in on-state



- Forward bias gate-channel junction to reduce depletion region width and open up channel.
- Substantial current flow into gate.

# JFET Switching Characteristics

- Equivalent circuits of JFETS nearly identical to those of MOSFETs

- Switching waveforms nearly identical to those of MOSFETs including values of various switching time intervals

- JFET $V_{GS}$ starts at negative values and steps to zero at turn-on while MOSFET $V_{GS}$ starts at zero and steps to positive value at turn-on

- FET on-state losses somewhat higher than for MOSFET - technology related not fundamental

- Normally-off JFET (Bipolar static induction transistor or BSIT) switching characteristics more similar to those of BJT

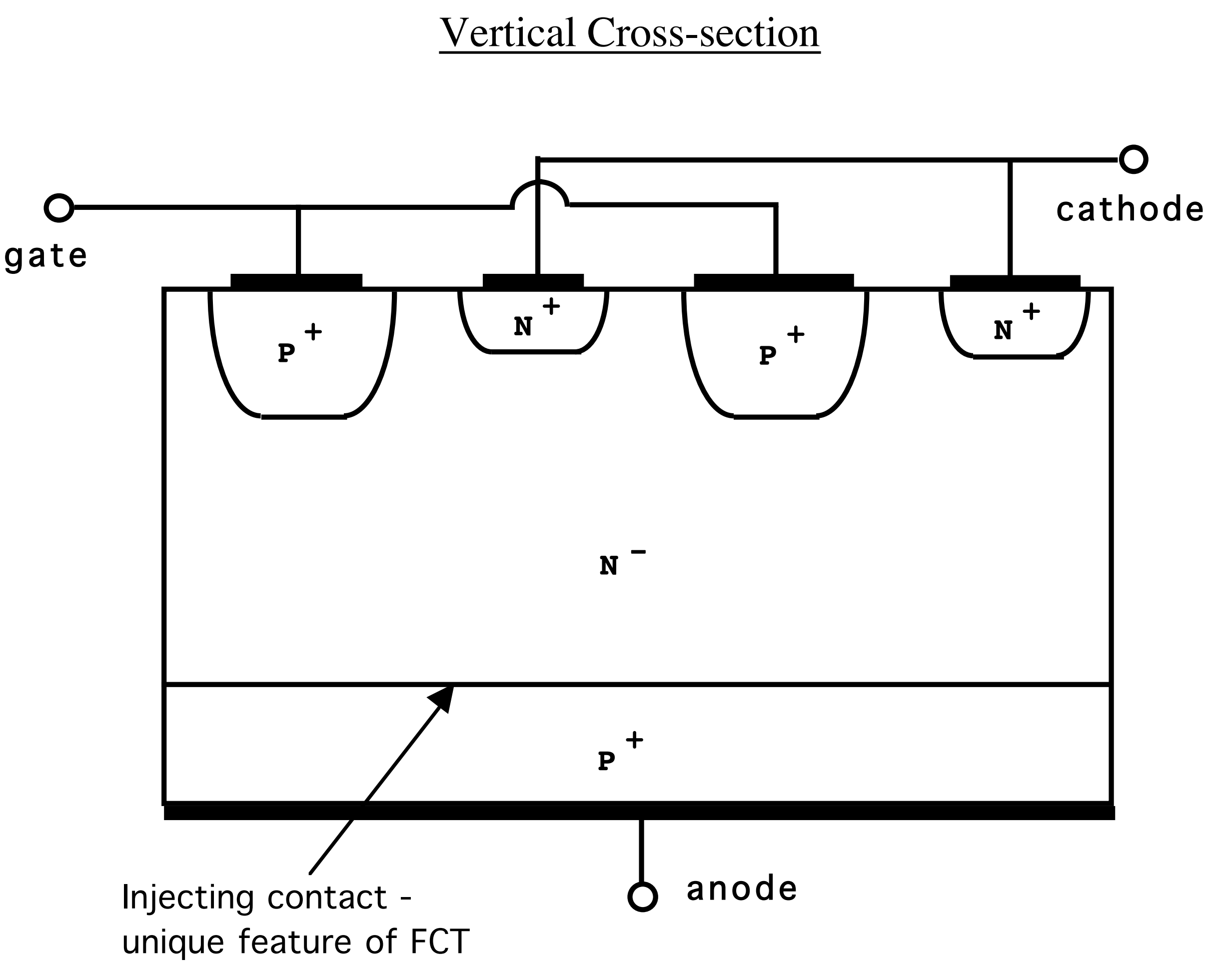
- Differences between BSIT and BJT observable mainly at turn-off

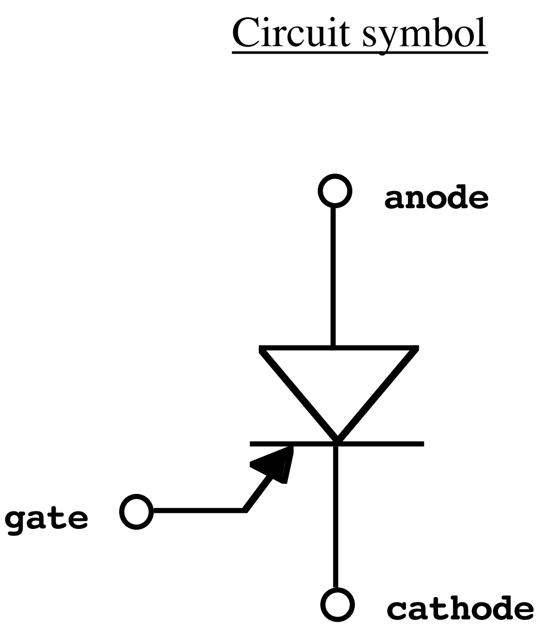
1. BSIT has no quasi-saturation region and thus only one current fall time (no current tailing) at turn-off.

2. Overall turn-off times of BSIT shorter than for BJT

3. Differences due to fact that BSIT has no in-line pn junction that can block sweep-out of excess carriers as does BJT

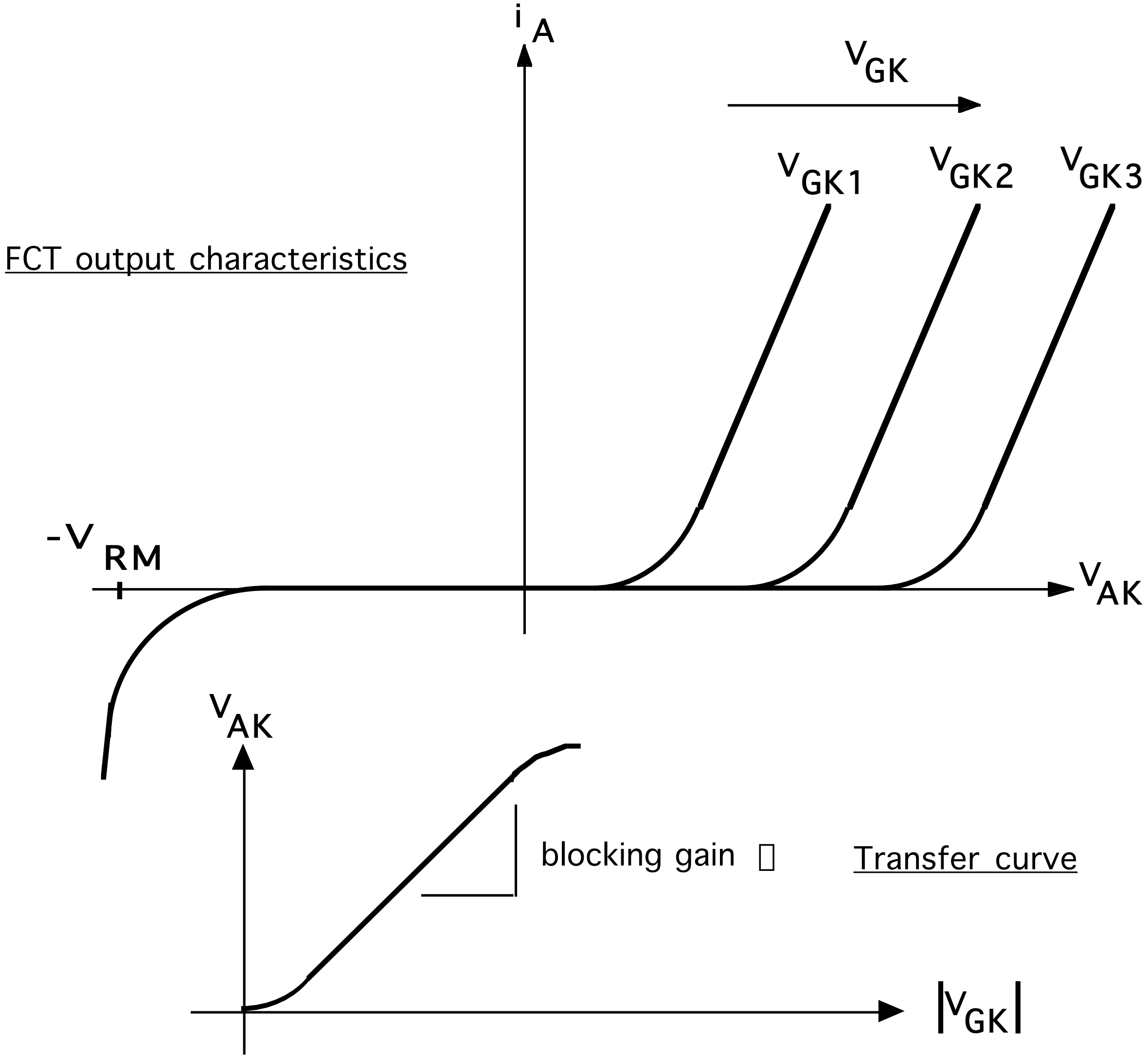
# Field-Controlled Thyristor (FCT)





- Sometimes termed a bipolar static induction thyristor (BSIThy).

# FCT I-V Characteristics



- FCT has a normally-on characteristic.
- Can be made to have a normally-off characteristic.

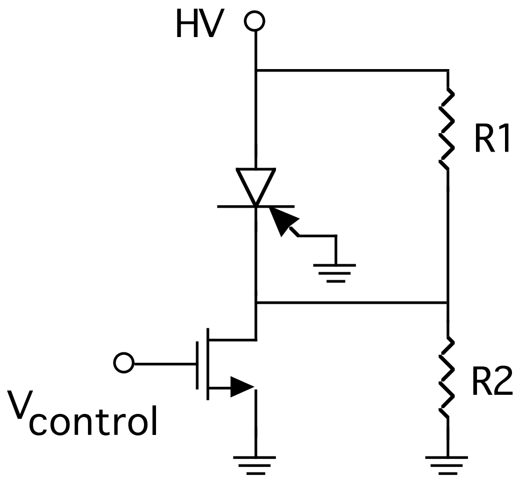
  1. Reduce channel width so that zero-bias depletion layer width of gate-channel junction pinches off channel

  2. Then termed a bipolar static induction thyristor (BSIThy).

# Physical Operation of FCT

- FCT essentially a power JFET with an injecting contact at the drain
- Injecting contact causes conductivity modulation of drain drift region and results in much lower on-state losses
- At turn-off, gate draws large negative current similar to a GTO because of stored charge in drift region
- FCT not a latching switch as is a GTO. FCT has no regenerative action.
- FCT can be made a normally-off device by using narrow channel widths so that zero-bias width gate depletion layer pinchs off channel.

- Cascode switching circuit.
- Implement a normally-off composite switch.
- R1 and R2 insure that voltage across MOSFET not overly large. Permits use of low voltage-high current device.



R1 >> R2 ≈ 1-10 Meg

# FCT Switching Characteristics

- FCT switching waveforms qualitatively similar to thyristor or GTO including large negative gate current at turn-off.

- FCT has gate-controlled turn-on and turn-off capabilities similar to GTO.

- FCT switching times somewhat shorter than GTO.

- Gate drive must be continuously applied to FCT because FCT has no latching characteristic.

- FCT has much larger re-applied dv/dt rating than GTO because of lack of latching action.

- FCT hasdi/dt  limits because of localized turn-on and then expansion of turned-on region across entire device cross-section.

# JFET-Based Devices Vs Other Power Devices

- Blocking voltage capability of JFETs comparable to BJTs and MOSFETs.

- JFET on-state losses higher than MOSFETs - technology limitation.

- Switching speeds of normally-on JFET somewhat slower than those of MOSFET - technology limitation.

- BSIT switching times comparable to BJTs - in principle should be faster because of lack of in-line pn junction trapping stored charge at turn-off.

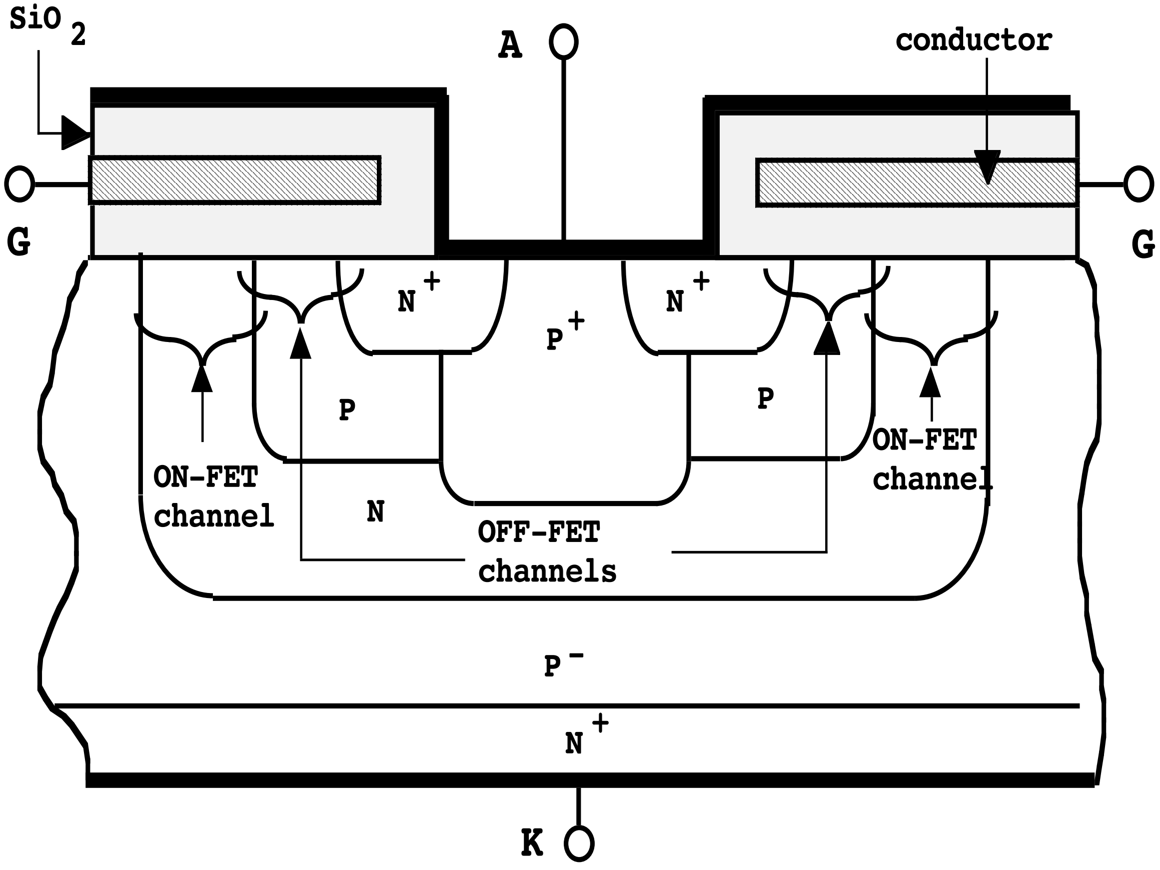
- No second breakdown in normally-on JFETs, similar to MOSFETs.

- BSITs and BSIThy have and possibly limitations.

- JFET-based power devices much less widely used because of normally-on characteristic. This has also slowed research and development efforts in these devices compared to other devices.

# P-MCT (P-type MOS-controlled Thyristor

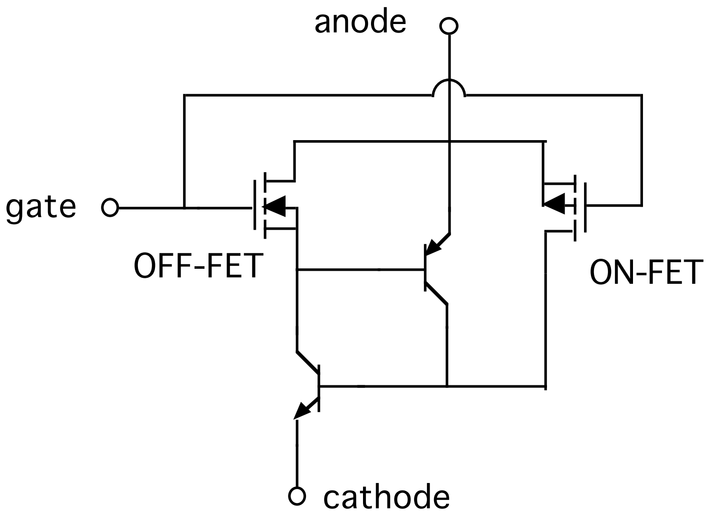
Unit cell vertical cross-section



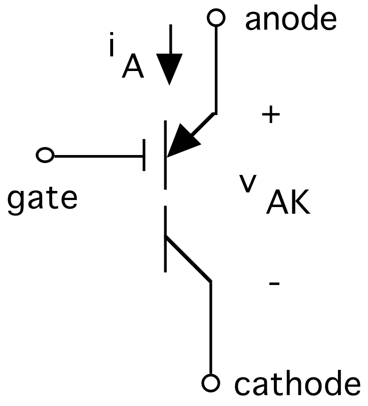
- Complete MCT composed of tens of thousands of identical cells connected in parallel.
- P-designation refers to doping of the lightly-doped $P^-$ layer which contains the depletion layer of the blocking junction.
- Note that ON and OFF FETs are positioned at the anode end of the device.

# P-MCT Equivalent Circuit & Circuit Symbol

P-MCT equivalent circuit



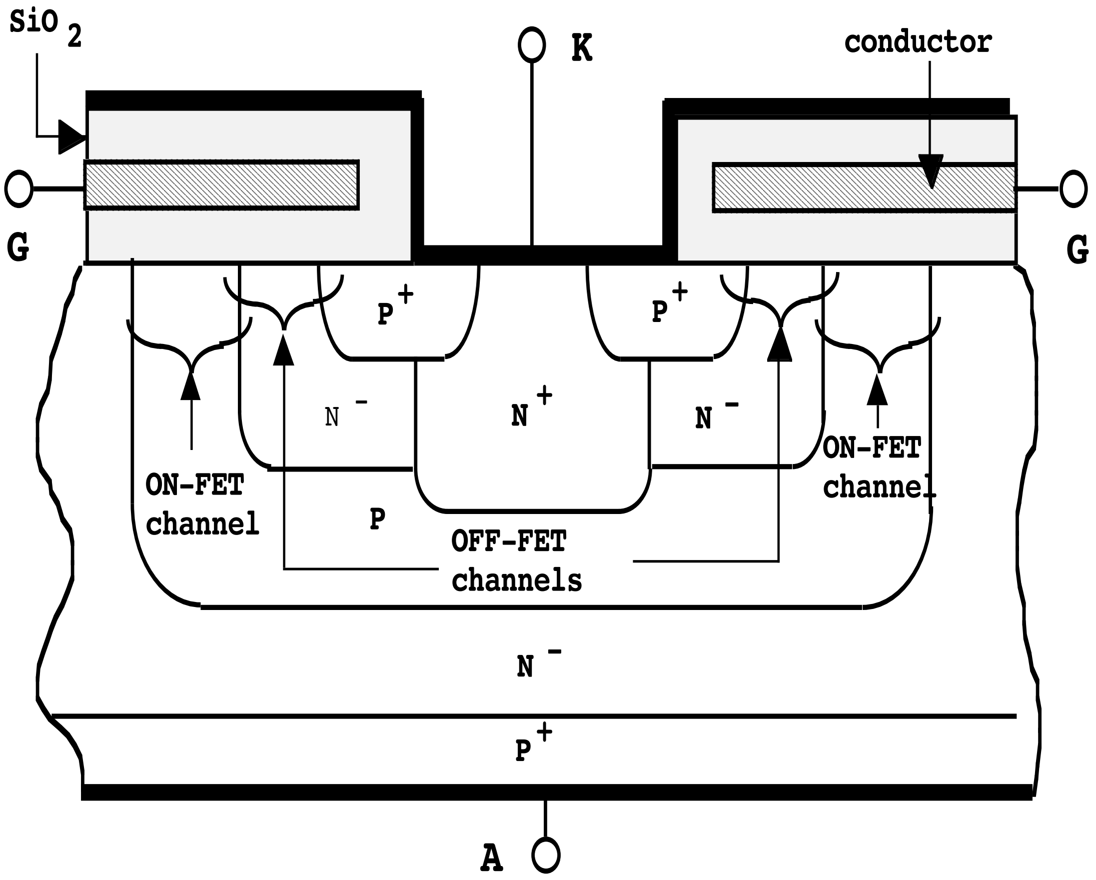
P-MCT circuit symbol



- P-MCT used with anode grounded.
- Gate-anode voltage is input drive voltage.
- Use P-MCT in circuits with negative voltages.

# N-MCT (N-type MOS-controlled Thyristor

Vertical cross-section of N-MCT unit cell



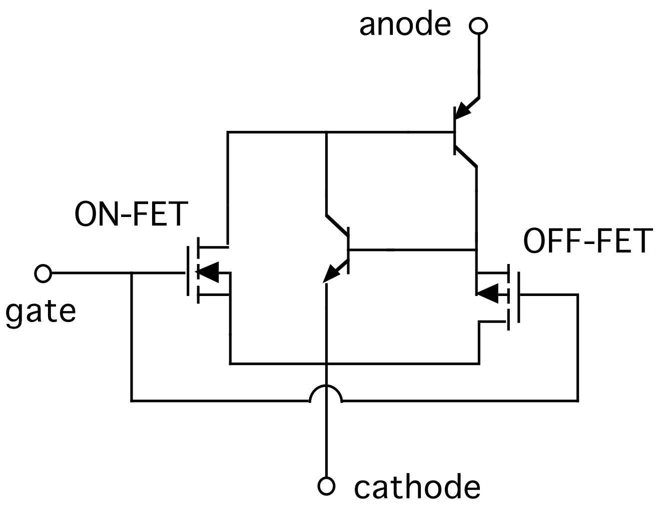
- N-MCT composed of thousands of cells connected electrically in parallel.

- N-designation refers to the $N^-$ layer which contains the depletion layer of the blocking junction.

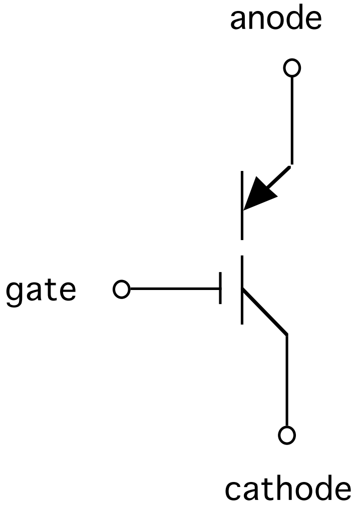
- Note that the ON and OFF FETs are positioned at the cathode end of the device.

# N-MCT Equivalent Circuit & Circuit Symbol

N-MCT equivalent circuit



N-MCT circuit symbol



- N-MCT used with cathode grounded.
- Gate-cathode voltage is input drive voltage.
- Use N-MCT in circuits with positive voltages.

# Gate-controlled Turn-on of MCTs

- Turn on MCT by turning on the ON-FET
  - Positive gate-cathode voltage for N-MCT
  - Negative gate-anode voltage for P-MCT
  - These polarities of gate voltage automatically keep the OFF-FET in cutoff.

- ON-FET delivers base current to the low-gain BJT in the thyristor equivalent circuit and activates that BJT.
  - PNP transistor in the N-MCT
  - NPN transistor in the P-MCT

- Low-gain transistor activates the higher gain transistor and thyristor latches on.

- Once higher gain transistor, which is in parallel with ON-FET is activated, current is shunted from ON-FET to the BJT and the ON-FET carries very little current in the MCT on-state.
  - Only 5-10% of the cells have an ON-FET.
  - Cells are close-packed. Within one excess carreier diffusion length of each other.
  - Adjacent cells without an ON-FET turned on via diffusion of excess carriers from turned-on cell.

# Gate-controlled Turn-off of MCTs

- Turn MCT off by turning on the OFF-FET
  - Negative gate-cathode for the N-MCT
  - Positive gate-anode voltage for the P-MCT
  - These gate voltage polarities automatically keep the ON-FET in cut-off.

- OFF-FET shunts base current away from the higher gain BJT in the thyristor equivalent circuit and forces it to cut-off.
  - NPN transistor in the N-MCT.
  - PNP transistor in the P-MCT.

- Cut-off of higher gain BJT then forces low-gain BJT into cut-off.

- Every MCT cell has an OFF-FET.

- OFF-FET kept activated during entire MCT off-state to insure no inadvertent activation of the thyristor.

# Maximum Controllable Anode Current

- If drain-source voltage of OFF-FET reaches approximately 0.7 V during turn-off, then MCT may remain latched in on-state.

- Higher-gain BJT remains on if OFF-FET voltage drop, which is the base-emitter voltage of the BJT reaches 0.7 volts.

- Thus maximum on-state current that can be turned off by means of gate control.

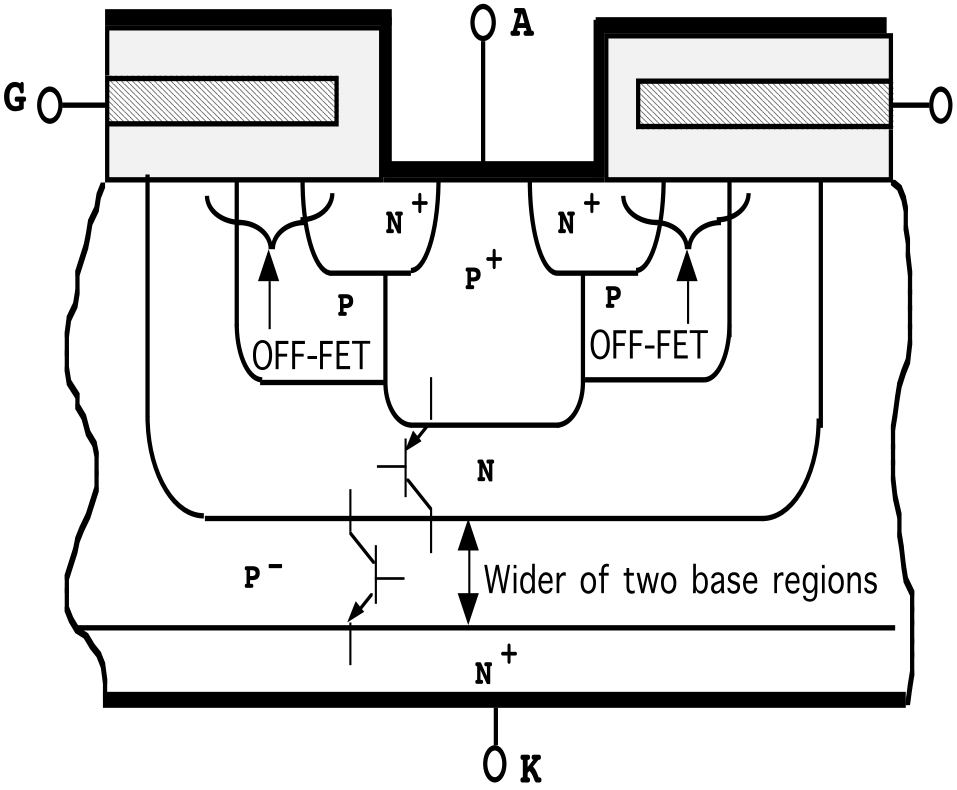
- P-MCT have approximately three times larger gate-controlled anode current rating than a similar (same size and voltage rating) N-MCT.

- OFF-FET of the P-MCT is an n-channel MOSFET which has three times larger channel mobility than the p-channel OFF-FET of the N-MCT.

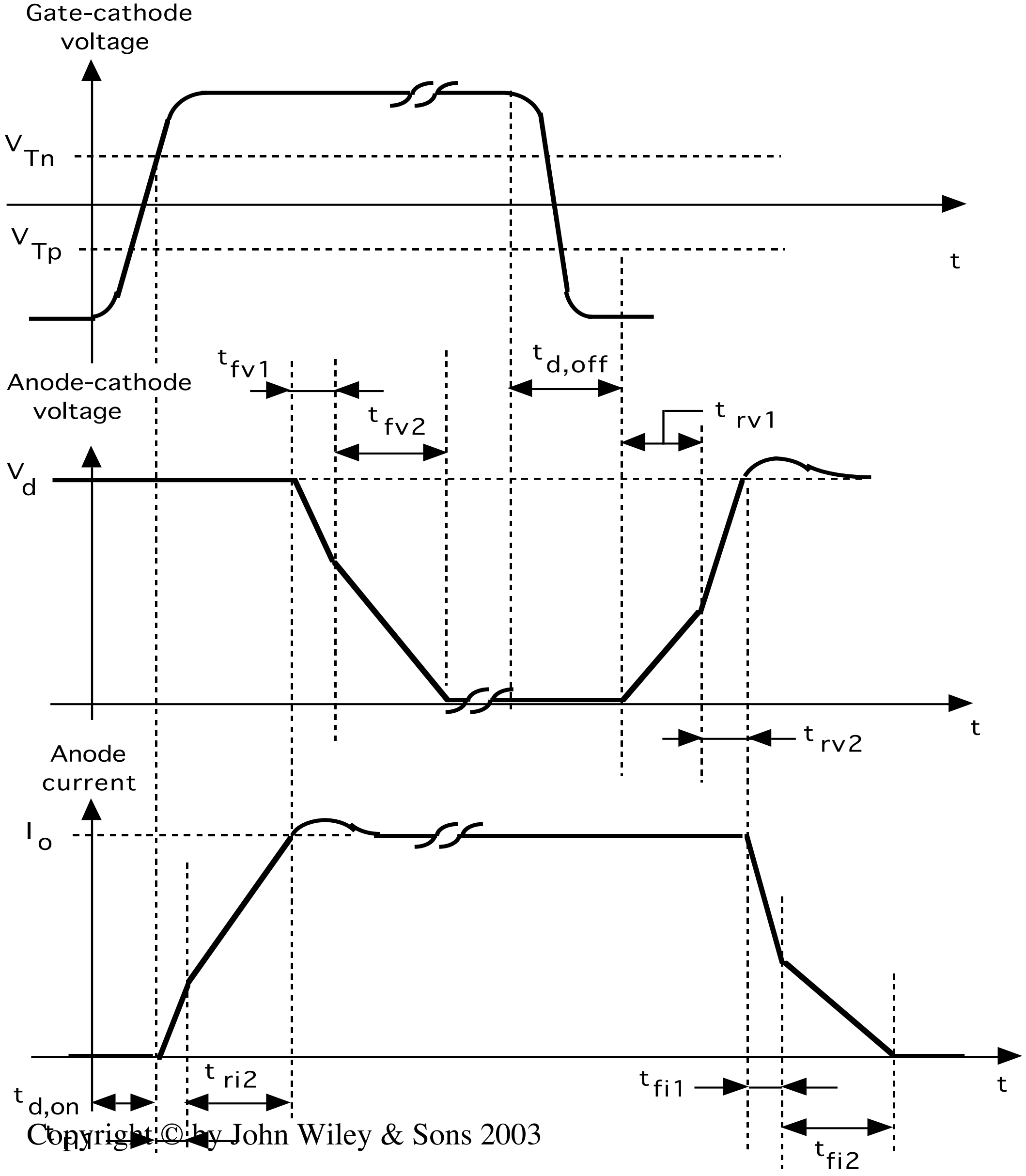
# Rationale of OFF-FET Placement

- Turning off the BJT with the larger value of ▯ most effective way to break the latching condition $\square_1 + \square_2 = 1$
- BJT with the smaller base width has the larger value of ▯.
  - P-MCT ; PNP BJT has smaller base width
  - N-MCT ; NPN BJT has smaller base width
- OFF-FET put in parallel with base-emitter of larger gain BJT so that OFF-FET shorts out base-emitter when the FET is activated.

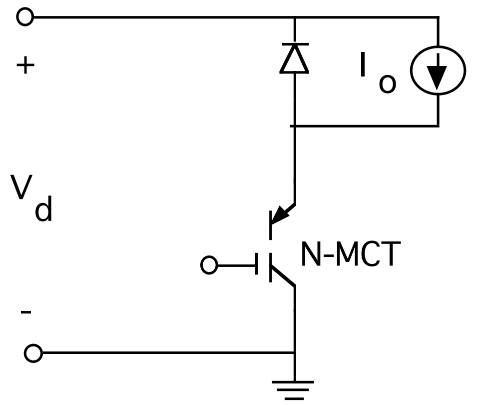
P-MCT cross-section showing rationale for OFF-FET placement



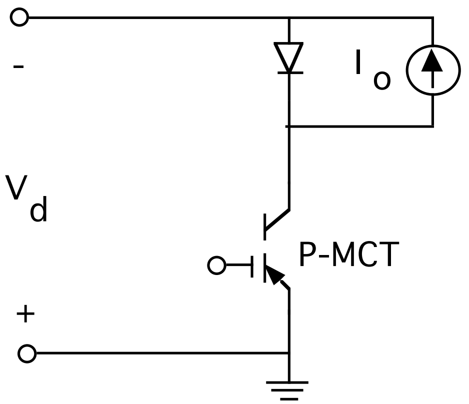
# MCT Switching Waveforms



## N-MCT Step-down Converter



## P-MCT Step-down Converter



# MCT Turn-on Process

- Turn-on delay time $t_{d,on}$ - time required for gate voltage to reach ON-FET threshold starting from reverse-bias value of $V_{GG,off}$

- Current rise time $t_{ri1}$ and $t_{ri2}$
  - $t_{ri1}$ ; ON-FET turns on accepting all the current the gate drive voltage will permit. ON-FET in its active region.
  - $t_{ri2}$ ; NPN and PNP BJTs turn on and current shunted away from ON-FET. BJTs and ON-FET in their active regions.

- Voltage fall time $t_{fv1}$ and $t_{fv2}$
  - $t_{fv1}$ ; BJTs in their active regions so voltage fall initially fast.
  - $t_{fv2}$ ; BJTs in quasi-saturation, so their gain is reduced and rate of voltage fall decreases.
  - At end of voltage fall time interval, BJTs enter hard saturation and MCT is in the on-state.

- Gate-cathode voltage should reach final on-state value in times no longer than a specified maximum value (typically 200 nsec). Insure that all paralleled cells turn on at the same time to minimize current crowding problems.

- Keep gate-cathode at on-state value for the duration of the on-state to minimize likelyhood of inadvertant turn-off of some cells if current is substantially reduced during on-state.

# MCT Turn-off Process

- Turn-off delay time $t_{d,off}$ - time required to turn-off the ON-FET, activate the OFF-FET, and break the latching condition by pulling the BJTs out of hard saturation and into quasi-saturation.
  - Requires removal of substantial amount of stored charge, especially in the base regions of the two BJTs ($n_1$ and $p_2$ thyristor layers).

- Voltage rise times $t_{rv1}$ and $t_{rv2}$
  - $t_{rv1}$ ; time required to remove sufficient stored charge so that BJTs leave quasi-saturation and enter active region and blocking junction ($J_2$) becomes reverse-biased.
  - $t_{rv2}$ ; BJTs in active region and their larger gain causes anode voltage to rapidly complete growth to power supply voltage $V_d$

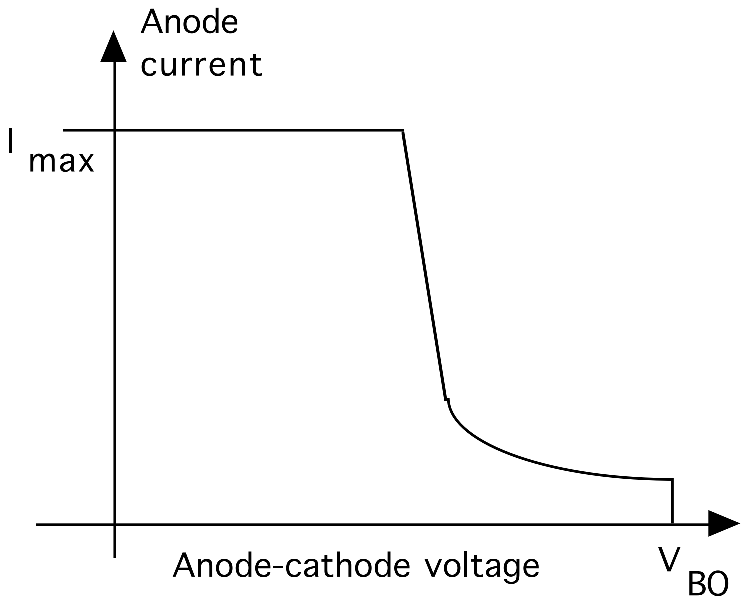
- Current fall time $t_{fi1}$ and $t_{fi2}$
  - $t_{fi1}$ ; Initial rapid fall in current until high gain BJT (NPN BJT in the P-MCT equivalent circuit) goes into cutoff.
  - $t_{fi2}$ ; stored charge still remaining in base (drift region of thyristor) of the low-gain BJT removed in this interval. The open-base nature of the turn-off casuses longer time interval giving a "tail" to the anode current decay.

- Gate-cathode voltage kept at off-state value during entire off-state interval to prevent accidental turn-on.

# MCT Operating Limitations

- $I_{max}$ set by maximum controllable anode current. Presently available devices have 50-100 A ratings.
- $V_{max}$ set by either breakover voltage of thyristor section or breakdown rating of the OFF-FET. Presently available devices rated at 600 V. 1000-2000 v devices prototyped.
- $\frac{dv_{DS}}{dt}$ limited by mechanisms identical to those in thyristors. Presently available devices rated at 500-1000 V/sec.
- $\frac{di_D}{dt}$ limited by potential current crowding problems. Presently available devices rated at 500 A/sec.

- MCT safe operating area. Very conservatively estimated.



# High Voltage (Power) Integrated Circuits

- Three classes of power ICs

  1. Smart power or smart/intelligent switches
     - Vertical power devices with on-chip sense and protective features and possibly drive and control circuits

  2. High voltage integrated circuits (HVICs)
     - Conventional ICs using low voltage devices for control and drive circuits and lateral high voltage power devices

  3. Discrete modules
     - Multiple chips mounted on a common substrate. Separate chips for drive, control, and power switch and possibly other functions.

- PIC rationale

  - Lower costs

  - Increased functionality

  - Higher reliability

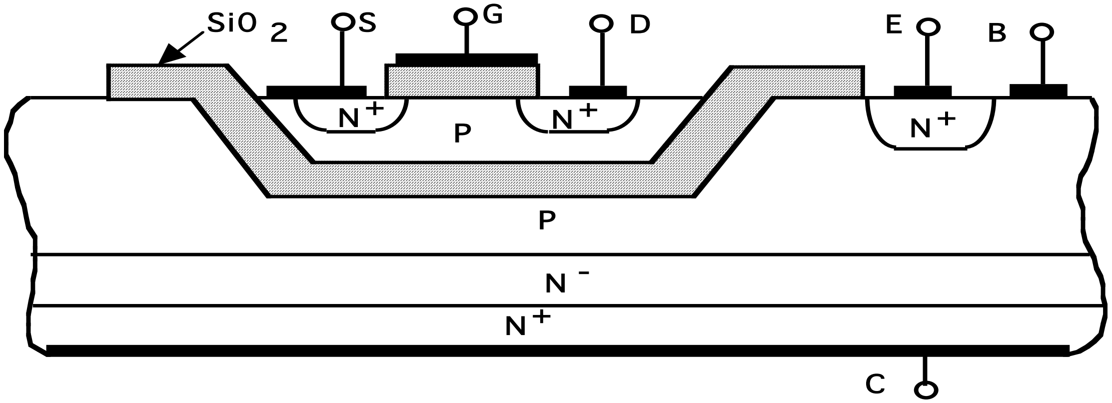
  - Less circuit/system complexity

# Issues Facing PIC Commercialization

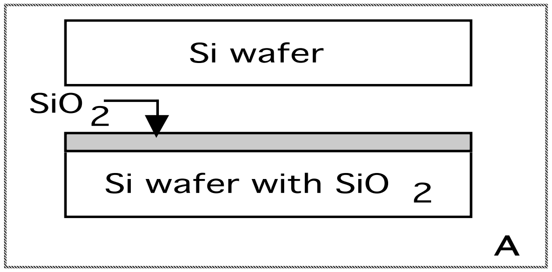
- Technical issues
  - Electrical isolation of high voltage devices from low voltage components
  - Thermal management - power devices generally operate at higher temperatures than low power devices/circuits.
  - On-chip interconnections with HV conductor runs over low voltage devices/regions.
  - Fabrication process should provide full range of devices and components - BJTs, MOSFETs, diodes, resistors, capacitors, etc.

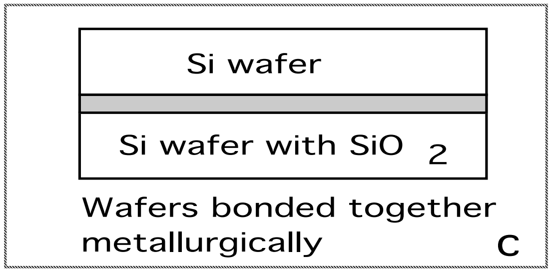
- Economic issues
  - High up-front development costs
  - Relative cost of the three classes of PICs
  - Need for high volume applications to cover development expenses.

# Dielectric Isolation

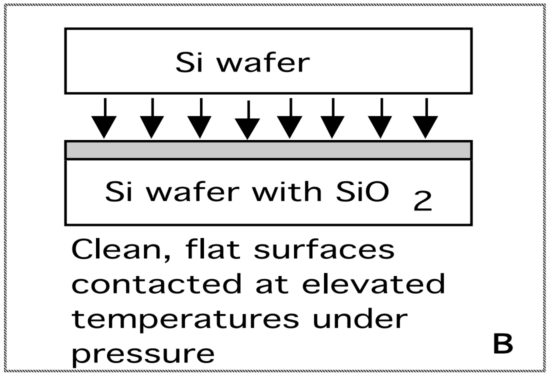


- Dielectrically isolated tubs - $SiO_2$ isolation and silicon thin film overgrowth.

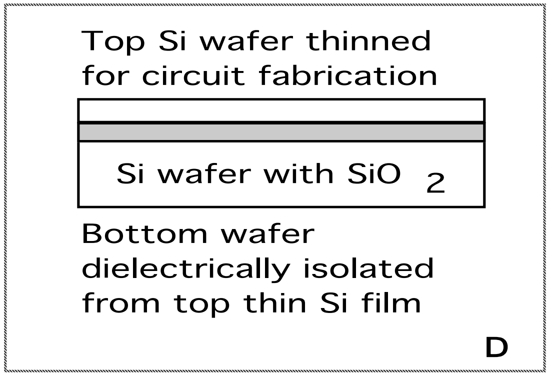




Wafers bonded together metallurgically



Clean, flat surfaces contacted at elevated temperatures under pressure

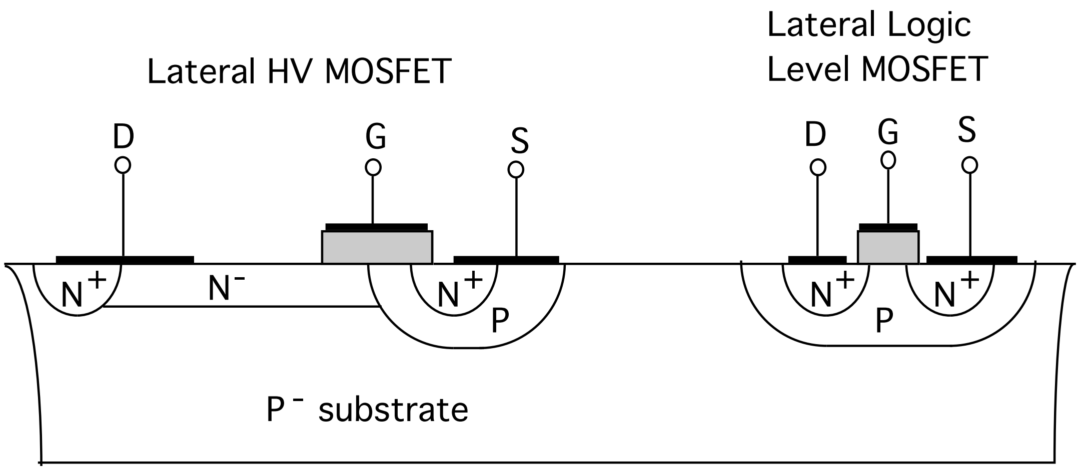


Top Si wafer thinned for circuit fabrication

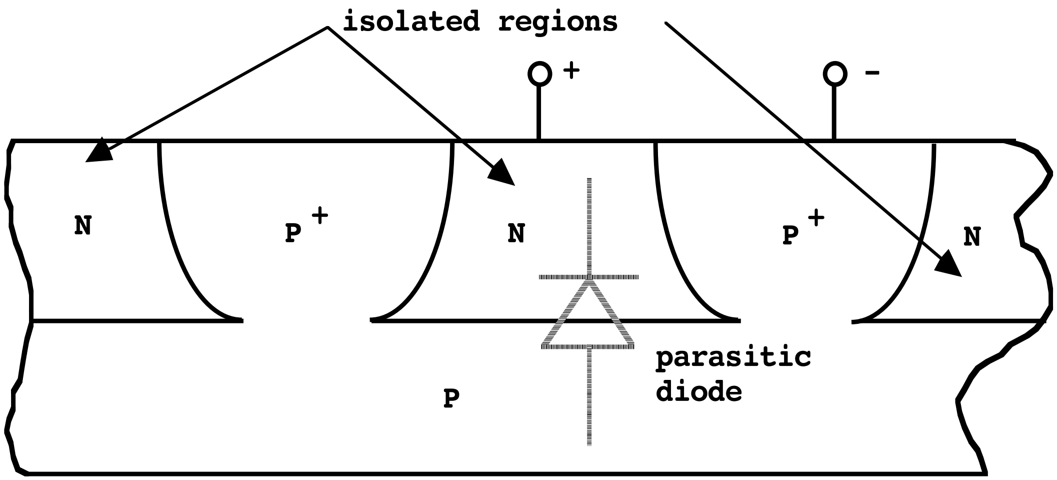
Bottom wafer dielectrically isolated from top thin Si film

- Wafer bonding and subsequent wafer thinning.

# Self-Isolation and Junction Isolation

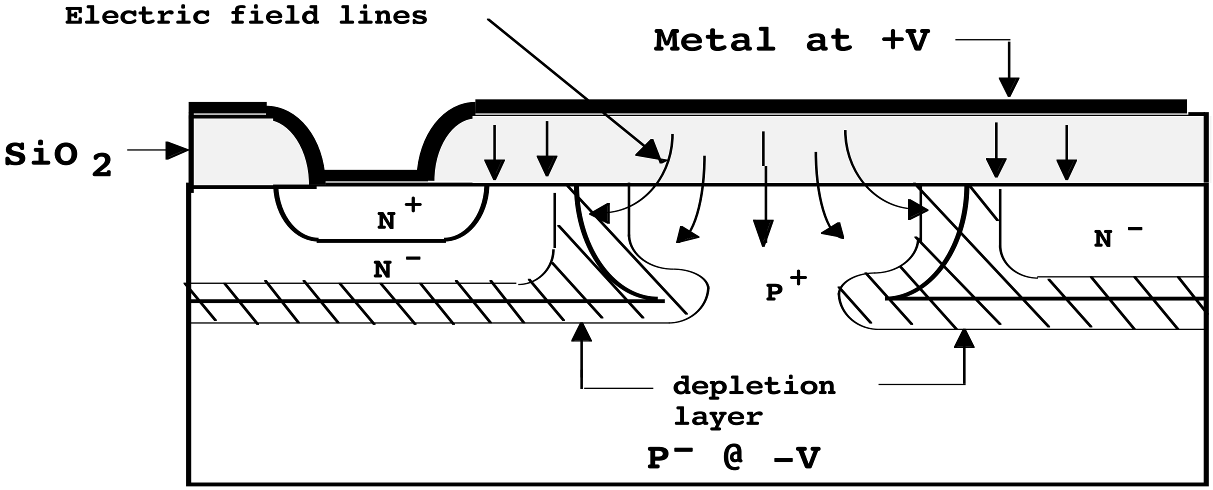


- Self-isolation - only feasible with MOSFET devices.

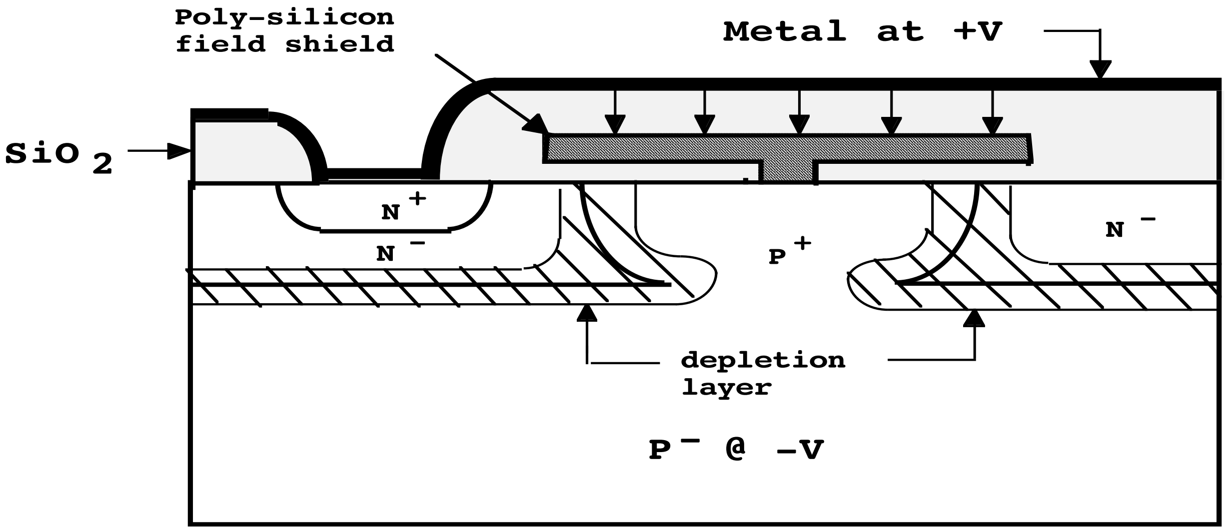


- Junction isolation.

# High-Voltage Low-Voltage Cross-overs

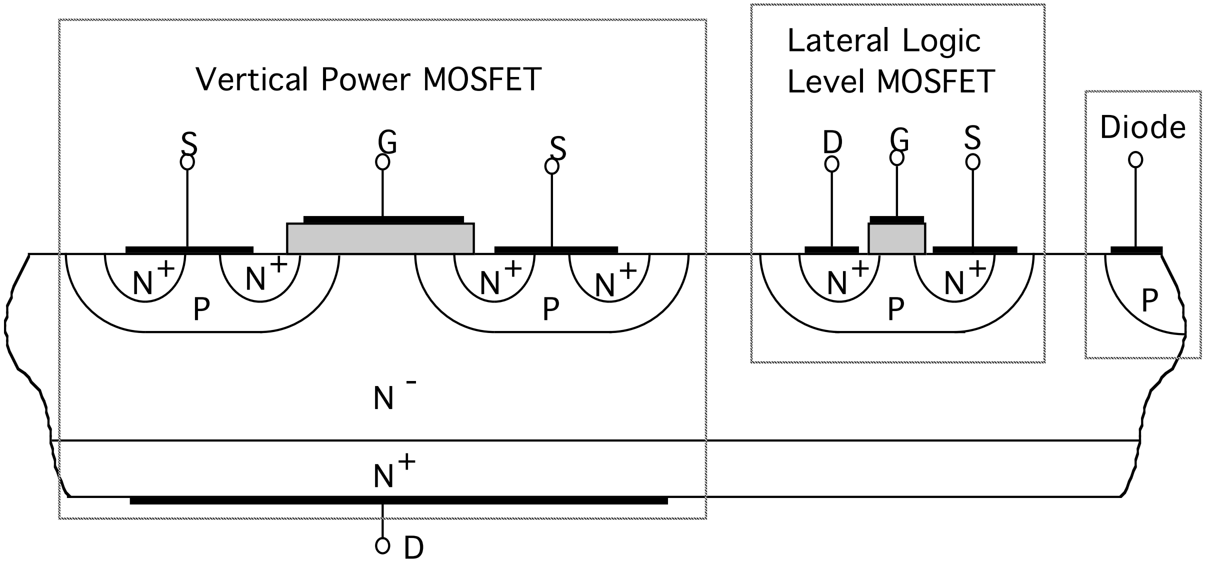


- Field-crowding and premature breakdown.



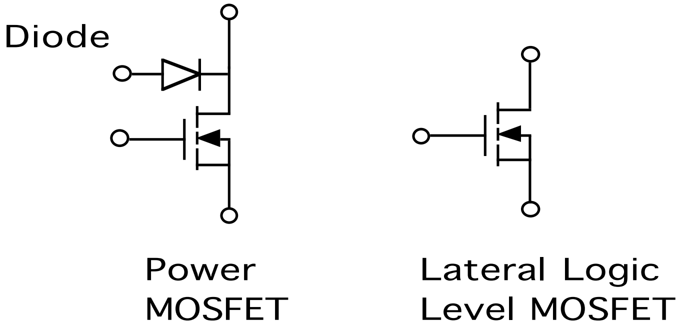
- Use of field shields to minimize field crowding problems at HV/LV cross-overs.

# Smart or Intelligent Switch Using MOSFETs



- Cross-sectional diagram of switch.

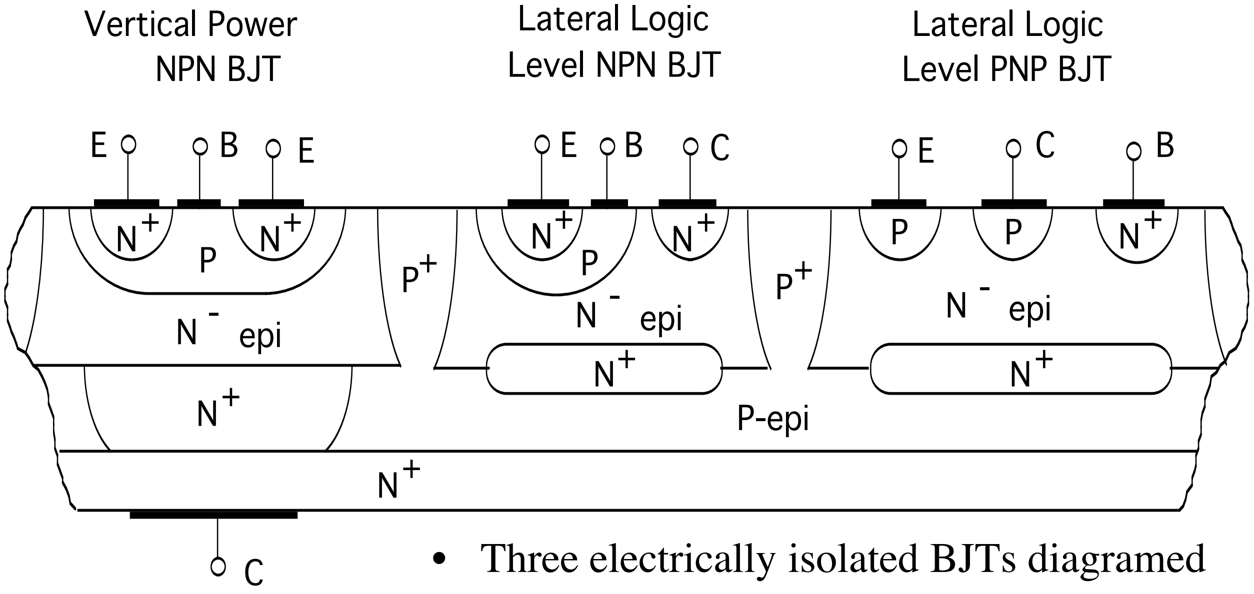
- Circuit diagram



- Add additional components on vertical MOSFET wafer as long as no major process changes required.

- PN junction formed from $N^-$ drift region and P-body region always reverse-biased if drain of power MOSFET positive respect to source. Provides electrical isolation of the two MOSFETs.

# Smart Power Switch Using BJTs

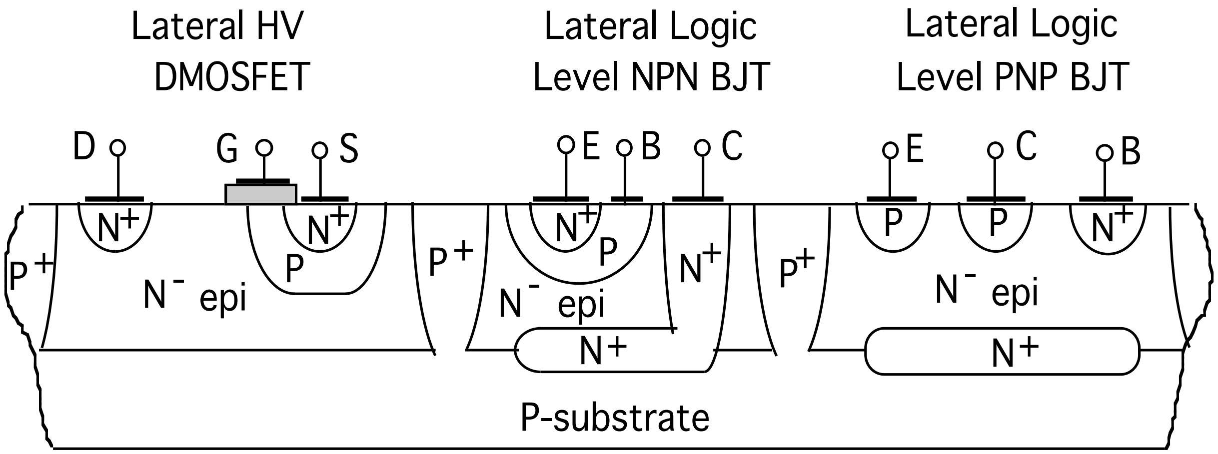


Cross-sectional view

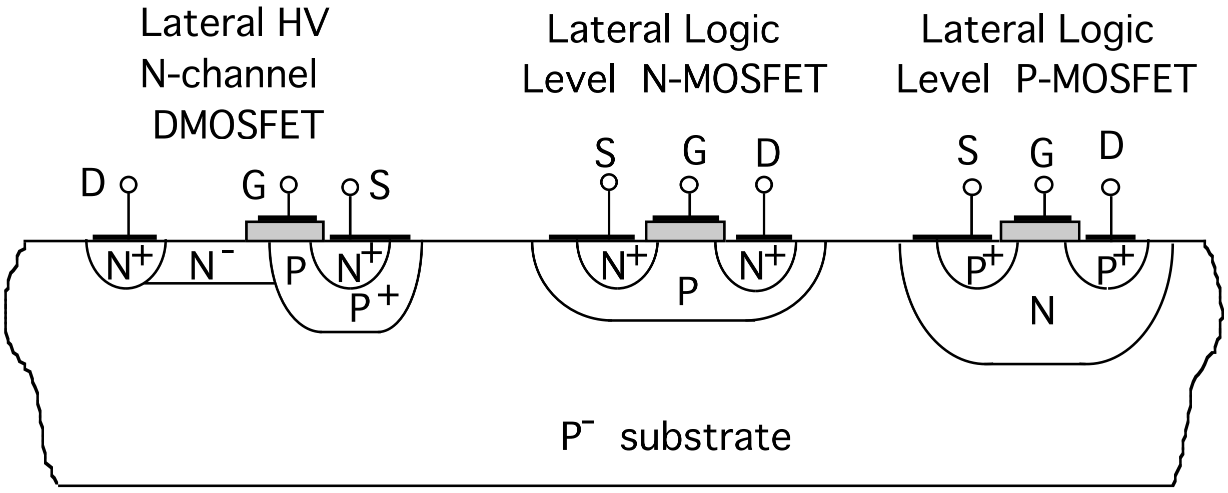
- Three electrically isolated BJTs diagramed
  - PN junction isolation via P-epi and top-side P$^+$ diffusion

- Double epitaxial process squence
  - P-epi grown on N$^+$ substrate
  - N$^+$ buried layer diffused in next
  - N-epi for drift region grown over P-epi
  - P$^+$ isolation diffusions to P-epi
  - Diffusion for base and emitters of BJTs

# High Voltage Integrated Circuits (HVICs)



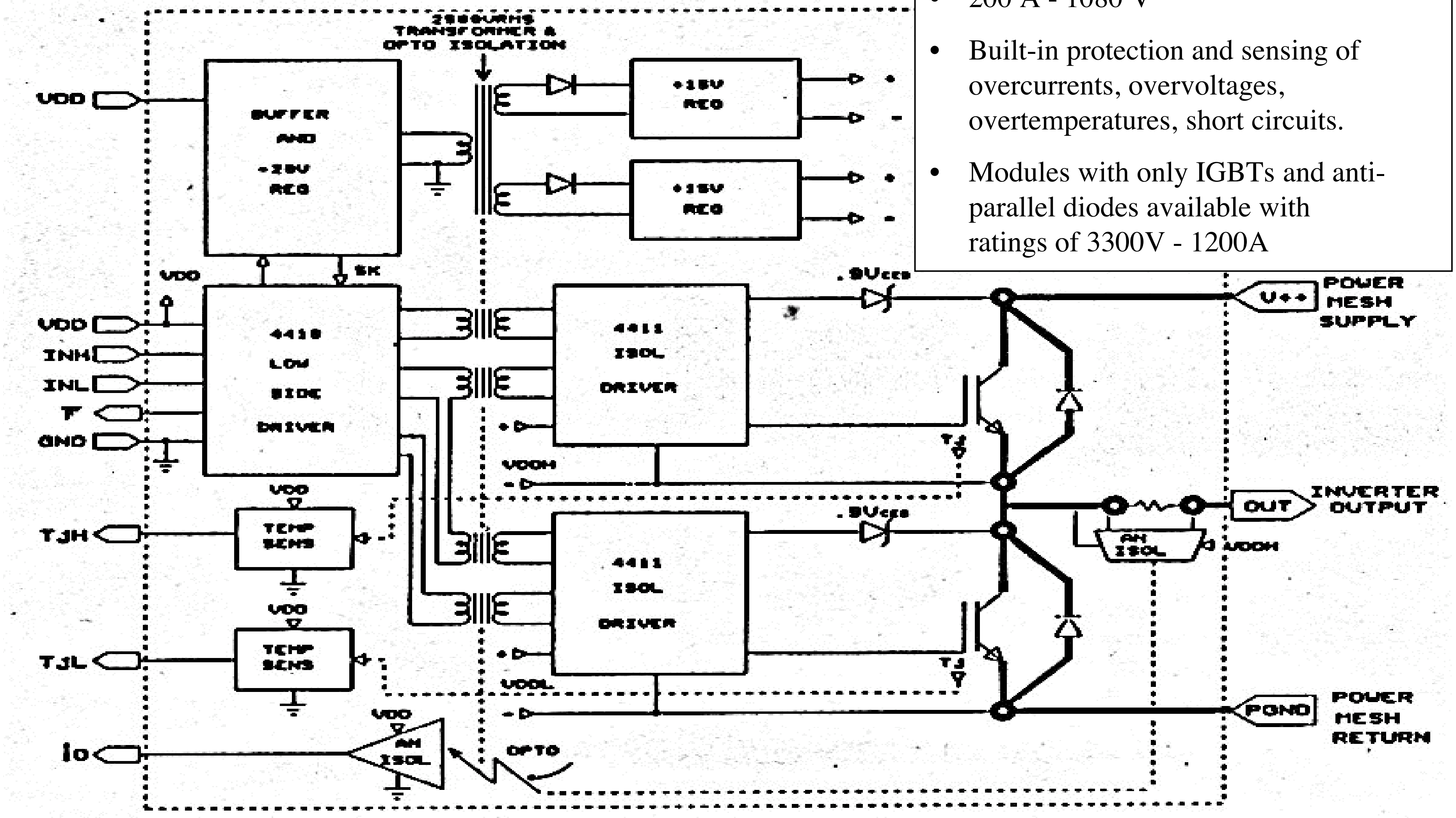
HVIC using junction isolation



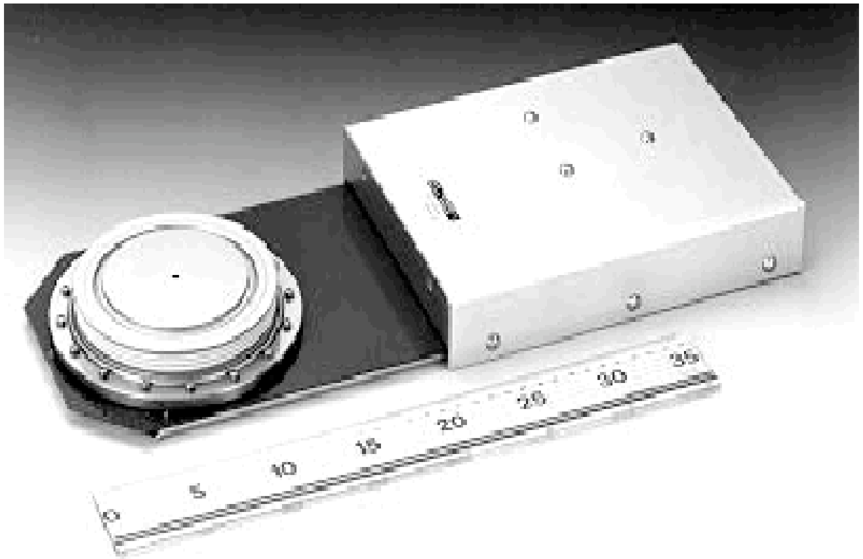
HVIC using self-isolation

# Discrete Module Example - IXYS I$^3$M IGBT Module

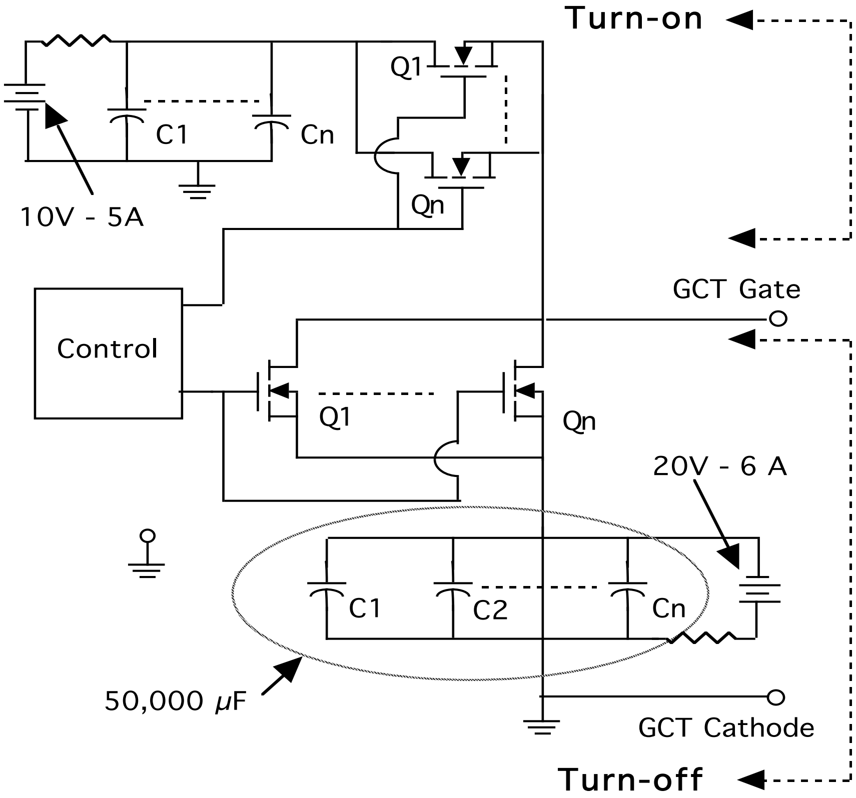
- Intelligent isolated half-bridge
- 200 A - 1080 V
- Built-in protection and sensing of overcurrents, overvoltages, overtemperatures, short circuits.
- Modules with only IGBTs and anti-parallel diodes available with ratings of 3300V - 1200A



# IGCT - Integrated Gate Commutated Thyristor

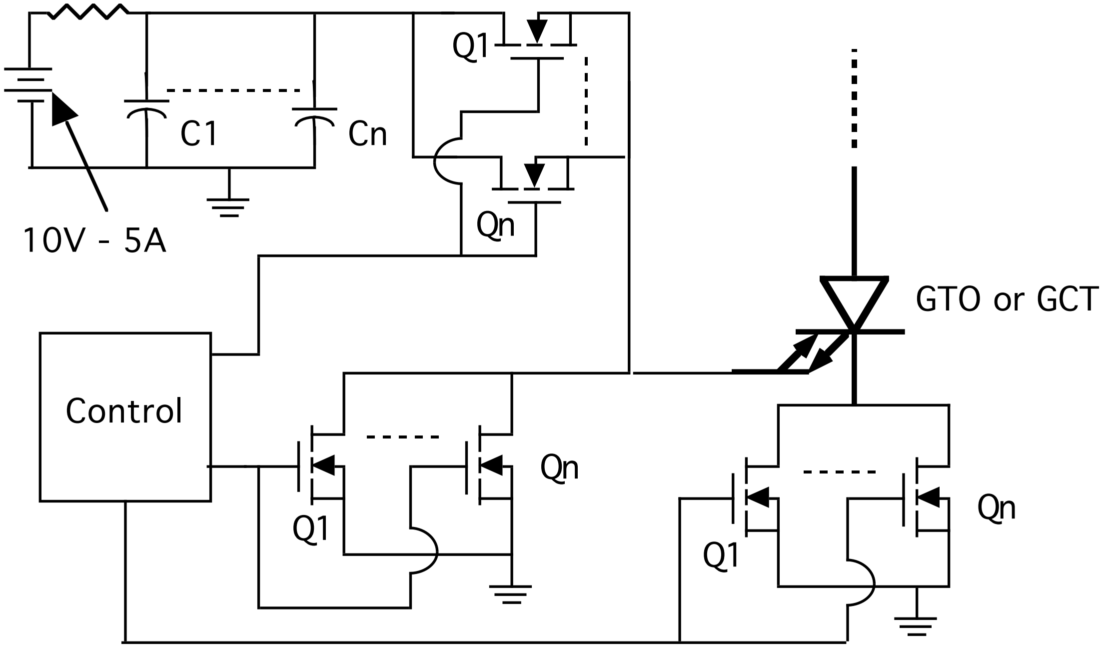


- Specially designed GTO with low inductance gate drive circuit
- Ratings
  - Blocking voltage - 4500V
  - Controllable on-state current - 4000A
  - Average fwd current - 1200A
  - Switching times - 10$\mu$sec

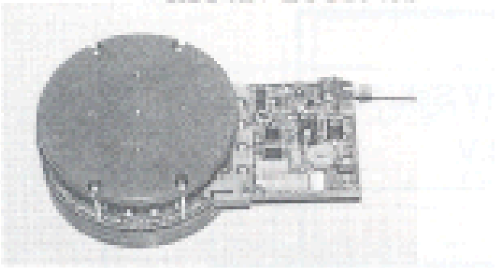


- Approximate gate drive circuit
  - Ion ≈ 500 A 10$\mu$sec
  - Ioff - full forward current 10 usec
- Very low series inductance - 3 nH

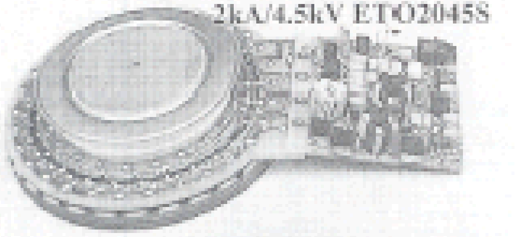
# Emitter Turn-off Thyristor



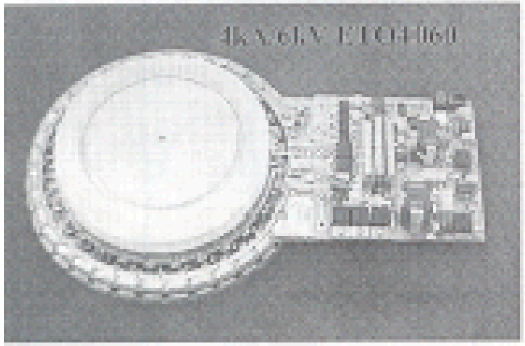
1kA/4kV ETO1045S



2kA/4.5kV ETO2045S



4kA/6kV ETO4060



- Performance similar to IGCTs
- Advantages over IGCTs
  - Simpler drive circuit
  - Easier to parallel - MOSFETs in series with GTO have positive temperature coefficient
  - Series MOSFETs can be used for overcurrent sensing

# Economic Considerations in PIC Availability

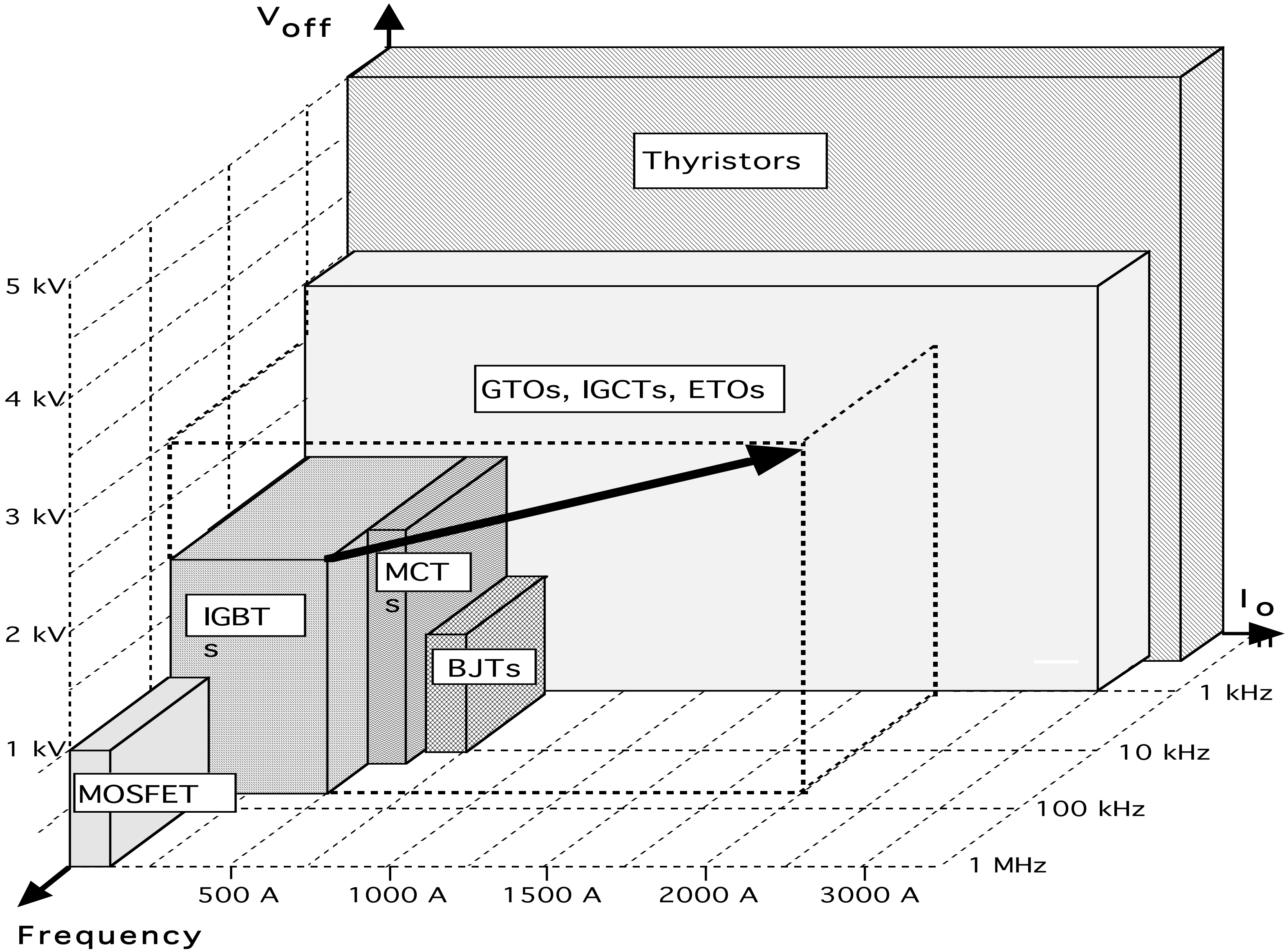
- PIC development costs (exclusive of production costs)
  - Discrete modules have lower development costs
  - Larger development costs for smart switches and HVICs

- Production costs (exclusive of development costs) of smart switches and HVICs lower than for discrete modules.

- Reliability of smart switches and HVICs better than discrete modules.
  - Greater flexibility/functionality in discrete modules
  - Wider range of components - magnetics, optocouplers

- PICs will be developed for high volume applications
  - Automotive electronics
  - Telecommunications
  - Power supplies
  - Office automation equipment
  - Motor drives
  - Flourescent lighting ballasts

# Summary of Silicon Power Device Capabilities



# New Semiconductor Materials for Power Devices

- Silicon not optimum material for power devices

- Gallium arsenide promising material
  - Higher electron mobilities (factor of about 5-6) - faster switching speeds and lower on-state losses
  - Larger band-gap $E_g$ - higher operating temperatures

- Silicon carbide another promising materials
  - Larger bandgap than silicon or GaAs
  - Mobilities comparable to Si
  - Significantly larger breakdown field strength
  - Larger thermal conductivity than Si or GaAs

- Diamond potentially the best materials for power devices

  - Largest bandgap
  - Largest breakdown field strength
  - Largest thermal conductivity
  - Larger mobilities than silicon but less than GaAs

# Properties of Important Semiconductor Materials

| Property | Si | GaAs | 3C-SiC | 6H-SiC | Diamond |
|---|---|---|---|---|---|
| Bandgap @ 300 °K [ev ] | 1.12 | 1.43 | 2.2 | 2.9 | 5.5 |
| Relative dielectric constant | 11.8 | 12.8 | 9.7 | 10 | 5.5 |
| Saturated drift velocity [cm/sec] | $1x10^7$ | $2x10^7$ | $2.5x10^7$ | $2.5x10^7$ | $2.7x10^7$ |
| Thermal conductivity [Watts/cm-°C] | 1.5 | 0.5 | 5.0 | 5.0 | 20 |
| Maximum operating temperature [°K] | 300 | 460 | 873 | 1240 | 1100 |
| Intrinsic carrier density [$cm^{-3}$] @ 25 °C | $10^{10}$ | $10^7$ | - | - | - |
| Melting temperature [°C] | 1415 | 1238 | Sublime >1800 | Sublime >1800 | Phase change |
| Electron mobility @ 300 °K [$cm^2$/V-sec] | 1400 | 8500 | 1000 | 600 | 2200 |
| Breakdown electric field [V/cm] | $2\text{-}3x10^5$ | $4x10^5$ | $2x10^6$ | $2x10^6$ | $1x10^7$ |

# On-State Resistance Comparison with Different Materials

- Specific drift region resistance of majority carrier device
  - $R_{on} \bullet A \approx \dfrac{4 \cdot q \cdot (BV_{BD})^2}{\epsilon \cdot \mu_n \cdot (E_{BD})^3}$
  - Normalize to silicon - assume identical areas and breakdown voltages

$$\frac{R_{on}(x) \cdot A}{R_{on}(Si) \cdot A} = \text{resistance ratio} = \frac{\epsilon_{Si} \cdot \mu_{Si}}{\epsilon_x \cdot \mu_x} \left( \frac{E_{BD,Si}}{E_{BD,x}} \right)^3$$

  - Numerical comparison

| **Material** | **Resistance Ratio** |
|---|---|
| Si | 1 |
| GaAs | $6.4 \times 10^{-2}$ |
| SiC | $9.6 \times 10^{-3}$ |
| Diamond | $3.7 \times 10^{-5}$ |

# Material Comparison: PN Junction Diode Parameters

- Approximate design formulas for doping density and drift region length of HV pn junctions
  - Based on step junction $P^{+}N^{-}N^{+}$ structure
  - $N_d$ = drift region doping level ≈ $\frac{\epsilon [E_{BD}]^2}{2 q BV_{BD}}$
  - $W_d$ = drift region length ≈ $\frac{2 BV_{BD}}{E_{BD}}$
- Numerical comparison - 1000 V breakdown rating

| **Material** | **$N_d$** | **$W_d$** |
|---|---|---|
| Si | $1.3 \times 10^{14}$ cm$^{-3}$ | 67 $\mu$m |
| GaAs | $5.7 \times 10^{14}$ | 50 |
| SiC | $1.1 \times 10^{16}$ | 10 |
| Diamond | $1.5 \times 10^{17}$ | 2 |

# Material Comparison: Carrier Lifetime Requirements

- Drift region carrier lifetime required for 1000 V pn junction diode
  - Approximate design formula based on step junction

$$\tau \approx \frac{q\,W_d^2}{k\,T\,\mu_n} = \frac{4\,q\,[BV_{BD}]^2}{k\,T\,\mu_n\,[E_{BD}]^2}$$

- Numerical comparison

| **Material** | **Lifetime** |
|---|---|
| Si | 1.2 μsec |
| GaAs | 0.11 μsec |
| SiC | 40 nsec |
| Diamond | 7 nsec |

  - Shorter carrier lifetimes mean faster switching minority carrier devices such as BJTs, pn junction diodes, IGBTs, etc.

# Recent Advances/Benchmarks

- Gallium arsenide
  - 600V GaAs Schottky diodes announced by Motorola. 250V available from IXYS
  - 3” GaAs wafers available
- Silicon carbide
  - 3” wafers available from Cree Research - expensive
  - 600V -6A Schottky diodes available commercially - Infineon Technologies AG (Siemens spinoff)
  - Controlled switches also demonstrated
    - 1800V - 3A BJT with beta of 20
    - 3100V - 12A GTO
- Diamond
  - Polycrystalline diamond films of several micron thickness grown over large (square centimeters) areas
  - Simple device structures demonstrated in diamond films.
    - PN junctions
    - Schottky diodes

# Projections

- GaAs
  - Devices such as Schottky diodes which are preesently at or near commercial introduction will become available and used.
  - GaAs devices offer only incremental improvements in performance over Si devices compared to SiC or diamond.
  - Broad introduction of several types of GaAs-based power devices unlikely.

- SiC
  - Rapid advances in SiC device technology
  - Spurred by the great potential improvement in SiC devices compared to Si devices.
  - Commercially available SiC power devices within 5-10 years.

- Diamond
  - Research concentrated in improving materials technology.
    - Growth of single crystal material
    - Ancilliary materials issues - ohmic contacts, dopants, etc.
  - No commercially available diamond-based power devices in the forseeable future (next 10-20 years).