Power Electronics

Day 10 – Power Semiconductor Devices

P. T. Krein
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Device Basics

- We have used several types of devices, and considered their basic properties (diodes, SCRs, MOSFETs, IGBTs, etc).
- Any real switch has three states:
  - On state (low V, high I)
  - Off state (low I, high V)
  - Commutation (the transition)

On State

- For the *on state*, we are concerned with current ratings.
- Devices usually have dc (continuous) current ratings, and might also have average ratings, RMS ratings, peak ratings, short-circuit ratings, etc.

On State

- In the on state, there is a *residual voltage*, V_R. The loss when on is $I_{on}V_R$. On average, the on-state loss is $DI_{on}V_R$ (for constant I).
- The residual voltage might have a fixed component, and also a resistive component.

Off State

- In the off state, we are concerned with voltage ratings.
- Current ratings are tied to thermal limits in general. (And therefore have a time aspect.)
- Voltage ratings are tied to internal device electric fields. (Instant.)

Off State

- In the off state, a residual current flows. The loss is $V_{off}I_R$ while off. On average, this is $(1\text{-}D)V_{off}I_R$ if the voltage is constant.
- If we exceed the voltage limit, avalanche currents are likely. Some devices can handle this.

Off State

- In power electronics, it is very rare to have enough residual current to have an important loss effect.
- Resistive models serve fairly well, but data are sparse.

Example

- An SCR is used in a three-pulse rectifier. The load current is 50 A. The device has a forward voltage drop of 1.5 V when on.
- Leakage current is about 1 mA with a blocking voltage of 400 V.
- Compare on-state and off-state losses.

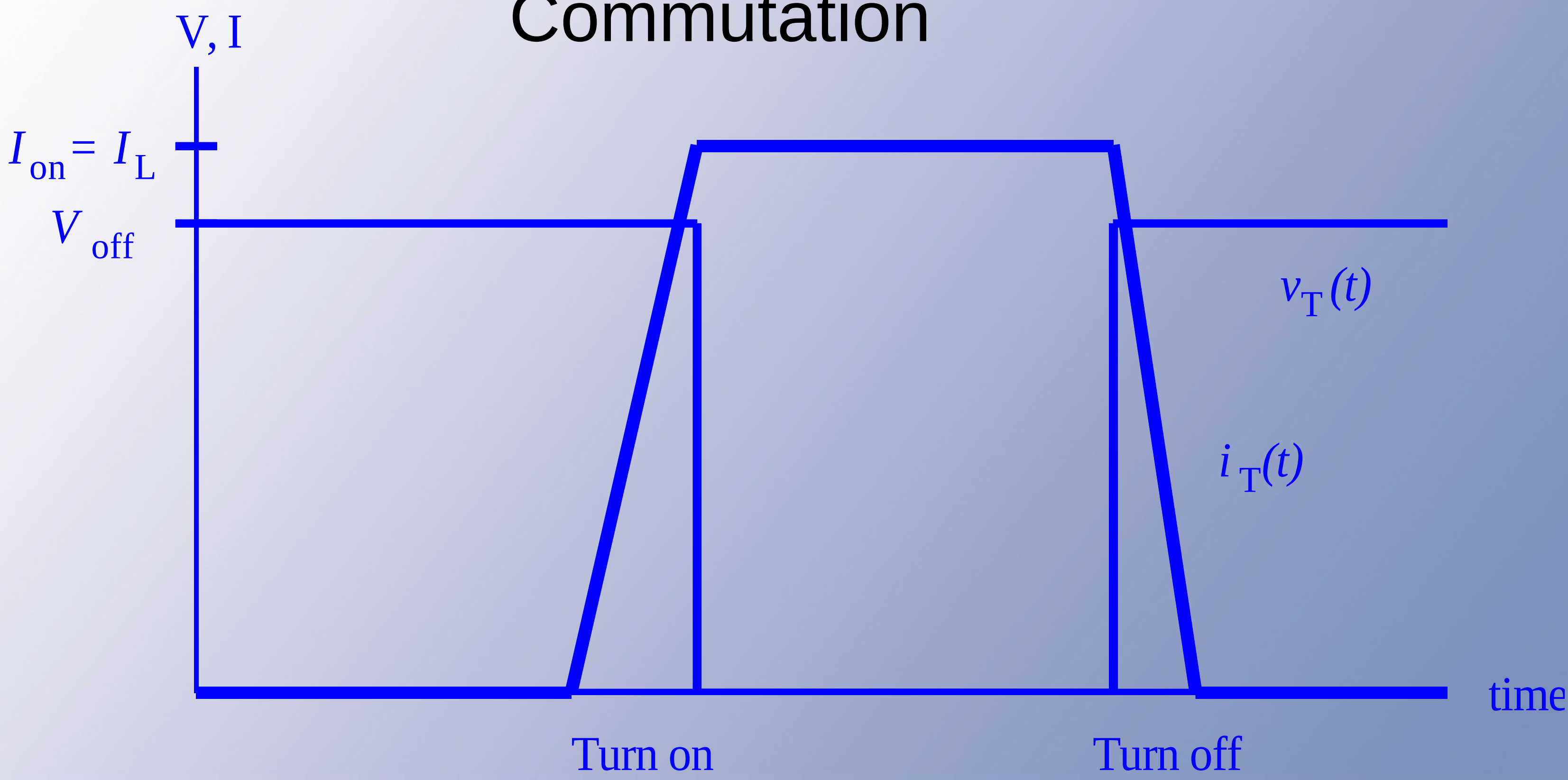
Example

- In the on state, the loss is D(50 A)(1.5 V).
- For three-pulse circuits, D=1/3.
- The on-state loss is 25 W.
- In the off state, the loss is (1-D)(1 mA)(400 V) = 0.27 W.
- The off-state loss is only 1% of the on-state loss. This is typical.

Commutation State

- *Commutation* is the transition from on to off (or off to on).
- During this time, the voltage and current are substantial.
- The external circuit has impact on the waveforms.

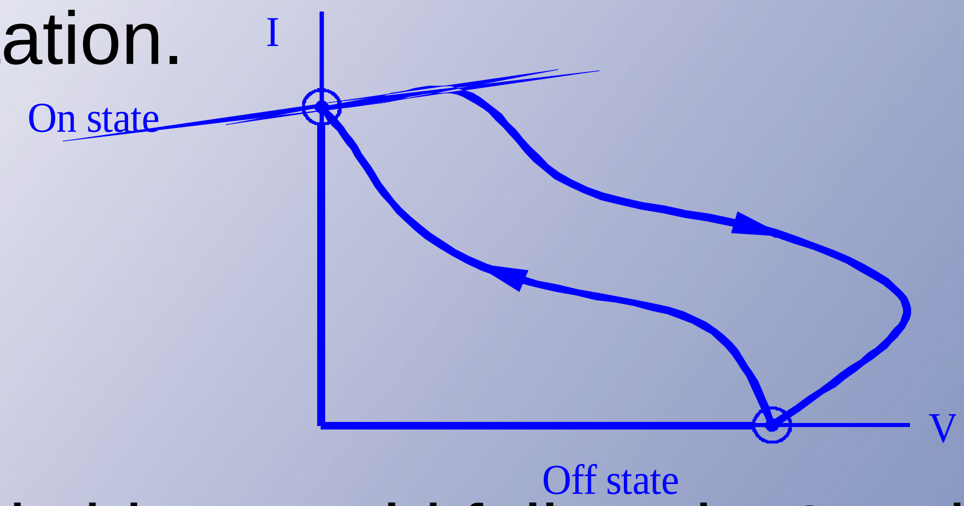
Commutation



- Waveforms in a typical dc-dc converter show high voltages while the current changes.

Switching Trajectory

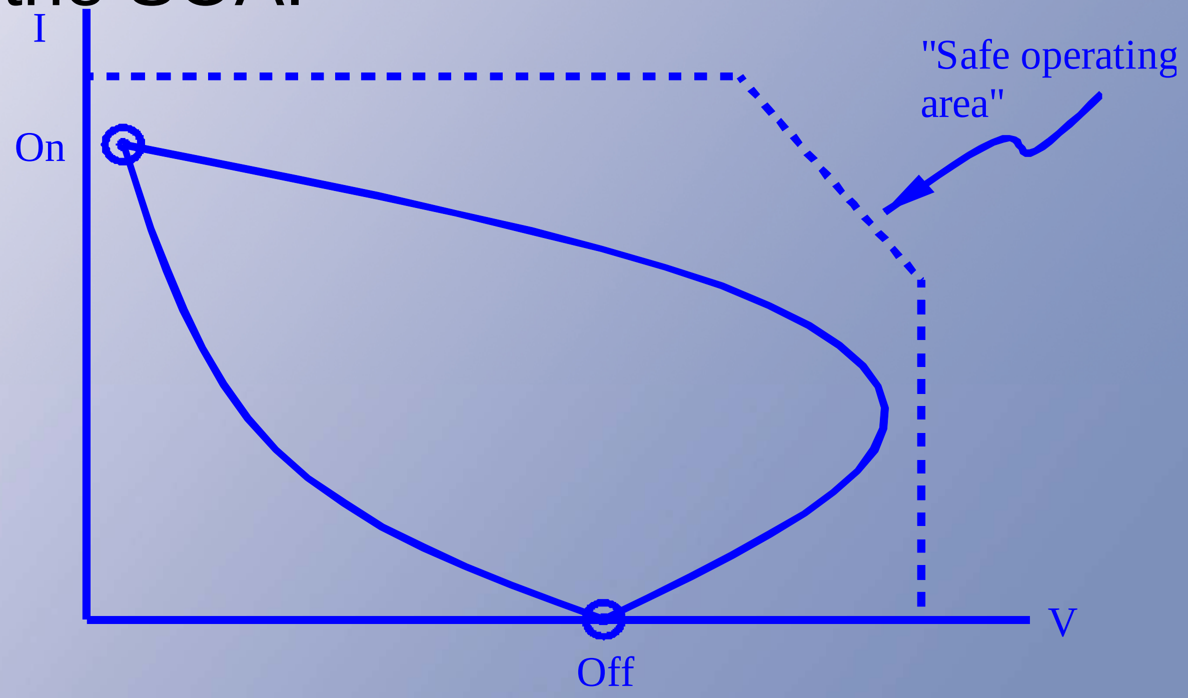
- A *switching trajectory* is a map of I vs. V during commutation.



- Ideal switching would follow the I and V axes, with no loss.
- This is unrealistic.

Safe Operating Area

- Devices have a *safe operating area* in the I-V plane.
- The switching trajectory in general must stay inside the SOA.



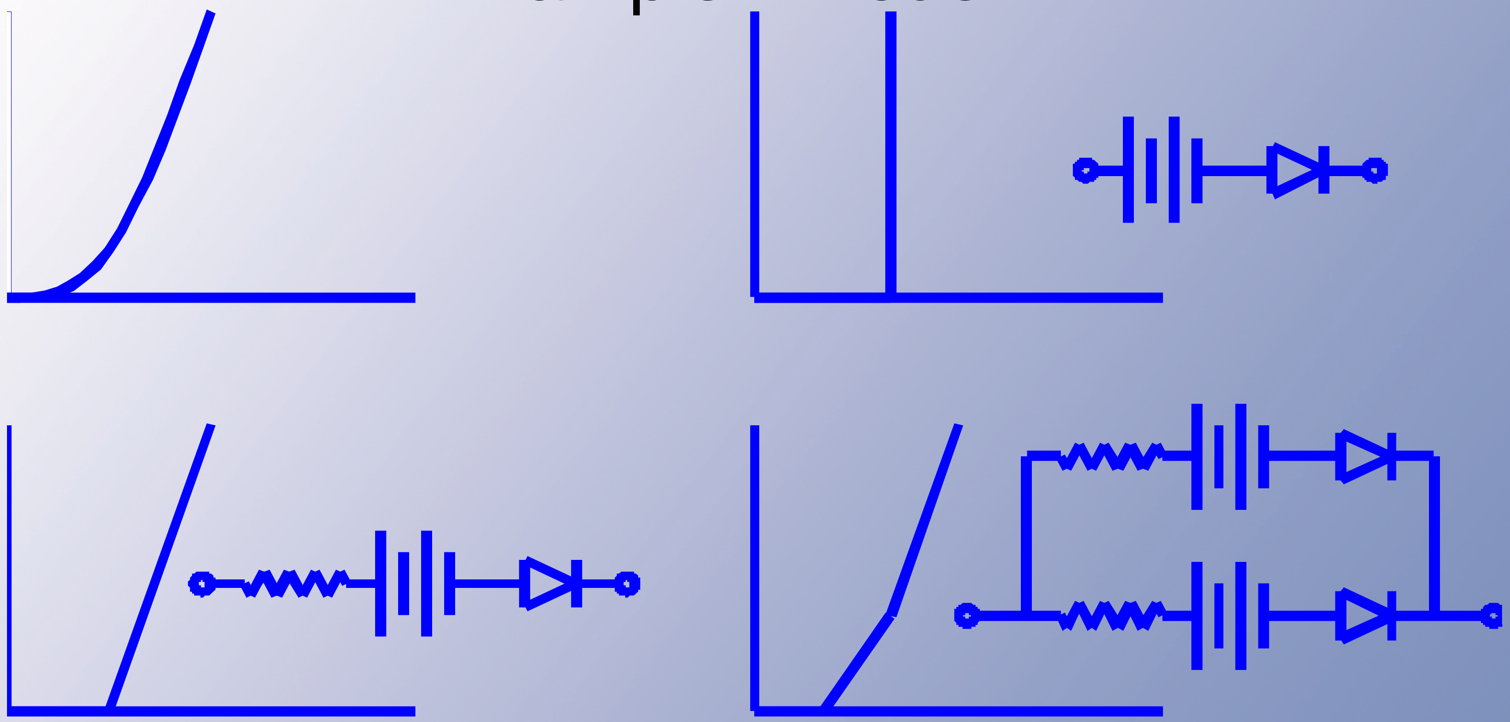
Static Models

- A *static model* uses resistors and voltage drops (static elements) in combination with restricted switches to model real switches.
- This captures on-state and off-state losses well.
- It does not address commutation.

Example: Diode

- Fixed forward drop is a classic (but not very accurate) static model of a diode.
- A much better model is a fixed drop in series with a resistor.
- We can add more elements to follow a curve in detail.

Example: Diode



- Most static models are *piecewise* circuits, like these three.

Static Models

- Static models attempt to track results from a curve tracer.
- The extra parts are called *static parasitics*.
- The objectives are to capture on-state losses, and to capture residual voltage effects on converter operation.

Some Device Cases

- Diode example: ideal diode in series with V_d and with R_d.
- Typical (high-current) samples have about 1 V if just V_d is used.
- With both V and R, a typical case is about 0.75 V in series with a few tens of milliohms.

Some Device Cases

- A real MOSFET is actually bidirectional.
- The model is $R_{ds(on)}$ in series with an ideal switch.
- But a reverse-parallel real diode model must be added. Example model: p. 493, with the gate.

Some Device Cases

- An SCR is built as four layers, and looks rather like two diodes in series when on.
- A real device, once on, acts like an ideal diode in series with a somewhat higher voltage drop, and usually a lower R.

Some Device Cases

- An IGBT has limited reverse blocking ability.
- Its construction effectively places a diode in series with a BJT, with a MOSFET to drive the base.
- This results in a FCBB switch with substantial V_R and with series R as well.

Static Models

- Consider, for instance, a boost converter.
- We want 5 V input, 100 kHz switching. The load is 10 Ω.
- How high a voltage can be provided, and at what duty?

Converter Model

- We have to recognize that all the devices have static parasitics.
- Take a typical situation: the inductor might have 0.5 Ω of resistance. The FET might have 0.1 Ω of on-state resistance. The diode might be a 1 V drop. There is ESR as well.

Equations

- With the FET as #1 and the diode as #2, the #1 voltage v_t is
  $v_t = q_1(I_L R_{ds(on)}) + q_2(V_{out} + 1)$.
- The inductor voltage: $V_{in} - I_L R_L - v_t$. On average, this must be zero.
- Thus $V_{in} - I_L R_L = D_1(I_L R_{dson}) + D_2(V_{out} + 1)$.

Equations

- The diode current: $i_d = q_2 I_L$.
- On average, this must match the load current V_{out}/R_{load}.
- Thus $V_{out}/R_{load} = D_2 I_L$.
- Combine: $V_{in} - V_{out}/R_{load}\, R_L/D_2 = D_1\, V_{out}/R_{load}\, R_{dson}/D_2 + D_2(V_{out}+1)$.

Equations

- Since $D_1 + D_2 = 1$, this gives us a relation between V_{in}, D_1, and V_{out}.
- We can solve for V_{out}, then plot it as a function of D_1.
- The maximum output is not quite 10 V! The drop across R_L is the largest effect.

Static Models

- Static models are very important for design, and for guiding the selection of parts.
- This is especially true when a converter is intended to provide boost action.

Switching Losses

- During commutation, voltage and current can be high as each crosses over the other.
- There is an energy loss, W_{switch}, the integrated V x I product during the commutation state.
- Average loss is $f_{switch}W_{switch}$.

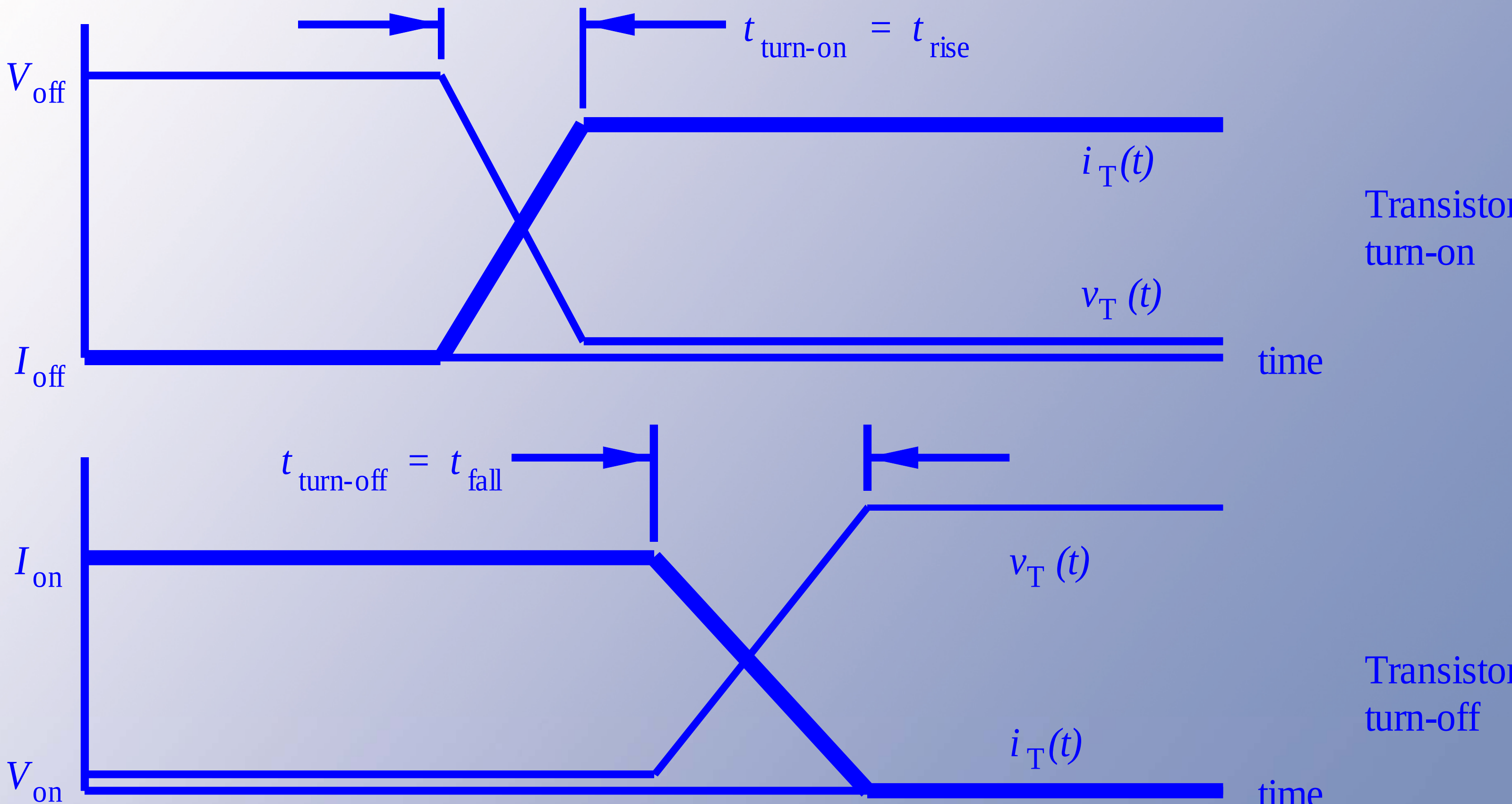
Switching Losses

- Switching losses often depend on the external circuit.
- Switch-off of inductors tends to yield high loss, etc.
- We can get a better idea with some test cases.

Linear Commutation

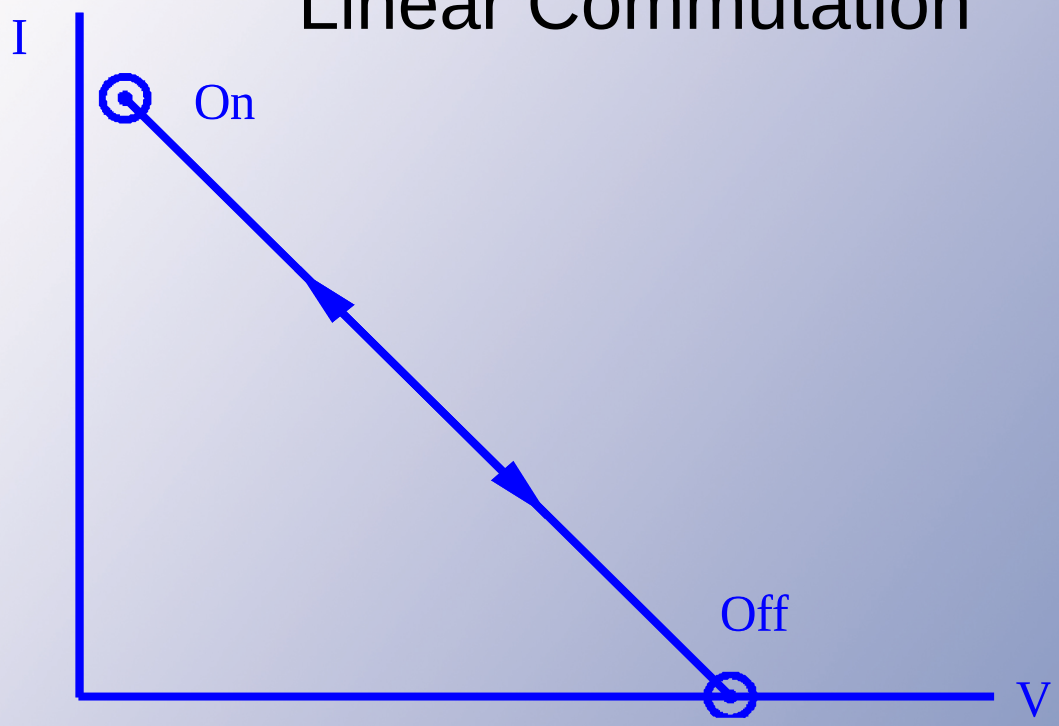
- Linear commutation is a useful test case.
- Here, we assume that the voltage and current change linearly during switching.
- The switching trajectory is also linear.

Linear Commutation



- These are time traces based on linear change of voltage and current.

Linear Commutation



- The switching trajectory can be plotted: a straight line between on and off points.

Linear Commutation

- When the linear action is integrated to get the turn-on and turn-off loss:

$$W_{switch} = \int_0^{t_{turn-on}} I_{on}/t_{turn-on}\, t \left(V_{off} - V_{off}/t_{turn-on}\, t \right) dt + \int_0^{t_{turn-off}} V_{off}/t_{turn-off}\, t \left(I_{on} - I_{on}/t_{turn-off}\, t \right) dt$$

- We can do this integration with a little effort.

Linear Commutation

- The result shows that the energy loss when the switch is operated is:

$$W_{switch} = \frac{V_{off} I_{on} t_{turn-on}}{6} + \frac{V_{off} I_{on} t_{turn-off}}{6}$$

- Define a *total switching time* or *total commutation time*, $t_{switch} = t_{turn\text{-}on} + t_{turn\text{-}off}$. Then

$$W_{switch} = \frac{V_{off} I_{on} t_{switch}}{6}$$

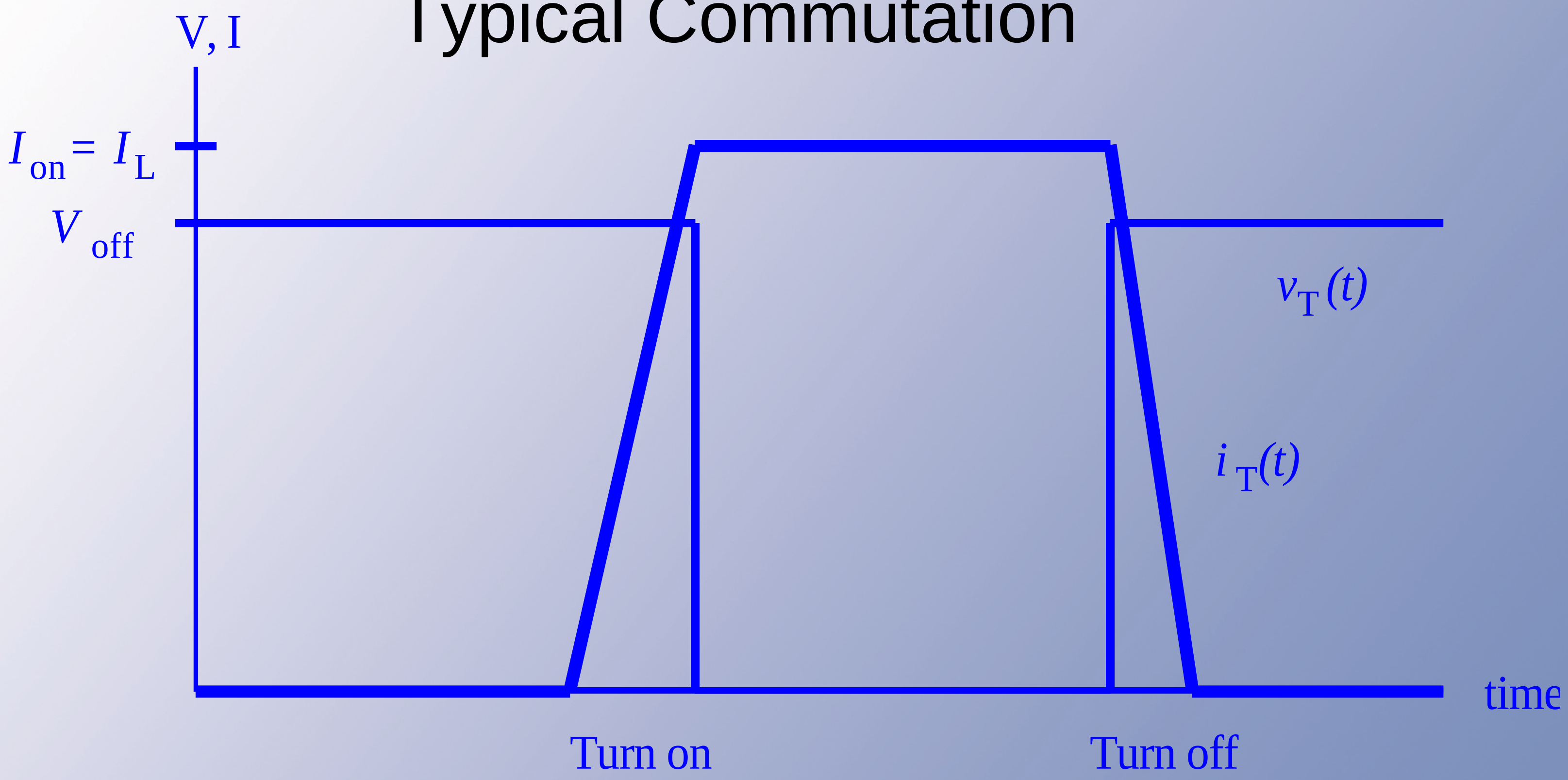
Linear Commutation

- This energy is lost in every period, so the average rate of energy loss – the power becomes:
  $P_{switch} = V_{off}I_{on}t_{switch}f_{switch}/6$.
- The values involved reflect the off-state voltage and the on-state current near the moment of switching.
- Linear commutation is a *best case* result.

Rectangular Commutation

- In a typical converter, if a true ideal diode were present, the active switch would have to maintain 100% voltage during the current transition.
- The voltage is high as the current changes.

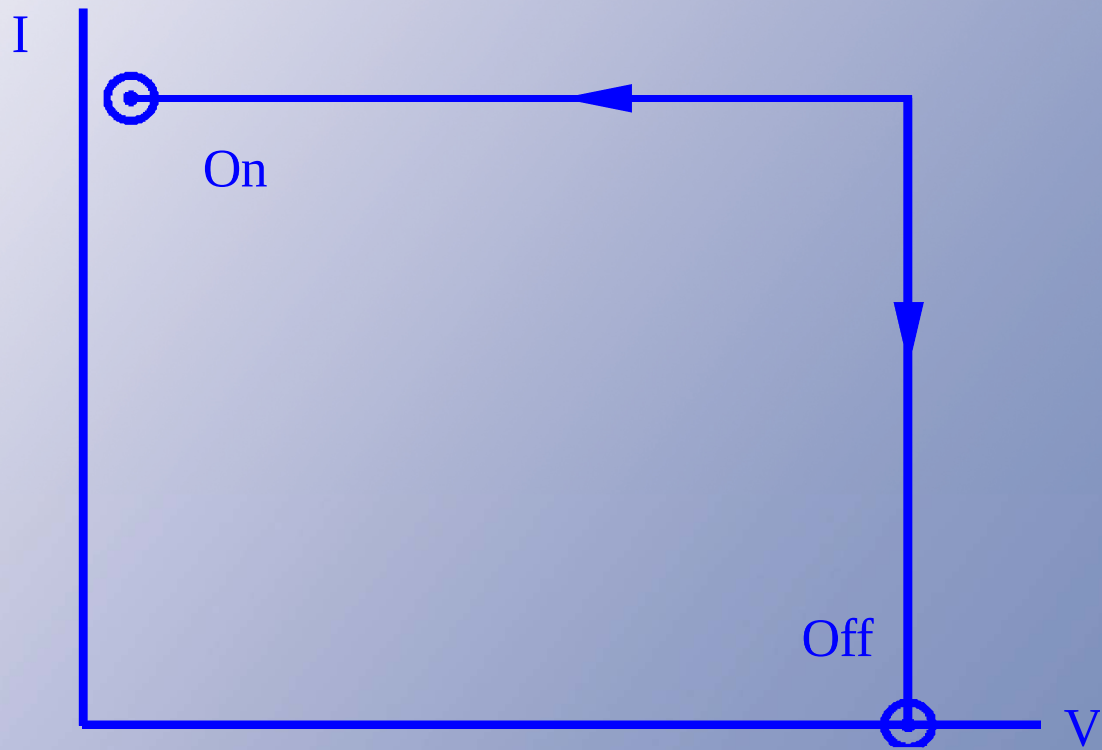
Typical Commutation



- (Idealized) waveforms in a typical dc-dc converter show high voltages while the current changes.

Typical Commutation

- If the switching trajectory is plotted, we get *rectangular commutation*.



Rectangular Commutation

- It is easy to show that in rectangular commutation, the power loss becomes $P_{switch} = V_{off} I_{on} t_{switch} f_{switch}/2$.
- This is $(V_{off} I_{on}\ t_{switch}/T)/2$.
- In general, commutation loss is proportional to the product of the off-state voltage and on-state current near the switching instants, and to the ratio of switching time to switching period.

Commutation

- We can define a *commutation parameter, a* such that
  $P_{switch} = (V_{off} I_{on} t_{switch}/T)/a.$
- Cases:

a=6	Linear
a=2	Rectangular (and a typical estimate)
a=1 to 1.5	Inductive switching

Commutation

- When only a little information is given, a value a = 2 generally gives a good estimate of the actual loss.
- Notice that the *total switching loss* should include the on state, the off state, and commutation.

Other Converters

- In more general converters, we need to know the voltage just before turn-on or just after turn-off, and the current just after or just before.
- This would be true if there is no fixed V_{off} or I_{on}.

Examples

- Dc-dc conversion: a 12 V to 48 V converter at 200 W for an automotive system. The switching frequency is 50 kHz. The inductor and capacitor are well above the critical values.
- Take a MOSFET with 0.05 Ω on-state resistance and a diode with 0.8 V in series with 20 mΩ.
- The switching time is 200 ns.

Examples

- There is loss, so the efficiency is less than 100%. We can check this later, but let us assume 85% efficiency (typical for such specs) and see what happens.
- P_{out}= 200 W and η = 85% so P_{in}= 235 W.
- Input voltage is 12 V, so input current is (235 W)/(12 V) = 19.6 A.

Switching Losses

- Commutation loss: V_{off} = 48 V, I_{on} = 19.6 A, t_{switch} = 200 ns, a = 2.
- P_{switch} = 4.7 W for each device.
- On-state loss: The average output current should be (200 W)/(48 V) = 4.17 A, so the duty ratio D_2 should be 21.3%.

Switching Losses

- Diode loss: The forward drop at 19.6 A will be 1.19 V. The on-state loss is D_2(19.6 A)(1.19 V) = 4.98 W.
- Transistor loss: The resistance is 0.05 Ω when on, so the loss is $D_1(19.6\ \text{A})^2(0.05\ \Omega)$ = 15.1 W.
- Total switching loss: 4.98 W + 15.1 W + 4.7 W + 4.7 W = 29.5 W.

Example

- Loss in a rectifier. The voltage and current values depend on what is happening at the moment of switching.
- Consider a six-pulse SCR bridge rectifier with 20 A load.
- The devices have on-state forward drop of 1.5 V.
- On-state loss is easy:
  $D(I_{on})(V_r)$ = (20 A)(1.5 V)/3 = 10 W.

Example

- Switching loss requires the off-state voltage near the moment of turn-off. The value depends on phase delay angle.
- Turn-off time for an SCR is rather long, while turn-on can be quick.
- The device I am using here has total switching time of about 17 us.

Summary so far

- Static models, plus an estimated commutation parameter, allow a good estimate of losses in a converter.
- Now, the actual duty ratios and other factors can be found to support efficiency estimates and similar analysis.
- In principle, we can analyze nearly any converter and design many types.

P-N Junctions as Power Devices

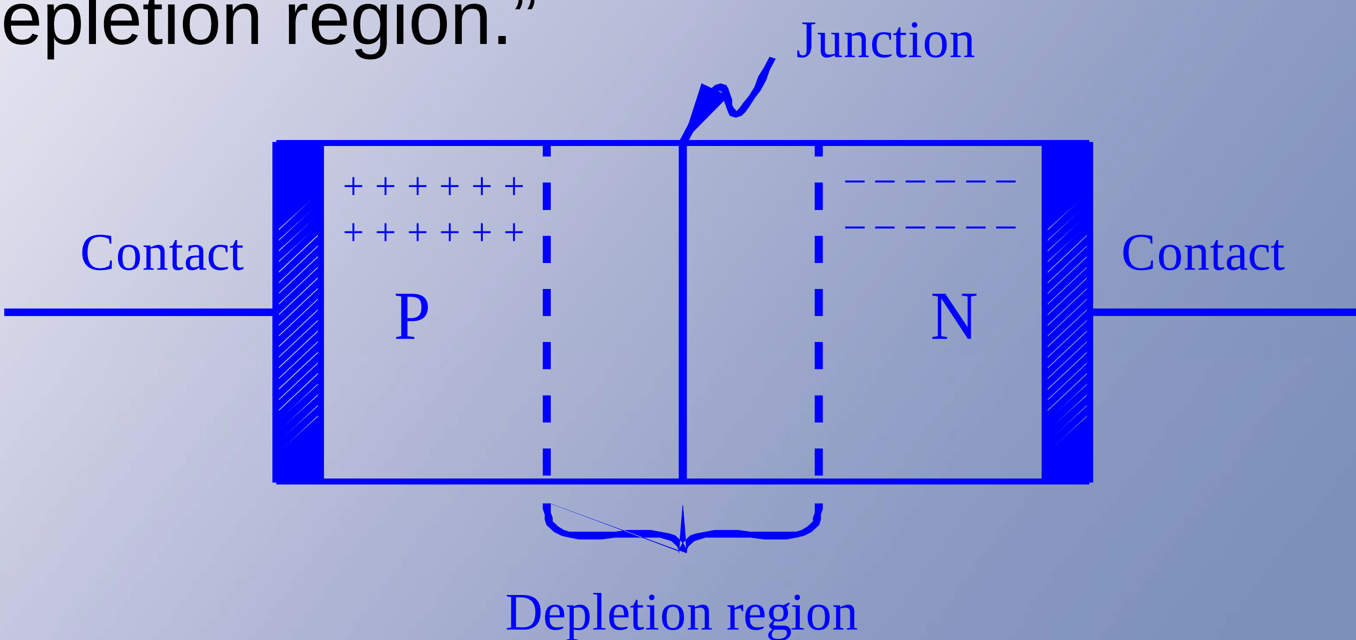
- Semiconductor devices are formed from junctions of dissimilar materials.
- As we know, such a junction has polarity-dependent conduction.
- Metal-semiconductor junctions are Schottky diodes, with limited blocking voltage but low forward drop.

P-N Junctions as Power Devices

- P-N junctions, and also “P-i-N” devices with an internal “intrinsic layer” are suitable for power diodes.
- The current rating depends on area (current density!)
- The voltage rating depends on the depth of the doped regions.

Dynamics

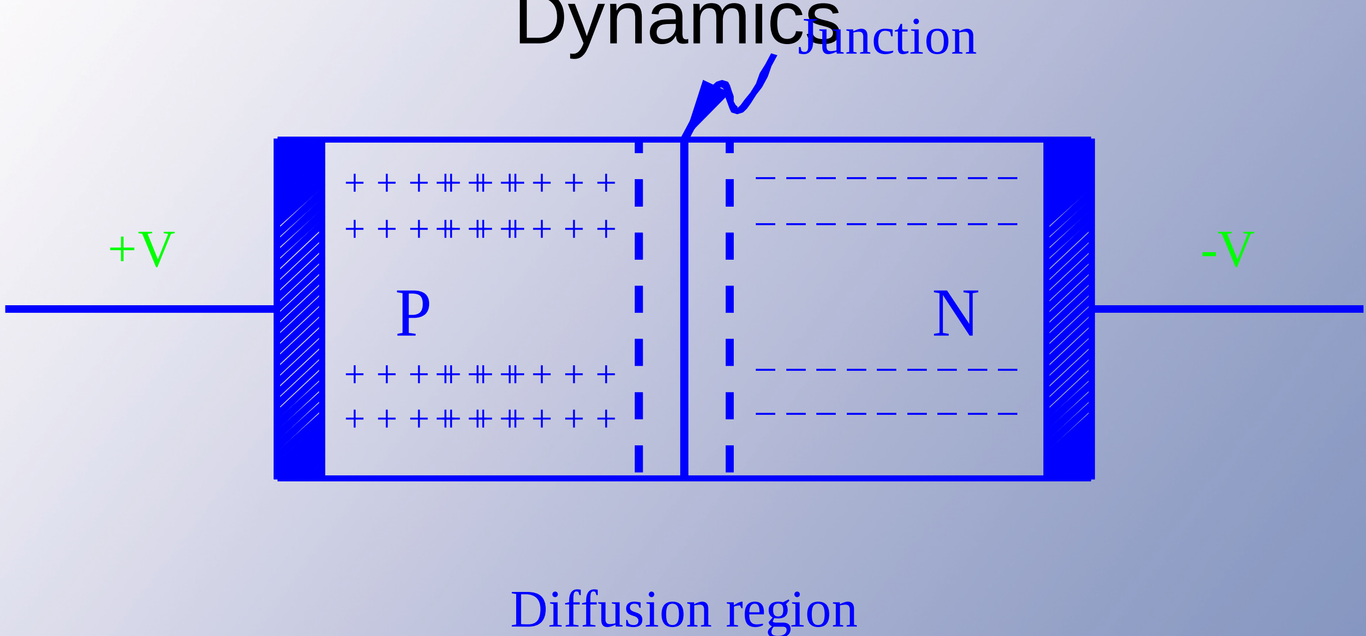
- When a PN junction is unbiased, the doping provides free charge.
- Near the junction, charges cancel and we have a “depletion region.”



Dynamics

- Notice that we have charges with a spatial separation: a capacitor.
- In forward bias, the imposed voltage drives the charges closer together.
- Current flows as charges actively diffuse into and recombine within the depletion region.

Dynamics

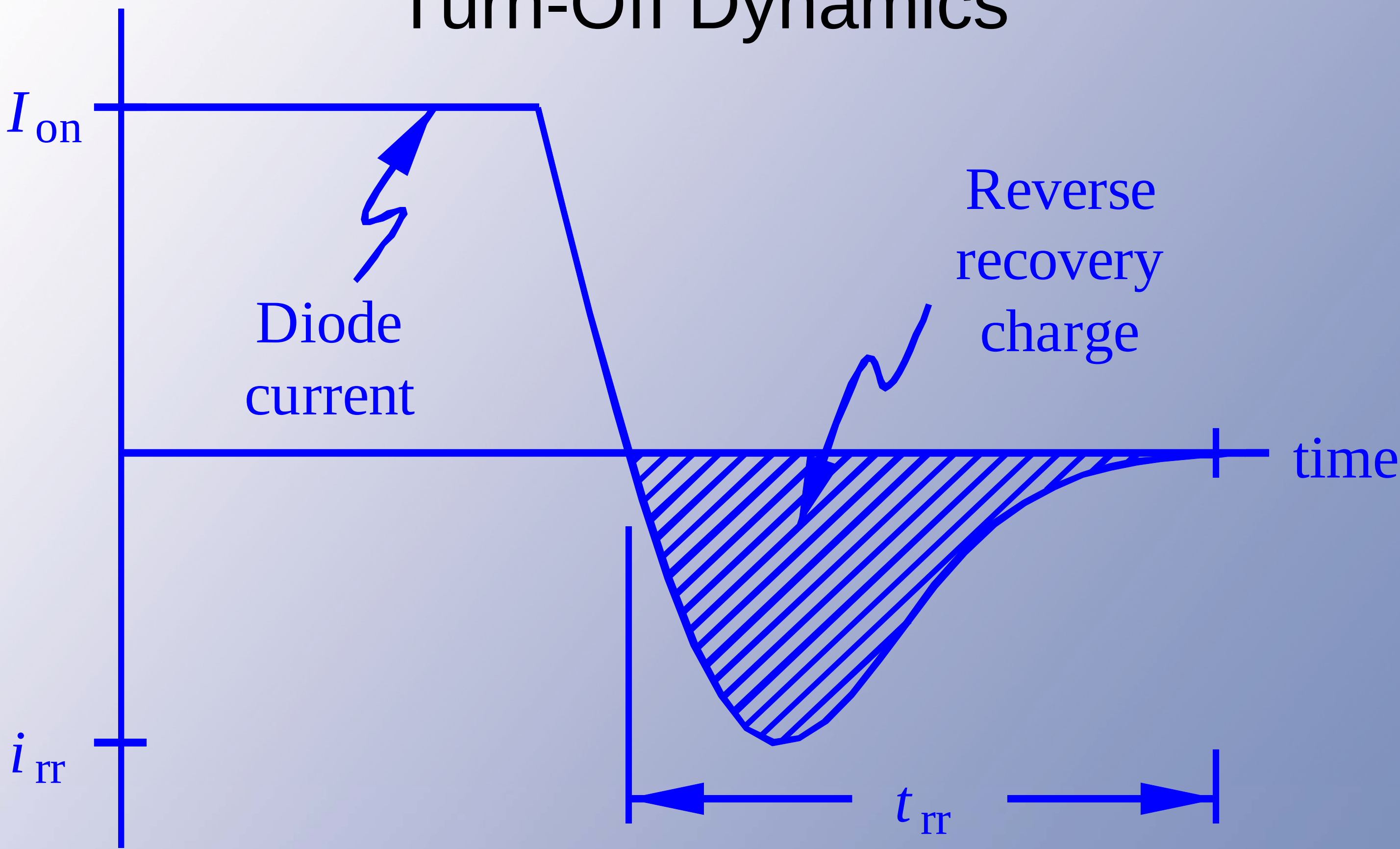


- With forward bias, the layer spacing is small and there is much more charge.
- We have a *diffusion capacitance* with a relatively high value.

Dynamics

- To turn the junction *off*, and allow it to block once again, the charge must be removed.
- In effect, the diffusion capacitance must be discharged before reverse blocking is supported again.
- The result is a *reverse recovery current*.

Turn-Off Dynamics



The discharge process takes time.

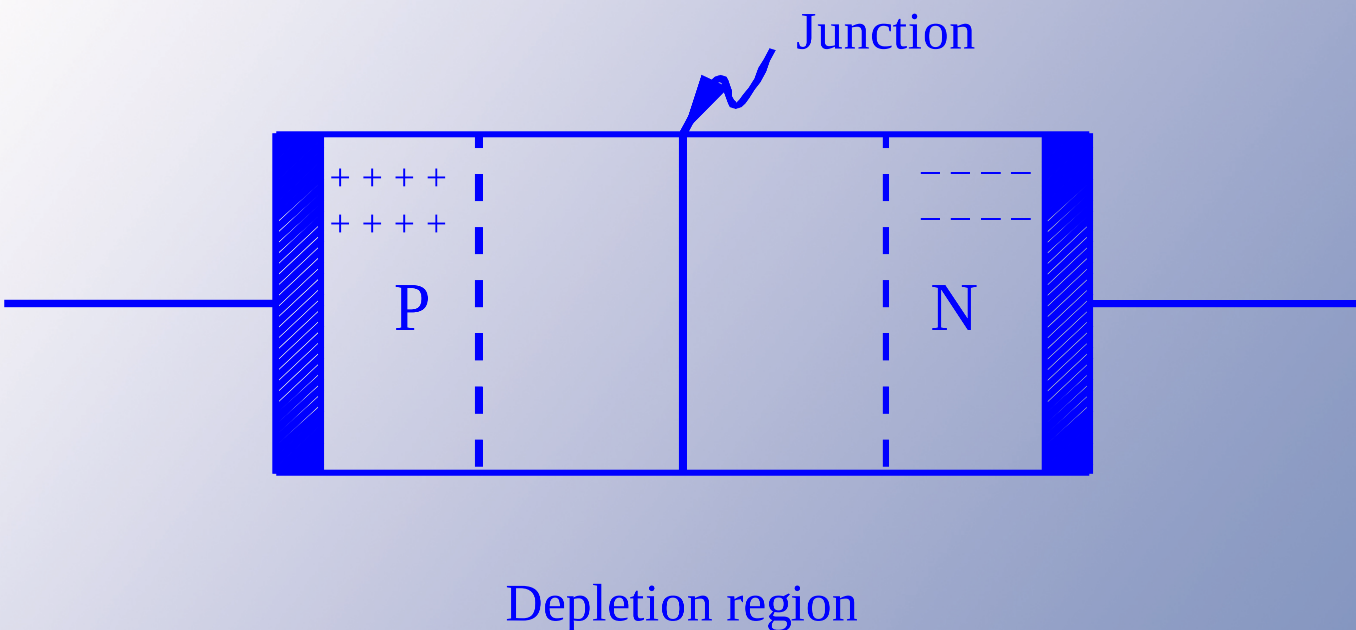
Turn-Off Dynamics

- The model is only approximate, since it is hard to speed up the turn-off process by *imposing* negative current.
- Most of the charge is removed through recombination .
- Power diodes often have special dopants to provide extra sites for charge recombination.

Turn-Off Dynamics

- The reverse recovery current is *not* related to off-state residual current.
- Power diode data sheets often convey information about reverse recovery time, current, or charge values.

Reverse Bias



- Once the device is off, a wider depletion layer forms.
- There is a *depletion capacitance* with a value much lower than for diffusion.

Turn-On Dynamics

- To turn the device on, we must charge up the depletion capacitance and form a smaller depletion region.
- There is a *forward recovery time* required to set up the charges and get current flowing.
- Forward recovery is always faster than reverse recovery (and rarely specified).

Alternatives

- P-i-N diodes use an additional intrinsic layer.
- This raises the voltage rating, and does not hurt speed.
- It tends to give a slightly higher forward drop.
- Common in power diodes

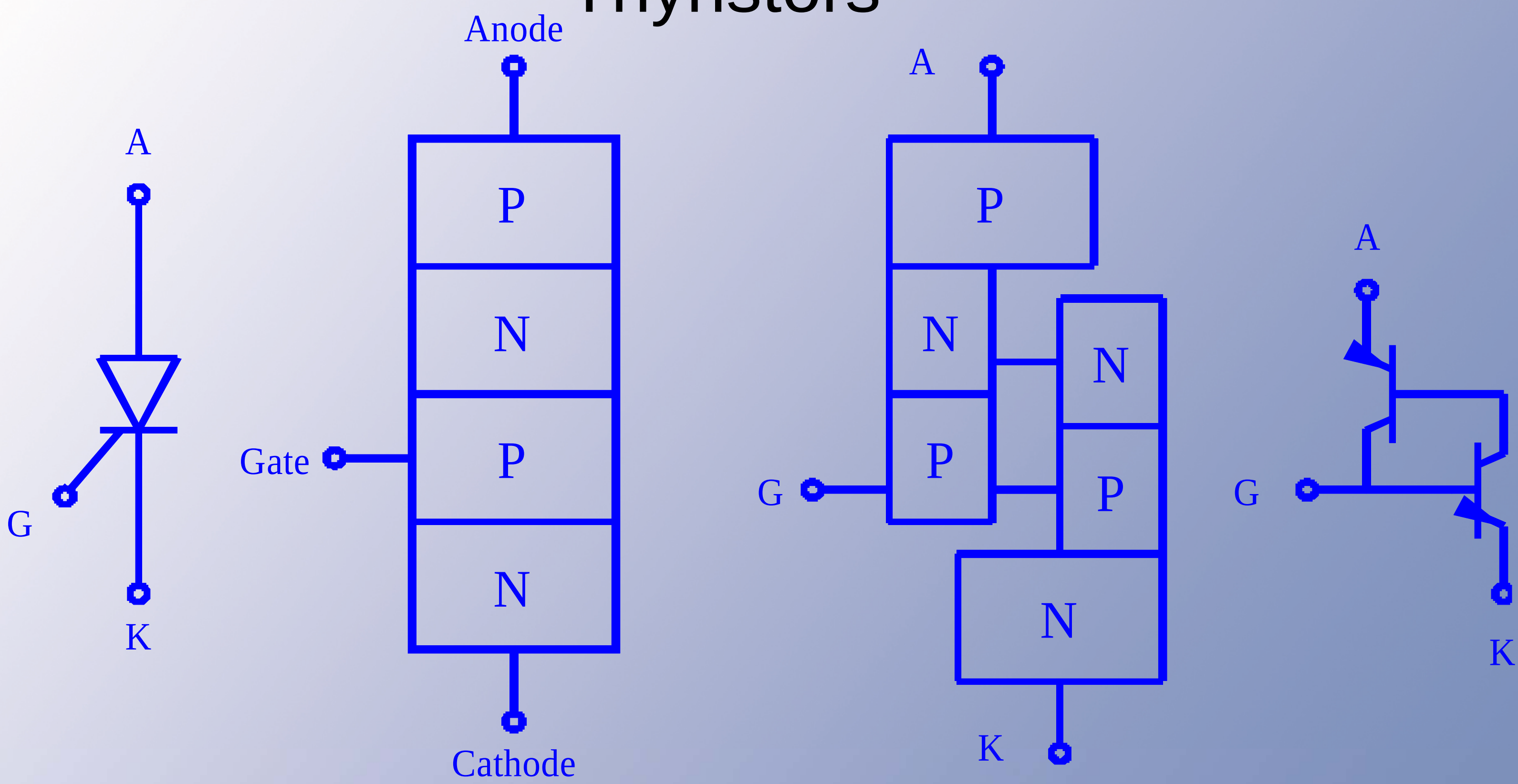
Alternatives

- Schottky barrier diodes do not function in the same manner.
- Charge must overcome a *work function* rather than diffuse into a depletion layer.
- The effective capacitances are much lower, and reverse recovery is minimal.
- But, the off-state voltages are low and leakage is high.

Thyristors

- The four-layer PNPN combination was the first type of *thyristor*. The SCR is most common.
- The action can be modelled with two transistors.
- Historically, the model was actually built and used before the semiconductor was made.

Thyristors



Two-transistor SCR model.

Thyristor Action

- When the gate is open, the center N-P combination can block forward voltage, while the others block reverse voltage.
- When gate current is applied, collector current flows in the bottom NPN.
- This applies base current to the top PNP.
- Collector current in the PNP then takes over for the gate.

Thyristor Action

- This is a *regeneration* process.
- But we notice that three semiconductor junctions must change.
- This requires extended time.
- If a “long” gate pulse is applied (~20 us for typical small devices), the regeneration process can work.

Thyristor Action

- The transistors must have some gain, but it is sufficient if $\beta_{PNP} \times \beta_{NPN} > 1$.
- This low gain constraint is helpful, because transistor gains are low at very high current densities.
- One problem is that stray capacitance can inject gate current if dv/dt is positive.

Gate Requirements

- Thyristors always have limits on dv/dt because of possible stray gate pulses.
- To turn off, the anode current must be removed.
- In fact, the gain goes below 1 if the current is low enough.
- We call this minimum value the *holding current*.

Turn-Off Issues

- In an SCR, turn-off is very slow. Two transistors must shut off, and charge is to be removed from multiple junctions.
- There are few external connections to allow us to force faster turn-off.
- However, a negative gate current can help if the NPN gain is "high."

GTO

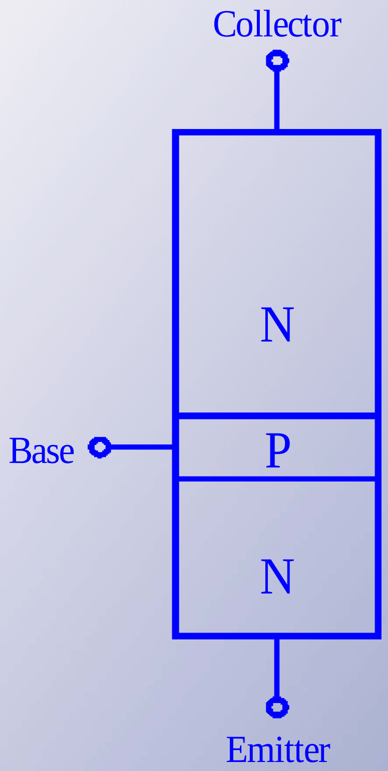
- In a gate-turn-off SCR (a GTO), the junctions are designed to give different gains to the two transistors.
- The NPN is provided with a “high” gain (which might be 5 to 10).
- A negative gate pulse can force the NPN collector current to zero.
- Then the device turns off.

GTO

- A GTO has a *turn-off gain*, typically about 5.
- For a 50 A on-state current, this means a turn-off pulse of 10 A is needed.
- The turn-on pulse is generally just a few milliamps!

Power BJTs

- While power BJTs are getting less common, an understanding of their dynamics helps with other devices.



- Most power BJTs are NPN because the current density is higher.
- The base region is narrow.
- For turn-on, the base-emitter junction first turns on, then base charge forms.

Power BJTs

- Off state: Zero base current (or connect base to a small negative voltage).
- On state: Inject the highest possible base current to drive the device close to saturation.

Power BJTs

- There is a *turn-on delay* as the base-emitter junction depletion layer is established.
- Then some electrons diffuse into the collector region, and electron flow takes place.
- The gain is low because considerable base charge is needed when the collector current is high.

Power BJTs

- Typically, the gain does not exceed 10, and can be much less.
- For turn-off, there is a challenge:
  - When base current is simply removed, base-emitter reverse recovery takes time.
  - After reverse recovery, charge in the base and collector recombines to turn off the flow.
- The result is the *storage time* required to remove all the charge.

Power BJTs

- Storage time is longer for higher collector current.
- We can speed up turn-off by imposing a negative base current.
- This reduces recovery time, but also gives a circuit path for charge removal.

Power BJTs: Active Region

- Notice that diodes and thyristors have only switch-like operation: an on state and an off state.
- Diodes and thyristors must commutate, but have no “in-between” operation.
- In contrast, BJTs have an active regime, and we could get stuck there without proper care.

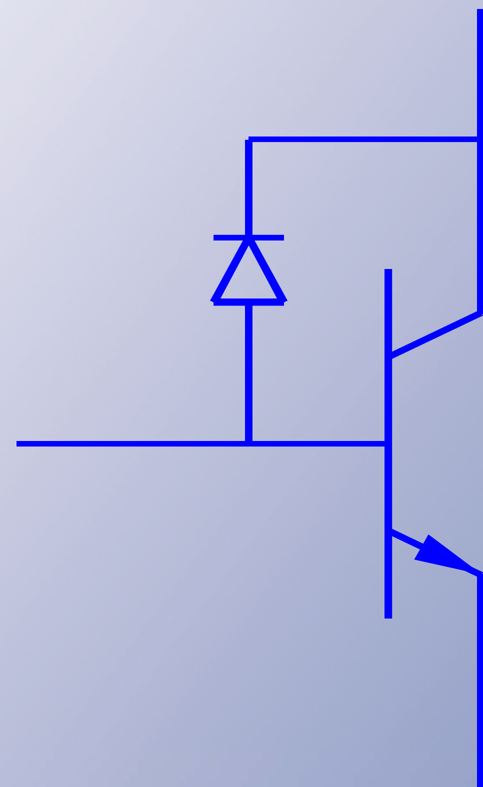
Power BJTs: Active Region

- With inadequate base current, the collector-emitter drop can be large.
- This produces high losses.
- The tradeoff is that high base current extends the storage time.

Saturation

- We want to be sure the base current is high enough to get into (or close to) saturation – but not too high.
- This is often accomplished through the use of a forced beta value.
- In this case, $i_b = i_c/\beta_f$, with β_f equal to a low "forced beta" value.

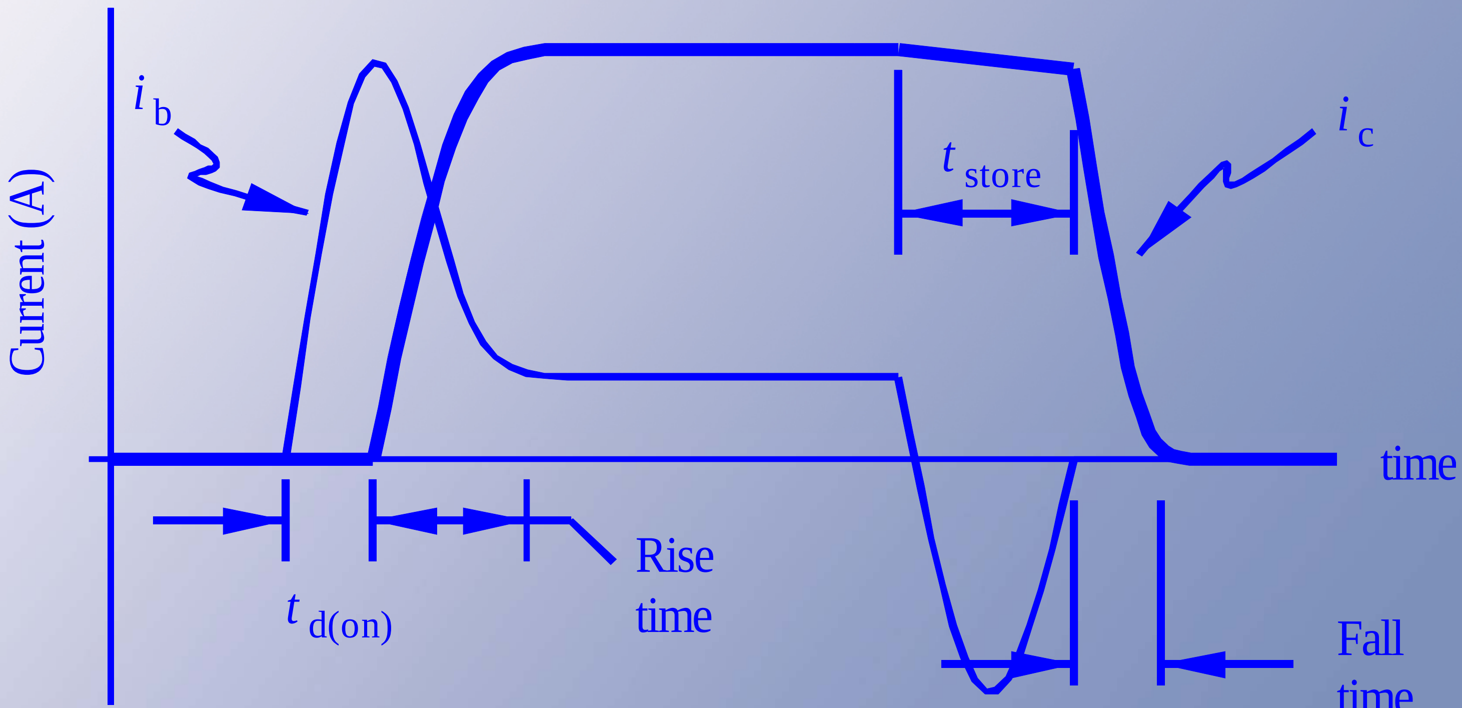
Anti-Saturation Circuit



- Sometimes a diode is added to divert excess base current. (A “Baker clamp.”)

Fast Operation

- To switch a BJT quickly, we can impose a high base current for fast turn-on, and a negative base current to speed turn-off.

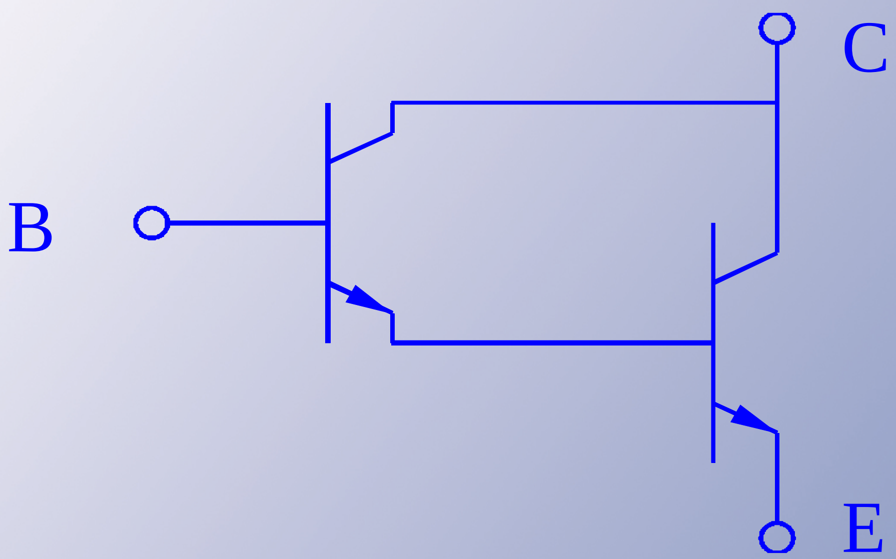


Fast Operation

- In this case, the base current approaches the intended i_c during the turn-on pulse.
- Then base current drops to the force beta value.
- The negative pulse helps reduce storage time.
- In typical devices, the rise and fall times are on a 1 microsecond time scale.

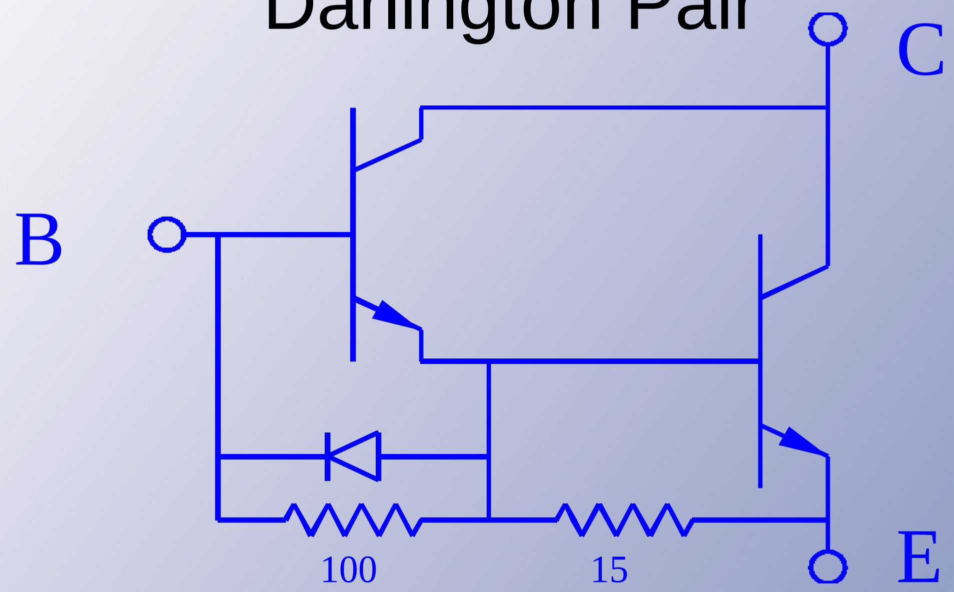
Darlington

- A Darlington pair enhances gain, at the expense of much slower operation.



- Gains of 1000 are possible.

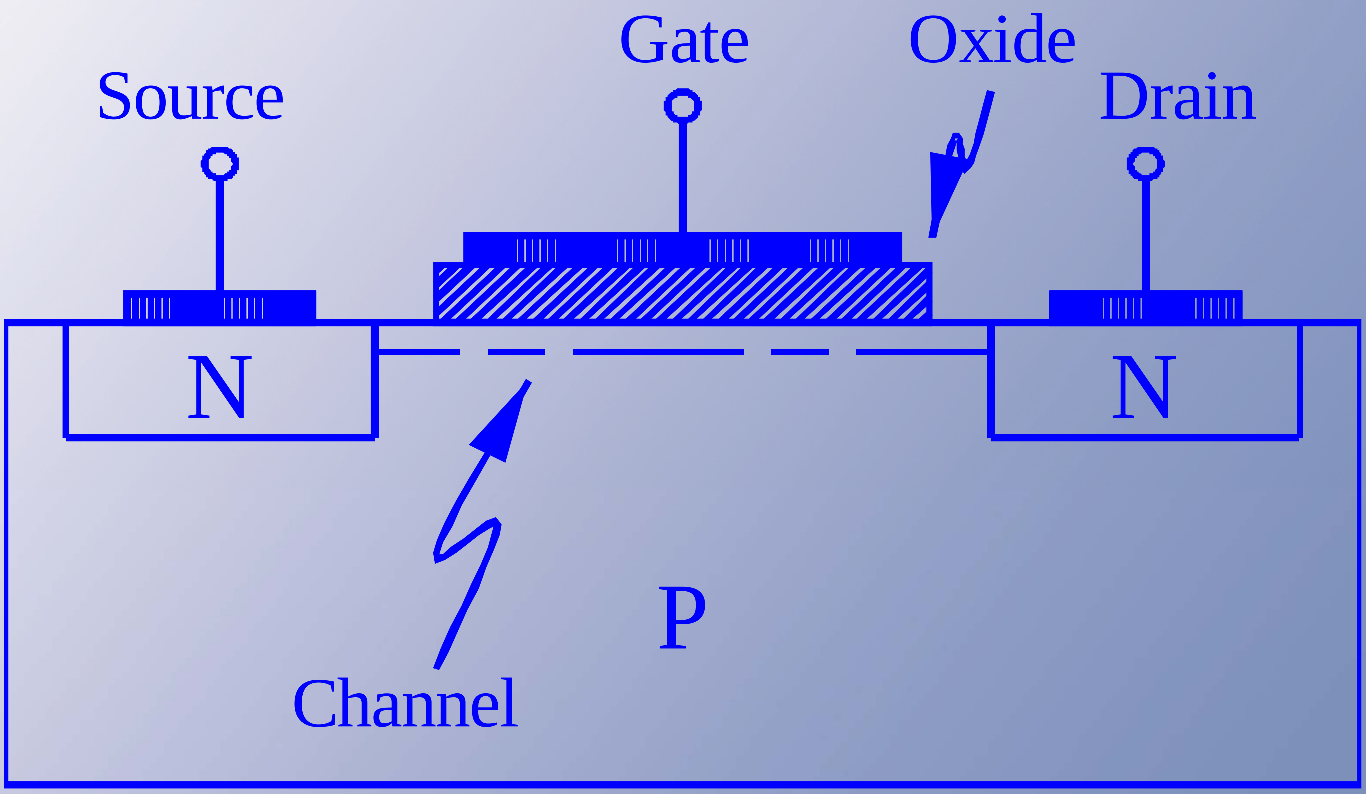
Darlington Pair



- Manufacturers often add internal diodes and other parts to try to speed the action of a Darlington pair.

Field-Effect Transistor

- Power FETs are almost always MOSFETs. The basic structure of a lateral part:



FET

- The concept is to apply an electric field between gate and source.
- The field strength should be high enough to bring some charge into the *channel* region.
- The channel region population inverts to give an effective continuous N-type path.
- This acts like a *voltage-controlled resistor*.

FET Dynamics

- The dynamics do not involve a PN junction.
- Once charge builds up below the gate, conduction can occur.
- The conduction process is simpler than in a BJT: we have formed a resistive path through the material.

FET Dynamics

- The drain current is not arbitrary, however, since voltage drop will interact with the gate-source electric field.
- MOSFETs in general are much faster than BJTs.
- The switching process can be modelled as the process of charging and discharging capacitance.

FET Operation

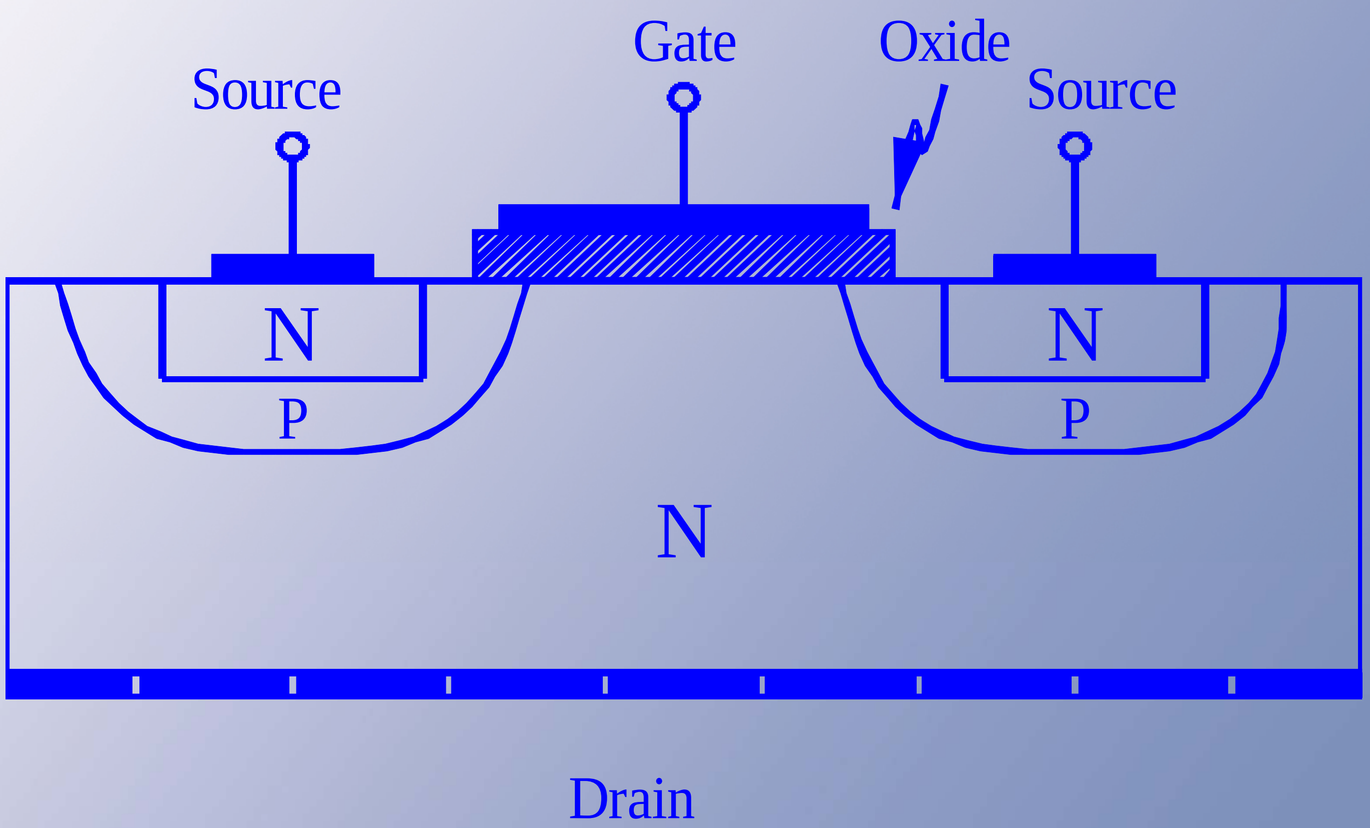
- Almost all power FETs are *enhancement mode* devices: They need an imposed field to form the channel.
- We can also build *depletion mode* devices, in which the channel has some doping, and a reverse field is used to invert it to P-type and turn the device off.

FET Operation

- An enhancement-mode FET acts as a “normally off” switch.
- A depletion-mode FET is a “normally on” switch.
- A drawback is the narrow channel: current flows in just a small region, and current density is very low.

Structure

Nearly all power FETs today use a vertical structure.



Structure

- There is more room for the channel.
- The channel is short -- resistance is low.
- Better current density -- better material use.
- BUT, notice the reverse diode.
- There is also a parasitic NPN transistor, with no connection to the base.
- The source metallization is set up to short the base and emitter so the NPN will not turn on.

Parallel Operation

- It would be useful to operate BJTs or FETs in parallel to enhance current capability.
- For the FET, this is easy. In silicon, resistance increases with temperature, and the electron flow will divide evenly among devices.

Parallel Operation

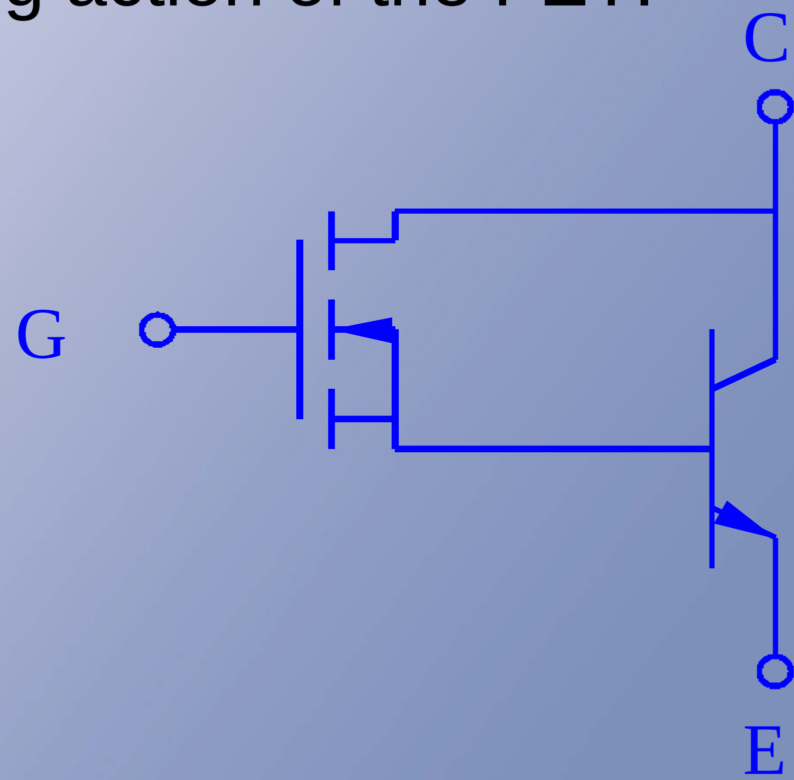
- For a BJT, this is more problematic. The carriers flow in P-type material, and the temperature coefficient of resistance is negative.
- This means that locally higher current might lead to local heating and even higher current – *current focusing*.

Parallel Operation

- Therefore, power FETs are always built as arrays of multiple cells.
- BJTs are single devices.
- It is hard (but possible) to use BJTs in parallel.

IGBTs

- The IGBT attempts to gain the larger current density advantage of the BJT and also the convenient switching action of the FET.
- This is rather like a Darlington combination of FET and BJT.



IGBTs

- IGBTs have ratings substantially higher than those of FETs of similar size.
- They are easy to use because of the voltage-based gate switching.
- Speed issues are dominated by the BJT.
- The Darlington arrangement leads to forward drop of 1.5 V or more.

Wrap-Up

- We have covered
  - Concepts
  - Converters
  - Connections
  - Devices
- These have brought together a wide range of electrical engineering topics to form a field of endeavor.

Wrap-Up

- Within the next several years, power electronic circuits and systems will dominate the processing and use of electrical energy.
- The field asks you to gain a new perspective on electrical circuits, their design, and their meaning.

Wrap-Up

- I hope you will have the opportunity to apply your knowledge.
- Even at a more general level, I strongly believe that the concepts and topics are helpful across many areas of electrical engineering.
- Thank you for participating in this course!