Lecture 6: Semiconductor Device Implementation

ECE 481: Power Electronics

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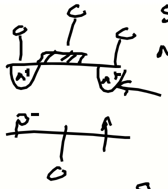
4.2. A brief survey of power semiconductor devices

- Power diodes
- Power MOSFETs
- Bipolar Junction Transistors (BJTs)
- Insulated Gate Bipolar Transistors (IGBTs)
- Thyristors (SCR, GTO, MCT)

- On resistance vs. breakdown voltage vs. switching times
- Minority carrier and majority carrier devices

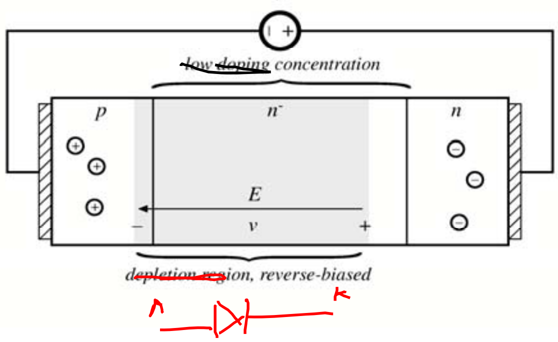


Signal MOSFET

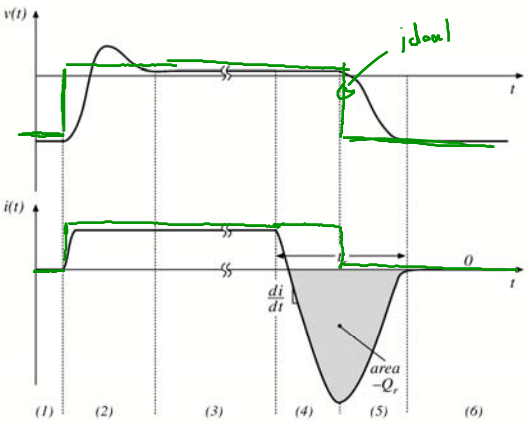
4.2.1. Power diodes

A power diode, under reverse-biased conditions:

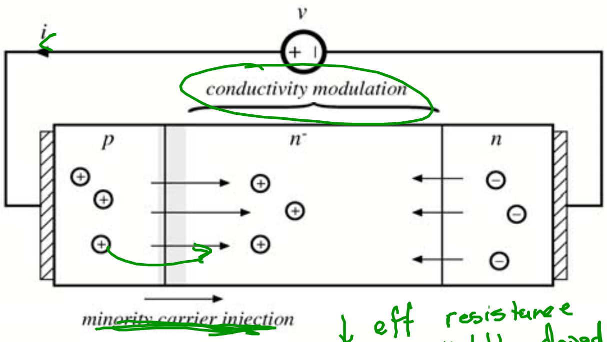
$W_{dep} \propto \frac{1}{\text{doping conc.}}$



Typical diode switching waveforms



Forward-biased power diode



↓ eff resistance of large, lightly doped region (req for large V_{BR})

Charge-controlled behavior of the diode

The diode equation:

$$q(t) = Q_0\left(e^{\lambda v(t)} - 1\right)$$

Charge control equation:

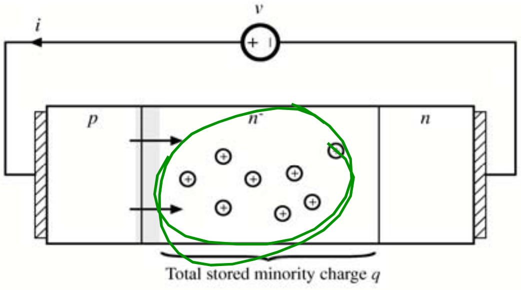
$$\boxed{\frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L}}$$

With:

λ= 1/(26 mV) at 300 K

τ_L = minority carrier lifetime

(above equations don't include current that charges depletion region capacitance)



In equilibrium: $dq/dt = 0$, and hence

$$i(t) = \frac{q(t)}{\tau_L} = \frac{Q_0}{\tau_L}\left(e^{\lambda v(t)} - 1\right) = I_0\left(e^{\lambda v(t)} - 1\right)$$

↑ τ, ↑ q

Charge-control in the diode: Discussion

- The familiar *i*–*v* curve of the diode is an equilibrium relationship that can be violated during transient conditions
- During the turn-on and turn-off switching transients, the current deviates substantially from the equilibrium *i*–*v* curve, because of change in the stored charge and change in the charge within the reverse-bias depletion region
- Under forward-biased conditions, the stored minority charge causes "conductivity modulation" of the resistance of the lightly-doped n^- region, reducing the device on-resistance

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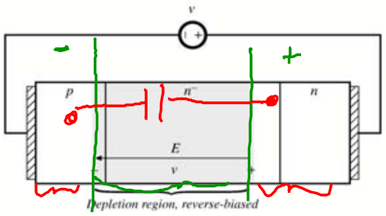
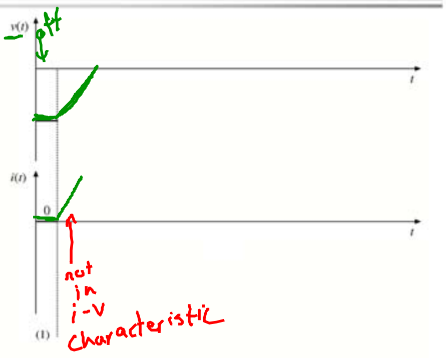
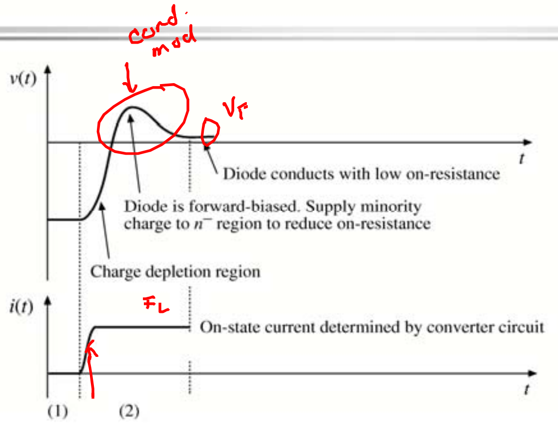
Diode in OFF state: reversed-biased, blocking voltage



- Diode is reverse-biased
- No stored minority charge: $q = 0$
- Depletion region blocks applied reverse voltage; charge is stored in capacitance of depletion region



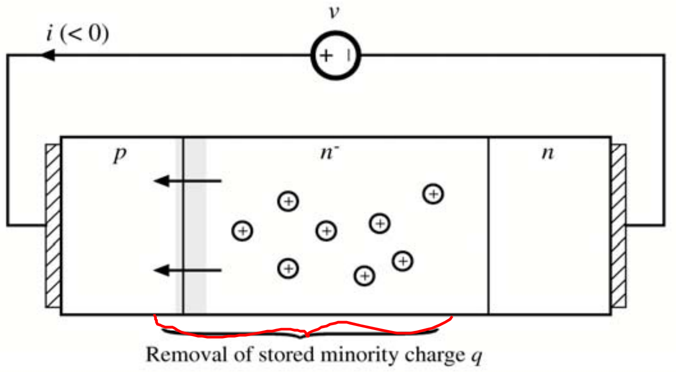
Turn-on transient



The current $i(t)$ is determined by the converter circuit. This current supplies:

- charge to increase voltage across depletion region
- charge needed to support the on-state current
- charge to reduce on-resistance of n^- region

Turn-off transient



"fast" t_r ∃ Q_r small

"slow"

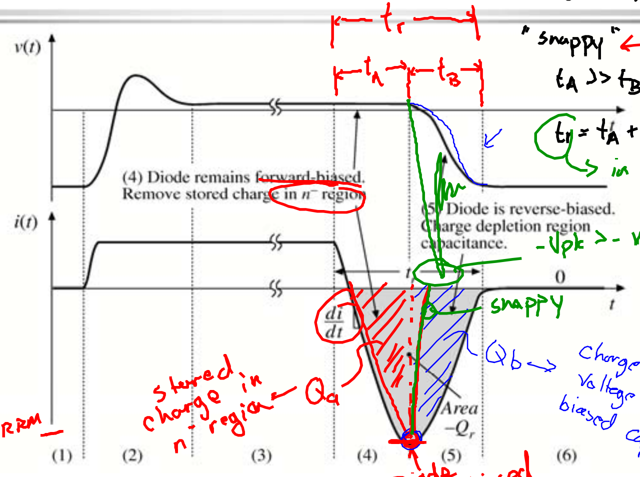
Diode turn-off transient

continued

"soft recovery" $t_B >> t_A$

"snappy" ← rare. $t_A >> t_B$

$t_{rr} = t_A + t_B$ → in datasheet



Datasheet Reported Turn-off Characteristics

$t_r = t_{rr}$

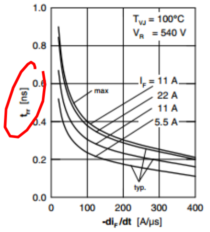


Fig. 5 Recovery time versus $-di_F/dt$

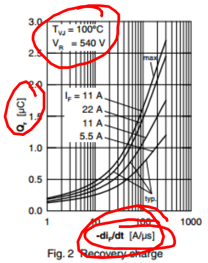


Fig. 2 Recovery charge versus $-di_F/dt$

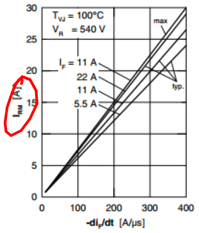
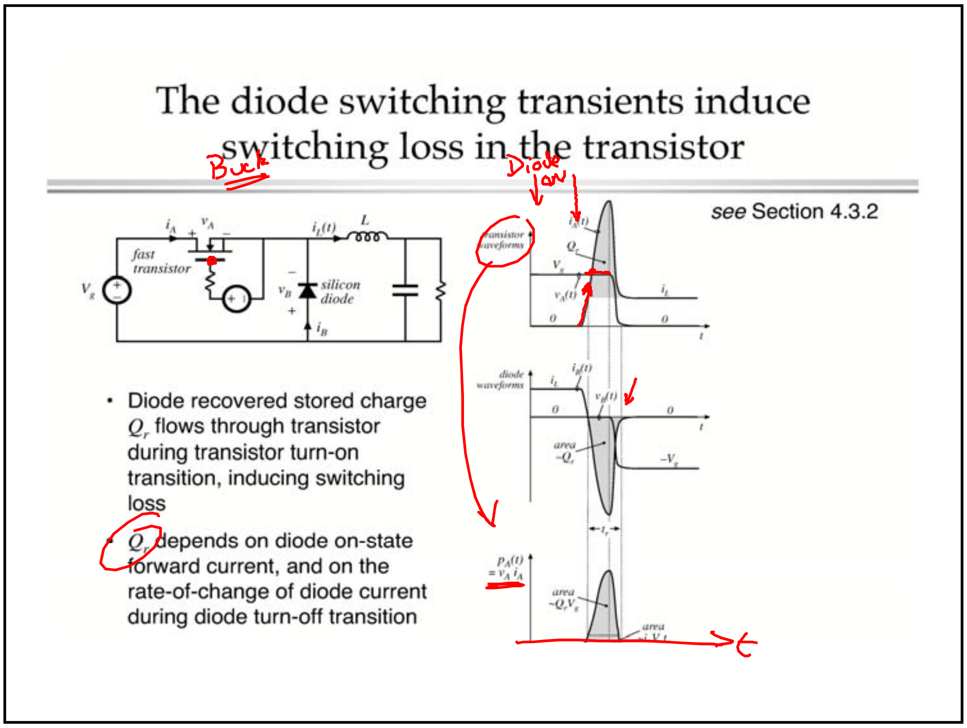


Fig. 3 Peak reverse current versus $-di_F/dt$

Turn-off waveforms depend on

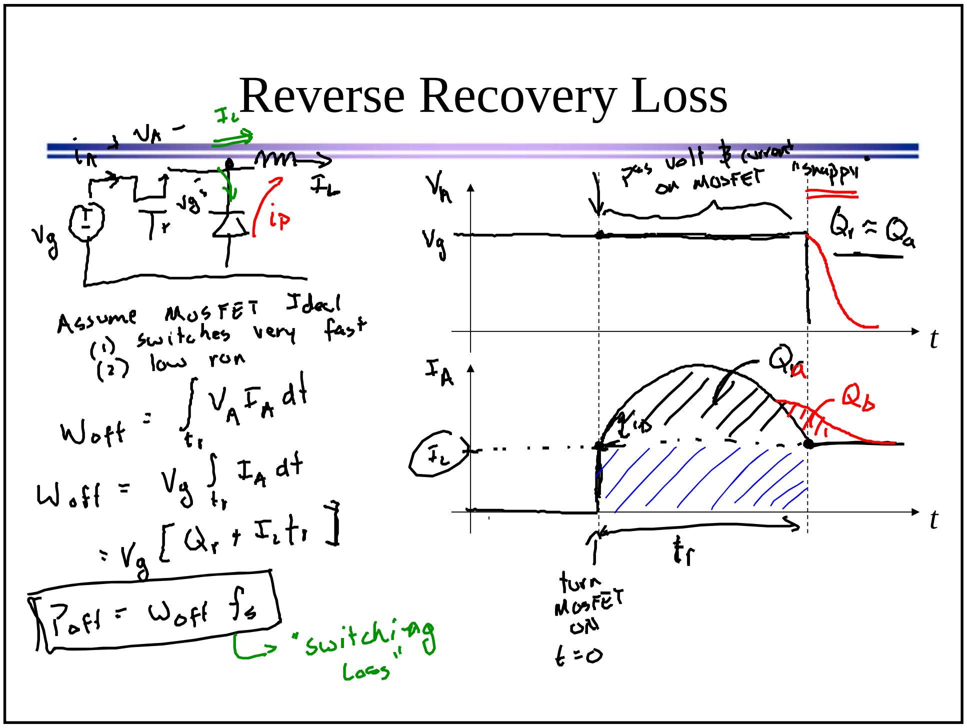
$\underbrace{T, \frac{di}{dt}, V_R, I_F}$



The diode switching transients induce switching loss in the transistor

see Section 4.3.2

- Diode recovered stored charge Q_r flows through transistor during transistor turn-on transition, inducing switching loss
- Q_r depends on diode on-state forward current, and on the rate-of-change of diode current during diode turn-off transition



Reverse Recovery Loss

Assume MOSFET Ideal
(1) switches very fast
(2) low ron

$$W_{off} = \int_{t_r} V_A I_A \, dt$$

$$W_{off} = V_g \int_{t_r} I_A \, dt$$

$$= V_g \left[Q_r + I_L t_r \right]$$

$$\boxed{P_{off} = W_{off} f_s}$$

→ "switching Loss"

$Q_r \approx Q_a$

Switching loss calculation

Energy lost in transistor:

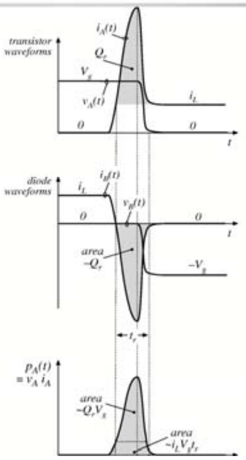
$$W_D = \int_{\substack{\text{switching}\\\text{transition}}} v_A(t)\, i_A(t)\, dt$$

With abrupt-recovery diode:

$$W_D \approx \int_{\substack{\text{switching}\\\text{transition}}} V_g\, (i_L - i_B(t))\, dt$$

$$= V_g\, i_L\, t_r + V_g\, Q_r$$

- *Often, this is the largest component of switching loss*



Soft-recovery diode:

$(t_2 - t_1) >> (t_1 - t_0)$

Abrupt-recovery diode:

$(t_2 - t_1) << (t_1 - t_0)$

Types of power diodes

Standard recovery → "slow"

Reverse recovery time not specified, intended for 50/60Hz

→ *Fast recovery and ultra-fast recovery*

Reverse recovery time and recovered charge specified

Intended for converter applications → 10's of kHz & up

Schottky diode

A majority carrier device

Essentially no recovered charge → no conductivity modulation

Model with equilibrium i-v characteristic, in parallel with depletion region capacitance

Restricted to low voltage (few devices can block 100V or more)

Characteristics of several commercial power rectifier diodes

hyperfast

Part number	Rated max voltage	Rated avg current	V_F (typical)	t_r (max)
Fast recovery rectifiers				
1N3913	400V	30A	1.1V	400ns
SD453N25S20PC	2500V	400A	2.2V	2μs
Ultra-fast recovery rectifiers				
MUR815	150V	8A	0.975V	35ns
MUR1560	600V	15A	1.2V	60ns
RHRU100120	1200V	100A	2.6V	60ns
Schottky rectifiers				
MBR6030L	30V	60A	0.48V	
444CNQ045	45V	440A	0.69V	
30CPQ150	150V	30A	1.19V	
SiC Schottky				
SCS220AGC	600V	20A	1.55V	0ns
APT30SCD120S	1.2kV	99A	1.8V	0ns

→ minority carrier concentration increases w/ temp.

Paralleling diodes

Attempts to parallel diodes, and share the current so that $i_1 = i_2 = i/2$, generally don't work.

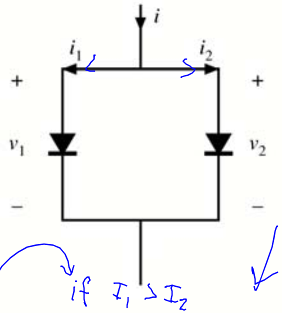
Reason: thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

One diode will hog the current.

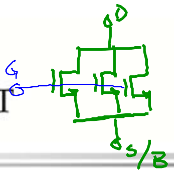
To get the diodes to share the current, heroic measures are required:

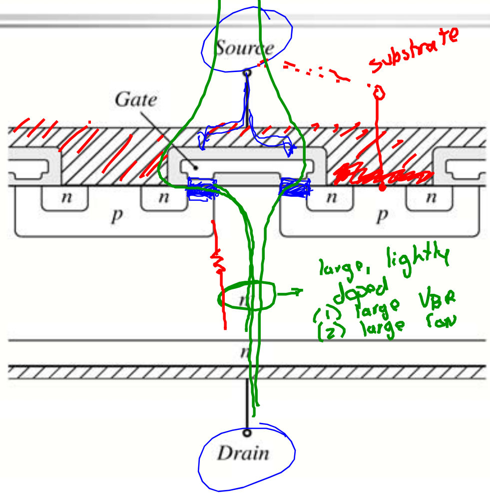
- Select matched devices → on-chip
- Package on common thermal substrate
- Build external circuitry that forces the currents to balance



if $I_1 > I_2$
↳ $T_1 > T_2$
↳ M.C concentration in D_1 increases
↳ ρ of D_1 decreases
↳ I_1 increases

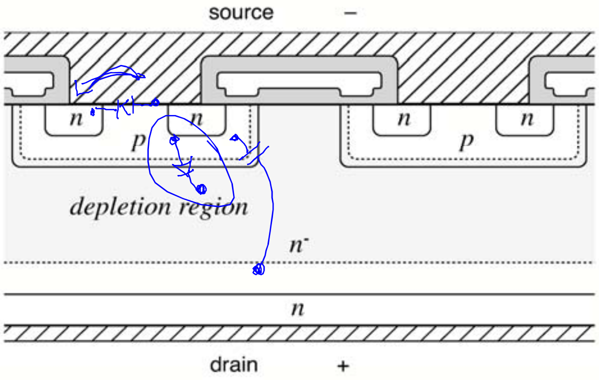
4.2.2. The Power MOSFET





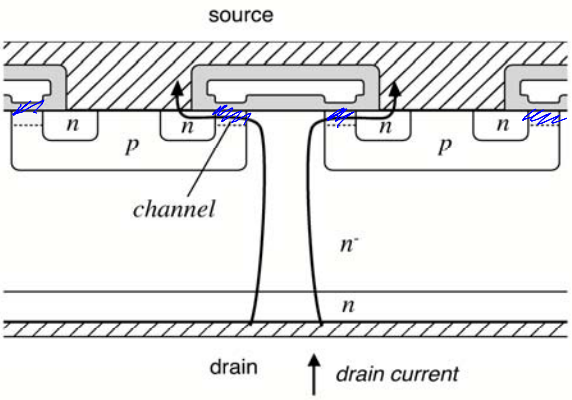
- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown

MOSFET: Off state



- *p*-n^- junction is reverse-biased
- off-state voltage appears across n^- region

MOSFET: on state



- p-n^- junction is slightly reverse-biased
- positive gate voltage induces conducting channel
- drain current flows through n^- region and conducting channel
- on resistance = total resistances of n^- region, conducting channel, source and drain contacts, etc.