

ELEC2208 Power Electronics and Drives

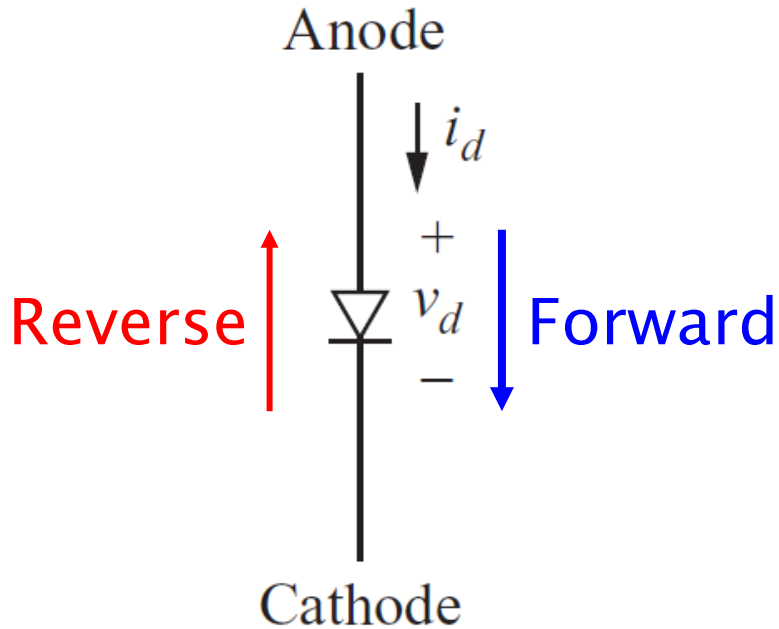
Diode

Yoshi Tsuchiya
Smart Electronic Materials and Systems (SEMS) Group
yt2@ecs.soton.ac.uk
59/4219

Diode

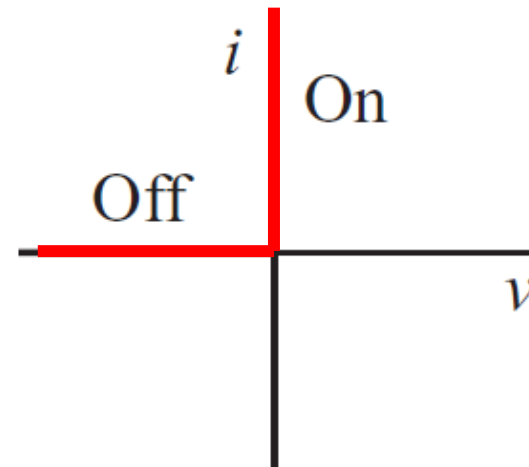
- Have you ever studied “diode”?
- How many terminals on a diode?
- Can you explain typical current-voltage behaviour?
- Do you think we can use this device for switches?

Diode



Circuit symbol

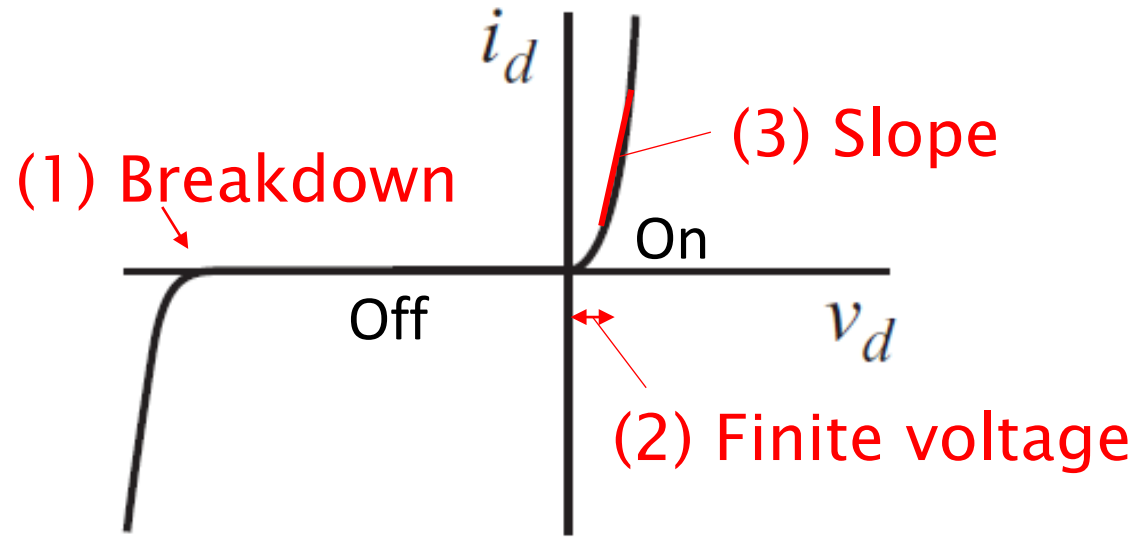
- Two terminals \longrightarrow No control gate
On and off conditions are determined by voltages and currents in the circuit.
- Ideal $i_d - v_d$ characteristics



Forward-biased (on) when the current i_d is positive and reverse biased (off) when v_d is negative.

Practical diode and diode equation

$i_d - v_d$ characteristics of practical diode



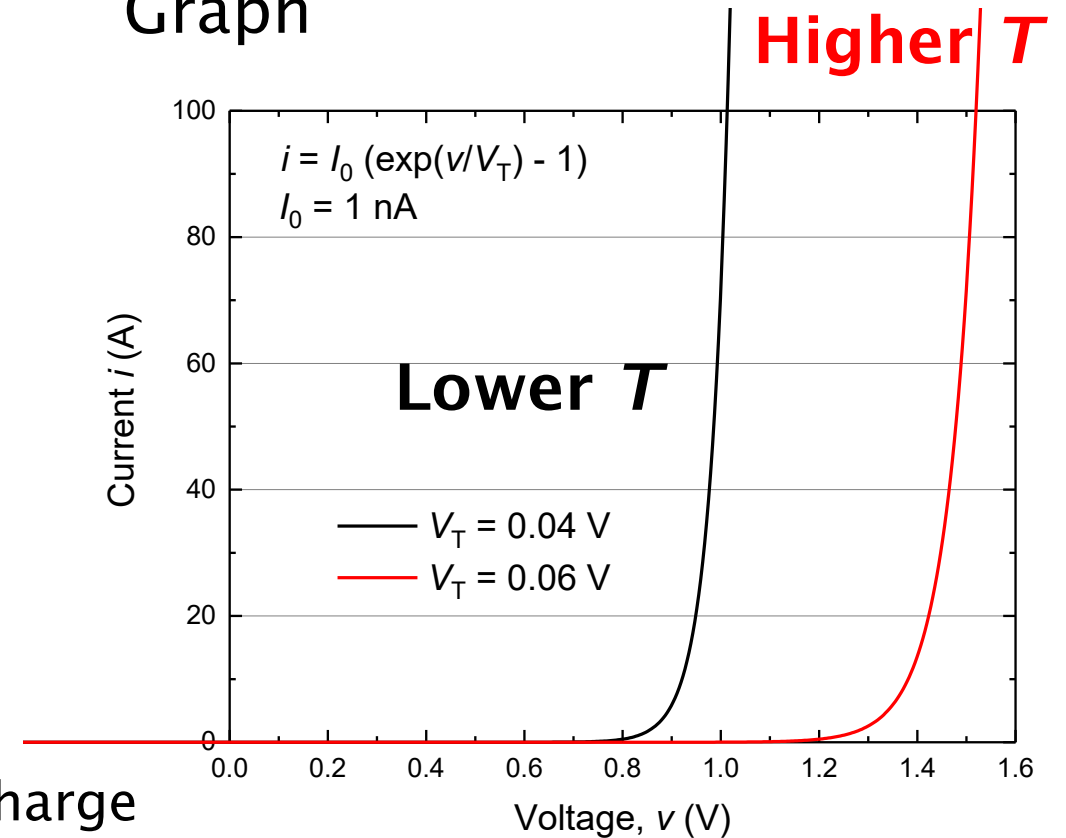
Diode current equation

$$i = I_0 \left(e^{\frac{v}{V_T}} - 1 \right) = I_0 e^{\frac{v}{V_T}} - I_0$$

$$V_T = \frac{nkT}{q}$$

q : elementary charge
 k : Boltzmann constant
 T : Temperature
 n : Ideality factor
 I_0 : Saturation current

Graph

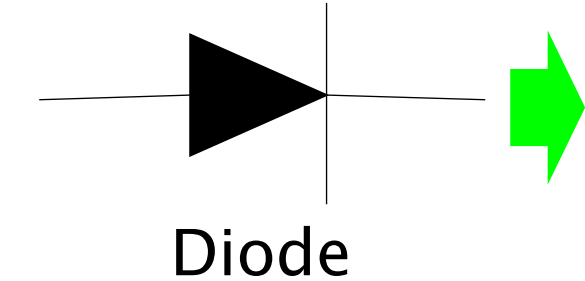


Practical diode characteristics

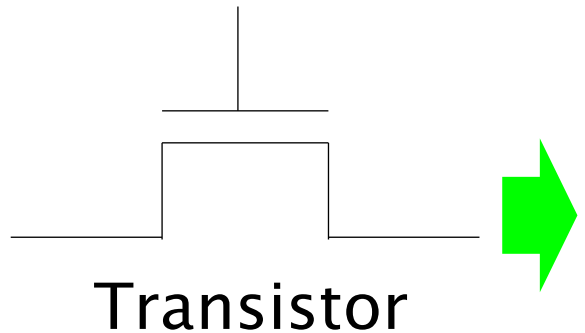
- Practical diodes are based on semiconductor PN junction that have maximum blocking voltage and maximum current.
- At very large reverse bias, beyond the peak inverse voltage or peak reverse voltage, practical diodes breakdown that causes a large increase in current in reverse direction.
- Practical diodes have significant voltage drop during forward conduction.
- The i - v characteristics of practical diode is nonlinear.

Mathematical modelling

Circuit elements

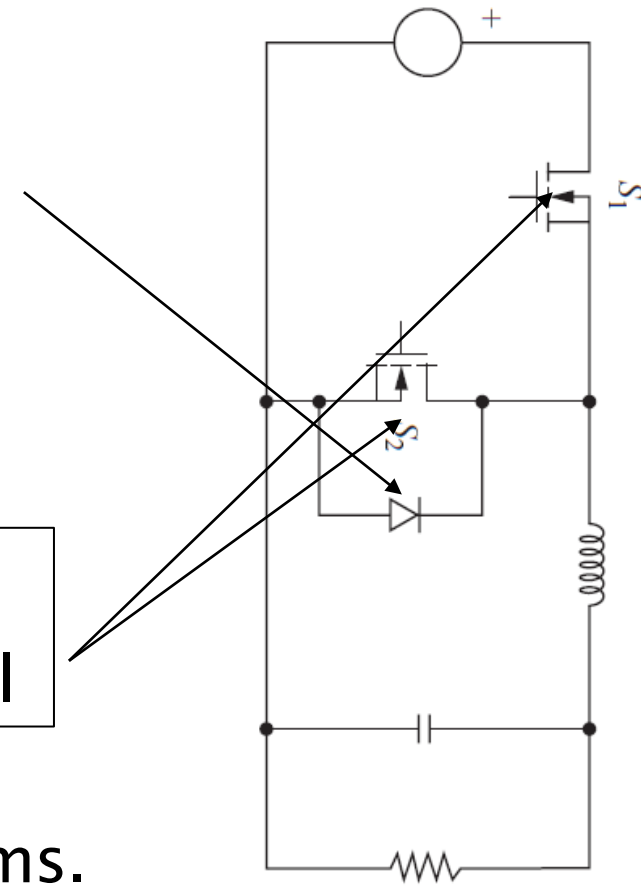


Mathematical
Diode model



Mathematical
Transistor model

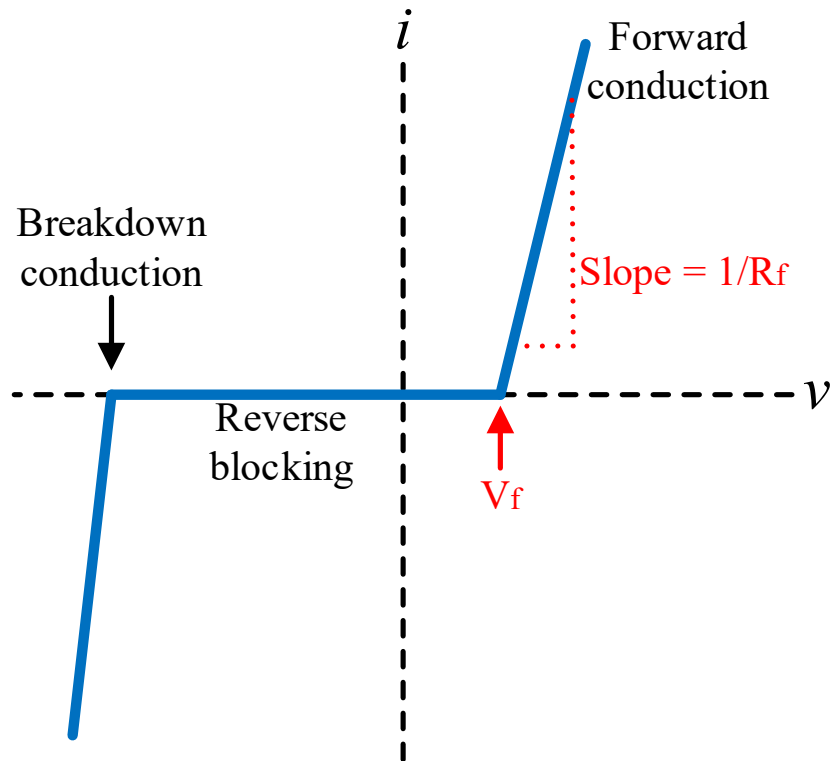
Circuit simulation



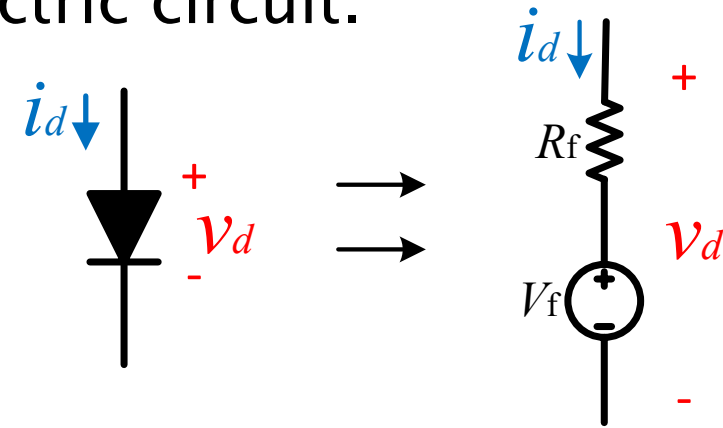
- Very important for designing large systems.
- Model should be accurate and simple.

Linear diode model

The i - v curve of diode can be linearized so that the diode model during conduction can be represented in linear electric circuit.



V_f : Approximate forward voltage
 R_f : Approximate resistance



Linear diode model during forward conduction

Under forward bias

Voltage drop

$$v_d = V_f + i_d R_f$$

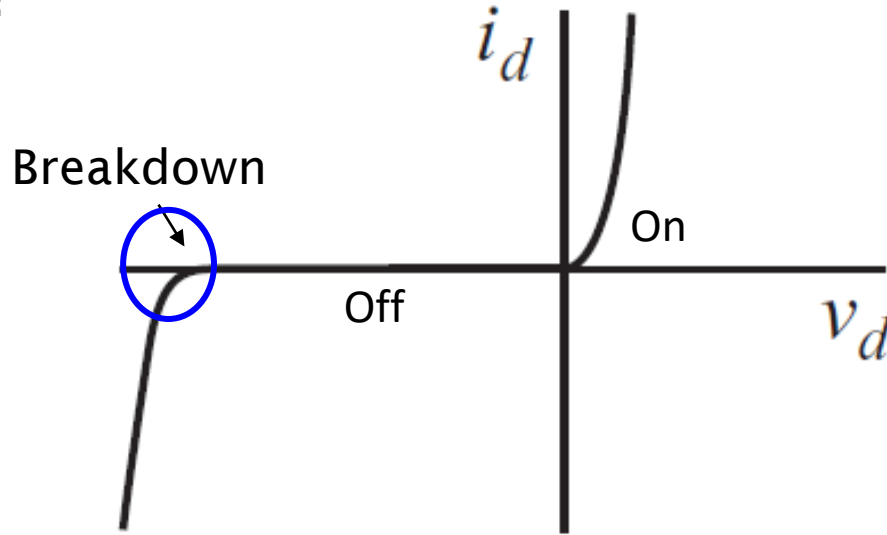
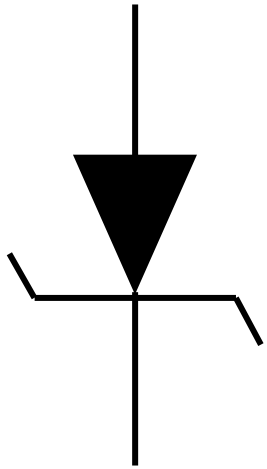
Power dissipation

$$P_d = V_f I_{avg} + I_{d,rms}^2 R_f$$

I_{avg} : Mean of i_d
 $I_{d,rms}$: RMS of i_d

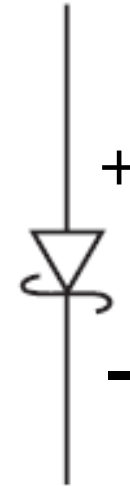
Other types of diodes

Zener diode



- Designed to operate **at the reverse breakdown voltage in reverse conduction.**
- Used for voltage reference devices or a voltage clamp.

Schottky diode



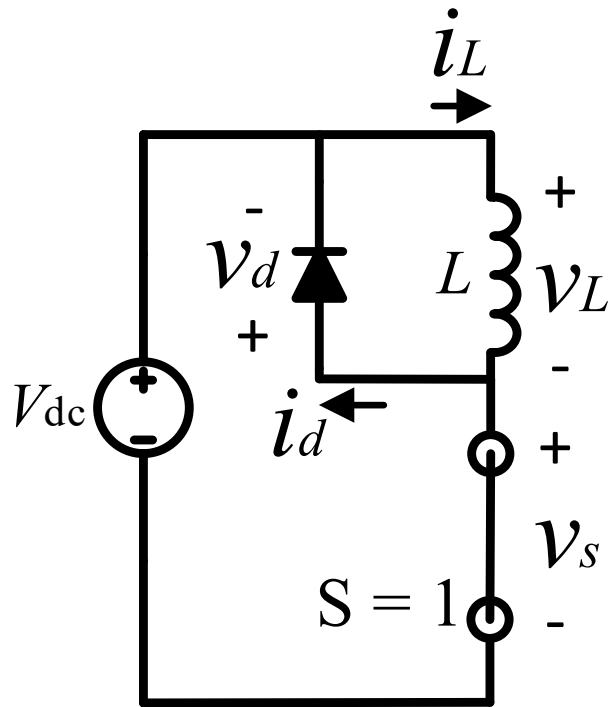
- For Schottky diodes, **Schottky barrier junction** (such as metal-semiconductor contact) is used.

- Schottky diodes have a very high switching rate.
- Used for low-voltage application.

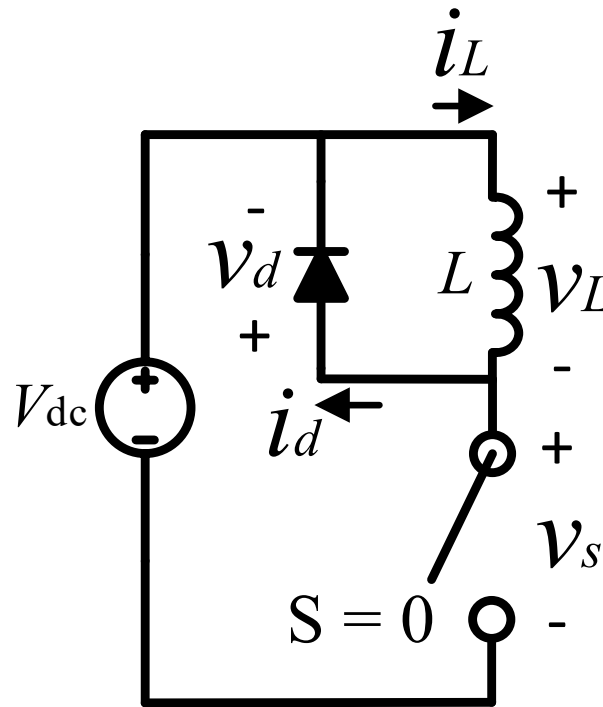
Comparison – PN vs Schottky

	PN junction diode	Schottky diode
Average forward current	~ 3000 A	~ 30 A
Reverse voltage	~ 9000 V	~100 V
Forward bias voltage	0.7 V (IC) 1.2 V (power)	0.3 V
Switching rate	Varies	Very high

Freewheeling diode



Mode 1: Switch on



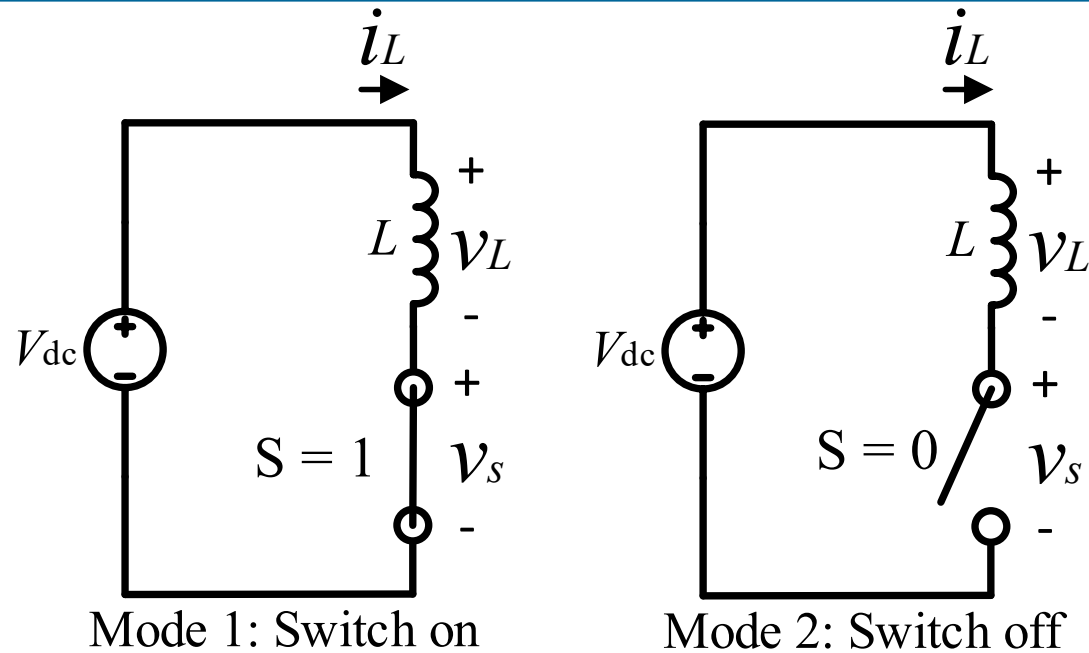
Mode 2: Switch off

- Very common use of diode in power circuits.
- Used for inductive load connected to a switch.
- **Diode is connected across the inductor.**

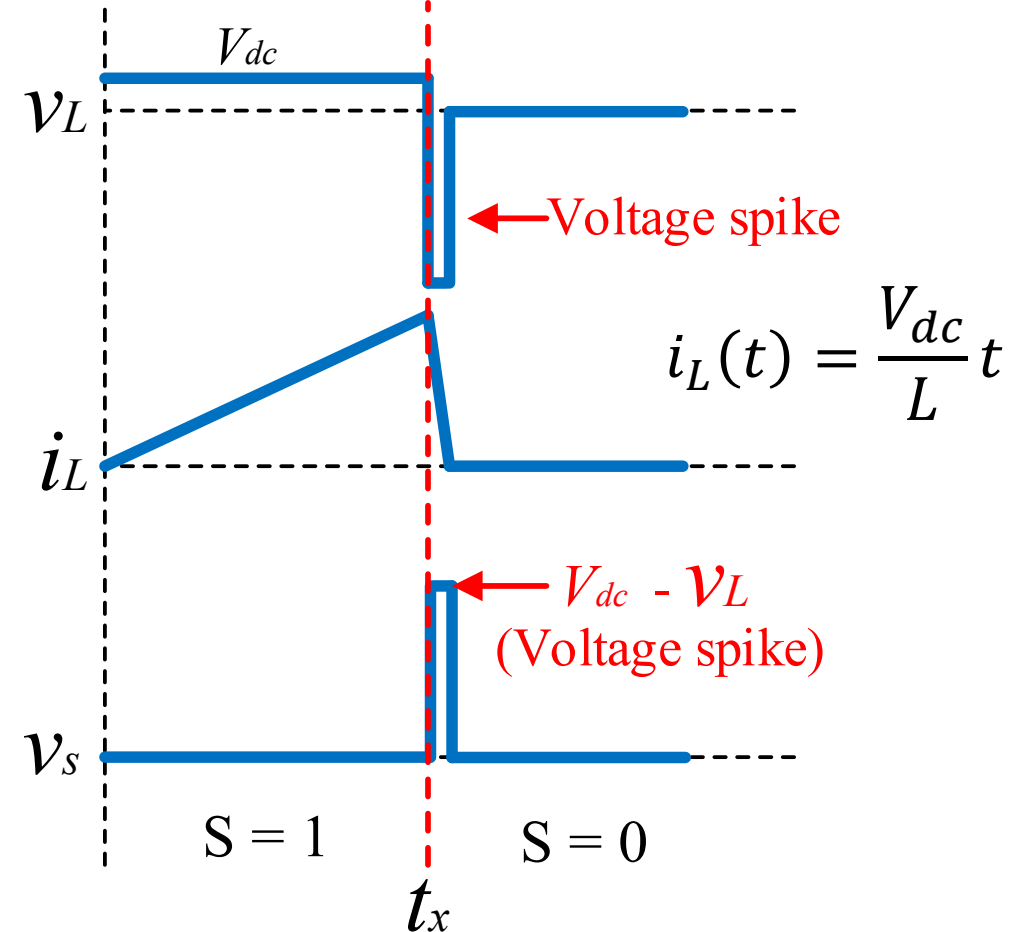
- **Freewheeling diode provides an alternative path for inductor current to prevent voltage spike.**

Other names: Snubber diode, Flyback diode, Clamp diode, Kickback diode etc.

Without freewheeling diode



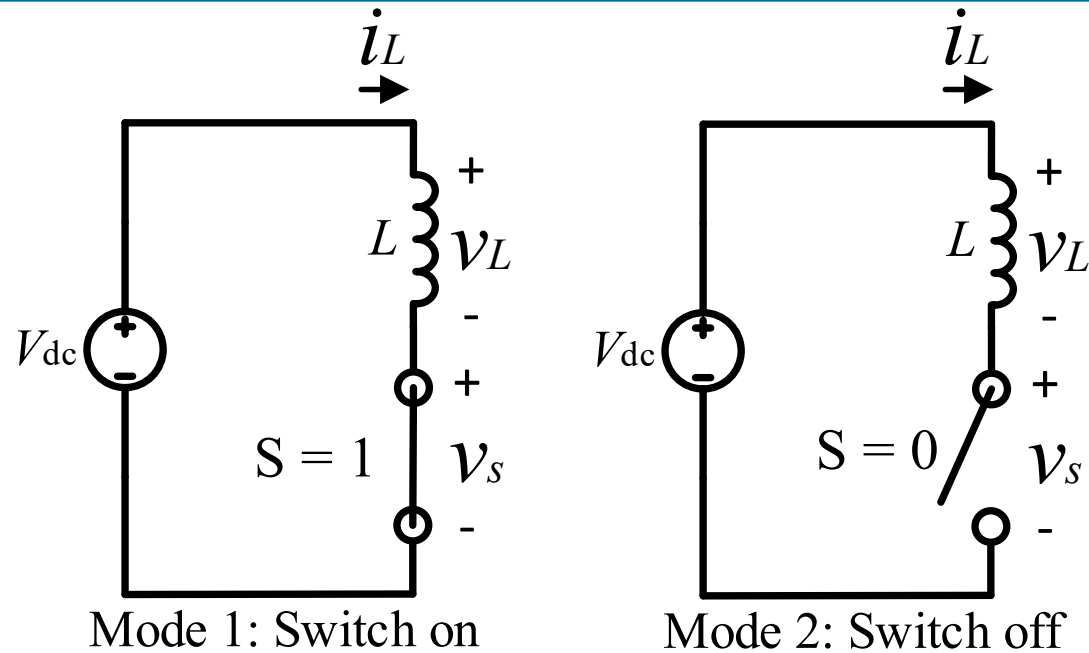
$$v_L(t) = L \frac{di_L(t)}{dt}$$



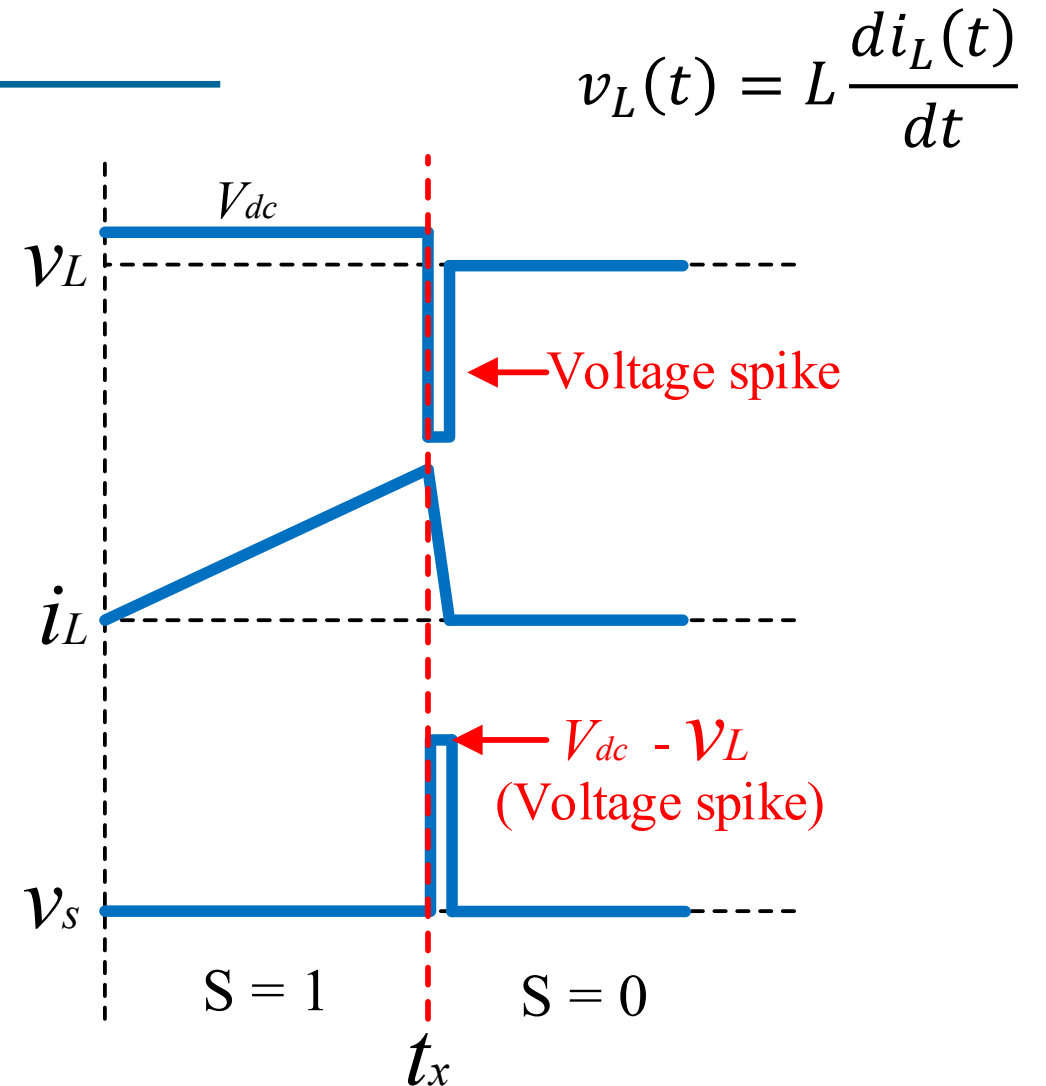
- At $t = 0$, the switch is on.
- i_L rises linearly due to constant voltage applied across inductor.

- Energy stored in inductor is $w(t) = \frac{1}{2} L i_L^2$

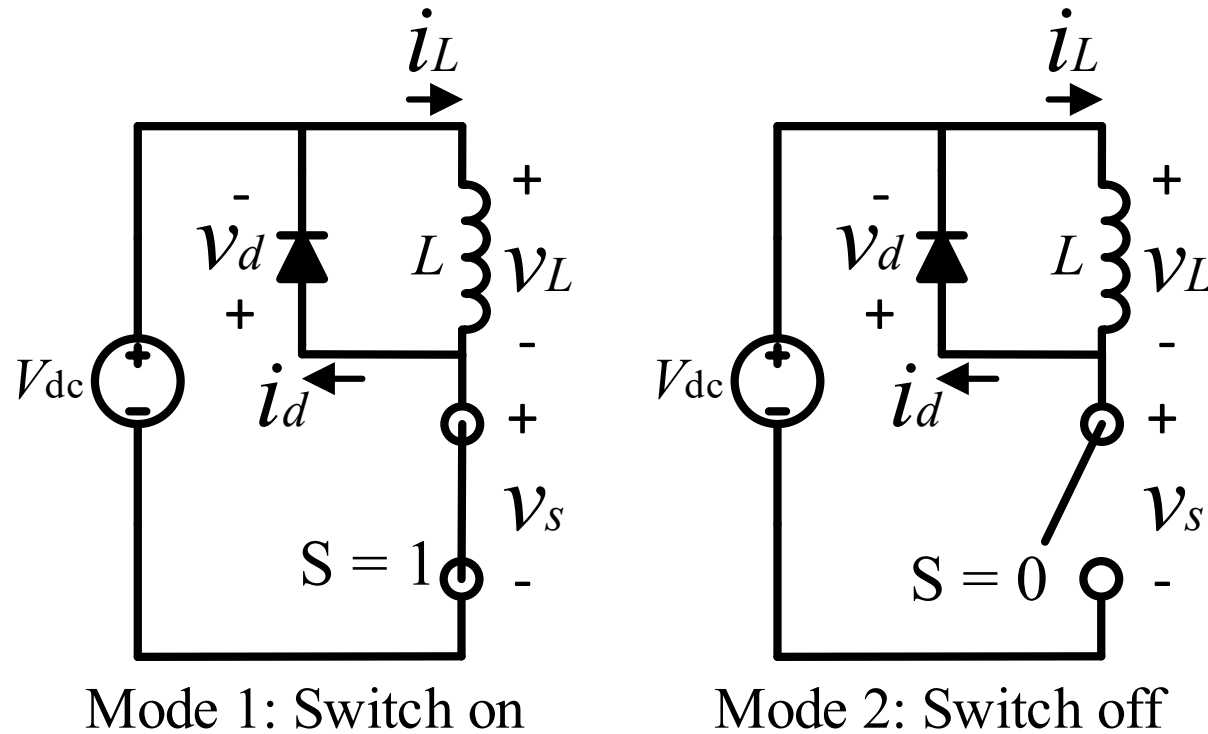
Without freewheeling diode



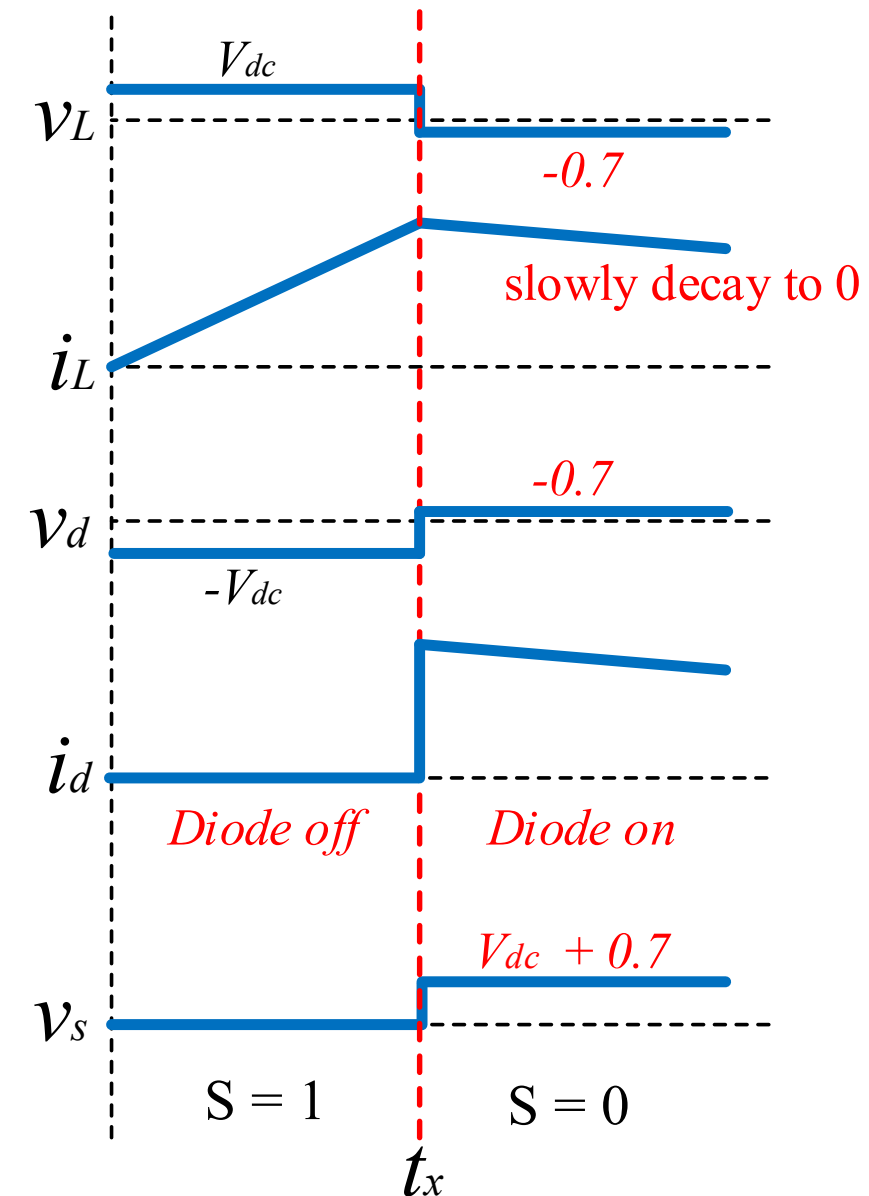
- At $t = t_x$, the switch is turned off.
- The stored magnetic energy released instantly causing a voltage spike.
- High di/dt causing overvoltage up to \sim kV could damage the switch.



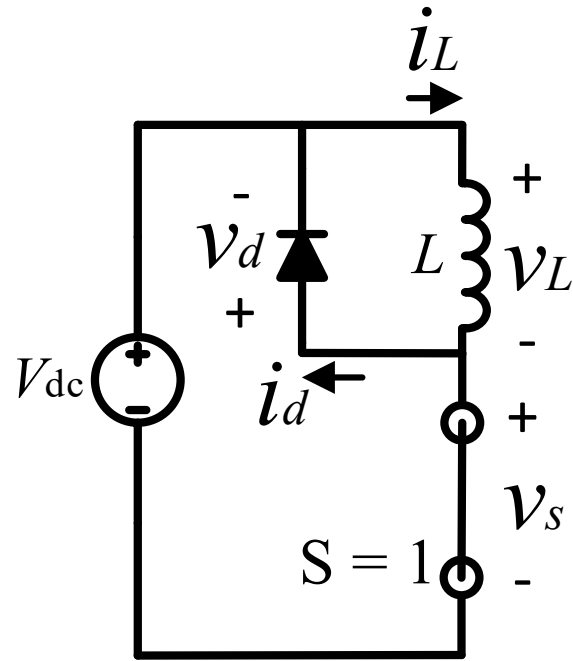
Freewheeling diode



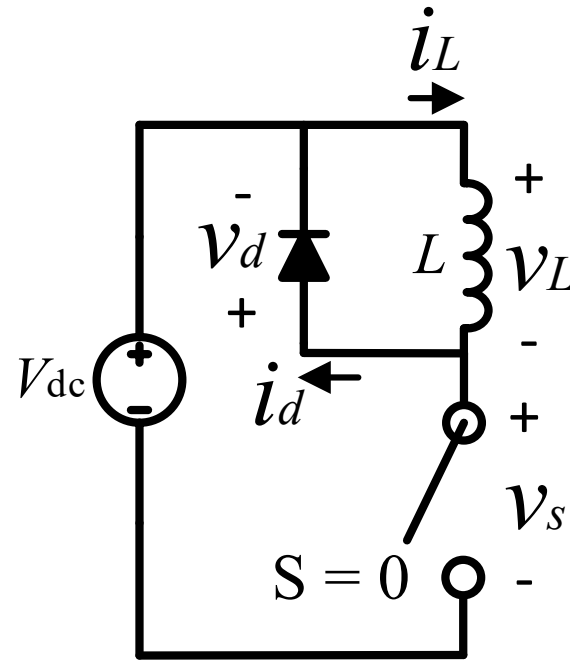
- At $t = 0$, the switch is on, i_L rises linearly and energy is stored in inductor (the same without the diode).
- The diode is off as reverse-biased.**



Freewheeling diode

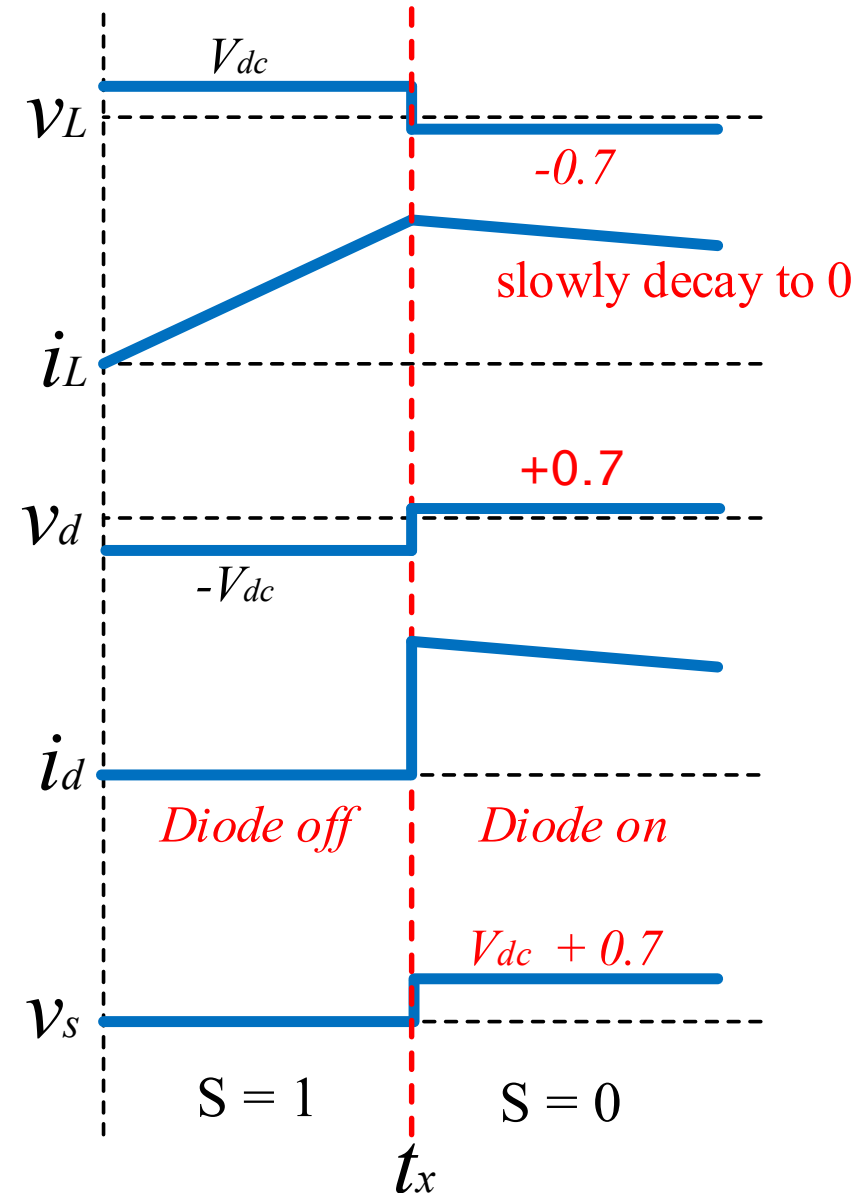


Mode 1: Switch on



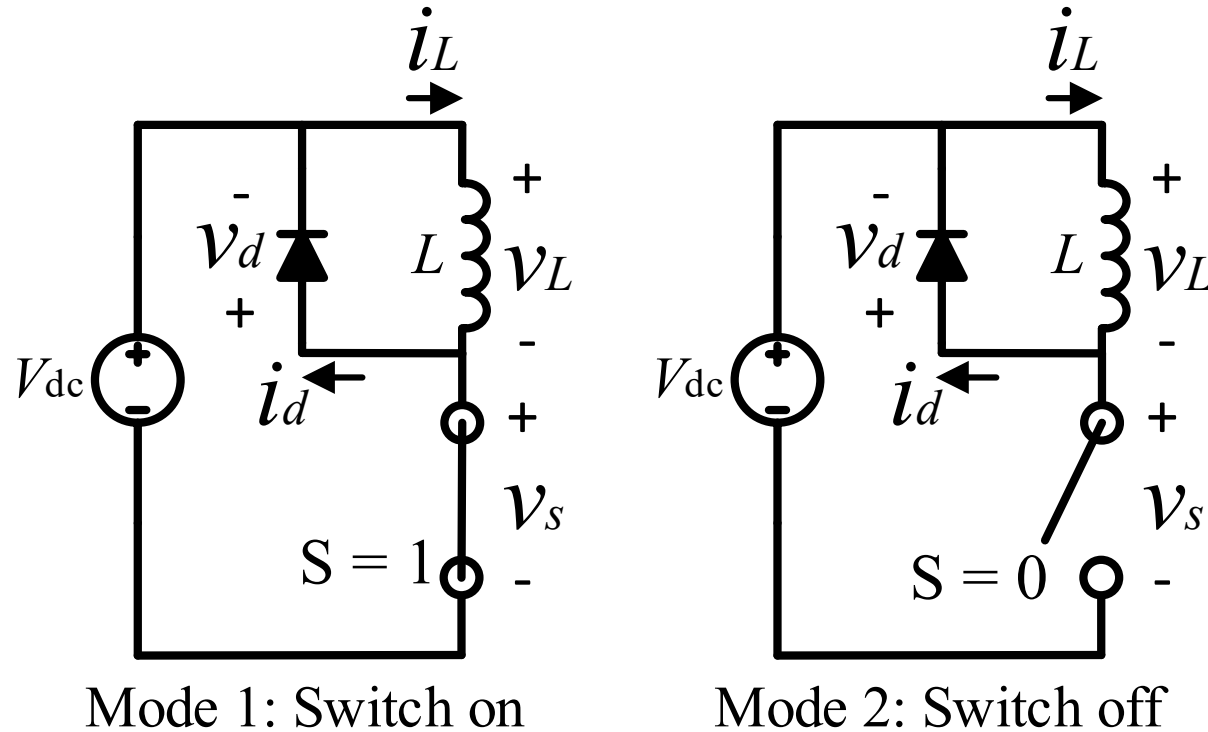
Mode 2: Switch off

- When the switch is turned off at $t = t_x$, freewheeling diode becomes forward biased.
- Current flows to the diode and the inductor voltage is kept by the forward voltage drop of the freewheeling diode. ($v_L = -v_d = -0.7 \text{ V}$)

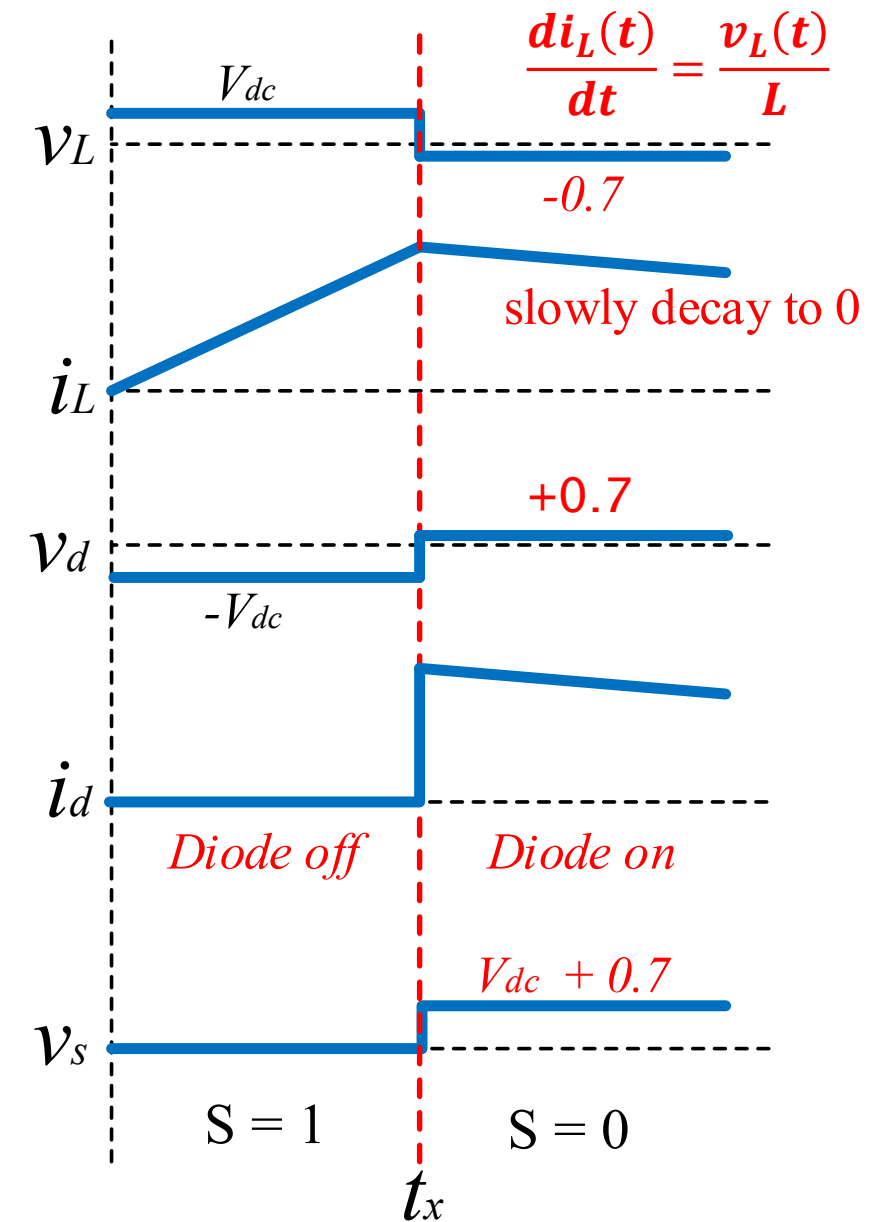


Note: Diode forward voltage drop = 0.7 V

Freewheeling diode

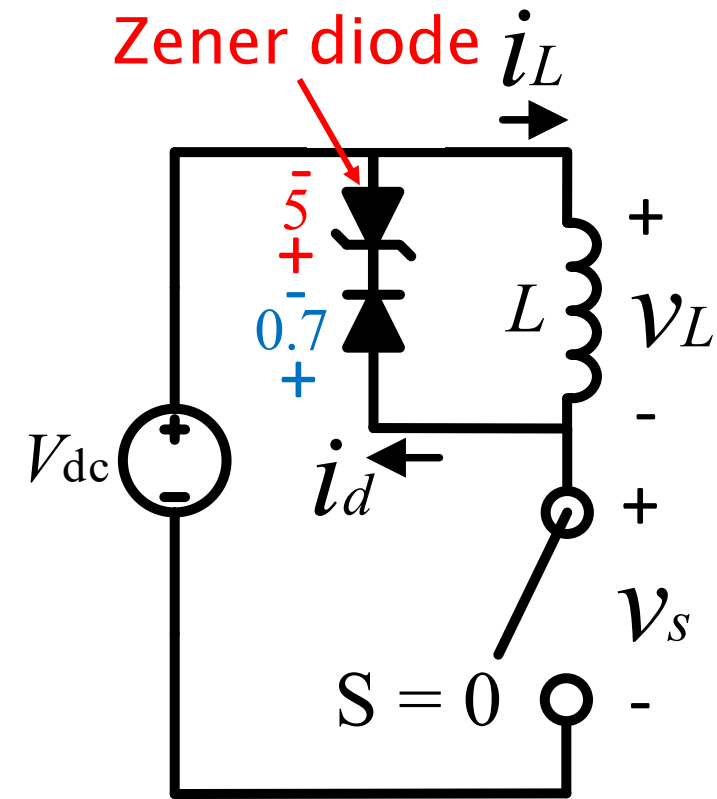


- The magnetic energy is released slowly and the inductor current decays to 0.
- Voltage spike is prevented and the voltage across switch v_s is kept low.



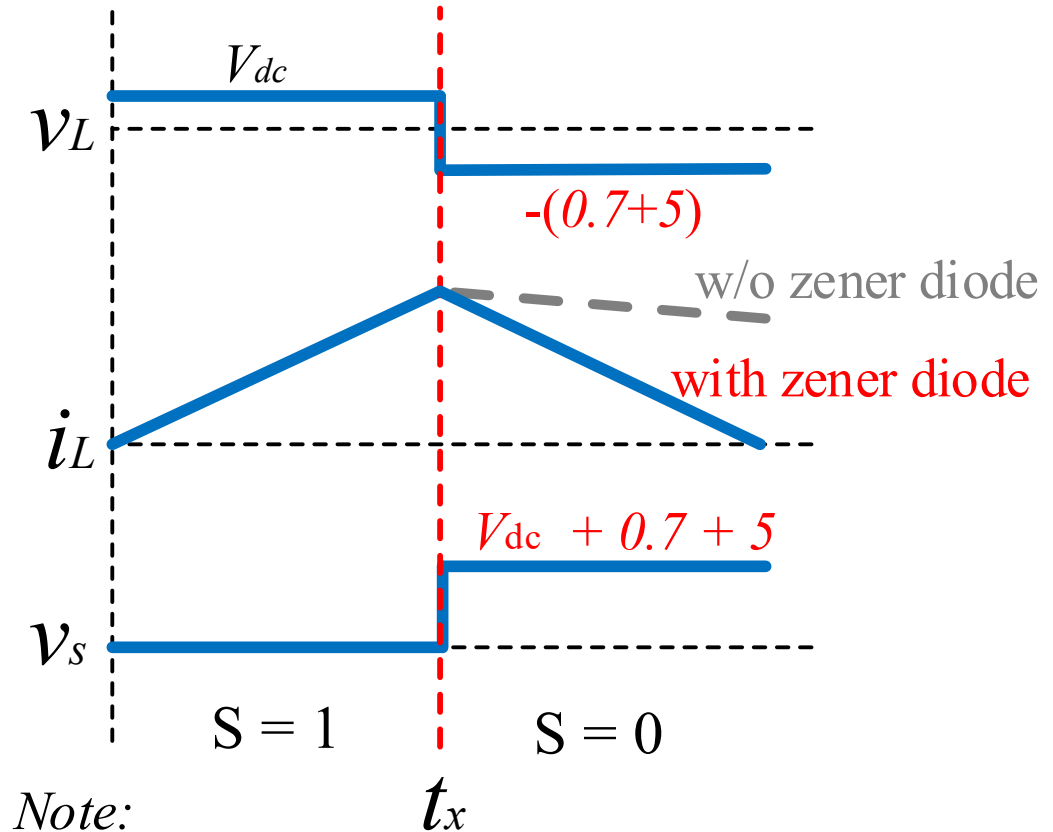
Note: Diode forward voltage drop = 0.7V

Voltage clamping with Zener diode



Mode 2: Switch off

- Zener diode connected in series to freewheeling diode clamps the voltage across inductor to -5.7 V
- The inductor current decays faster without causing voltage spike.



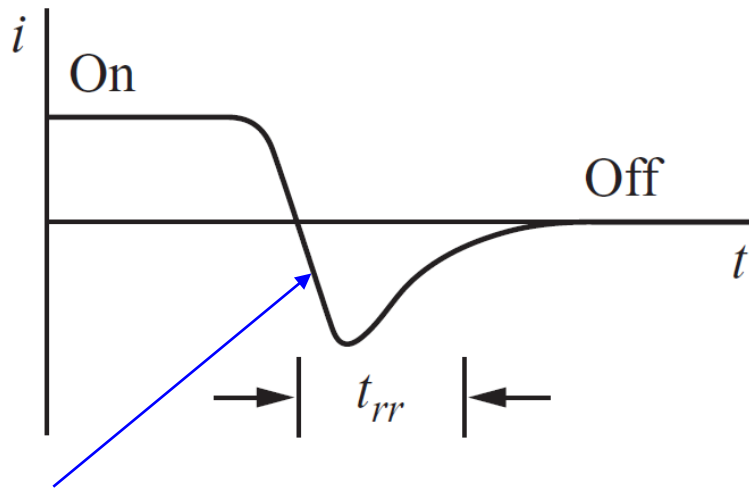
Note:

1. Diode forward voltage drop = 0.7V
2. Zener diode reverse breakdown voltage = 5V

- This circuit is normally used for switching/controlling solenoid coil for electromechanical relays.

Reverse recovery in switching

Switching characteristics of practical diode



Reverse recovery current

t_{rr} : Reverse recovery time

- When a diode turns off, the current in it decreases and momentarily becomes negative before becoming zero.
- This phenomenon may become important in high frequency applications as switching loss increases with frequency.
- Schottky diodes have very little reverse recovery, resulting in more efficient in high-frequency applications.

- Using wide bandgap semiconductors such as silicon carbide (SiC) is an option to reduce reverse recovery current.

Summary - Diode

- Diode is on when forward-biased and off when reverse-biased to be used as a two-terminal switch.
- Breakdown takes place with large reverse-biased voltage.
- Varieties of diodes include PN junction diode, Zener diode, and Schottky diode.
- Freewheeling diode is useful to prevent voltage spike in switching circuits for inductive load.

