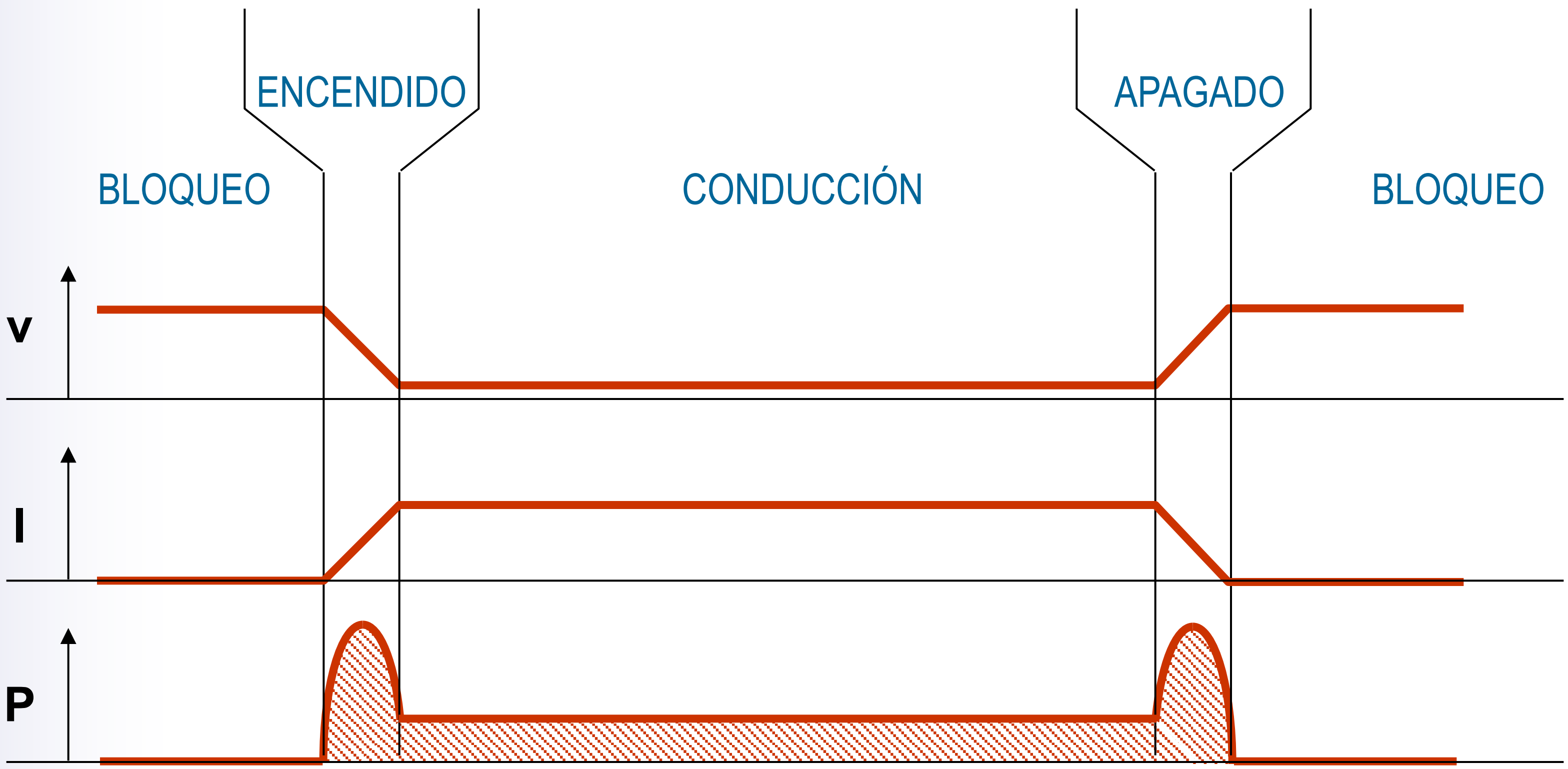
UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros Industriales
DIVISIÓN DE INGENIERÍA ELECTRÓNICA

Power Switches

Dispositivos de potencia

Formas de onda típicas

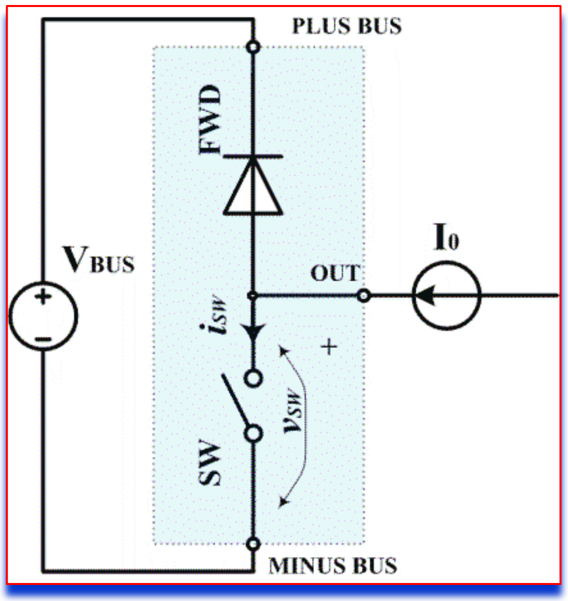


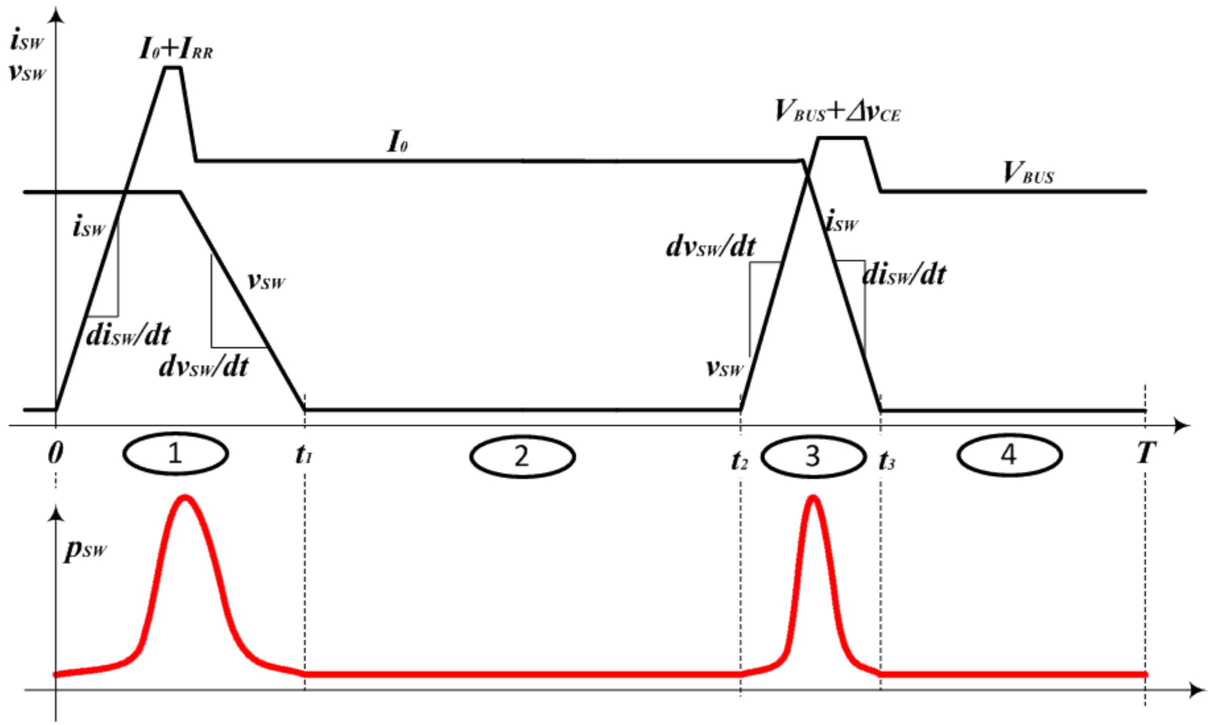
Los semiconductores actuan como interruptores casi ideales

Power Semiconductor Switch: Performances

Basic Switching Cell

- A core of any power converter



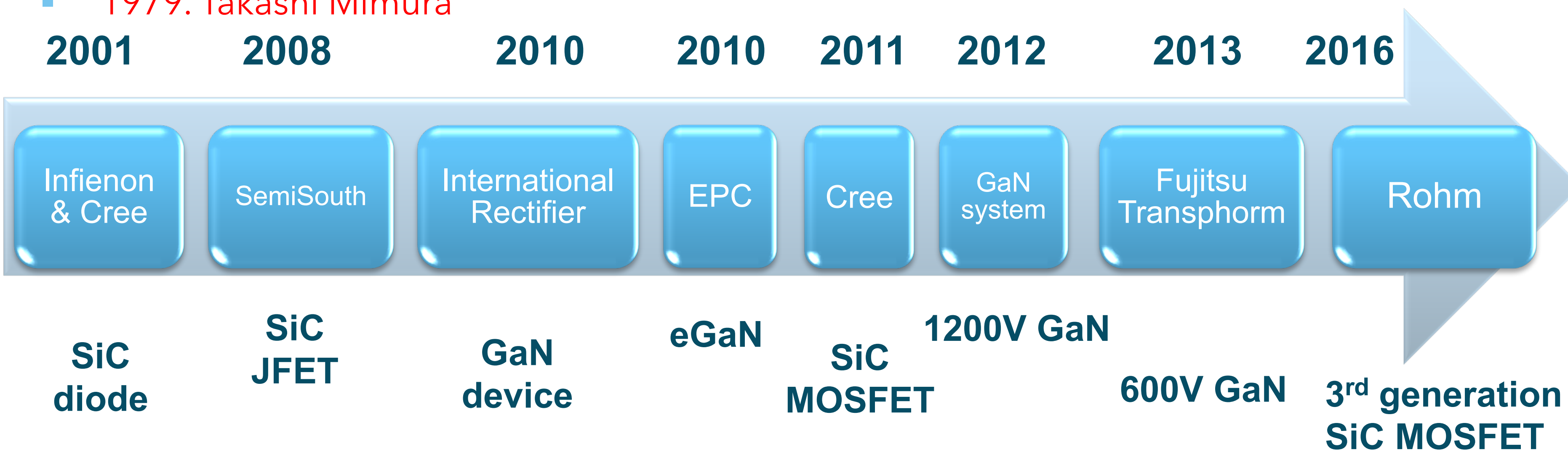


$$P = \frac{1}{T}\int_{0}^{T} v_{SW} i_{SW}\, dt = \frac{1}{T}\left(\underbrace{\int_{0}^{t1} v_{SW} i_{SW}\, dt}_{1} + \underbrace{\int_{t1}^{t2} v_{SW} i_{SW}\, dt}_{2} + \underbrace{\int_{t2}^{t3} v_{SW} i_{SW}\, dt}_{3} + \underbrace{\int_{t3}^{T} v_{SW} i_{SW}\, dt}_{4} \right)$$

1. Turn-On switching losses
2. Conduction Losses
3. Turn-Off switching Losses
4. Blocking Losses

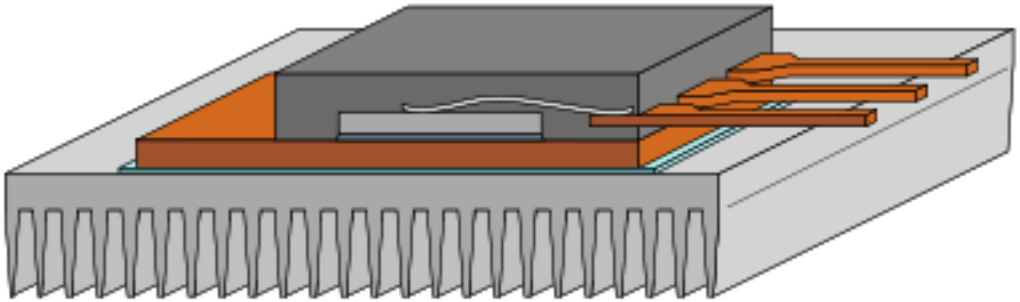
Brief history of semiconductors

- 1874. Karl Ferdinand Braun → "unilateral conduction" of crystals
- 1894. Jagadish Chandra Bose → crystal for detecting radio waves
- 1925. Julius Edgar Lilienfeld → first patent on the Field Effect transistor
- 1940. Bell labs → inexpensive germanium diodes
- 1947. William Schoklley and Gerald Pearson → first bipolar transistor
- 1959. Dawon Kahng and Martin M. (John) Atalla → first MOSFET
- 1979. Takashi Mimura → HEMT idea

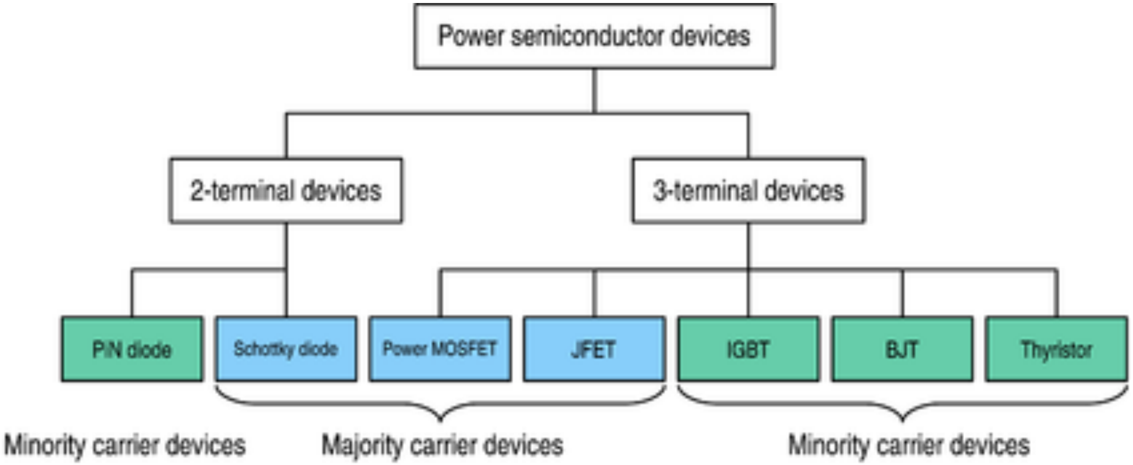


General Parameters to look at…

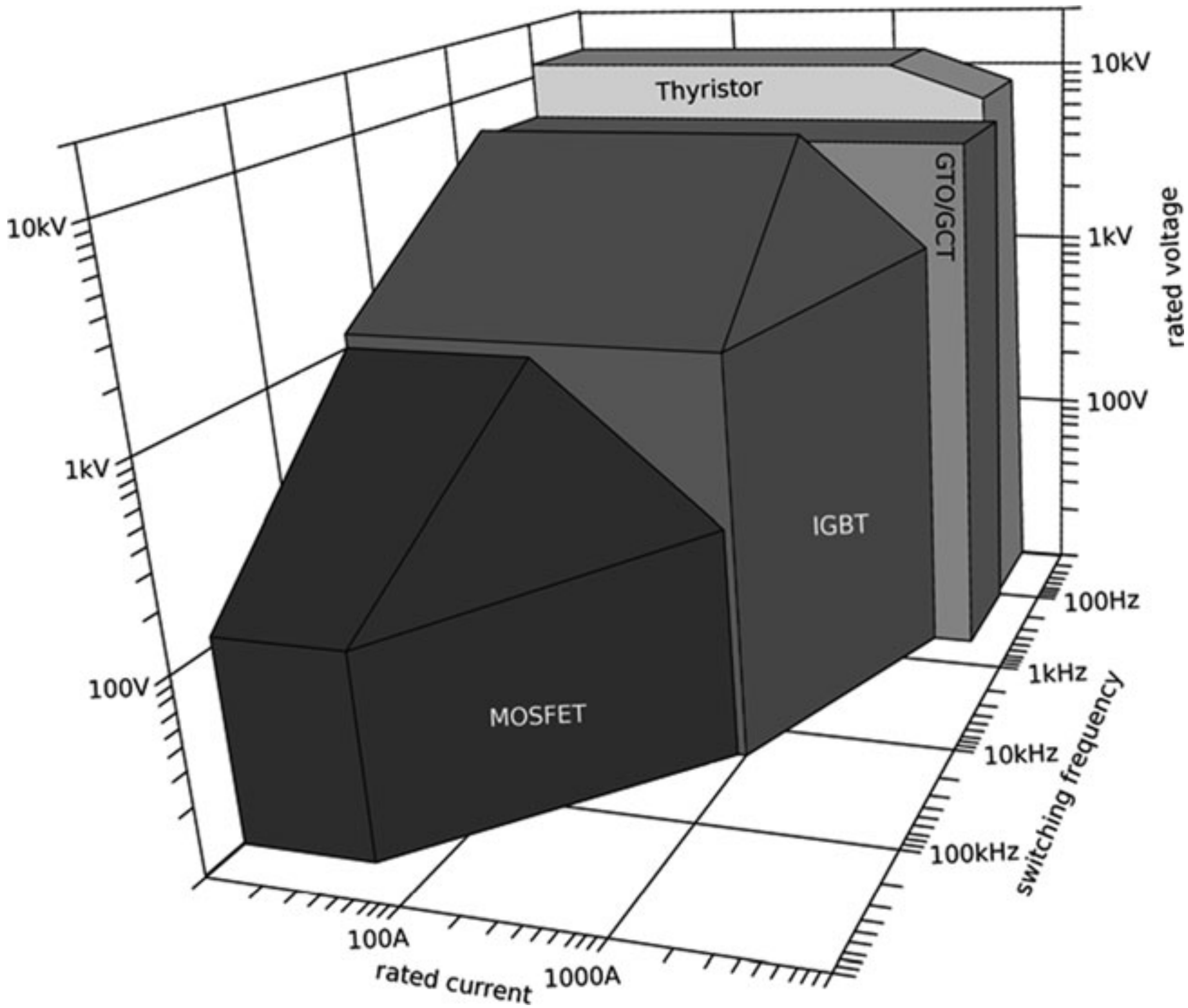
- Physics
- Static characteristics:
  - ✓ ON: Voltage drop, i_{max}
  - ✓ OFF: Breakdown voltage
- Dynamic characteristics :
  - ✓ Rise & fall times, losses
- Safe Operating Area
  - ✓ Voltage, Current, Power, Latch-up
- Package, Thermal resistance



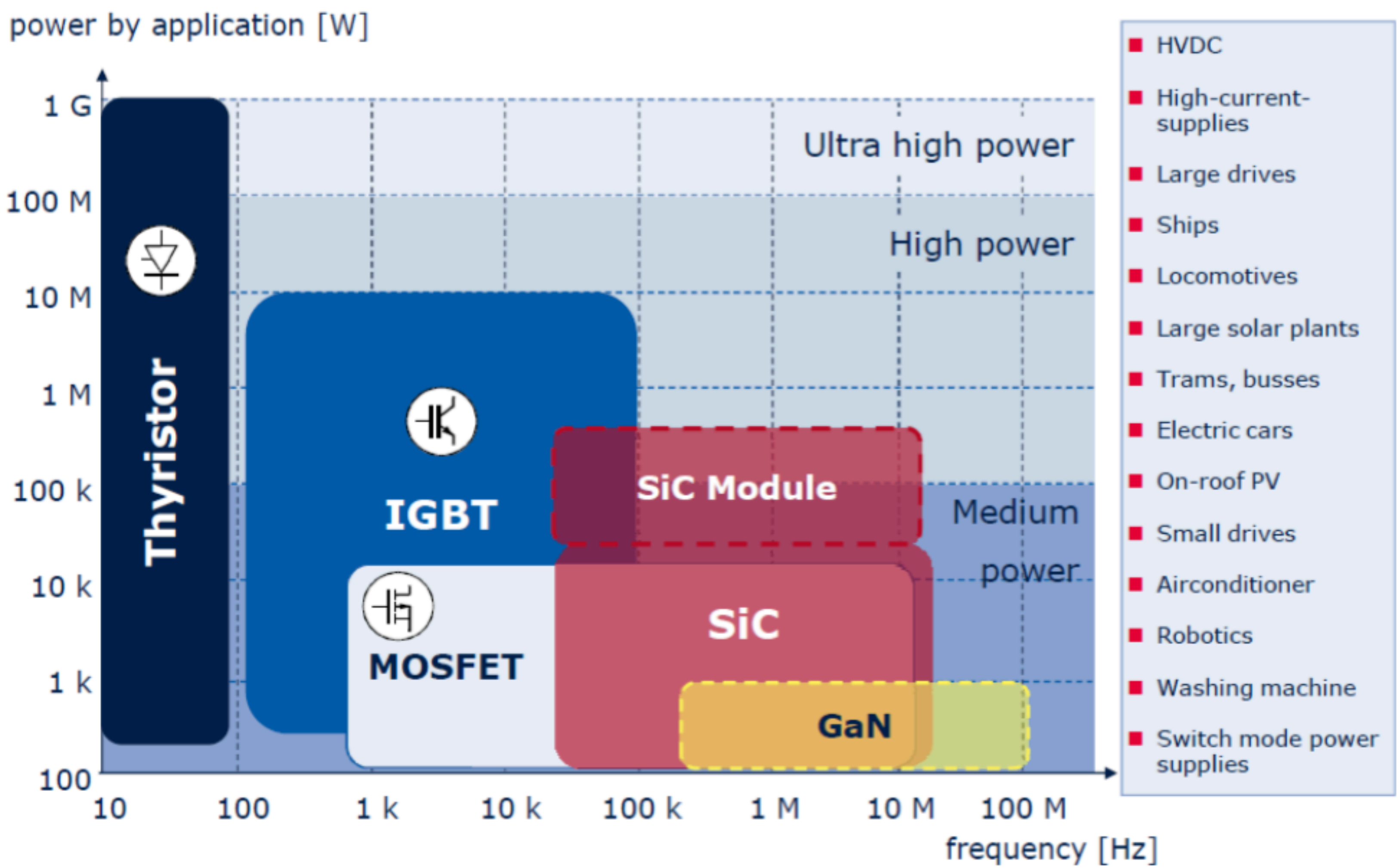
Classification, History & trends



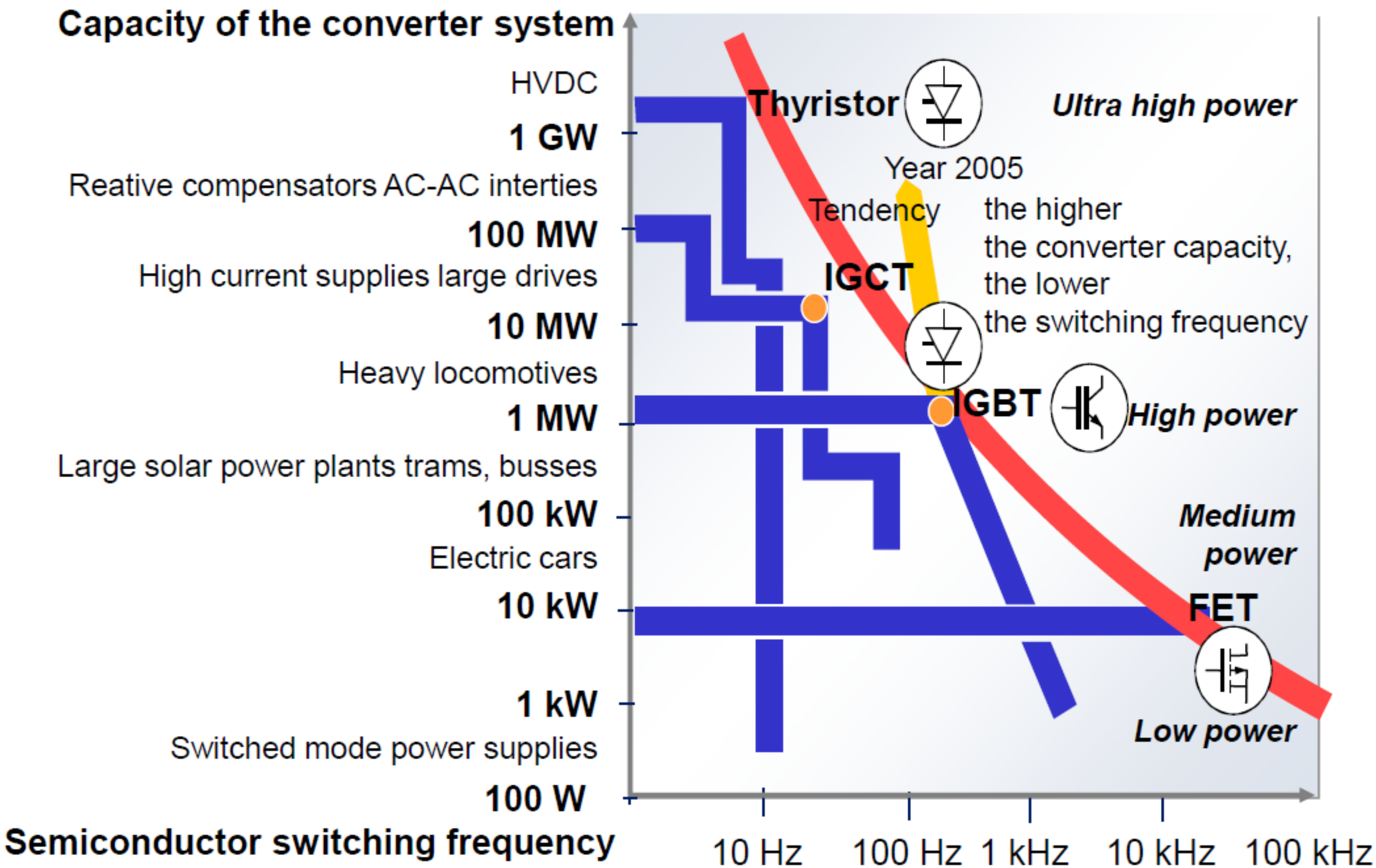
Power Semiconductor Switches



Infineon Portfolio of Power Technologies



Application for Power Semiconductor Components



Source: IPEC 2000

Power Semiconductor Switches

Diode	Thyristor	BJT	MOSFET	IGBT	
PiN	SCR	PNP	VMOSFET	PT	PLANAR
SBD (Schottky)	GTO	NPN	SuperJunction	NPT	TRENCH
	IGCT			SPT	
	Triac				

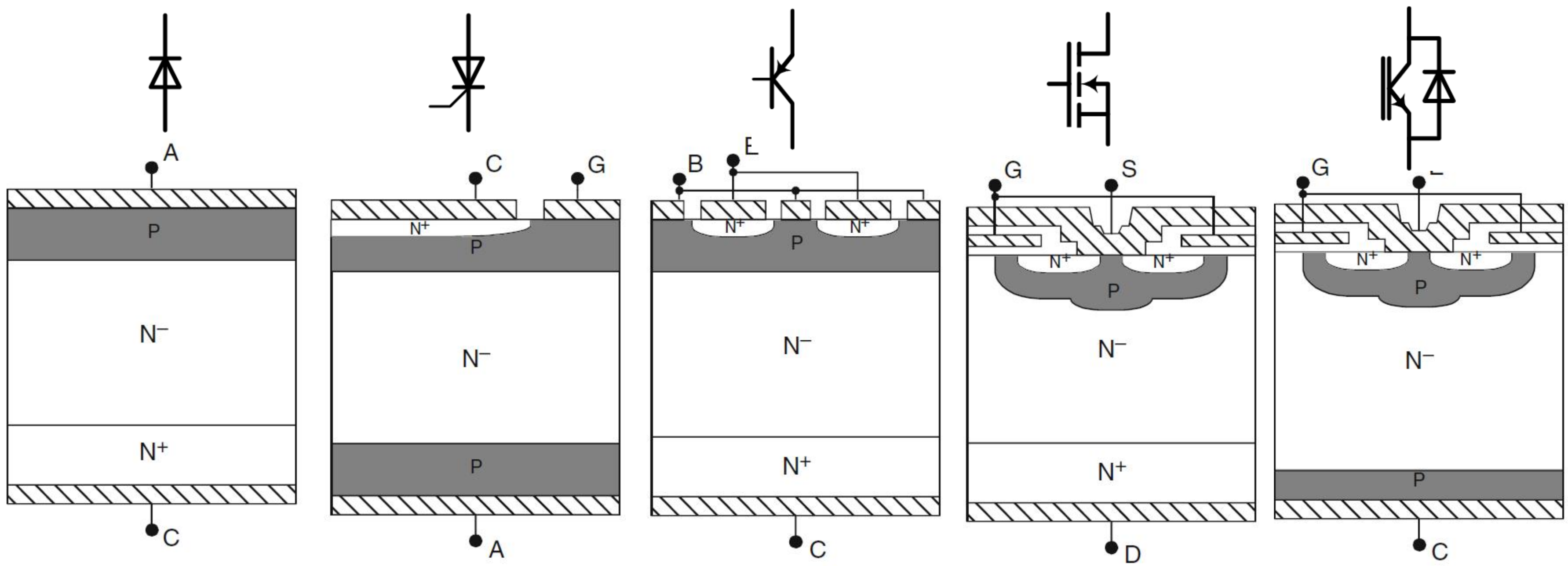


Table 1.2
Power electronics semiconductor devices

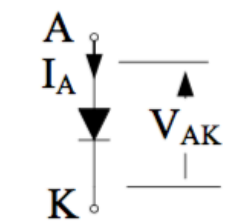
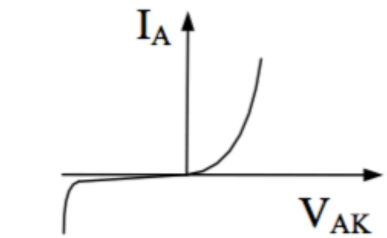
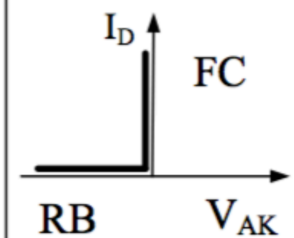
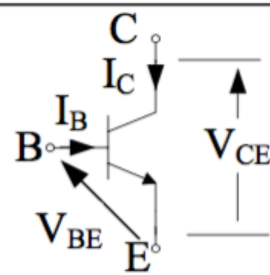
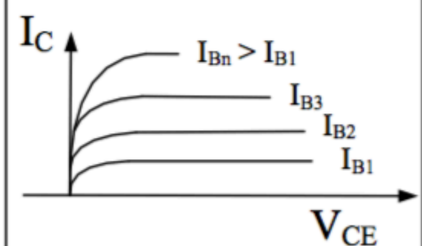
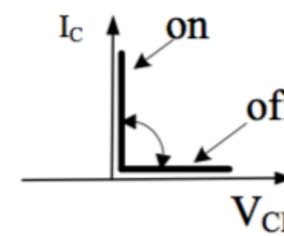
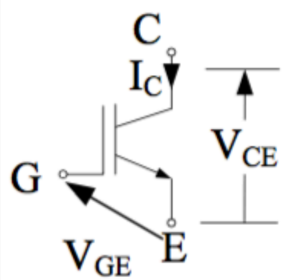
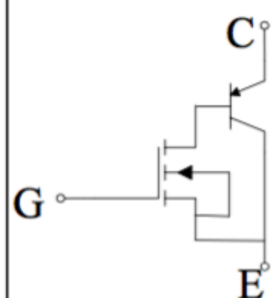
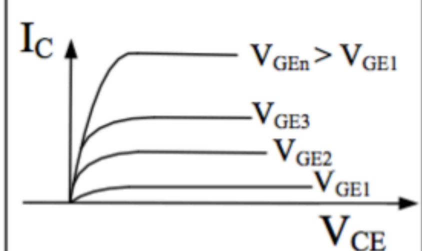
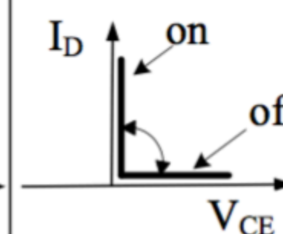
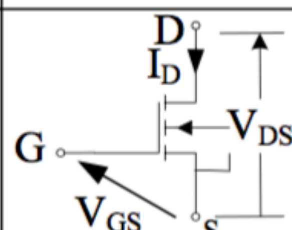
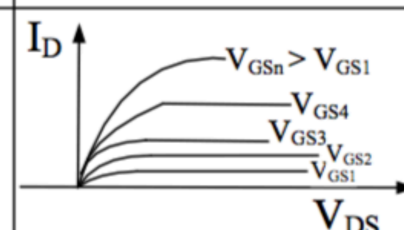
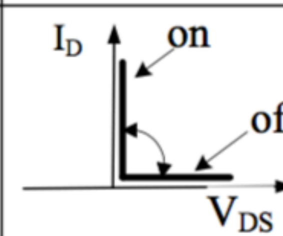
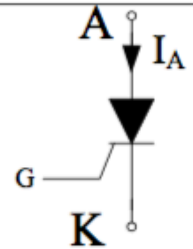
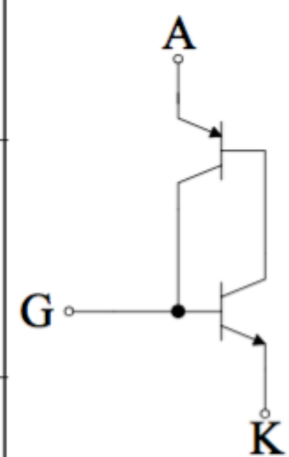
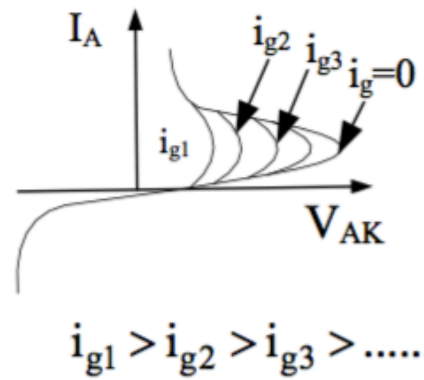
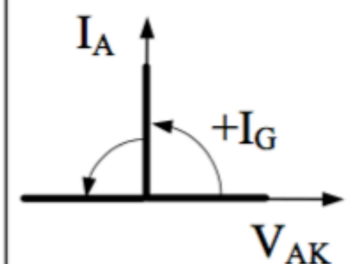
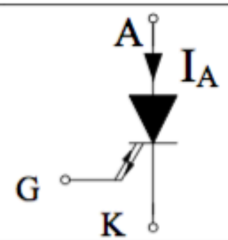
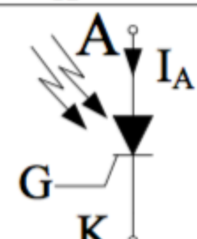
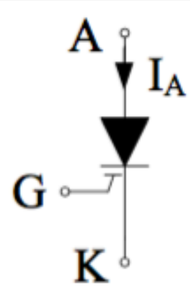
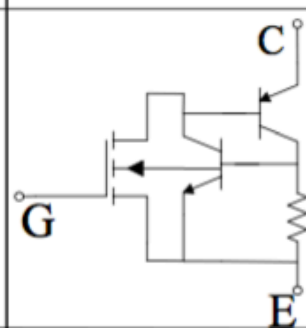
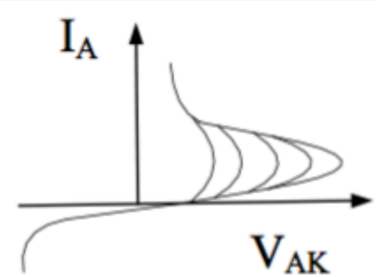
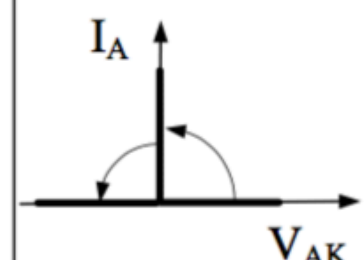
Power semiconductor device	Symbol	Equivalent circuit	I-V characteristics	Ideal I-V characteristics
Diode				
Power Transistor npn				
IGBT Insulated Gate Bipolar Transistor				
MOSFET				

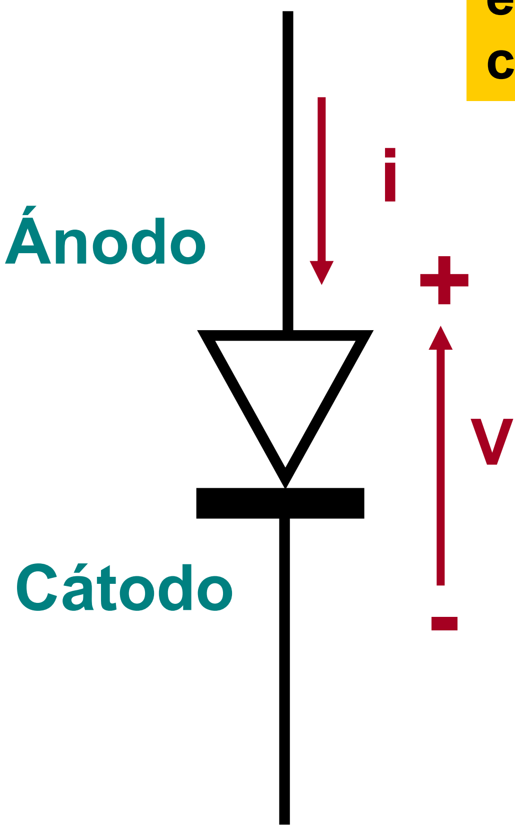
Table 1.2
Power electronics semiconductor devices

Power semiconductor device	Symbol	Equivalent circuit	I-V characteristics	Ideal I-V characteristics
Thyristor, SCR Silicon Control Rectifier				
GTO Gate Turn-off Thyristor				
LASCR Light Activated SCR Opto-Thyristor				
MCT MOS Controlled Thyristor				

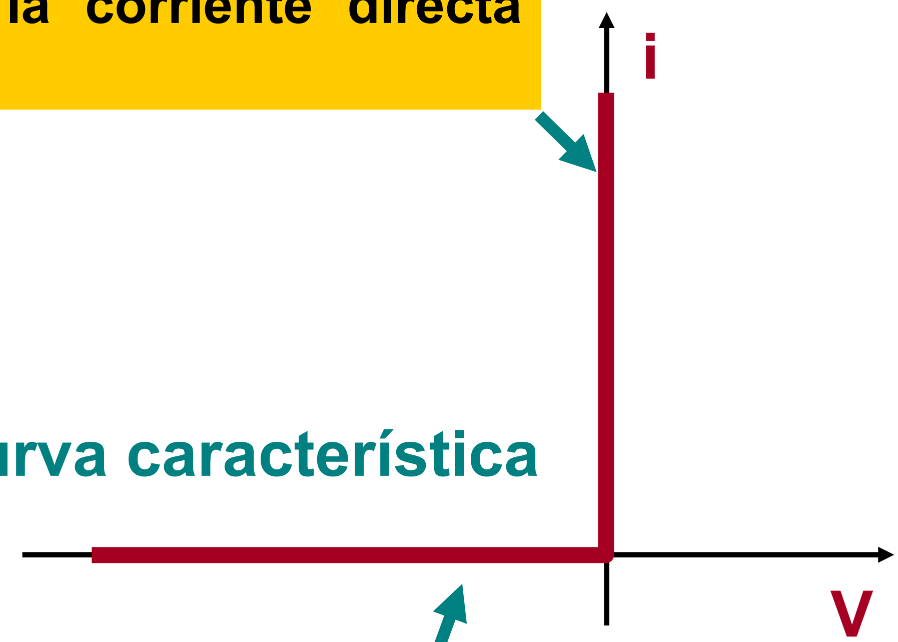
Diodes

Concepto de diodo ideal

En polarización directa, la caída de tensión es nula, sea cual sea el valor de la corriente directa conducida



curva característica



En polarización inversa, la corriente conducida es nula, sea cual sea el valor de la tensión inversa aplicada

Ecuación característica del diodo

$$i = I_S \cdot (e^{\frac{V}{V_T}} - 1)$$

donde:

$V_T = k \cdot T/q$

$I_S = A \cdot q \cdot n_i^2 \cdot (D_p/(N_D \cdot L_p) + D_n/(N_A \cdot L_n))$

- *Polarización directa con $V_O > V >> V_T$*

$$i \approx I_S \cdot e^{\frac{V}{V_T}}$$

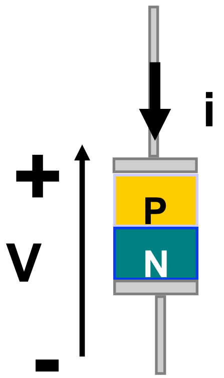
(dependencia exponencial)

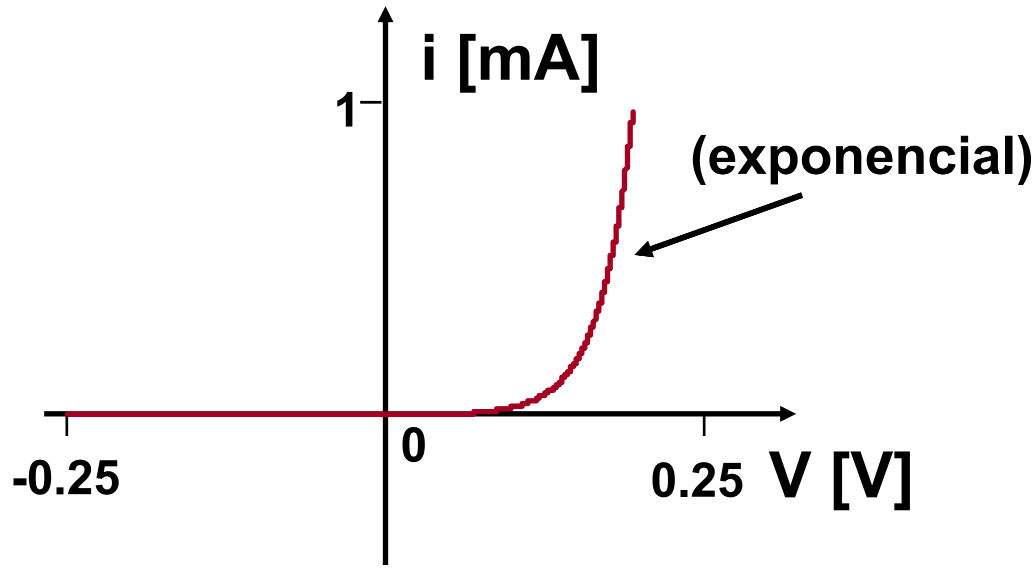
- *Polarización inversa con $V << -V_T$*

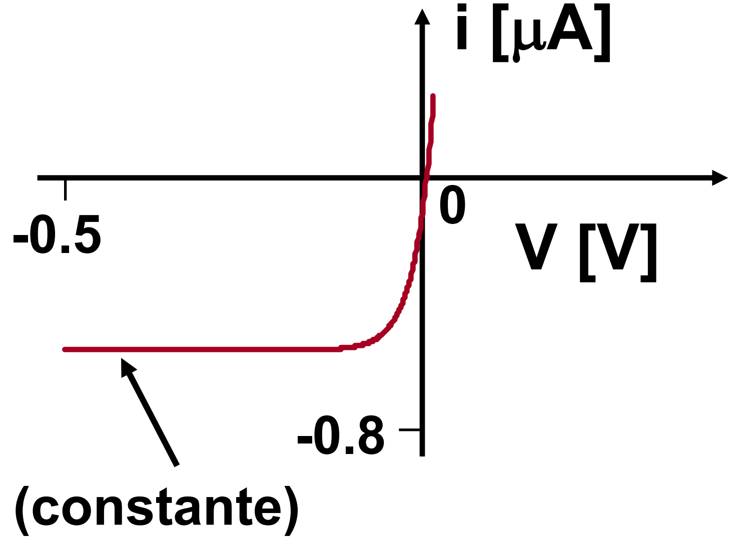
$$i \approx -I_S$$

Corriente inversa de saturación (constante)

Curva característica



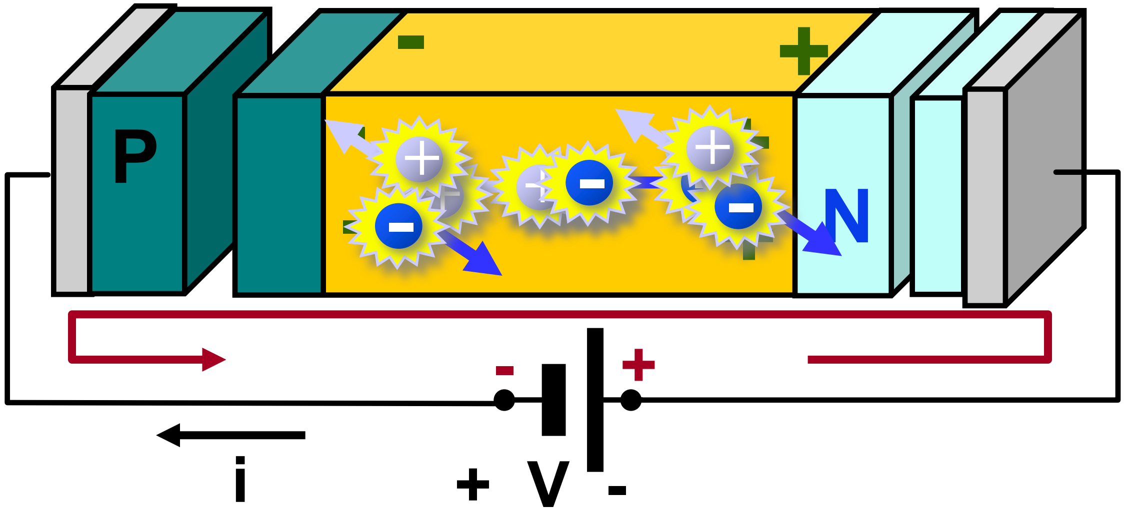




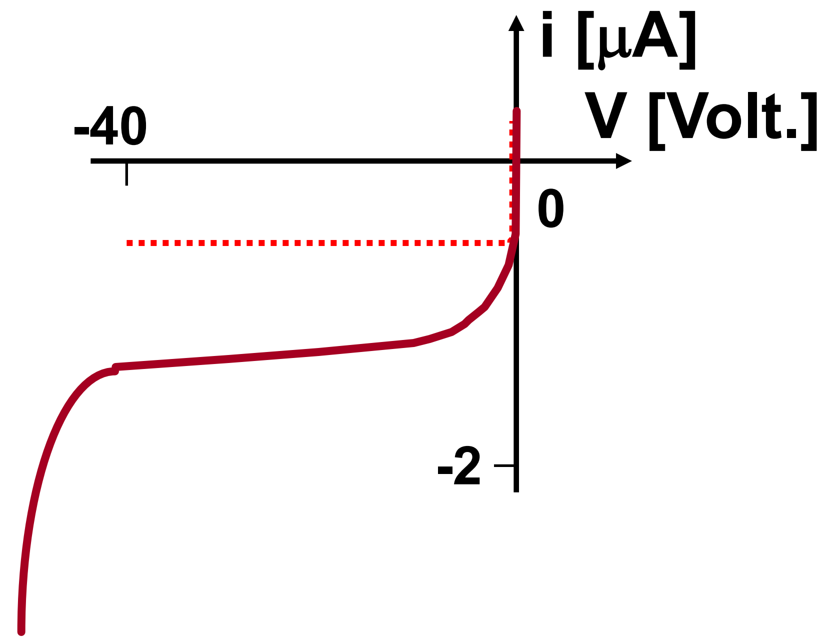
DIODOS DE POTENCIA

Curva característica

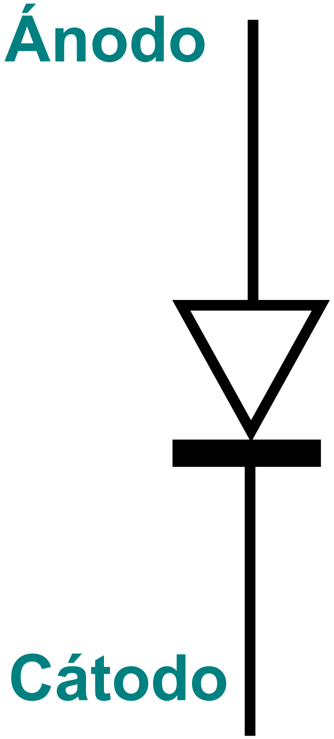
Avalancha primaria

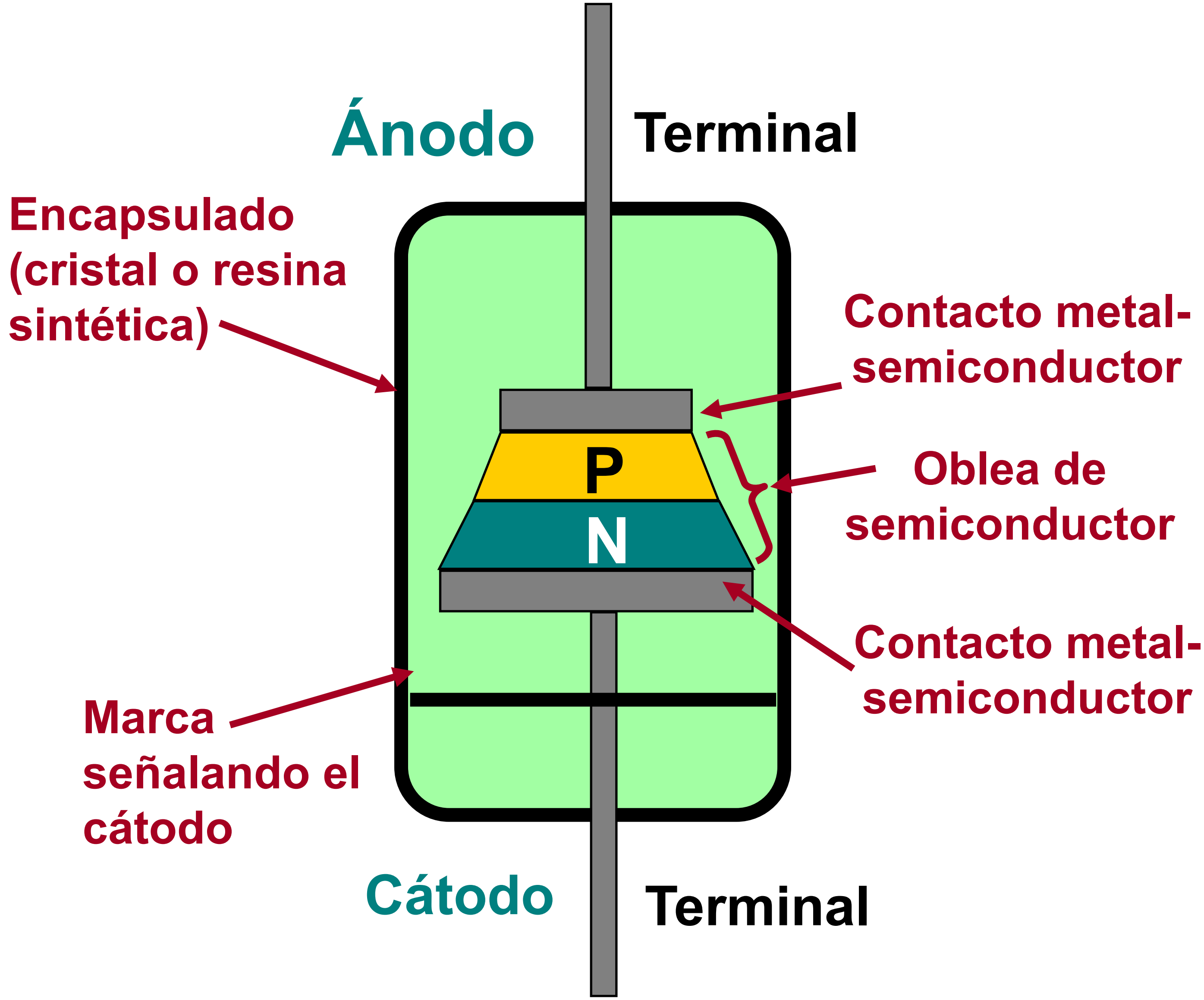


La corriente aumenta fuertemente si se producen pares electrón-hueco adicionales.

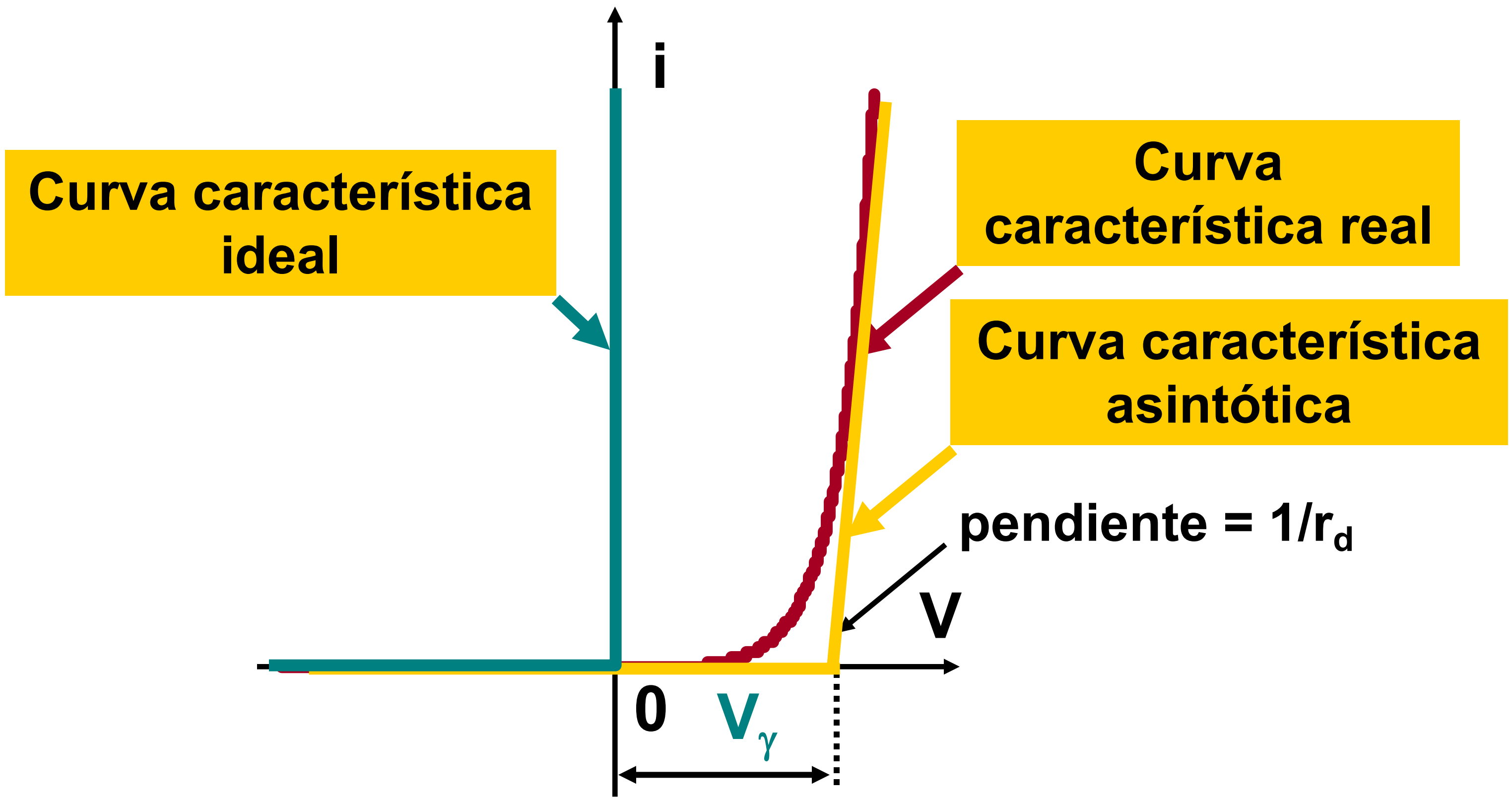


El diodo semiconductor

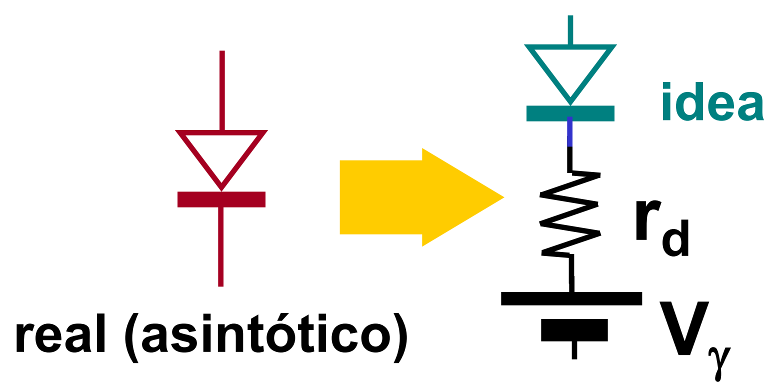




Curvas características y circuitos equivalentes



Circuito equivalente asintótico



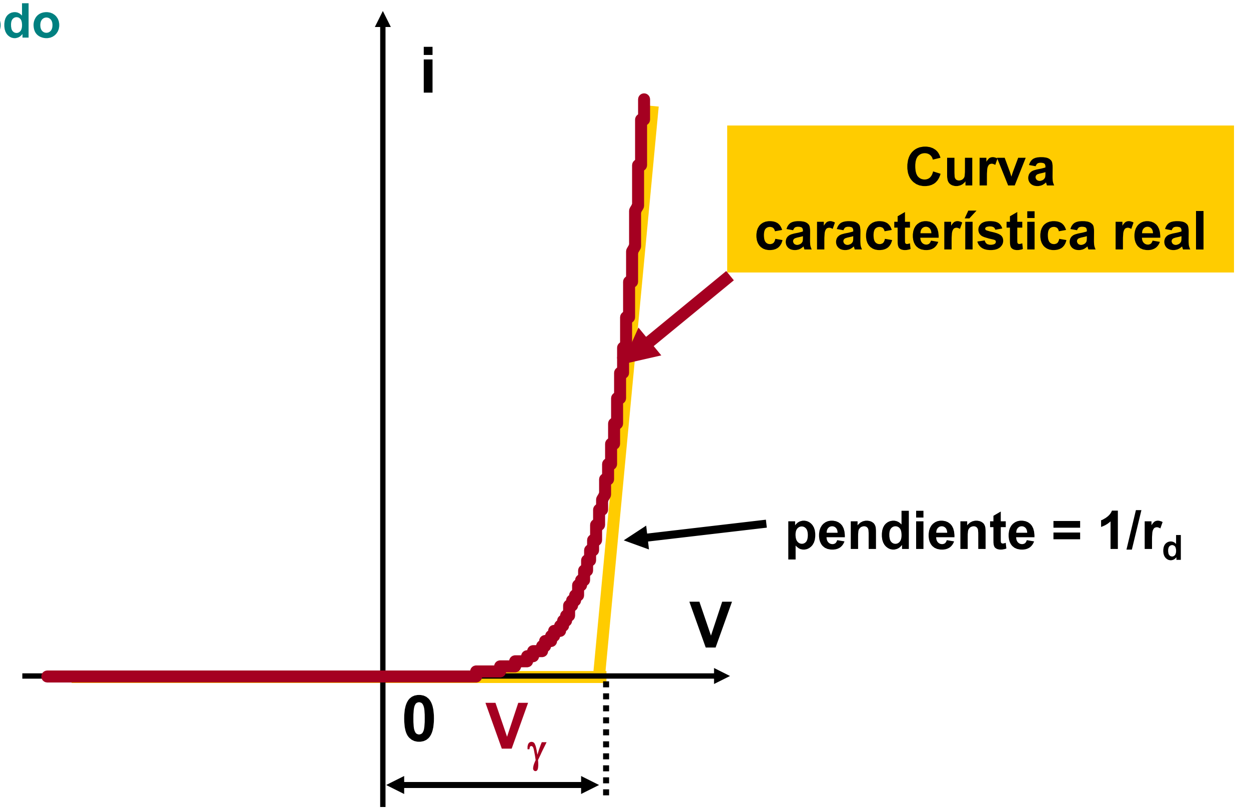
Características fundamentales

- Tensión de ruptura
- Caída de tensión en conducción
- Corriente máxima
- Velocidad de conmutación

Tensión de ruptura

Baja tensión	Media tensión	Alta tensión
15 V	100 V	500 V
30 V	150 V	600 V
45 V	200 V	800 V
55 V	400 V	1000 V
60 V		1200 V
80 V		

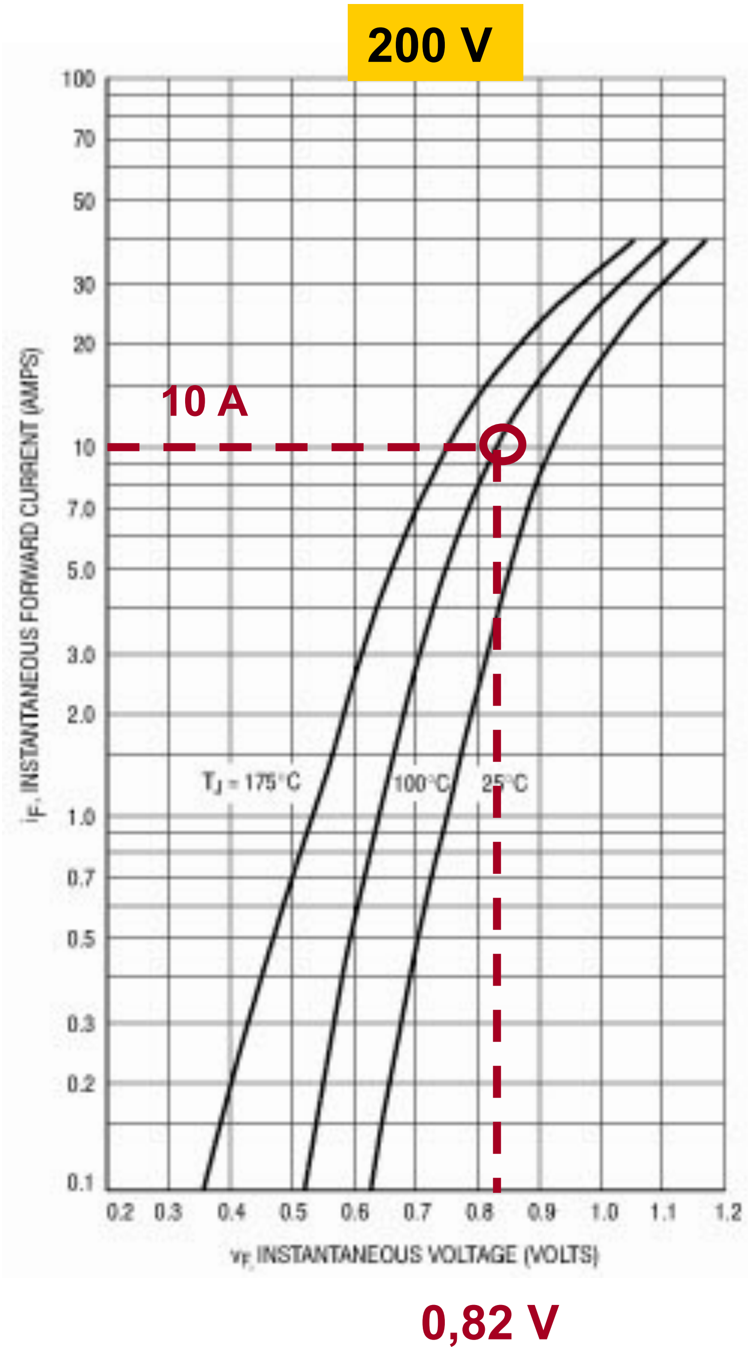
Tensión de codo

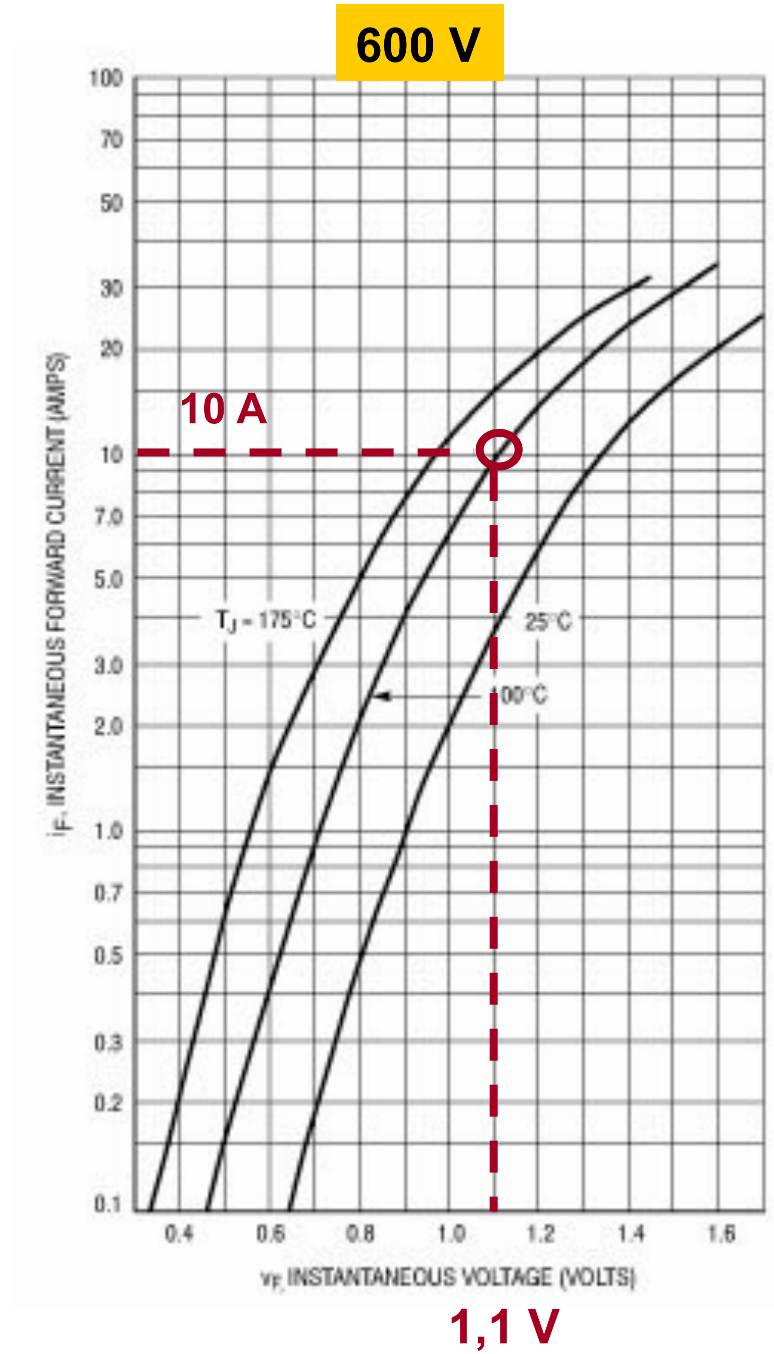


A mayor tensión de ruptura , mayor caída de tensión en conducción

	Señal	Potencia	Alta tensión
$V_{Ruptura}$	< 100 V	200 – 1000 V	10 – 20 kV
V_{Codo}	0,7 V	< 2 V	> 8 V

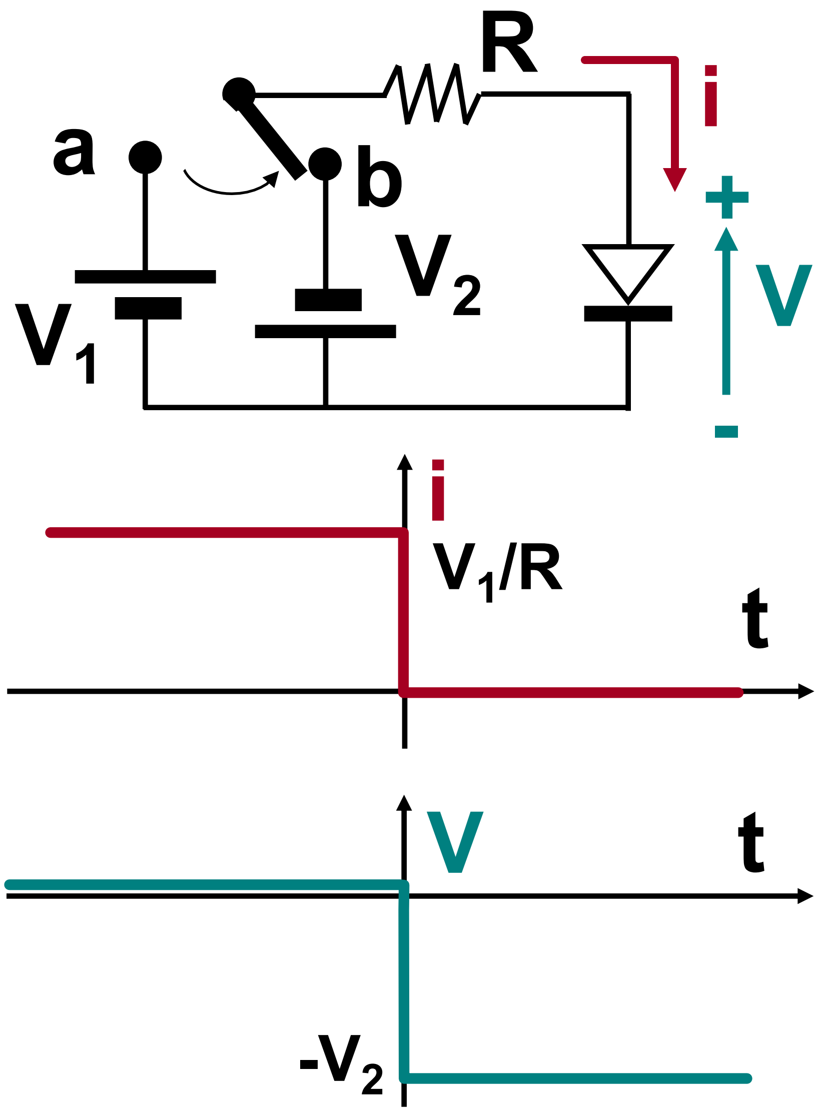
Curva real de un dispositivo





Características dinámicas

Indican capacidad de conmutación del diodo

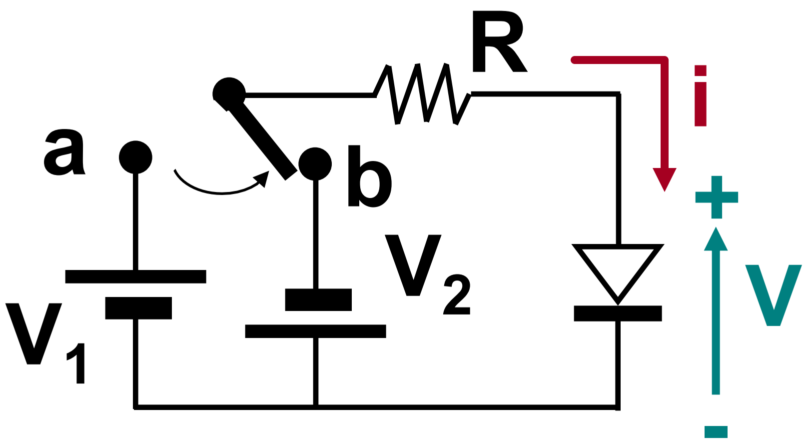


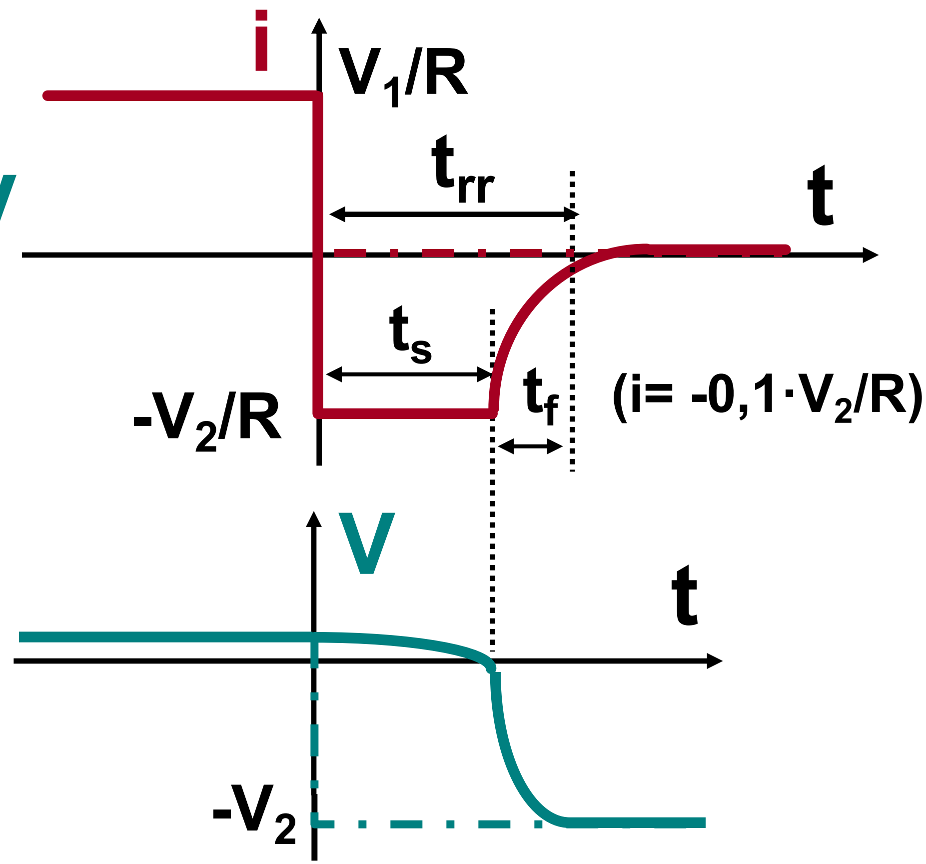
Transición de “a” a “b”

Comportamiento dinámicamente ideal

Características dinámicas

Transición de “a” a “b”





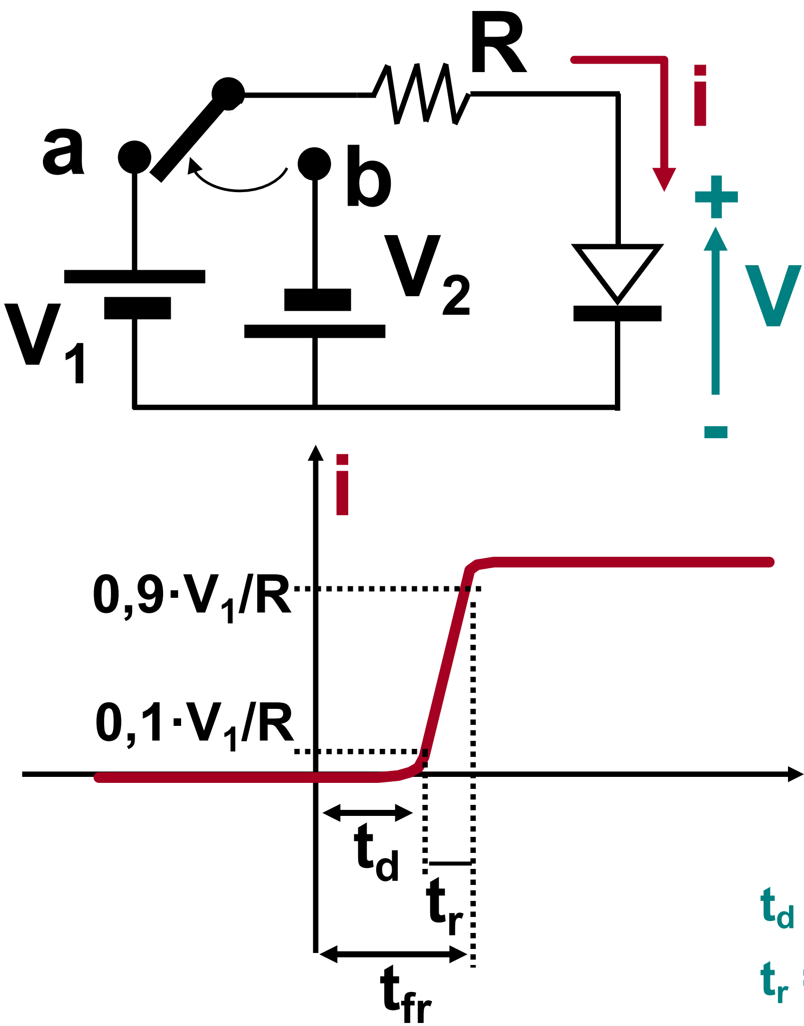
t_s = tiempo de almacenamiento (storage time)

t_f = tiempo de caída (fall time)

t_{rr} = tiempo de recuperación inversa (reverse recovery time)

Transición de “b” a “a” (encendido)

El proceso de encendido es más rápido que el apagado.



t_d = tiempo de retraso (delay time)

t_r = tiempo de subida (rise time)

$t_{fr} = t_d + t_r$ = tiempo de recuperación directa (forward recovery time)

Características Principales

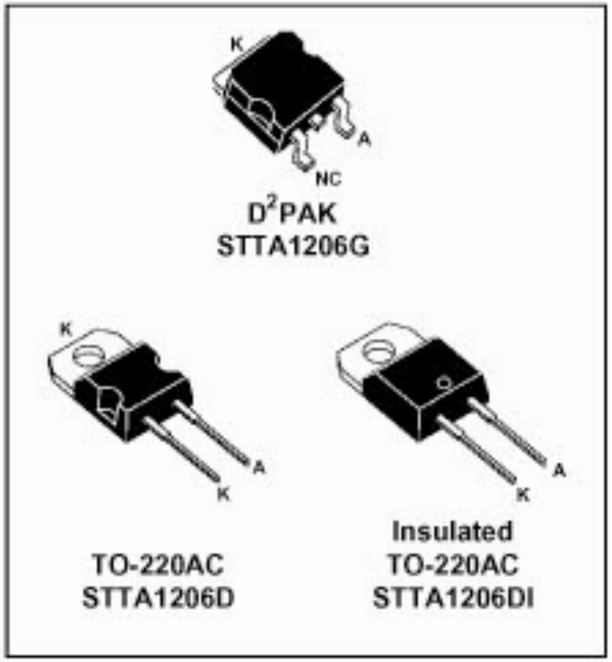
Corriente directa
Tensión inversa
Tiempo de recuperación
Caída de tensión
en conducción

MAIN PRODUCT CHARACTERISTICS

$I_{F(AV)}$	12A
V_{RRM}	600V
t_{rr} (typ)	28ns
V_F (max)	1.5V

FEATURES AND BENEFITS

- SPECIFIC TO "FREEWHEEL MODE" OPERATIONS: FREEWHEEL OR BOOSTER DIODE.
- ULTRA-FAST AND SOFT RECOVERY.
- VERY LOW OVERALL POWER LOSSES IN BOTH THE DIODE AND THE COMPANION TRANSISTOR.
- HIGH FREQUENCY OPERATIONS.
- INSULATED PACKAGE : TO-220AC
  Electrical insulation : $2500V_{RMS}$
  Capacitance < 7 pF



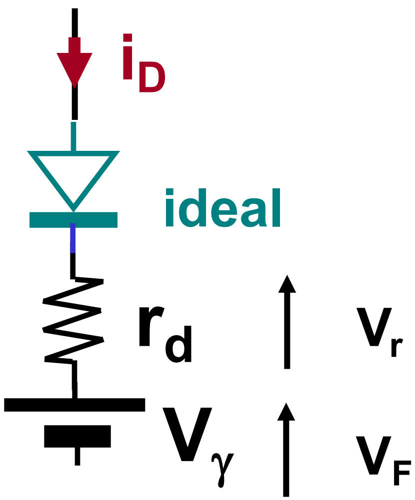
Encapsulado

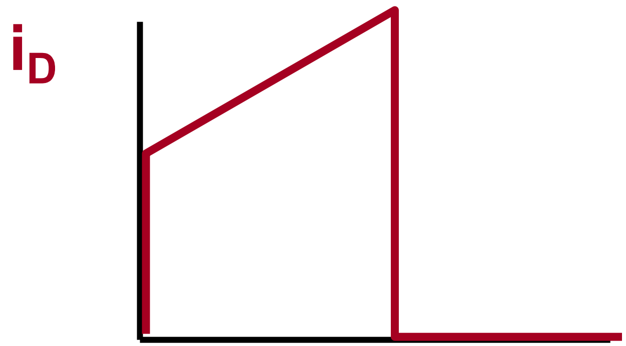
Pérdidas en el diodo

2 Tipos

- **Estáticas**
- **Dinámicas**

Pérdidas estáticas





$$P_D\,(t) = v_D\,(t)\cdot i_D\,(t) = (V_\gamma + r_D \cdot i(t)) \cdot i(t)$$

$$P_D = \frac{1}{T}\int_0^T P_D(t)\cdot dt$$

$$P_D = V_\gamma \cdot I_D + r_D \cdot I_{ef}^2$$

I_D : Valor medio

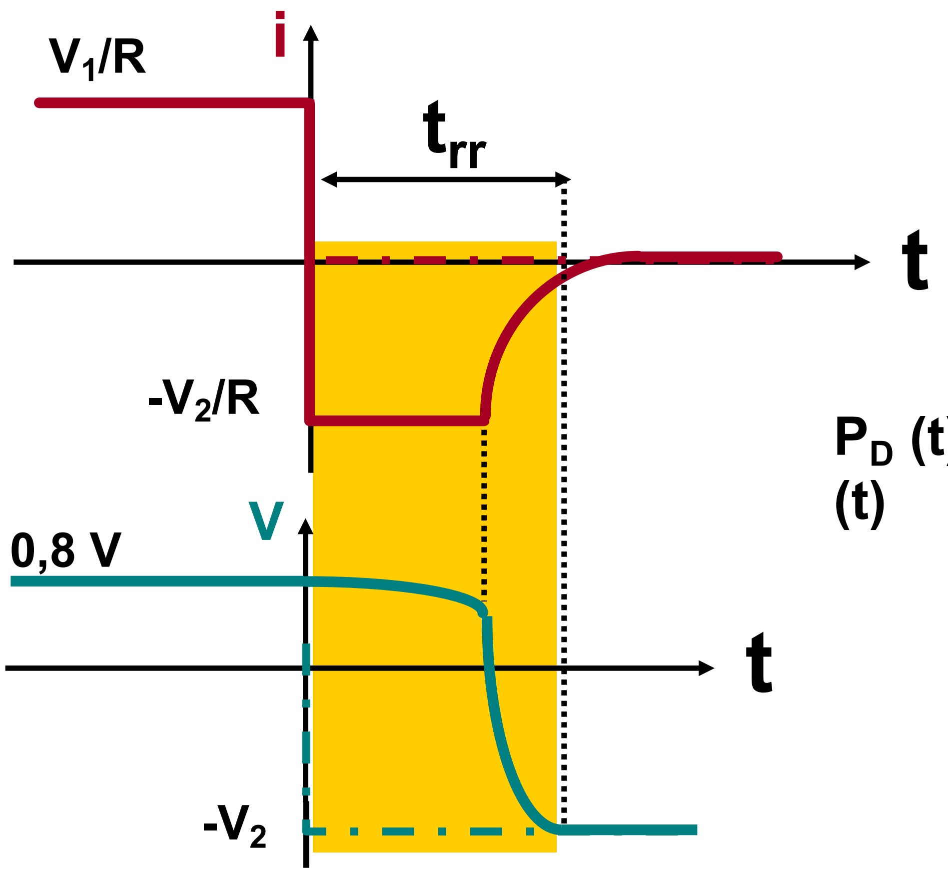
I_{ef} : Valor eficaz

Pérdidas en el diodo

Pérdidas dinámicas *(Perdidas de conmutación)*

Las conmutaciones no son perfectas

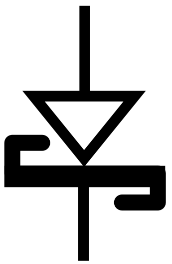
Hay instantes en los que conviven tensión y corriente



$P_D\ (t) = v_D\ (t) \cdot i_D\ (t)$

Rectifying contacts (III)

- There is a type of diode based on the operation of a rectifying contact. It is the ***Schottky diode***. Schottky diodes are widely used in many applications, including RF (telecom) circuits and low-voltage, medium-power power converters.



Schematic Symbol

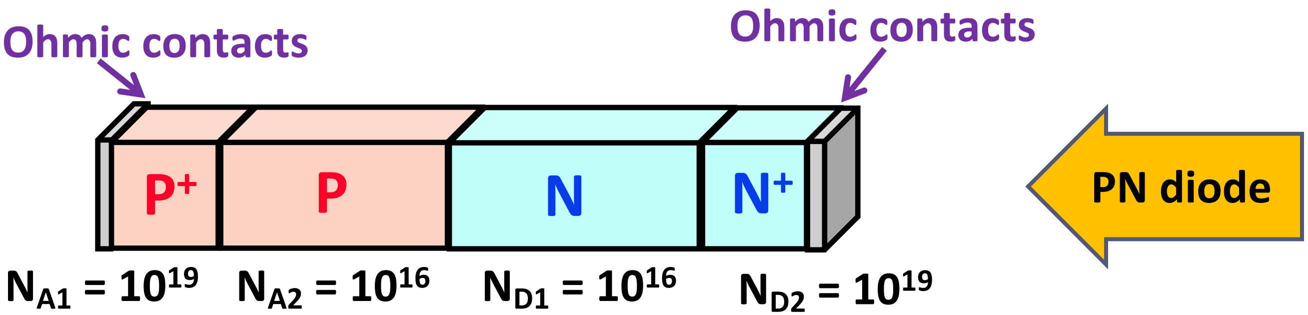
- **Main features:**
  - **Lower forward voltage drop than a similar-range, PN-junction diode.**
  - **They are faster than PN diodes because minority carriers hardly play any role in the current conduction process. They are *majority carrier devices*.**
  - **However, they always have a higher reverse current (this is not a big problem).**
  - **When they are made up of silicon, the maximum reverse voltage (compatible with reasonable drop voltage in forward bias) is about 200 V.**
  - **However, Schottky diodes made up of wide-bandgap materials (such as silicon carbide and gallium nitride) reach breakdown voltages as high as 600-1200 V.**

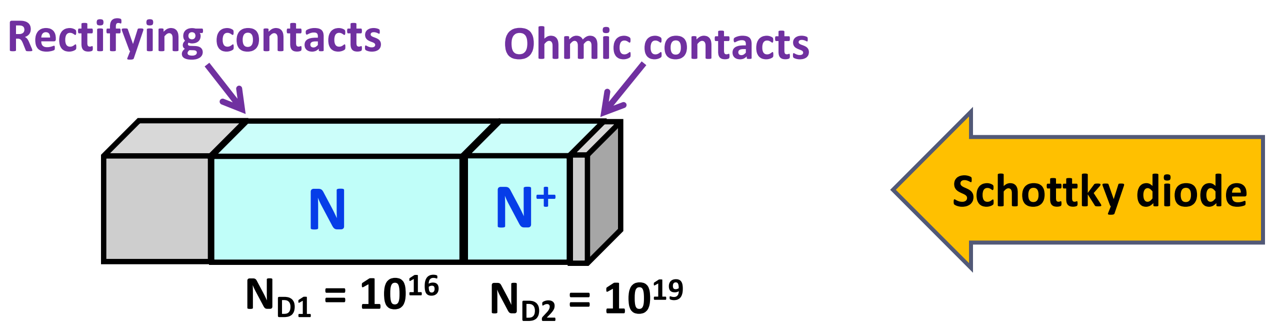
- **There are two different possibilities to obtain ohmic contacts:**

a) According to the previous slides, to have an MS junction corresponding to Case #3 or to Case #4.

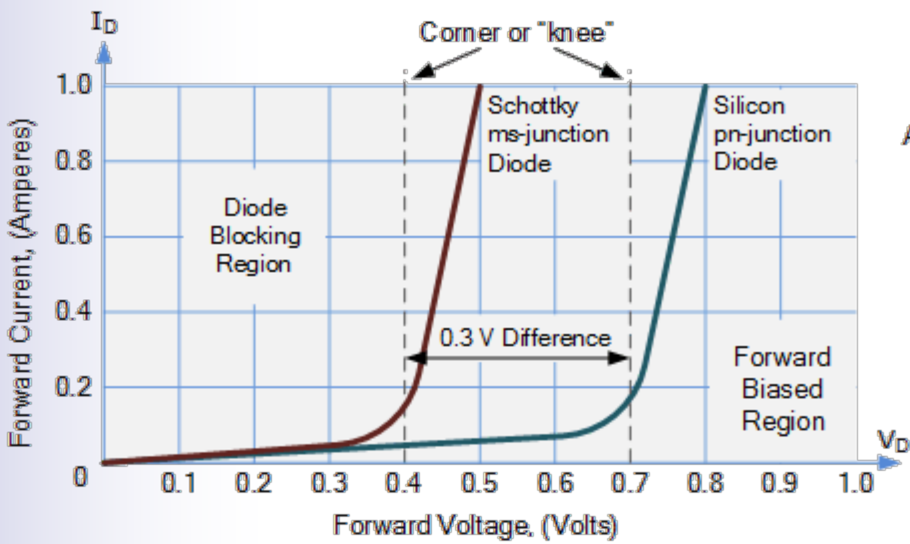
b) To have MS junctions corresponding to Cases #1 or #2, but with an extremely-doped semiconductor side (10^{19} atoms/cm^3). In this situation, electrons can flow in both directions by a *tunneling* process.

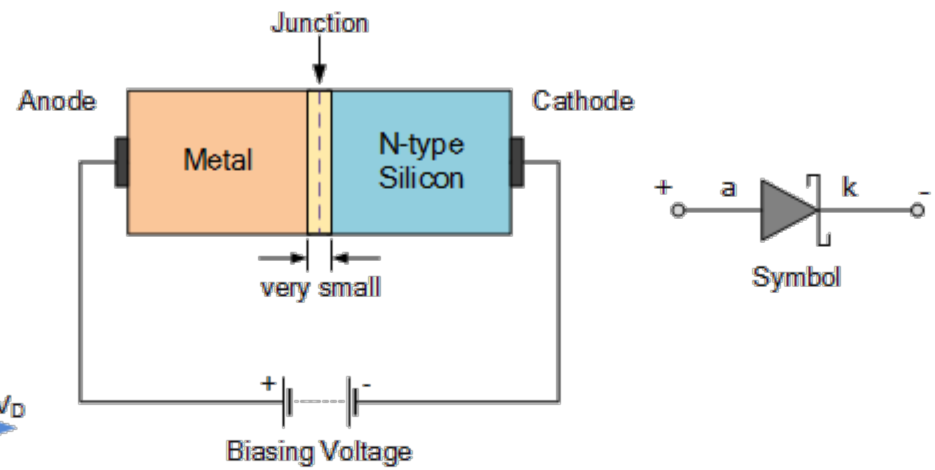
Beyond the scope of this course, as well.





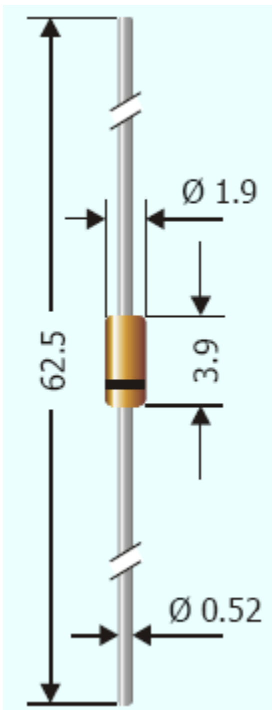
Schotcky diode



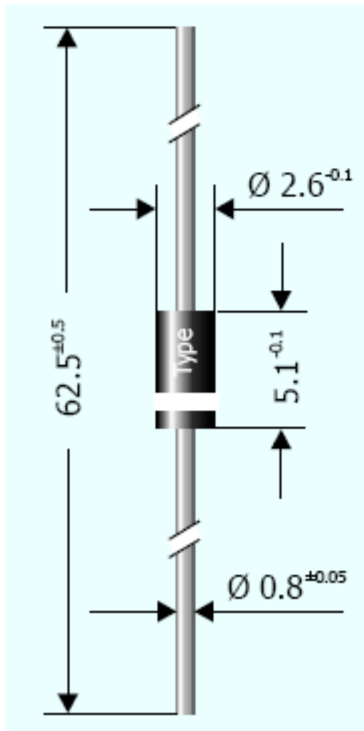


Packages for diodes (I)

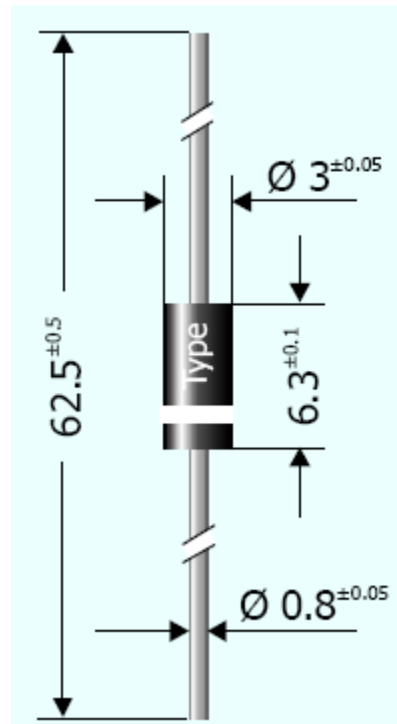
- **Axial leaded through-hole packages (low power).**



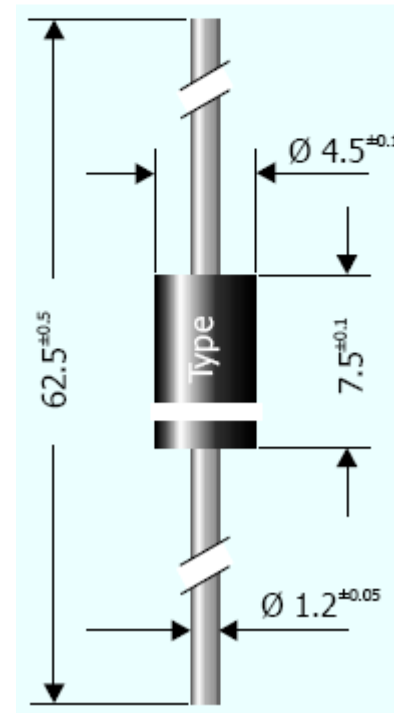
DO 35



DO 41



DO 15

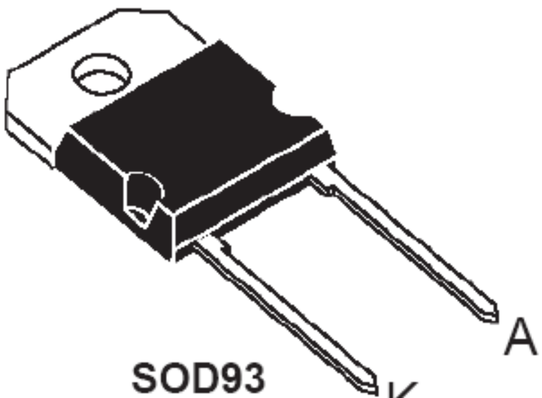


DO 201

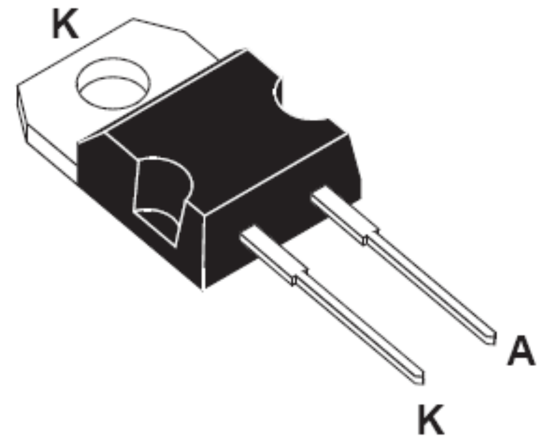
Packages for diodes (II)

- **Packages to be used with heat sinks.**

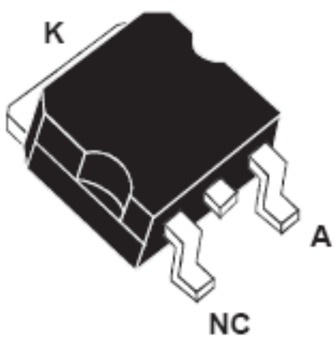
Cathode connected to case



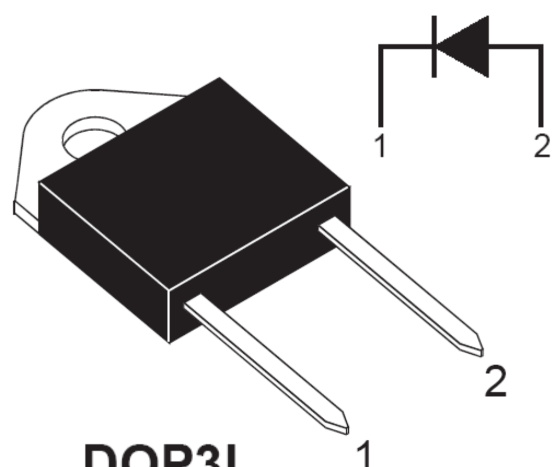
SOD93
(Plastic)



TO-220AC



D^{2}PAK



DOP3I

Packages for diodes (III)

- **Packages to be used with heat sinks (higher power levels).**

DO 5

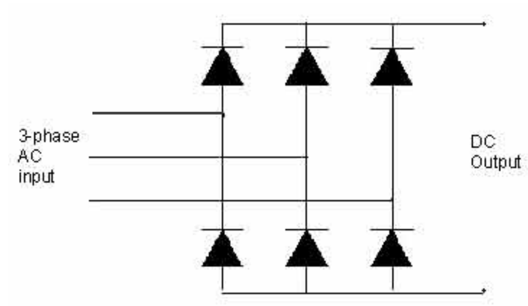
E 14

B 44

E 35

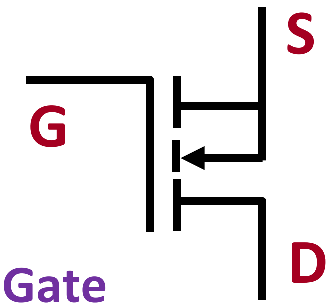
Packages for diodes (XI)

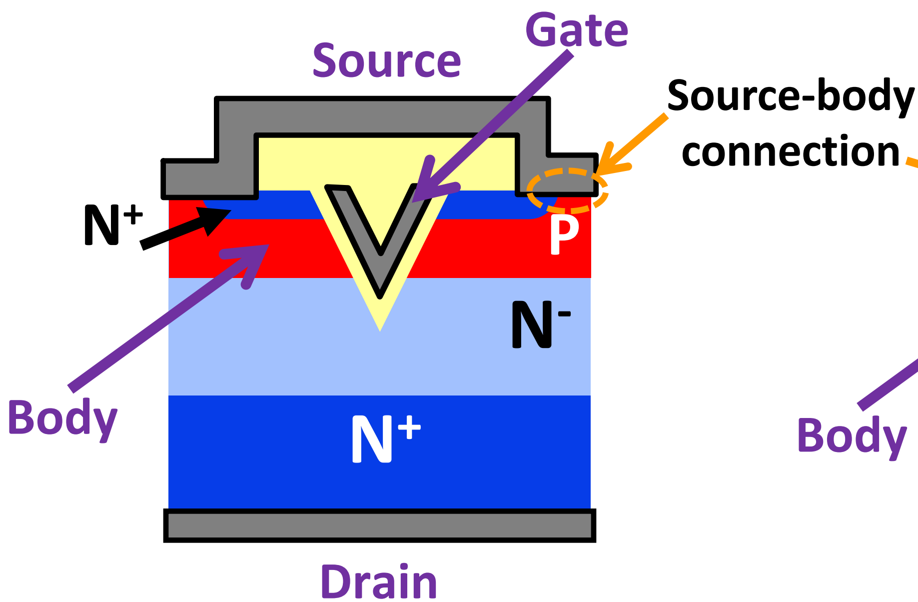
- **Assembly of 6 diodes (Three-phase bridge rectifiers)**



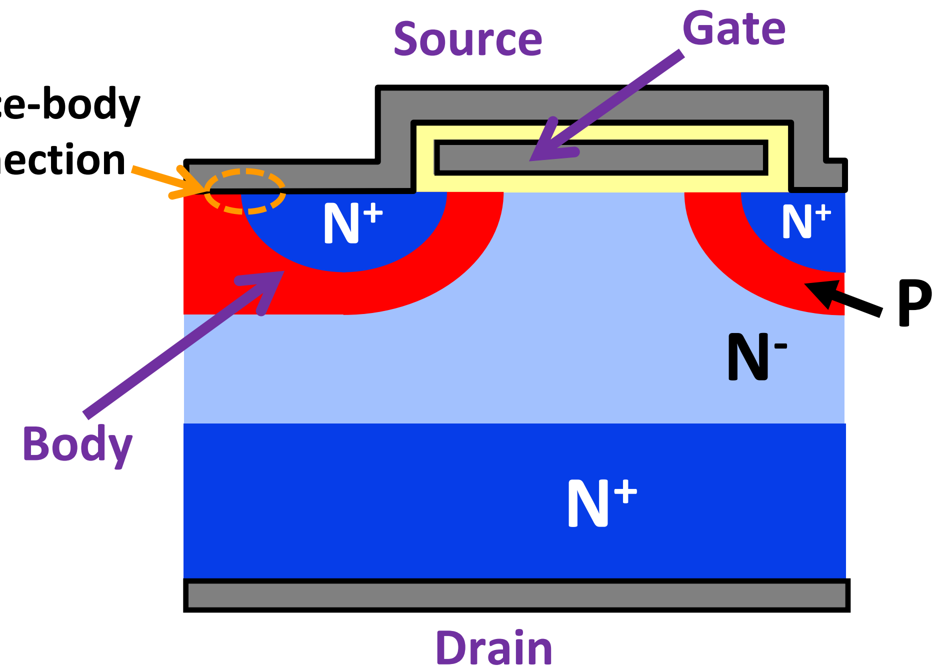
MOSFET

- A typical transistor is constituted of several thousand cells.
- As all the FET devices, MOSFET can be easily connected in parallel.
- They are vertical MOSFETs.
- Examples of cells:



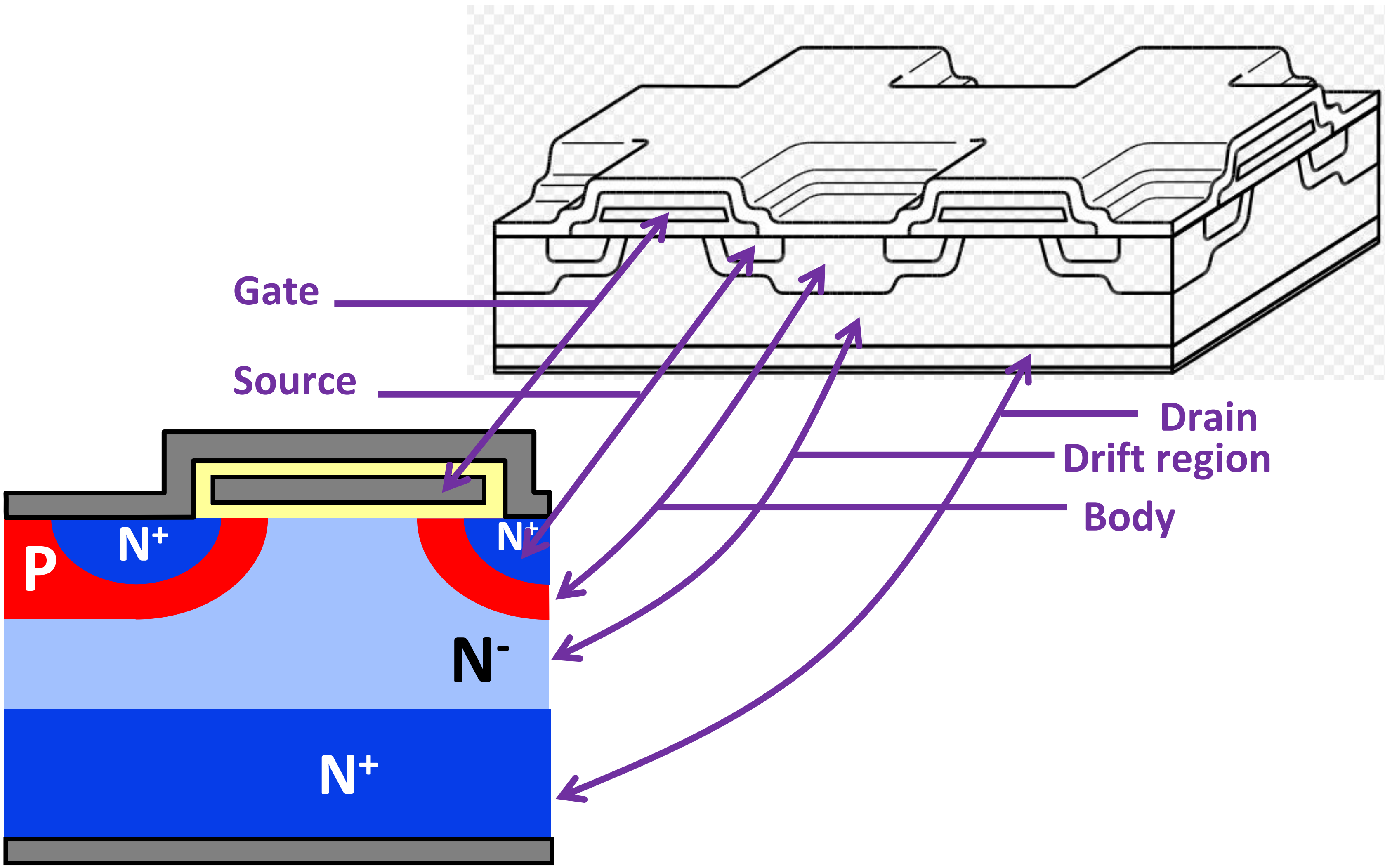


V-groove MOS (VMOS)



Double diffused MOSFET (DMOS)

- **Tridimensional structure of a DMOS:**



Packages for power MOSFETs (I).

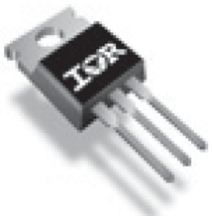
- **Packages are similar to those of power diodes (except axial leaded through-hole packages).**
- **There are many different packages.**
- **Examples: 60V MOSFETs.**

International IOR Rectifier THE POWER MANAGEMENT LEADER

SO-8

IRF7855PbF

$R_{DS(on)}$ = 9.4 mΩ, I_D = 12 A



TO-220AB

IRFZ44VZPbF

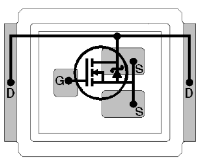
D²Pak

IRFZ44VZSPbF

TO-262

IRFZ44VZLPbF

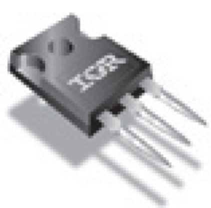
$R_{DS(on)}$ = 12 mΩ, I_D = 57 A



DirectFET™ ISOMETRIC

IRF6648

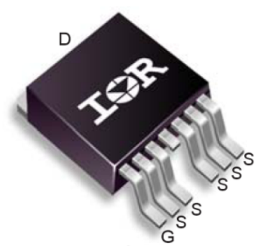
$R_{DS(on)}$ = 5.5 mΩ, I_D = 86 A



TO-247AC

IRFP054VPbF

$R_{DS(on)}$ = 9 mΩ, I_D = 93 A



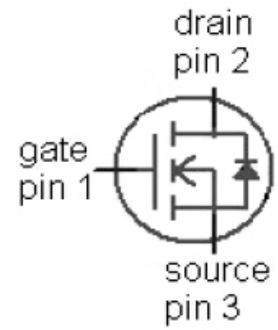
D²Pak 7 Pin

IRFS3006-7PPbF

$R_{DS(on)}$ = 1.5 mΩ, I_D = 240 A

Packages for power MOSFETs (II).

- **Other examples of 60V MOSFETs.**



Type	IPB034N06L3 G	IPI037N06L3 G	IPP037N06L3 G
			
Package	PG-TO-263-3	PG-TO-262-3	PG-TO-220-3
Marking	034N06L	037N06L	037N06L

$\mathbf{R_{DS(on)} = 3.4\ m\Omega,\ \ I_D = 90\ A}$

• **Power MOSFETs are faster than other power devices (such as bipolar transistors, IGBTs, thyristors, etc.).**

• **This is because MOSFETs are unipolar devices (no minority carriers are stored at the edges of PN junctions).**

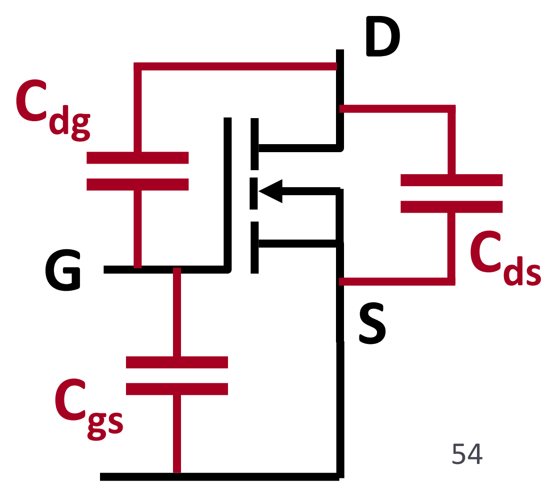
• **The switching speed is limited by parasitic capacitances.**

• **Three parasitic capacitances should be taken into account:**

- C_{gs}, which is a quite linear capacitance.

- C_{ds}, which is a non-linear capacitance.

- C_{dg}, Miller capacitance, which is also a non-linear capacitance.



Power losses in power MOSFETs (I).

- **Static losses:**

  - Reverse losses ⇒ negligible in practice due to the low value of the drain current at zero gate voltage, I_{DSS}.

SYMBOL	PARAMETER	CONDITIONS	MIN.	TYP.	MAX.	UNIT
I_{DSS}	Zero gate voltage drain current	V_{DS} = 100 V; V_{GS} = 0 V	-	0.05	10	µA
		V_{DS} = 80 V; V_{GS} = 0 V; T_j = 175°C	-	-	250	µA

  - Conduction losses, due to $R_{DS(on)}$:

  $$P_{MOS\_cond} = R_{DS(ON)} \cdot I_{D\_RMS}^2,$$

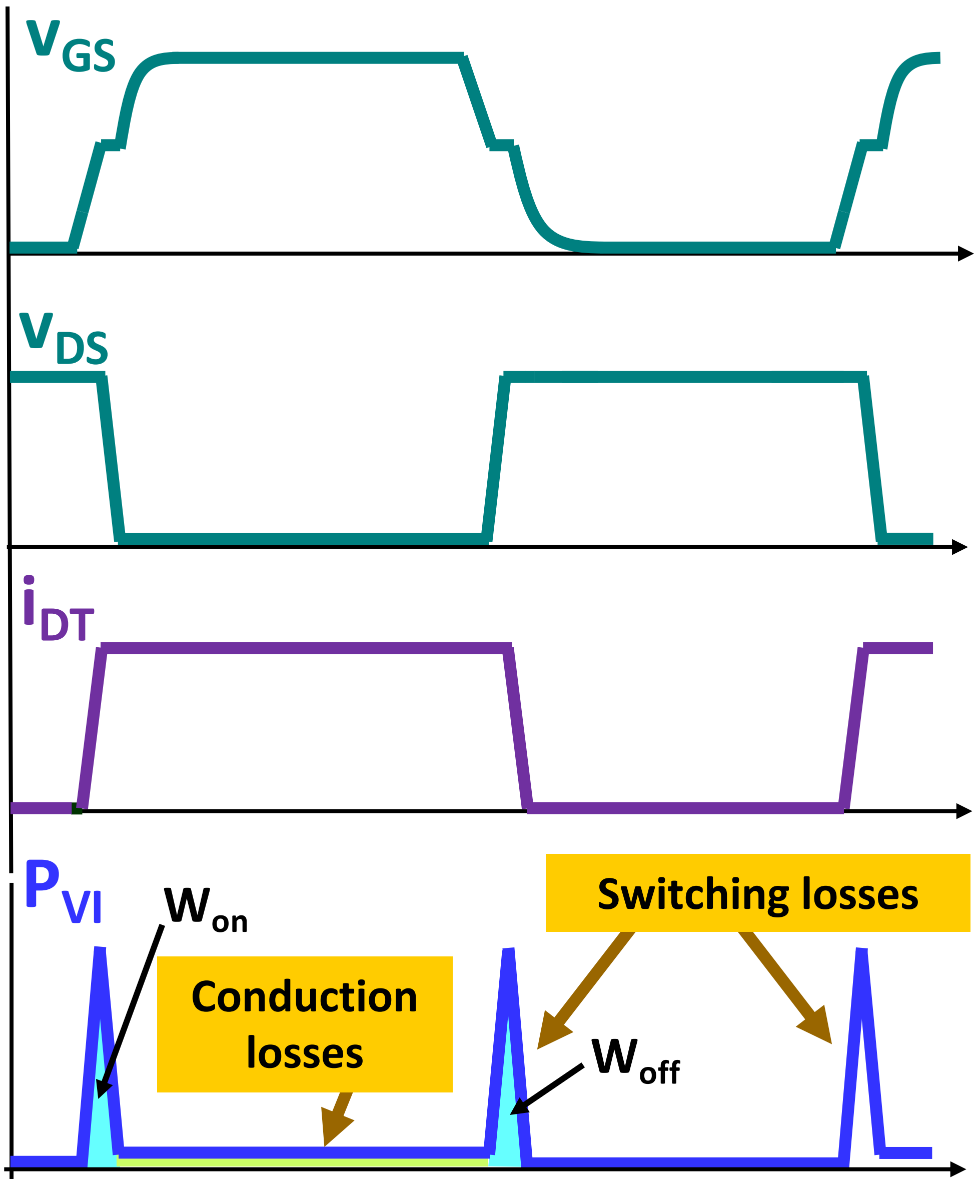
  where I_{D_RMS} is the RMS value of the drain current.

- **Switching (dynamic) losses:**

  - Turn-on losses and turn-off losses.

- **Driving losses.**

Power losses in power MOSFETs (II).

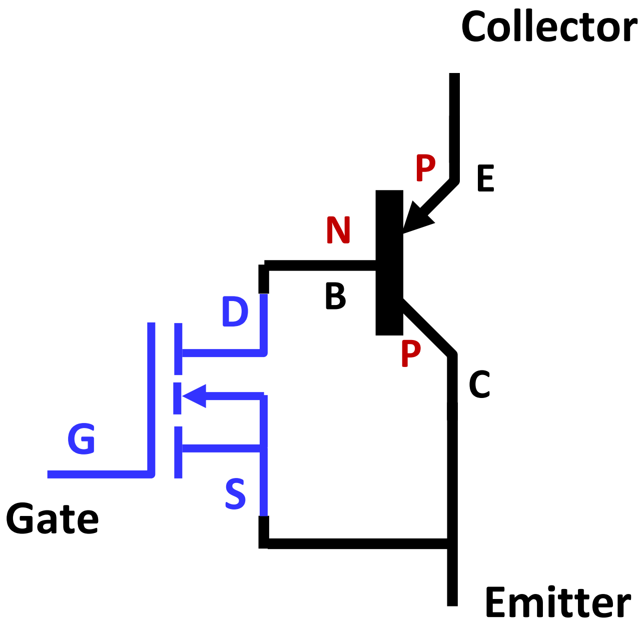


$$P_{MOS\_cond} = R_{DS(on)} \cdot I_{D\_RMS}^2$$

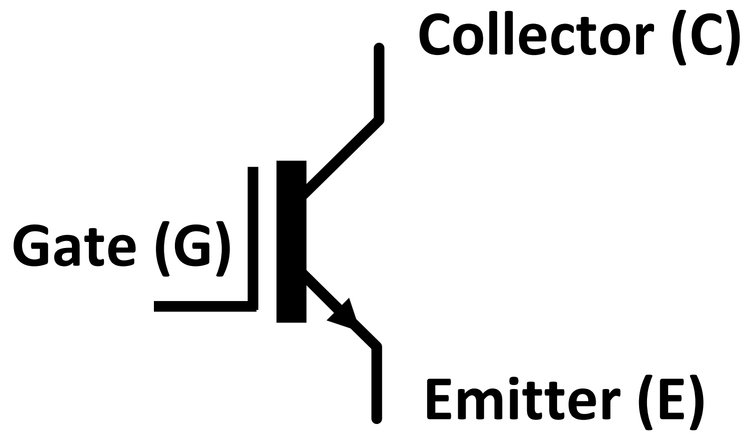
$$P_{MOS\_S} = f_S(w_{on} + w_{off})$$

IGBT

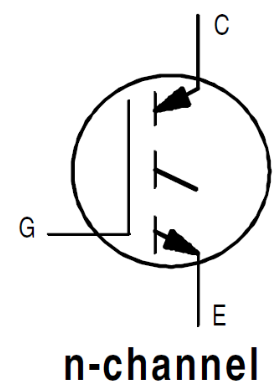
Principle of operation and structure of the IGBT (II).



Simplified equivalent circuit for an IGBT.

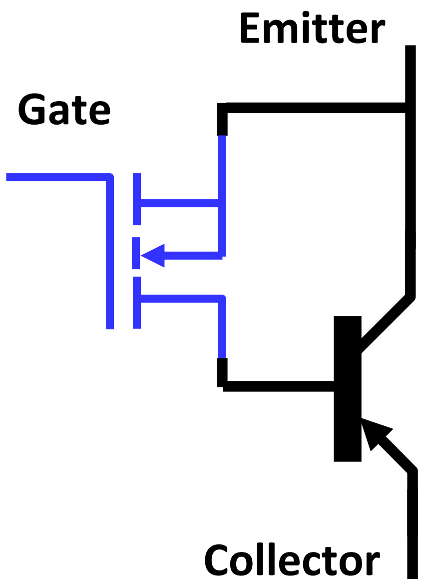


Schematic symbol for a N-channel IGBT.

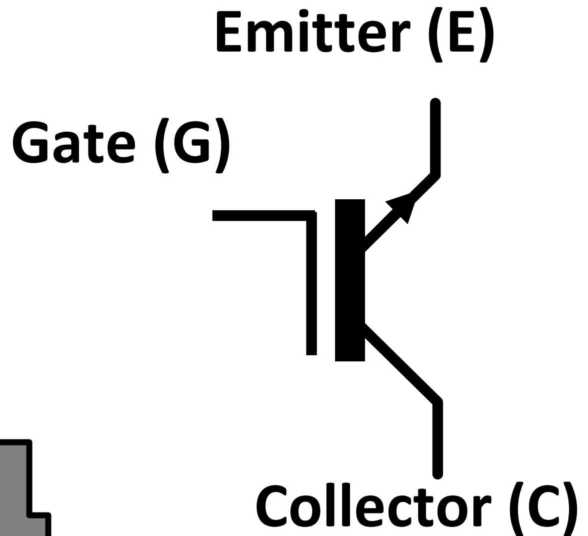


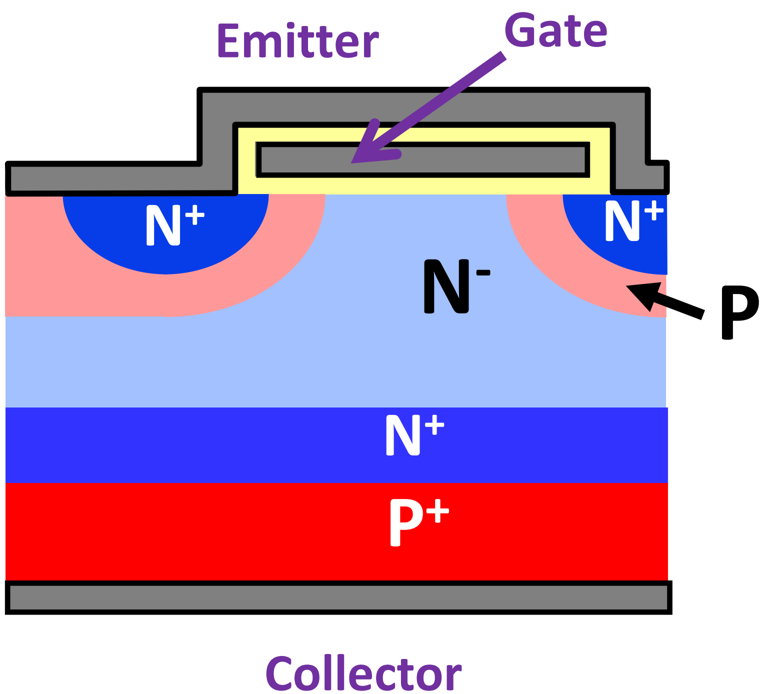
Another schematic symbol also used.

Principle of operation and structure of the IGBT (III).

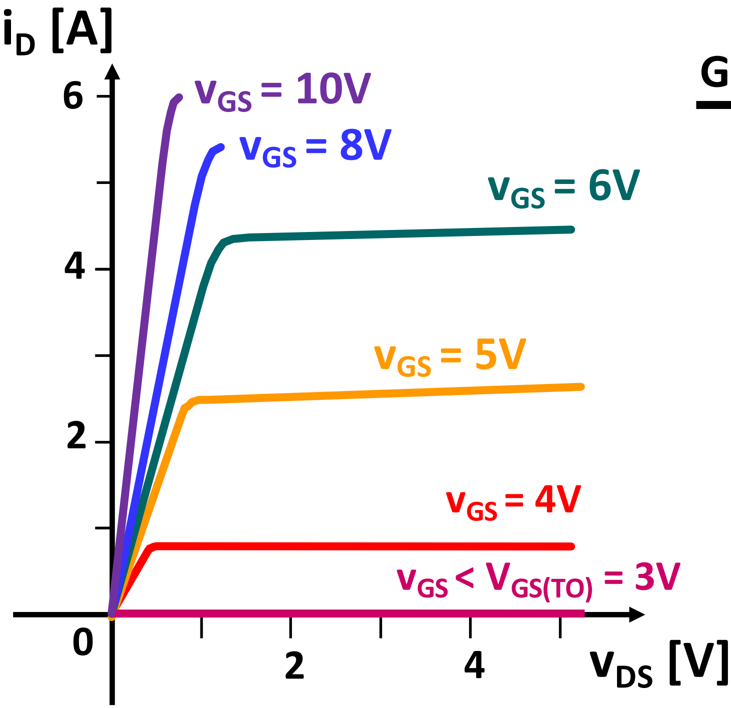


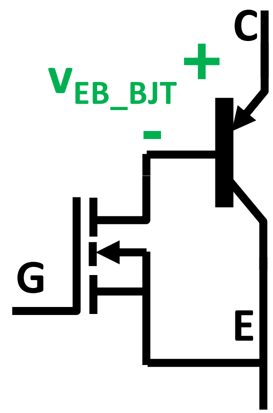
- **Internal structure (I).**

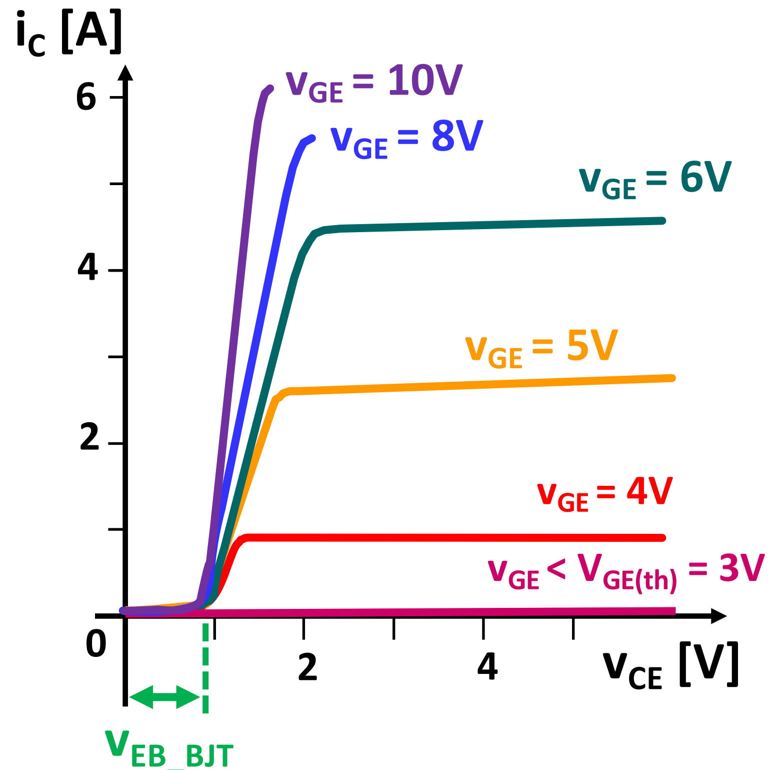




Static output characteristic curves of a IGBT.







- Static output characteristic curve of a MOSFET.
- It is also the one corresponding to the MOSFET part of a IGBT.

- Static output characteristic curve of a IGBT.
- It can be easily obtained from the MOSFET characteristic curve by adding the voltage drop v_{EB_BJT} corresponding to the emitter-to-base junction of the BJT part of the IGBT.

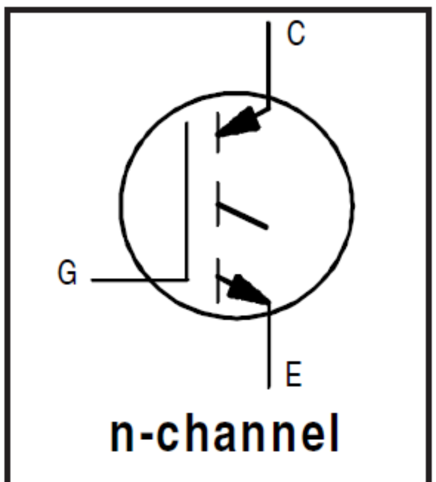
General characteristics of the IGBTs (I).

- **We will use a specific IGBT to address the general IGBT characteristics.**

International
IOR Rectifier

INSULATED GATE BIPOLAR TRANSISTOR

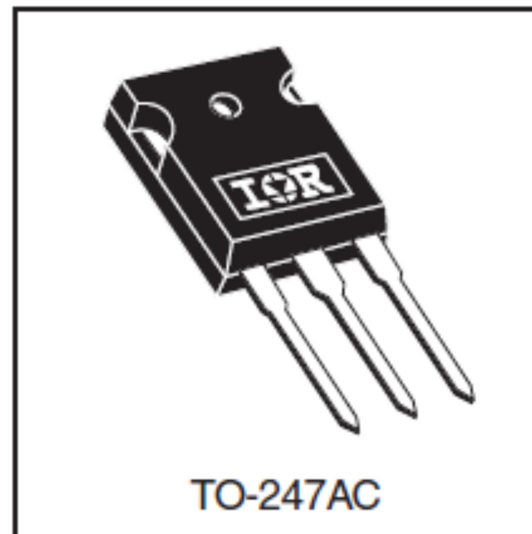
IRG4PC50W



$V_{CES} = 600V$

$V_{CE(on)\ max.} = 2.30V$

$@V_{GE} = 15V,\ I_C = 27A$



General characteristics of the IGBTs (II).

- **General information regarding the IRG4PC50W.**

Features

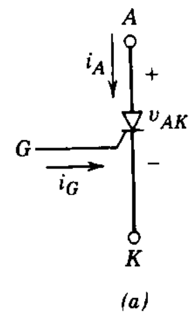
- Designed expressly for Switch-Mode Power Supply and PFC (power factor correction) applications
- Industry-benchmark switching losses improve efficiency of all power supply topologies
- 50% reduction of Eoff parameter
- Low IGBT conduction losses
- Latest-generation IGBT design and construction offers tighter parameters distribution, exceptional reliability

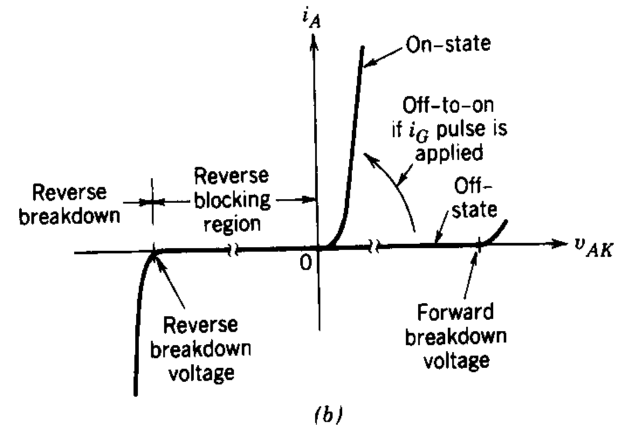
Benefits

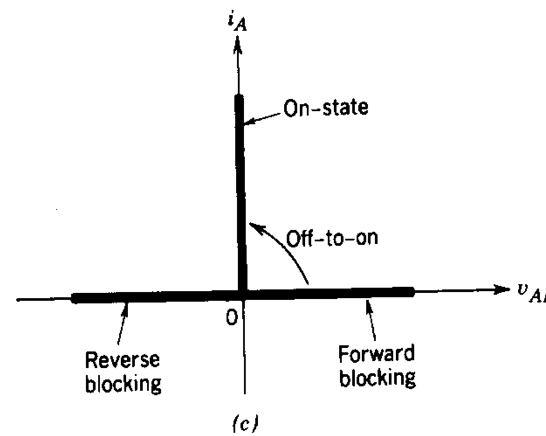
- Lower switching losses allow more cost-effective operation than power MOSFETs up to 150 kHz ("hard switched" mode)
- Of particular benefit to single-ended converters and boost PFC topologies 150W and higher
- Low conduction losses and minimal minority-carrier recombination make these an excellent option for resonant mode switching as well (up to >300 kHz)

Silicon Controlled Rectifier

- Controlable el encendido
- Apagado:
  - ✓ Natural: la corriente decrece por si sola (rectificadores)
  - ✓ Forzado: hacen falta componentes adicionales para bloquear la corriente
- Caída de tensión ≈ 2V

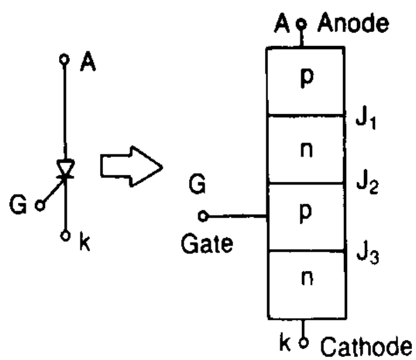


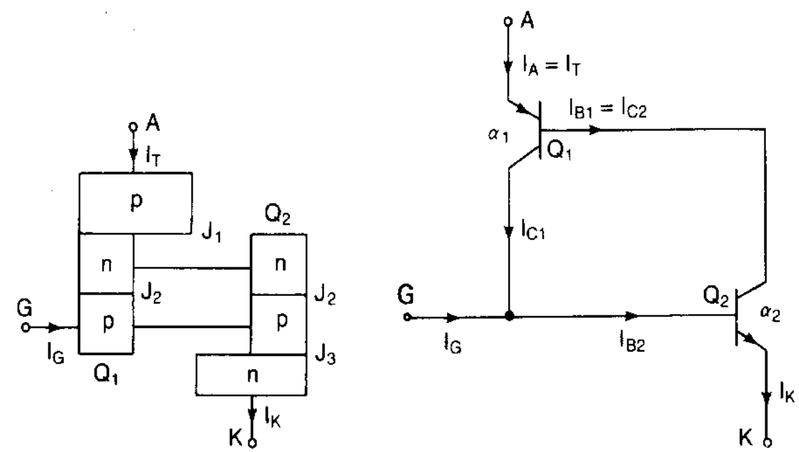




Tiristor (SCR)

Estructura interna y circuito equivalente





(a) Basic structure

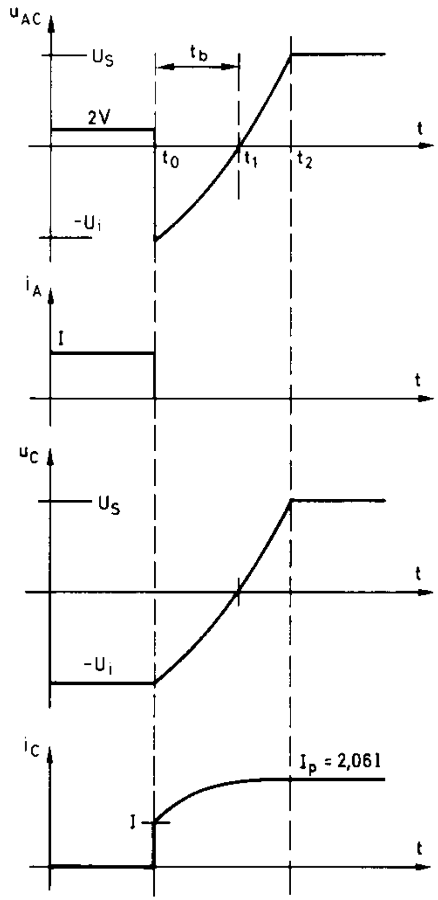
(b) Equivalent circuit

Formas de disparo:

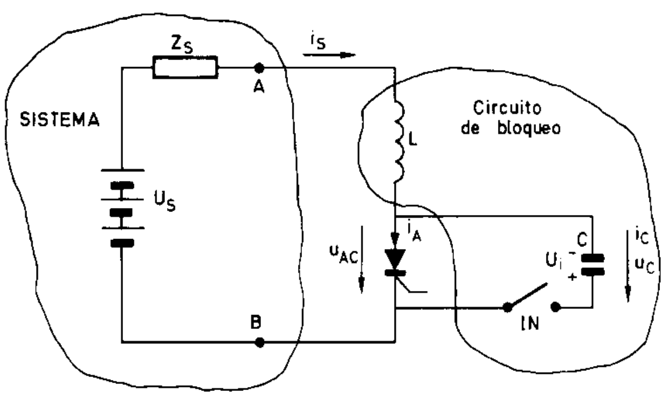
- ✓ Corriente de puerta
- ✓ Luz: light activated thyristors (LASCR)
- ✓ Formas no recomendadas:
  - Tensión alta
  - Estrés térmico
  - Alta derivada de tensión dv/dt

Tiristor (SCR)

Circuito de bloqueo

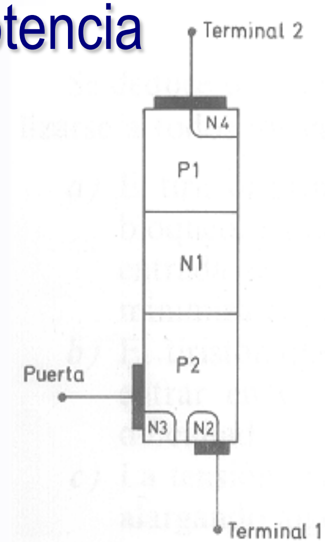


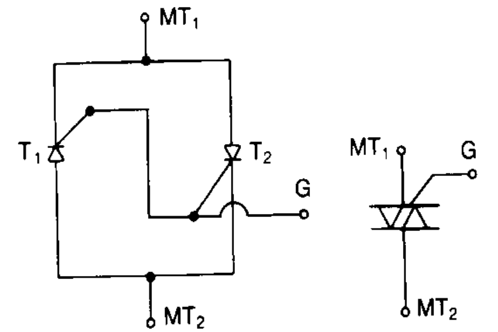
- Tiristor adicional
- Condensador
- Bobina
- Circuito de disparo



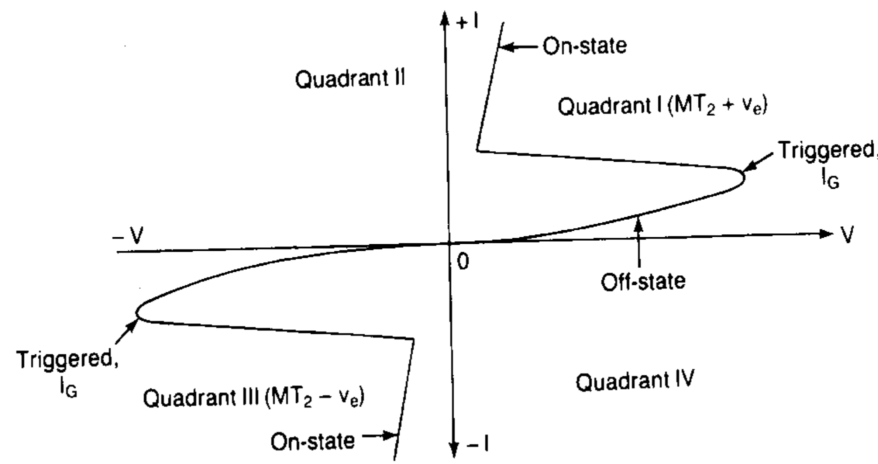
Triac

- Controlable el encendido
- Bi-direccional
- Casi simétrico
- Ideal para control de fase en CA
- Aplicaciones de baja frecuencia y potencia





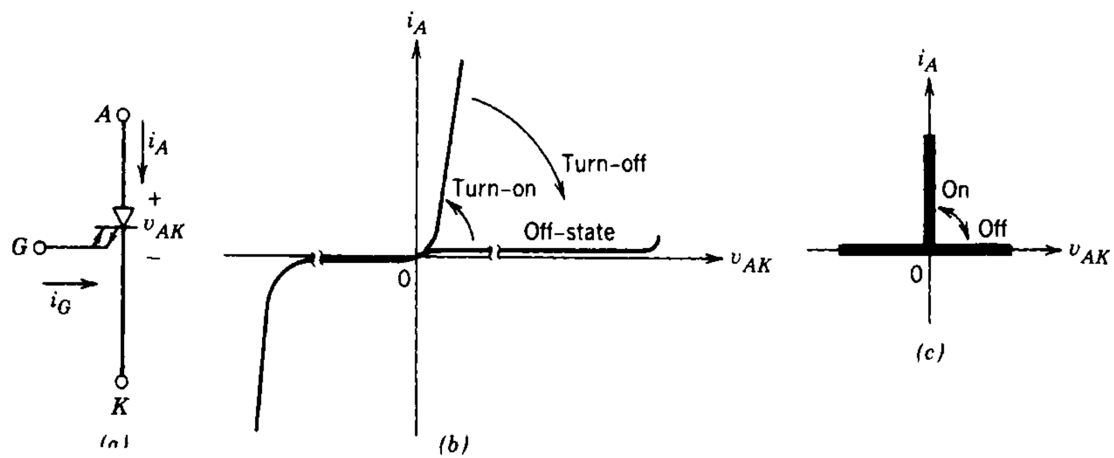
(a) Equivalent of TRIAC (b) TRIAC symbol



(c) v-i characteristics

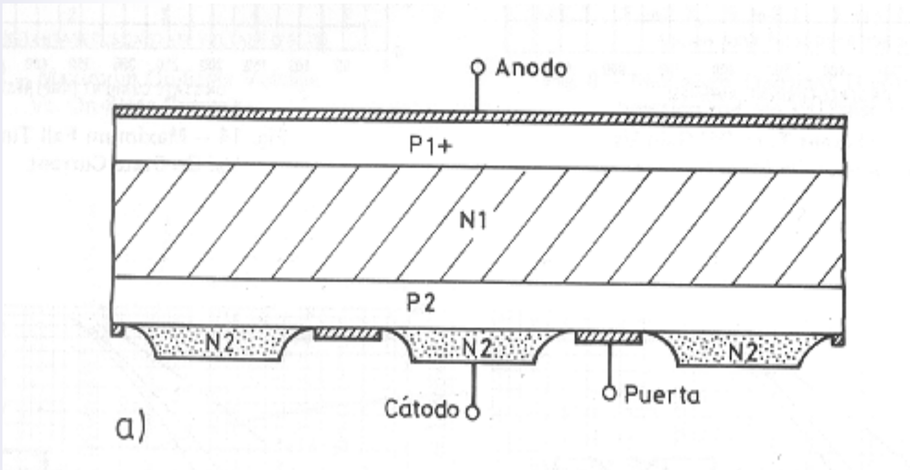
GTO

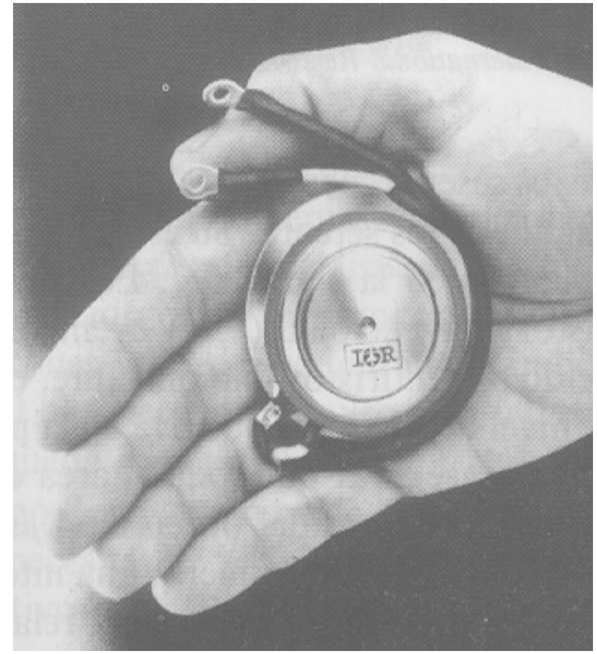
Gate Turn-Off thyristor



- Encendido y apagado controlado por puerta
- Necesita gran corriente para apagarlo por puerta
- Mayor frecuencia que el SCR (pocos kHz)
- Aplicación típica: inversores de alta potencia

GTO



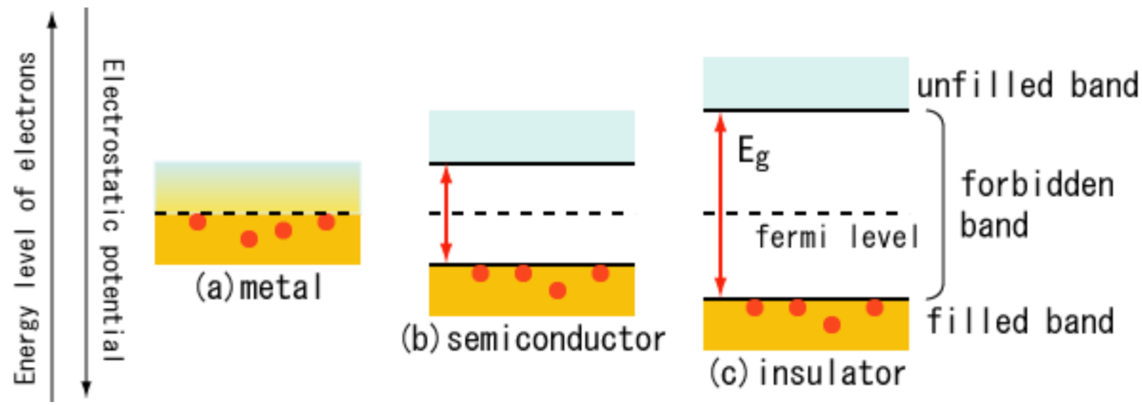


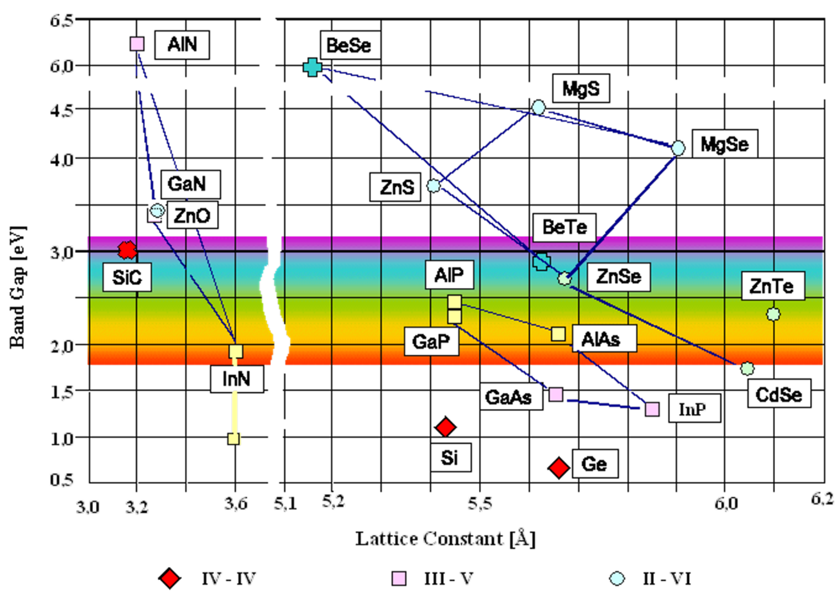
- Estructura interna similar al SCR pero con mayor influencia de la puerta
- Mayor caída de tensión en conducción (3V) que el SCR y dependiente de la corriente de puerta

Wide bandgap semiconductors

How do we define them?

- Wide bandgap → electronic band-gaps significantly higher than 1 eV (Si has a gap of 1.1eV)



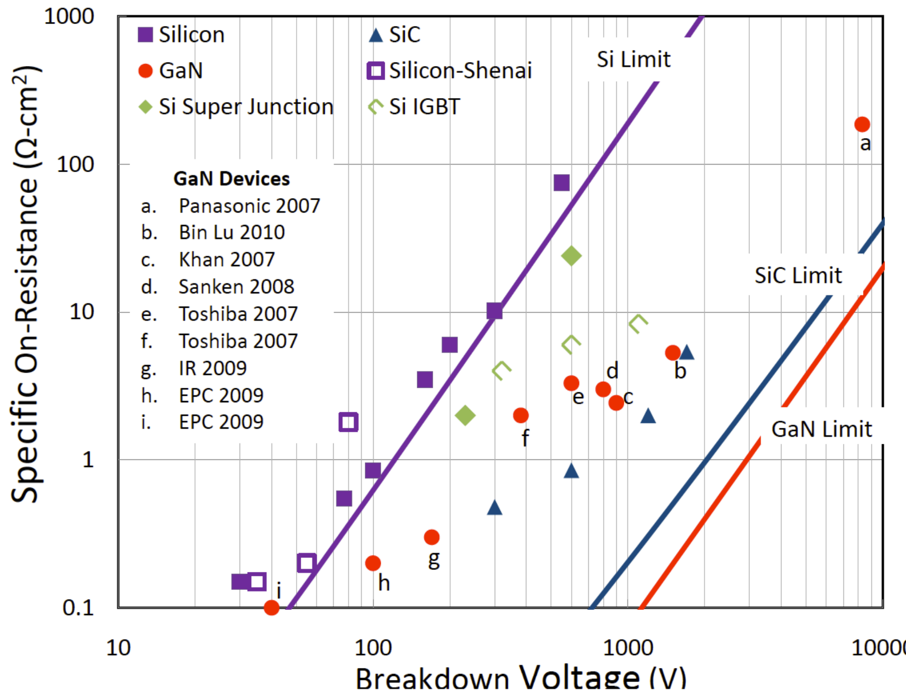


- We will see a little bit of physics…
- …and some applications, of course
- Two devices will be considered:
  - SiC MOSFET
  - GaN HEMT

1. Comparación materiales semiconductores

Ventajas

- Para **la misma tensión**, el SiC es ***220 veces menos resistivo***
- Para **la misma resistencia**, la de SiC soporta ***15 veces más tensión***

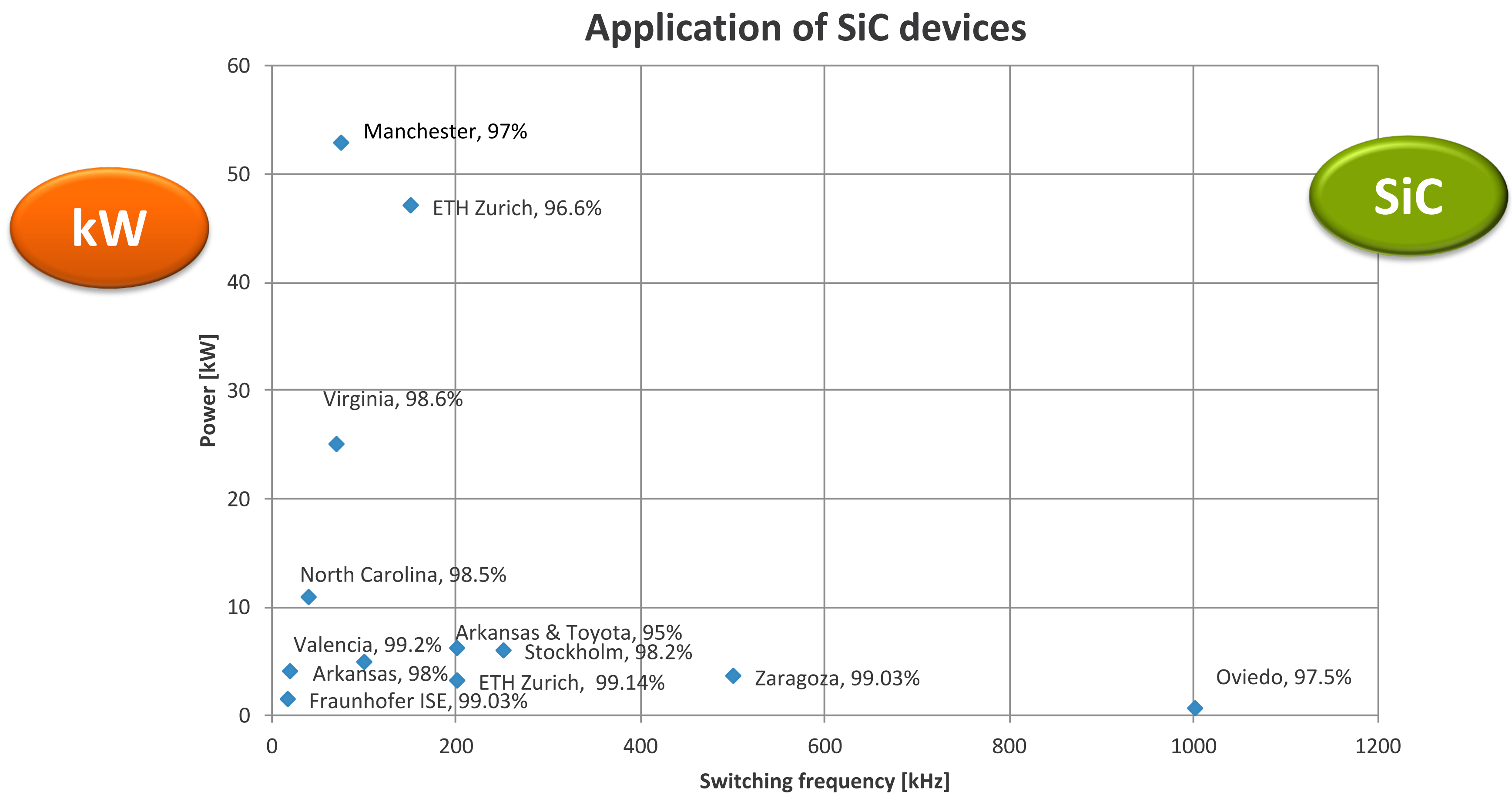


K. Shenai et al,
IEEE Transactions on Electron Devices

Inconvenientes

- **Tecnologías no maduras**:
  - Crecimiento de obleas
  - El sustrato se comba
  - Efectos piezoeléctricos
- El **encapsulado** limita algunas de las ventajas
- Mucho **más caros**

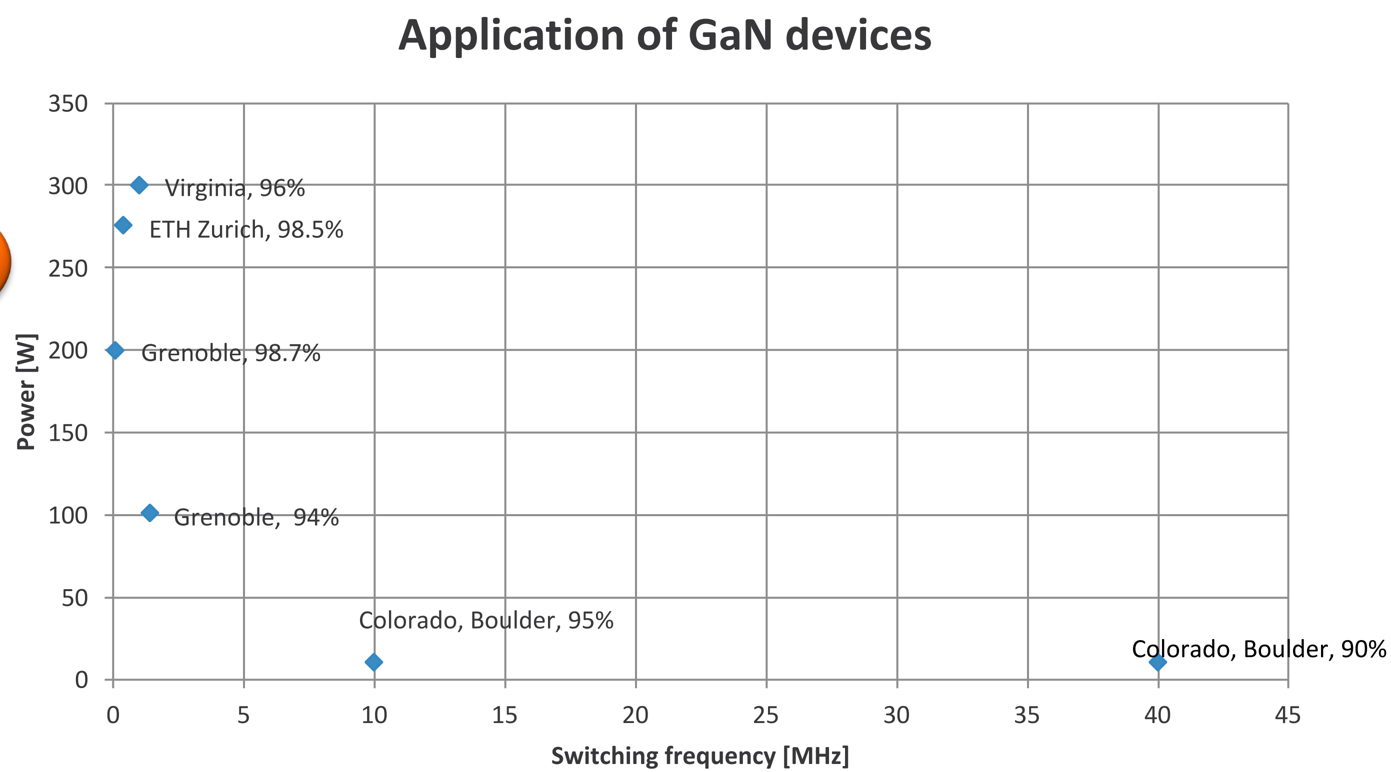
3. Estado del arte



3. Estado del arte

GaN

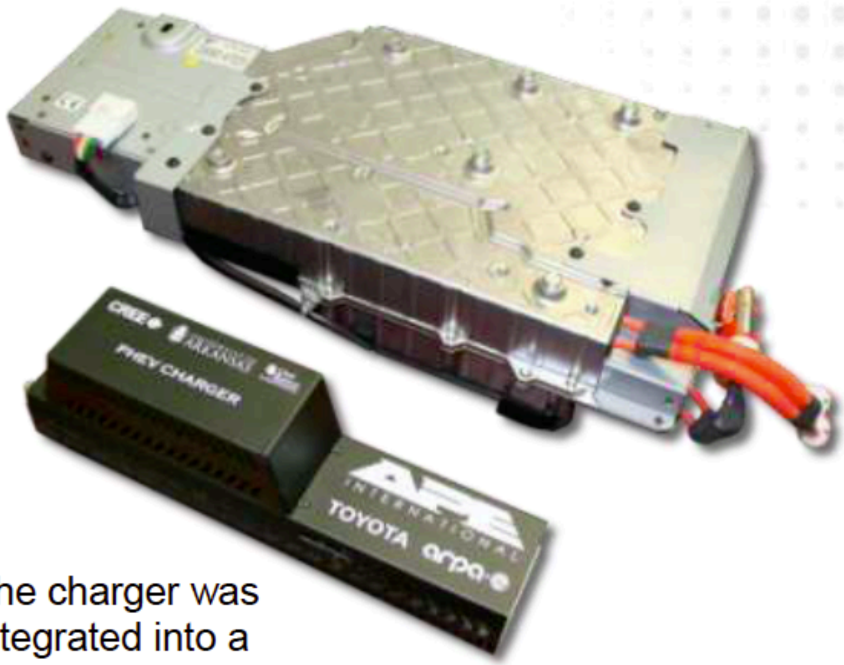
W



4. Ejemplos del IEEE APEC 2014 (Tim Heidel ARPA-E)

SiC Galvanically-Isolated Vehicle Battery Charger Provides 10x Increase in Power Density

Parameter	Baseline	Prototype
Volumetric Power Density	7.4 W/in^3 (387.5 in^3)	83.3 W/in^3 (73.2 in^3)
Gravimetric Power Density	0.44 kW/kg (6.6 kg)	3.8 kW/kg (1.6 kg)
Power	2.88 kW	6.1 kW
Efficiency	-	95% peak



The charger was integrated into a 2010 model Toyota Prius Plug-in Hybrid

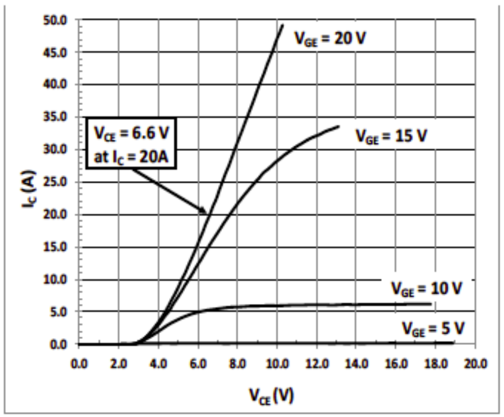
10x Increase in Power Density *and* Increased Efficiency!

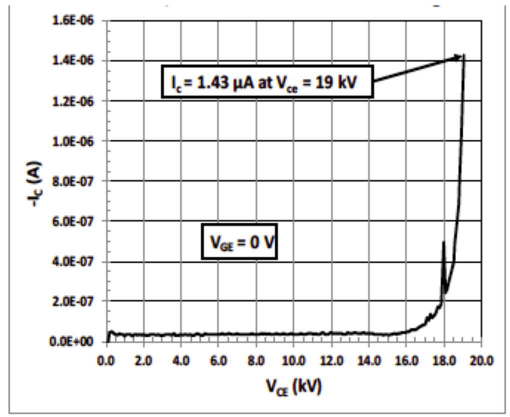
As shown at booth #544.

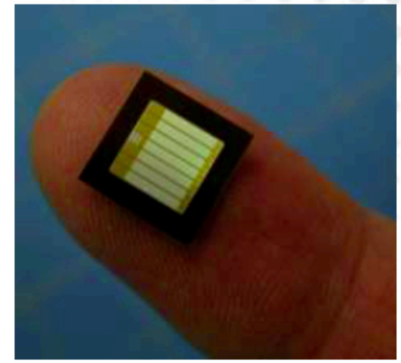
arpa-e CHANGING WHAT'S POSSIBLE | APE International | CREE | TOYOTA | UNIVERSITY OF ARKANSAS | OAK RIDGE National Laboratory

4. Ejemplos del IEEE APEC 2014 (Tim Heidel ARPA-E)

15kV+ SiC IGBTs

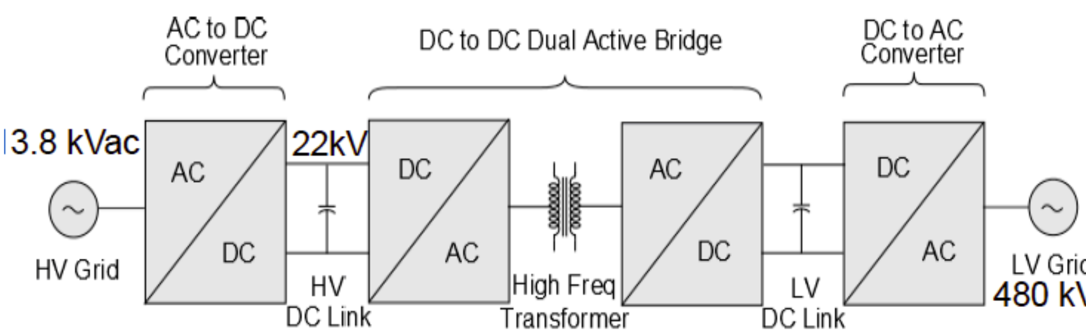


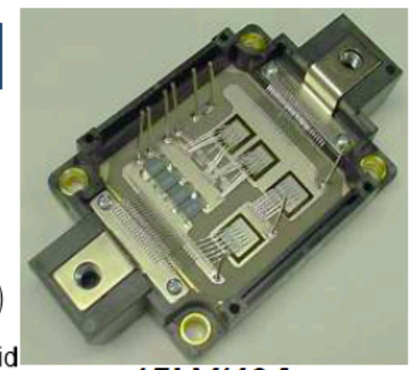




19 kV/20 A SiC n-IGBT

Transformerless Intelligent Power Substation (TIPS)





15kV/40A SiC IGBT Copack

arpa·e CHANGING WHAT'S POSSIBLE

CREE POWEREX NC STATE UNIVERSITY ABB

19

Conclusiones

- **Los nuevos dispositivos de SiC y GaN empiezan a ser una alternativa real sobre los de Si.**
- **De manera comercial sólo hay algunos dispositivos disponibles:**
  - **SiC: diodos, JFETs, MOSFETs (tipicamente de 1200V)**
  - **GaN: HEMTs de 100 y 650V**
- **La tecnología no está madura pero avanza muy rápido.**
  - **Hay prototipos de tensiones más altas**
  - **Hay prototipos de IGBTs y dispositivos bidireccionales**

2 Relevant applications
Where could GaN play a role?