Instituto Federal de Educação, Ciência e Tecnologia de Santa Catarina
Departamento Acadêmico de Eletrônica
Pós-Graduação em Desen. de Produtos Eletrônicos
Conversores Estáticos e Fontes Chaveadas

Semicondutores, Perdas e Cálculo Térmico

Prof. Clovis Antonio Petry.
Prof. Joabel Moia.

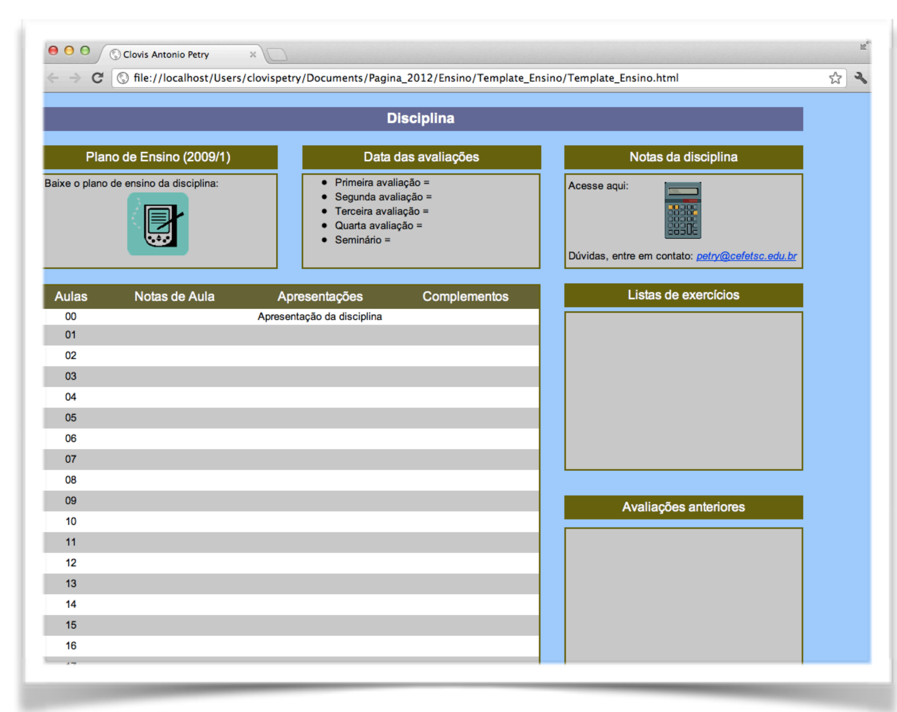
Florianópolis, fevereiro de 2014.

Biografia para Esta Aula

Semicondutores para eletrônica de potência:

- Semicondutores;
- Perdas;
- Cálculo térmico.

www.ProfessorPetry.com.br



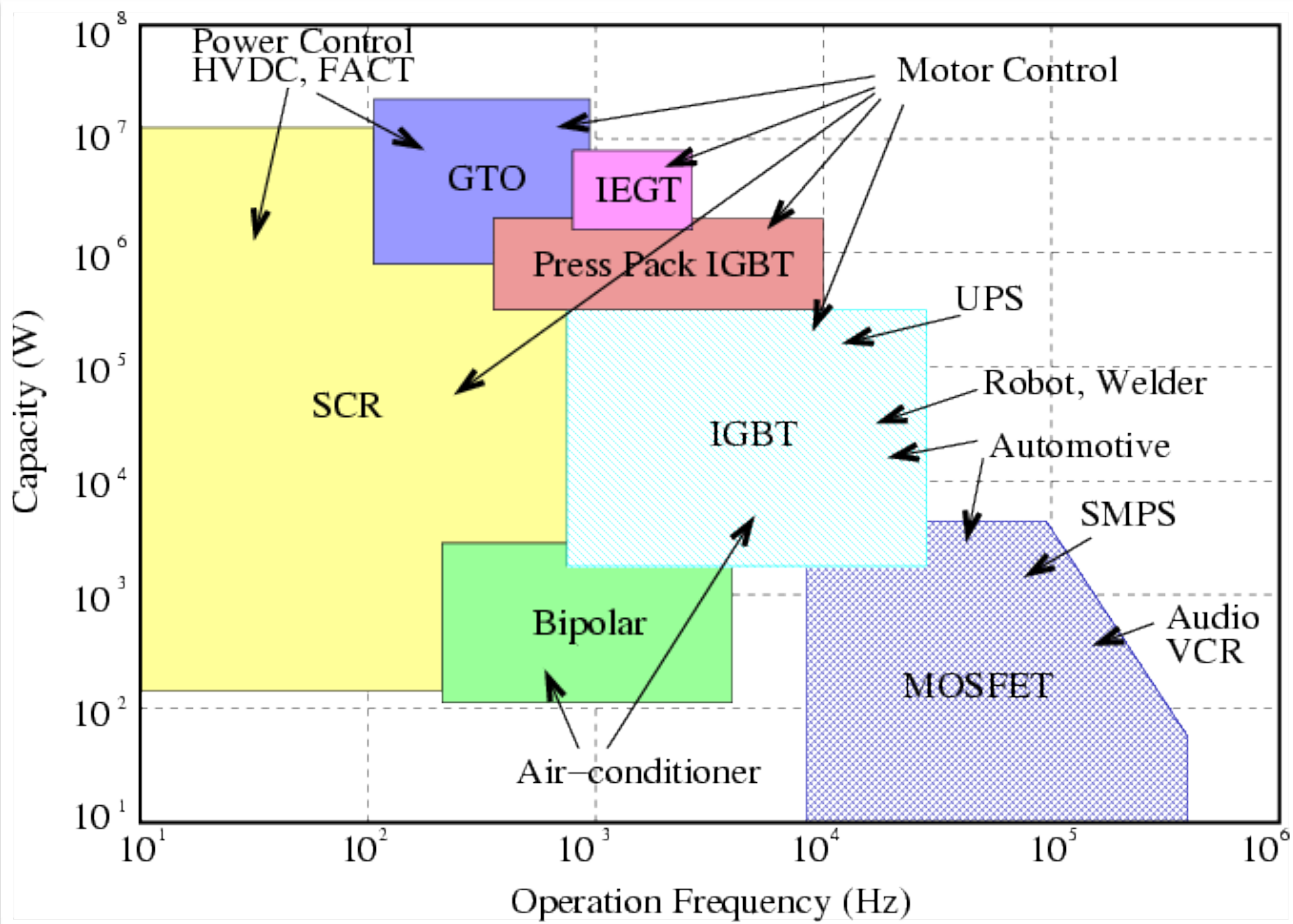
Nesta Aula

Semicondutores de potência:

- Semicondutores para eletrônica de potência;
- Diodos ideais;
- Diodos reais;
- Comutação de diodos;
- Perdas em diodos;
- Características importantes de diodos;
- Revisão de BJT;
- BJT x FET;
- FETs;
- MOSFETs;
- IGBTs;
- Cálculo térmico;
- Outros componentes importantes.

Semicondutores de Potência

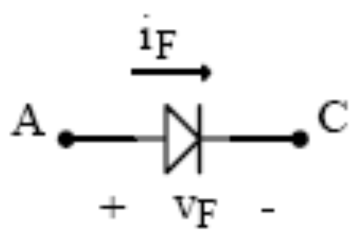
Semicondutores aplicados à eletrônica de potência:

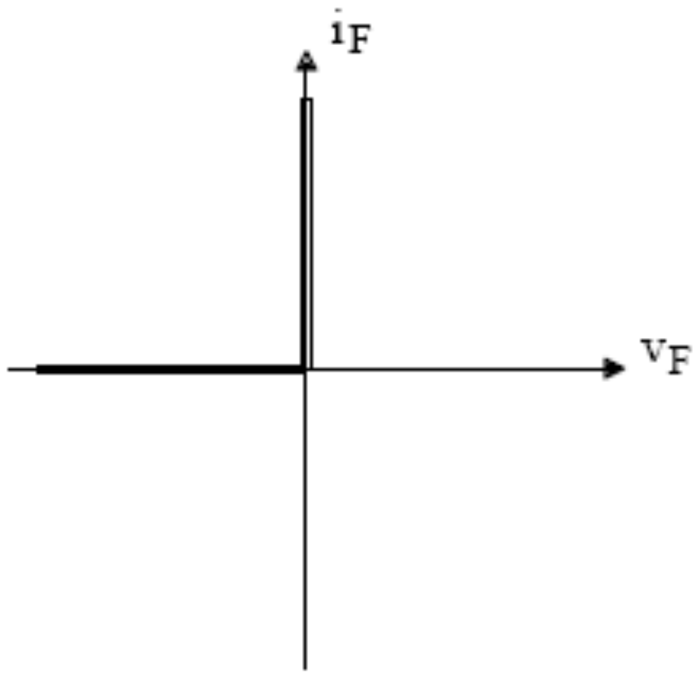


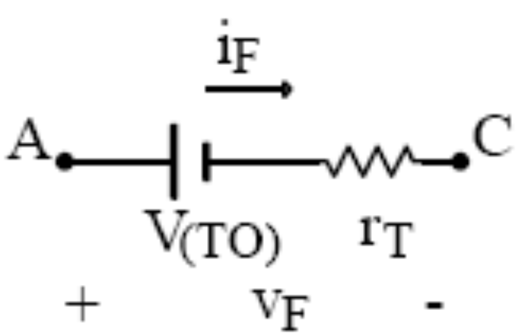
Diodo Ideal x Diodo Real

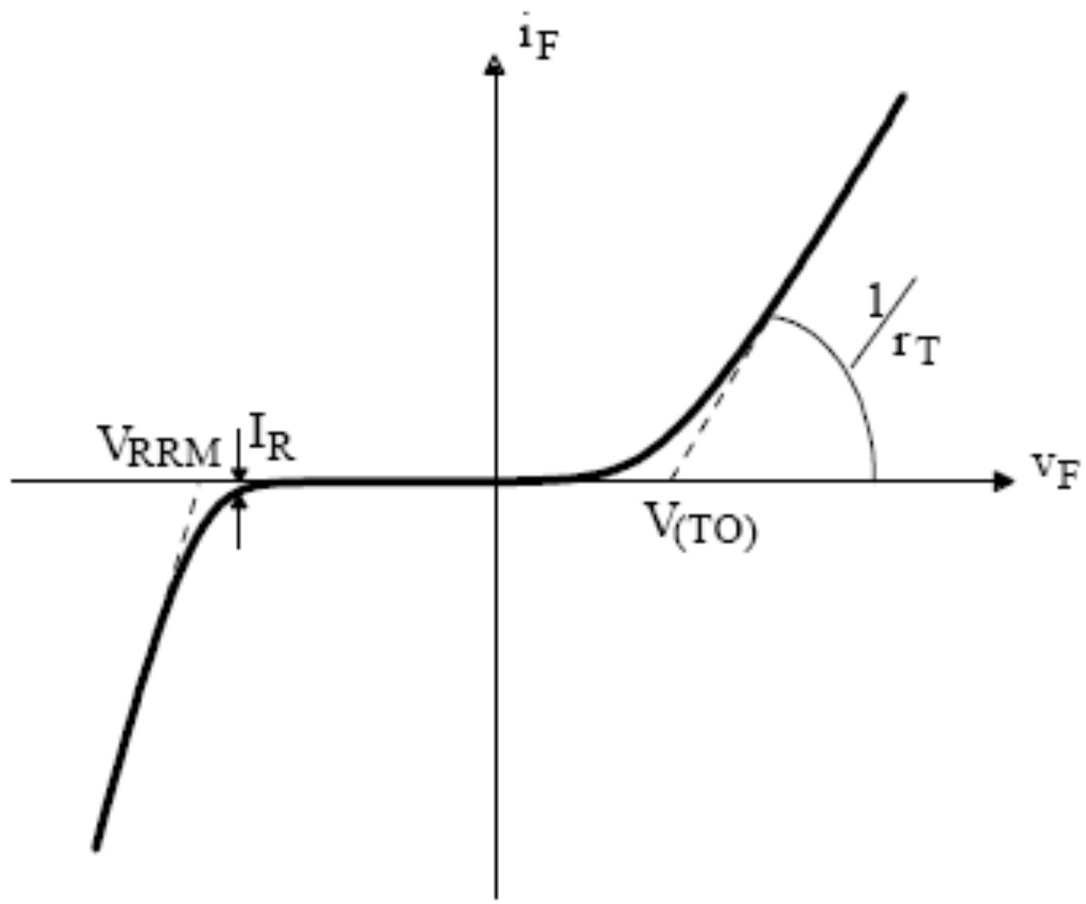
Exemplo: Diodo SKN20/08

- VRRM = 800 V;
- V(TO) = 0,85 V;
- rT = 11 mΩ;
- IDmed = 20 A;
- IR = 0,15 mA.





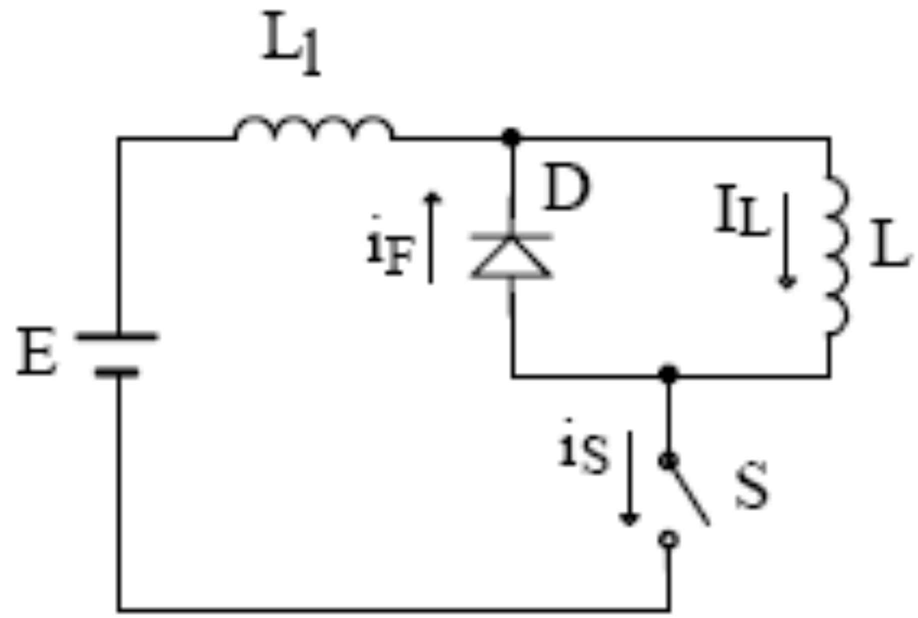




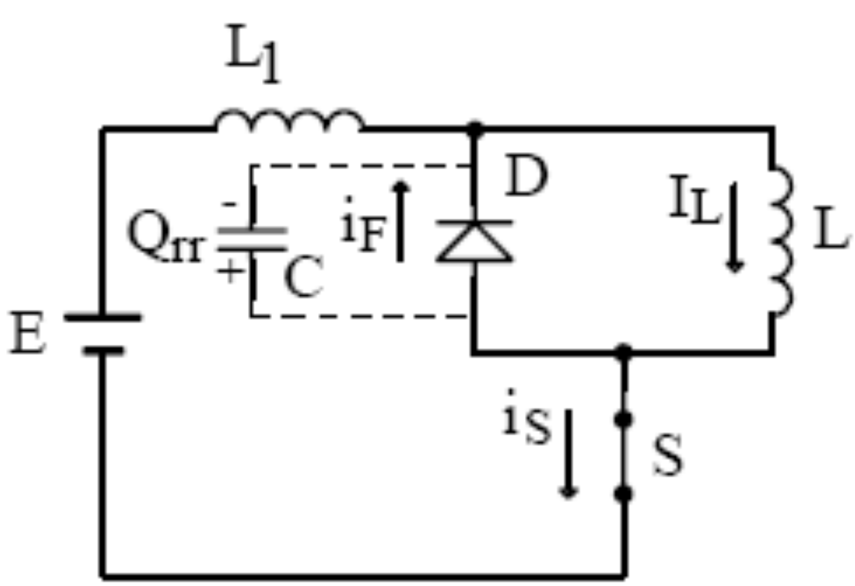
Característica estática

Comutação de Diodos

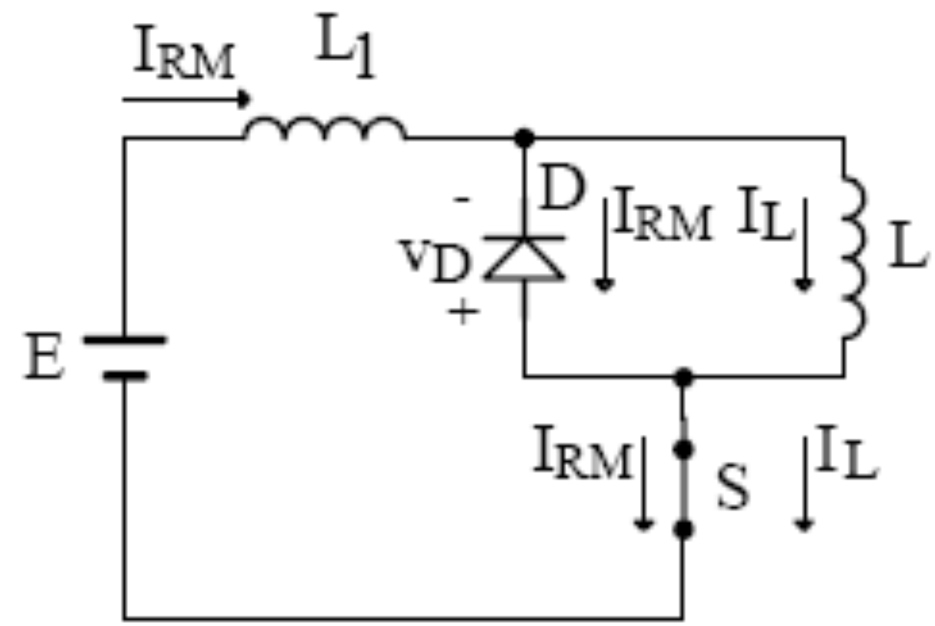
Bloqueio:



Circuito para estudo da comutação



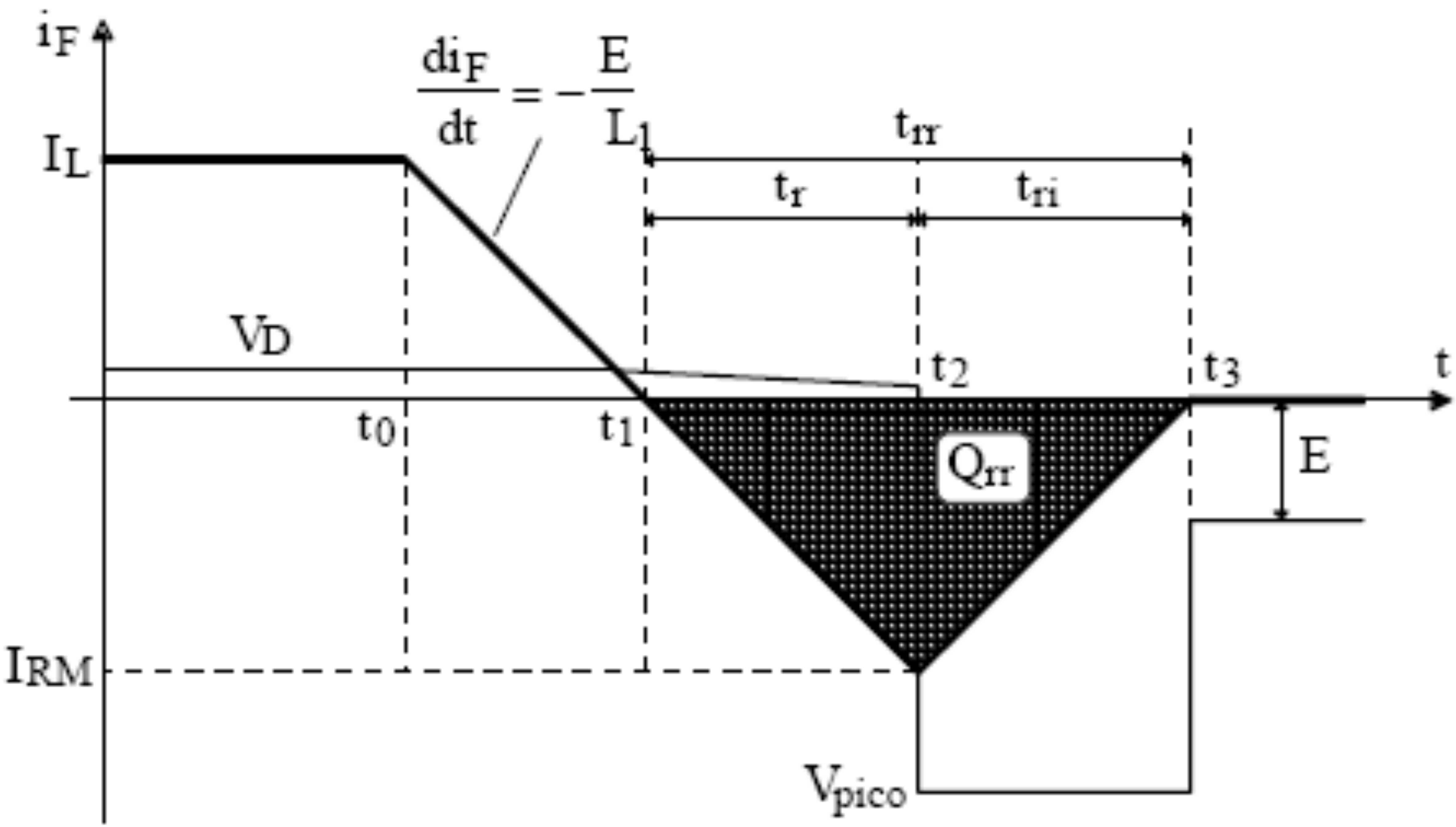
Primeira etapa de comutação



Segunda etapa de comutação

Comutação de Diodos

Bloqueio:



Comutação de Diodos

No bloqueio do diodo (comutação crítica):

$$\frac{di_F}{dt} = -\frac{E}{L_1}$$

Derivada da corrente depende da indutância

$$t_{rr} \cong \sqrt{\left(\frac{3Q_{rr}}{di_F/dt}\right)}$$

Tempo de recuperação reversa

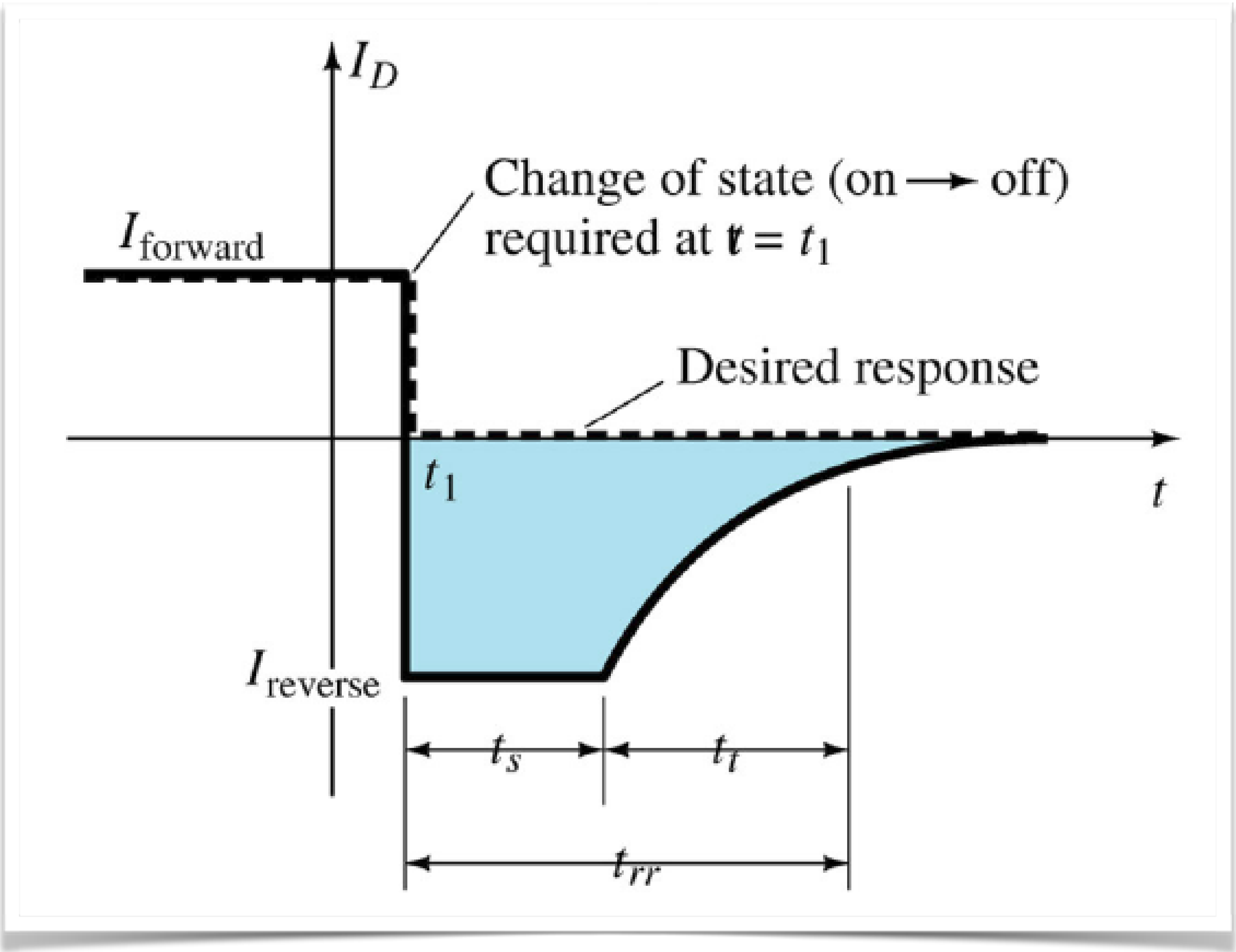
$$I_{RM} \cong \sqrt{\left(\frac{4}{3} Q_{rr} \frac{di_F}{dt}\right)}$$

Corrente máxima devido a recuperação reversa

Comutação de Diodos

Diodos de carbeto de silício (silicon carbide):

- Diminuem acentuadamente o fenômeno da recuperação reversa.



www.infineon.com

www.cree.com

Comutação de Diodos

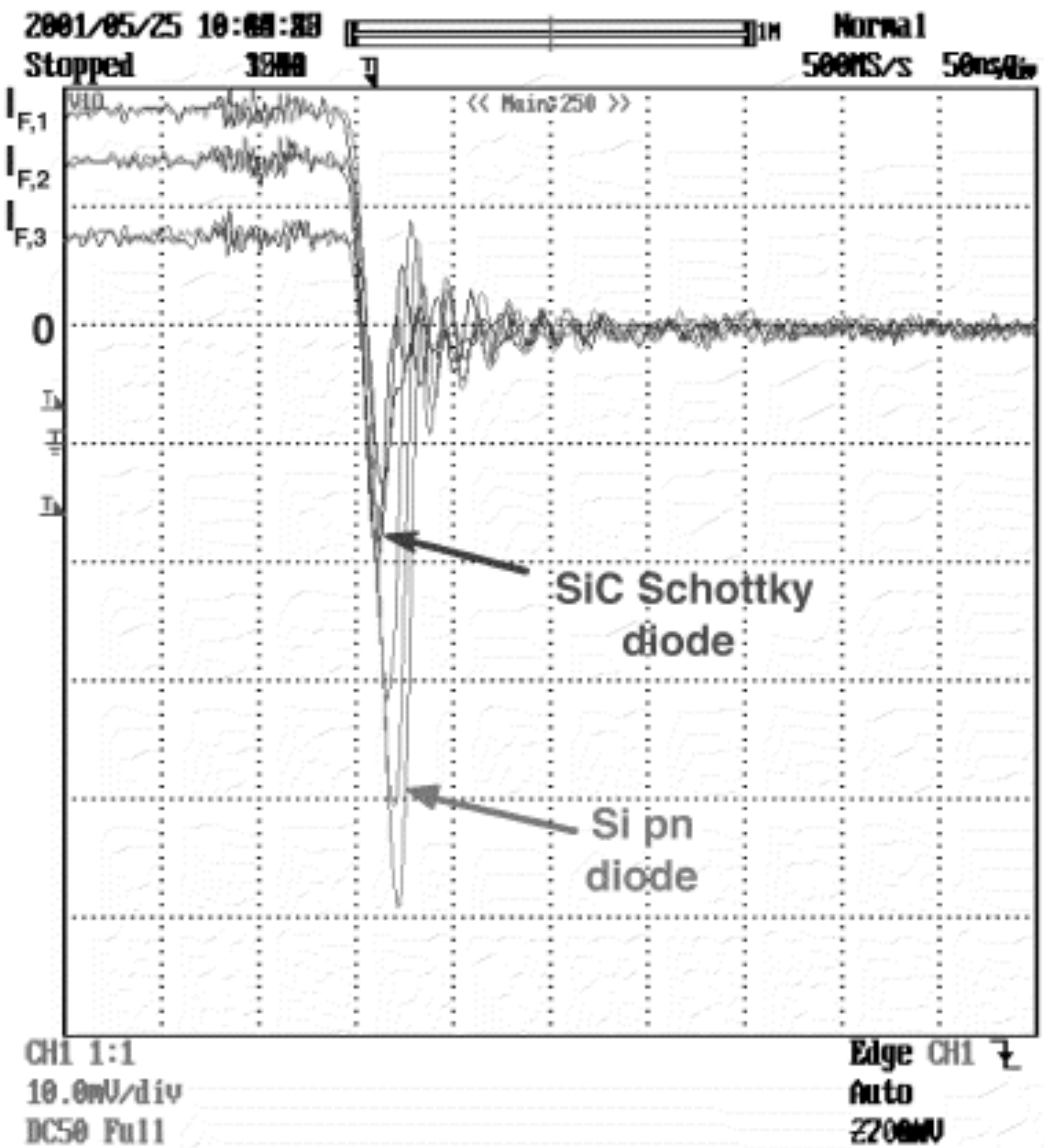


Fig. 5. Typical reverse recovery waveforms of the Si pn and SiC Schottky diode for three different forward currents (2 A/div.).

http://powerelec.ece.utk.edu/pubs/pels_letters_SiC_june_2003.pdf

Comutação de Diodos

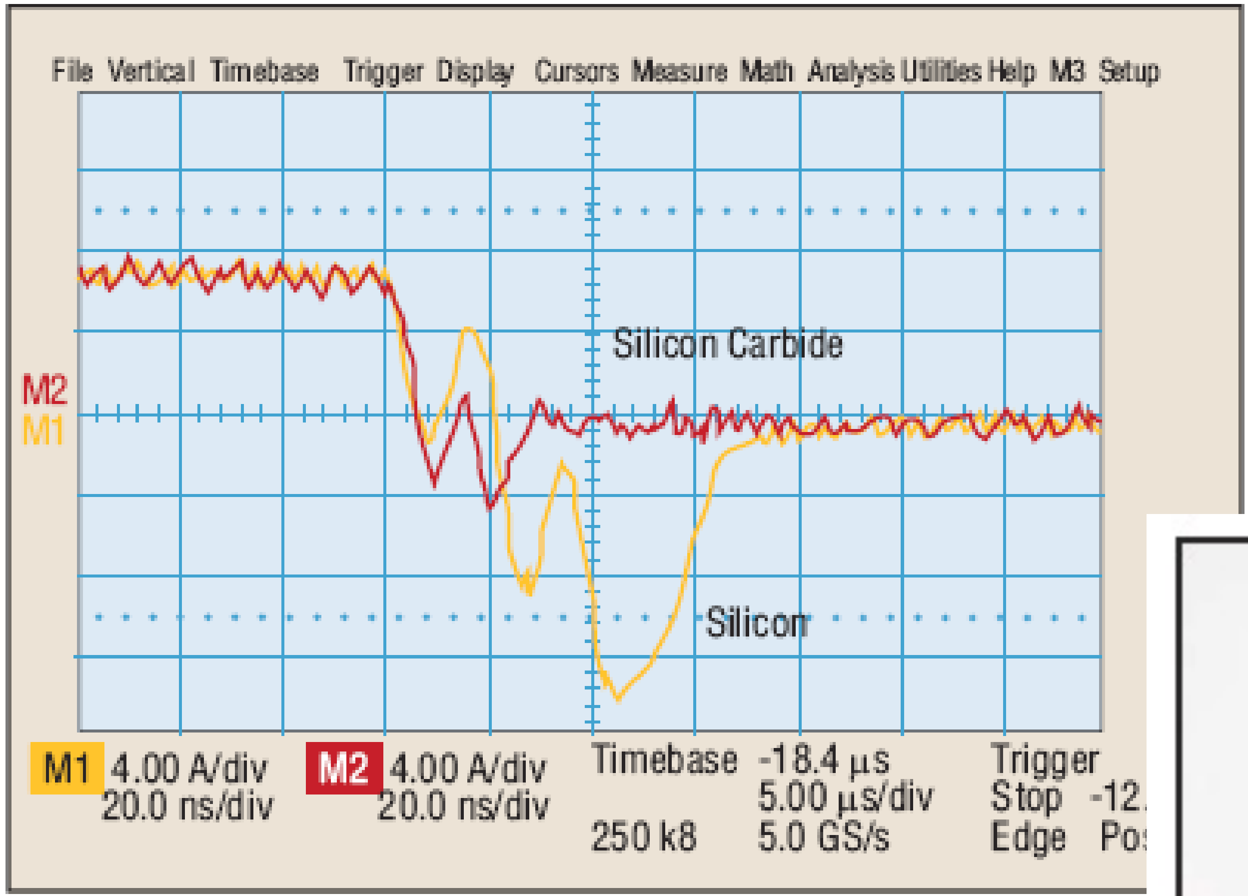


Fig. 4. *Low-line diode recovery currents in PFC front-end conver*

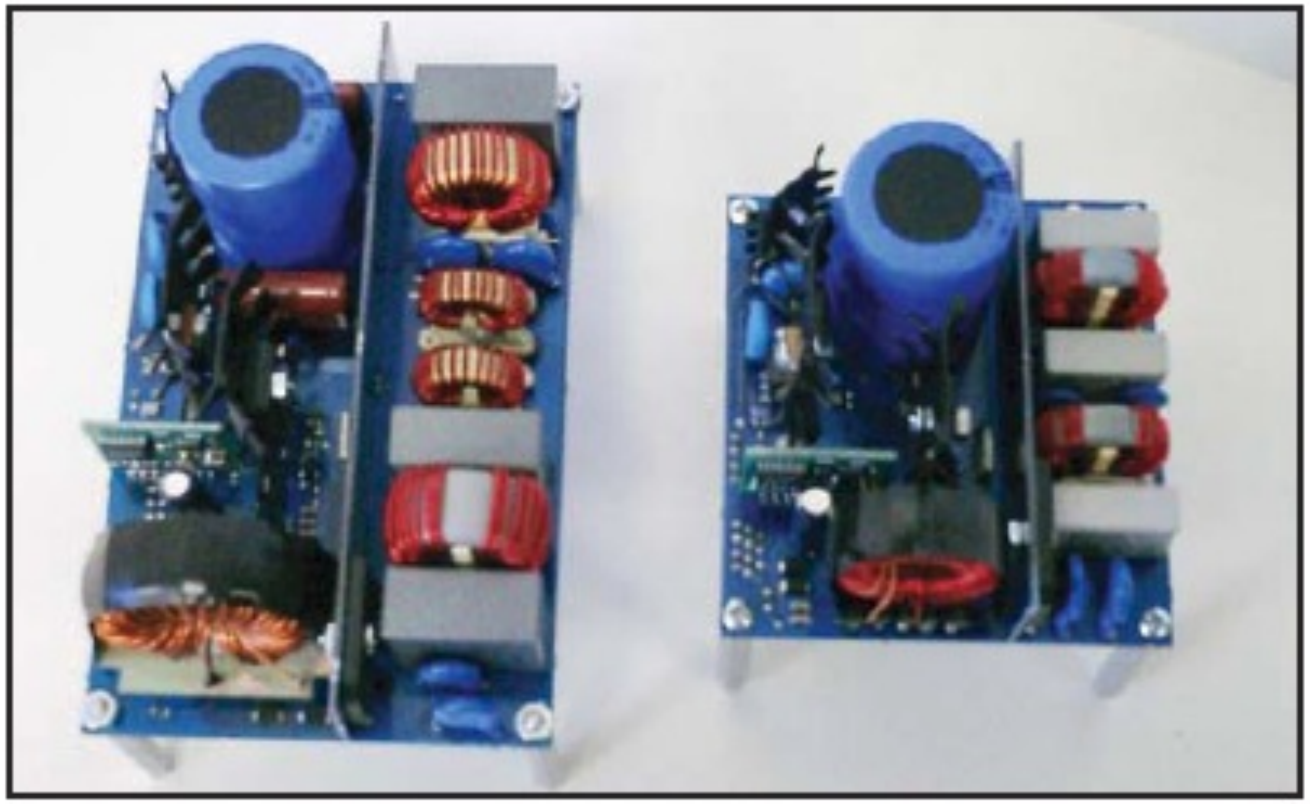


Fig. 8. *A size comparison of an 80-kHz PFC front-end built with Si rectifiers (left) and a 200-kHz PFC front-end with SiC rectifiers.*

http://www.cree.com/Products/pdf/Power_Article_1.pdf

Perdas nos Diodos

Classificação das perdas:

1. Condução;

$$P = V_{(TO)} \cdot I_{Dmed} + r_T \cdot I_{Def}^{\ 2}$$

2. Comutação:
   - Entrada em condução;

$$P_1 = 0{,}5\left(V_{FP} - V_F\right) I_o \cdot t_{rf} \cdot f$$

   - Bloqueio.

$$P_2 = Q_{rr} \cdot E \cdot f$$

Características de Diodos Comerciais

Principais características:

- Tensão de pico reversa;
- Queda de tensão direta;
- Corrente de pico;
- Corrente média;
- Corrente eficaz;
- Tempo de recuperação reversa.

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	200	V
Average Rectified Forward Current (Rated V_R, T_C = 158°C)	$I_{F(AV)}$	3.0	A
Peak Repetitive Forward Current (Rated V_R, Square Wave, 20 kHz, T_C = 158°C)	I_{FRM}	6.0	A
Non−Repetitive Peak Surge Current (Surge Applied at Rated Load Conditions Halfwave, 60 Hz)	I_{FSM}	75	A
Operating Junction and Storage Temperature Range	T_J, T_{stg}	−65 to +175	°C

MURD320

THERMAL CHARACTERISTICS

Rating	Symbol	Value	Unit
Thermal Resistance − Junction−to−Case	$R_{\theta JC}$	6	°C/W
Thermal Resistance − Junction−to−Ambient (Note 1)	$R_{\theta JA}$	80	°C/W

ELECTRICAL CHARACTERISTICS

Maximum Instantaneous Forward Voltage Drop (Note 2) (i_F = 3 Amps, T_J = 25°C) (i_F = 3 Amps, T_J = 125°C)	v_F	 0.95 0.75	Volts
Maximum Instantaneous Reverse Current (Note 2) (T_J = 25°C, Rated dc Voltage) (T_J = 125°C, Rated dc Voltage)	i_R	 5 500	μA
Maximum Reverse Recovery Time (I_F = 1 Amp, di/dt = 50 Amps/μs, V_R = 30 V, T_J = 25°C) (I_F = 0.5 Amp, i_R = 1 Amp, I_{REC} = 0.25 A, V_R = 30 V, T_J = 25°C)	t_{rr}	 35 25	ns

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Características de Diodos Comerciais

Tipos de diodos:

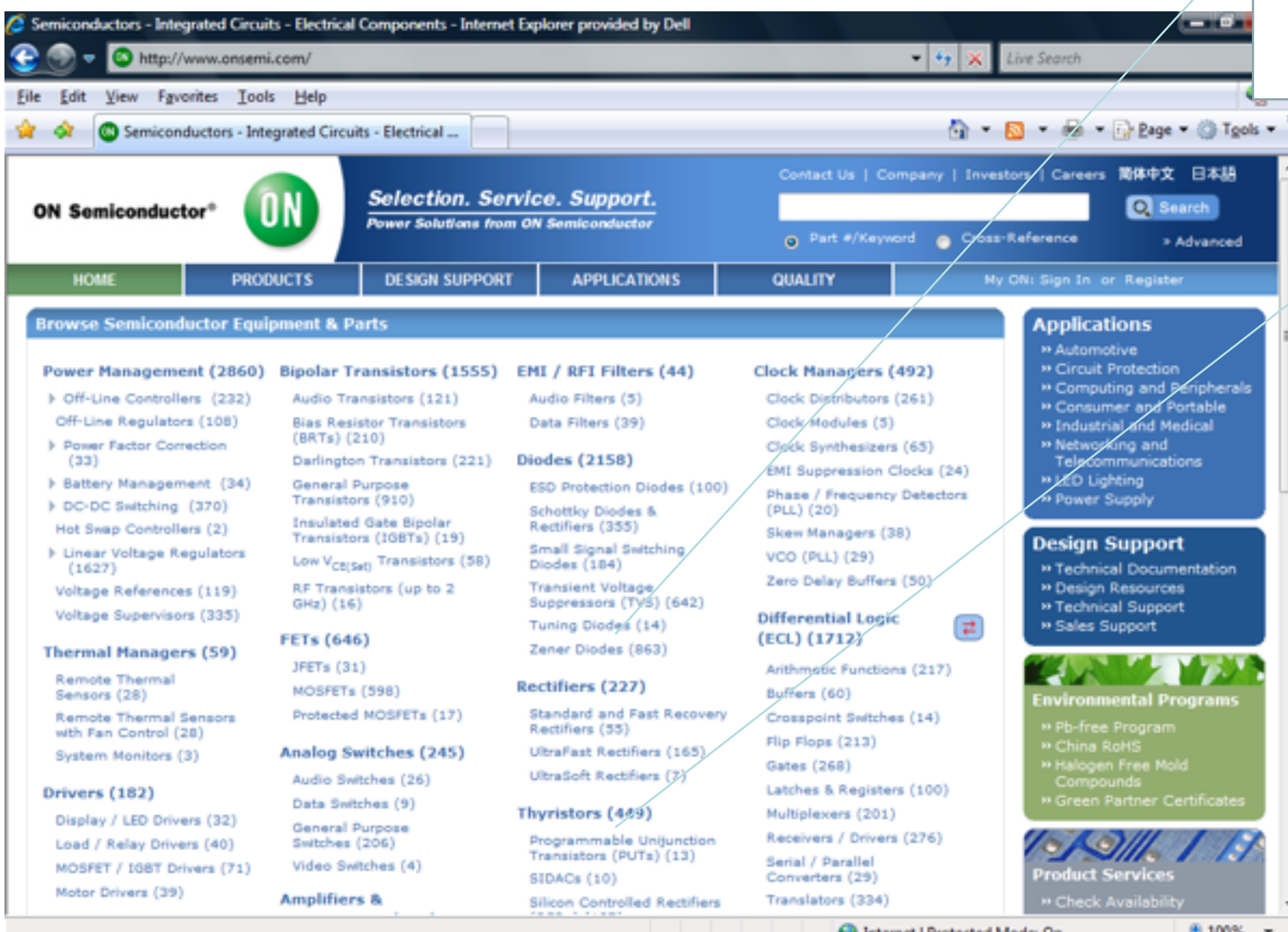
1. Standard and fast recovery;
2. Ultrafast rectifiers;
3. Ultrasoft rectifers;
4. Silicon carbide (zero recovery).

Rectifiers (227)

Standard and Fast Recovery Rectifiers (55)

UltraFast Rectifiers (165)

UltraSoft Rectifiers (7)



www.onsemi.com

Características de Diodos Comerciais

CREE

C2D20120D–Silicon Carbide Schottky Diode

ZERO RECOVERY® RECTIFIER

V_{RRM} = 1200 V
I_F = 20 A
Q_c = 122 nC

Features

- 1200-Volt Schottky Rectifier
- Zero Reverse Recovery
- Zero Forward Recovery
- High-Frequency Operation
- Temperature-Independent Switching Behavior
- Extremely Fast Swtitching
- Positive Temperature Coefficient on V_F

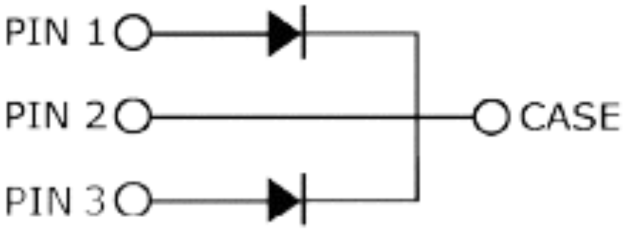
Benefits

- Replace Bipolar with Unipolar Rectifiers
- Essentially No Switching Losses
- Higher Efficiency
- Reduction of Heat Sink Requirements
- Parallel Devices Without Thermal Runaway

Package

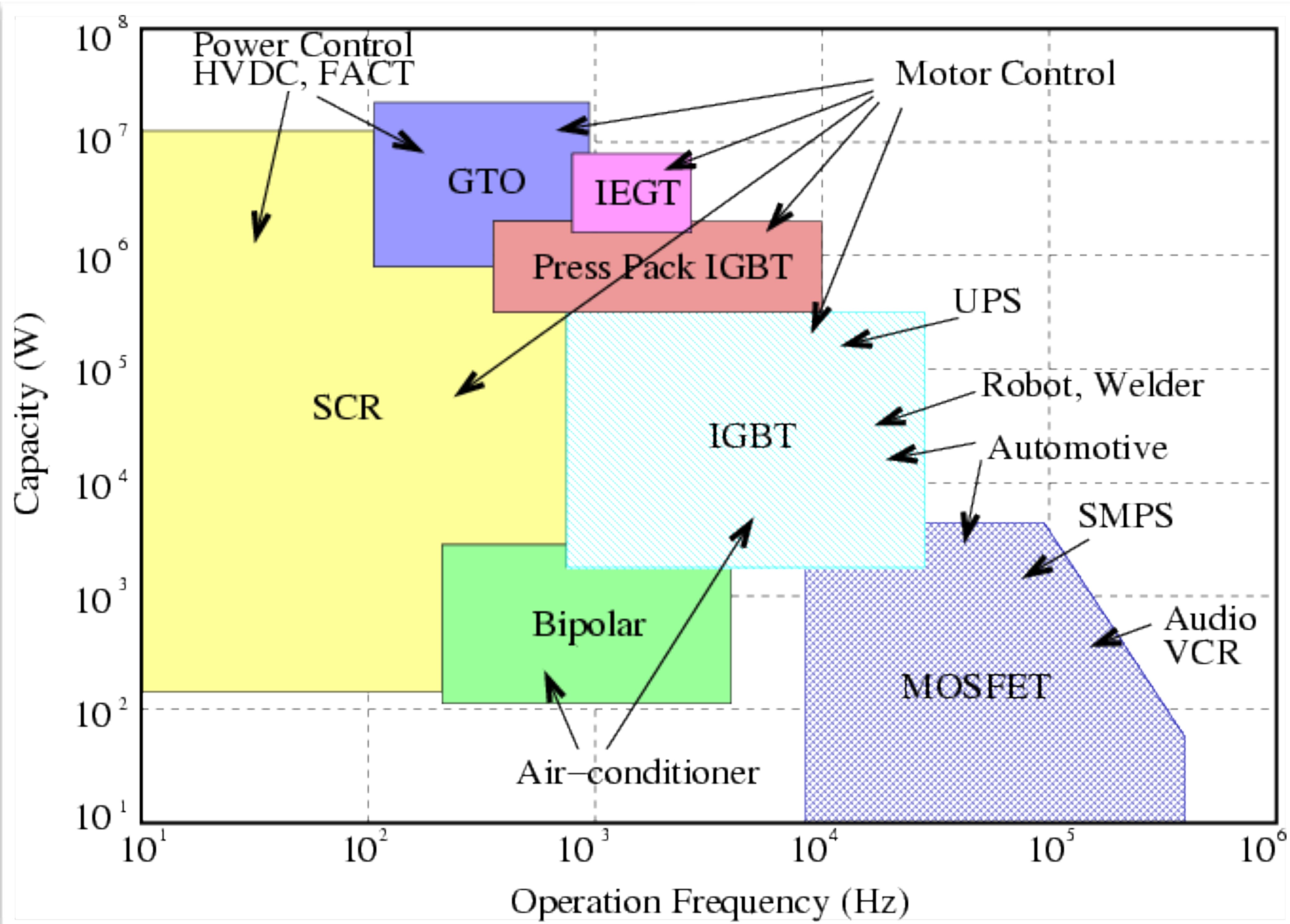
TO-247-3

www.cree.com

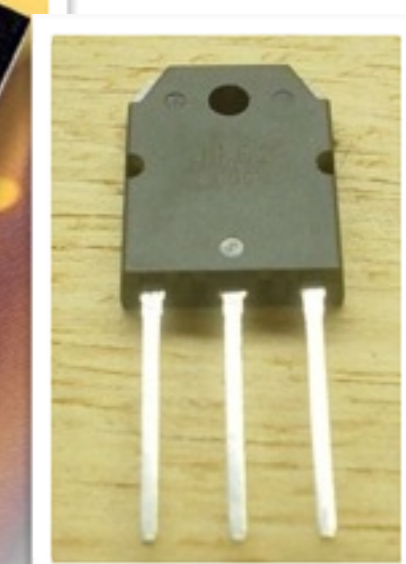


Semicondutores de Potência

Semicondutores aplicados à eletrônica de potência:

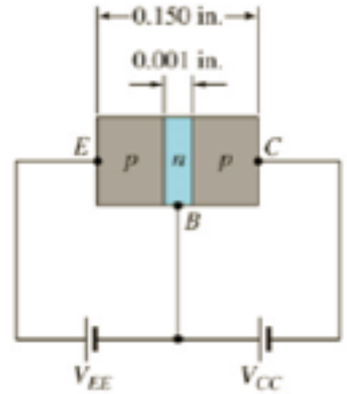


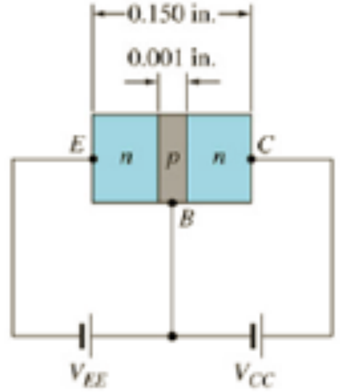
Semicondutores de Potência

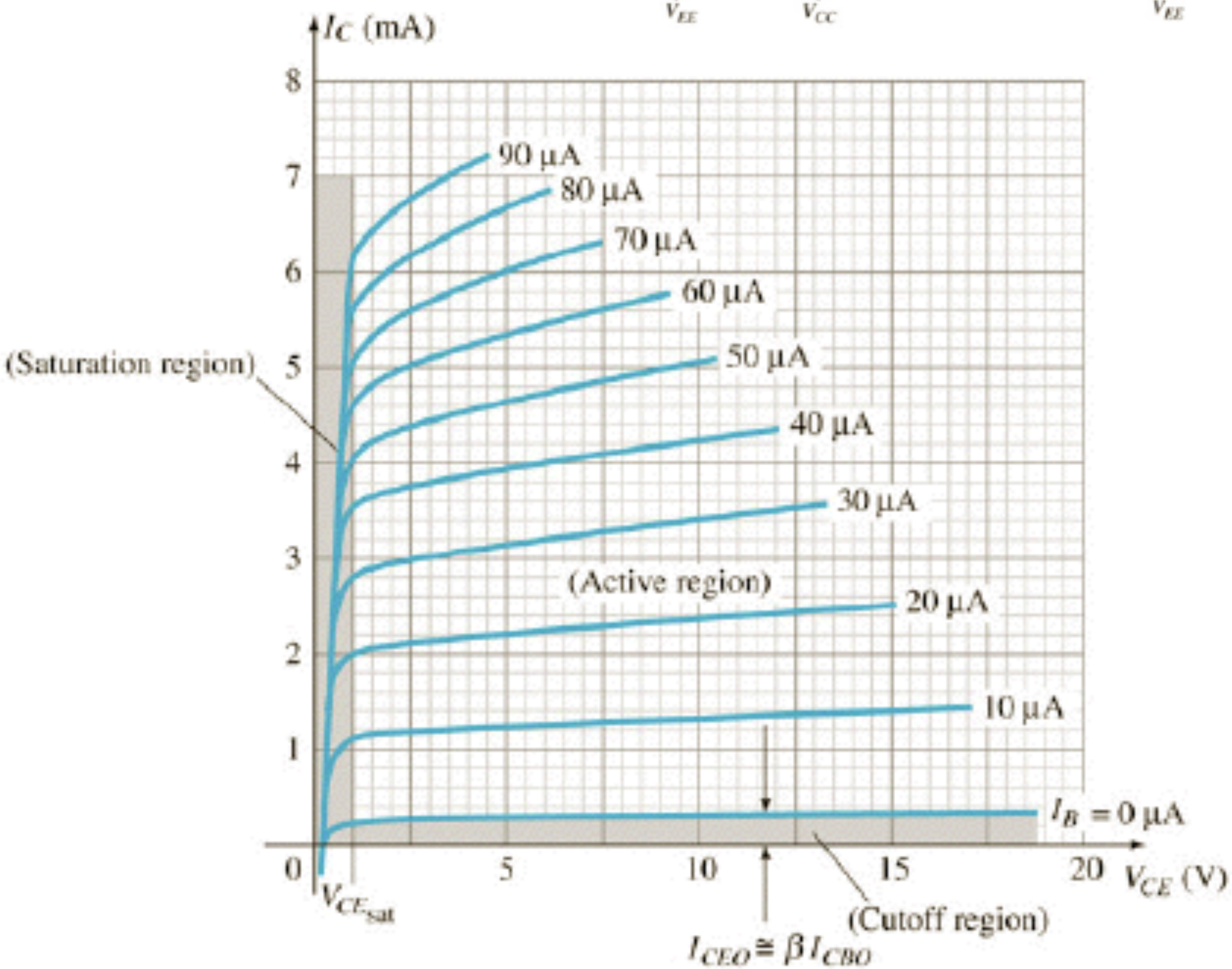


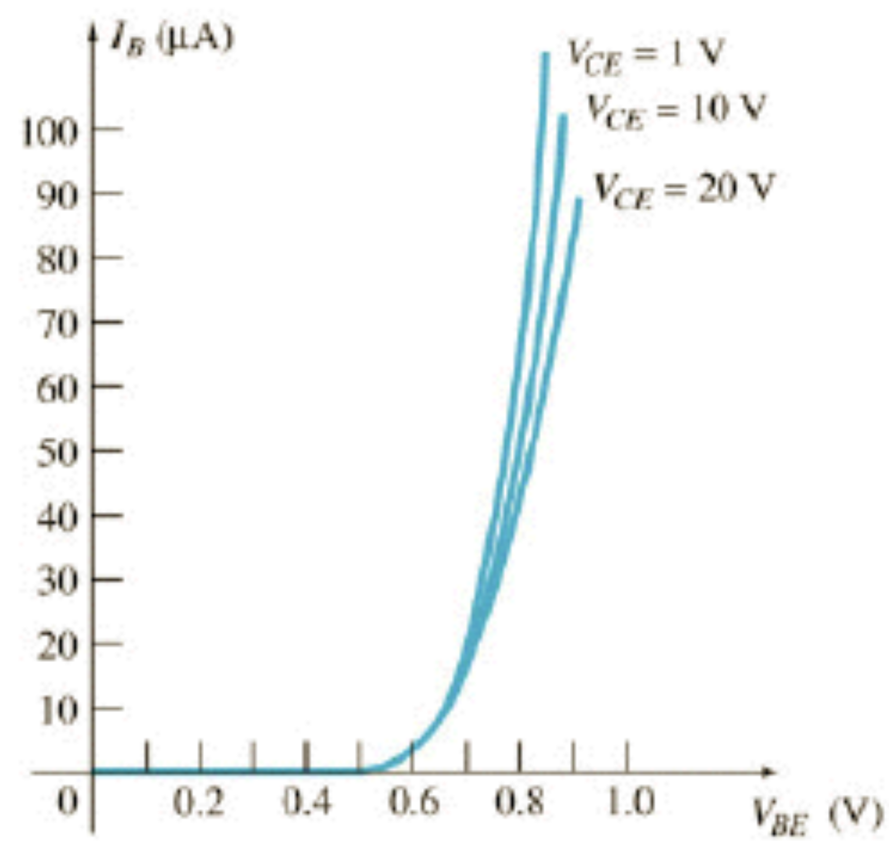
Revisão - BJT

BJT - Transistor bipolar de junção

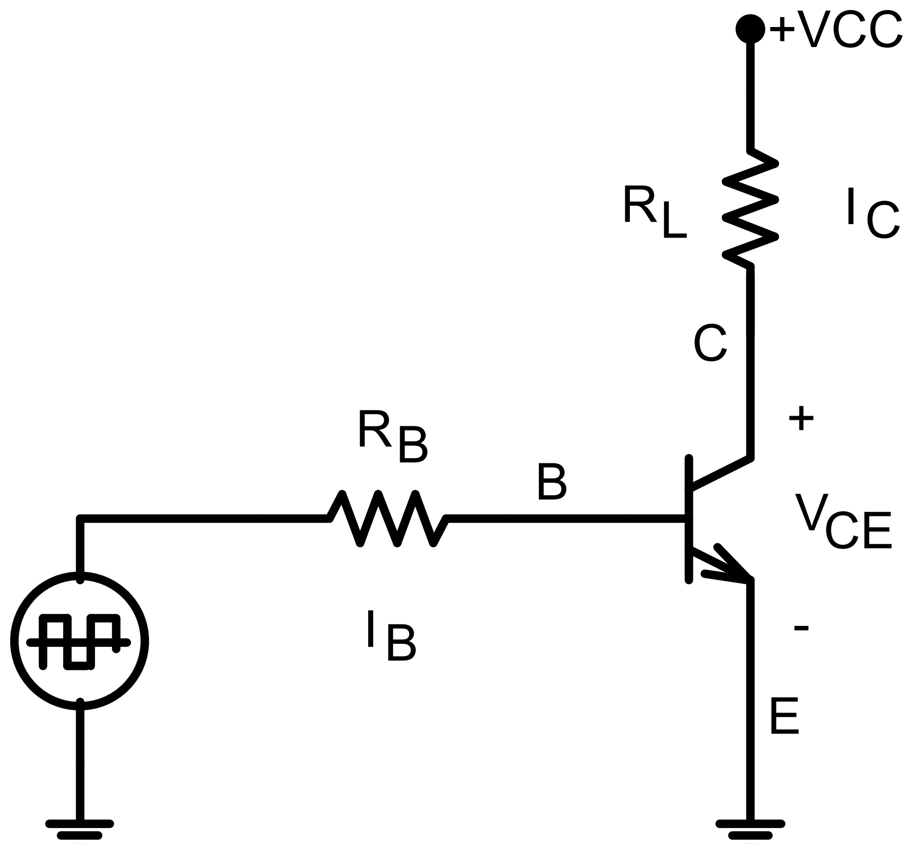






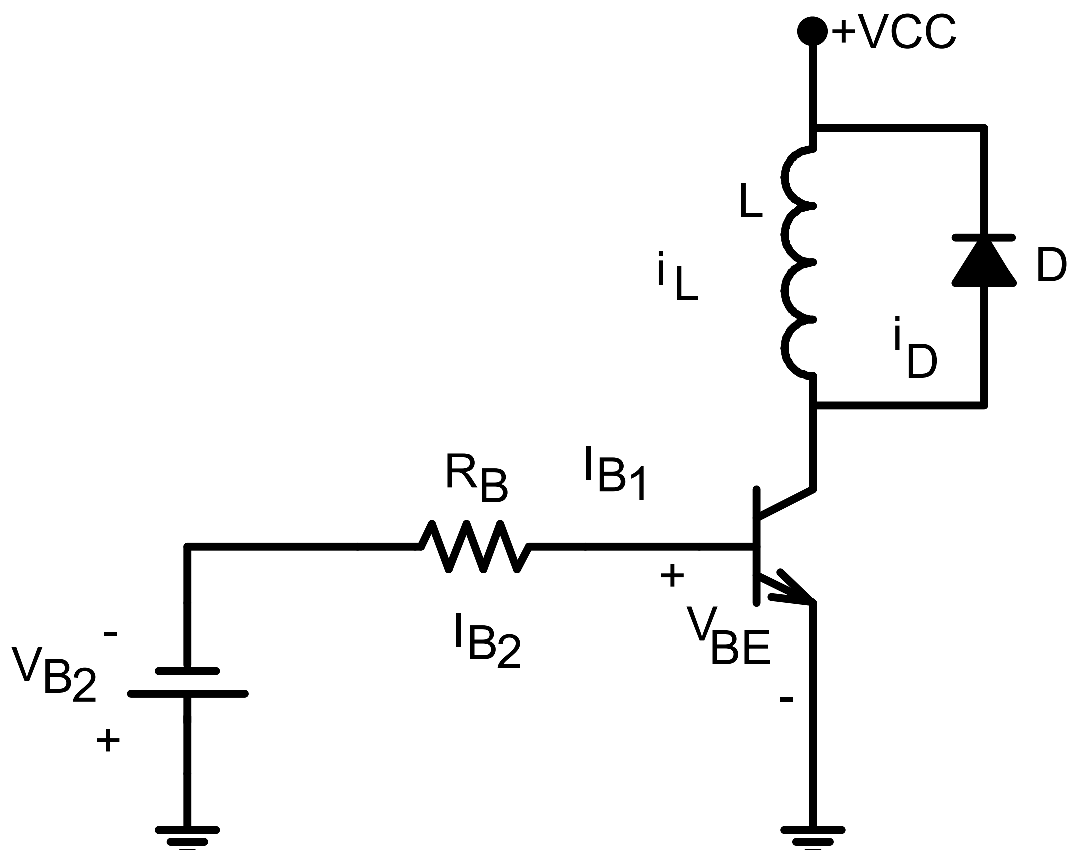


BJT



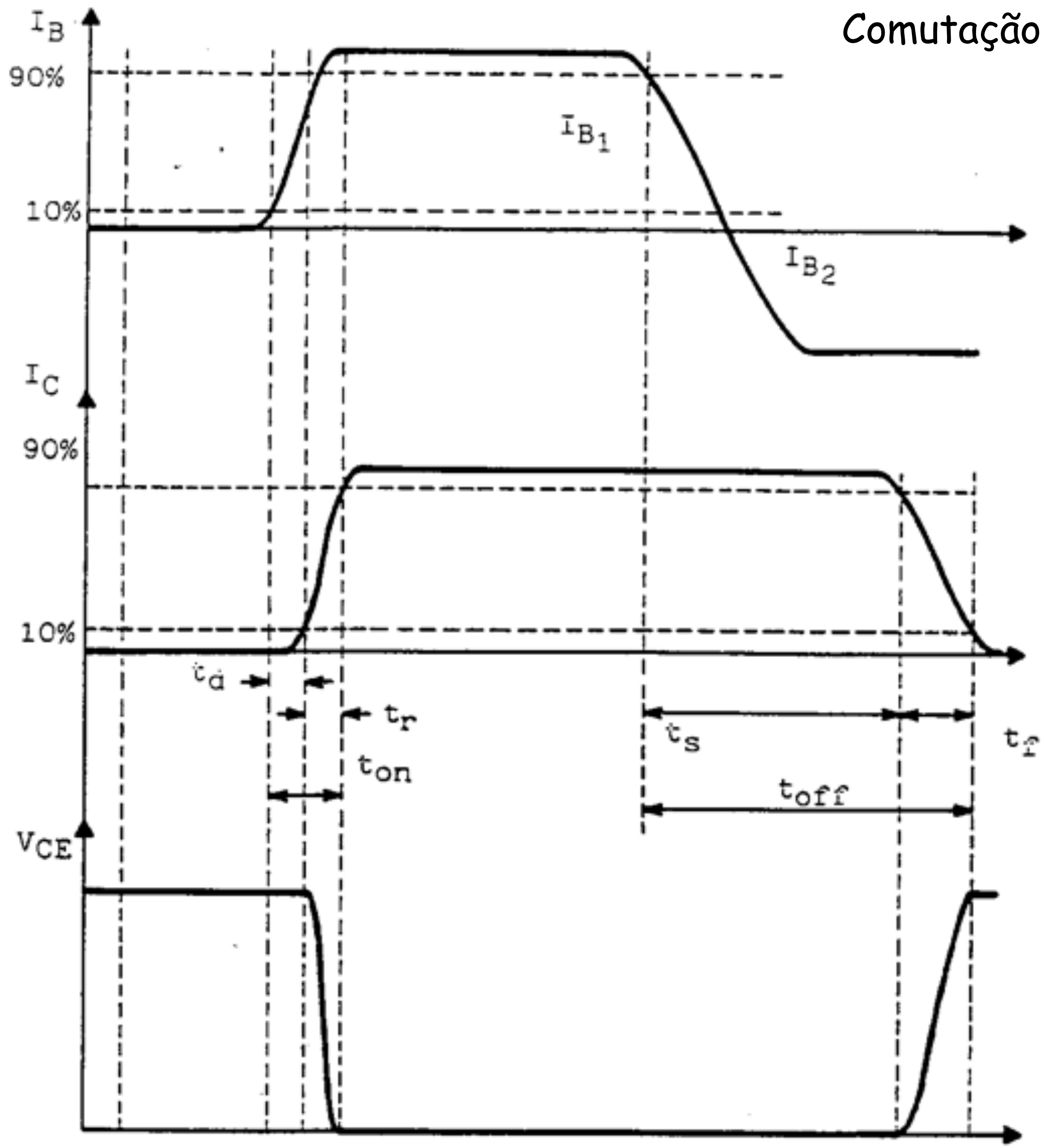
Comutação do BJT com carga resistiva

Comutação do BJT com carga indutiva



BJT

Comutação do BJT com carga resistiva



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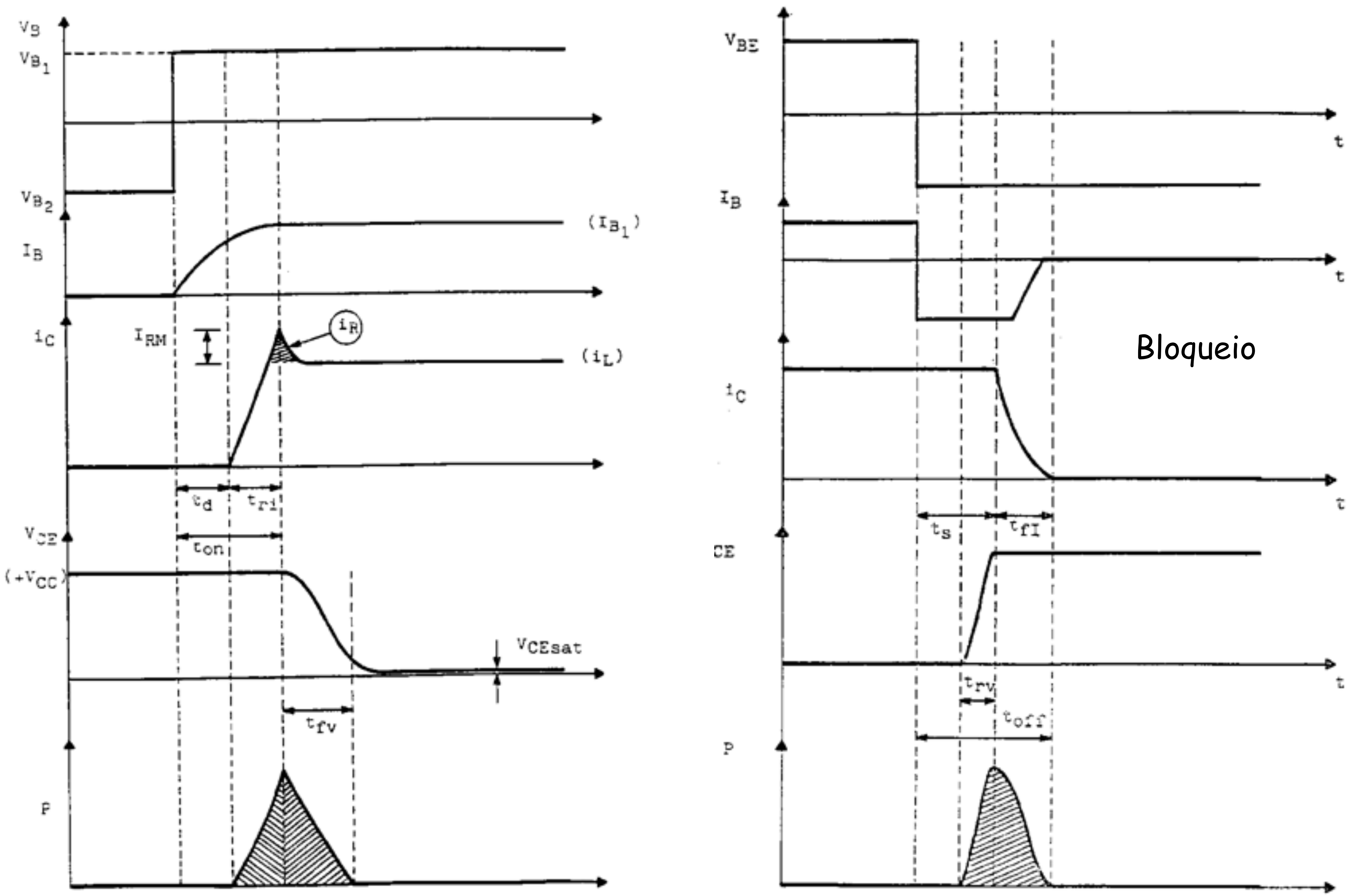
BJT

Entrada em condução



Comutação do BJT com carga indutiva

SIC BJT

The SiC BJT: Most Efficient 1200 V Power Conversion Switch Ever Made

A growing assortment of power switch technologies are on the market and in development today, including several that leverage the features of silicon carbide. Most promising among these choices are SiC bipolar junction transistors (BJTs). They offer very fast switching speed; the industry's lowest conduction losses; easy high temperature operation; very good robustness; and ease of manufacturing. Working in conjunction with a properly designed gate driver, SiC BJTs also offer safe operation with high ruggedness and reliability.

SiC BJT vs Si IGBT

	V	I	V_{CE}	E_{ON}	E_{OFF}
Si IGBT	1200	40	3	2500	1800
SiC BJT	1200	40	1.6	1000	600
Improvement (lowered by)			47%	60%	67%

SiC BJT Features

Lowest Losses on the Market

- Lowest conduction losses (R_{ON} <2.2 mΩcm² @ RT)
- Very low switching losses
- Lowest total losses; including driver losses
- High gain; SiC BJT DC current gain >70

Fast Switching

- Approximately 20 ns for turn-on and turn-off
- Switching behavior is not temperature dependent
- No current tailing for SiC BJT

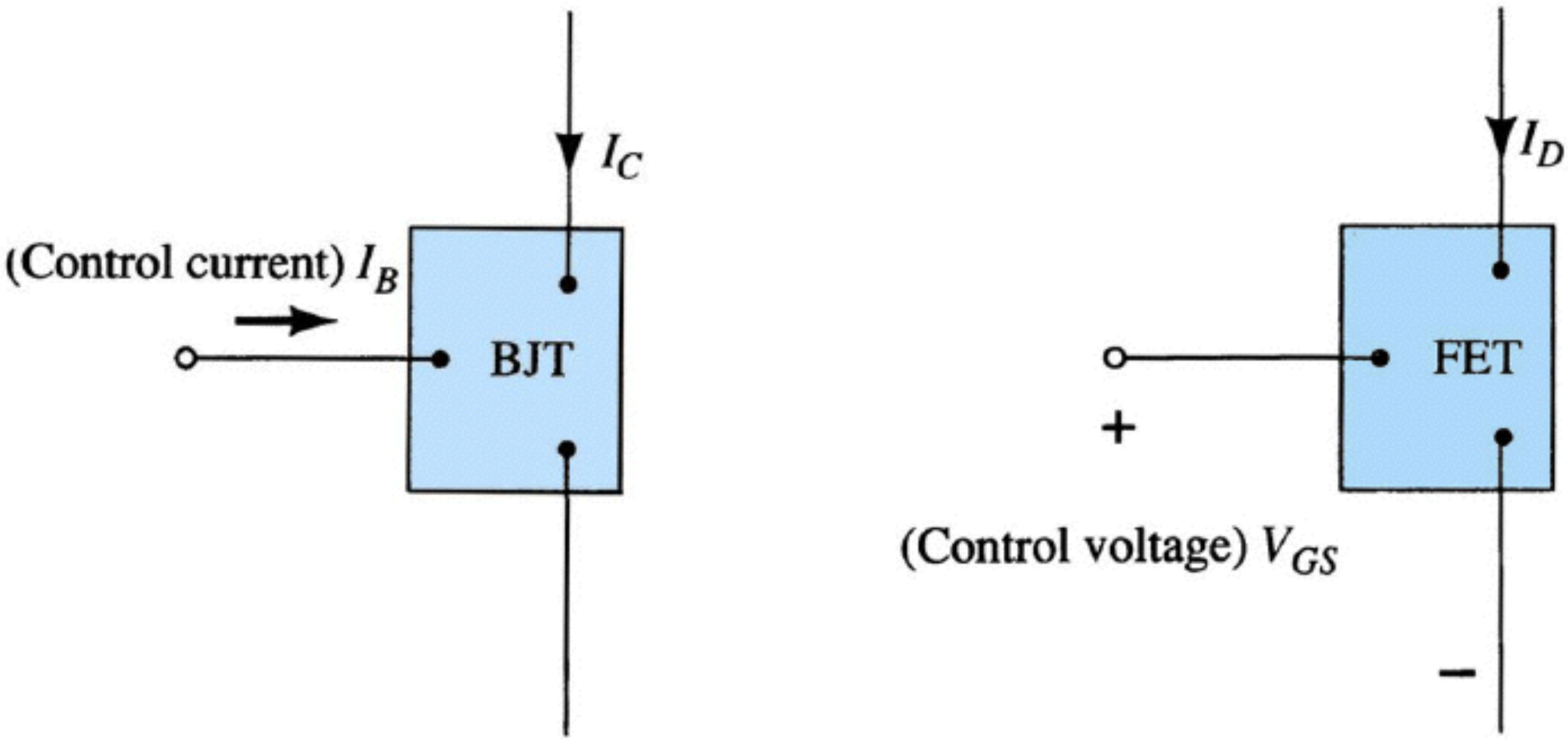
Robust and Reliable

- Normally OFF device
- Highest rated operating temperature; T_J = 175°C
- Positive temperature coefficient (R_{ON}); Easy paralleling
- No secondary breakdown for SiC BJT
- No SiO_2 gate oxide reliability issue
- Short circuit resistant
- Low leakage current

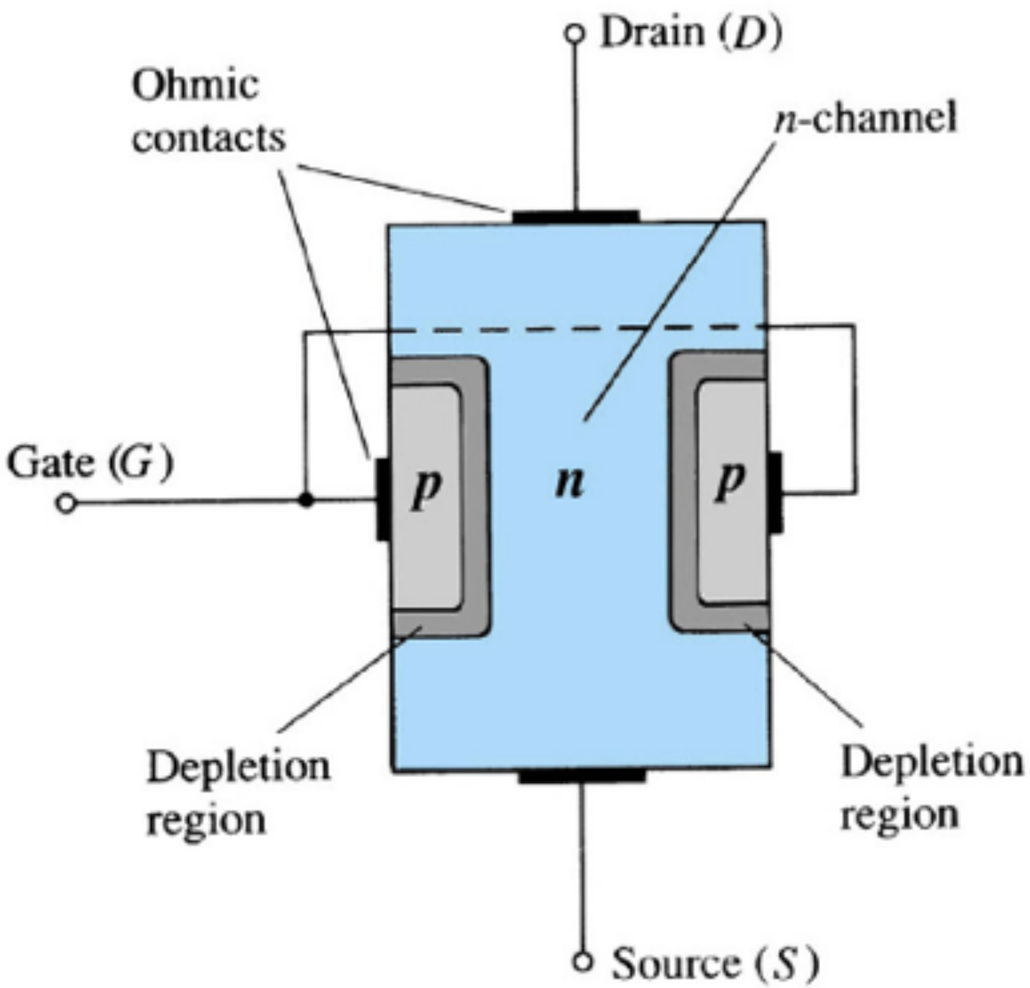
www.fairchildsemi.com

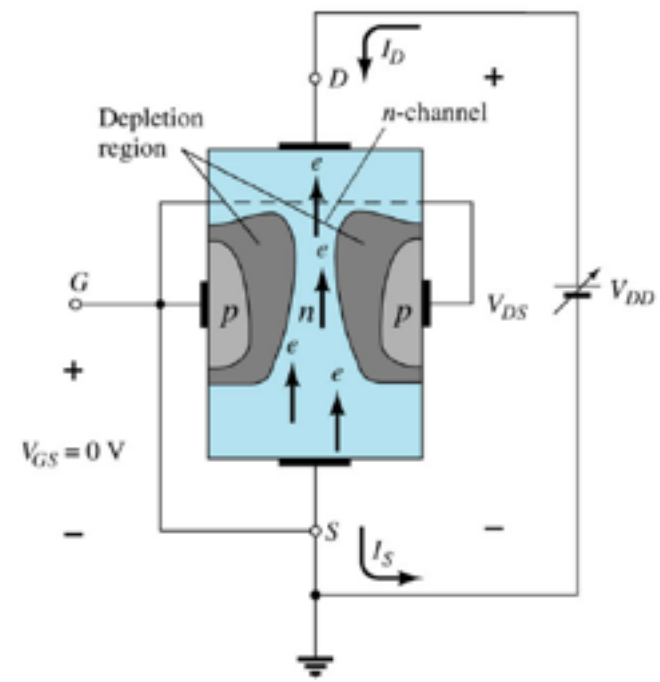
BJT x FET

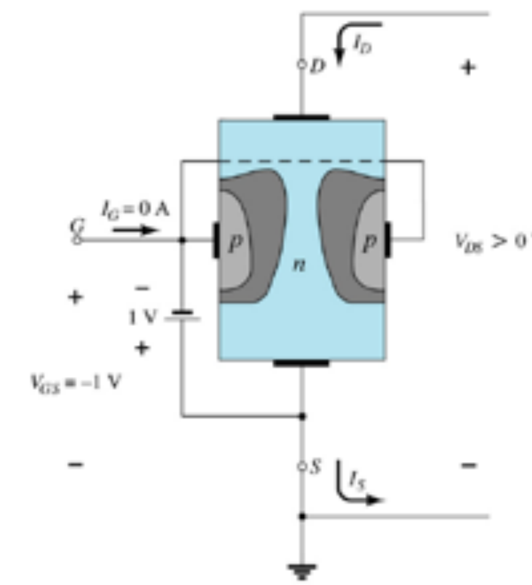
FET - Transistor de efeito de campo

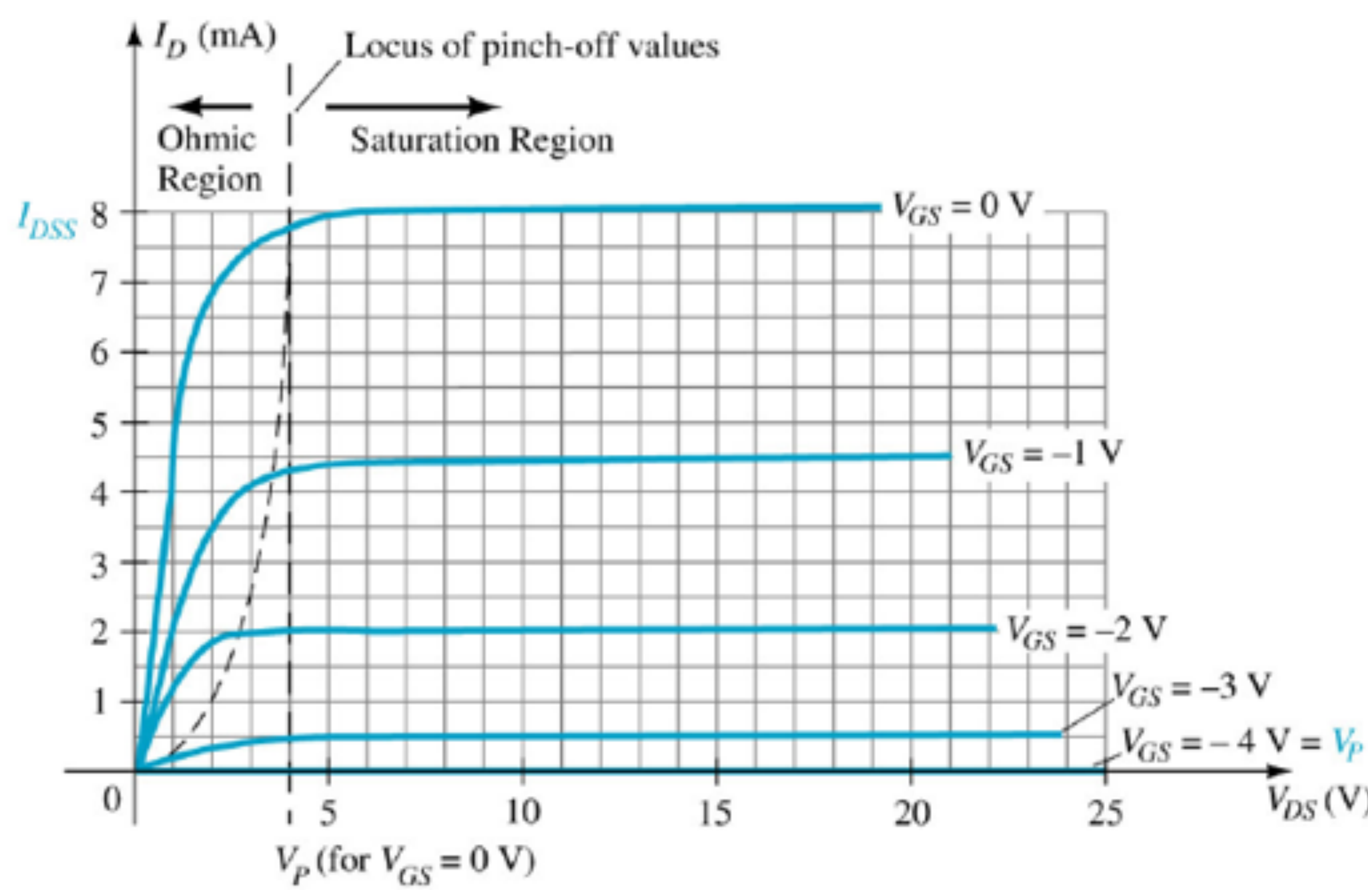


FET









JFET: Operação básica

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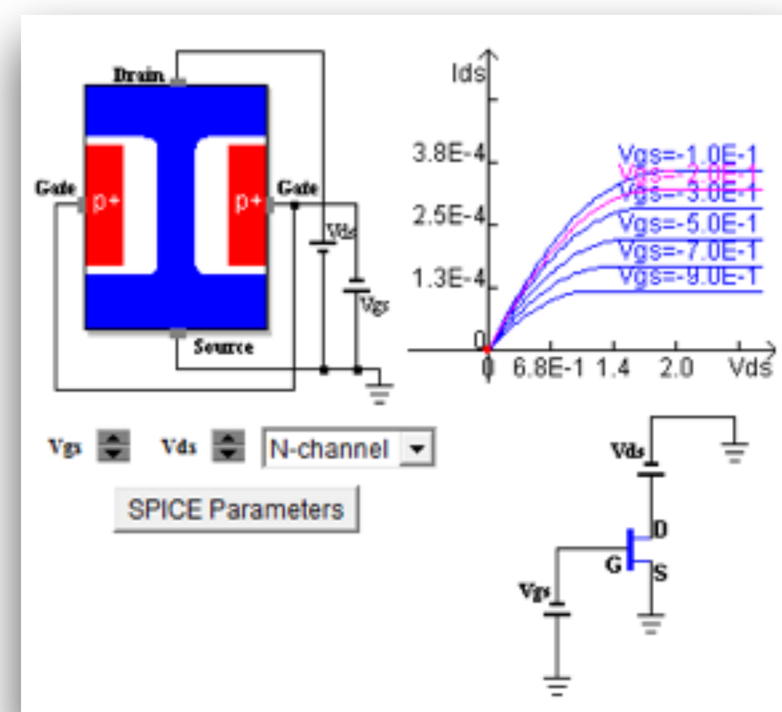
FET

http://jas.eng.buffalo.edu/



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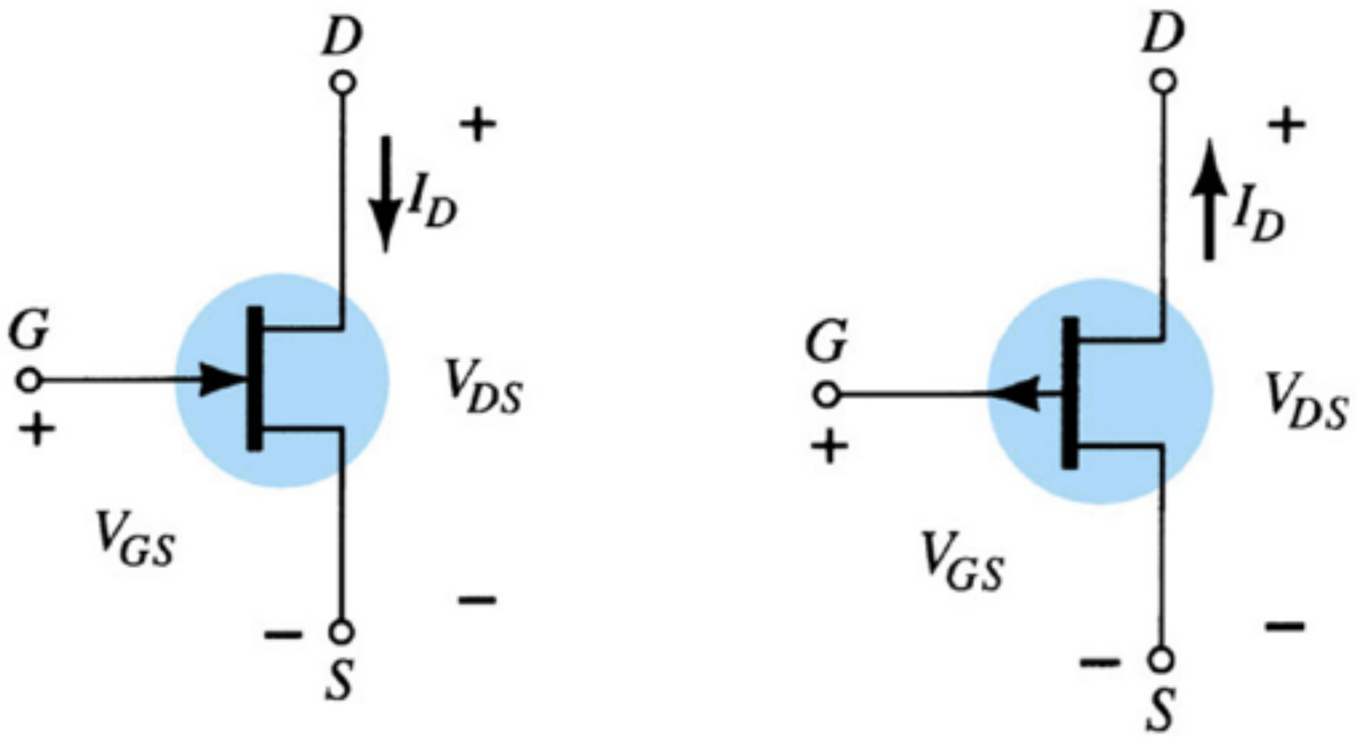
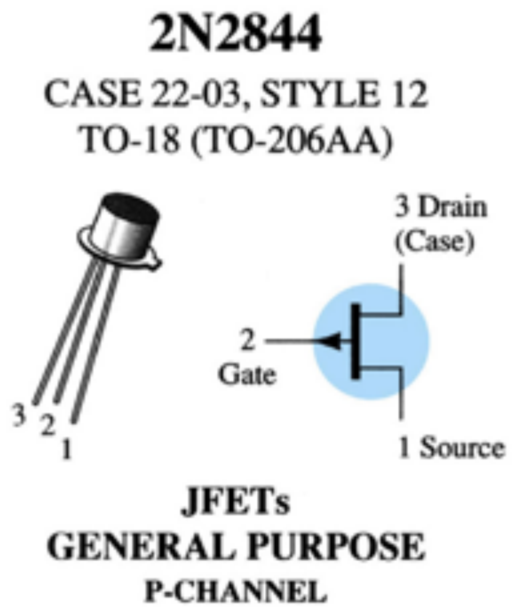
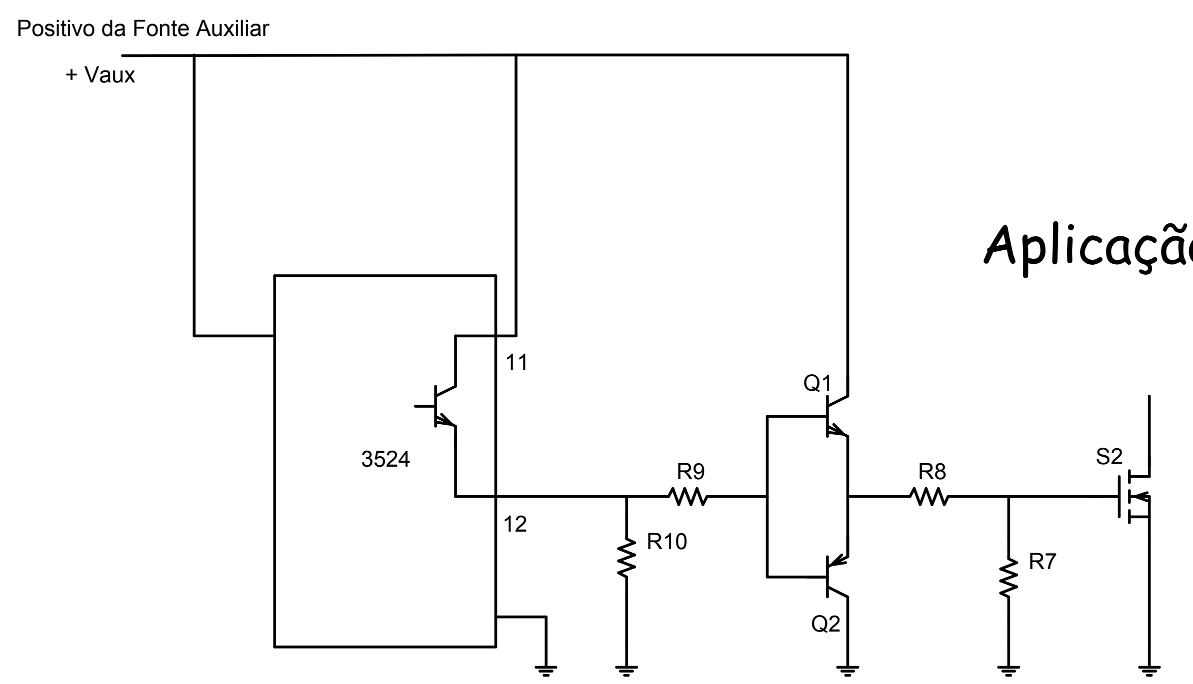
FET



JFET canal n e canal p

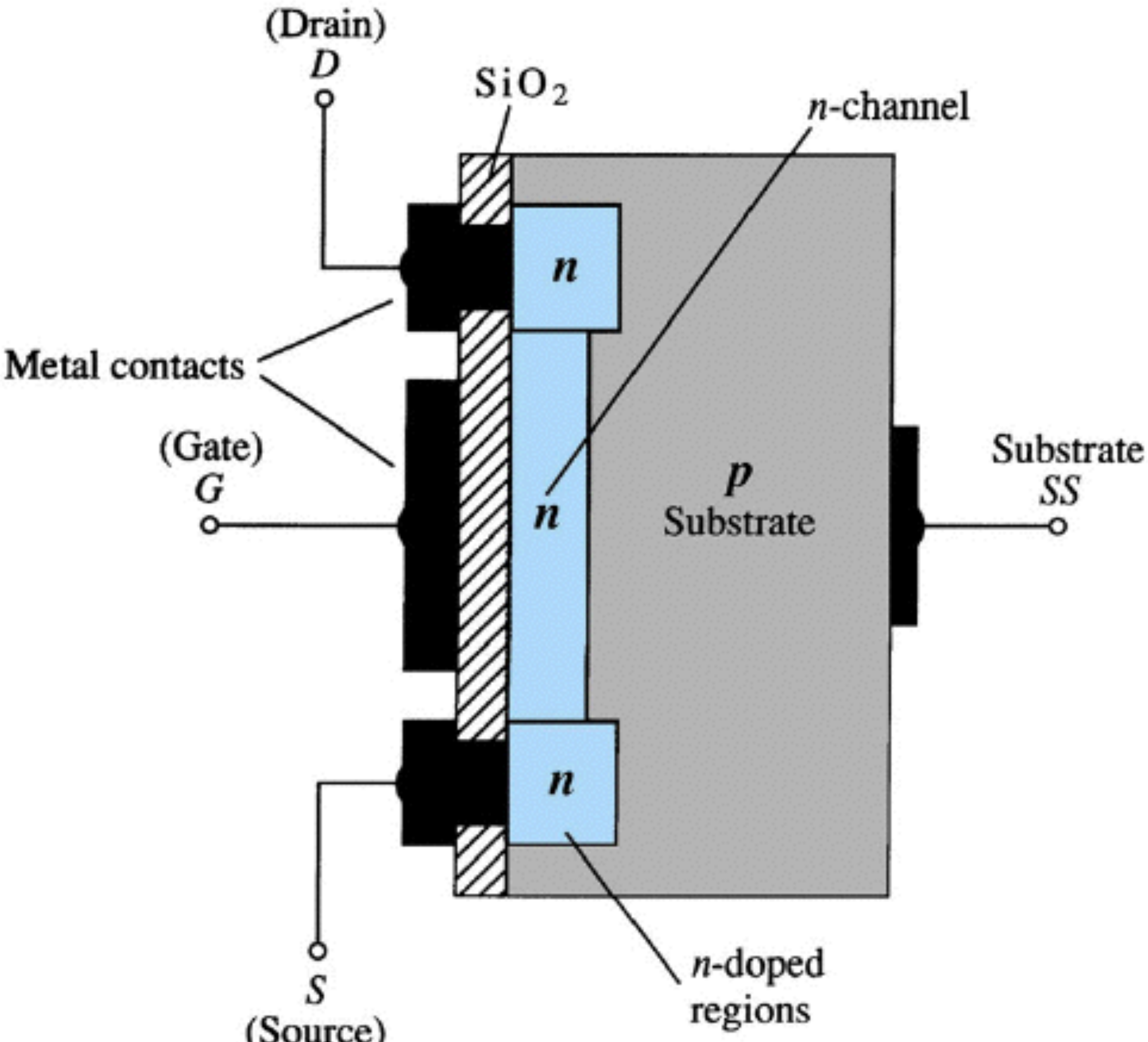




Aplicação do JFET

MOSFET

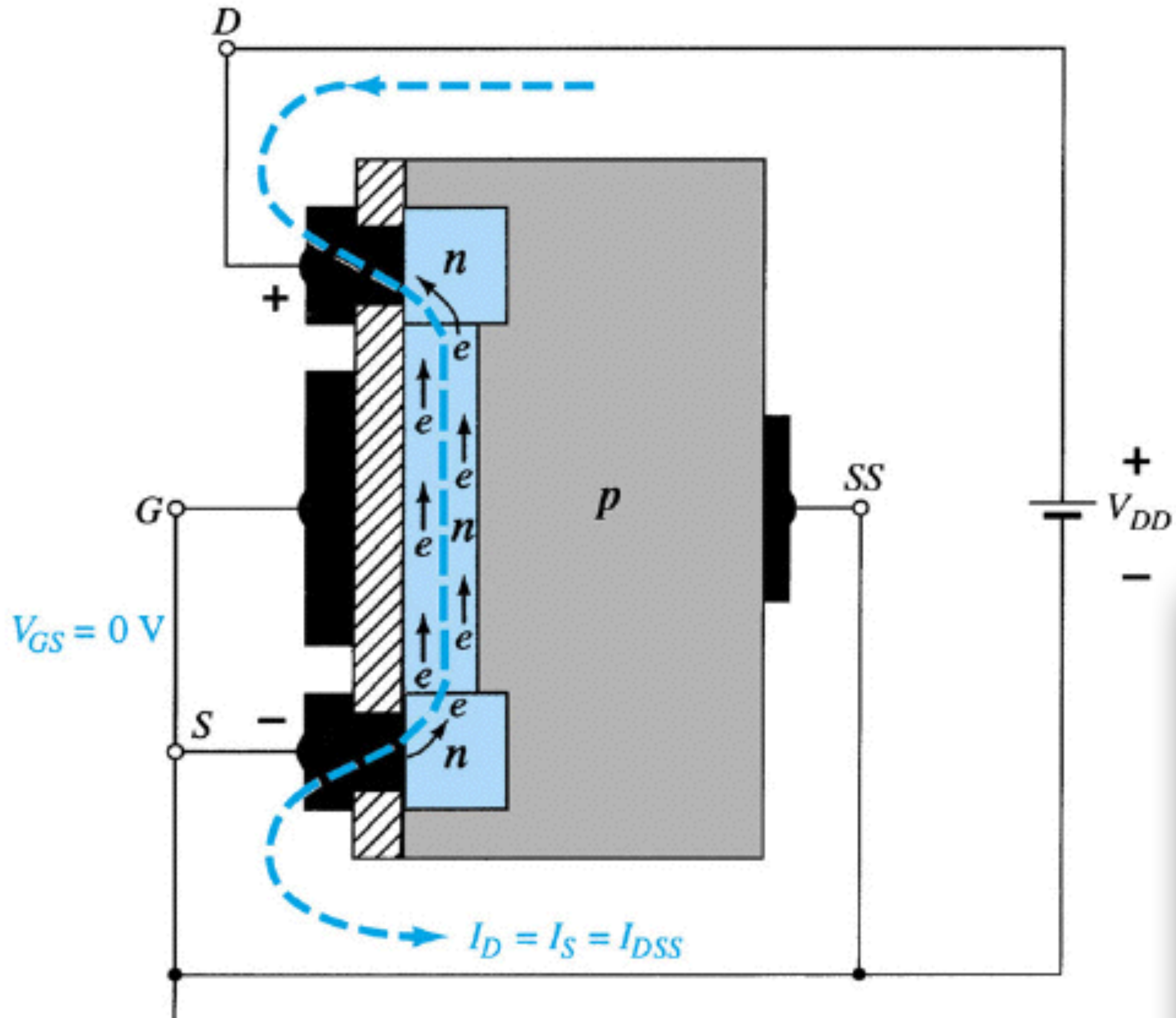
MOSFET – Metal Oxide Semiconductor Field Effect Transistor



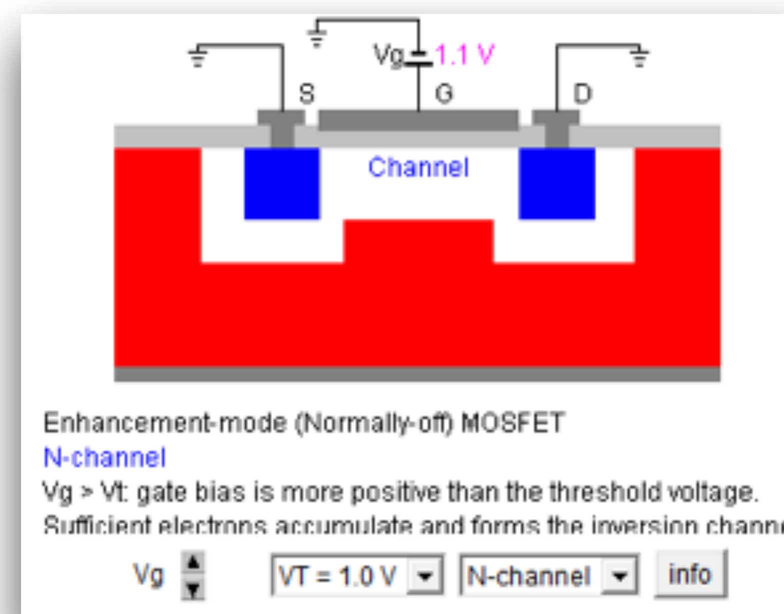
MOSFET tipo Depleção

MOSFET

MOSFET tipo Depleção



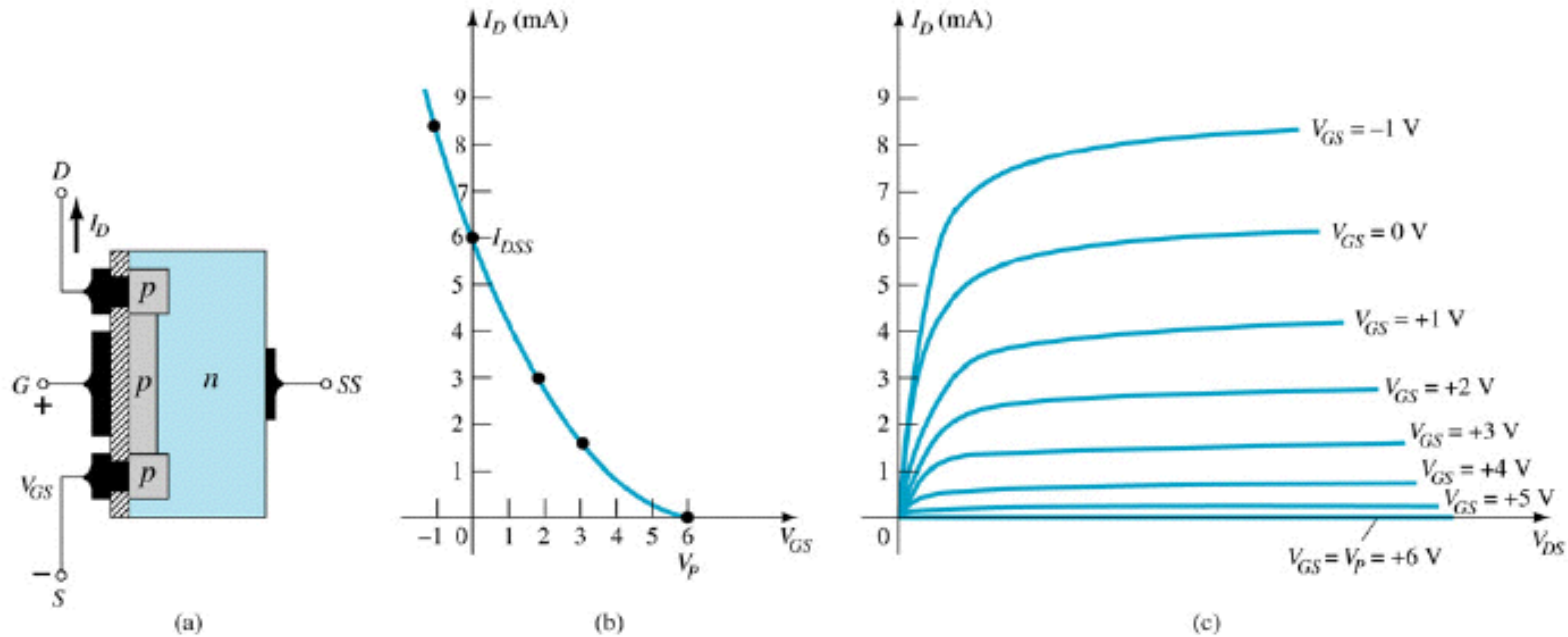
MOSFET: Operação básica.



http://jas.eng.buffalo.edu/

MOSFET

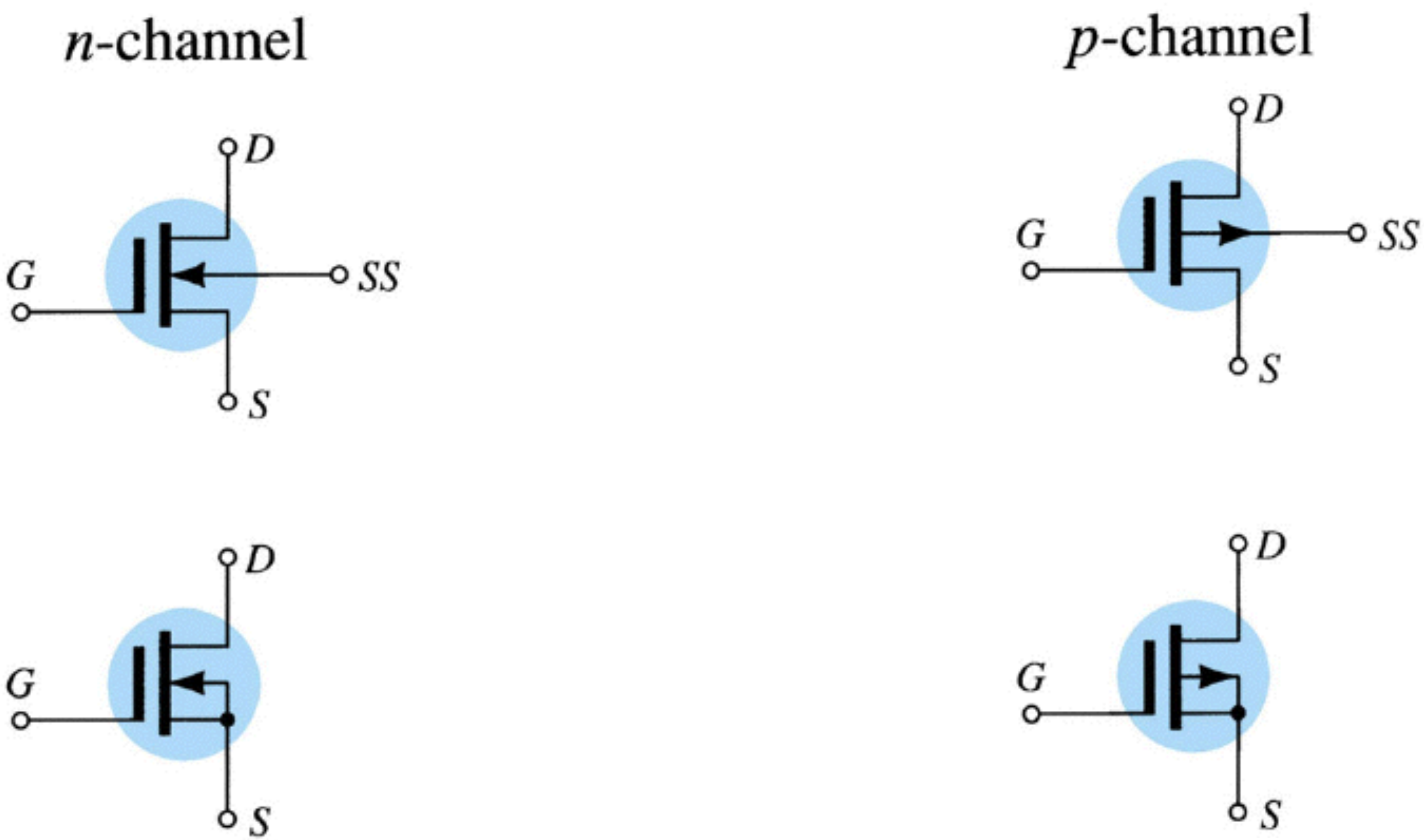
MOSFET tipo Depleção



MOSFET: Operação básica.

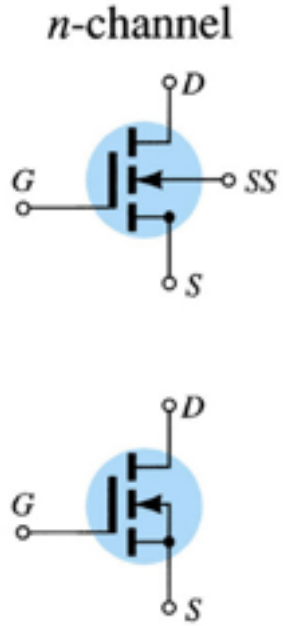
MOSFET

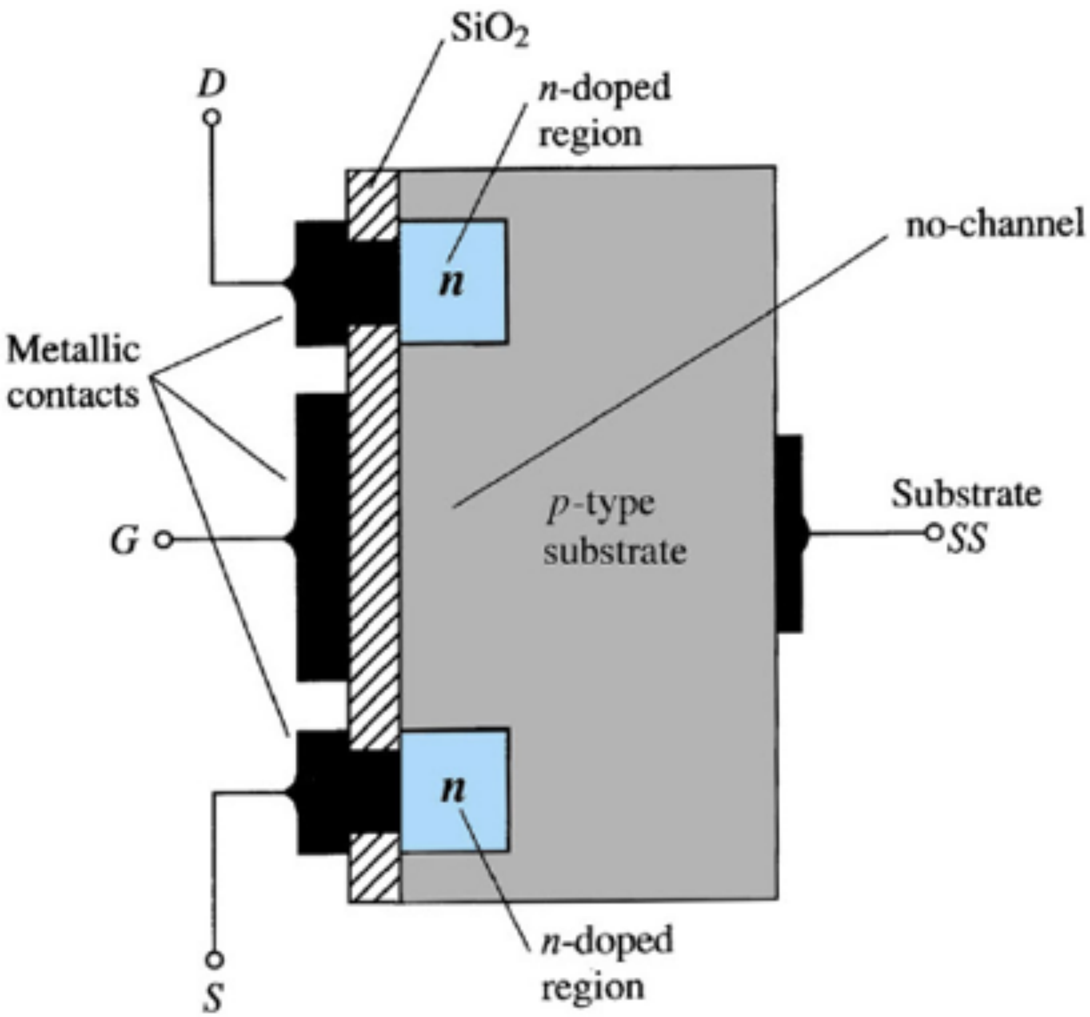
MOSFET tipo Depleção

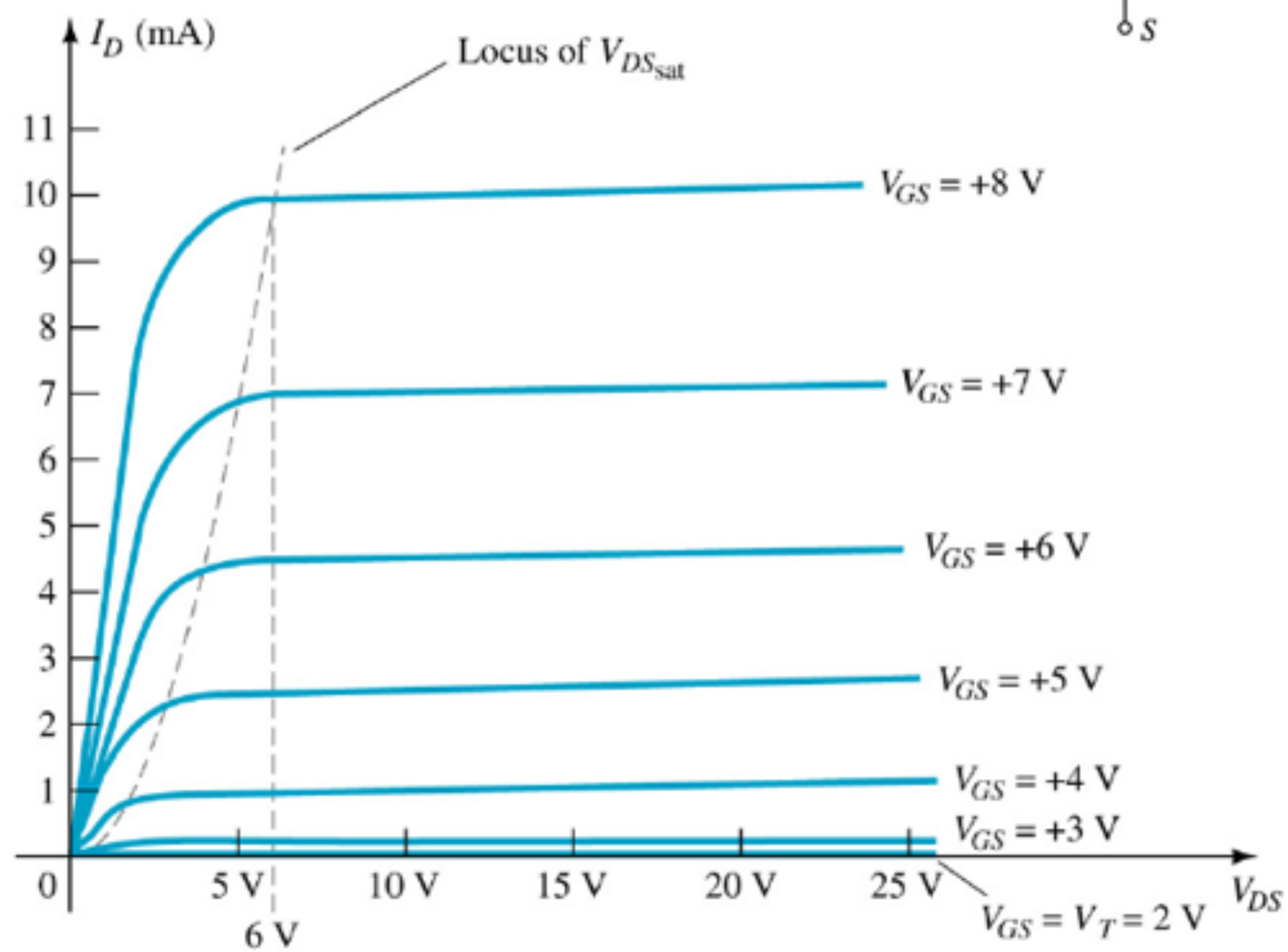


MOSFET

MOSFET tipo Intensificação



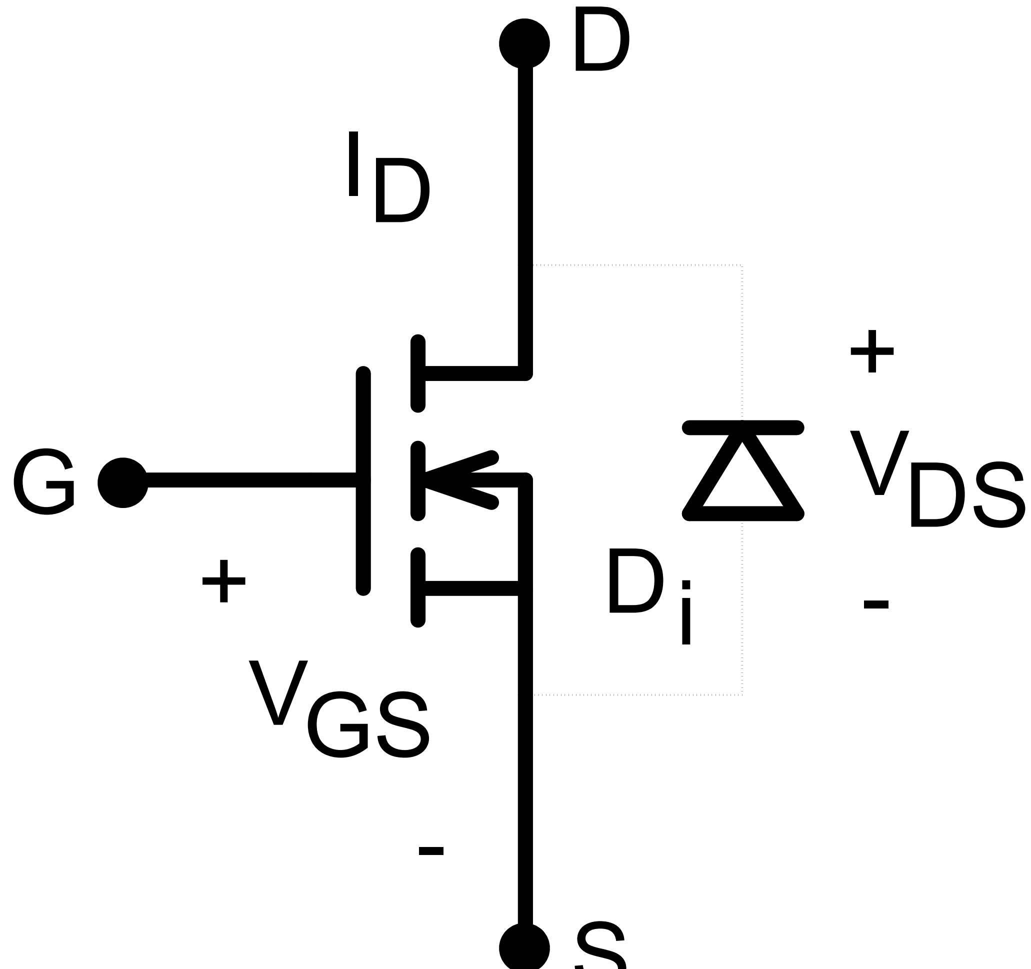


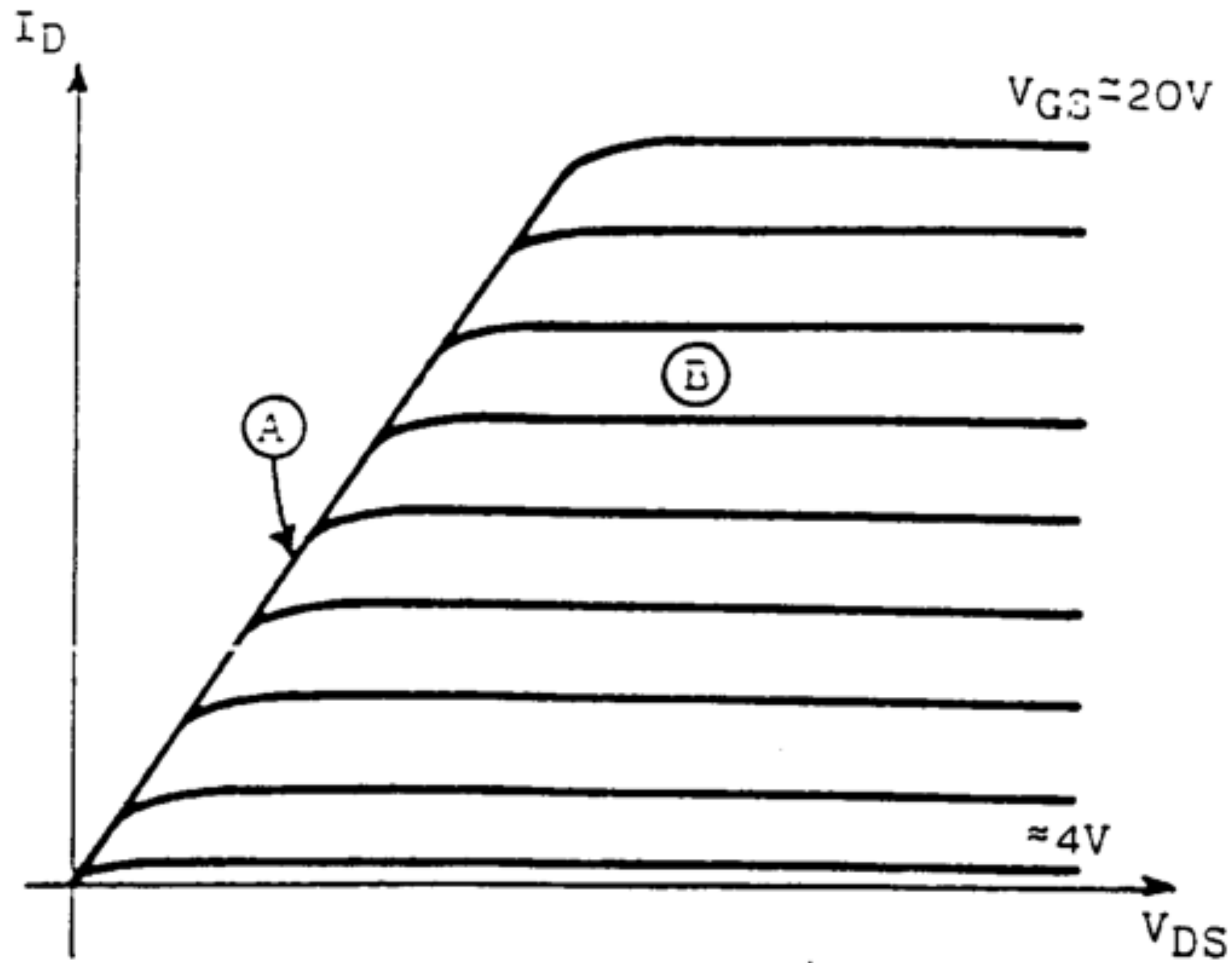


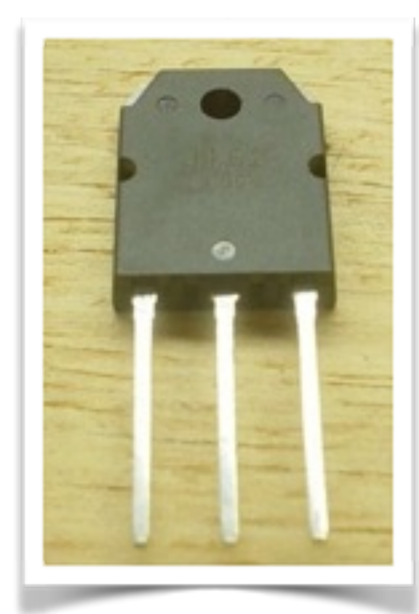
Canal n

MOSFET

MOSFET de Potência

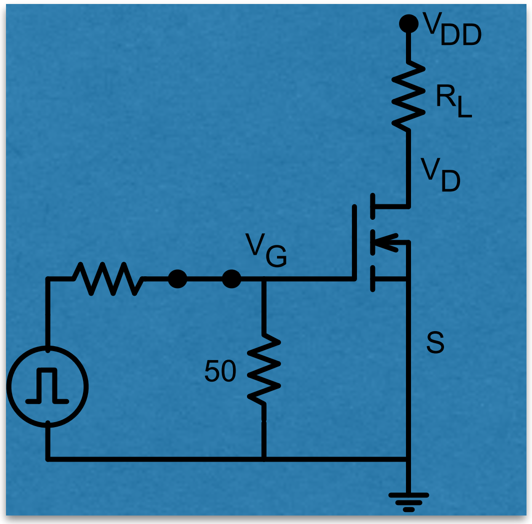


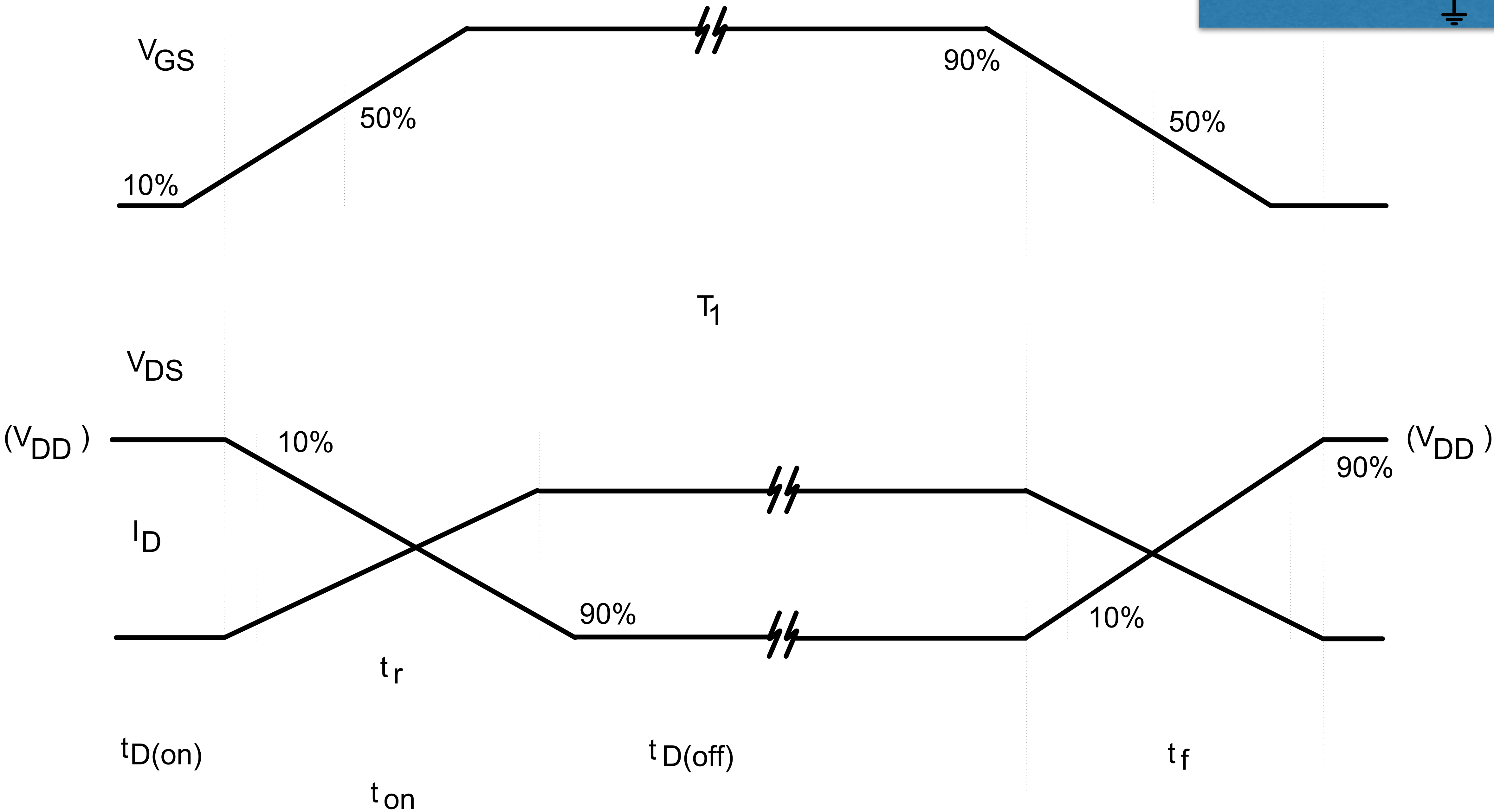




MOSFET

MOSFET de Potência

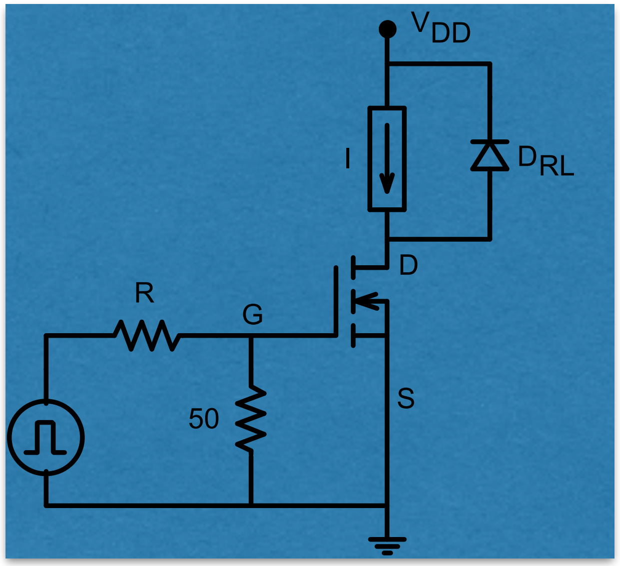


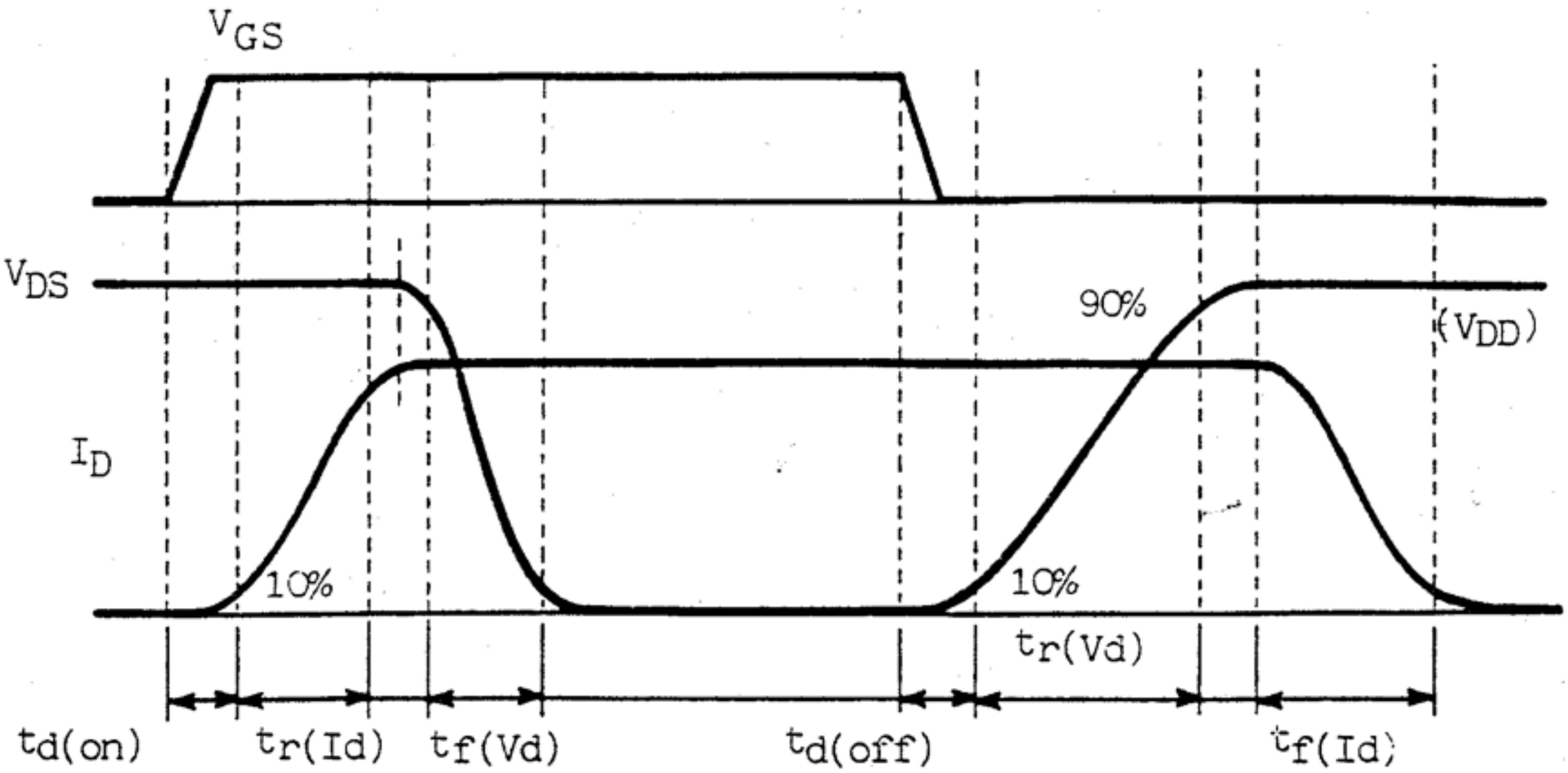


Comutação do MOSFET com carga resistiva

MOSFET

MOSFET de Potência





Comutação do MOSFET com carga indutiva

MOSFET

Classificação das perdas:

1. Condução;

$$P_{cond} = \frac{t_{on}}{T} \cdot r_{ds(on)} \cdot i_{d(on)}{}^{2}$$

2. Comutação:
   - Entrada em condução e bloqueio;

   - Onde:

$$t_f \cong t_{on}$$

$$t_r \cong t_{off}$$

MOSFET

Dados de catalogo:

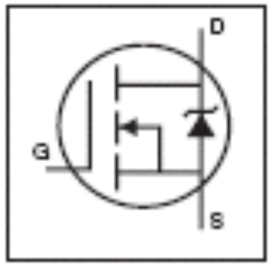
PD - 94459A

International Rectifier

IRFP150V

HEXFET® Power MOSFET

- Advanced Process Technology
- Ultra Low On-Resistance
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated



$V_{DSS} = 100V$

$R_{DS(on)} = 24m\Omega$

$I_D = 47A$

Description

Advanced HEXFET® Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-247 package is preferred for commercial-industrial applications where higher power levels preclude the use of TO-220 devices. The TO-247 is similar but superior to the earlier TO-218 packcage because of its isolated mounting hole.

TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ $T_C = 25°C$	Continuous Drain Current, V_{GS} @ 10V	46	A
I_D @ $T_C = 100°C$	Continuous Drain Current, V_{GS} @ 10V	32	
I_{DM}	Pulsed Drain Current ①	230	
P_D @ $T_C = 25°C$	Power Dissipation	140	W
	Linear Derating Factor	0.91	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
I_{AR}	Avalanche Current①	28	A
E_{AR}	Repetitive Avalanche Energy①	20	mJ
dv/dt	Peak Diode Recovery dv/dt ③	5.8	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 srew	10 lbf•in (1.1N•m)	

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	1.1	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.24	—	
$R_{\theta JA}$	Junction-to-Ambient	—	40	

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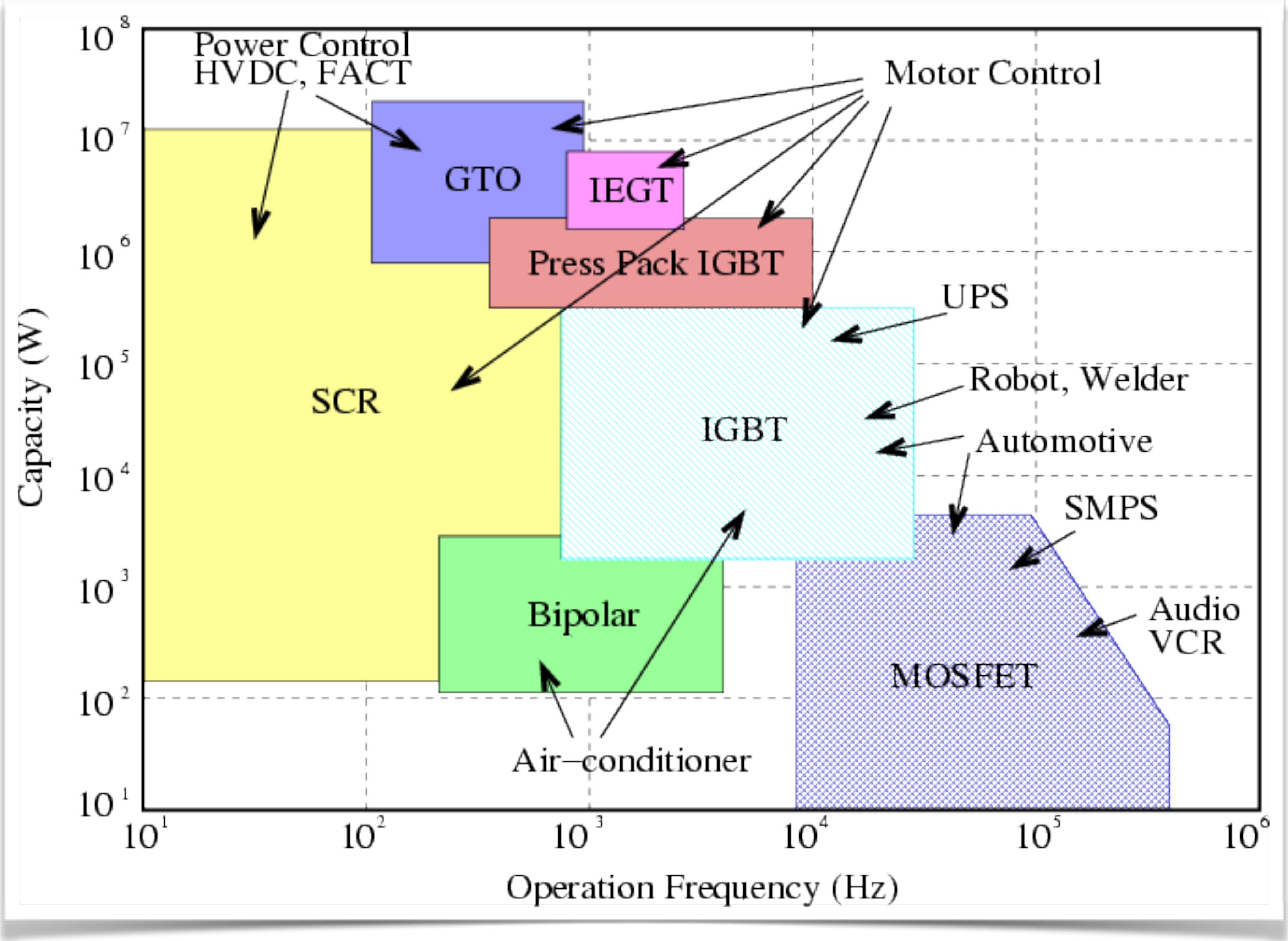
03/03/03

MOSFET

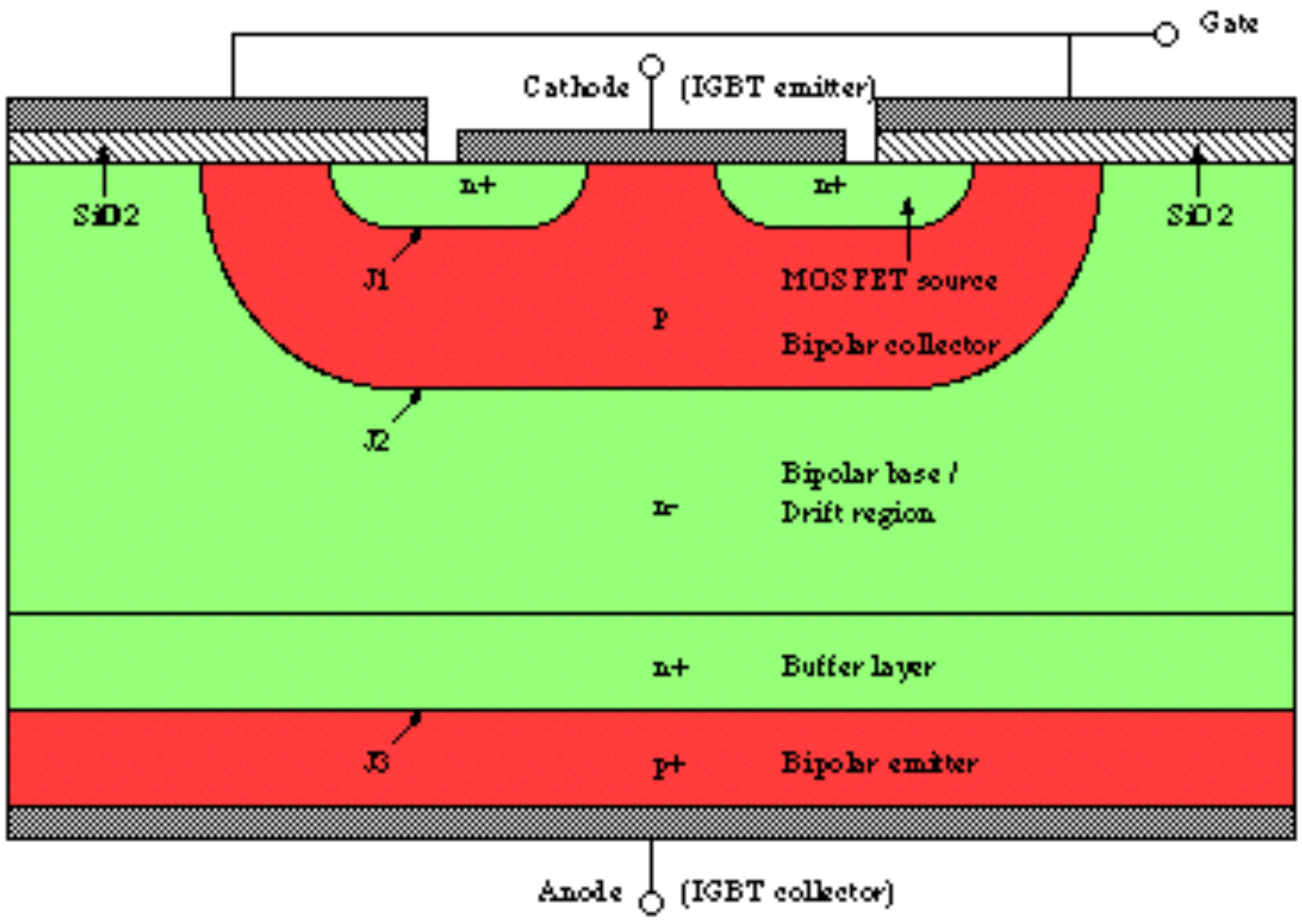
Quando usar MOSFET:

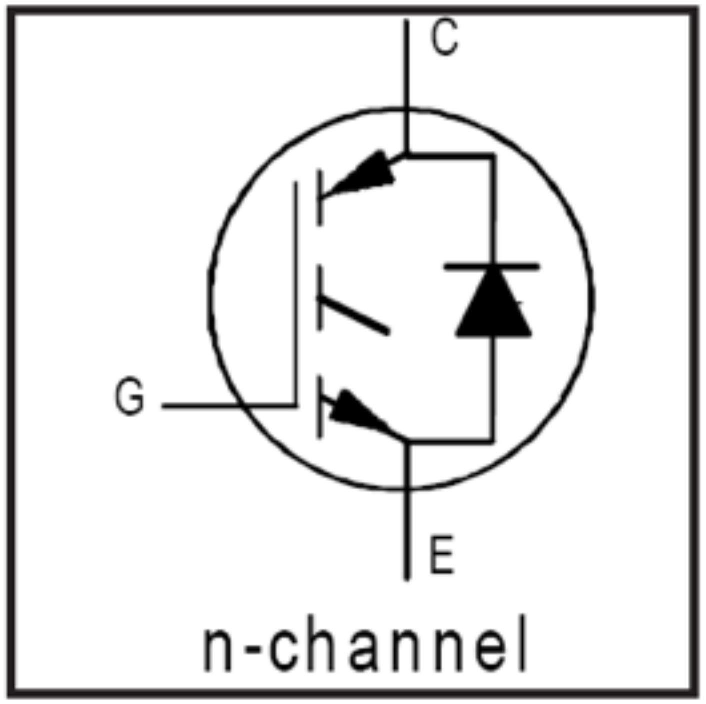
1. Freqüências altas (acima de 50 kHz);
2. Tensões muito baixas (< 500 V);
3. Potências baixas (< 1 kW).

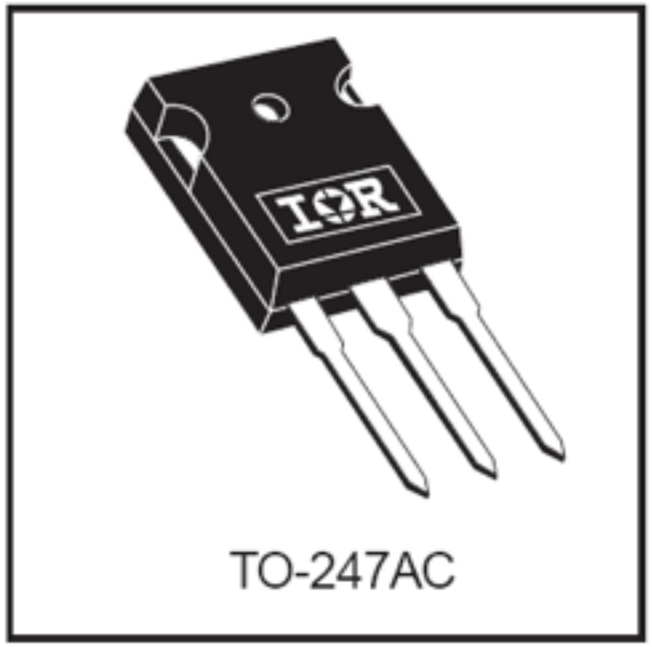


IGBT

IGBT - Insulated Gate Bipolar Transistor







Características de BJT e MOSFET

IGBT

Classificação das perdas:

1. Condução;

$$P_{cond} = \left(i_C \cdot V_{CEsat} + \overbrace{i_B \cdot V_{BEsat}}^{0}\right) \cdot t_{on} \cdot f$$

2. Comutação:
   - Entrada em condução e bloqueio;
   - Onde:

$$P_{com} = \frac{1}{2}\left(t_r + t_f\right) \cdot I \cdot E \cdot f$$

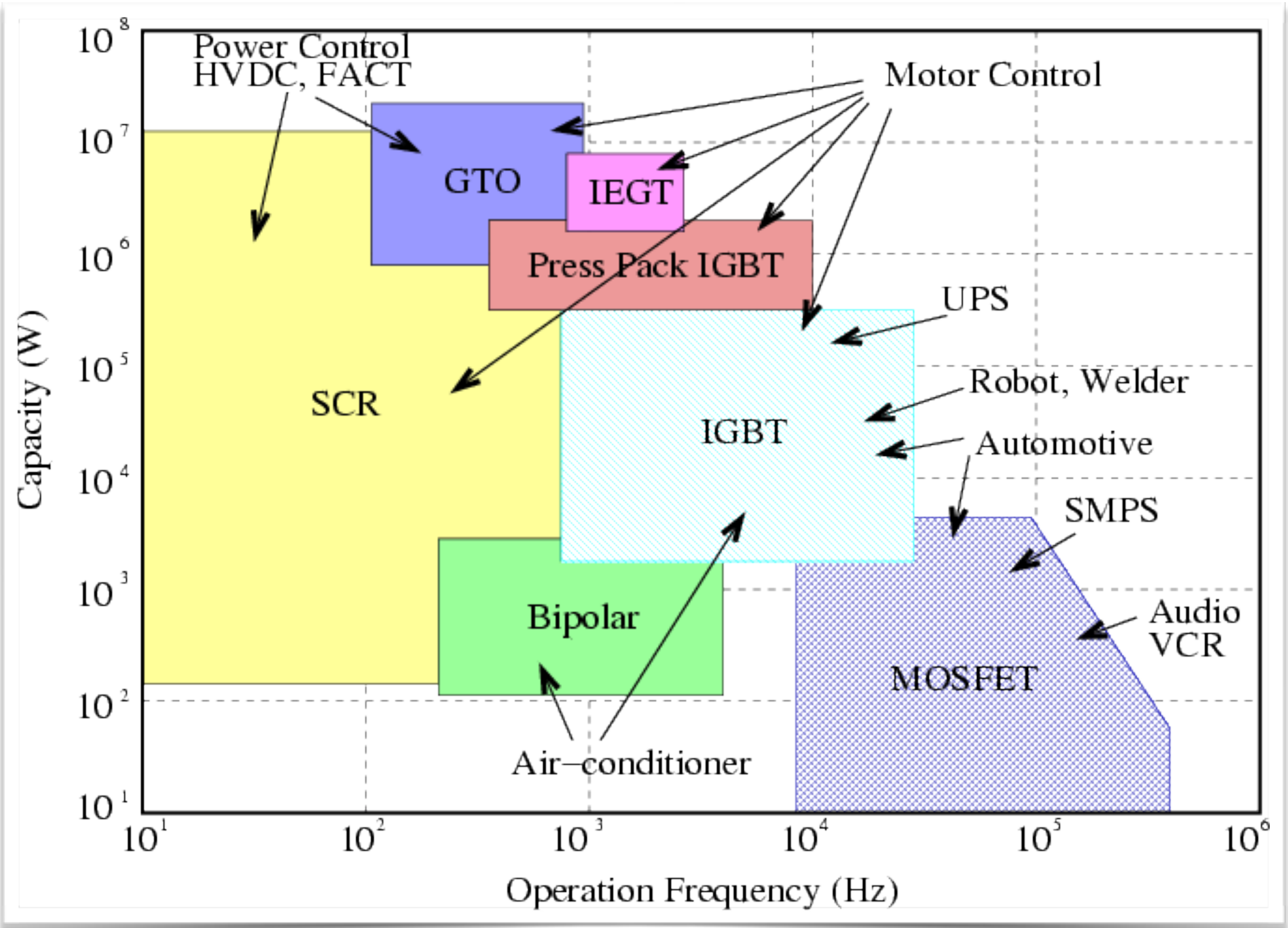
Detalhamento do cálculo de perdas

IGBT

Quando usar IGBT:

1. Freqüências baixas (menor que 50 kHz);
2. Tensões altas (> 500 V);
3. Potências altas (> 1 kW).

Part	Family	Package	Circuit	Switching Speed
IRG4PH30K	IGBT Discretes	TO-247AC	Discrete	ULTRAFAST 4-20 kHz
IRG4PC20U	IGBT Discretes	TO-247AC	Discrete	ULTRAFAST 8-60 kHz
IRG4PC30S	IGBT Discretes	TO-247AC	Discrete	DC-1 kHz (STANDARD)
IRG4PC60U	IGBT Discretes	TO-247AC	Discrete	ULTRAFAST 8-60 kHz
IRG4BC30W	IGBT Discretes	TO-220AB	Discrete	WARP 60-150 kHz
IRGB30B60K	IGBT Discretes	TO-220AB	Discrete	ULTRAFAST 10-30 kHz
IRGB8B60K	IGBT Discretes	TO-220AB	Discrete	ULTRAFAST 10-30 kHz
IRGS6B60K	IGBT Discretes	D2-Pak	Discrete	ULTRAFAST 10-30 kHz
IRGS14C40L	IGBT Discretes	D2-Pak	Discrete	Low-Vceon
IRGP4050	IGBT Discretes	TO-247AC	Discrete	Low-Vceon



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IGBT

Quando usar IGBT:

1. Freqüências baixas (menor que 50 kHz);
2. Tensões altas (> 500 V);
3. Potências altas (> 1 kW).

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Part	Family	Package	Circuit	Switching Speed	VCES (V)	VCE(ON) (V)	IC @ 25C (A)	IC @ 100C (A)	PD @25C (W)
IRG4PH30K	IGBT Discretes	TO-247AC	Discrete	ULTRAFAST 4-20 kHz	1200	4.20	20	10	100
IRG4PC20U	IGBT Discretes	TO-247AC	Discrete	ULTRAFAST 8-60 kHz	600	2.1	13	6.5	60
IRG4PC30S	IGBT Discretes	TO-247AC	Discrete	DC-1 kHz (STANDARD)	600	1.60	34	18	100
IRG4PC60U	IGBT Discretes	TO-247AC	Discrete	ULTRAFAST 8-60 kHz	600	2.00	75	40	520
IRG4BC30W	IGBT Discretes	TO-220AB	Discrete	WARP 60-150 kHz	600	2.70	23	12	100
IRGB30B60K	IGBT Discretes	TO-220AB	Discrete	ULTRAFAST 10-30 kHz	600	2.35	78	50	370
IRGB8B60K	IGBT Discretes	TO-220AB	Discrete	ULTRAFAST 10-30 kHz	600	2.2	17	9.0	140
IRGS6B60K	IGBT Discretes	D2-Pak	Discrete	ULTRAFAST 10-30 kHz	600	1.80	13	7	90
IRGS14C40L	IGBT Discretes	D2-Pak	Discrete	Low-Vceon	430	1.40	20	14	125
IRGP4050	IGBT Discretes	TO-247AC	Discrete	Low-Vceon	250	1.90	104	56	330

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IGBT

Package/Switching	Frequency	Voltage
IGBT SINGLE / Soft	Ultrafast <30kHz	300V
		600V
		1200V
IGBT SINGLE / Hard	Standard <1kHz	600V
		1200V
	Fast 1-8kHz	600V
	Ultra Fast 8-30kHz	300V
		600V
		1200V
	Warp 30-150kHz	600V
		900V
IGBT Co-Pack / Soft	Ultrafast <30kHz	1200V
IGBT Co-Pack / Hard	Standard <1kHz	600V
	Fast 1-8kHz	600V
	Ultra Fast 8-30kHz	300V
		600V
		1200V
	Warp 30-150kHz	600V
		900V

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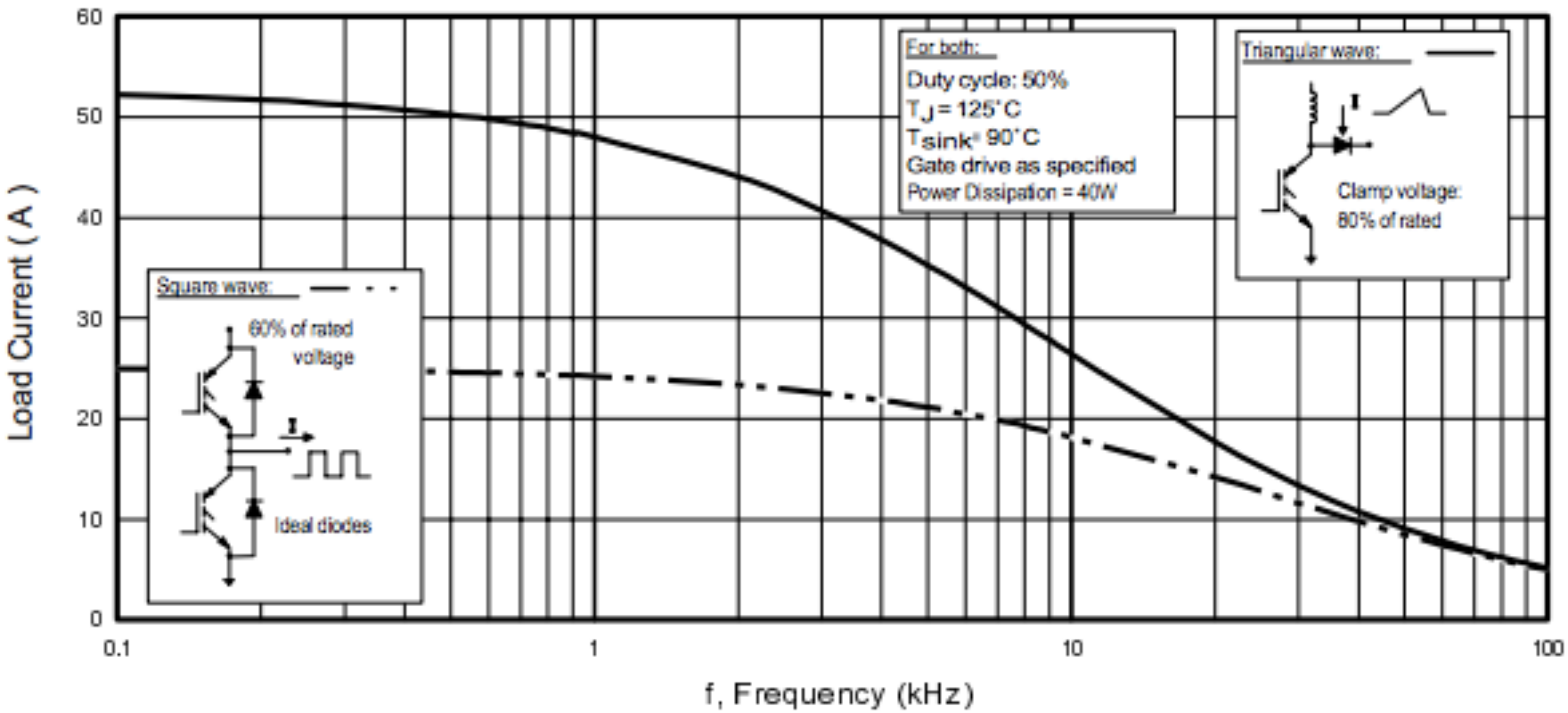
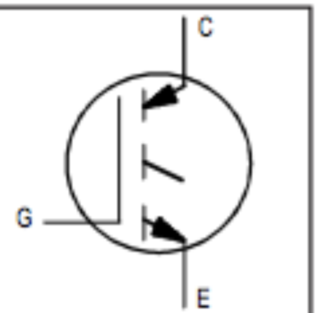
IGBT

IRG4PF50W



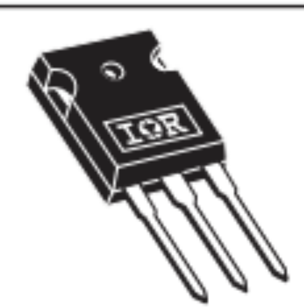


n-channel

V_{CES} = 900V

$V_{CE(on)\ typ.}$ = 2.25V

@V_{GE} = 15V, I_C = 28A



TO-247AC

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IGBT

Encapsulamentos:

www.semikron.com

IGBT

Encapsulamentos:

D-PAK

TO-252AA

TO-220AB
IRGB6B60K

D^2Pak
IRGS6B60K

TO-262
IRGSL6B60K

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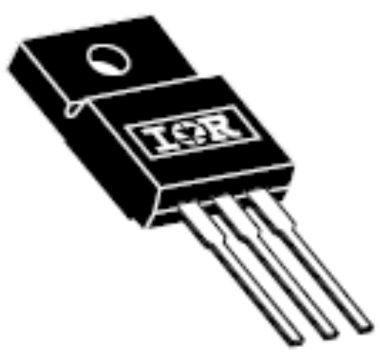
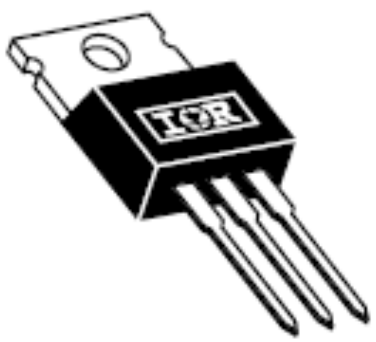
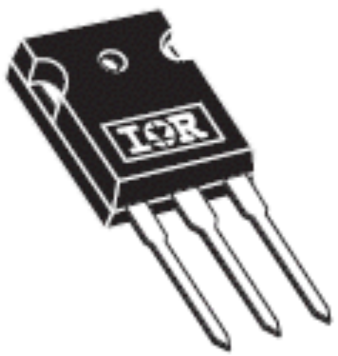


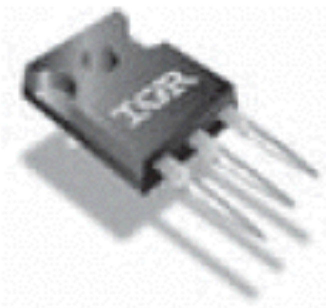
TO-220 FULLPAK



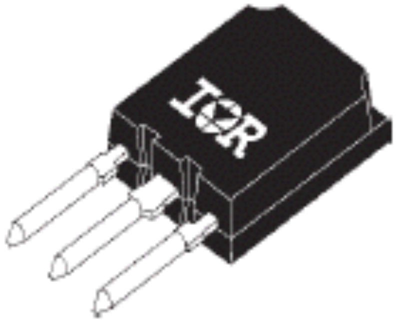
TO-220AB



TO-247AC



TO-247AC



SUPER - 247

IGBT

Dados de catalogo:

International
IOR Rectifier

PD - 94443

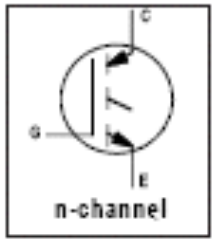
IRG4PC60U

INSULATED GATE BIPOLAR TRANSISTOR

UltraFast Speed IGBT

Features

- UltraFast: Optimized for high operating frequencies up to 50 kHz in hard switching, >200 kHz in resonant mode.
- Generation 4 IGBT design provides tighter parameter distribution and higher efficiency.
- Industry standard TO-247AC package.



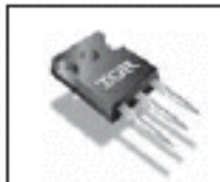
V_{CES} = 600V

$V_{CE(on)\ typ.}$ = 1.6V

@V_{GE} = 15V, I_C = 40A

Benefits

- Generation 4 IGBT's offer highest efficiency available.
- IGBT's optimized for specified application conditions.
- Designed for best performance when used with IR Hexfred & IR Fred companion diodes.



TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
V_{CES}	Collector-to-Emitter Breakdown Voltage	600	V
I_C @ T_C = 25°C	Continuous Collector Current	75	A
I_C @ T_C = 100°C	Continuous Collector Current	40	
I_{CM}	Pulsed Collector Current ①	300	
I_{LM}	Clamped Inductive Load Current ②	300	
V_{GE}	Gate-to-Emitter Voltage	± 20	V
E_{ARV}	Reverse Voltage Avalanche Energy ③	200	mJ
P_D @ T_C = 25°C	Maximum Power Dissipation	520	W
P_D @ T_C = 100°C	Maximum Power Dissipation	210	
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 150	°C
	Soldering Temperature, for 10 seconds	300 (0.063 in. (1.6mm from case)	
	Mounting torque, 6-32 or M3 screw.	10 lbf•in (1.1N•m)	

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	----	0.24	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.24	----	
$R_{\theta JA}$	Junction-to-Ambient, typical socket mount	----	40	
Wt	Weight	6 (0.21)	----	g (oz)

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International
IOR Rectifier

PD 9.1457D

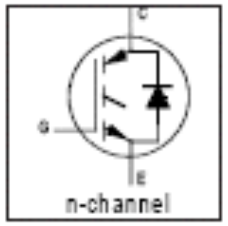
IRG4PC40UD

INSULATED GATE BIPOLAR TRANSISTOR WITH ULTRAFAST SOFT RECOVERY DIODE

UltraFast CoPack IGBT

Features

- UltraFast: Optimized for high operating frequencies 8-40 kHz in hard switching, >200 kHz in resonant mode
- Generation 4 IGBT design provides tighter parameter distribution and higher efficiency than Generation 3
- IGBT co-packaged with HEXFRED™ ultrafast, ultra-soft-recovery anti-parallel diodes for use in bridge configurations
- Industry standard TO-247AC package



V_{CES} = 600V

$V_{CE(on)\ typ.}$ = 1.72V

@V_{GE} = 15V, I_C = 20A

Benefits

- Generation -4 IGBT's offer highest efficiencies available
- IGBT's optimized for specific application conditions
- HEXFRED diodes optimized for performance with IGBT's . Minimized recovery characteristics require less/no snubbing
- Designed to be a "drop-in" replacement for equivalent industry-standard Generation 3 IR IGBT's

TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
V_{CES}	Collector-to-Emitter Voltage	600	V
I_C @ T_C = 25°C	Continuous Collector Current	40	A
I_C @ T_C = 100°C	Continuous Collector Current	20	
I_{CM}	Pulsed Collector Current ①	160	
I_{LM}	Clamped Inductive Load Current ②	160	
I_F @ T_C = 100°C	Diode Continuous Forward Current	15	
I_{FM}	Diode Maximum Forward Current	160	
V_{GE}	Gate-to-Emitter Voltage	± 20	V
P_D @ T_C = 25°C	Maximum Power Dissipation	160	W
P_D @ T_C = 100°C	Maximum Power Dissipation	65	
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 sec.	300 (0.063 in. (1.6mm) from case)	
	Mounting Torque, 6-32 or M3 Screw.	10 lbf•in (1.1 N•m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case - IGBT	——	——	0.77	°C/W
$R_{\theta JC}$	Junction-to-Case - Diode	——	——	1.7	
$R_{\theta CS}$	Case-to-Sink, flat, greased surface	——	0.24	——	
$R_{\theta JA}$	Junction-to-Ambient, typical socket mount	——	—-	40	
Wt	Weight	——	6 (0.21)	——	g (oz)

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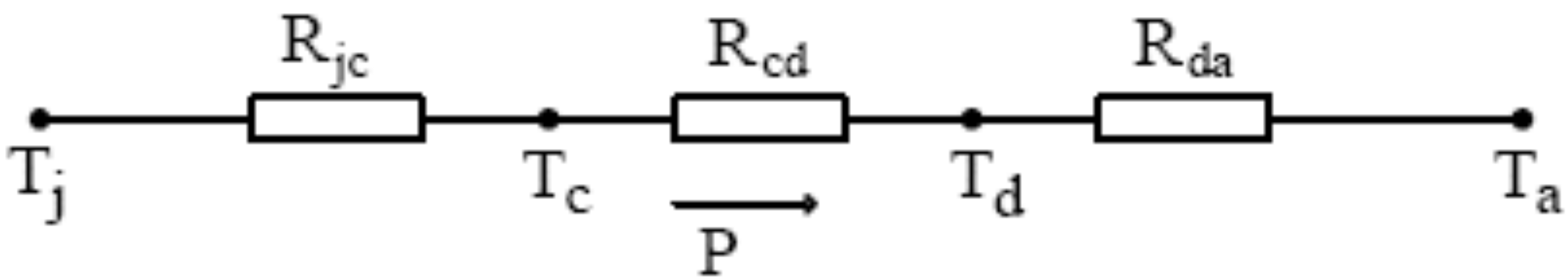
BJT x MOSFET x IGBT

	MOSFET	IGBT	BJT
Tipo de comando	Tensão	Tensão	Corrente
Potência do comando	Mínima	Mínima	Grande
Complexidade do comando	Simples	Simples	Média
Densidade de corrente	Elevada em baixas tensões e Baixa em altas tensões	Muito elevada	Média
Perdas de comutação	Muito baixa	Baixa para Média	Média para Alta

Cálculo Térmico

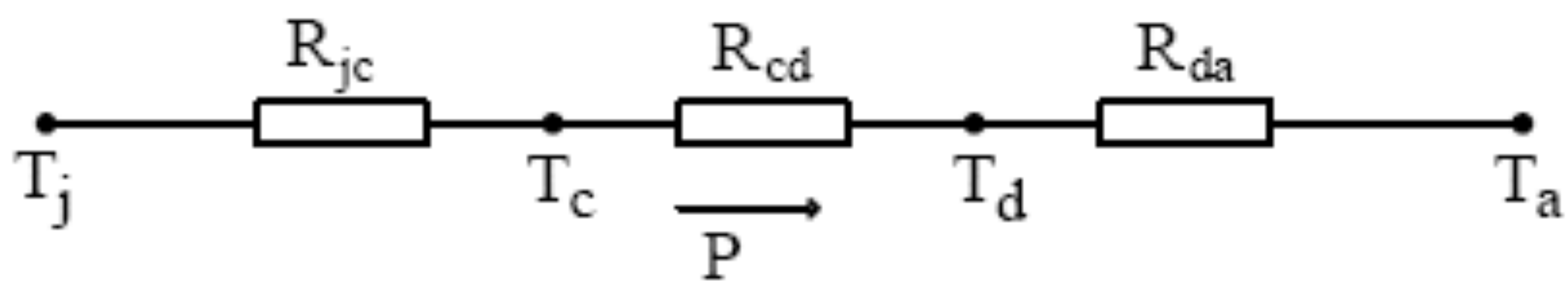
Cálculo térmico:

- Objetivo de verificar a necessidade de uso de dissipador de calor ou não.
- Modelo térmico:



- T_j = temperatura na junção (°C);
- T_c = temperatura na cápsula (°C);
- T_d = temperatura no dissipador (°C);
- T_a = temperatura ambiente (°C);
- R_{jc} = resistência térmica entre junção e cápsula (°C/W);
- R_{cd} = resistência térmica entre cápsula e dissipador (°C/W);
- R_{da} = resistência térmica entre dissipador e ambiente (°C/W);
- P = potência dissipada no componente (W).

Cálculo Térmico

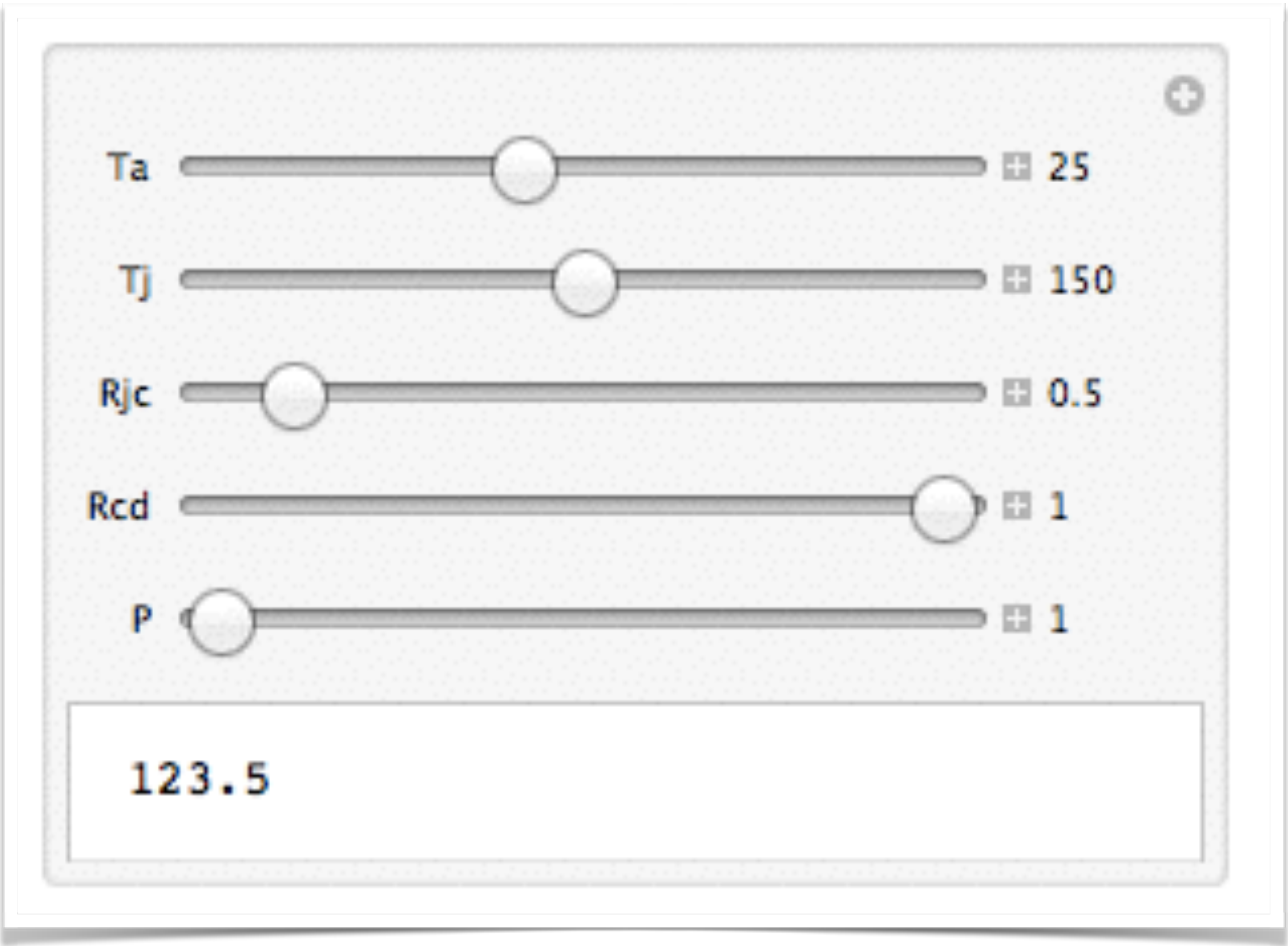


$$R_{ja} = R_{jc} + R_{cd} + R_{da}$$

$$T_j - T_a = R_{ja} \cdot P \quad \Rightarrow \quad R_{ja} = \frac{T_j - T_a}{P}$$

$$R_{da} = R_{ja} - R_{jc} - R_{cd}$$

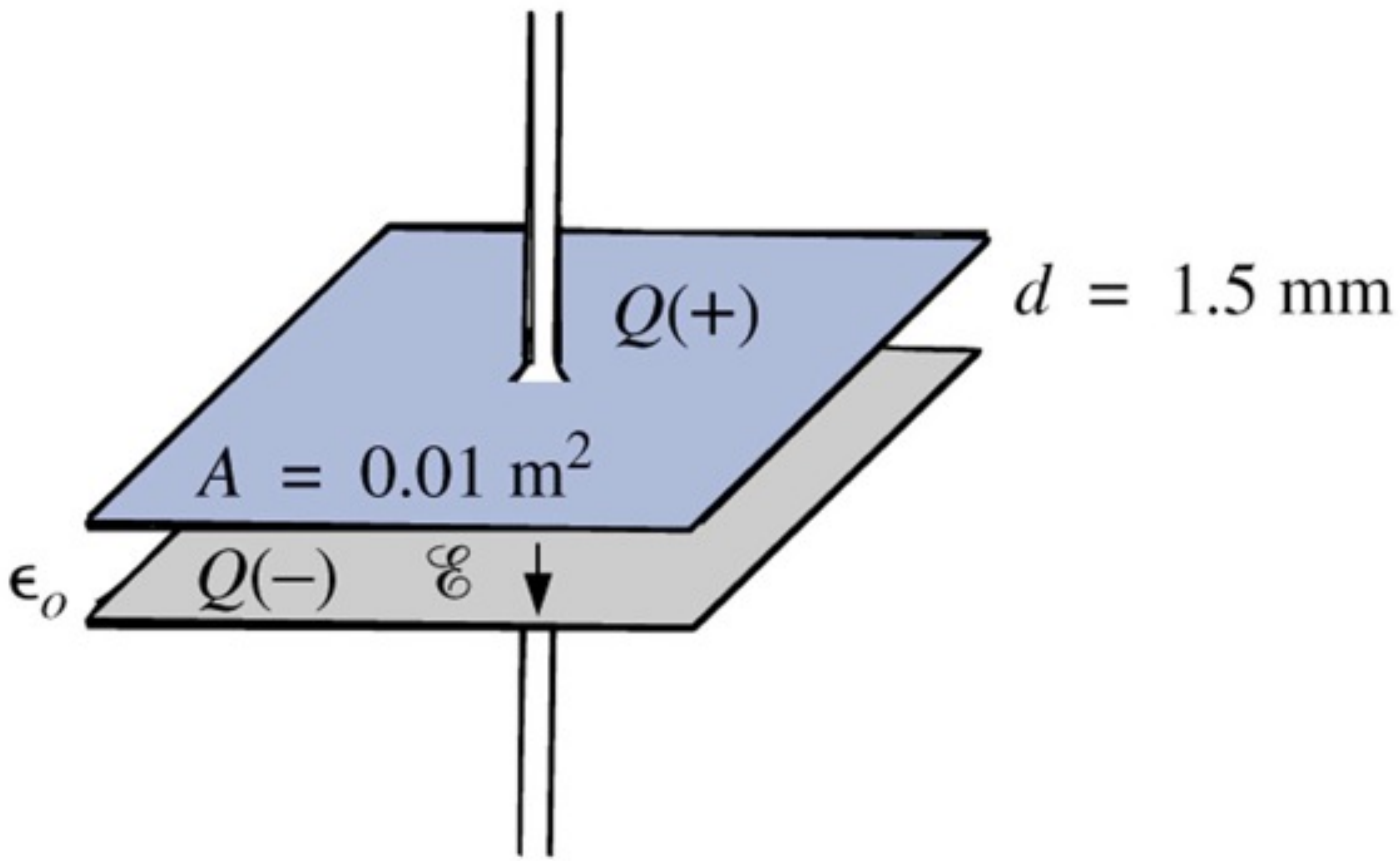
Cálculo Térmico

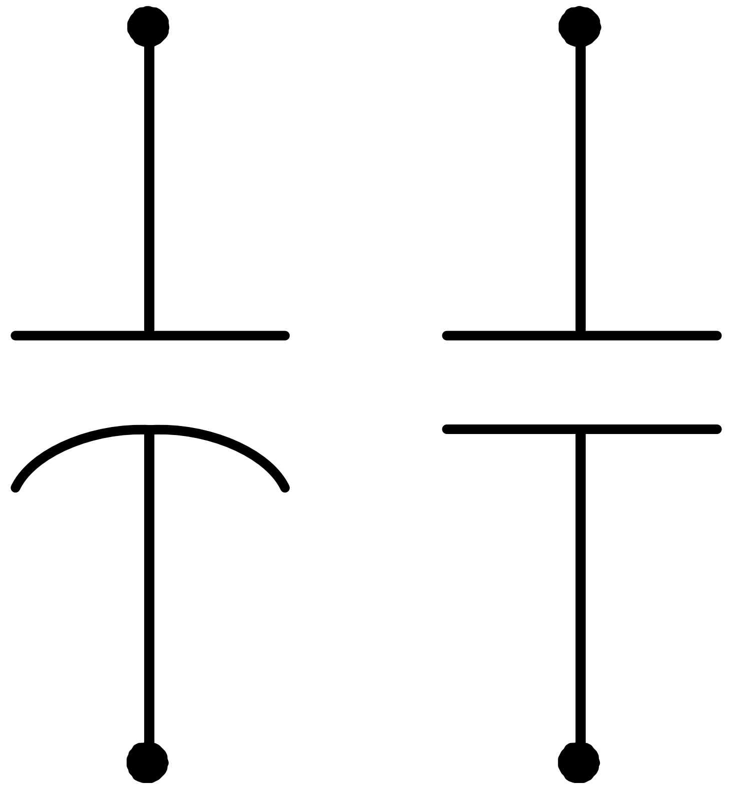


Capacitores

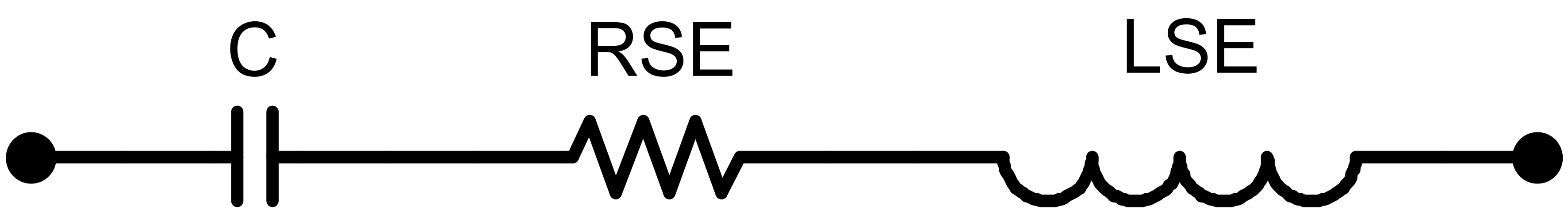
A capacitância depende de:

- Dielétrico (permissividade);
- Área das placas;
- Distância entre as placas.





Capacitores



Modelo equivalente do capacitor

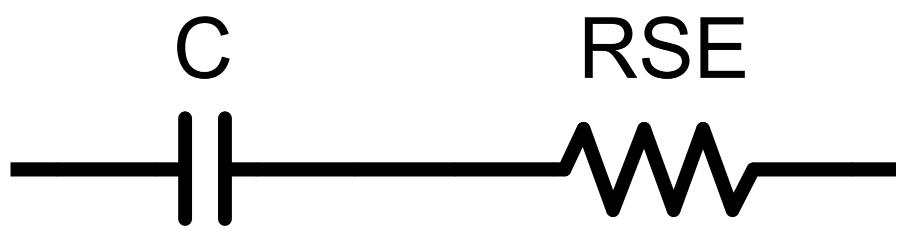
Onde:

- C = Capacitância;
- RSE = Resistência série equivalente;
- LSE = Indutância série equivalente.

Perdas devido à RSE:

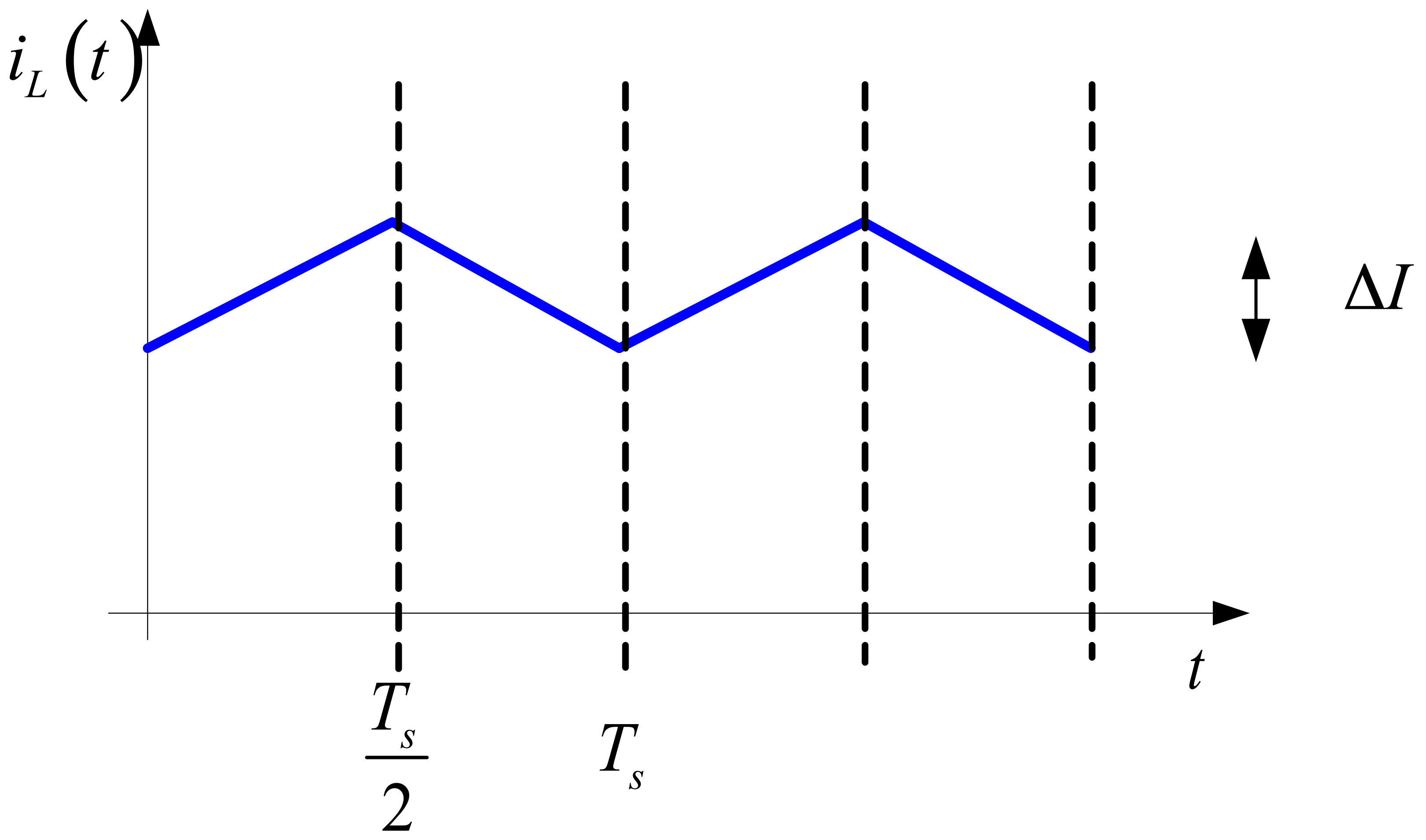
$$P = RSE \cdot I_{ef}^{2}$$

Capacitores



Ondulação da tensão:

$$\Delta V = RSE \cdot \Delta I$$



Capacitores

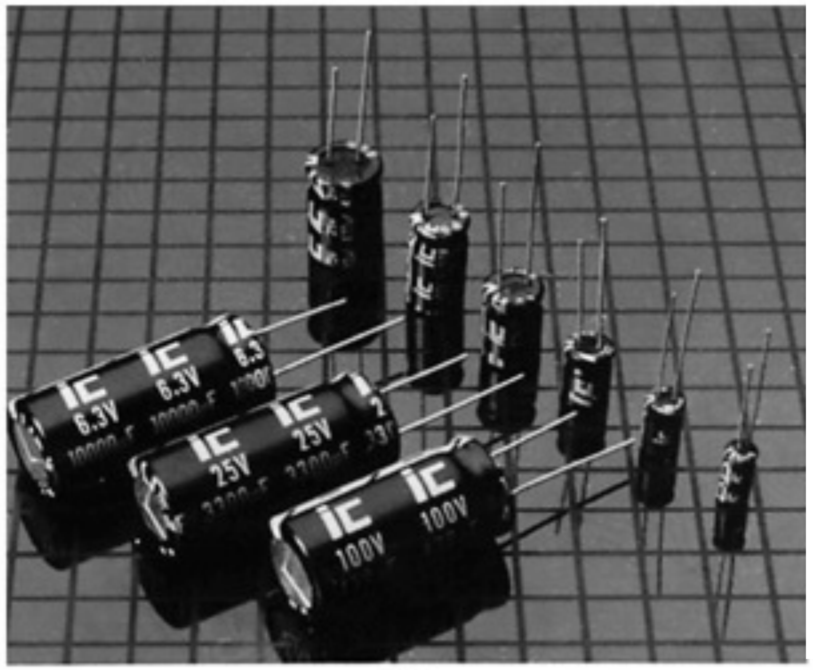
Tecnologias de capacitores:

- Filtro do retificador de entrada – São empregados capacitores eletrolíticos de alta tensão e grandes capacitâncias;

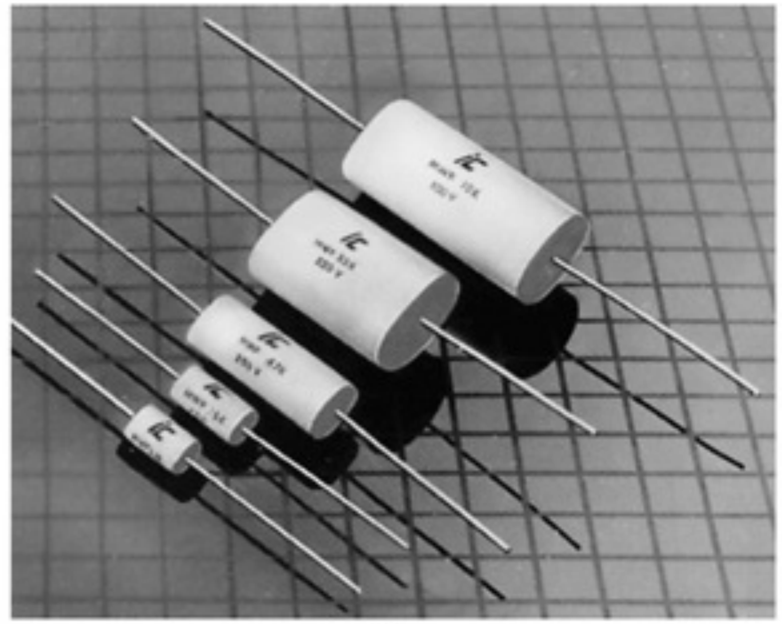
- Filtro de saída dos conversores – Empregam-se capacitores eletrolíticos alumínio com baixa RSE;

- Circuitos de grampeamento (snubber) – São utilizados capacitores com dielétricos de polipropileno para regime intermitente de funcionamento.

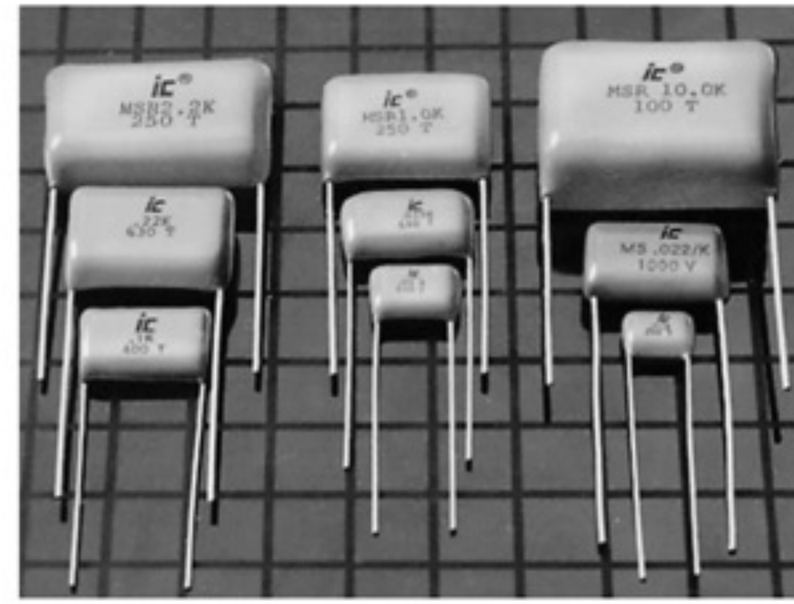
Capacitores



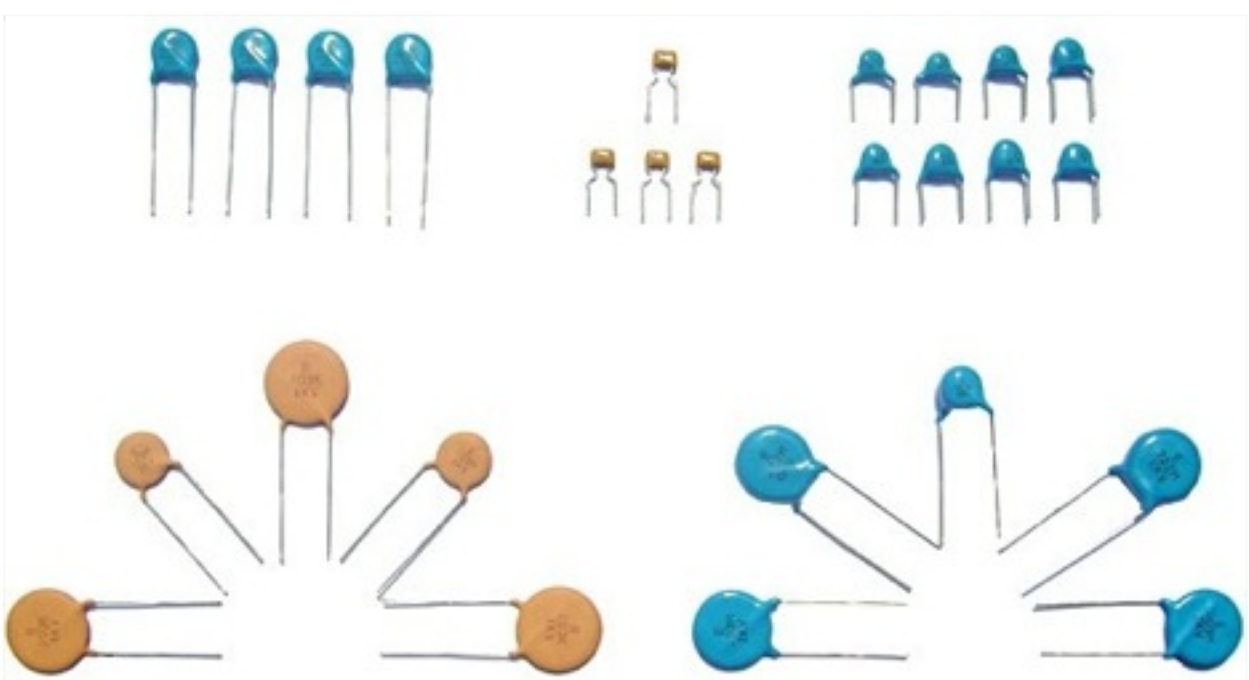
(a)

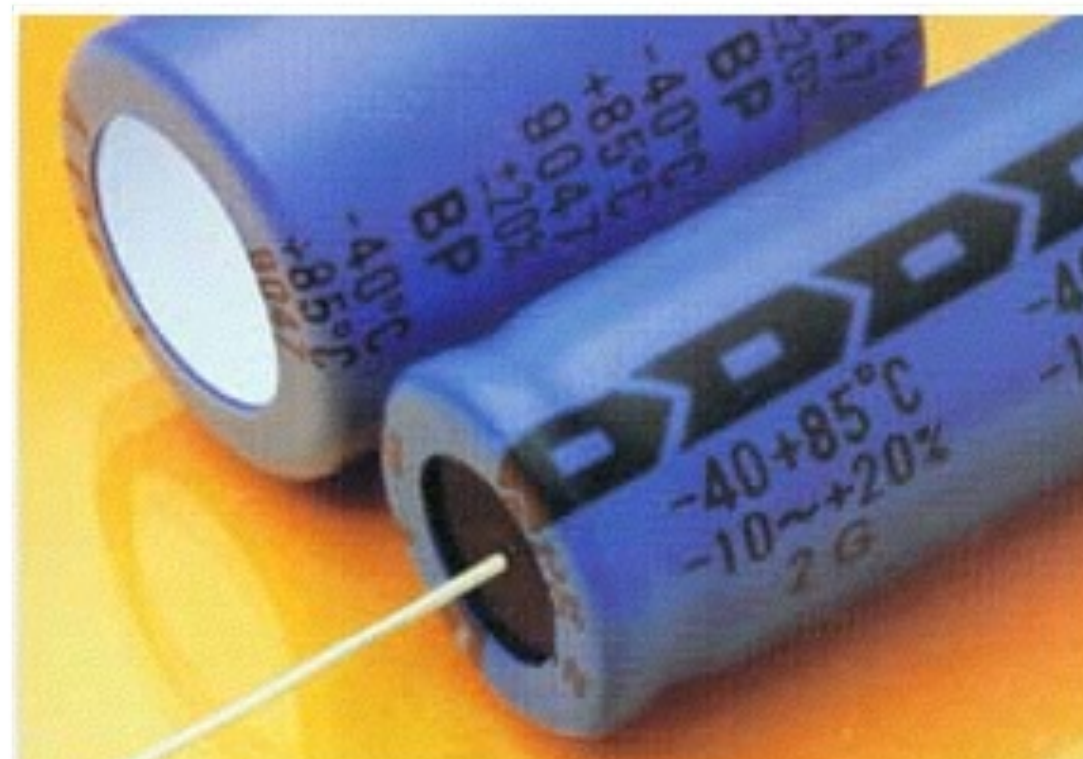


(a)



(b)



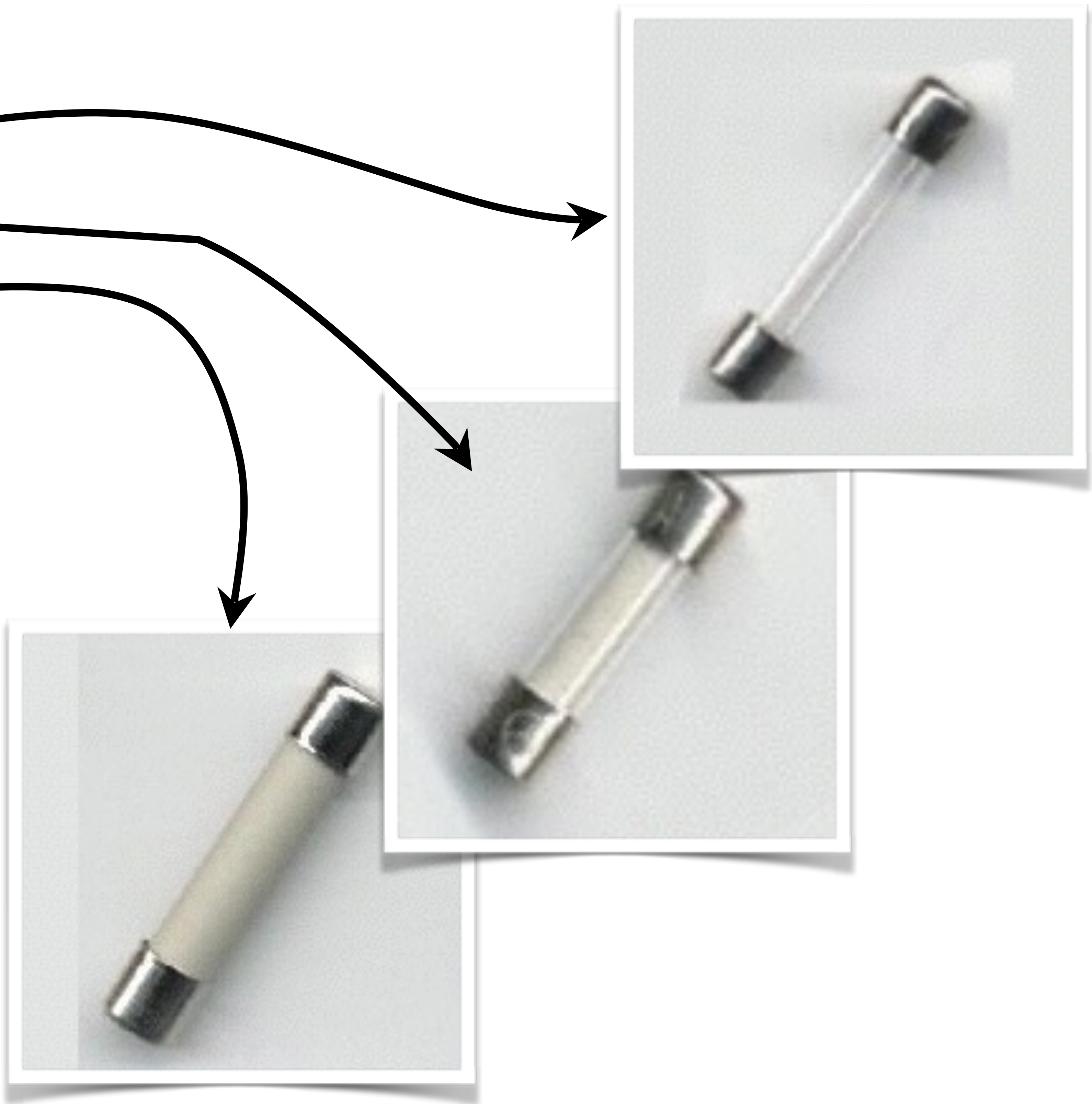


Fusíveis

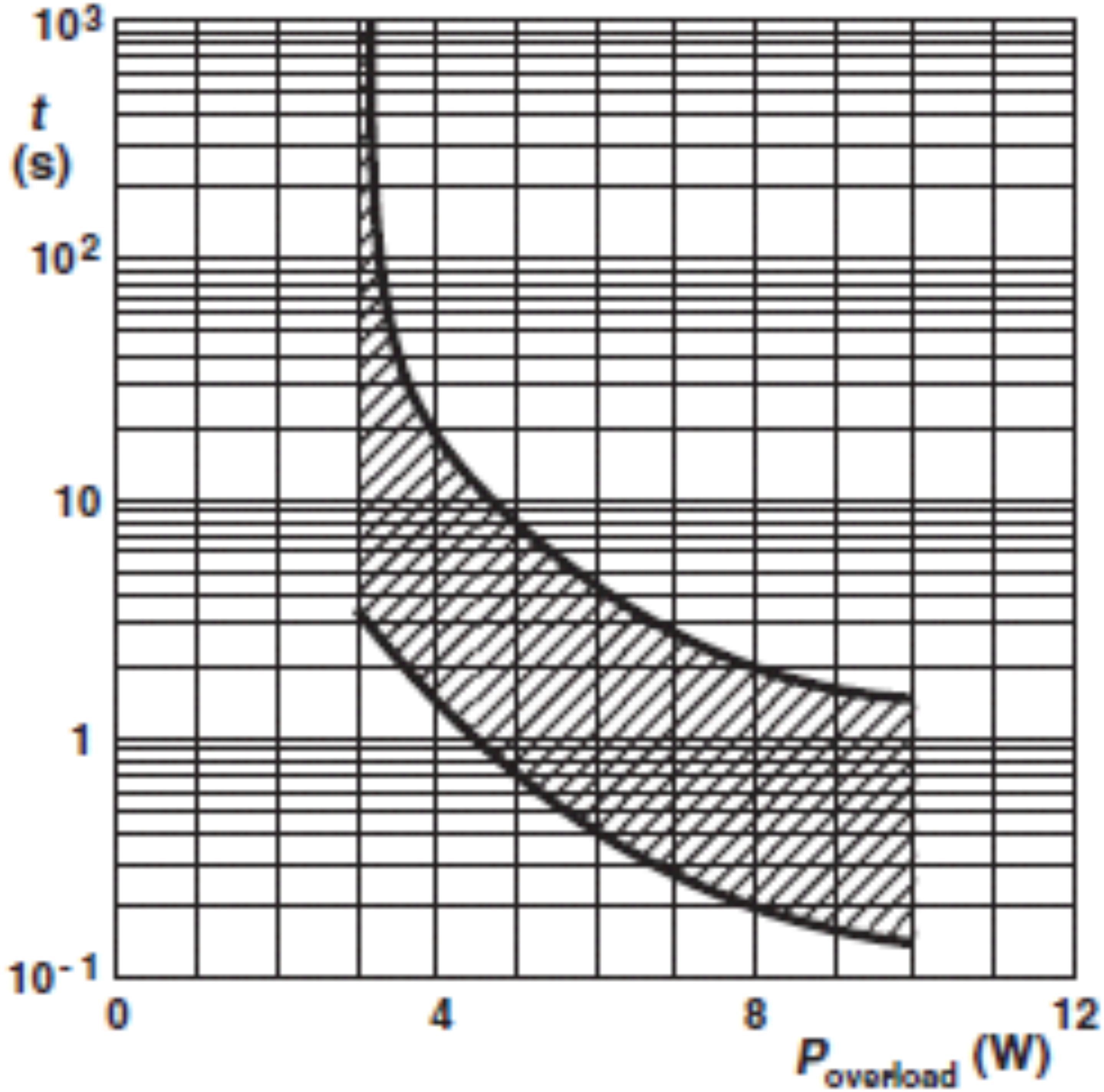
Fusíveis de ação lenta:
- Vidro;
- Areia;
- Cerâmica.

Fusíveis de ação rápida:
- Vidro;
- Areia;
- Cerâmica.

Resistores fusíveis.



Fusíveis



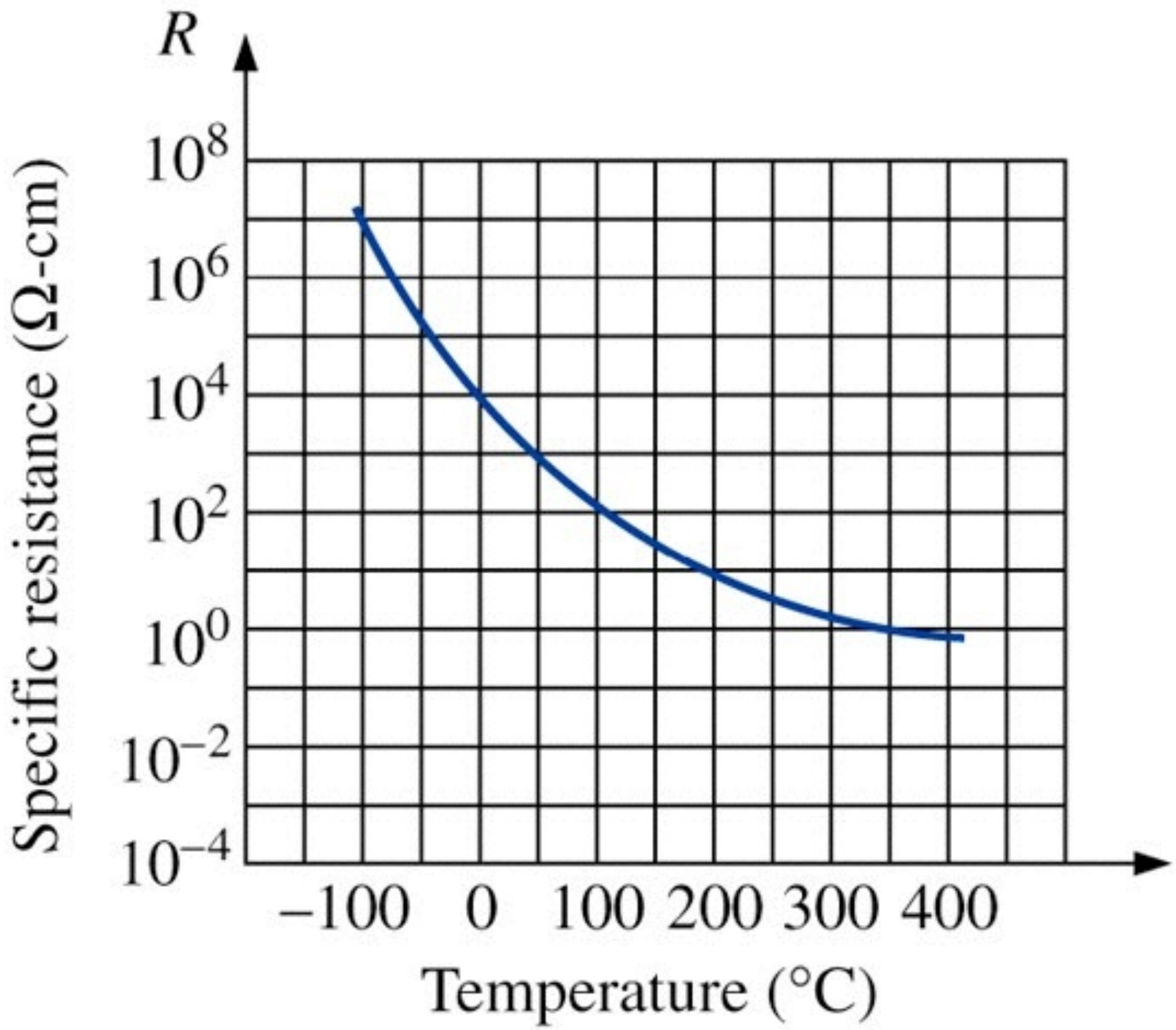
NR25 – 1 Ω < R < 15 Ω

www.vishay.com

Termistores

Termistor:

- Resistor cuja resistência é sensível à variação da temperatura.



(a)

(b)

Próxima Aula

Conversores ca-cc:

- Retificadores e filtro capacitivo.