Introdução à Física do Estado Sólido
Física Moderna II-B

Caetano R. Miranda

Carlos A. Martins Jr.

AULA 21 – 07/11/2022

crmiranda@usp.br

Cronograma - revisado

CRONOGRAMA TENTATIVO - Introdução à Física do Estado Sólido - Física Moderna IIB - 2S 2022						
DATA	aula nº	Segundas (19h - 21h) - Sala 2001 - Ala Central	aula nº	Quartas (21h - 23h) - Sala 2001 - Ala Central	DATA	
15-Aug			1	Apresentação - Curso	18-Aug	
22-Aug	2	Revisão - Particulas e ondas - Chocolate	3	Átomos e Ions (Eletrons em átomos) - Tabela Periodica	25-Aug	
29-Aug	4	Átomos e Ions (Eletrons em átomos) - Simulacao	5	Moléculas e sólidos (Eletrons em sólidos) - impressao 3D	01-Sep	
05-Sep	Feriado	Independência do Brasil. Não haverá aula.	Feriado	Independência do Brasil. Não haverá aula.	08-Sep	
12-Sep	6	Ordem e Simetria	7	Ondas em cristais – Estruturas cristalinas - Corte/Colar - Origan	15-Sep	ENTREGA 1
19-Sep	8	Estruturas - Atomos em cristais - VR1	9	Estruturas - Atomos em cristais - VR2	22-Sep	
26-Sep	10	Oficina - Construção Oculus VR	11	BNCC & Wikipédia	29-Sep	
03-Oct	12	Vibrações térmicas e Fonons	13	Vibrações térmicas e Fonons	06-Oct	
10-Oct	14	Eletrons livres	15	Eletrons livres	13-Oct	ENTREGA 2
17-Oct	16	Condutividade elétrica e teoria de bandas	17	Condutividade elétrica e teoria de bandas	20-Oct	
24-Oct	18	Semicondutores	19	Semicondutores	27-Oct	
31-Oct	20	Junção PN - Criação Jogos	21	Junção PN	03-Nov	
7/11	22	Magnetismo	23	Magnetismo	10-Nov	
14/11	Feriado	Dia - Republica. Não haverá aula.	24	Projeto - Escolha do Tema / Oficina - Infográfico	17-Nov	ENTREGA 3
21/11	25	Supercondutividade	26	Supercondutividade	24-Nov	
28/11	27	Nanotecnologia	27	Materiais quânticos	01-Dec	
05-Dec	29	PROJETO - Acompanhamento	30	Projeto - Acompanhamento	08-Dec	
12-Dec	31	PROJETO	32	PROJETO	15-Dec	PROJETO

Material baseado no:

Capítulo 7 do Kittel (Introduction to Solid State Physics – 8ª edição)
Capítulos 7 e 8 do Rosenberg (The Solid State – 3ª edição)
Capitulo 10 – Física Moderna – Paul A. Tipler & Ralph A. Llewellyn

Junção metal - semicondutor

Nobel 1956 – (William Bradford Shockley, John Bardeen, Walter Houser Brattain)

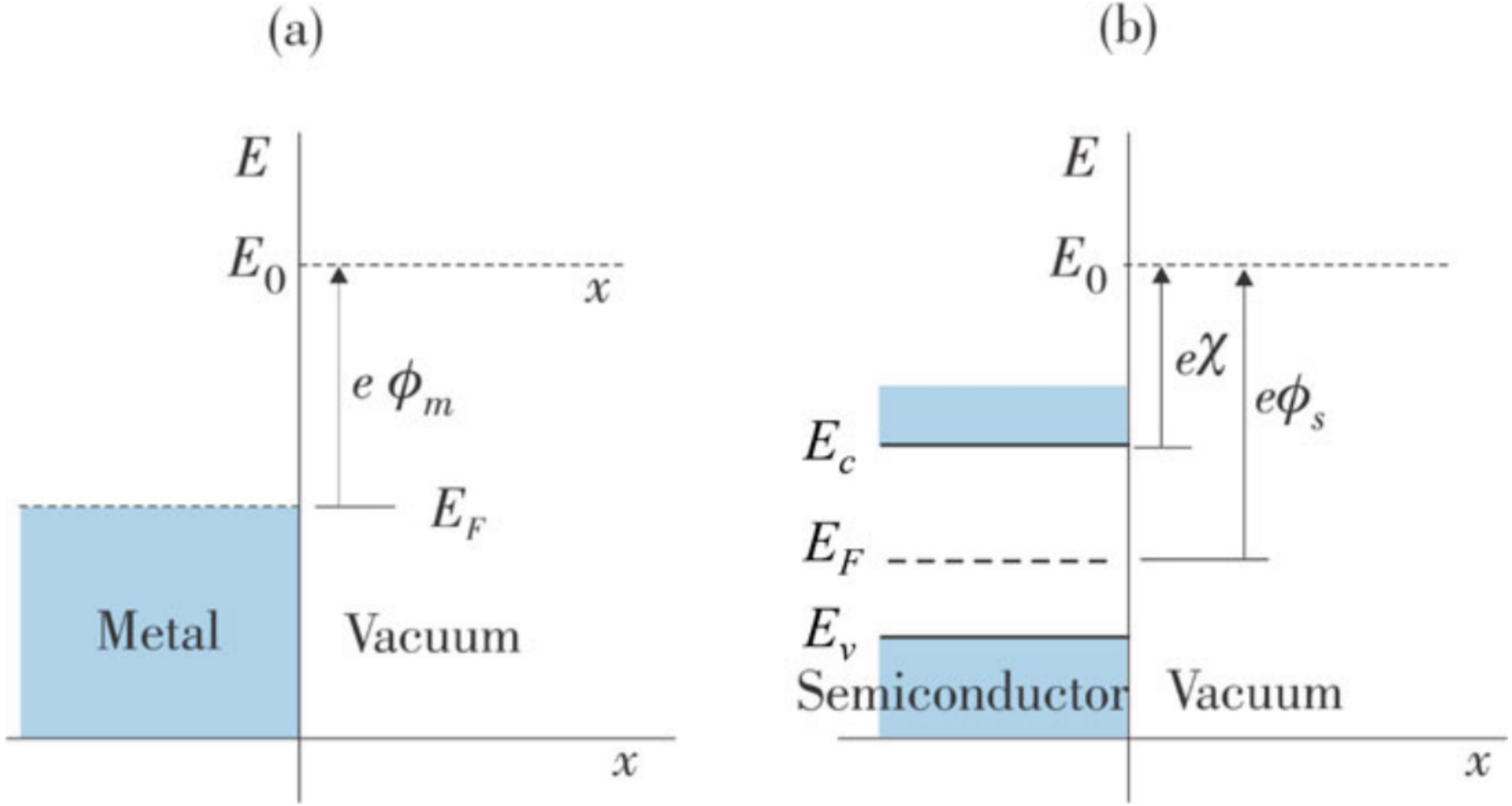


Fig. 6.8 Illustration of the concept of work function in the energy diagrams for two cases: **a** Isolated metal. **b** Isolated semiconductor

Junção Metal-Semicondutor

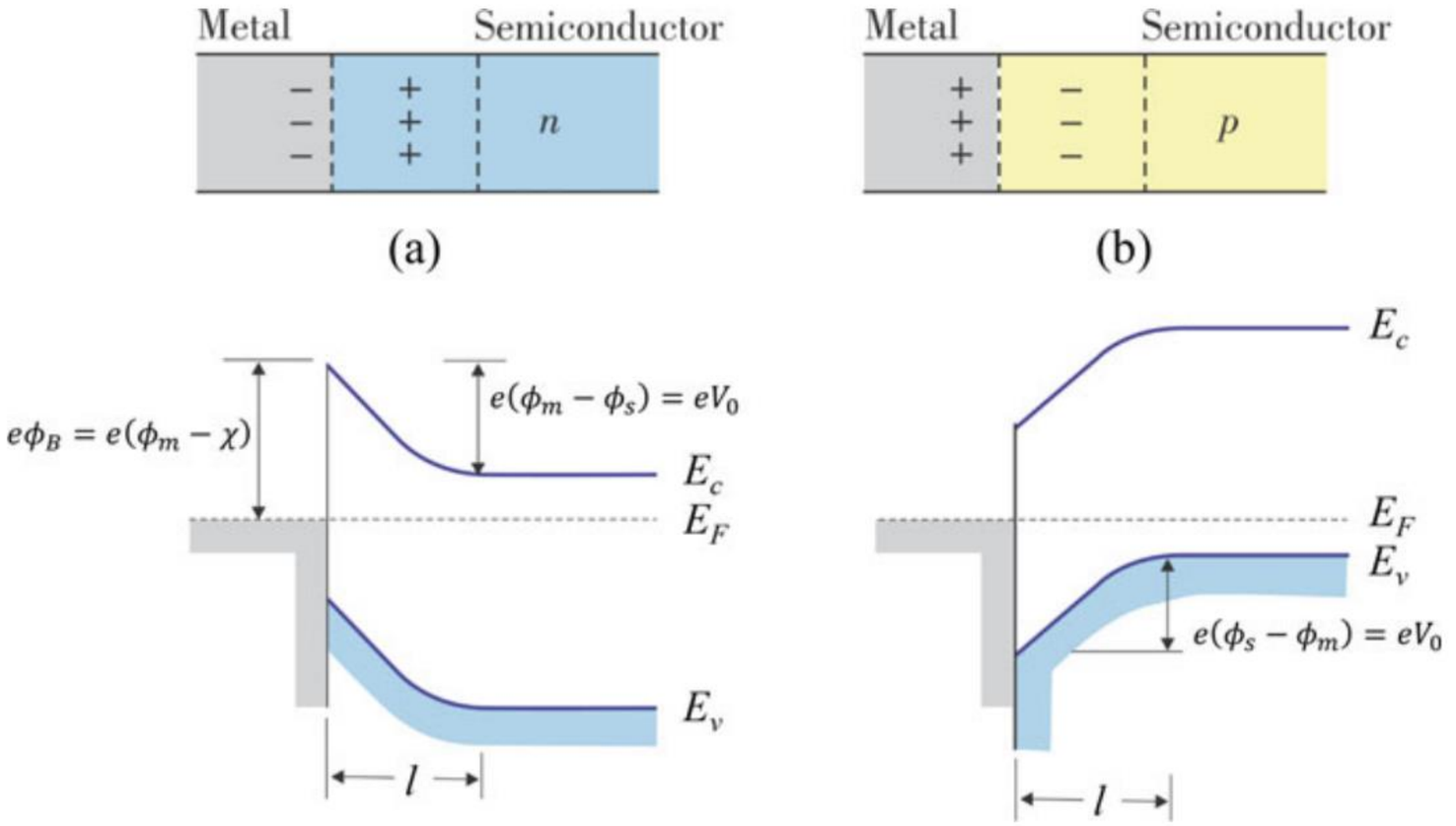
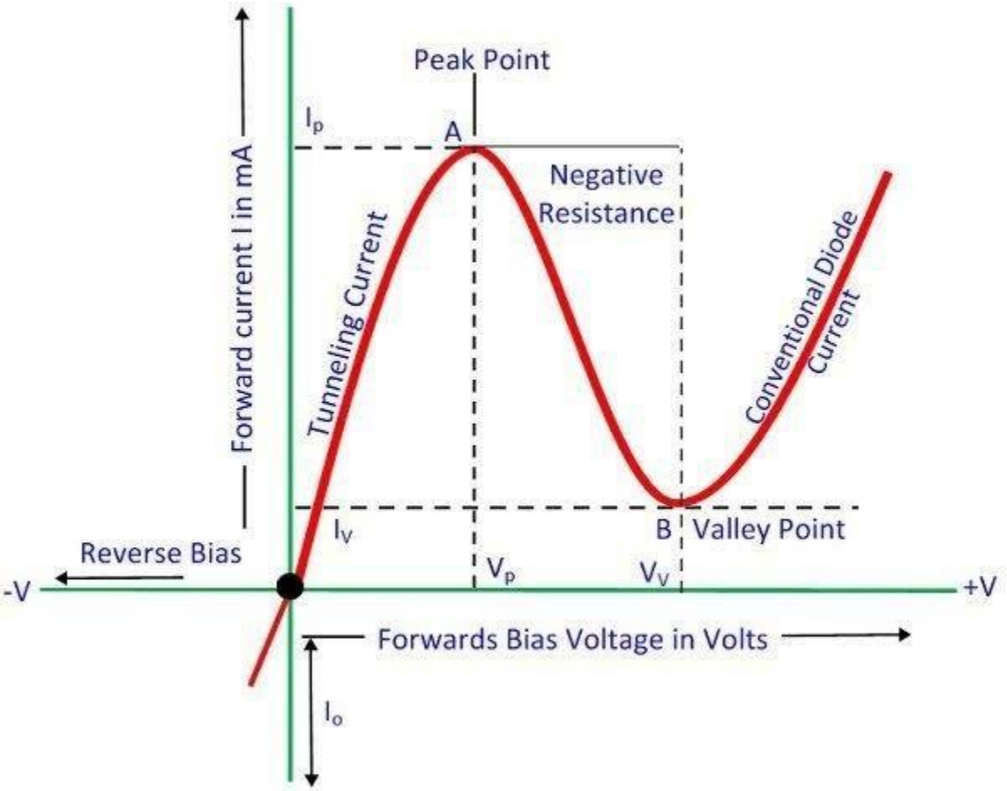
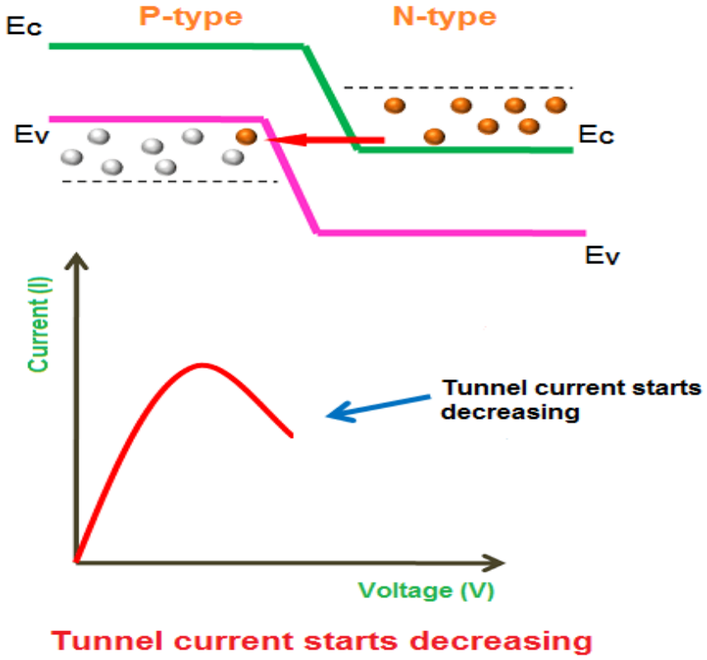


Fig. 6.9 Energy diagrams of metal–semiconductor junctions in equilibrium. **a** Type n semiconductor with $\phi_s < \phi_m$. **b** Type p semiconductor with $\phi_s > \phi_m$

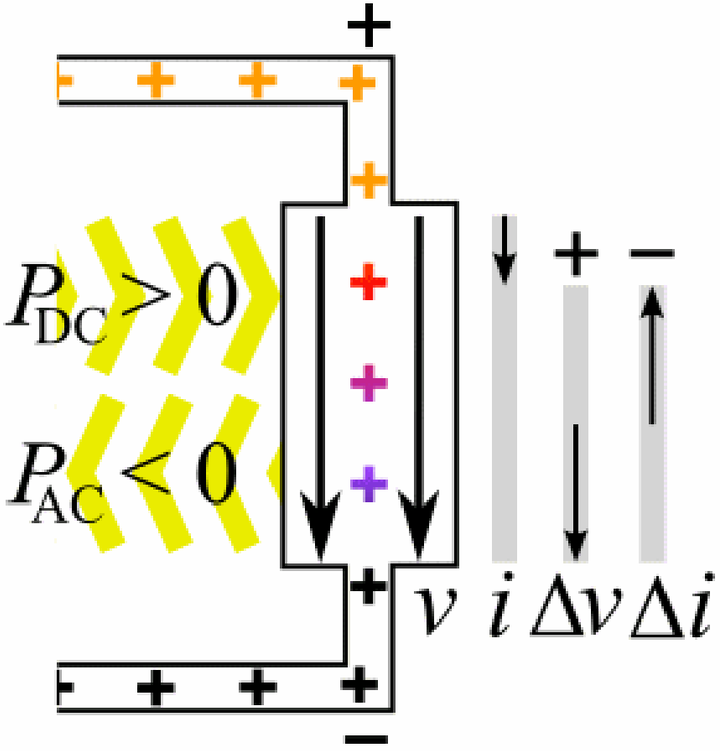
Dispositivos: diodo tunel e transistor

Diodo túnel (Premio Nobel de Física – 1973 – Esaki)





Tunnel current starts decreasing



Diodo túnel

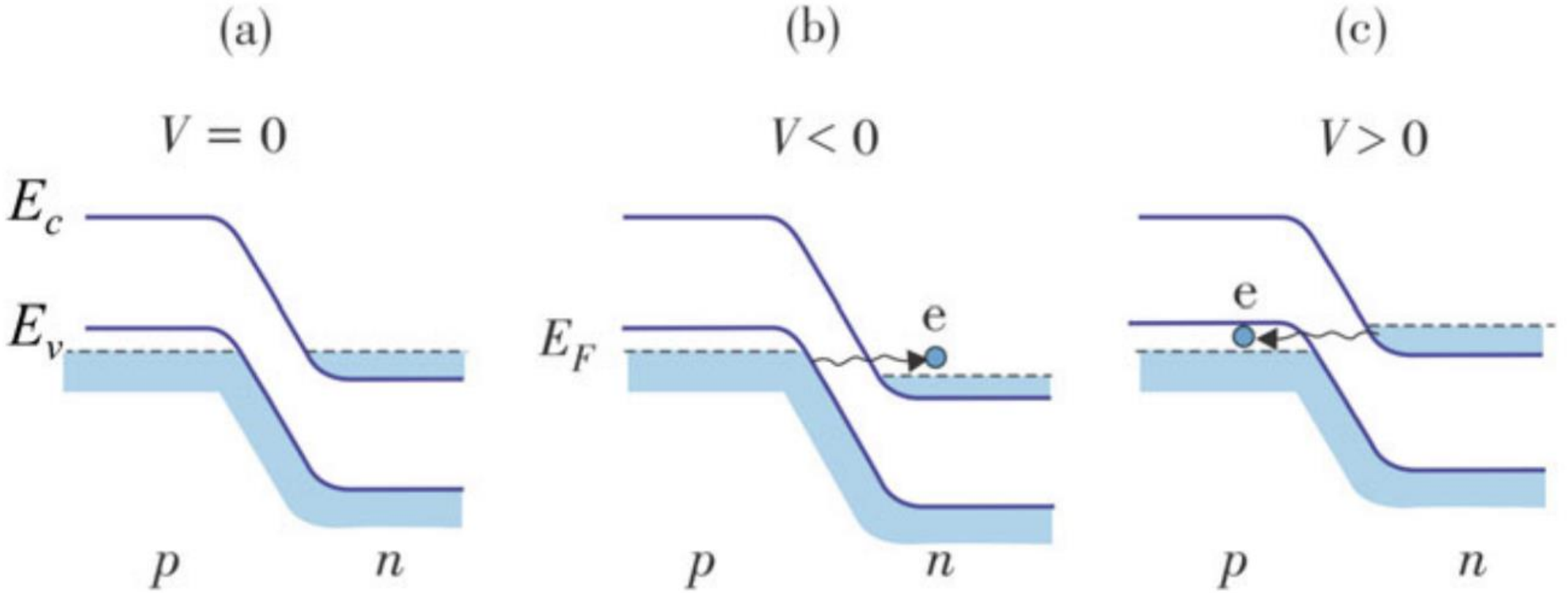


Fig. 6.21 Energy diagrams of a *p–n* junction in a tunnel diode. **a** $V = 0$, junction in equilibrium. **b** $V < 0$, tunneling current in the reverse direction. **c** $V > 0$, tunneling current in the forward direction

Transistor – Nobel 1956 – (William Bradford Shockley, John Bardeen, Walter Houser Brattain)

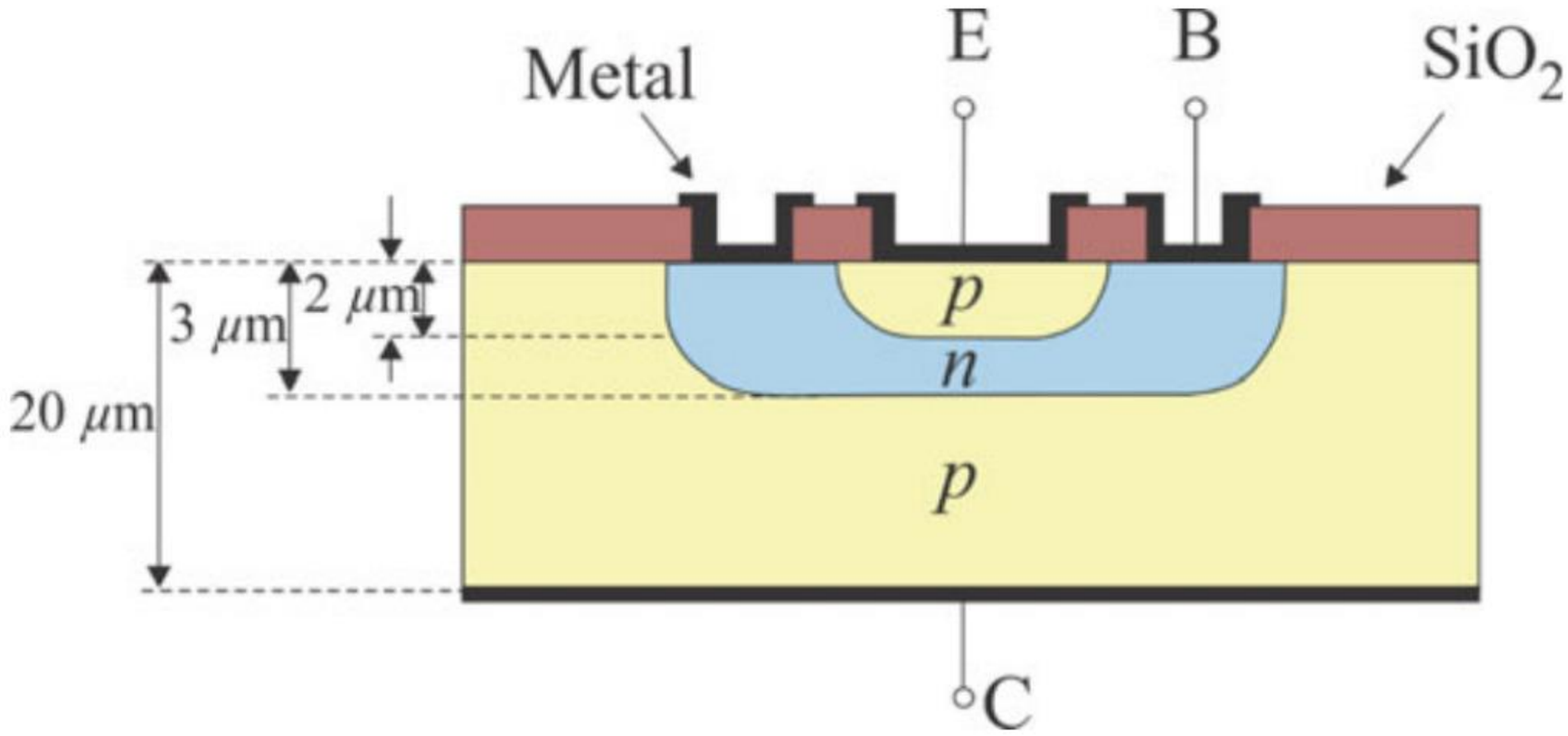


Fig. 7.2 Planar structure of the bipolar junction transistor with some typical dimensions in discrete devices. The letters E, B, and C represent the terminals of the emitter, base, and collector, respectively

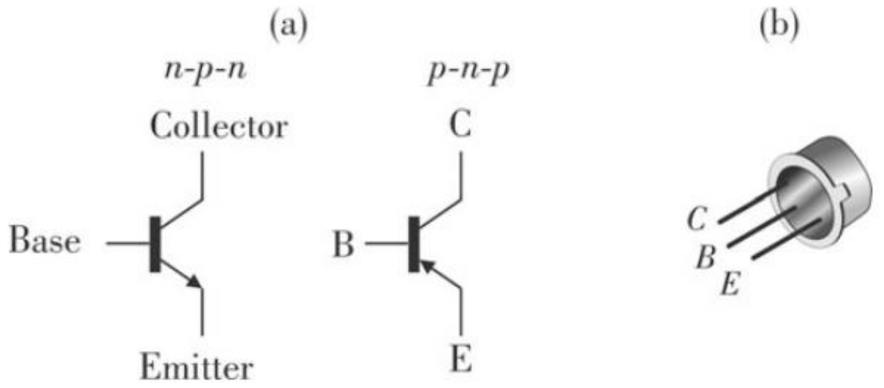


Fig. 7.8 **a** Circuit symbols of *n-p-n* and *p-n-p* transistors. **b** View of an encapsulated low power transistor

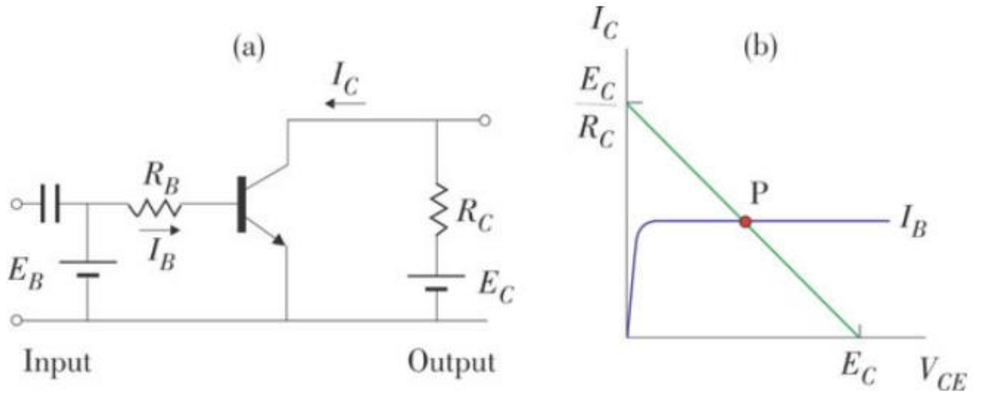
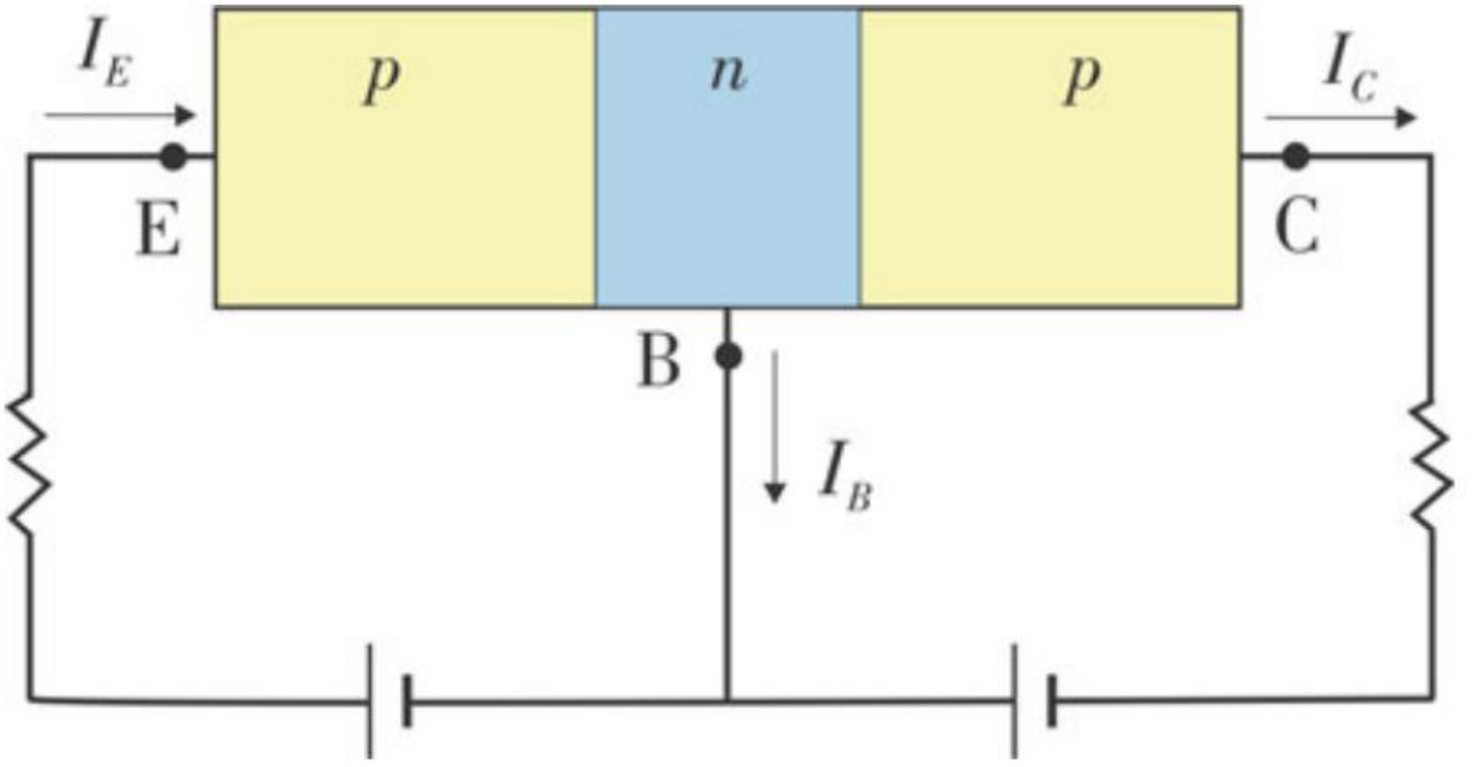


Fig. 7.9 **a** Simple amplifier circuit with a *n-p-n* transistor in the common-emitter configuration. **b** Graphic illustration of the method for determining the operating point P

Fig. 7.3 Schematic representation of a *p-n-p* transistor with a simple common base polarization circuit



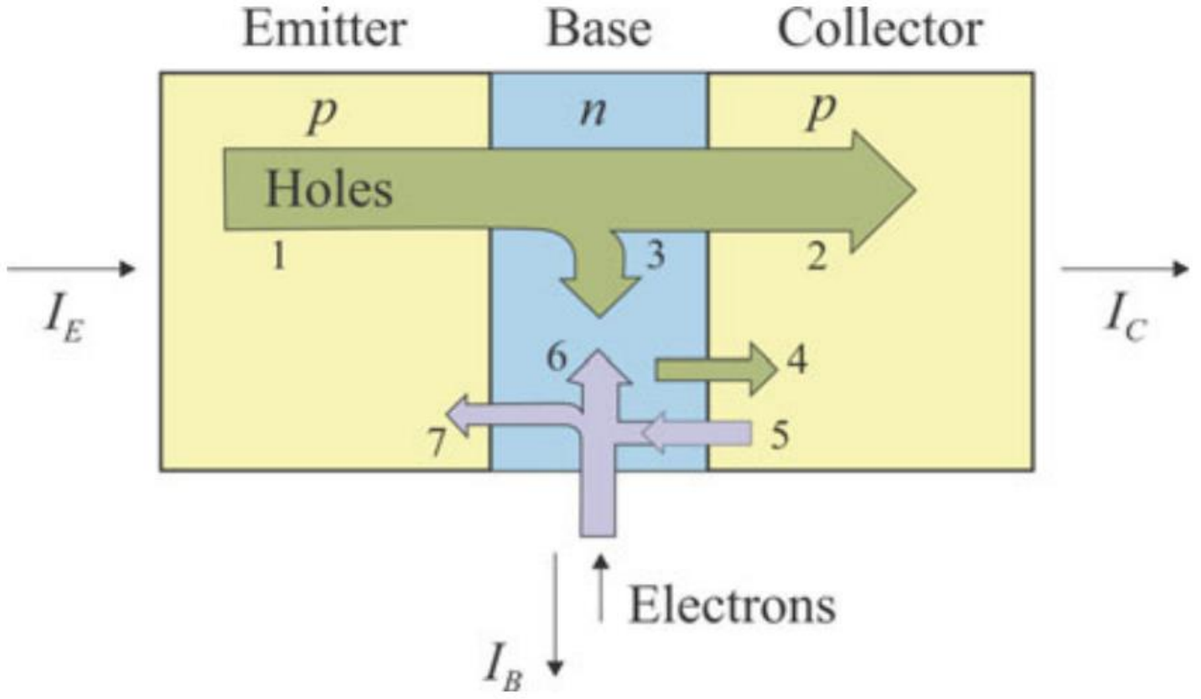


Fig. 7.4 Illustration of the flow of electrons and holes in a *p-n-p* transistor: 1-Holes in drift motion in the emitter; 2-Holes that reach the collector by diffusion; 3-Holes that disappear in the base due to recombination; 4 and 5-Holes and electrons thermally generated and that form the reverse saturation current of the collector junction; 6-Electrons that recombine with holes in component 3; 7-Electrons injected from the base into the emitter forming the current I_{En}

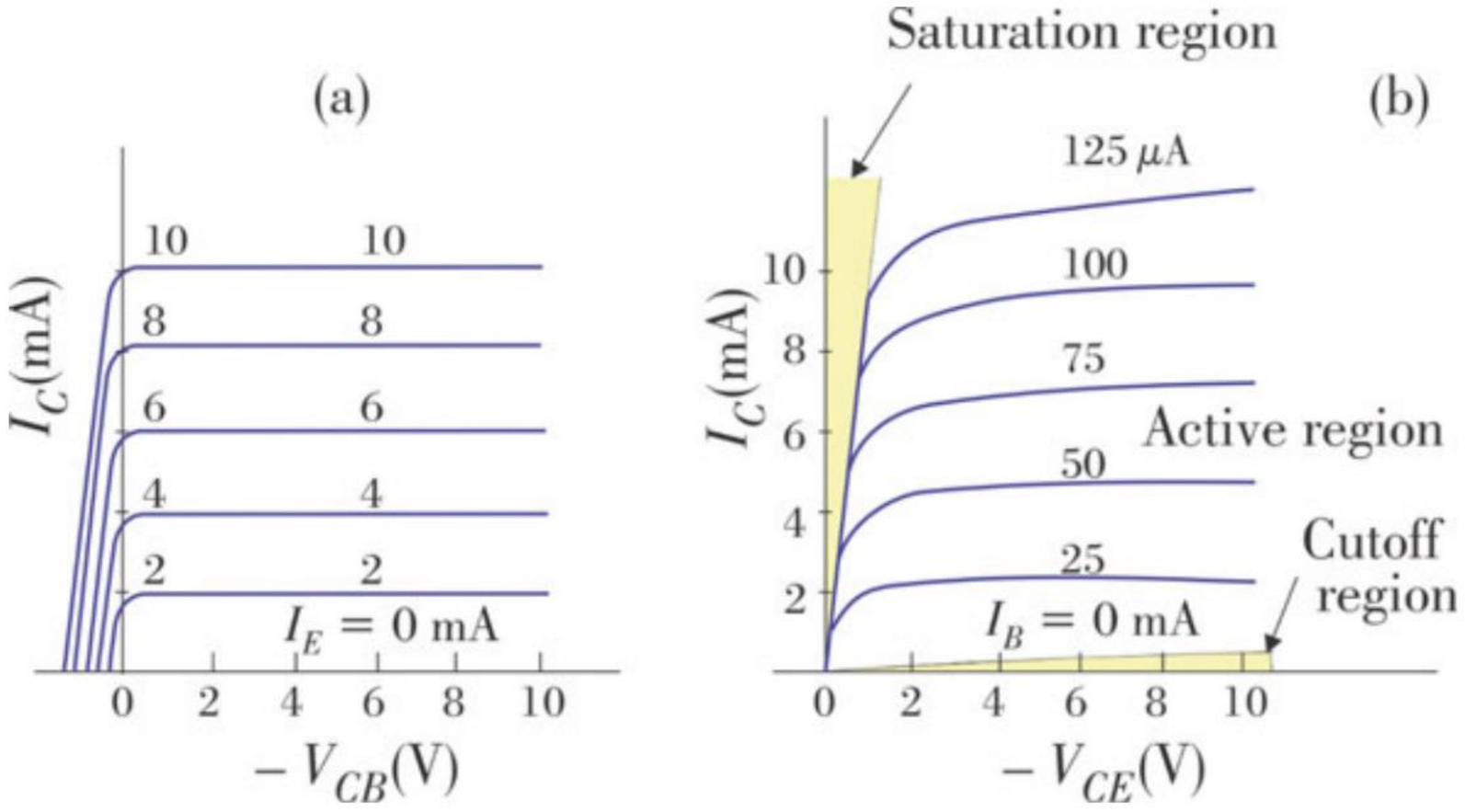


Fig. 7.7 *I-V* characteristic curves of a *p-n-p* transistor: **a** curves with I_E as a parameter used in the common-base configuration; **b** curves with I_B as a parameter for common-emitter configuration

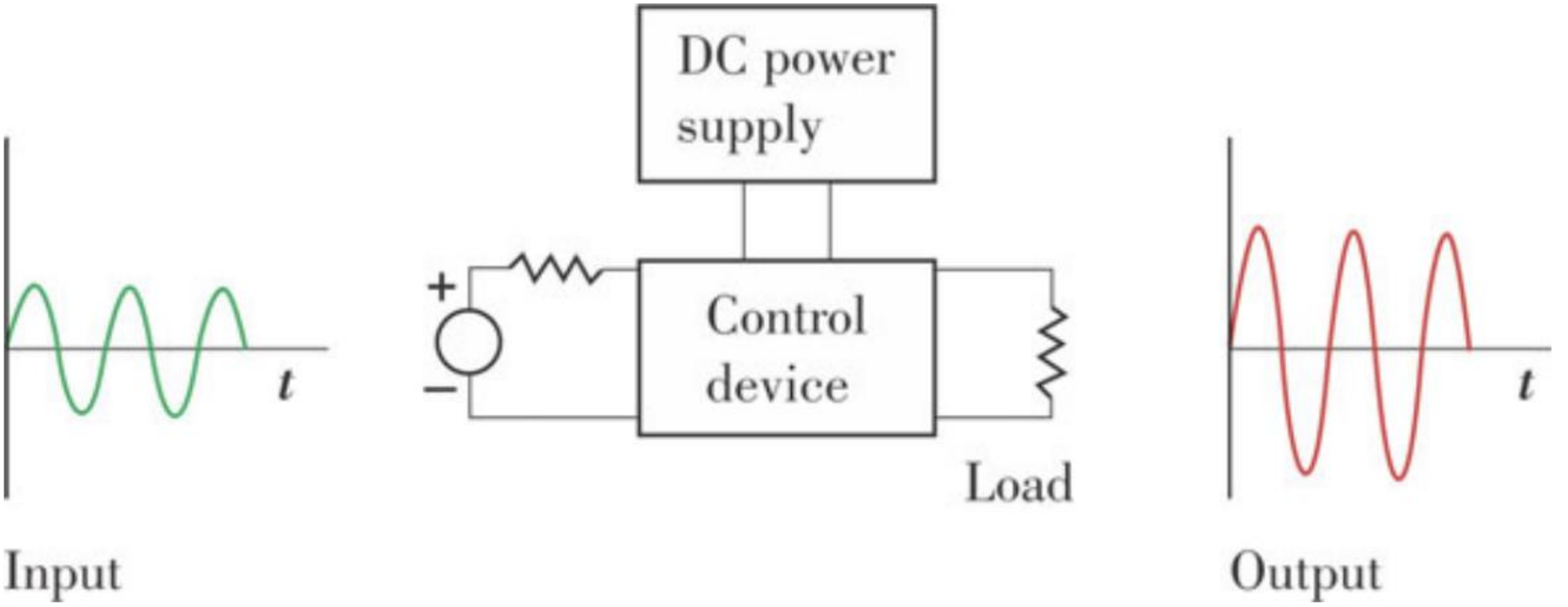
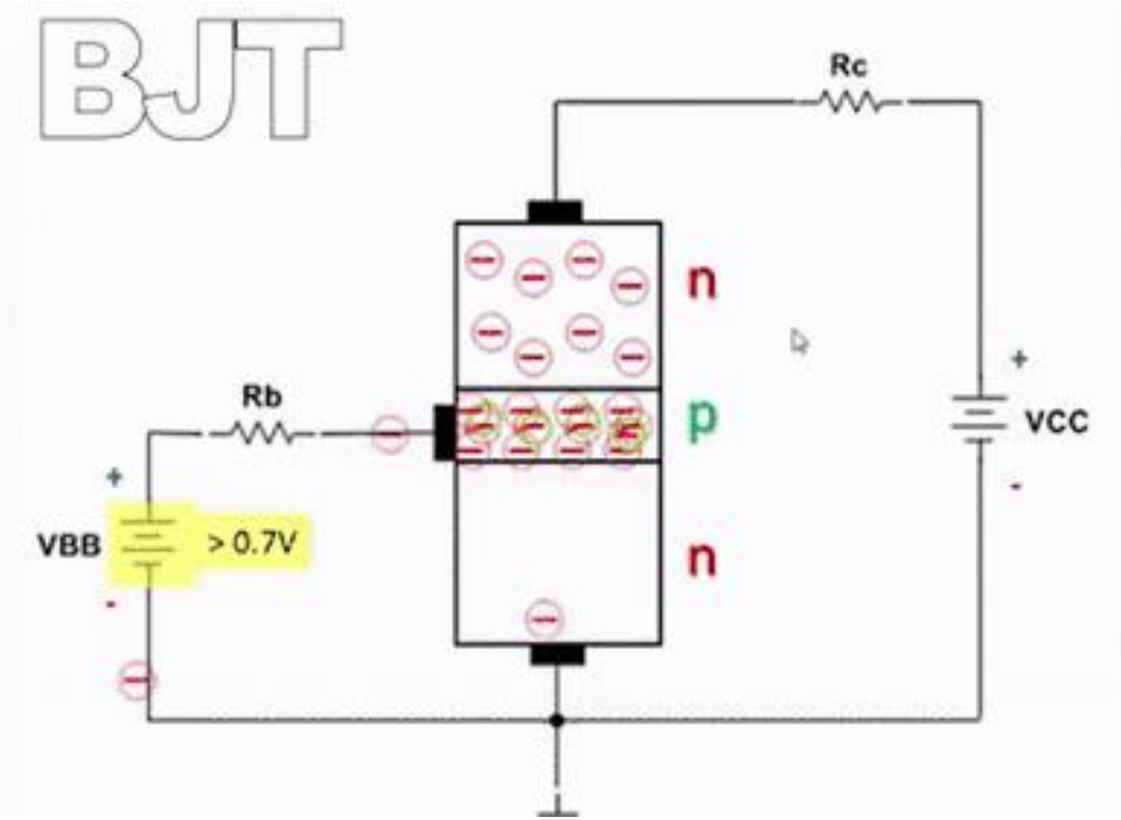
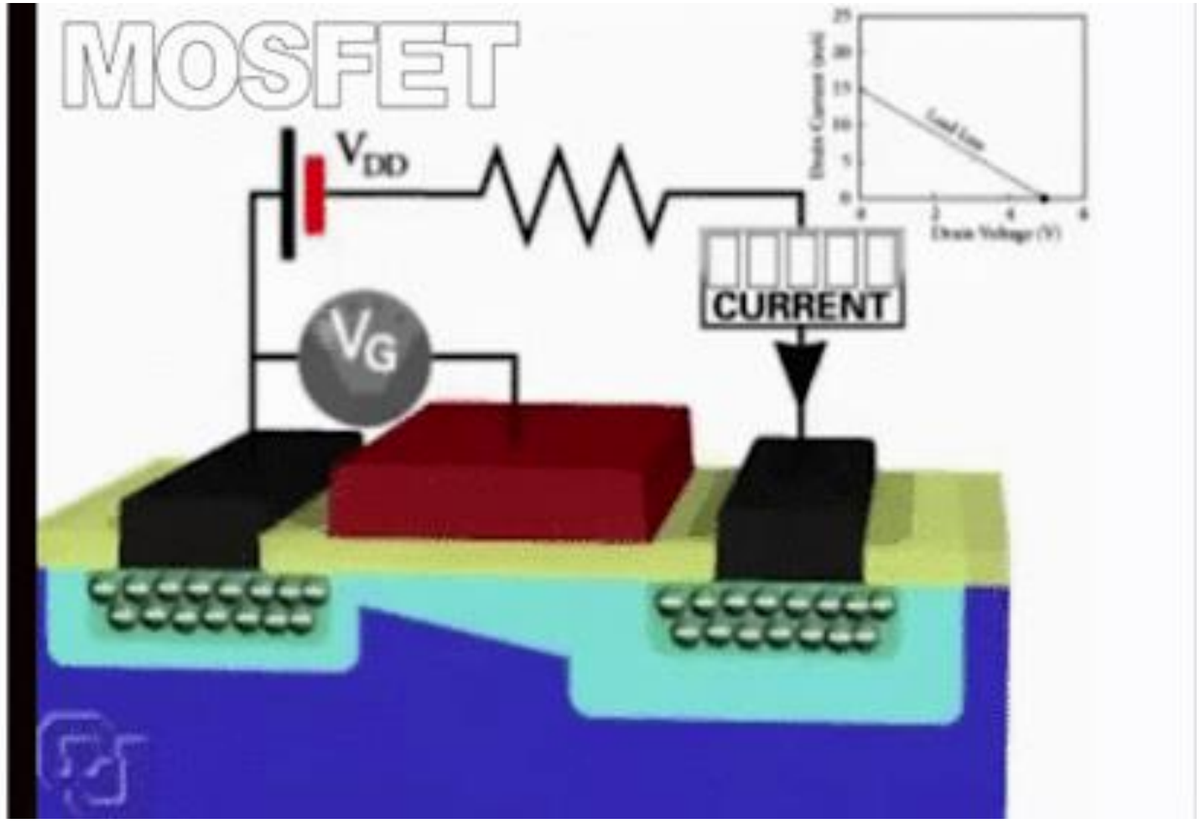


Fig. 7.1 Input and output signals in an amplification device, such as a transistor

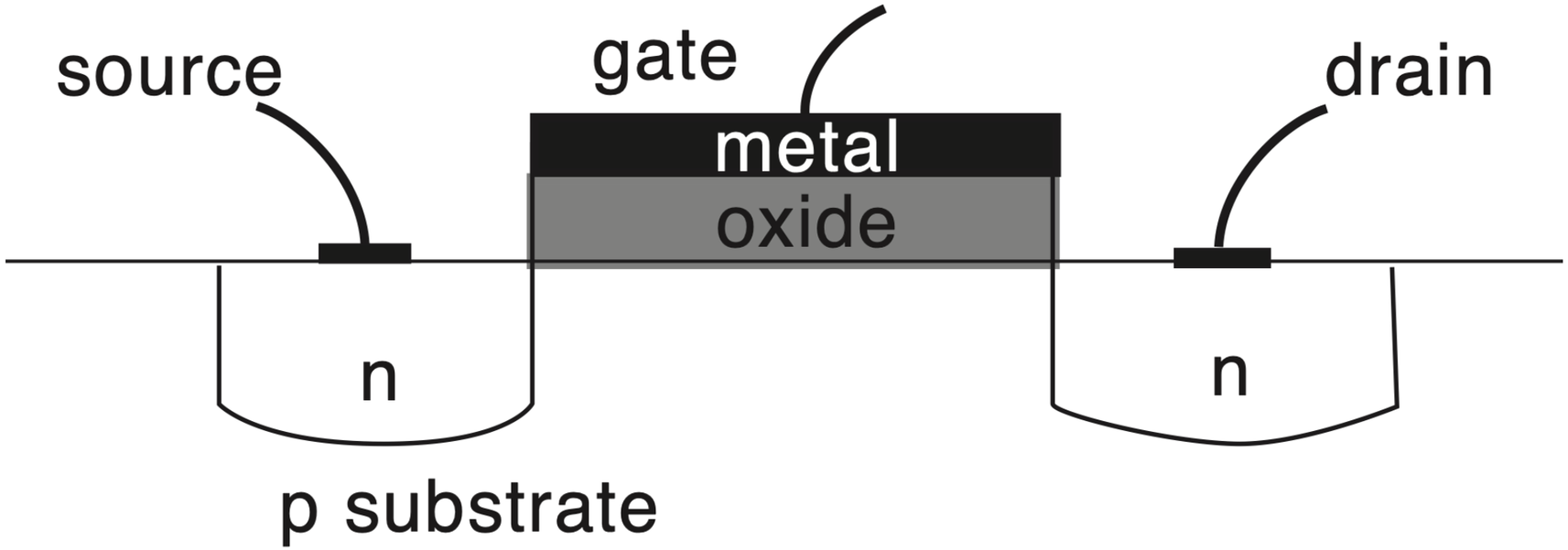
Transistor - funcionamento





The Metal Oxide Field Effect Transistor (MOSFET)

ideia geral: controlar a condutividade de um semicondutor por uma tensão corrente da fonte para o dreno, controlada pela tensão na porta.



O transistor de efeito de campo: princípio de operação

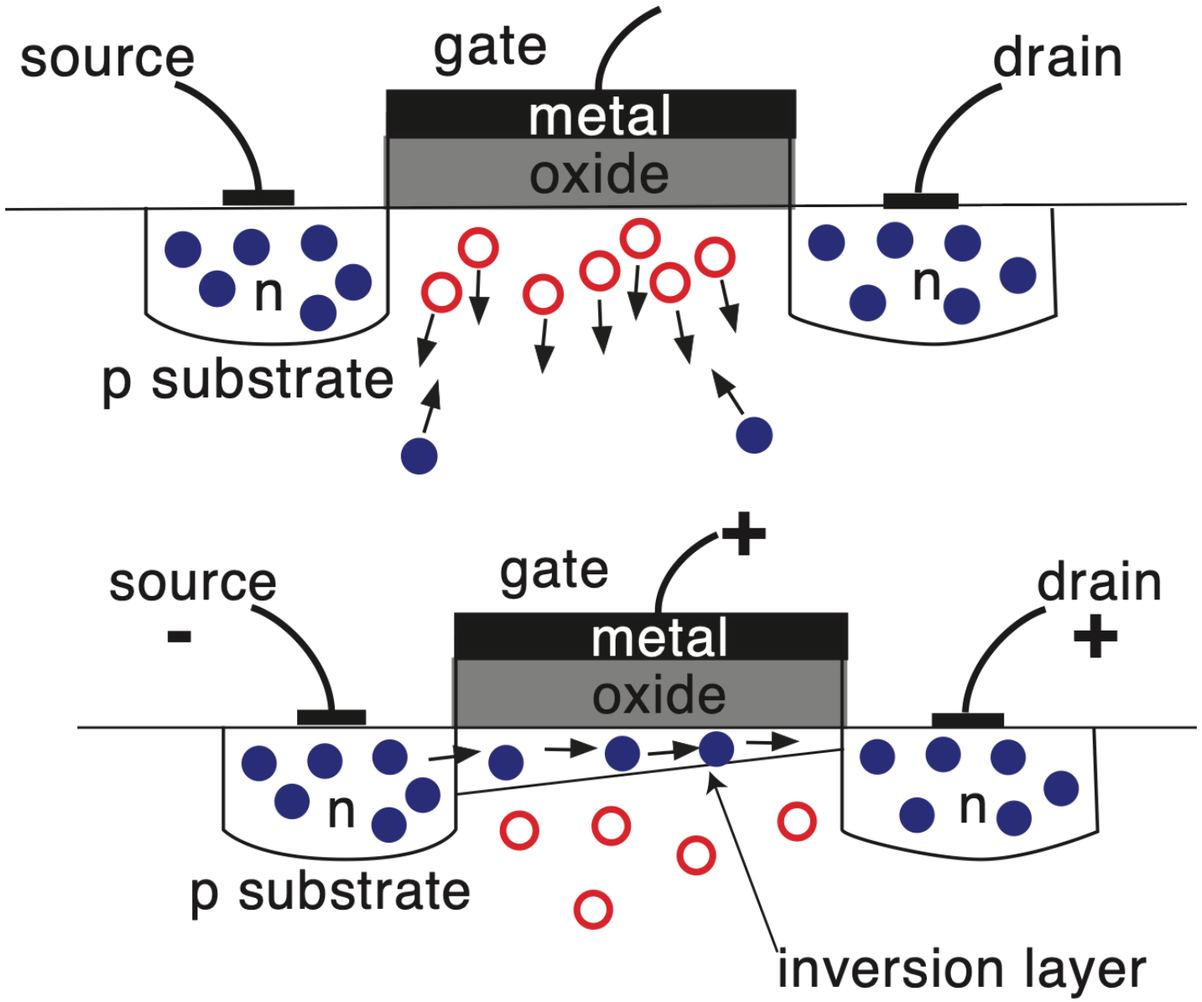
a tensão positiva repele os buracos da maioria e atrai a minoria elétrons

uma camada de inversão é formada que conduz.

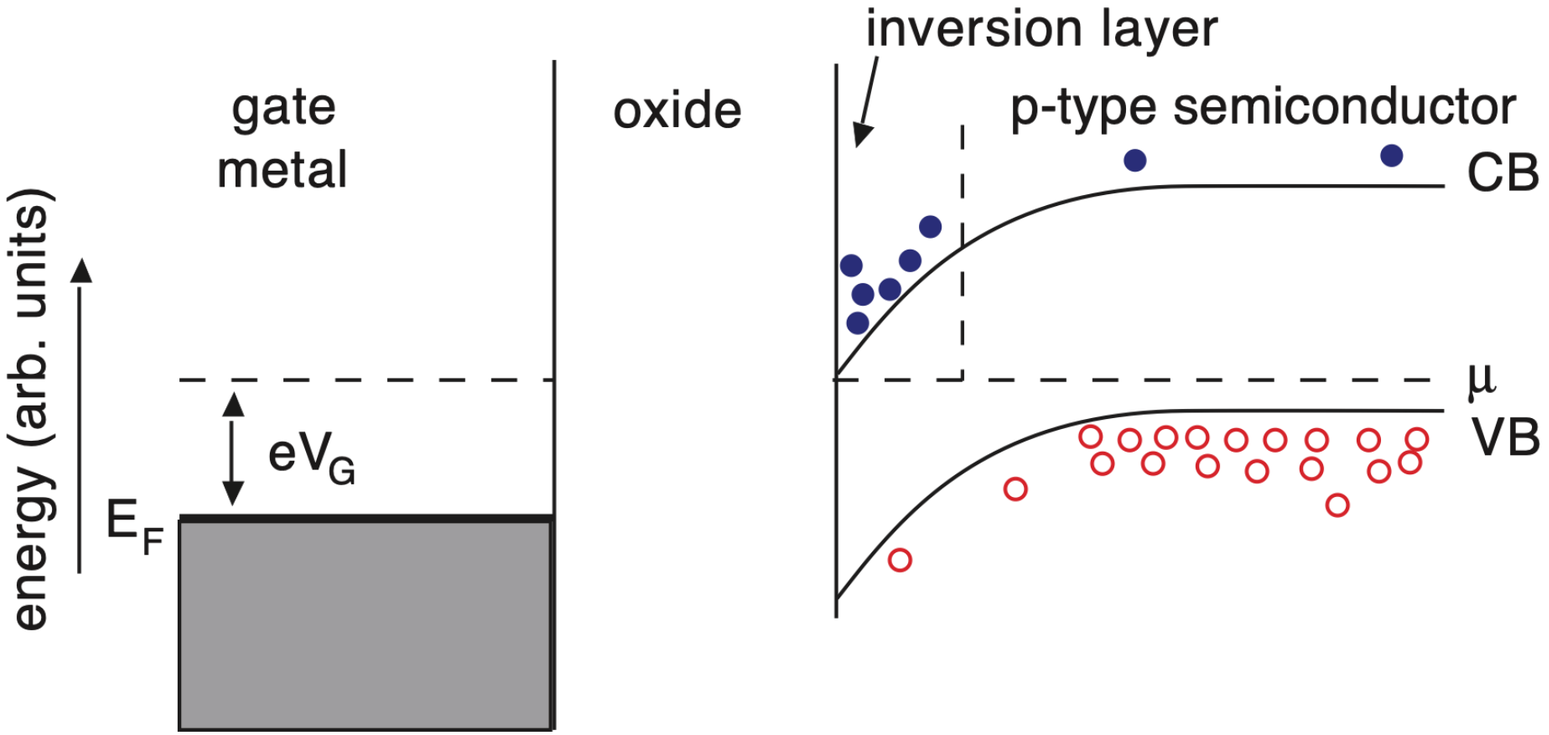
camada de inversão: alta densidade eletrônica: assimétrico porque a superposição do campo E aplicado e do campo E intrínseco das junções

$U_{gate} > U_{threshold}$

Acima da tensão limite: funciona como um interruptor

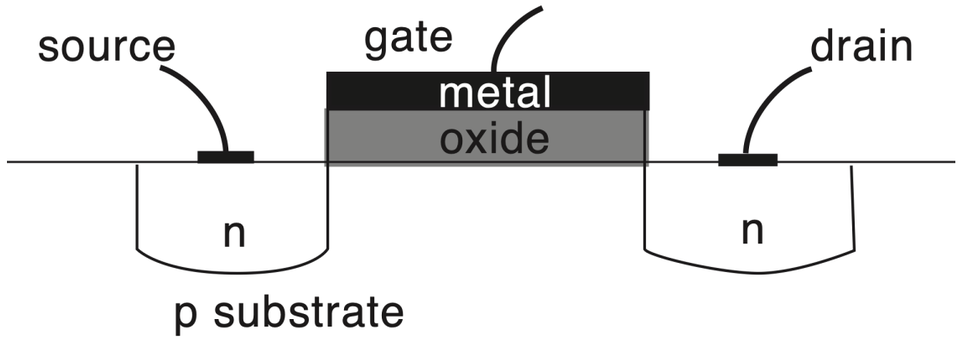


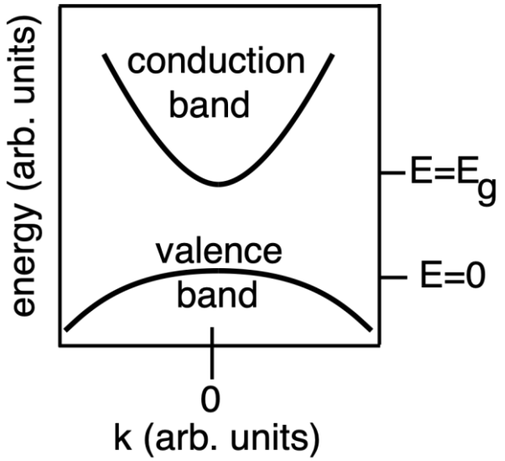
O transistor de efeito de campo: princípio de operação



A tensão da porta induz uma flexão de banda próxima à interface.
Para uma tensão suficientemente alta, o CB está mais próximo do potencial químico do que o VB e o semicondutor mostra um comportamento do tipo n.

The Metal Oxide Field Effect Transistor (MOSFET)





MOSFETs pnp também são possíveis, mas eles têm a desvantagem de que a corrente é transportada pelos buracos.

Os buracos tendem a ser mais pesados que os elétrons na maioria dos semicondutores.

Interação com fótons

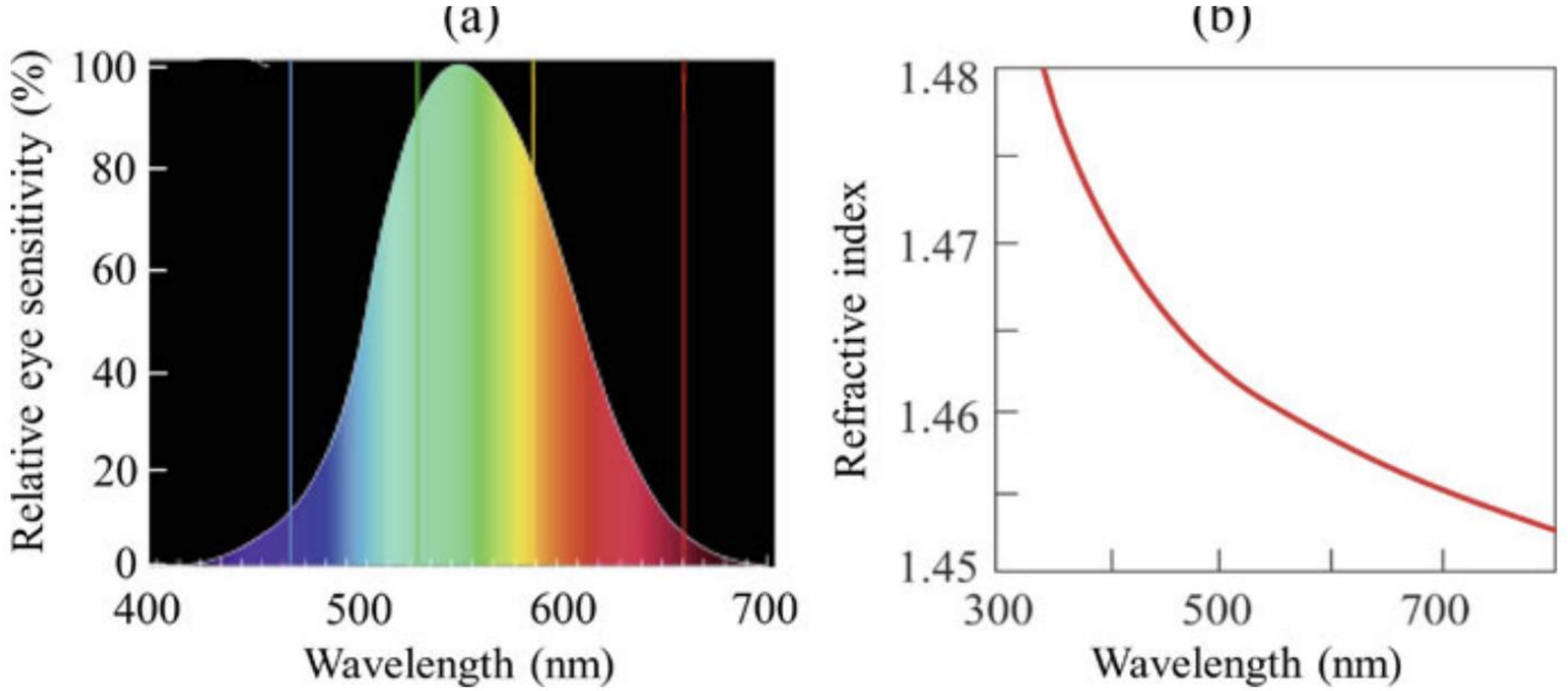


Fig. 8.1 **a** Relative sensitivity of the human eye as a function of the light wavelength (Wikipedia). **b** Variation of the refractive index of fused quartz with the wavelength

Interação com fótons

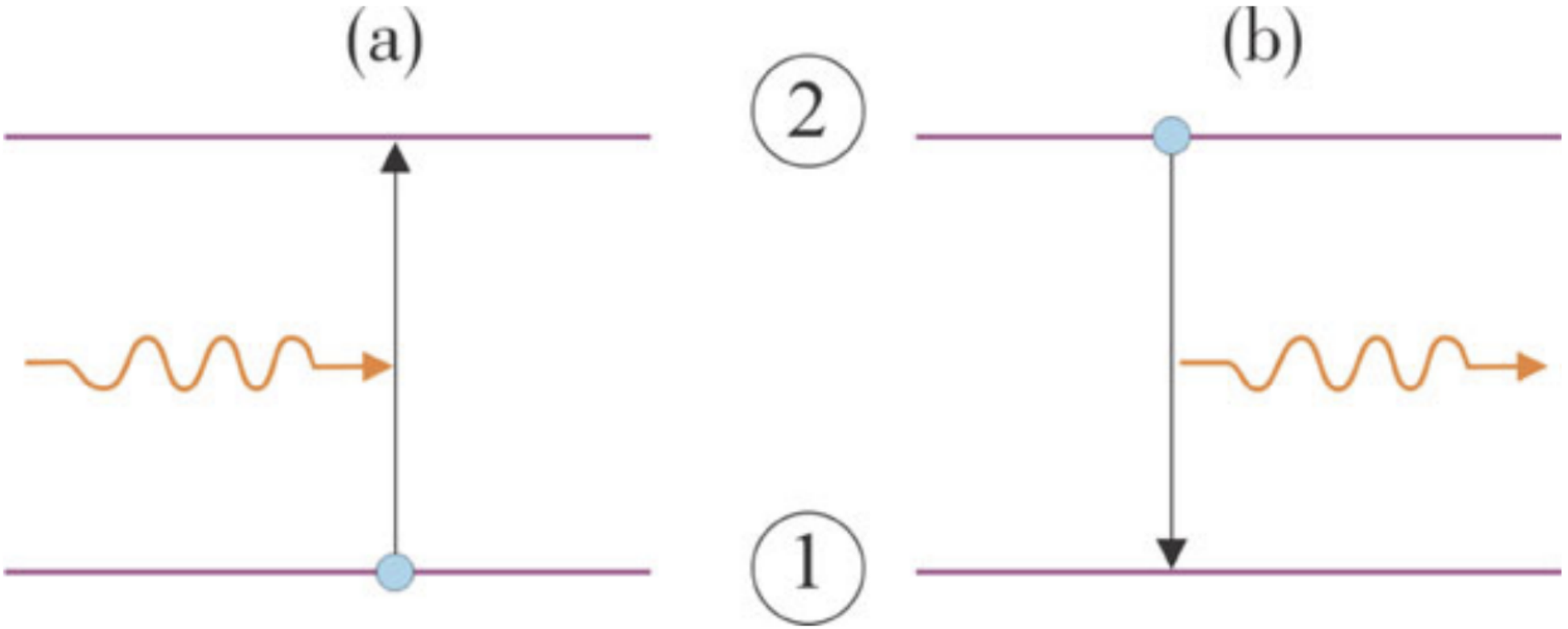
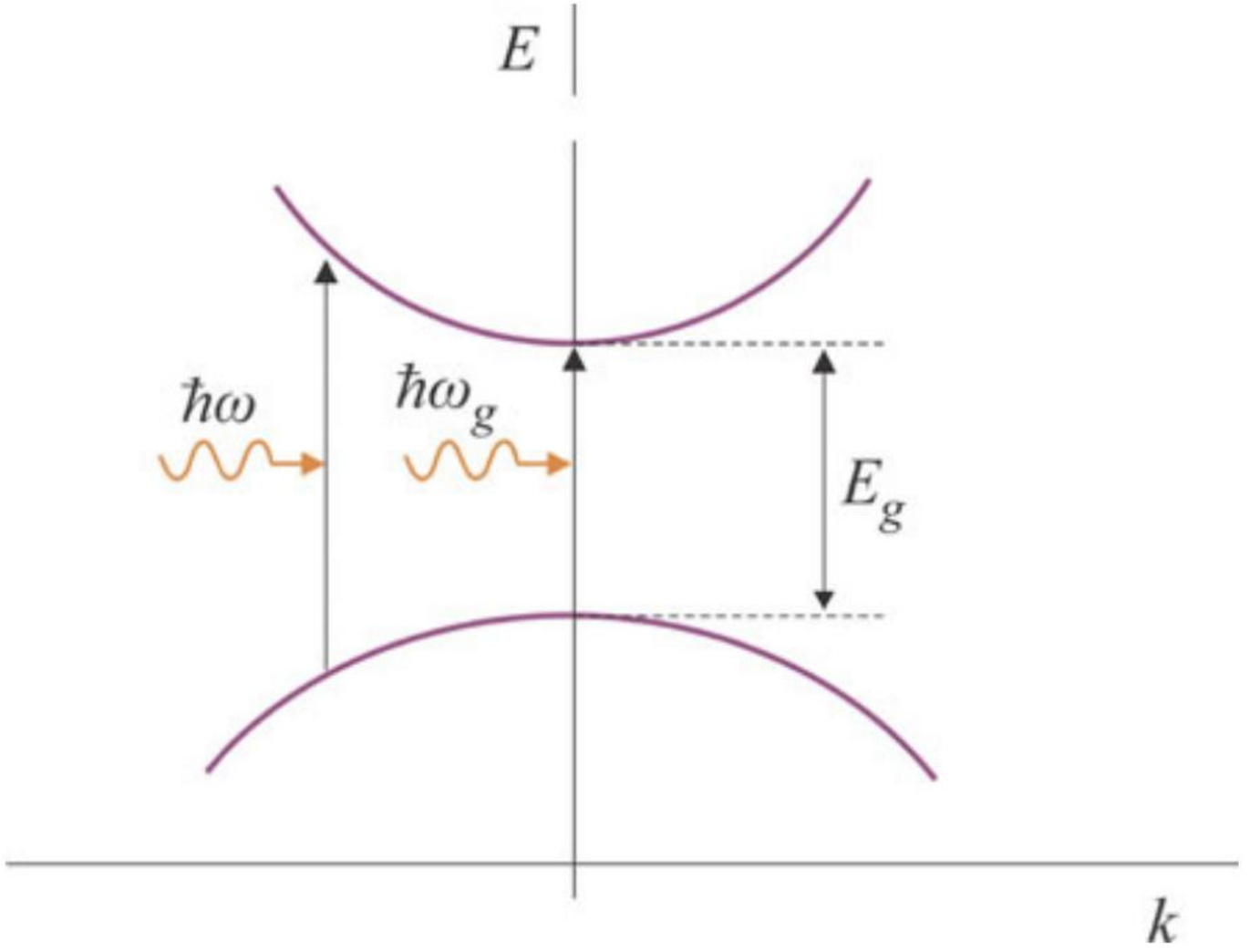


Fig. 8.7 Electronic transitions in a two-level system, by absorption (**a**) and by emission (**b**) of photons

Interação com fótons

Fig. 8.8 Photon absorption in direct gap semiconductors. The photon with minimum energy that is absorbed has frequency $\omega_g = E_g/\hbar$



Interação com fótons

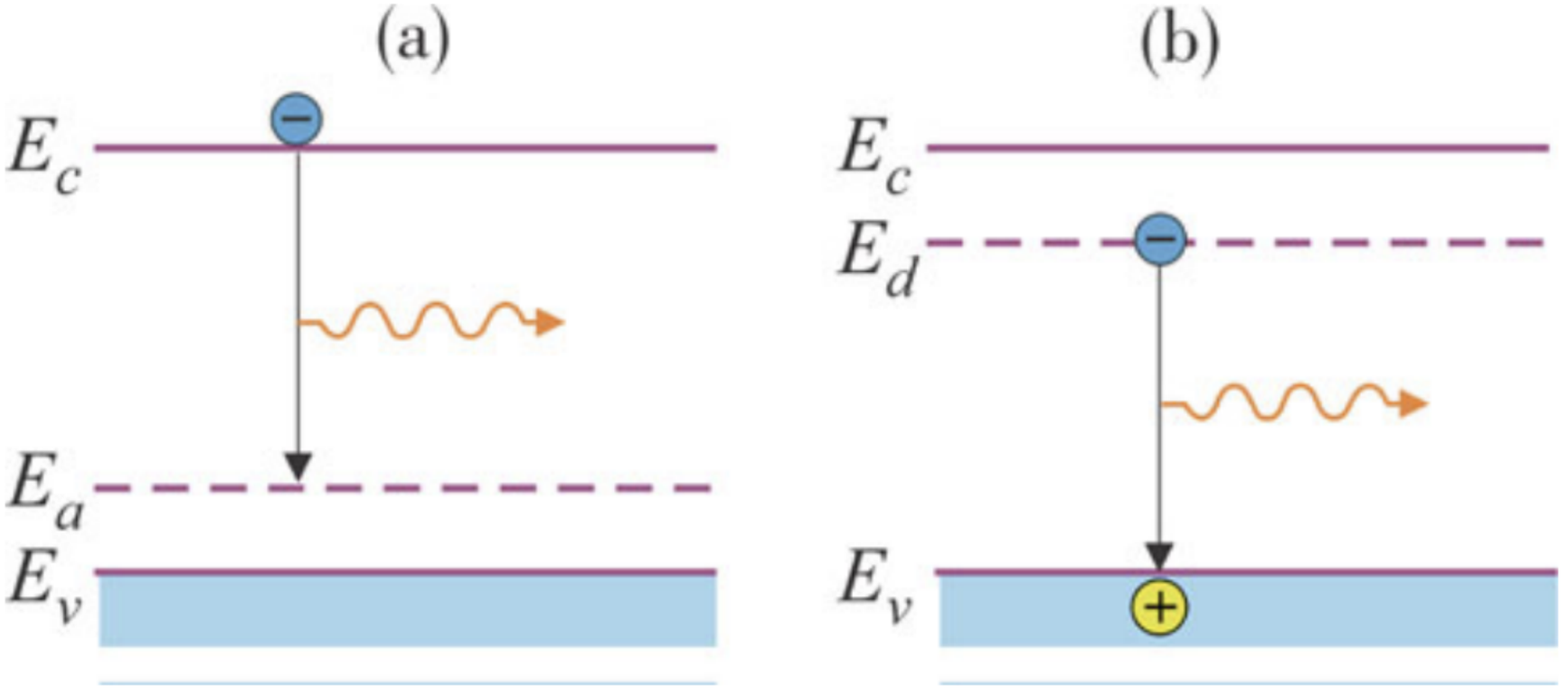
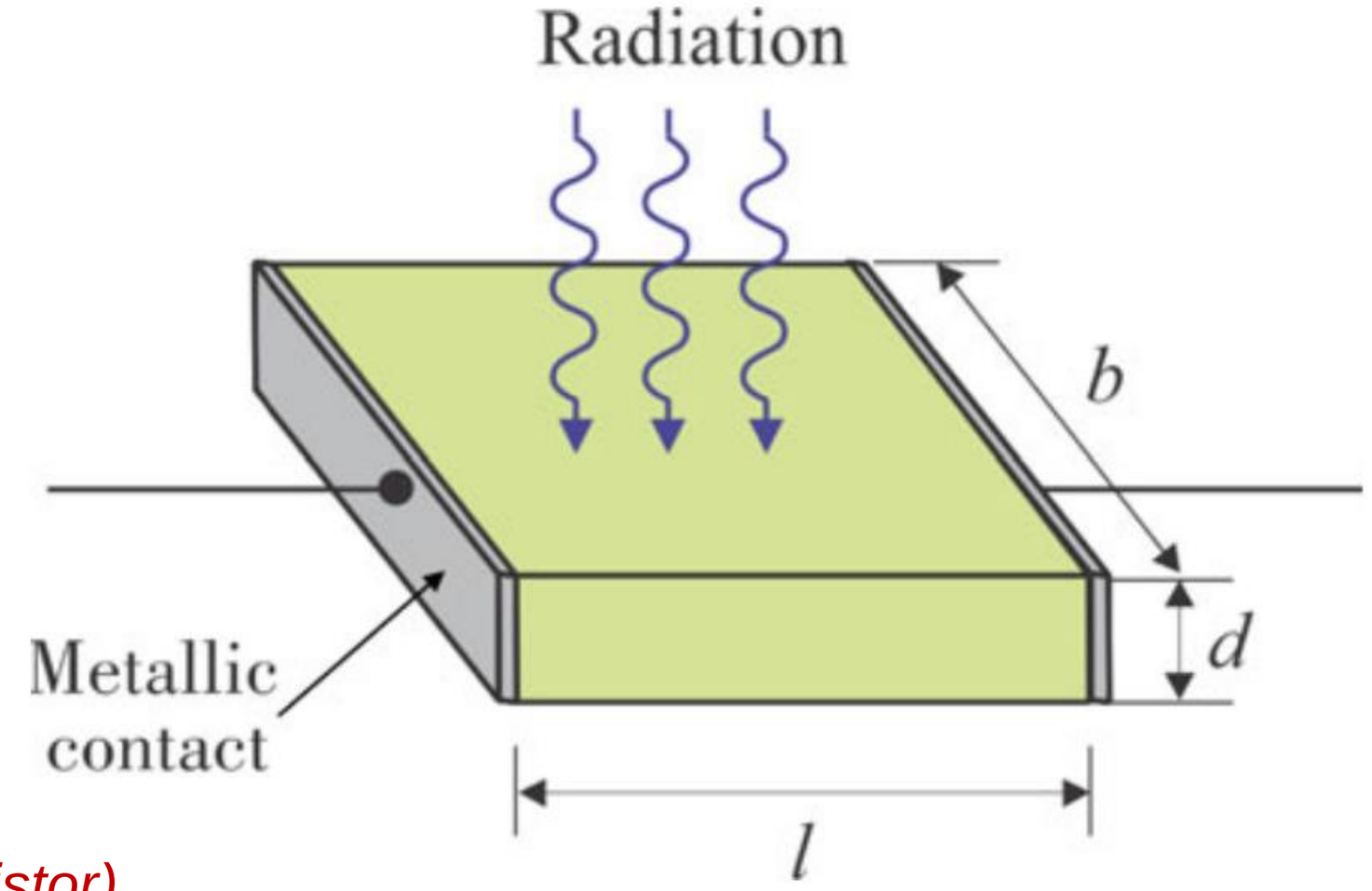


Fig. 8.13 Illustration of two types of electron–hole recombination involving impurity levels with emission of photons. **a** Acceptor impurity in *p*-type semiconductor. **b** Donor impurity in *n*-type semiconductor

Fotoresistor

Fig. 8.16 Simple structure of a photoresistor, or LDR



LDR (Light Dependent Resistor)

Fotoresistor

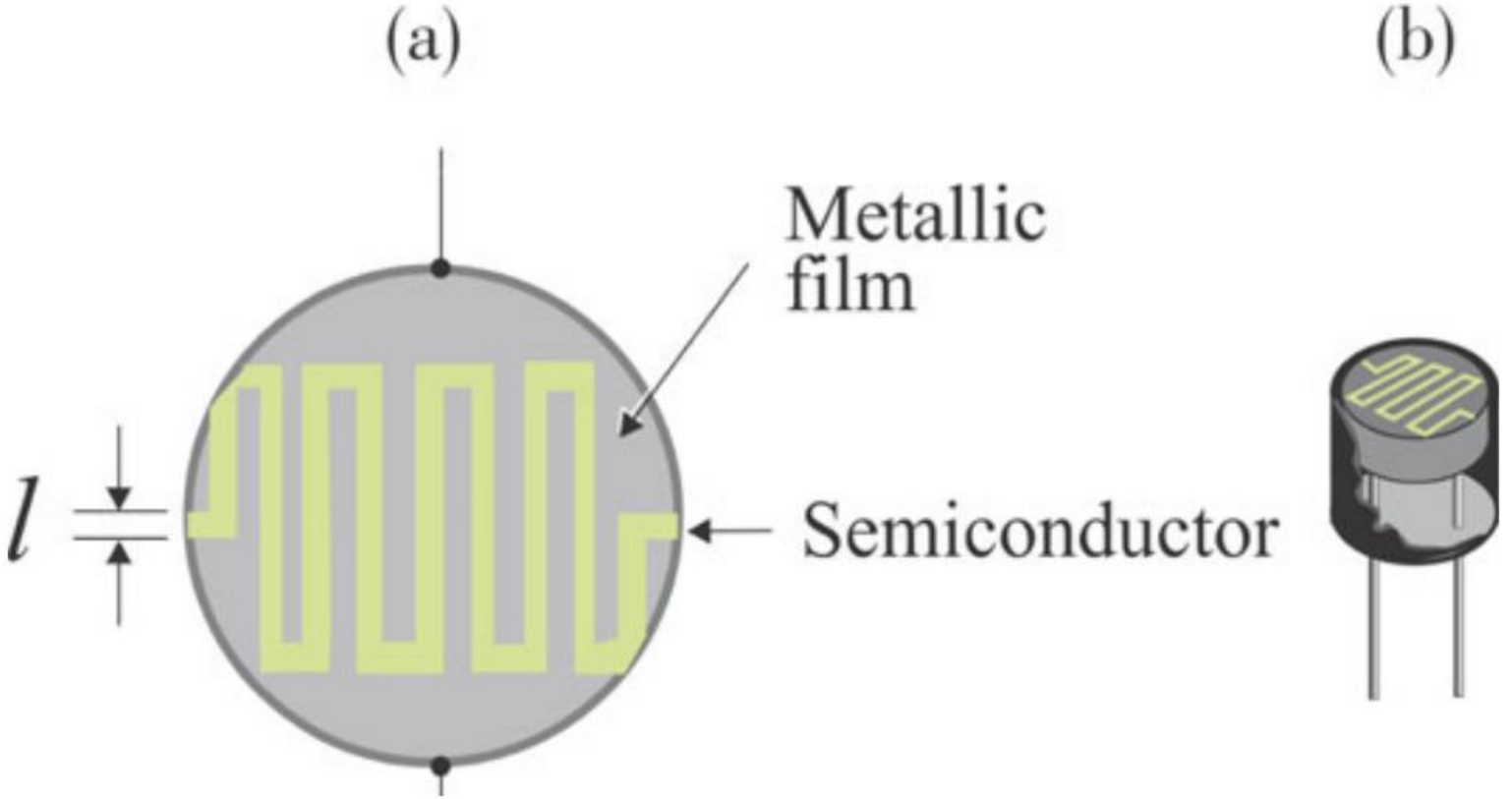
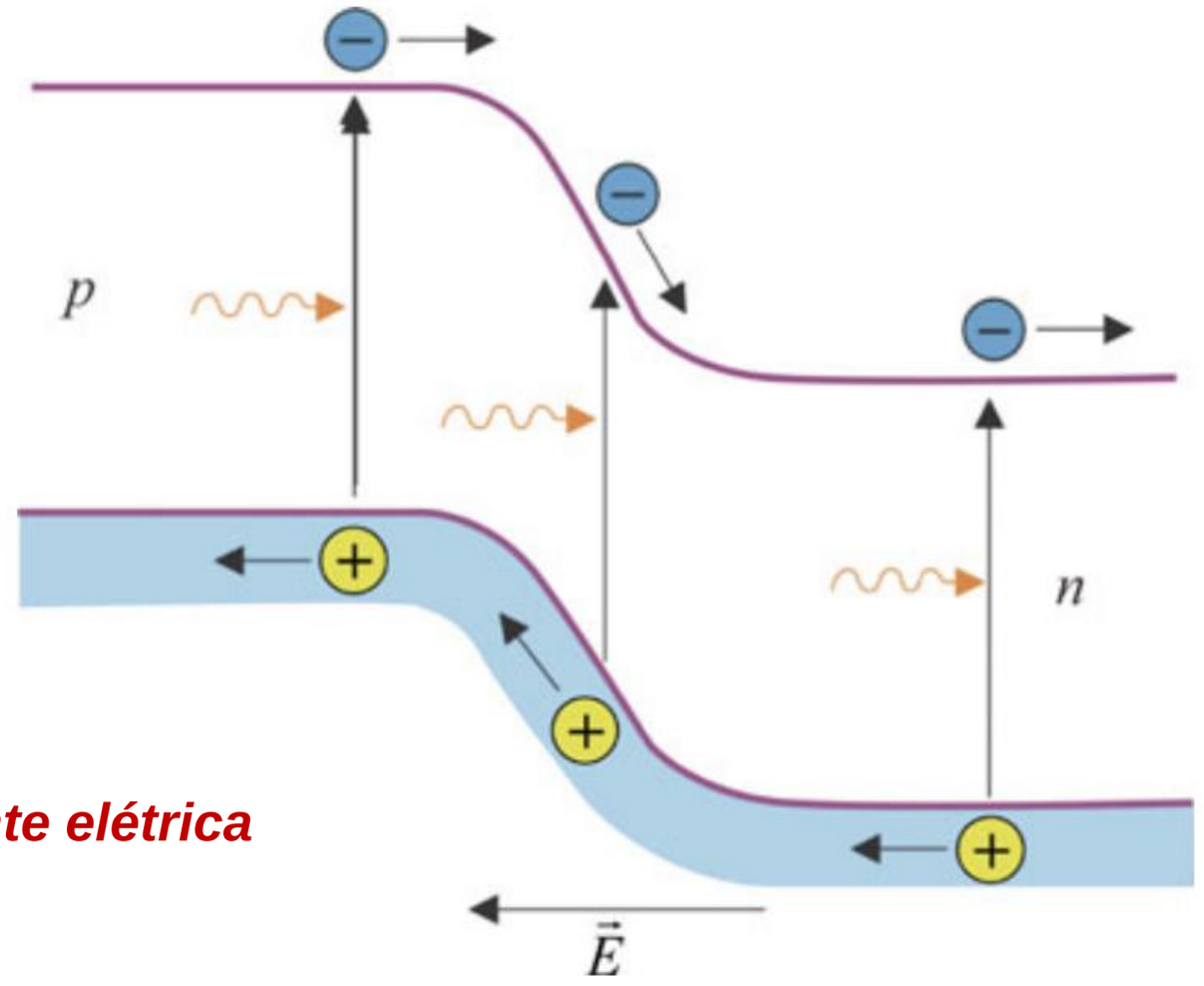


Fig. 8.17 **a** Top view of the photoconductive element with the metal electrode. **b** View of a typical commercial photoresistor

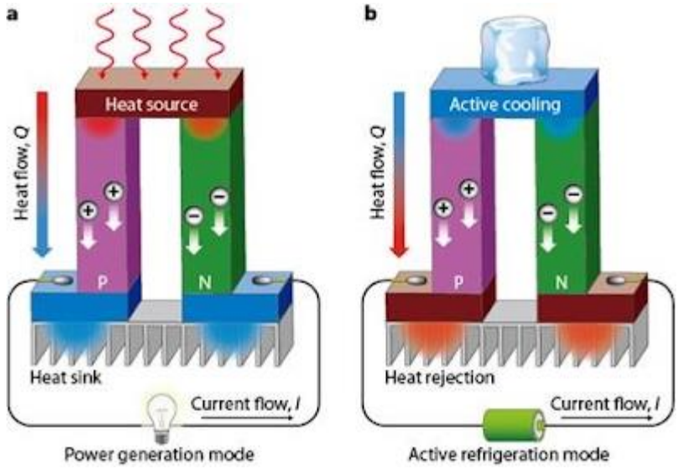
Fotodiodo

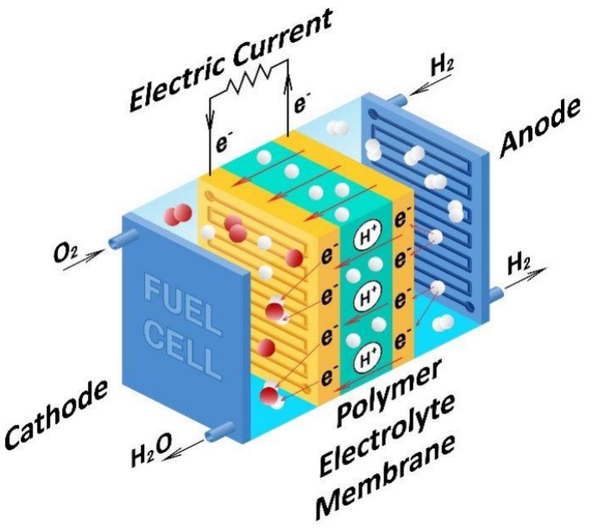
Fig. 8.19 Illustration of the electron-hole pair generation by absorption of photons in the depletion region of a *p*-*n* junction in a photodiode, followed by the acceleration of charges in opposite directions

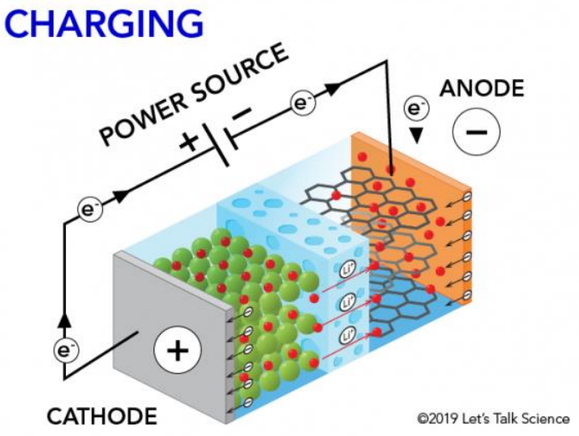


- ***diodo de junção***
- ***utilização da luz no controle da corrente elétrica***

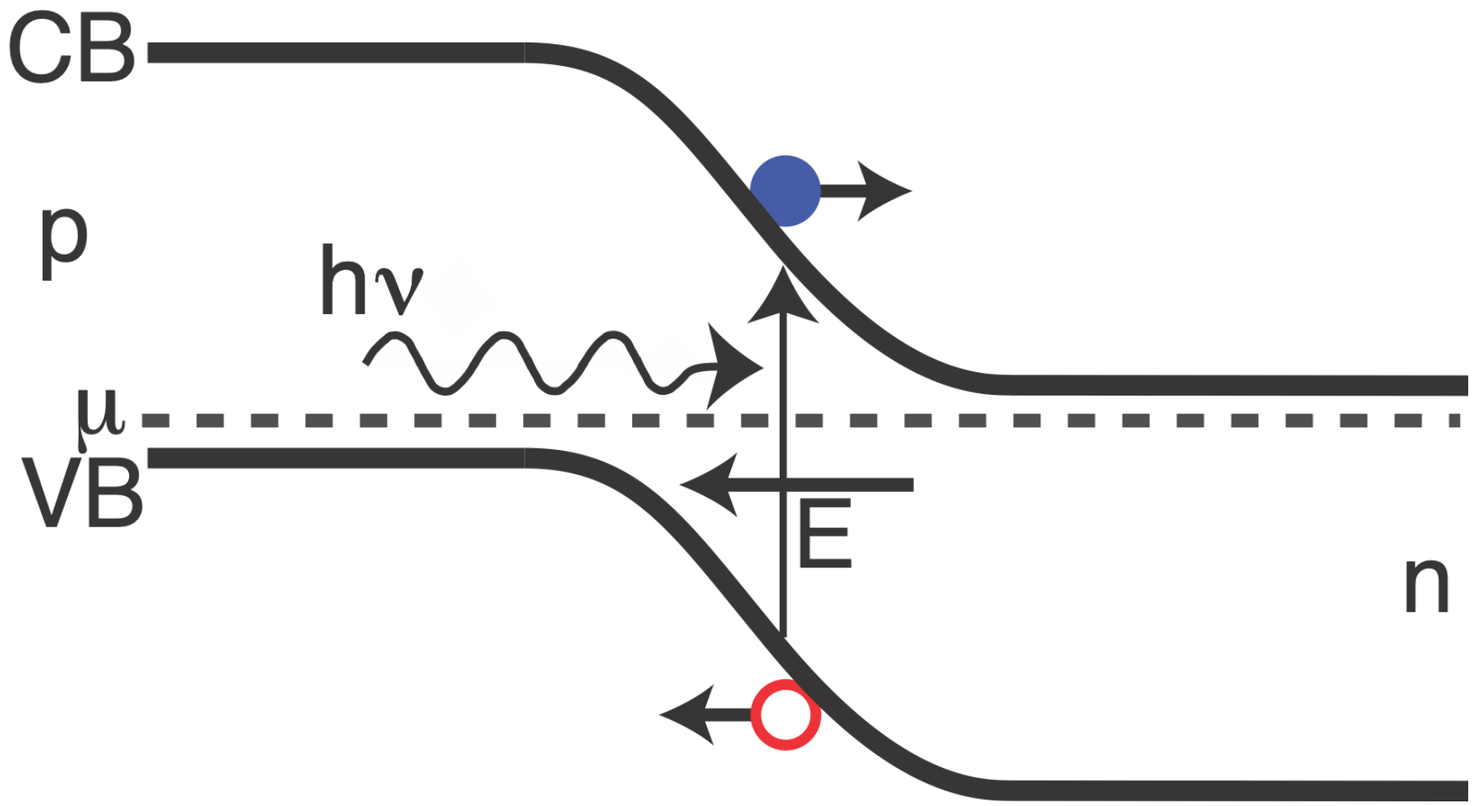
Dispositivos para energia







Célula Solar



tensão induzida por luz (corrente) para diodo com polarização reversa

Célula solar

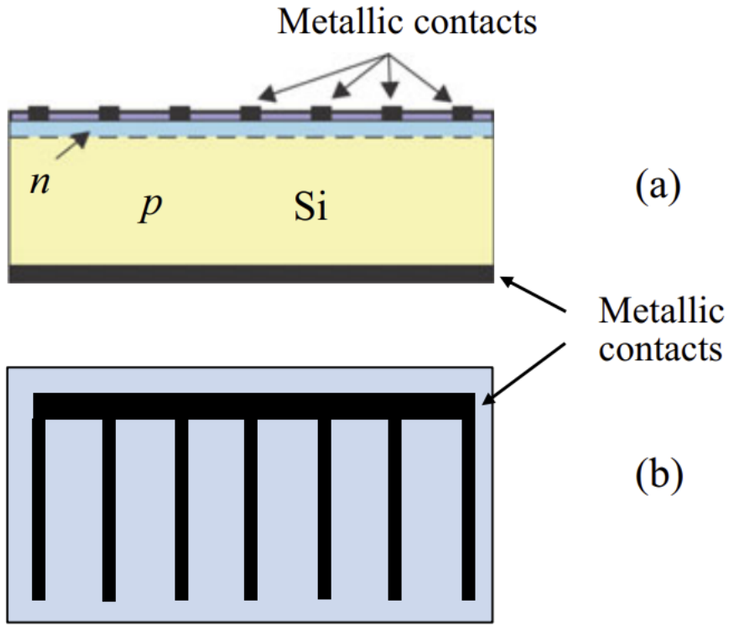


Fig. 8.26 Structure of a rectangular Si solar cell. **a** Cross section. **b** View from above

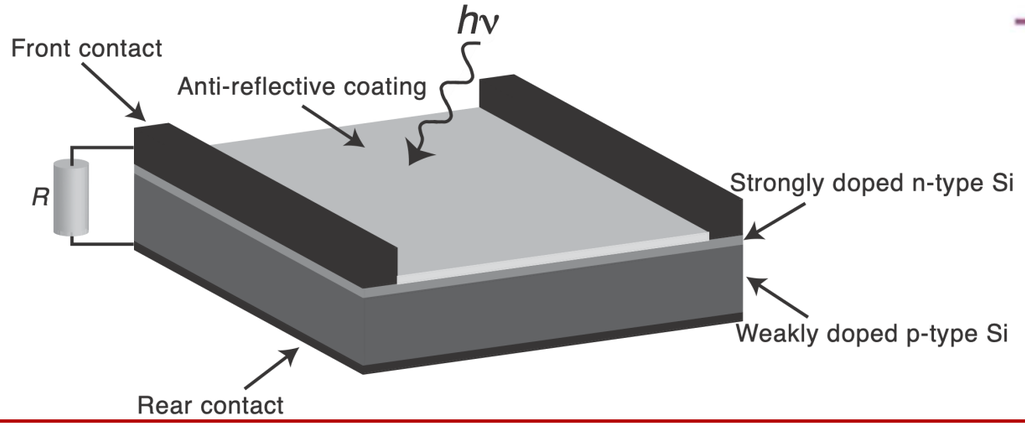
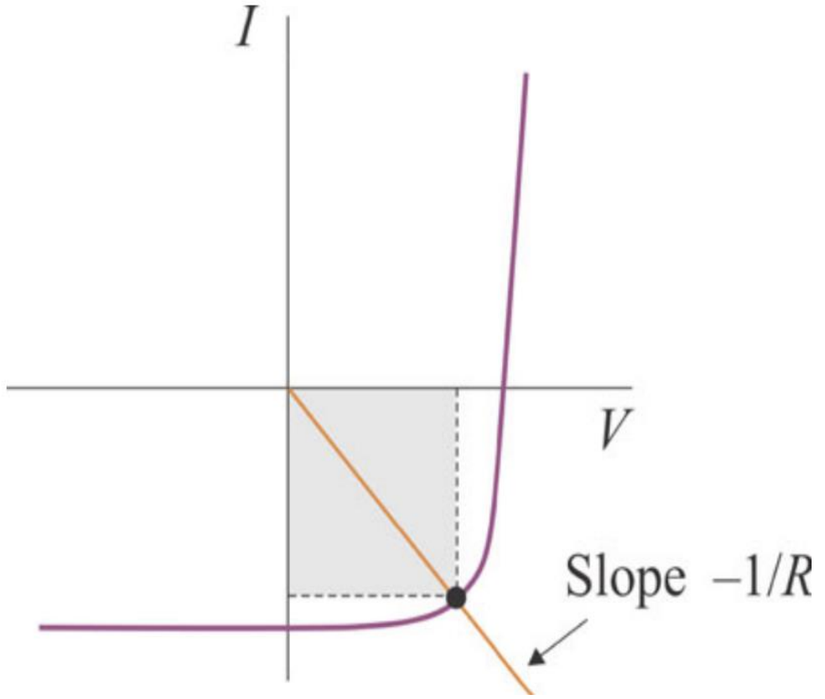
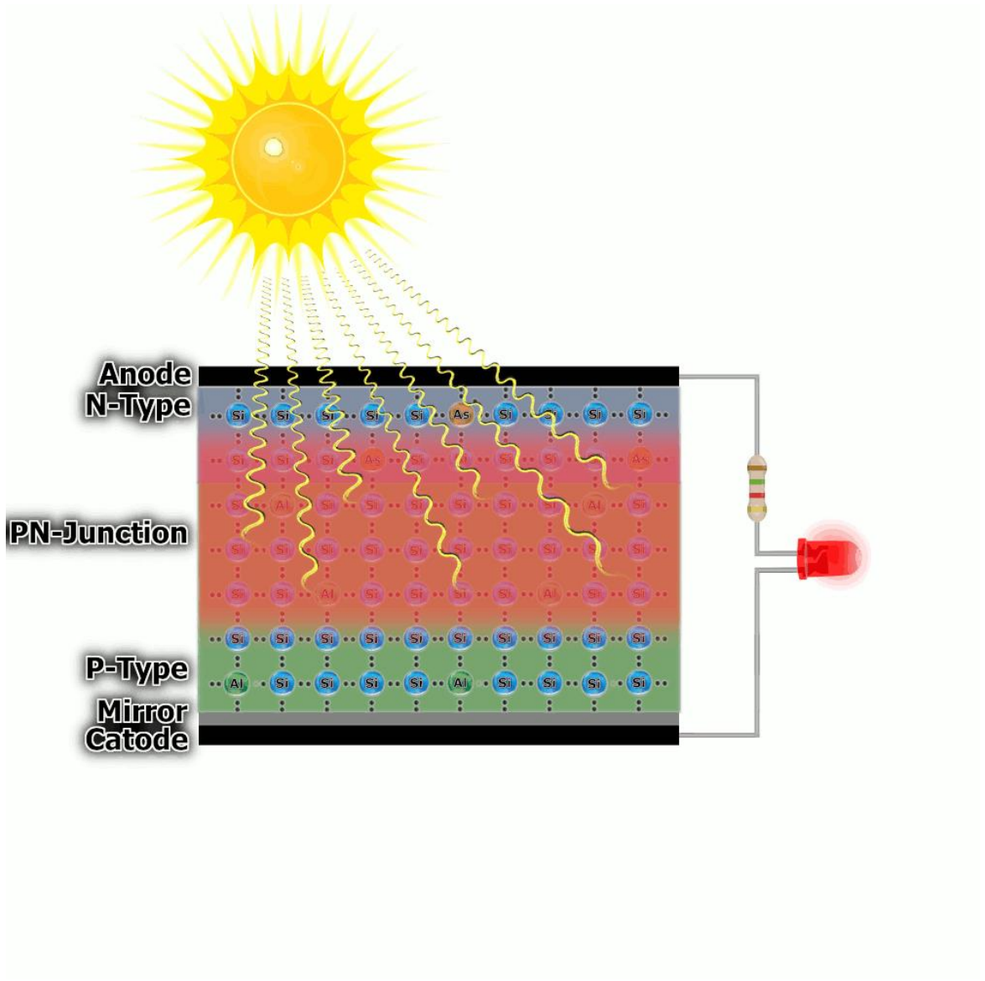
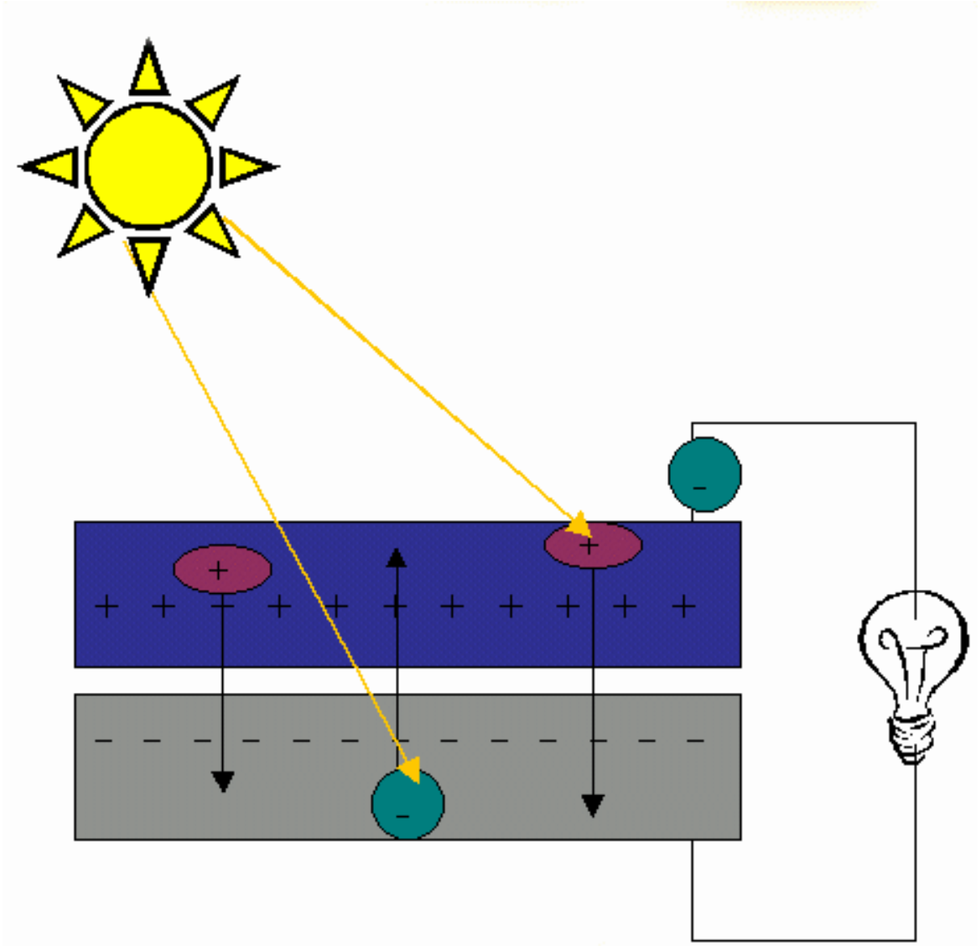


Fig. 8.25 Graphical determination of the operating point of a circuit with a solar cell in series with a resistor R_L

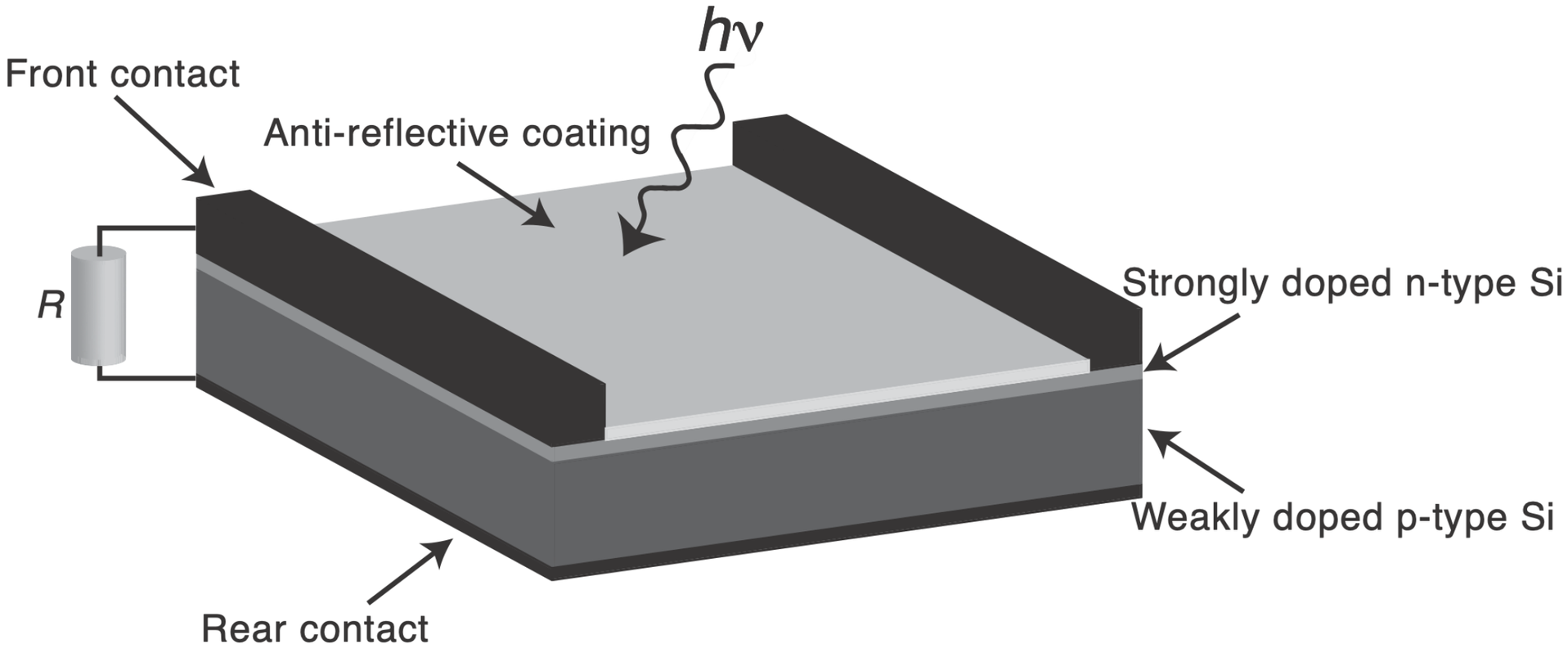


Célula solar





Solar cell


hν
Front contact
Anti-reflective coating
R
Strongly doped n-type Si
Weakly doped p-type Si
Rear contact

CCD (charge-coupled device) - Sensor de imagem
Nobel de Física – 2009 - Willard S Boyle and George E Smith)

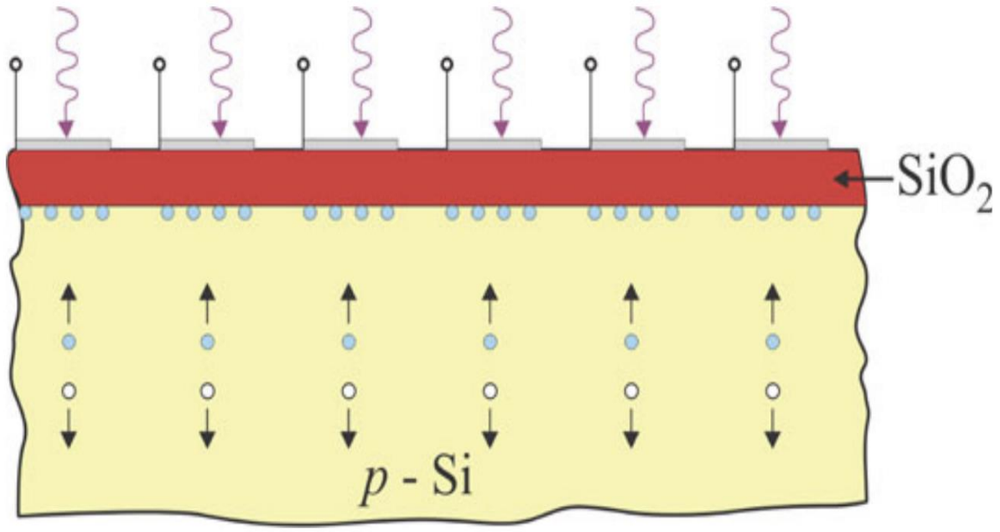


Fig. 8.27 Basic structure of a Si CCD image sensor

Luz visível: Si

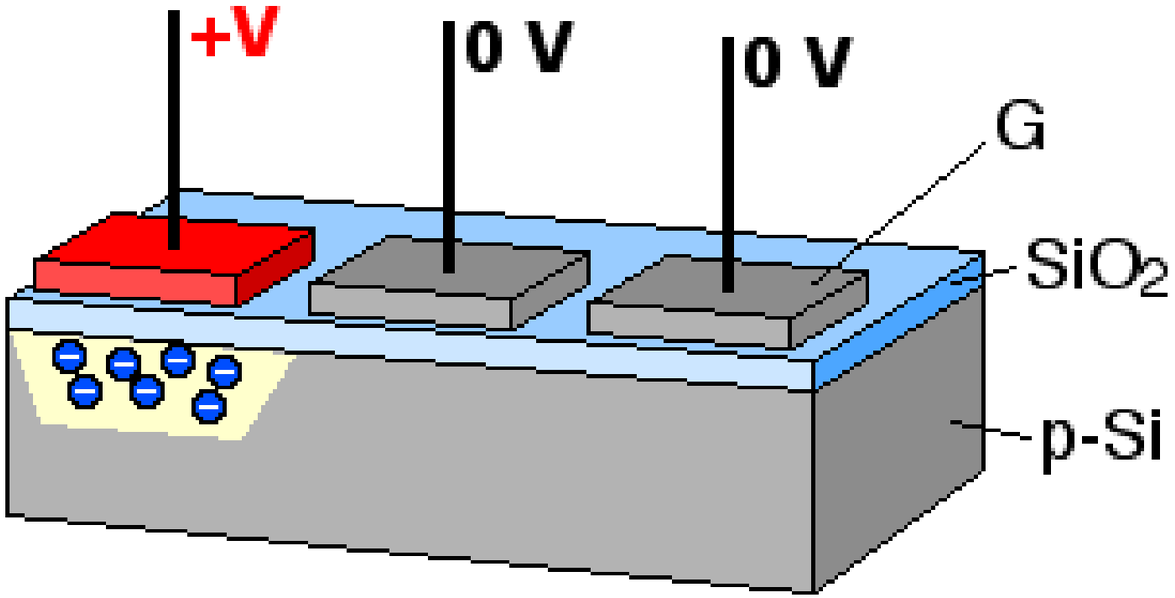
Infra-Vermelho: InSb e HgCdTe

1. A imagem é formada na área do dispositivo por meio do sistema óptico da câmera, fazendo com que um certo fluxo de fótons foque em cada pixel.

2. Os fótons com energia maior que o gap de energia criam na região próxima à superfície do semicondutor *pares elétron-buraco*, com uma taxa proporcional à intensidade da luz em cada pixel.

3. Uma tensão aplicada entre a porta e o eletrodo do outro lado da wafer atrai elétrons para a superfície e remove os buracos, que se difundem no substrato e são capturados no circuito externo.

CCD



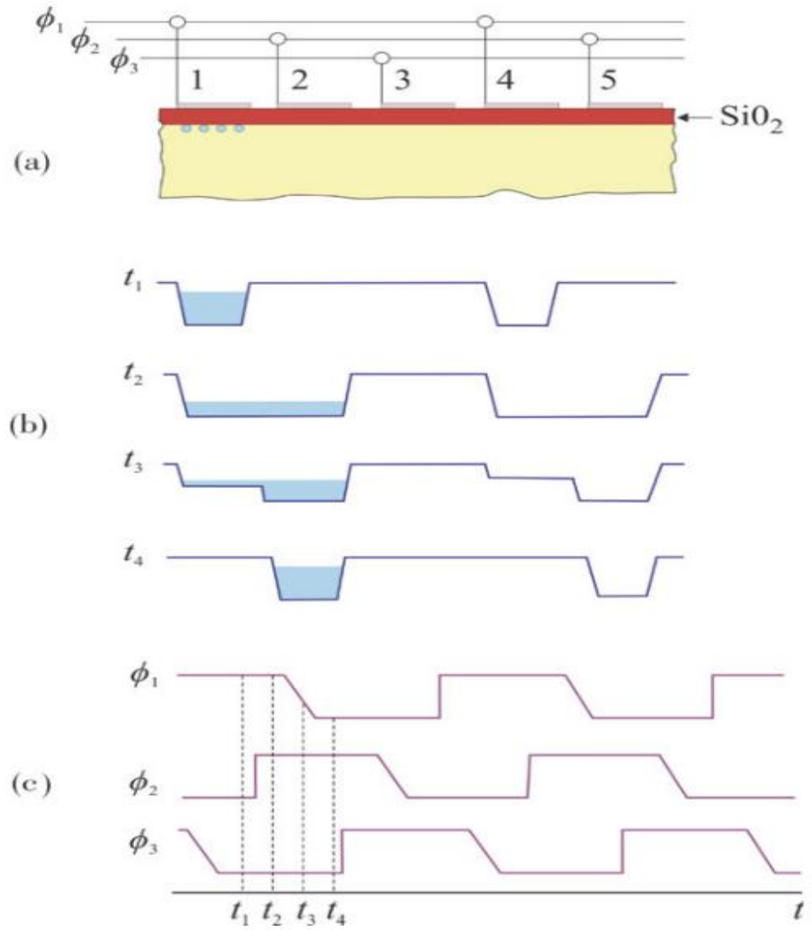


Fig. 8.28 Illustration of the charge transfer process in a CCD device. **a** MOS capacitor connections. **b** Variation in the electric potential of the charge distribution. **c** Variation in time of the potentials of the three lines

Durante um intervalo de tempo característico da operação do dispositivo (variando de 100 μs a 100 ms), pacotes de elétrons se formam sob cada porta do capacitor, cada um com carga total proporcional à intensidade da luz integrada no intervalo.

Após esse intervalo de exposição, as informações armazenadas em cada linha de capacitores na forma de pacotes de carga são deslocadas rapidamente até a borda da linha, produzindo um sinal de corrente elétrica correspondente à imagem na linha.

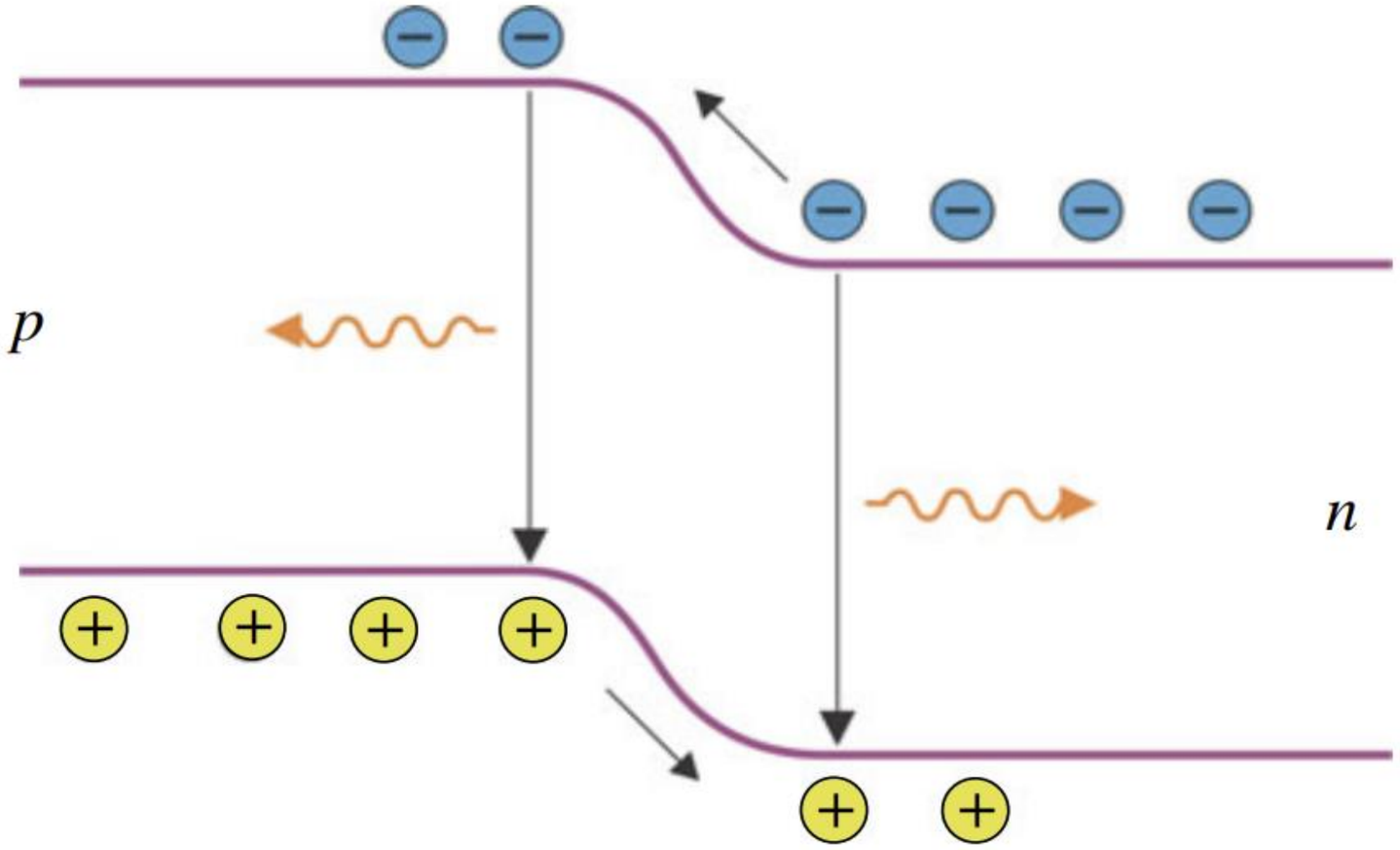
O sinal variável no tempo correspondente a uma linha é seguido pelo sinal da próxima linha, e assim por diante, em um processo de varredura vertical, de cima para baixo. O sinal correspondente ao conjunto de linhas forma um quadro.

A imagem estática é formada por apenas um quadro, enquanto uma imagem em movimento é formada por uma sequência de quadros, normalmente a uma taxa de 60 Hz.

A transferência dos pacotes de carga de cada capacitor para o final da linha é feita pela ação de uma sequência de pulsos de tensão, aplicados nas portas dos capacitores, em um processo característico de dispositivos de transferência, ou dispositivos de carga acoplada.

LED (Light emission diode)

Fig. 8.29 Recombination of electron–hole pairs with emission of photons in interband transitions, due to the injection of minority carriers in a forward biased *p*-*n* junction



LED (Light emission diode)

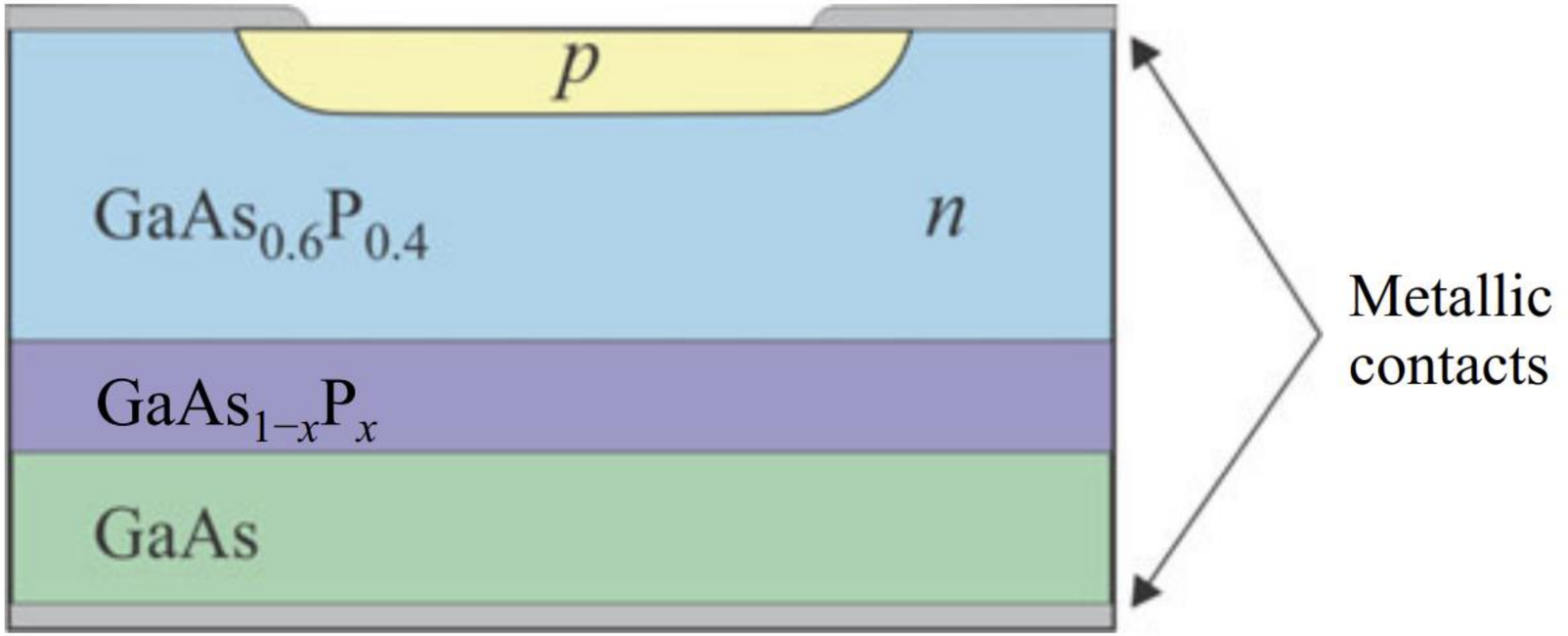
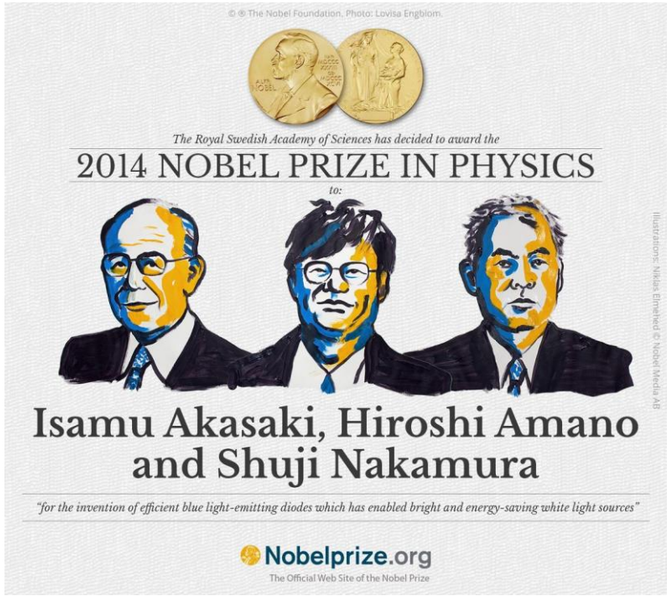
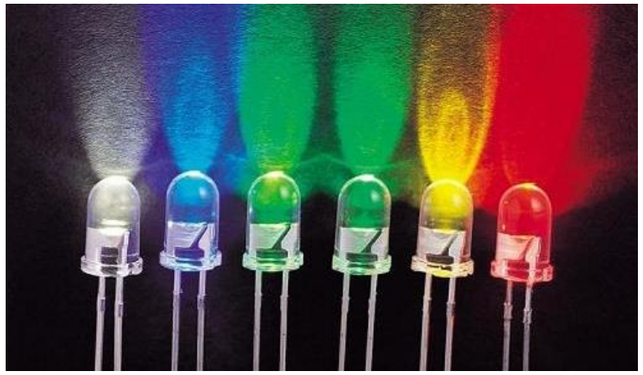
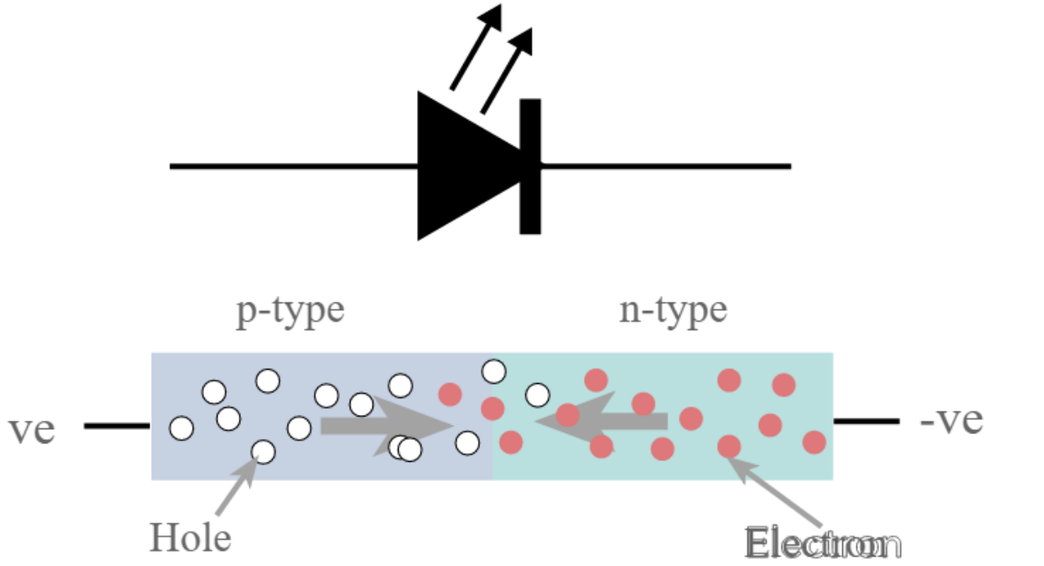


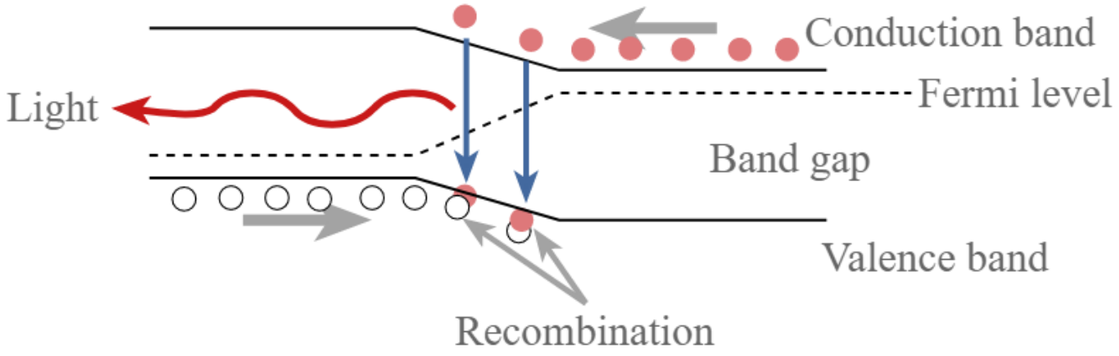
Fig. 8.30 Typical structure of a light emitting diode (LED)

LED (light-emitting diode)

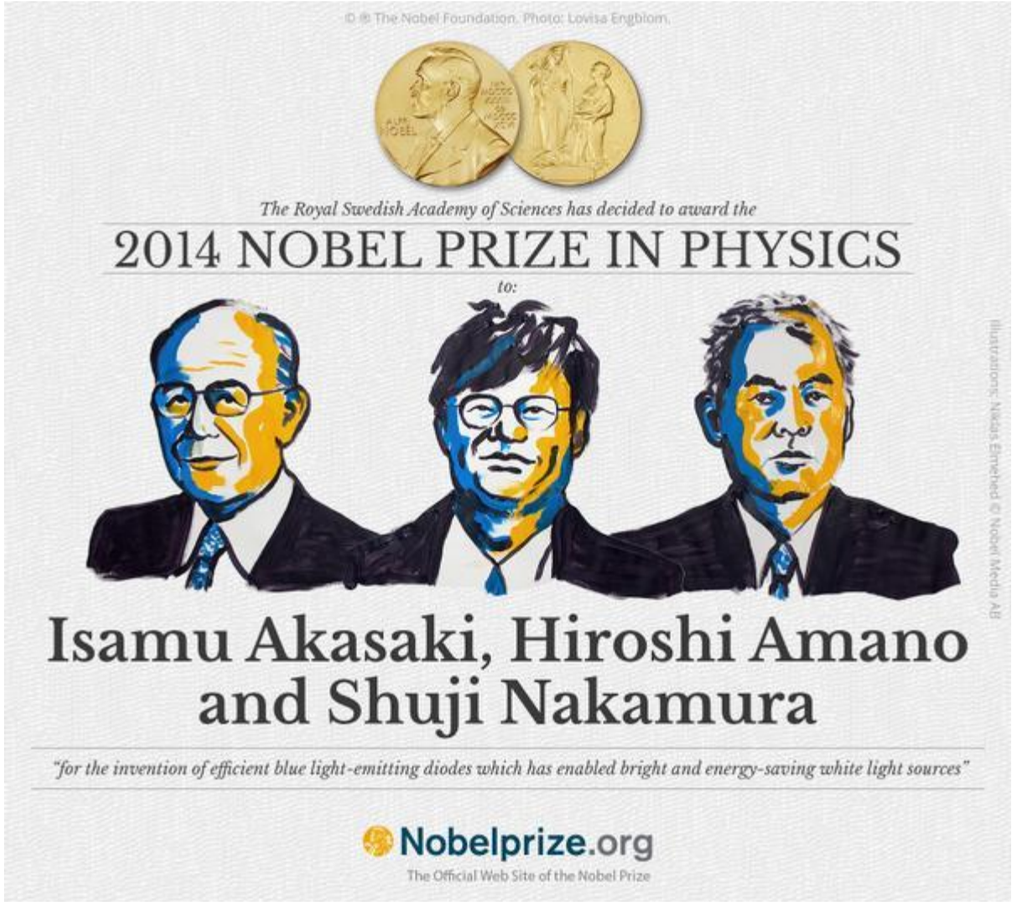


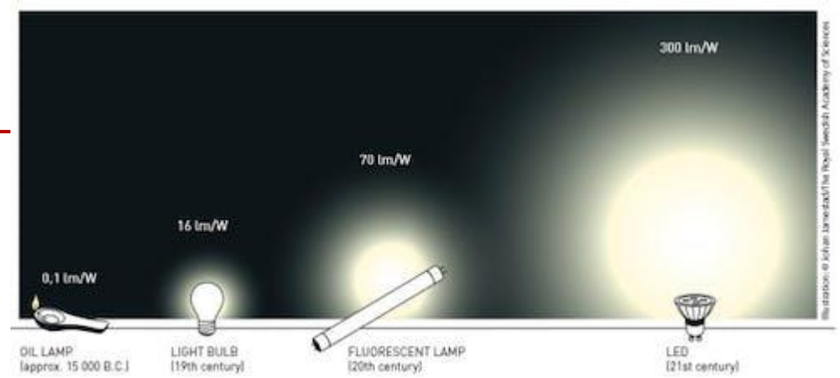


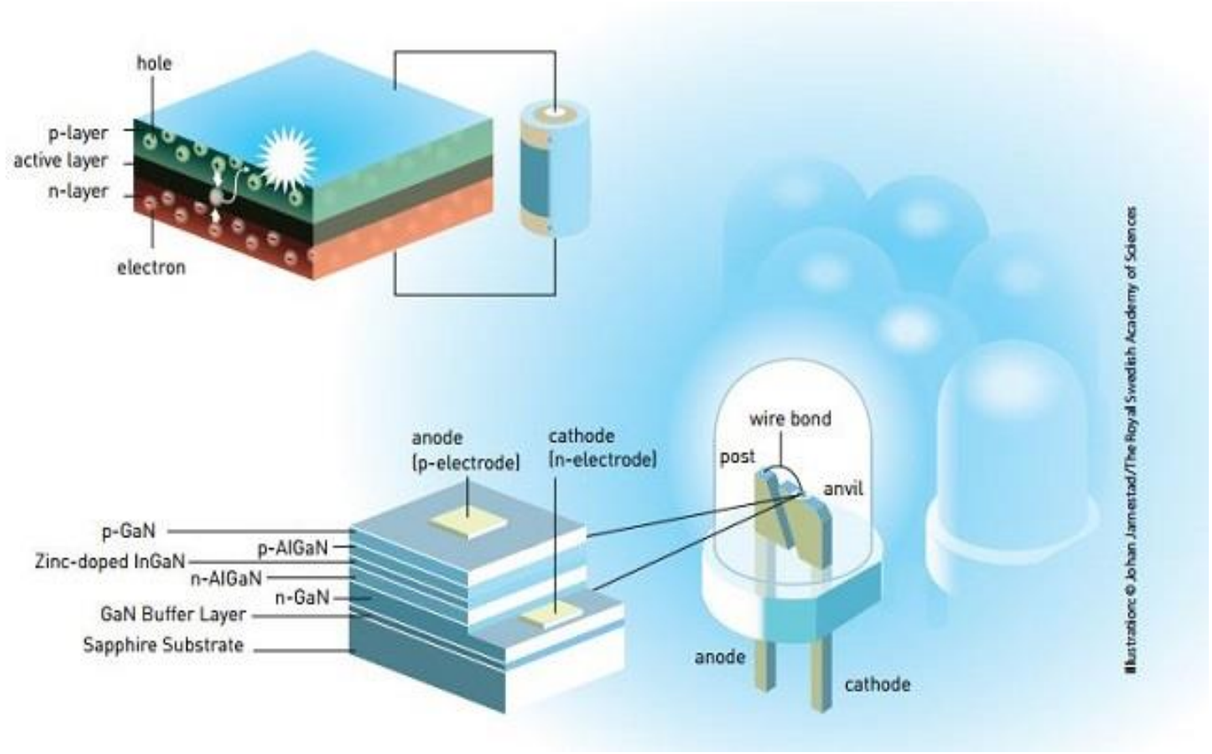




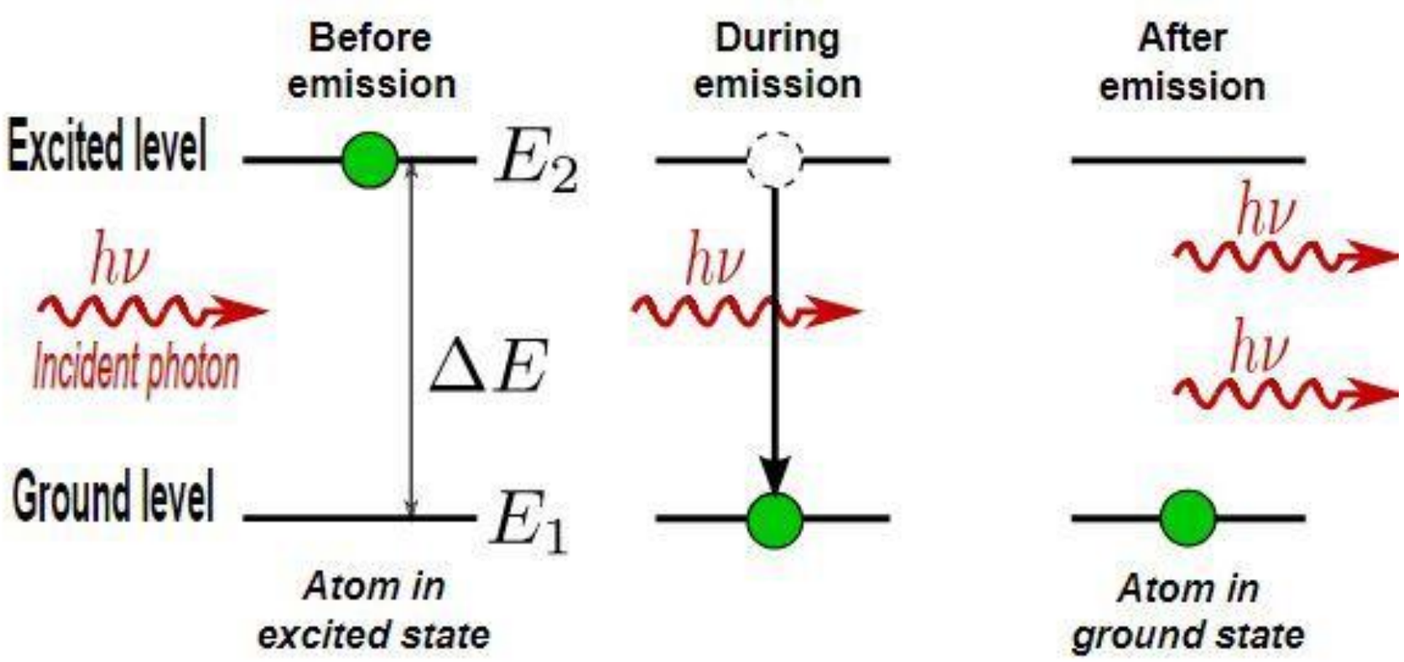
Prêmio Nobel - 2014







LASER (light amplification by stimulated emission of radiation)



$$E_2 - E_1 = \Delta E = h\nu$$

Laser point

Base do laser: inversão de população

Ocorre naturalmente em uma junção p-n com polarização direta feita com um semicondutor de gap direto.

os elétrons do lado n que se mover em direção à região de junção e são injetados no lado p,

Banda de condução (p) com concentração maior do equilíbrio térmico.

A recombinação dos pares elétron-buraco, que ocorre para que as concentrações atinjam o equilíbrio em ambos os lados, produz a emissão espontânea característica dos LEDs.

Se a injeção é forte o suficiente, a condição de limiar para operação do laser pode ser alcançada e o diodo emite radiação estimulada

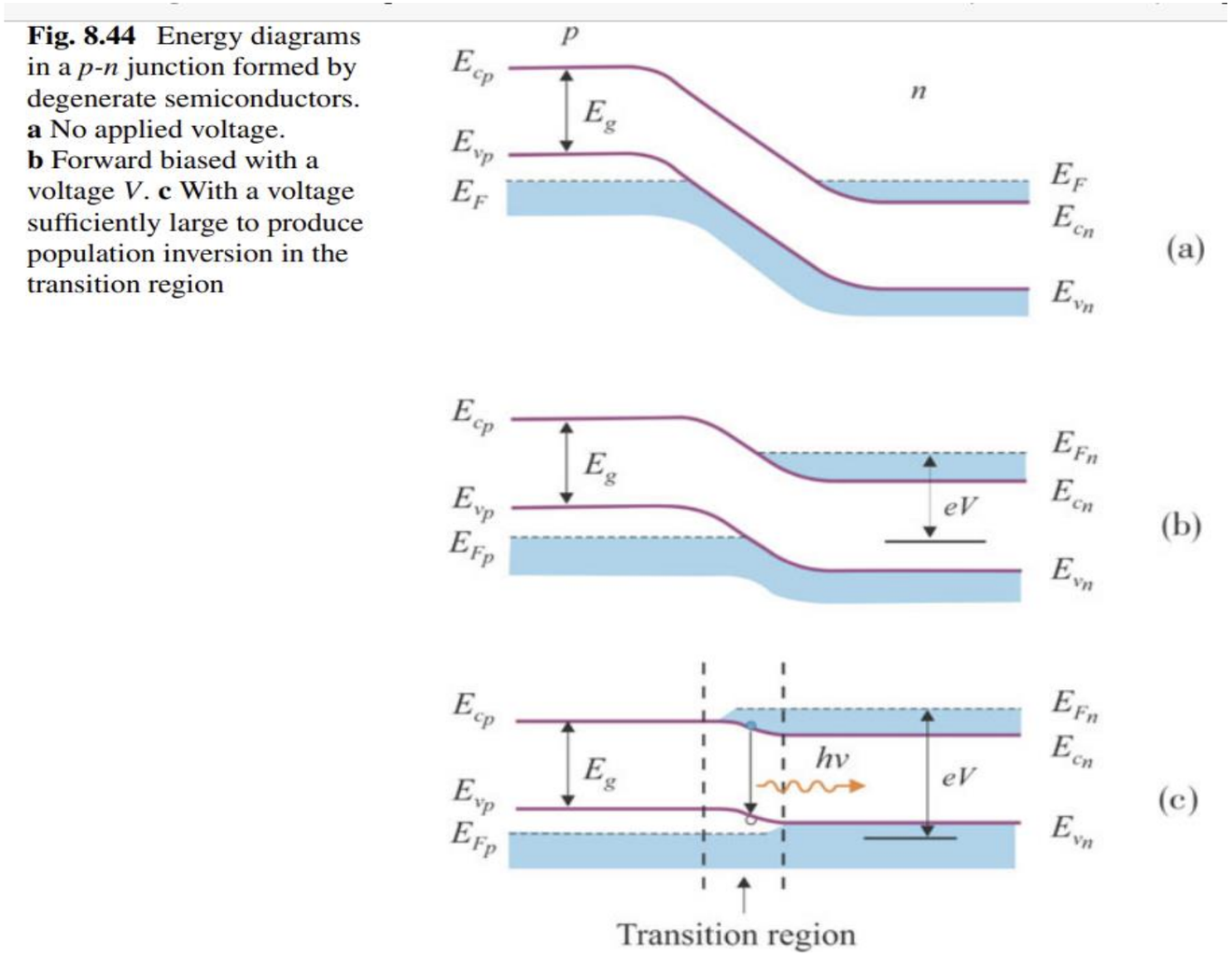


Fig. 8.44 Energy diagrams in a *p-n* junction formed by degenerate semiconductors. **a** No applied voltage. **b** Forward biased with a voltage *V*. **c** With a voltage sufficiently large to produce population inversion in the transition region

Laser point (Premio Nobel – 2000)

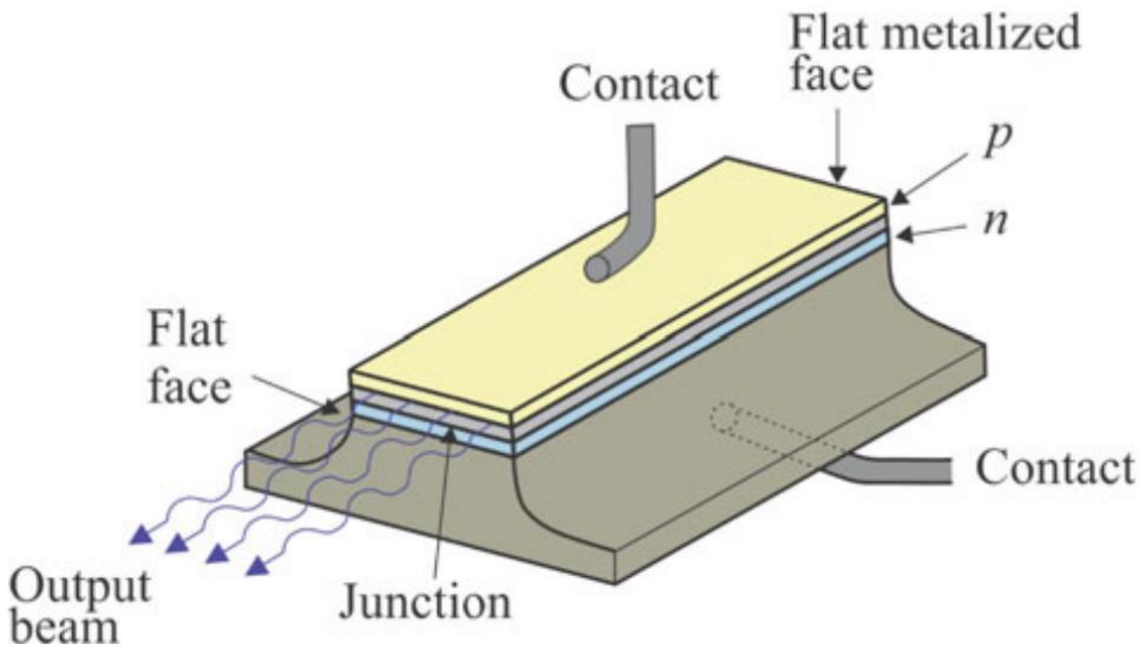
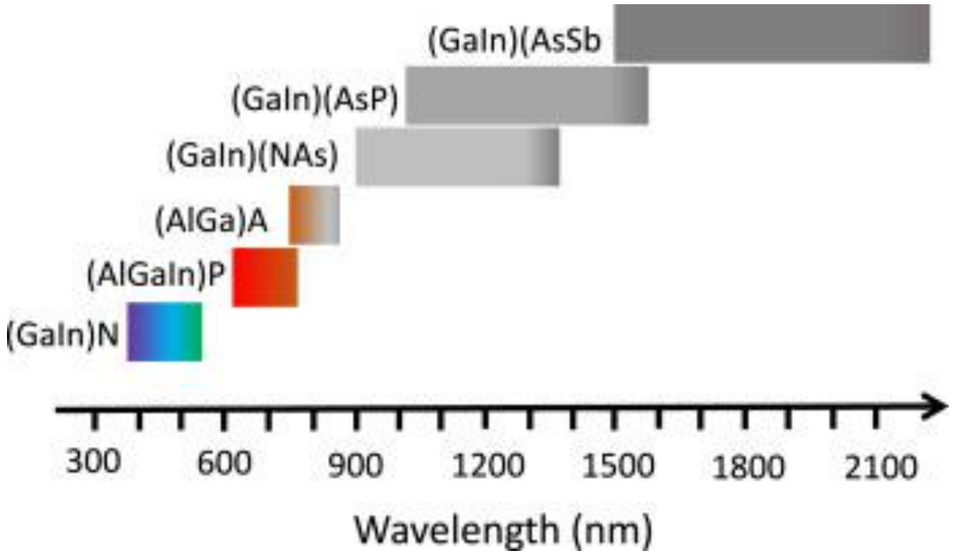


Fig. 8.45 Illustration of a simple *p-n* junction diode laser

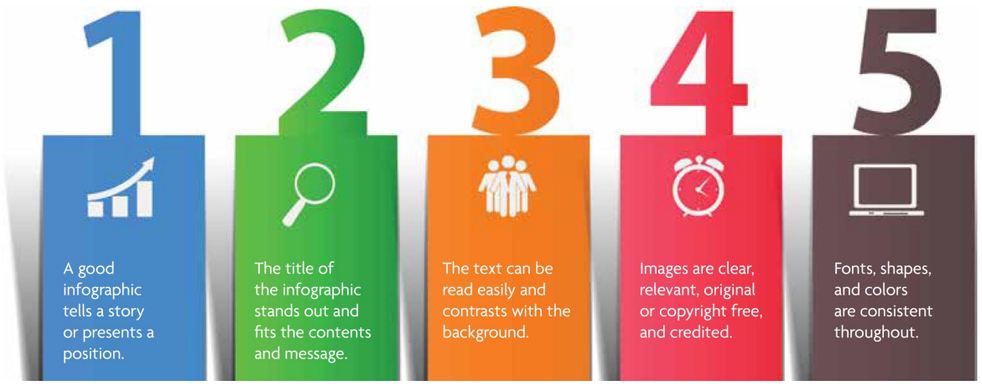


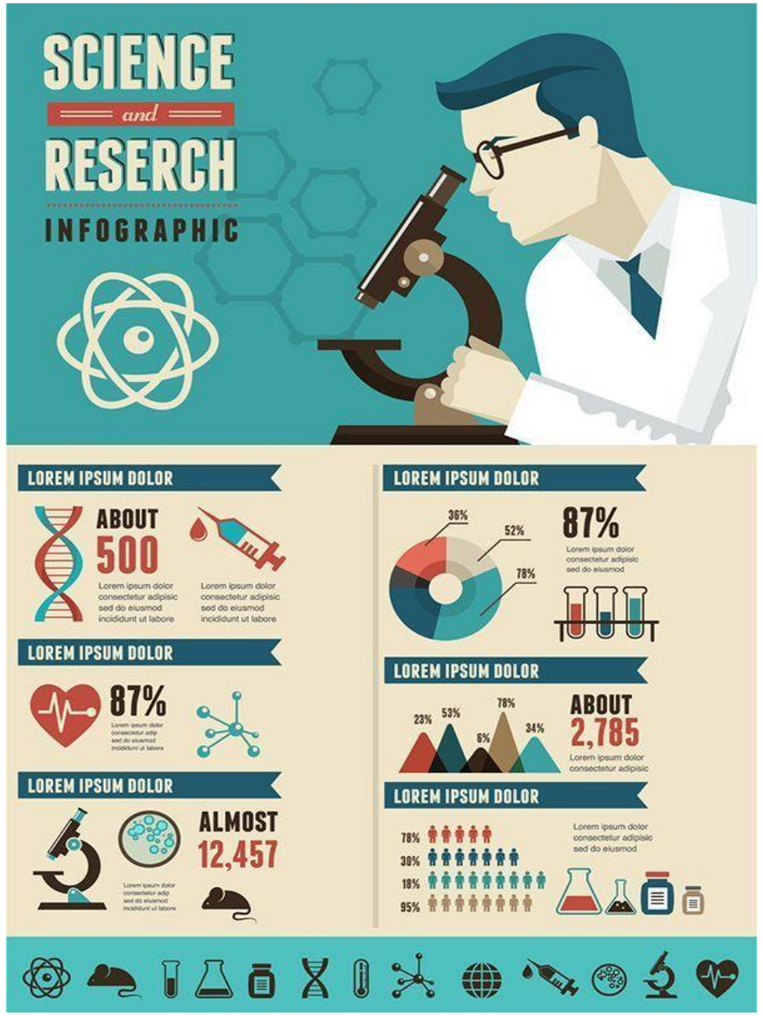
The Nobel Prize in Physics 2000 was awarded "for basic work on information and communication technology" with one half jointly to Zhores I. Alferov and Herbert Kroemer "for developing semiconductor heterostructures used in high-speed- and opto-electronics" and the other half to Jack S. Kilby "for his part in the invention of the integrated circuit

ENTREGA 3 - INFOGRÁFICO

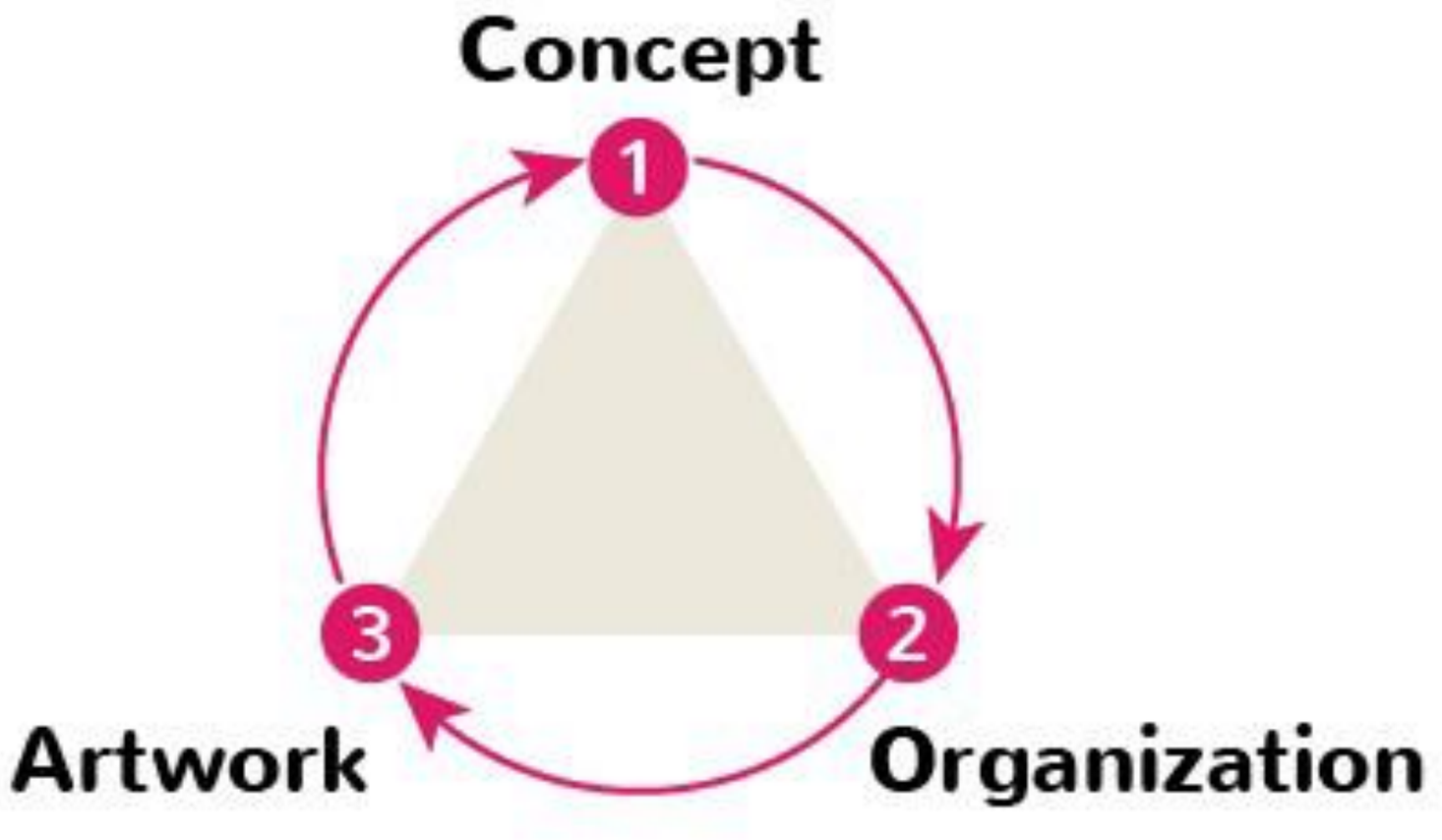
PRAZO - 27/11/2022

Entrega - Infográfico – exibição

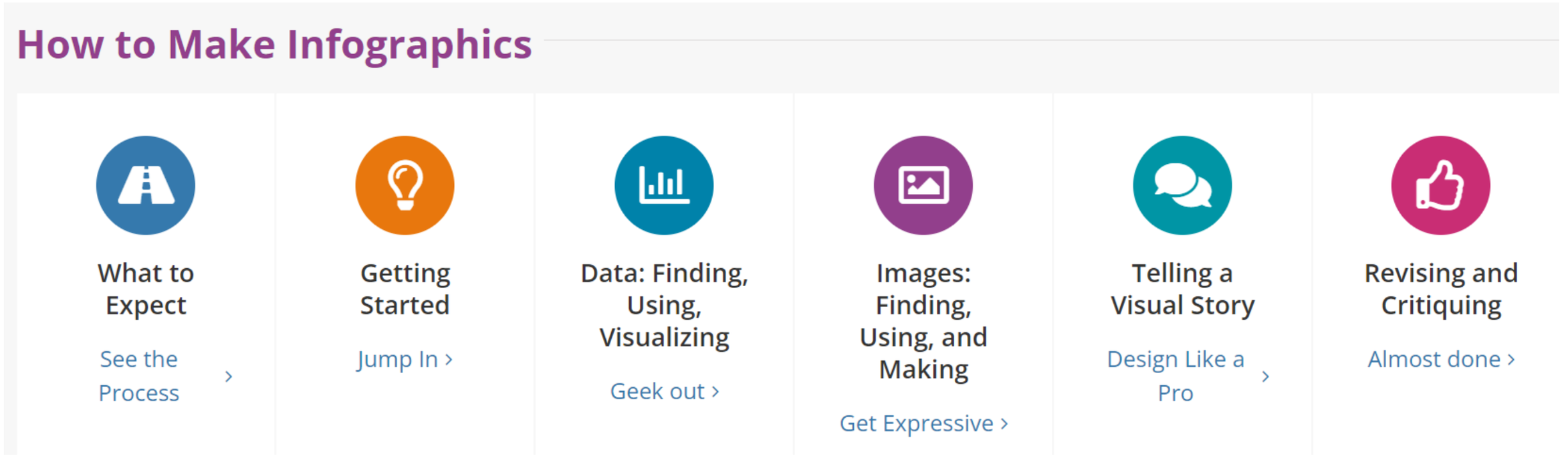




Aprendendo com infográficos populares



Aprendendo com infográficos populares



http://science-infographics.org/

Sugestões

Título - Visão geral

Objetivo/ foco

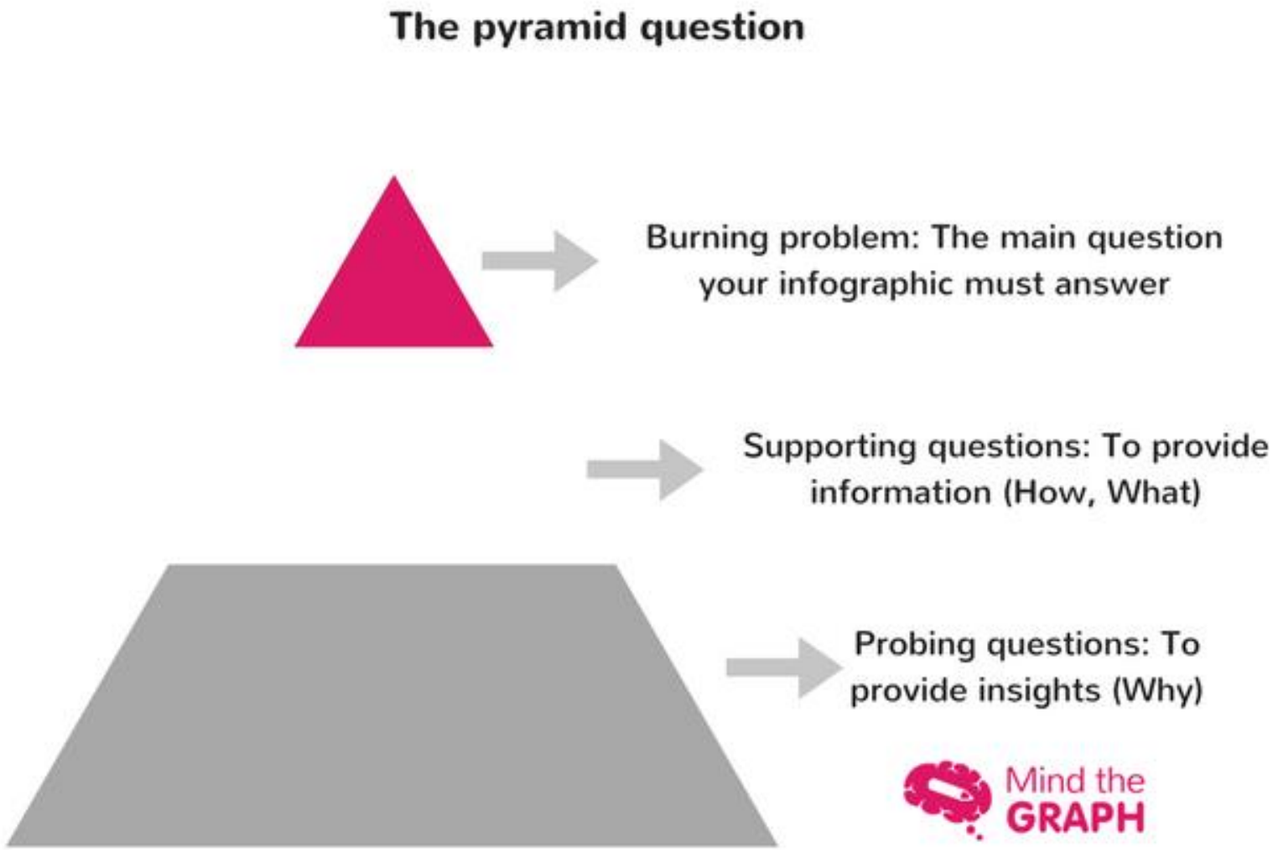
Contexto / Público(s)

Percepção científica atual sobre a linha de pesquisa
Dados principais

Tom e linguagem

Métricas de sucesso

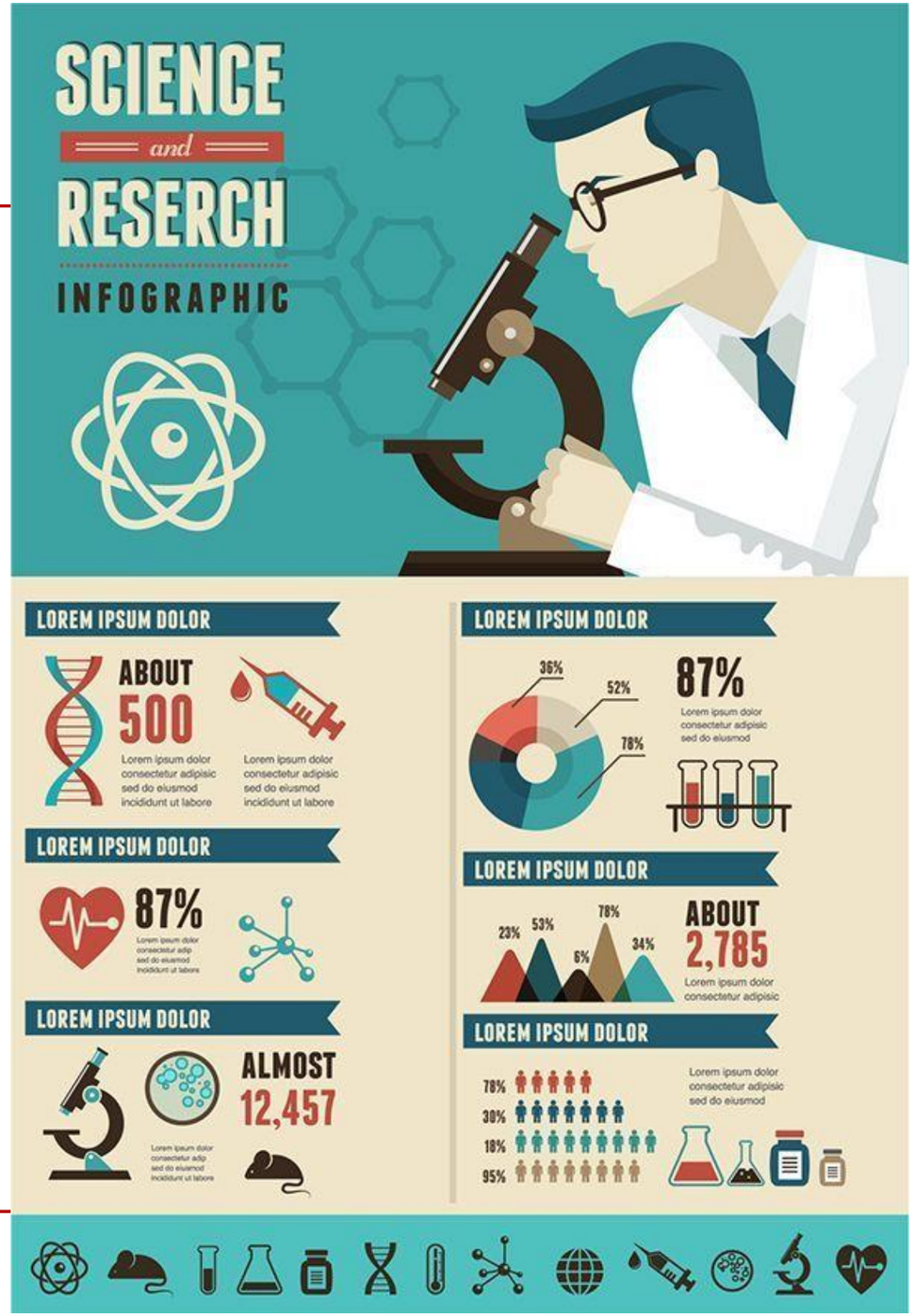
Referências ou inspiração



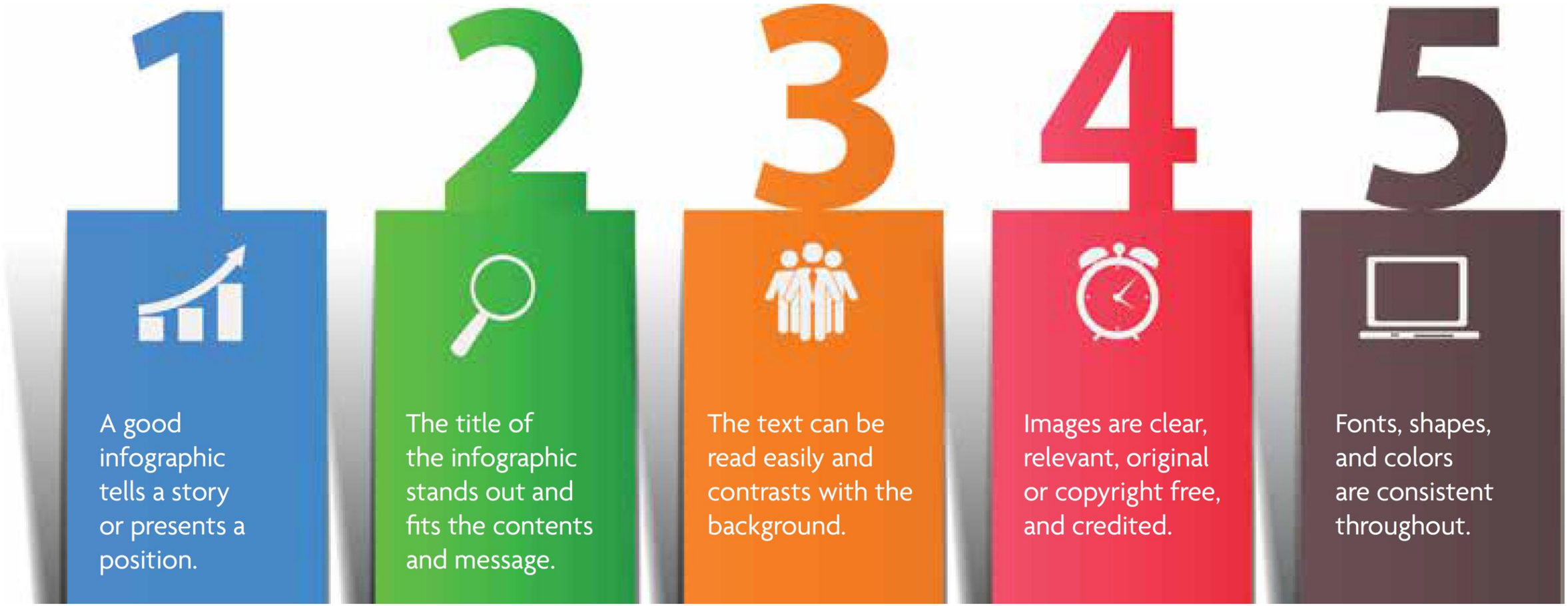
Representações visuais

(a) fluxo
(b) estrutura
(c) cluster
(d) irradiação
(e) pictórico
(f) exibição

Comece com a resposta primeiro.
Agrupe e resuma seus argumentos de apoio.
Ordene logicamente suas ideias de apoio.

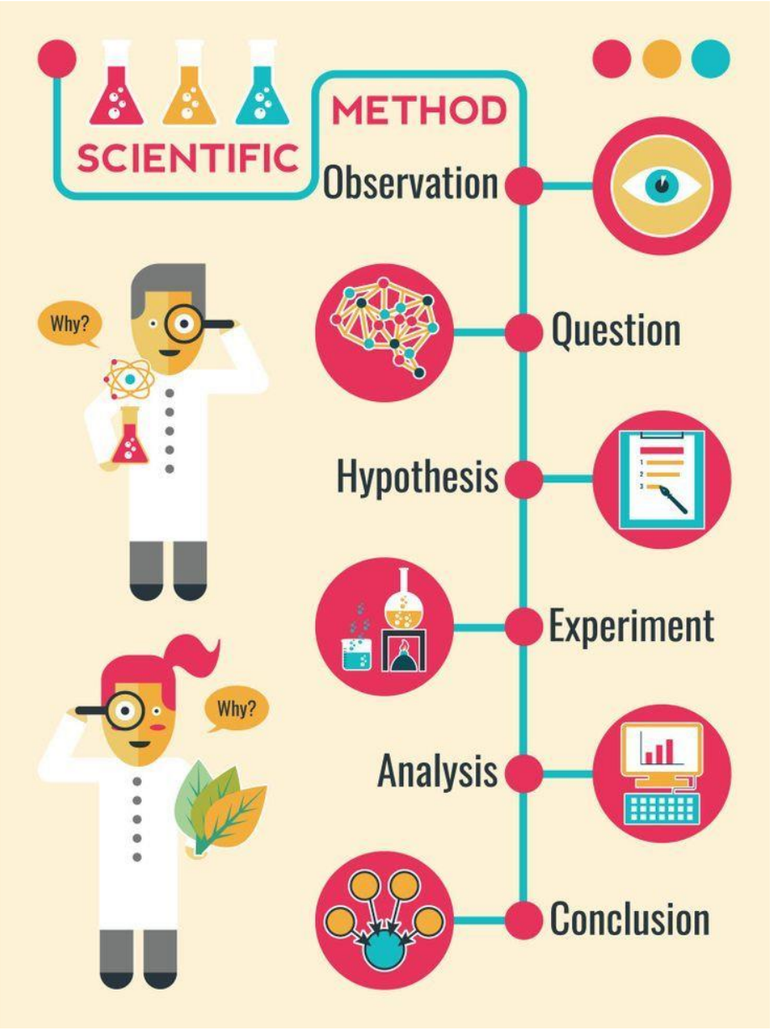


Aprendendo com infográficos populares



Estratégias

- Primeira impressão (imediato)



Reflexões 1

Related to *immediacy* component:

1. The infographic creates a sense of urgency. [Yes or No] How does this infographic create a sense of urgency? Or how does it not?
2. The infographic creates a sense of excitement. [Yes or No] How does this infographic create a sense of excitement? Or how does it not?
3. The infographic encourages users to take action. [Yes or No] How does this infographic encourage users to take action? Or how does it not?

Estratégias

- Primeira impressão (imediato)
- Maleabilidade

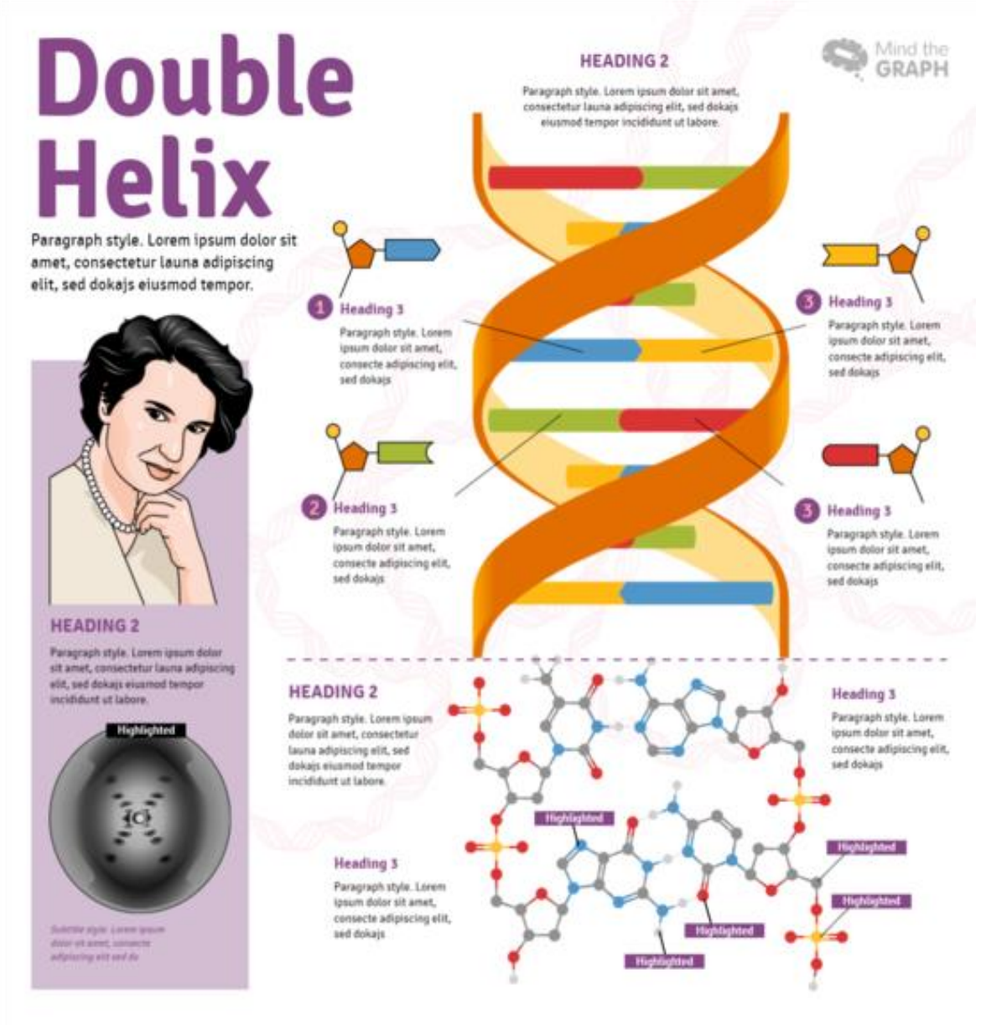
Reflexões 2

Related to *malleability* component:

4. The infographic enables users to apply the content in various ways. [Yes or No] How does this infographic enable users to apply the content in various ways? Or how does it not?
5. The infographic allows users to determine their own personal meaning and relevance. [Yes or No] How does this infographic allow users to determine their own personal meaning and relevance? Or how does it not?
6. The infographic allows users to explore the content. [Yes or No] How does this infographic allow users to explore the content? Or how does it not?

Estratégias

- Primeira impressão (imediato)
- Maleabilidade
- Convincente



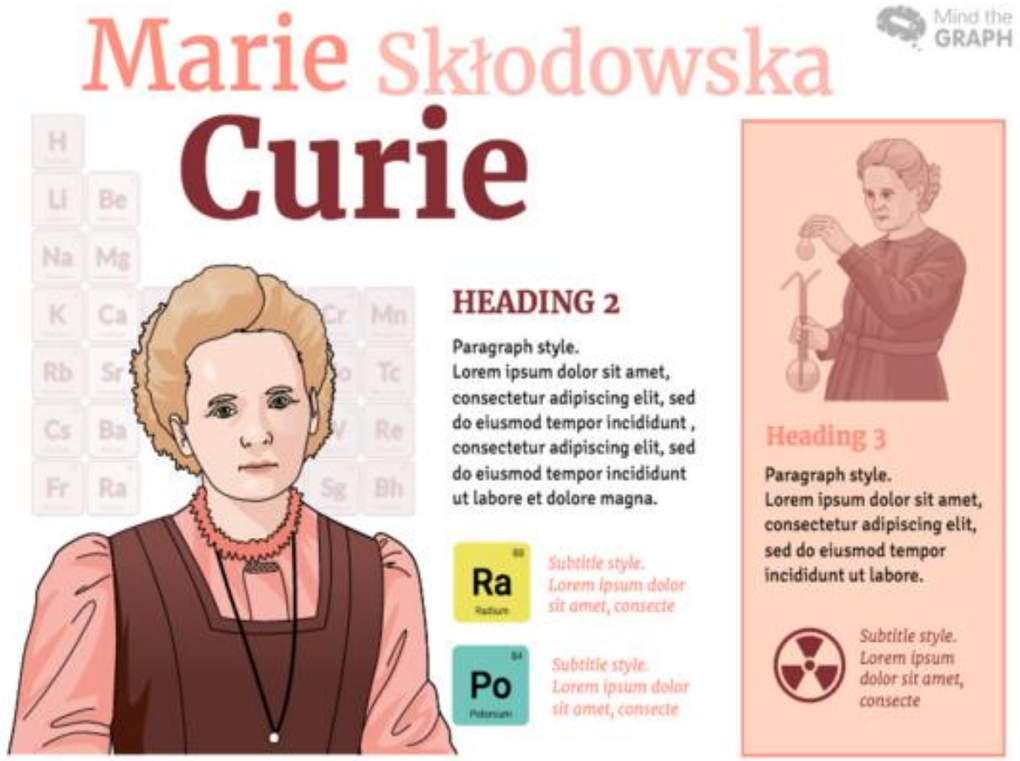
Reflexões 3

Related to *compellingness* component:

7. The infographic grabs users' attention. [Yes or No] How does this infographic grab users' attention? Or how does it not?
8. The infographic holds users' attention. [Yes or No] How does this infographic hold users' attention? Or how does it not?
9. The infographic shares a provocative idea or problem. [Yes or No] How does this infographic share a provocative idea or problem? Or how does it not?
10. The infographic shares a novel idea or problem. [Yes or No] How does this infographic share a novel idea or problem? Or how does it not?
11. The infographic uses storytelling to deliver the message. [Yes or No] How does this infographic use storytelling to deliver the message? Or how does it not?
12. The infographic uses unexpected design elements. [Yes or No] How does this infographic use unexpected design elements? Or how does it now?

Estratégias

- Primeira impressão (imediato)
- Maleabilidade
- Convincente
- Ressonância



Reflexões 4

Related to *resonance* component:

13. The infographic helps users see how the content is relevant to them. [Yes or No] How does this infographic help users see how the content is relevant to them? Or how does it not?

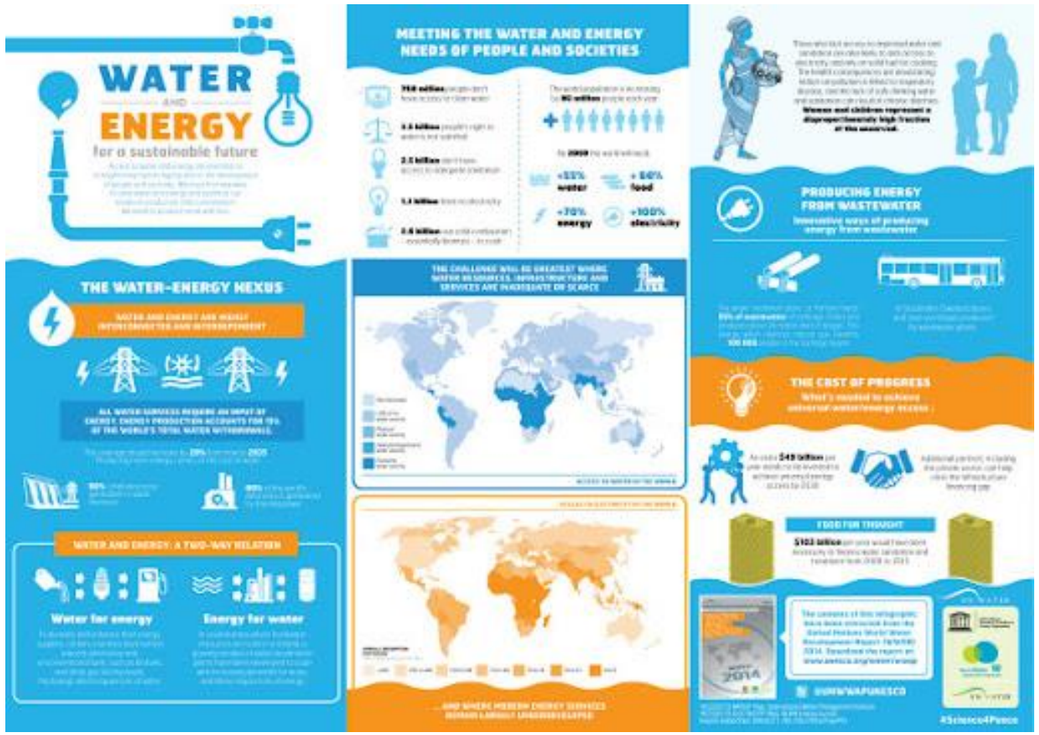
14. The infographic helps users see connections (e.g., past, present, and future; existing and new ideas and perspectives; theory and practice). [Yes or No] How does this infographic help users see connections? Or how does it not?

15. The infographic evokes users' emotions and memories. [Yes or No] How does this infographic evoke users' emotions and memories? Or how does it not?

16. The infographic is credible (e.g., includes reliable content from trusted sources). [Yes or No] How is this infographic credible? Or how is it not?

Estratégias

- Primeira impressão (imediato)
- Maleabilidade
- Convincente
- Ressonância
- Coerência



Reflexões 5

Related to *coherence* component:

17. The infographic presents a complete message. [Yes or No] How does this infographic present a complete message? Or how does it not?
18. The infographic presents a well-formed message. [Yes or No] How does this infographic present a well-formed message? Or how does it not?
19. The infographic is logically structured. [Yes or No] How is this infographic logically structured? Or how is it not?
20. The infographic's message is clear. [Yes or No] How is this infographic's message clear? How is it not?
21. The infographic includes relevant text and images. [Yes or No] How does this infographic include relevant text and images? Or how does it not?
22. The infographic includes consistent design elements. [Yes or No] How does this infographic include consistent design elements? Or how does it not?

Experimentações

https://visual.ly/science-infographics

http://science-infographics.org/

https://mindthegraph.com/templates/

Entrega III – Duplas - Entrega 27/11/2022 – 23:59

1. Junção PN - Diodo
2. Laser
3. CCD
4. Disco Rígido
5. LED
6. Transistor
7. Célula Solar
8. Baterias
9. Célula Combustível
10. Chip computador
11. Smartphone
12. Magnetos
13. Supercondutores
14. Nanotecnologia

Projeto

- Desenvolvimento de um plano de aula alinhado à BNCC sobre temas em torno da Física do Estado Sólido
- Desenvolvimento de objetos de aprendizagem
- Ciênciarte (apresentação e protocolo performance)
- Divulgação científica (podcast, vídeo, …)