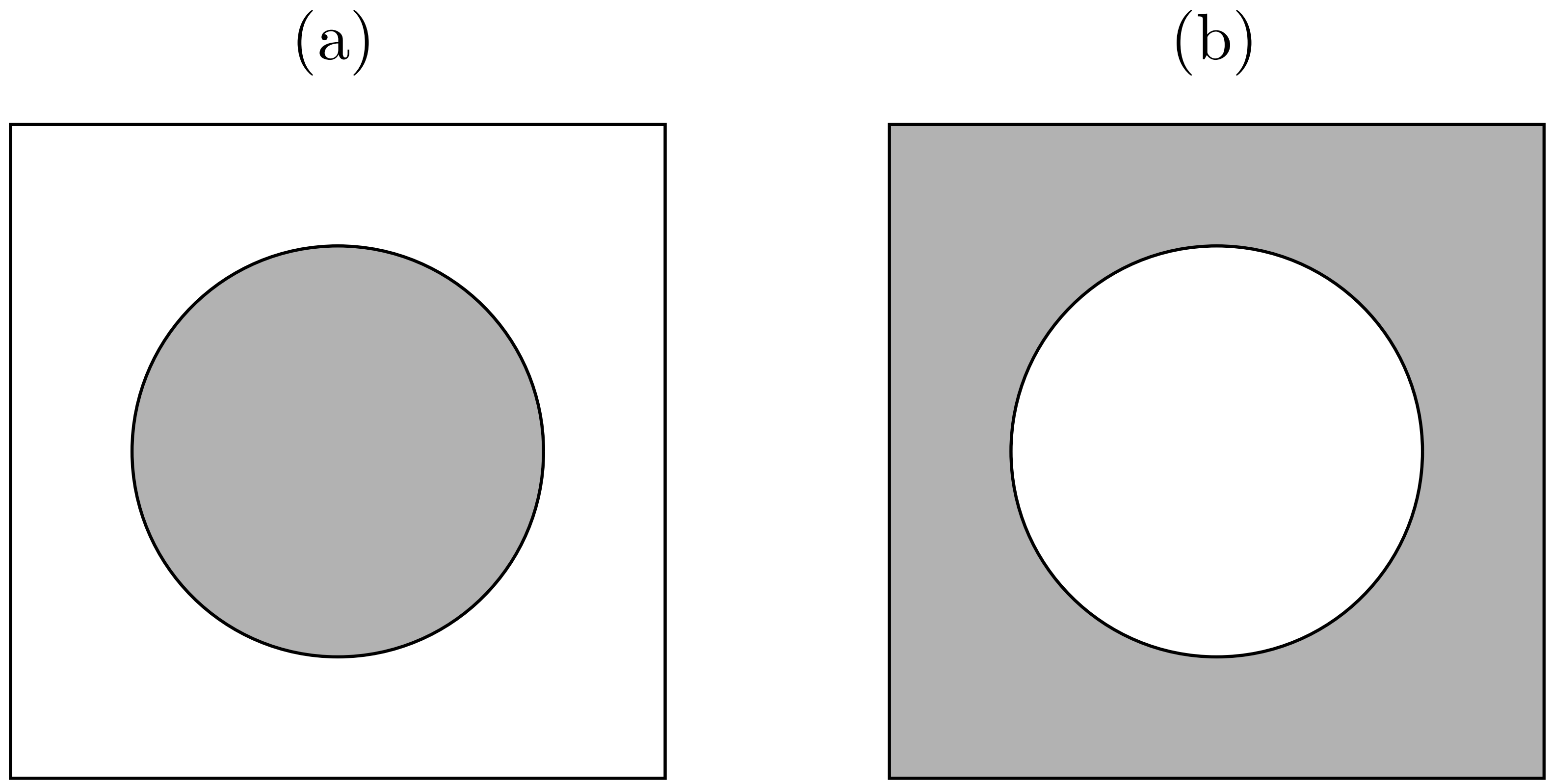
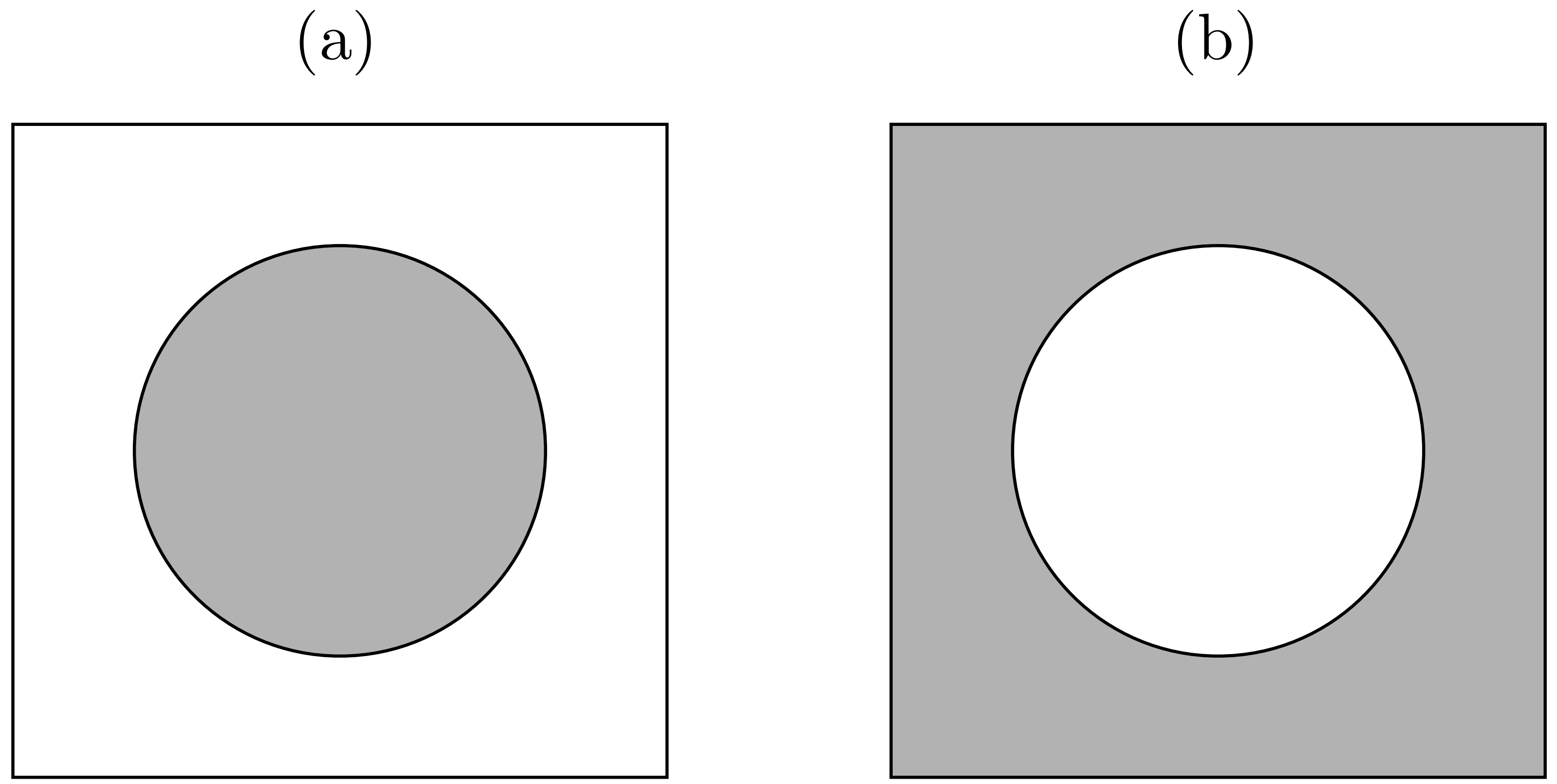
Holes



If you take an electron out of a band, what happens?

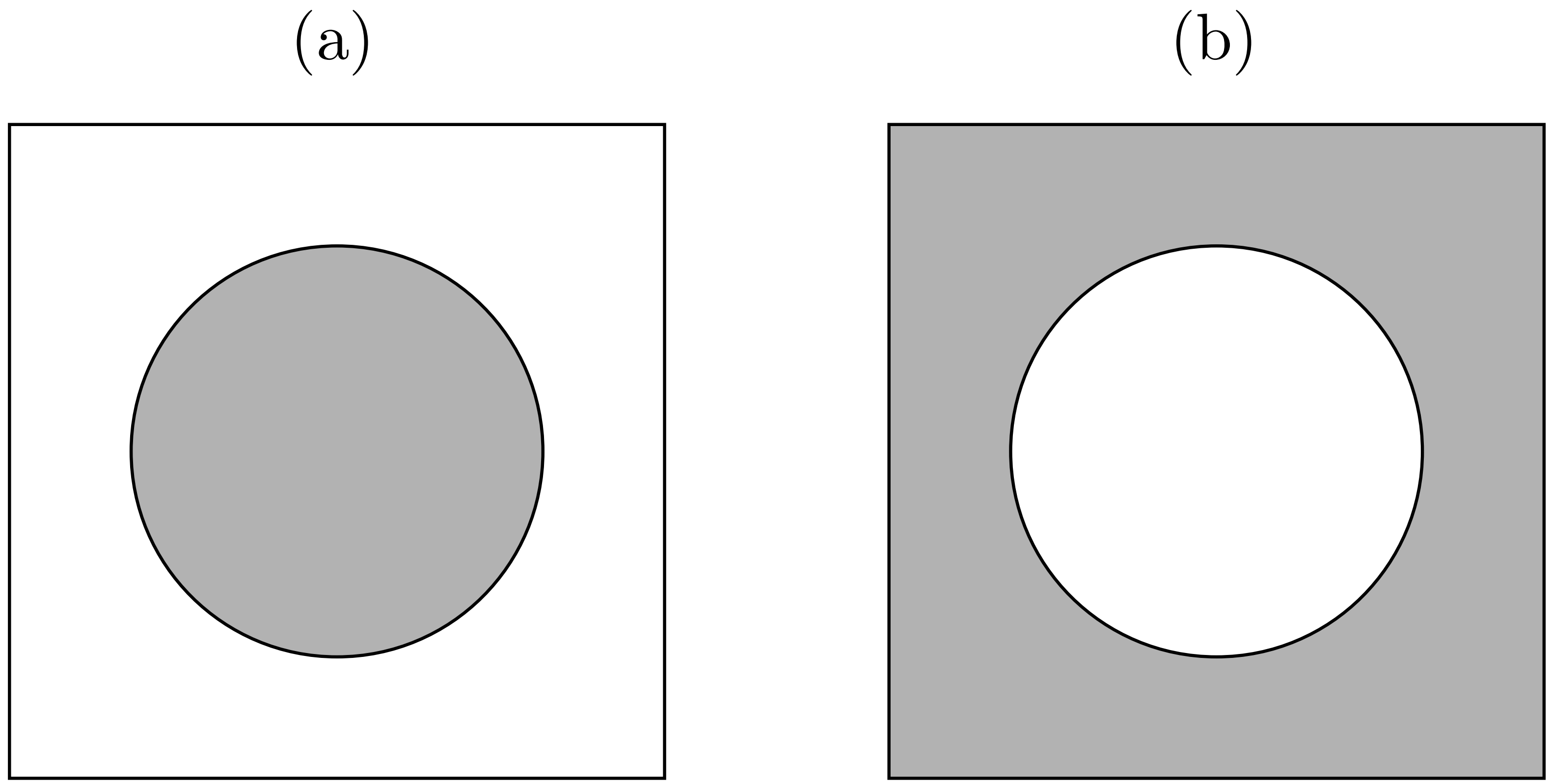
Holes



If you take an electron out of a band, what happens?

$$E_p = -E_n$$

Holes

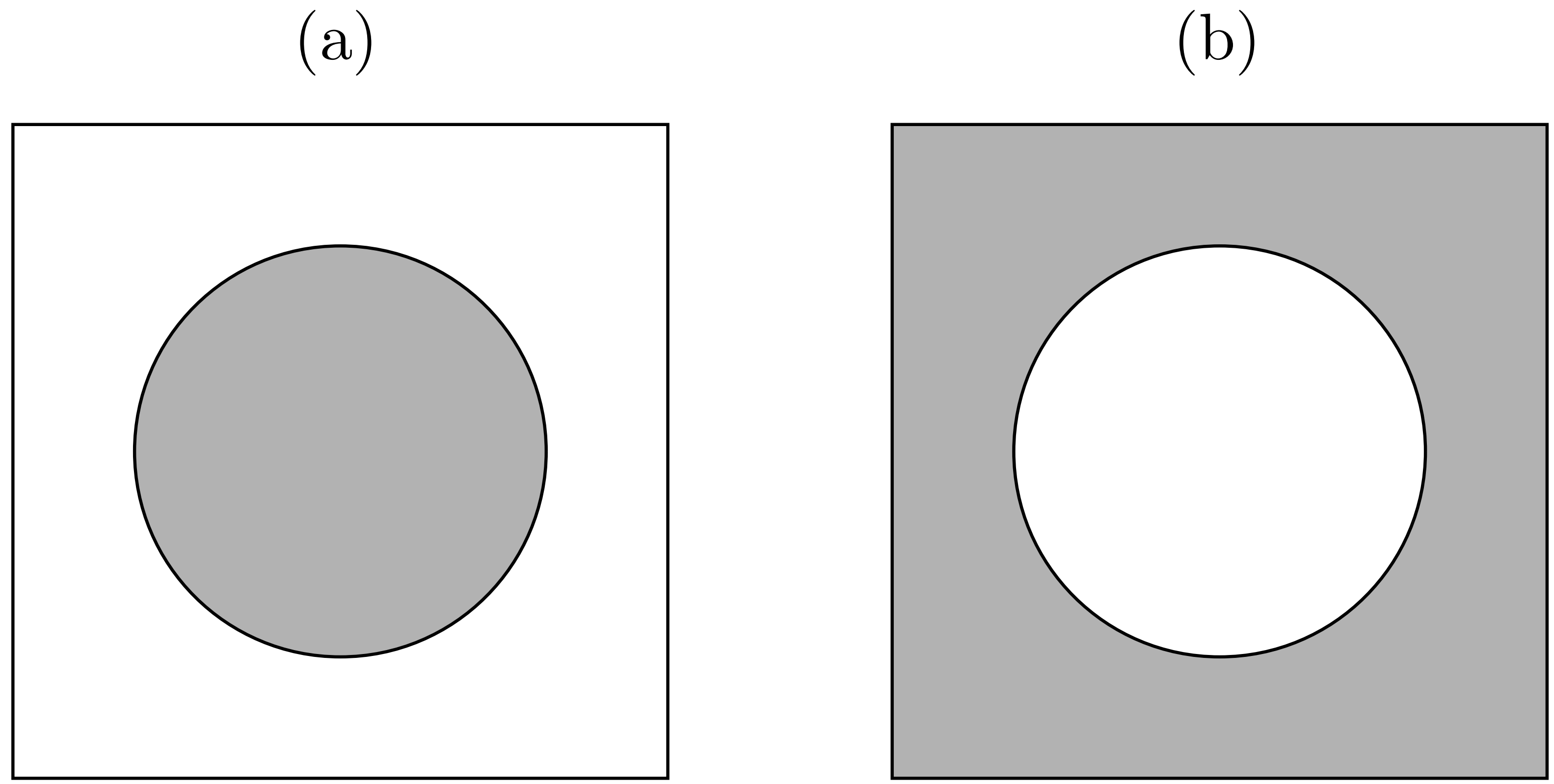


If you take an electron out of a band, what happens?

$$E_p = -E_n$$

The "missing" energy is the energy of the hole

Holes



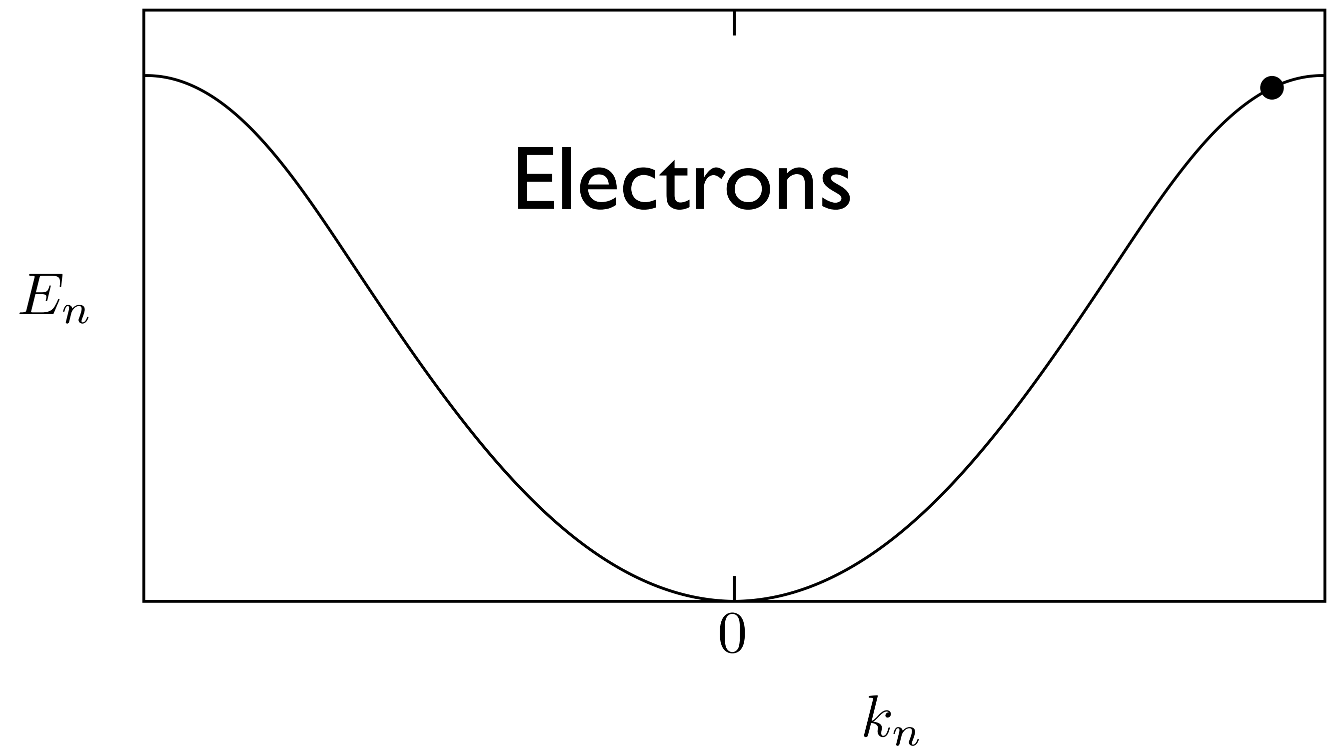
If you take an electron out of a band, what happens?

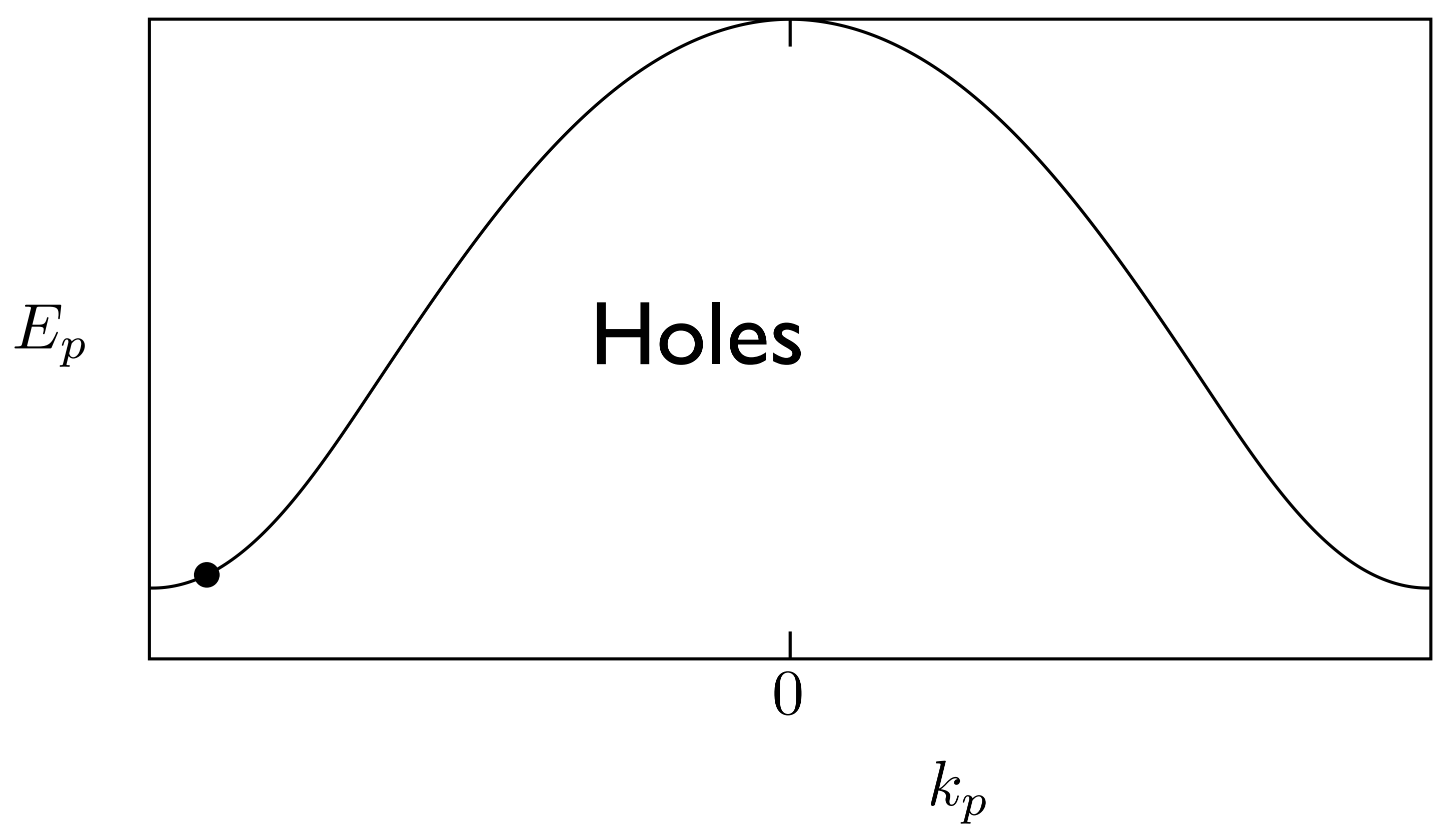
$$E_p = -E_n$$

$$\mathbf{k}_p = -\mathbf{k}_n$$

$$q_p = -q_n = +e$$

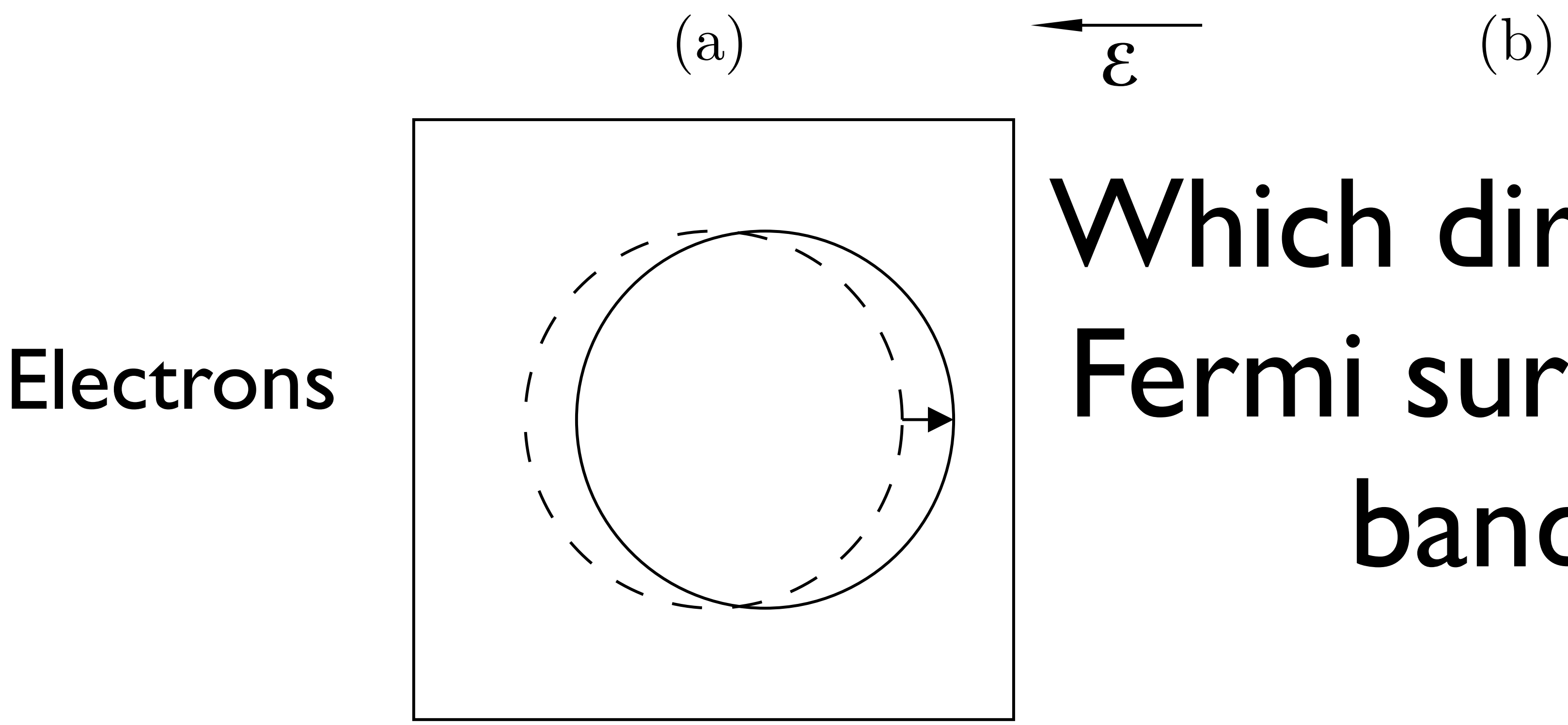
Holes in a band





Question #1

Current



Which direction does the Fermi surface move for a band of holes?

D) Left

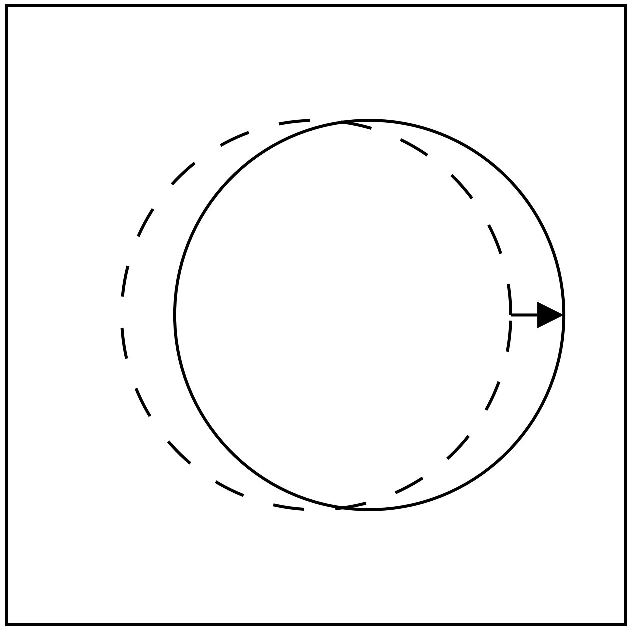
E) Right

Question #1

Current

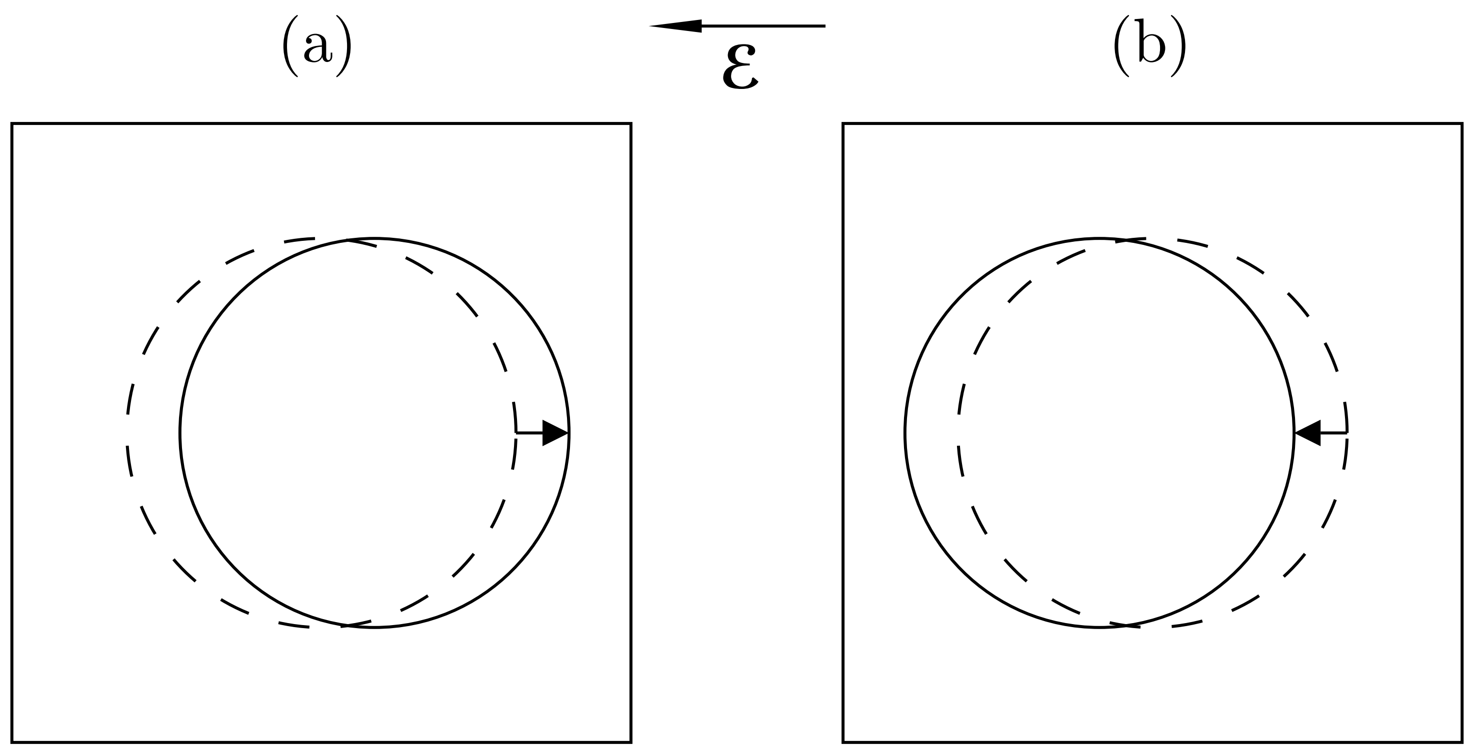
(a) $\leftarrow \mathcal{E}$ (b)

Electrons



Question #1

Current



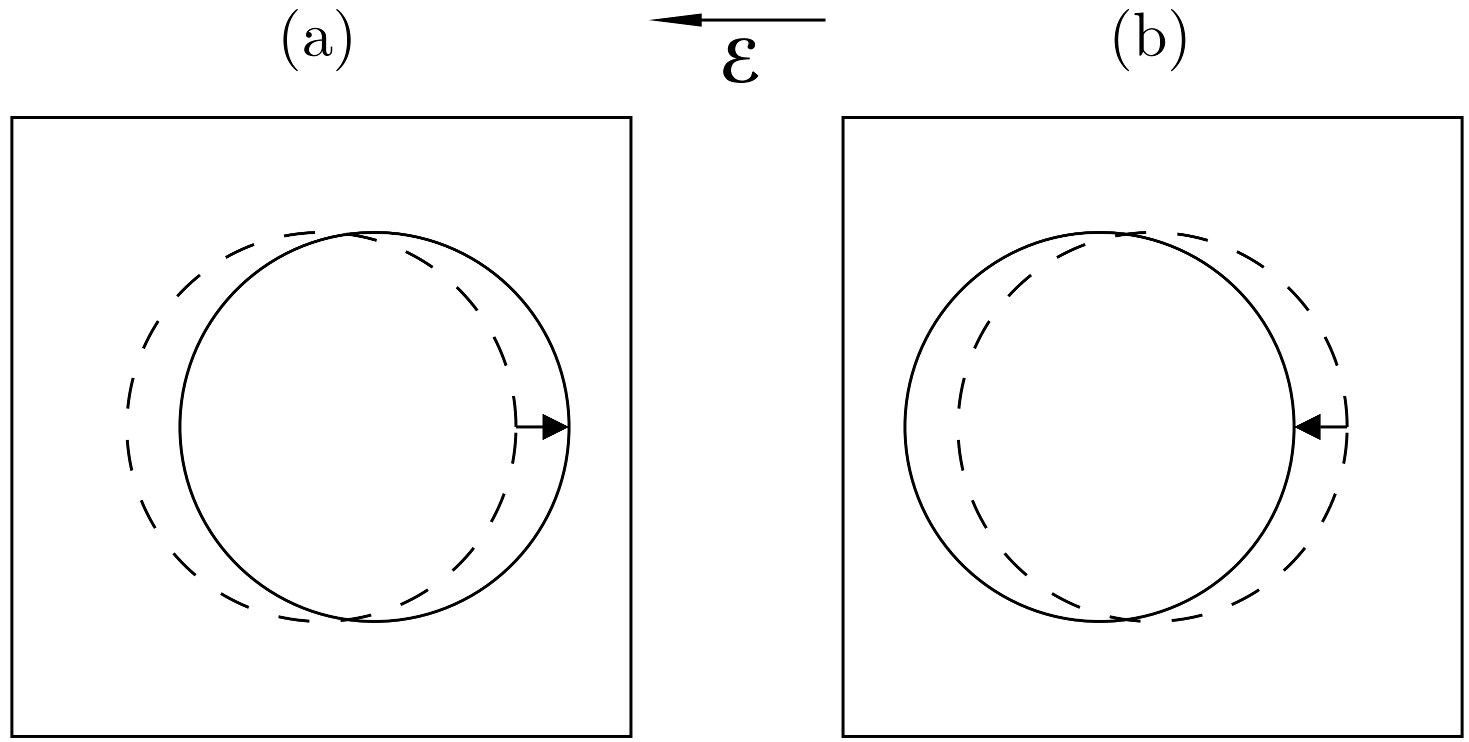
Electrons

Holes

Question #1

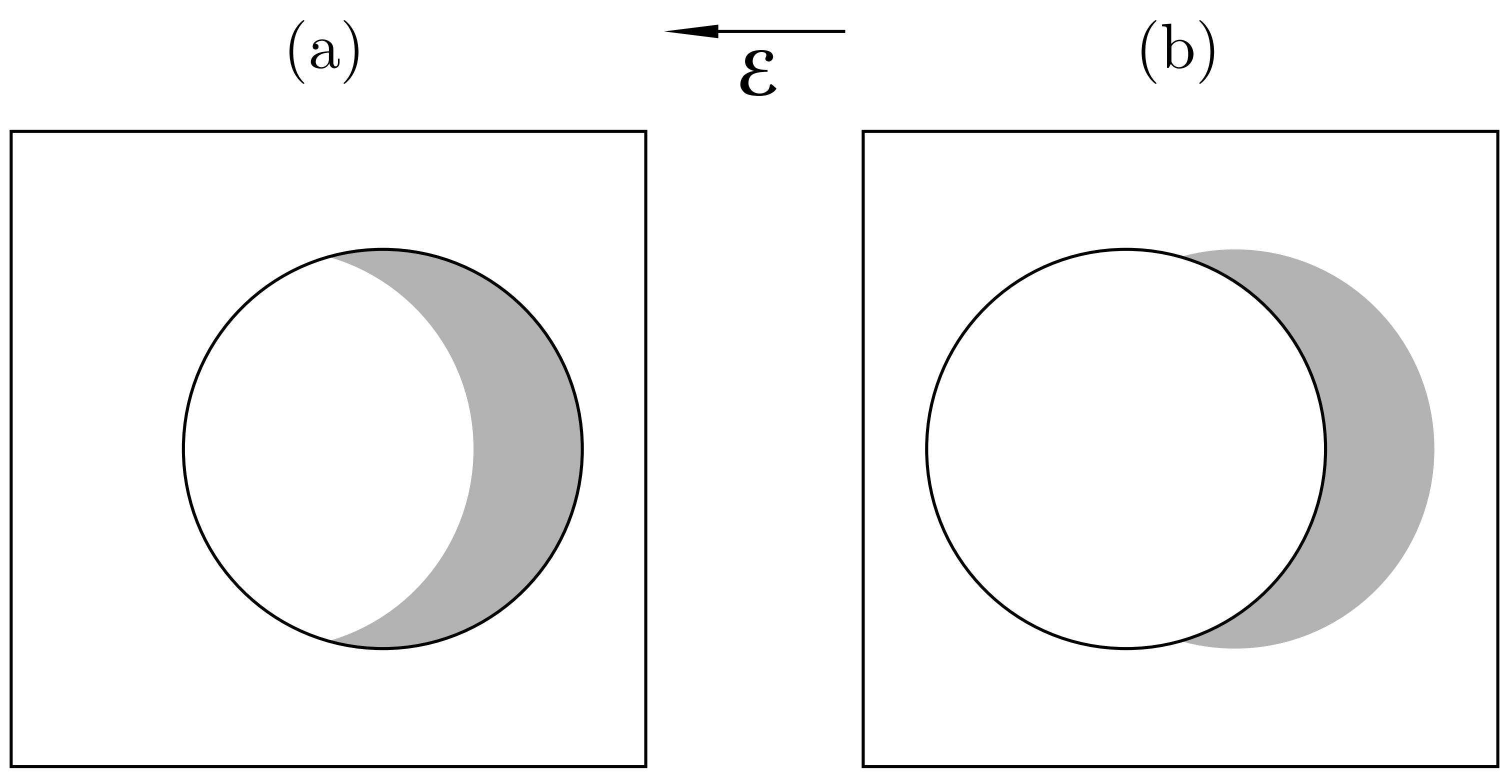
Current

Electrons



Holes

Electrons

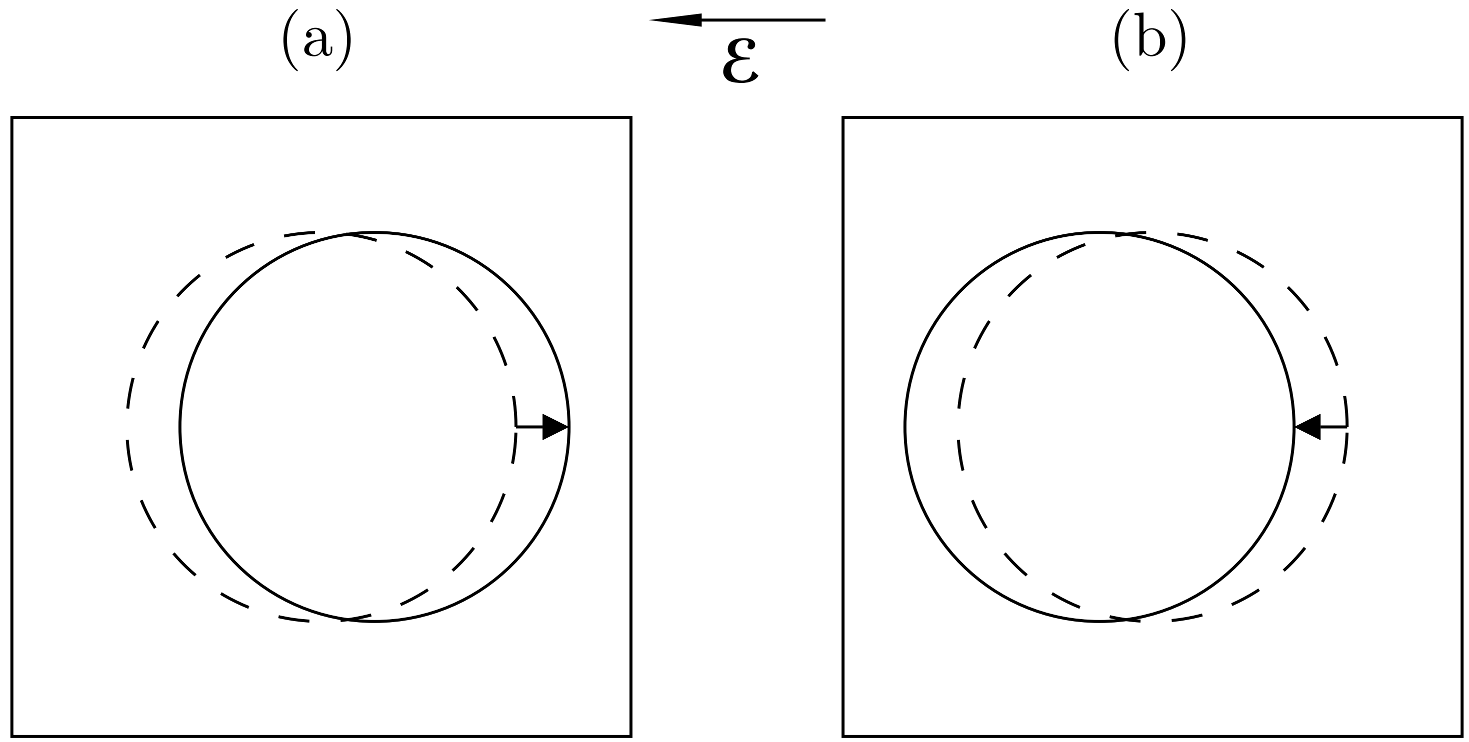


Holes

Question #1

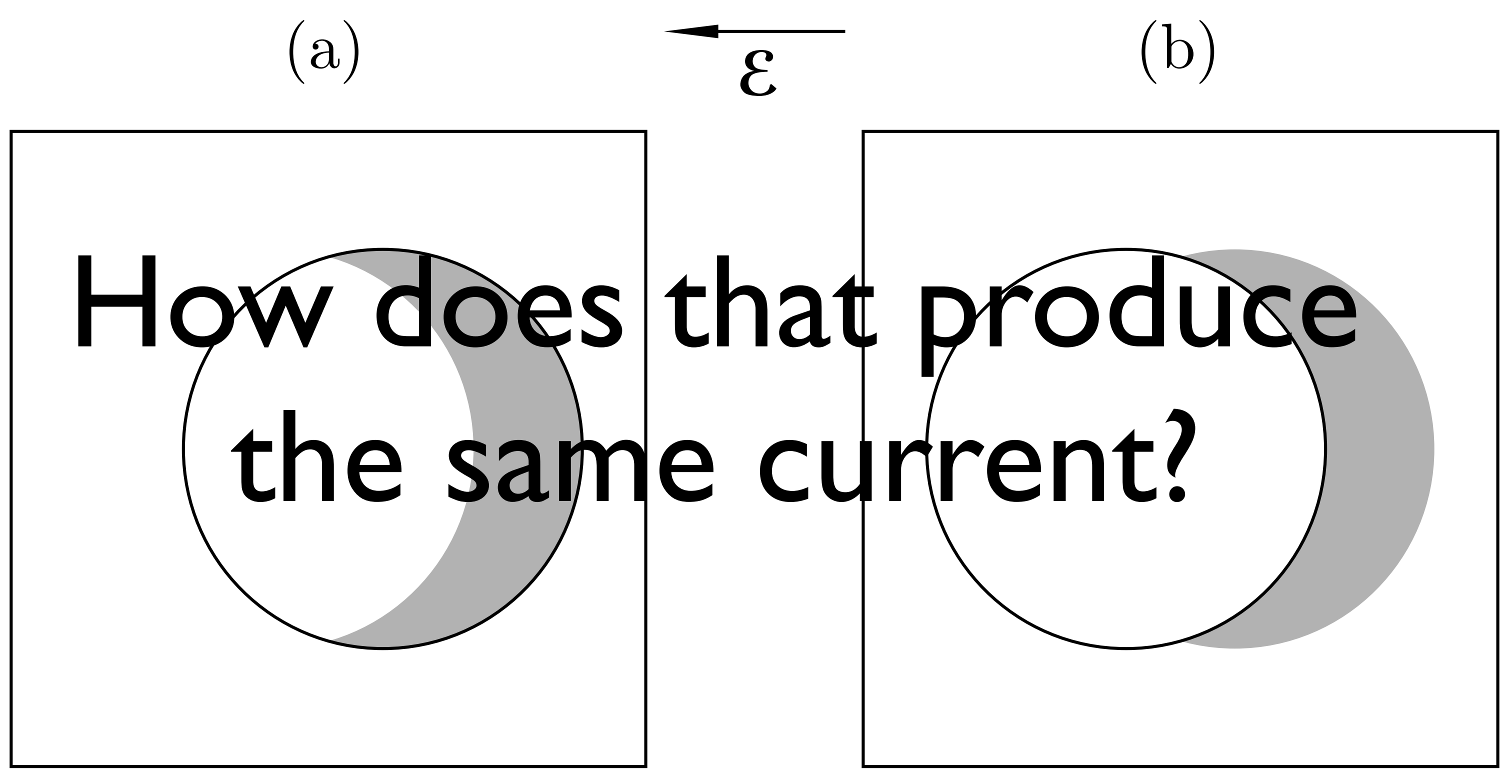
Current

Electrons



Holes

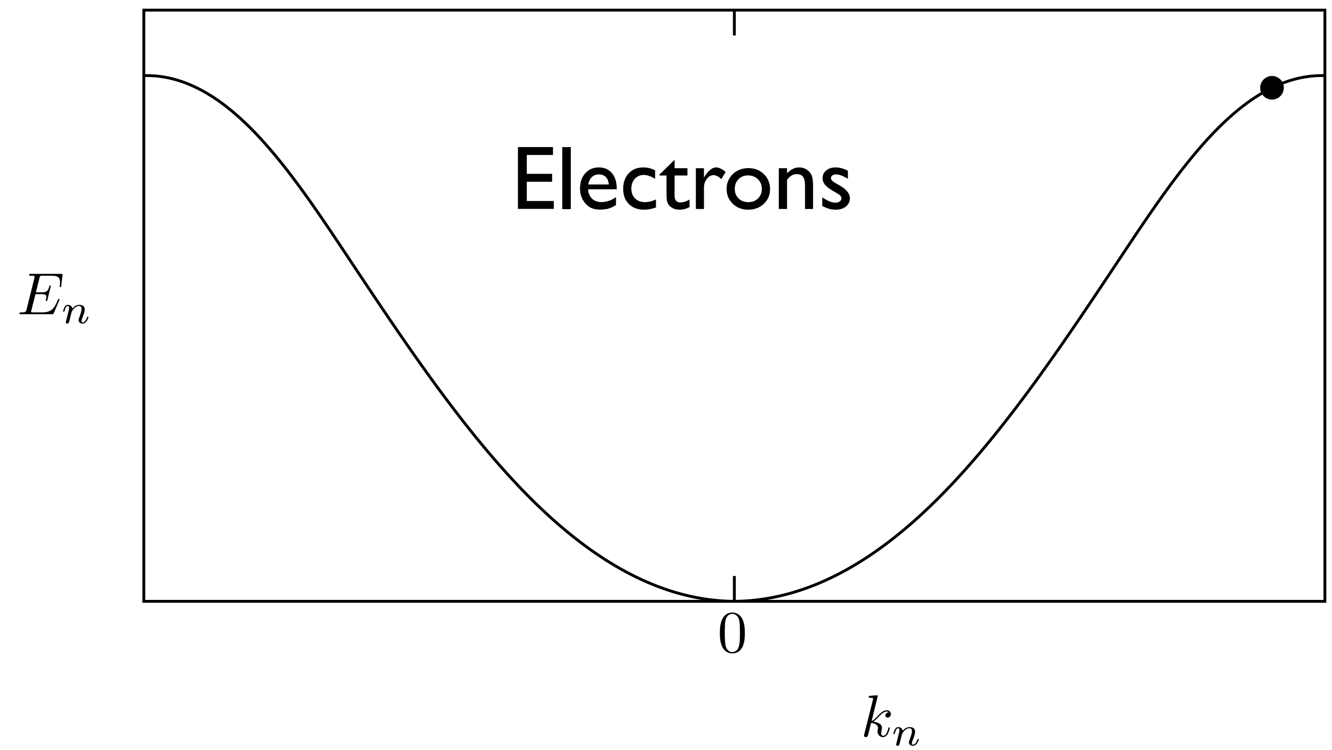
Electrons

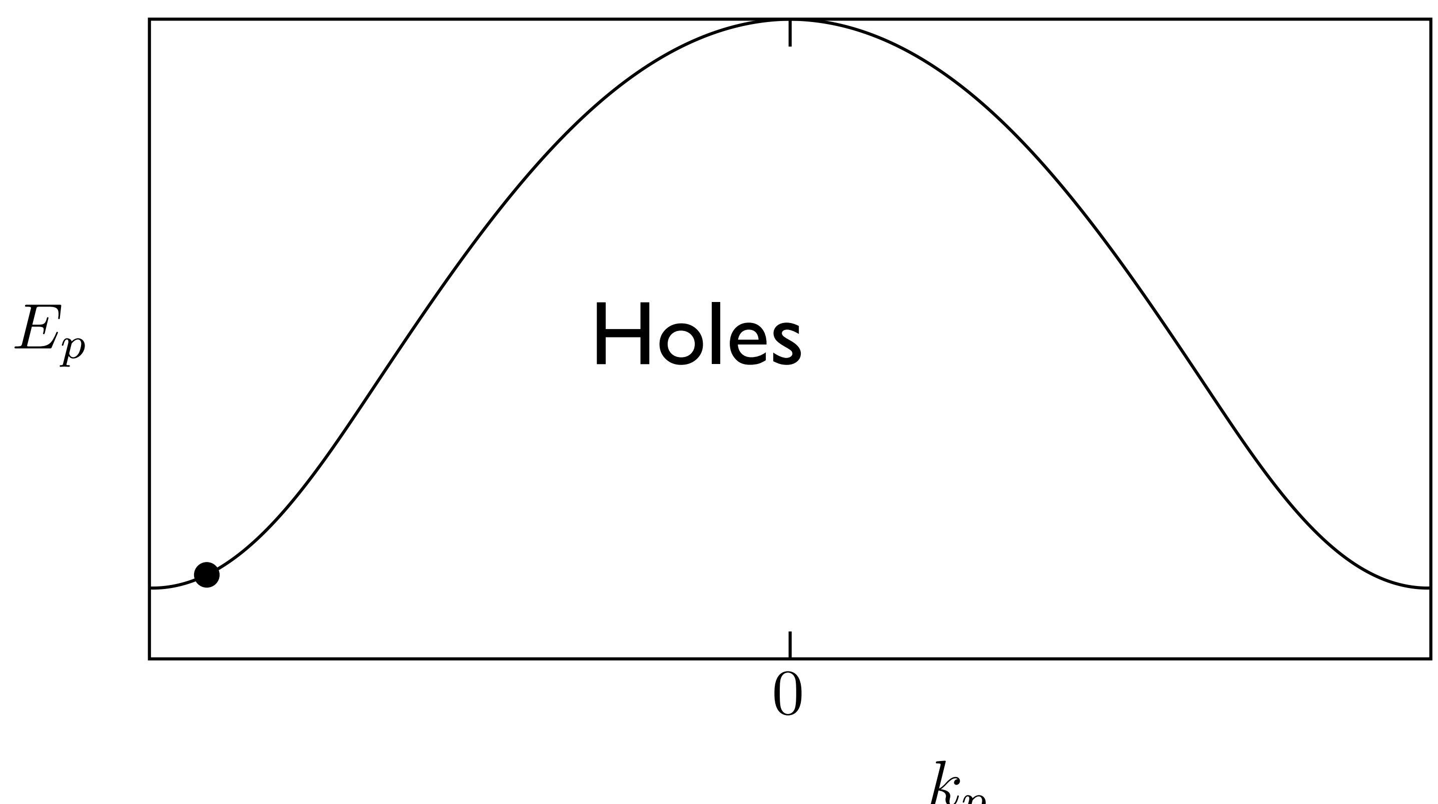


Holes

How does that produce the same current?

Holes in a band





The Hall effect

$$\mathbf{F} = -e\mathbf{v} \times \mathbf{B} \quad 1$$

$$F_{\text{ext}} = \hbar \frac{dk}{dt} \quad 2$$

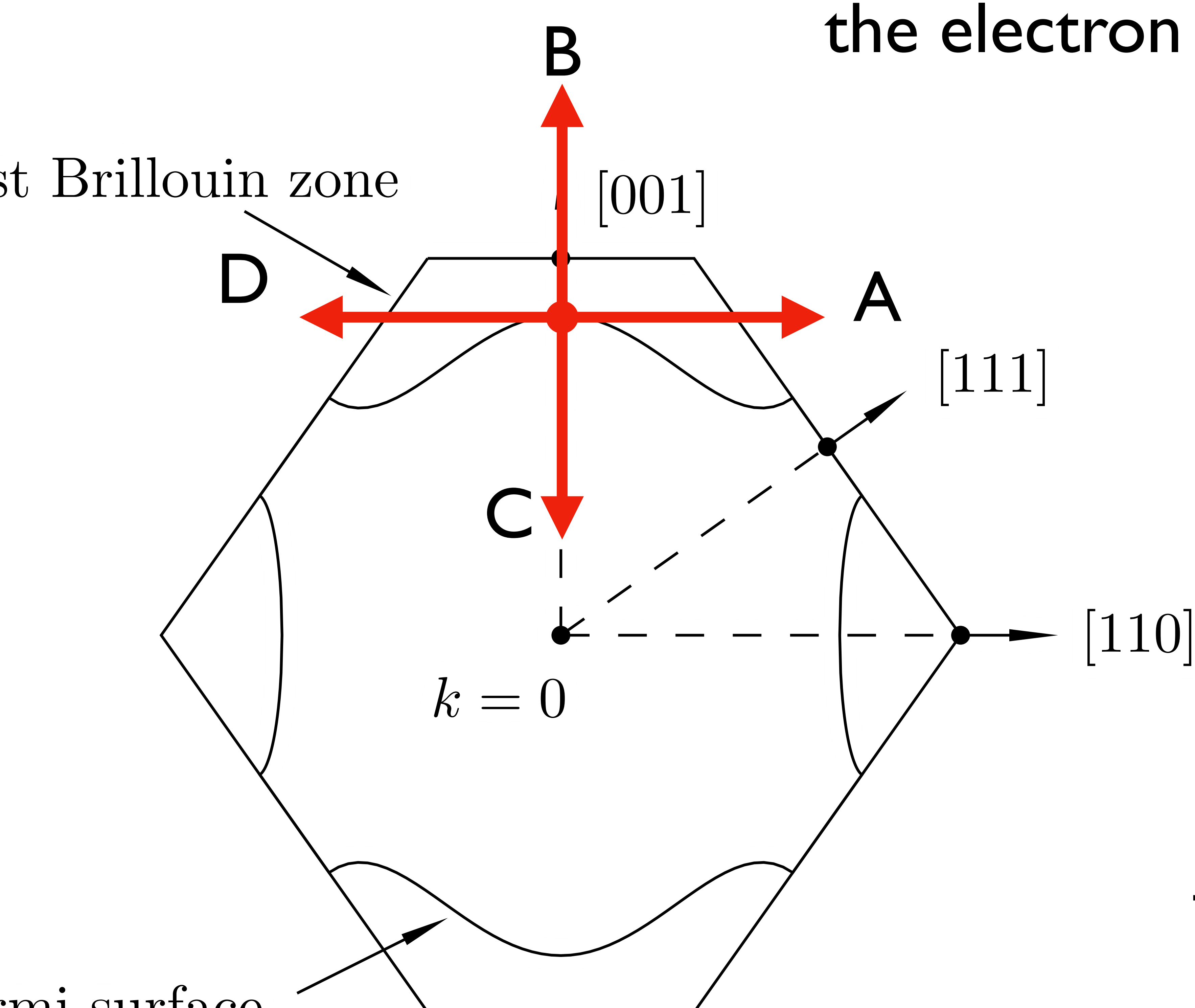
$$\mathbf{v} = \frac{1}{\hbar} \nabla_{\mathbf{k}} E \quad 3$$

$$\frac{d\mathbf{k}}{dt} = -\frac{e}{\hbar^2} \nabla_{\mathbf{k}} E \times \mathbf{B} \quad 4$$

The Hall effect

Question #2

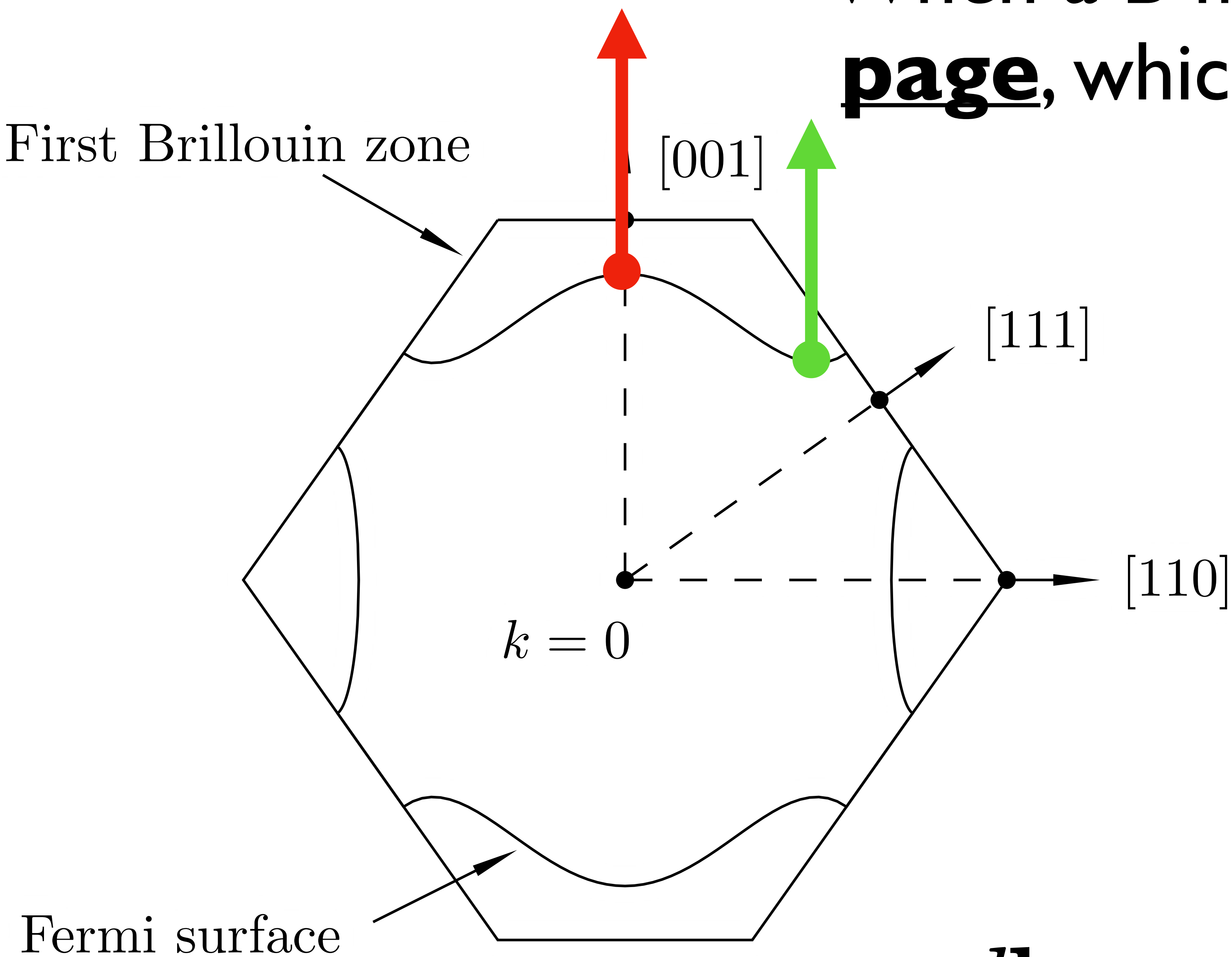
What is the group velocity vector for the electron in the state below?



$$\mathbf{v} = \frac{1}{\hbar}\nabla_{\mathbf{k}}E$$

The Hall effect

Question #3



When a B field is applied **<u>out of the page</u>**, which electron drifts leftward? (in real space)

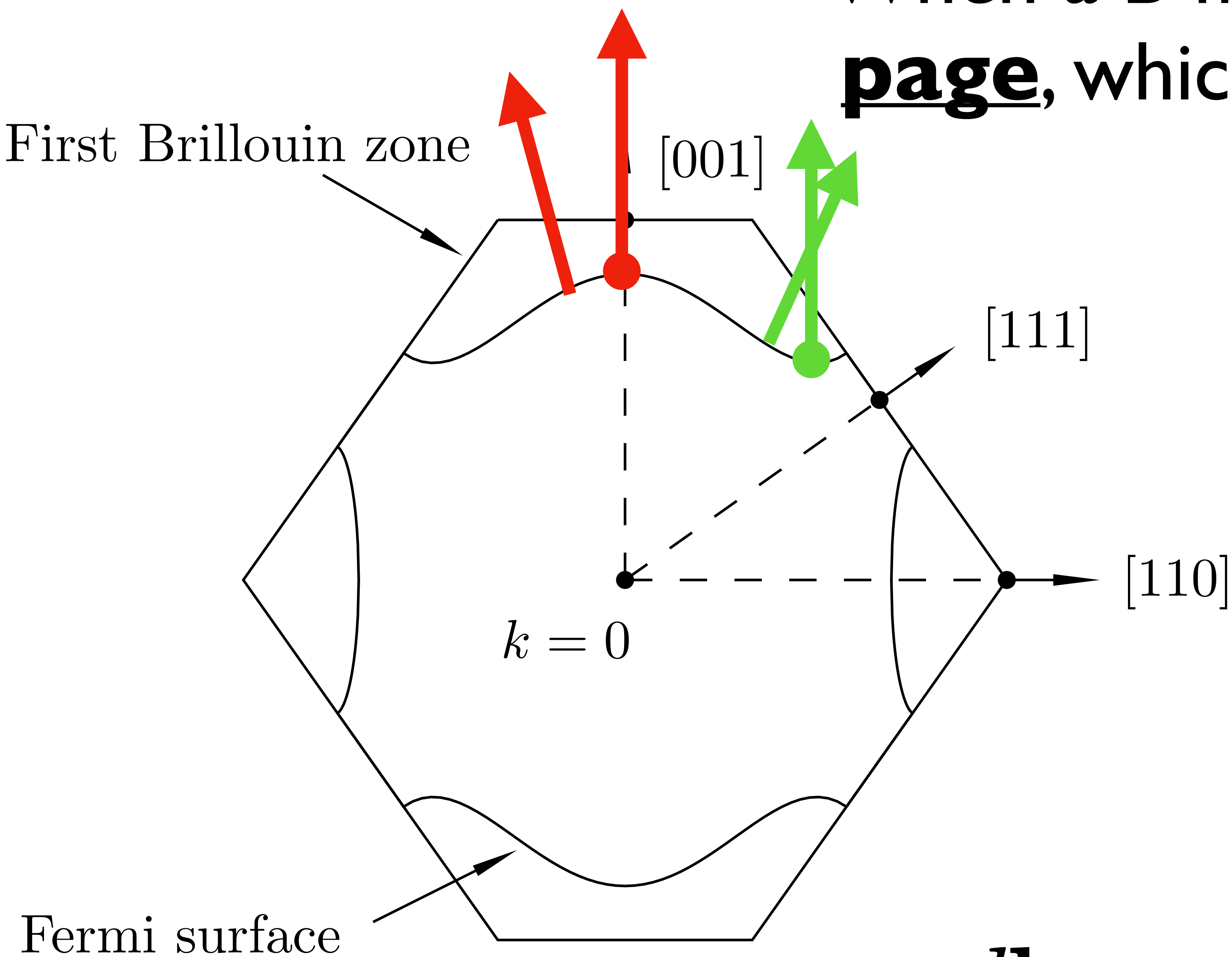
A) they both do
B) Green state
C) Red state
D) Neither do.

$$\frac{d\mathbf{k}}{dt} = -\frac{e}{\hbar^2}\nabla_{\mathbf{k}}E \times \mathbf{B}$$

The Hall effect

Question #3

When a B field is applied **out of the page**, which electron drifts leftward? (in real space)



A) they both do
B) Green state
C) Red state
D) Neither do.

$$\frac{d\mathbf{k}}{dt} = -\frac{e}{\hbar^2}\nabla_{\mathbf{k}}E \times \mathbf{B}$$

Question #4

At zero temperature, silicon is a
(D) metal, or
(E) insulator.

Question #5

Consider electrons in states with nearly the highest energy of the band. Generally, their effective mass is

(A) Infinite
(B) Zero
(C) Positive
(D) Negative
(E) Unknown

Nearly-free electron bands

Question #6

If there are 4 electrons per unit cell, how many bands are filled?

(A) 2
(B) 1.5
(C) 1
(D) 2.5
(E) 3

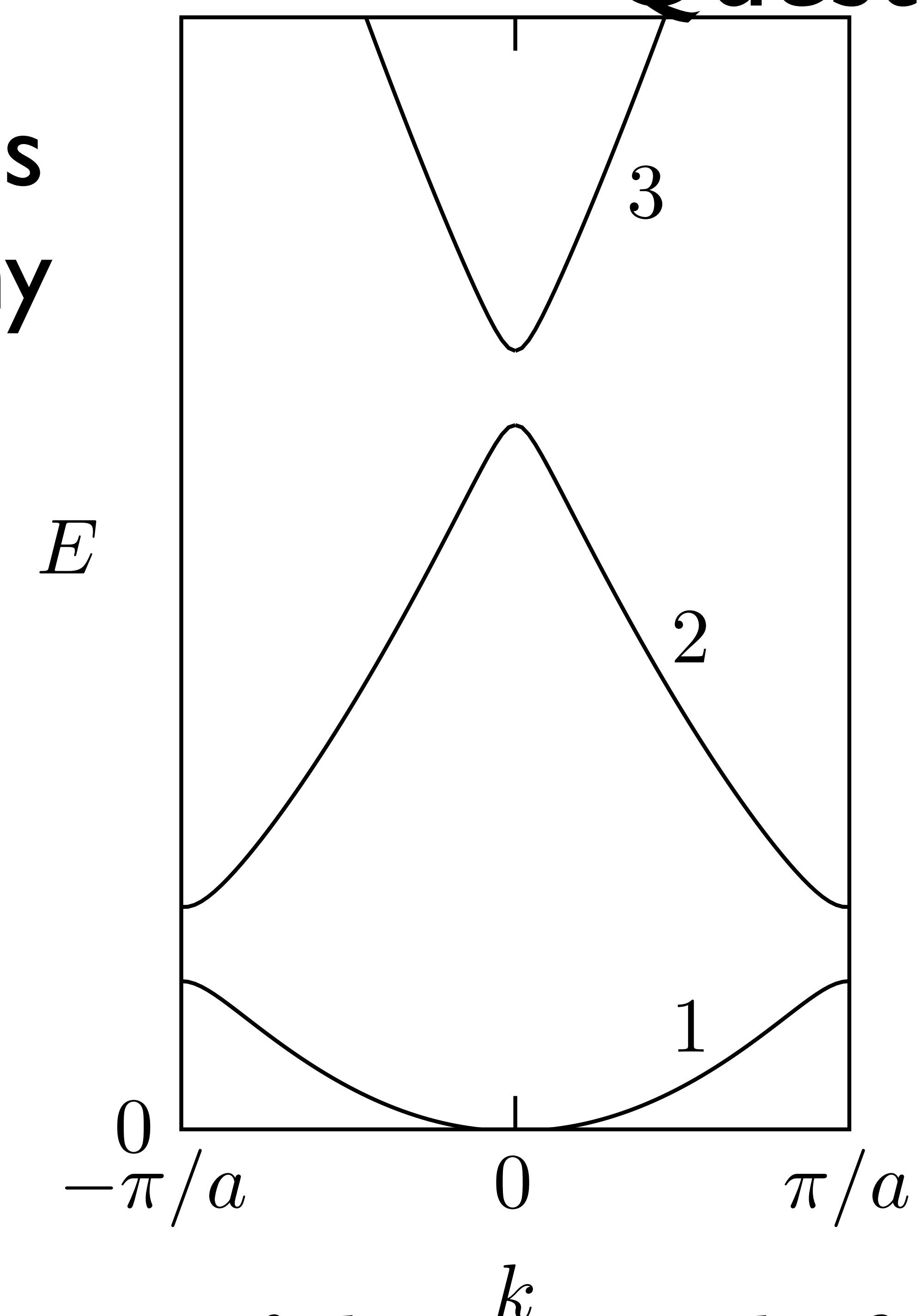


Fig. 8-4. Energy of electrons in the first Brillouin zone.

Nearly-free electron bands

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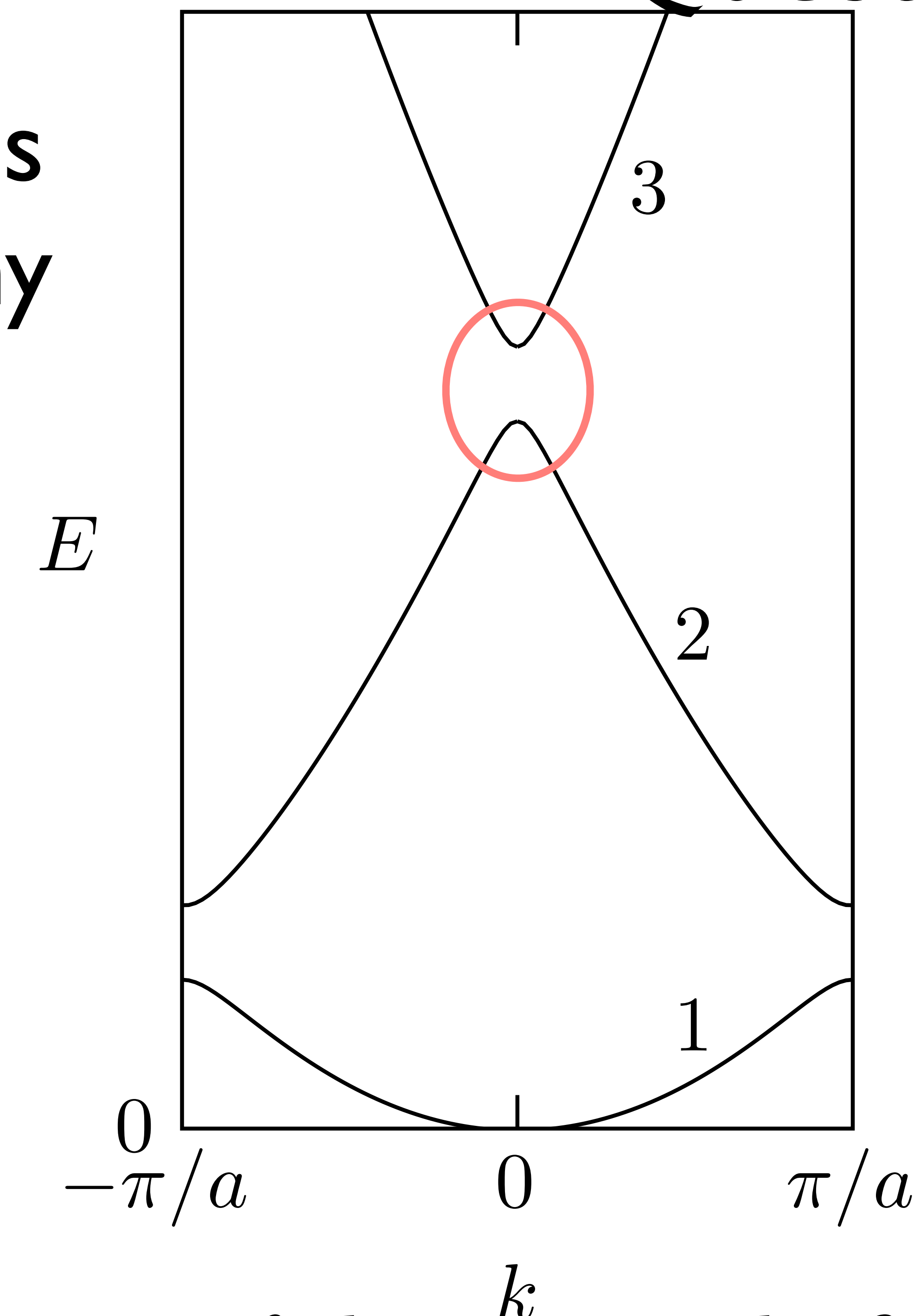


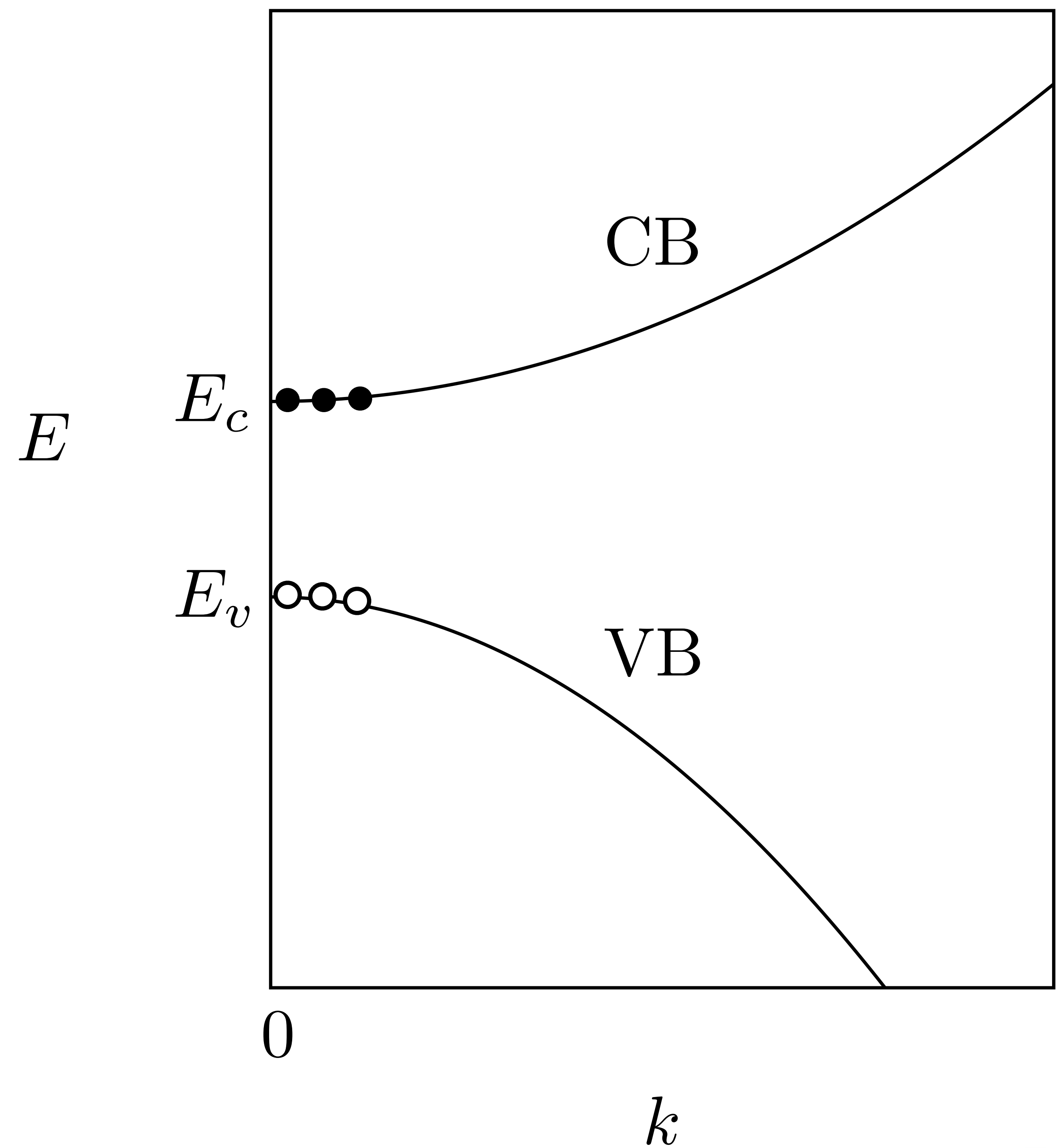
Fig. 8-4. Energy of electrons in the first Brillouin zone.

Typical semiconductor bands

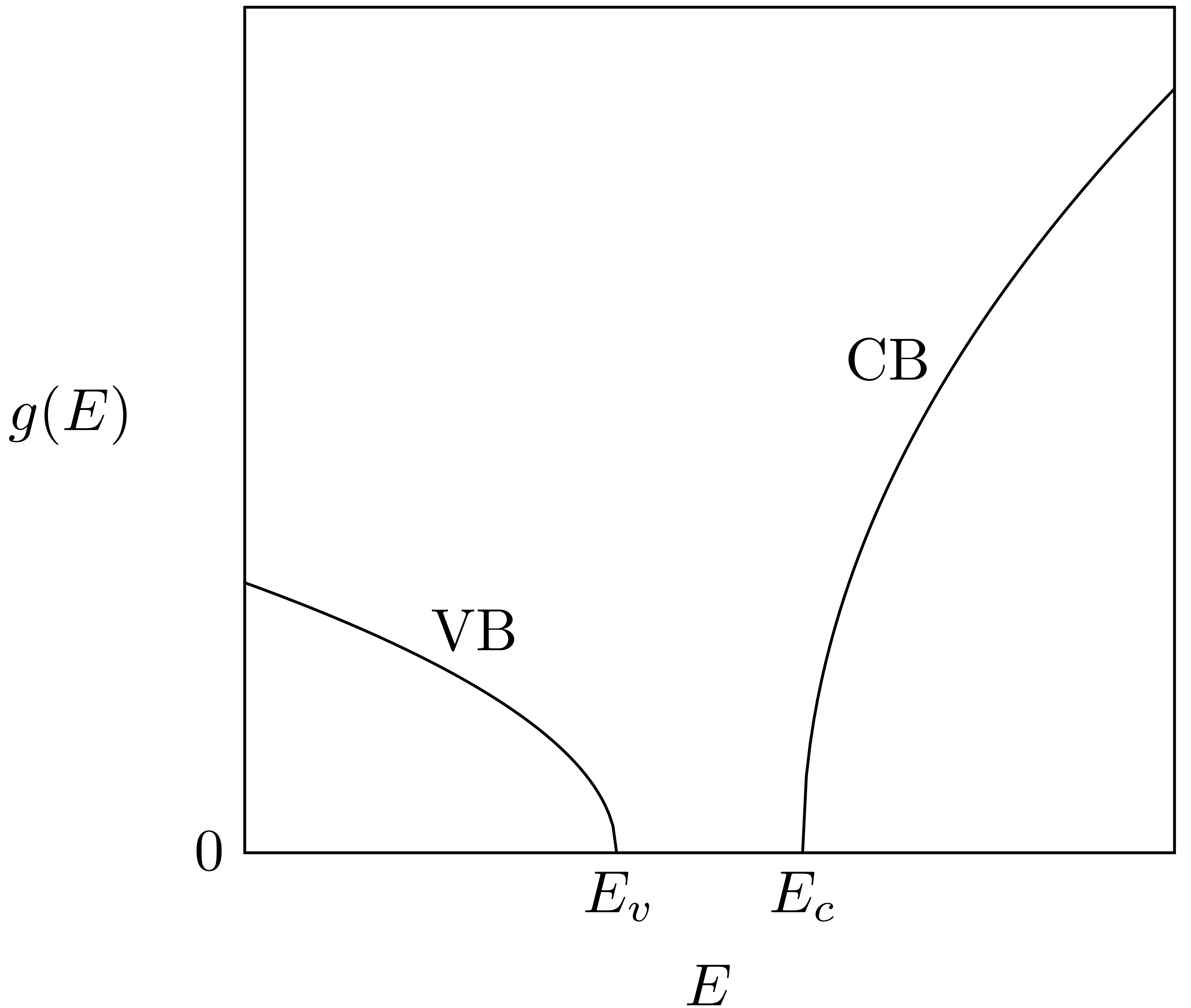
$$E(k) = E(0) + \left.\frac{dE}{dk}\right|_{k=0} k + \frac{1}{2}\left.\frac{d^2E}{dk^2}\right|_{k=0} k^2 + \cdots$$

$$E = E_c + \frac{\hbar^2}{2m_n^*}k^2$$

$$E = E_v - \frac{\hbar^2}{2m_p^*}k^2$$

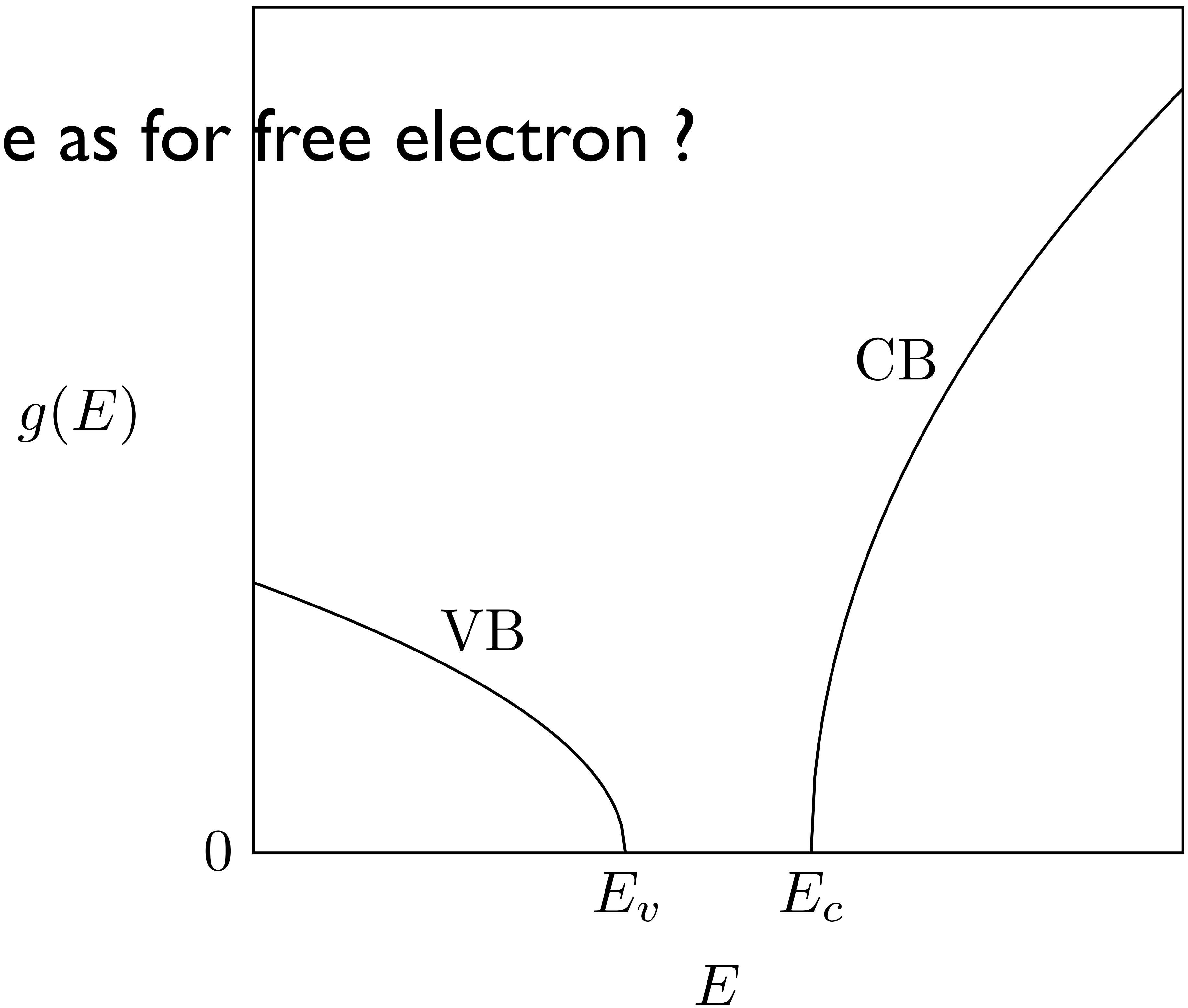


Density of states

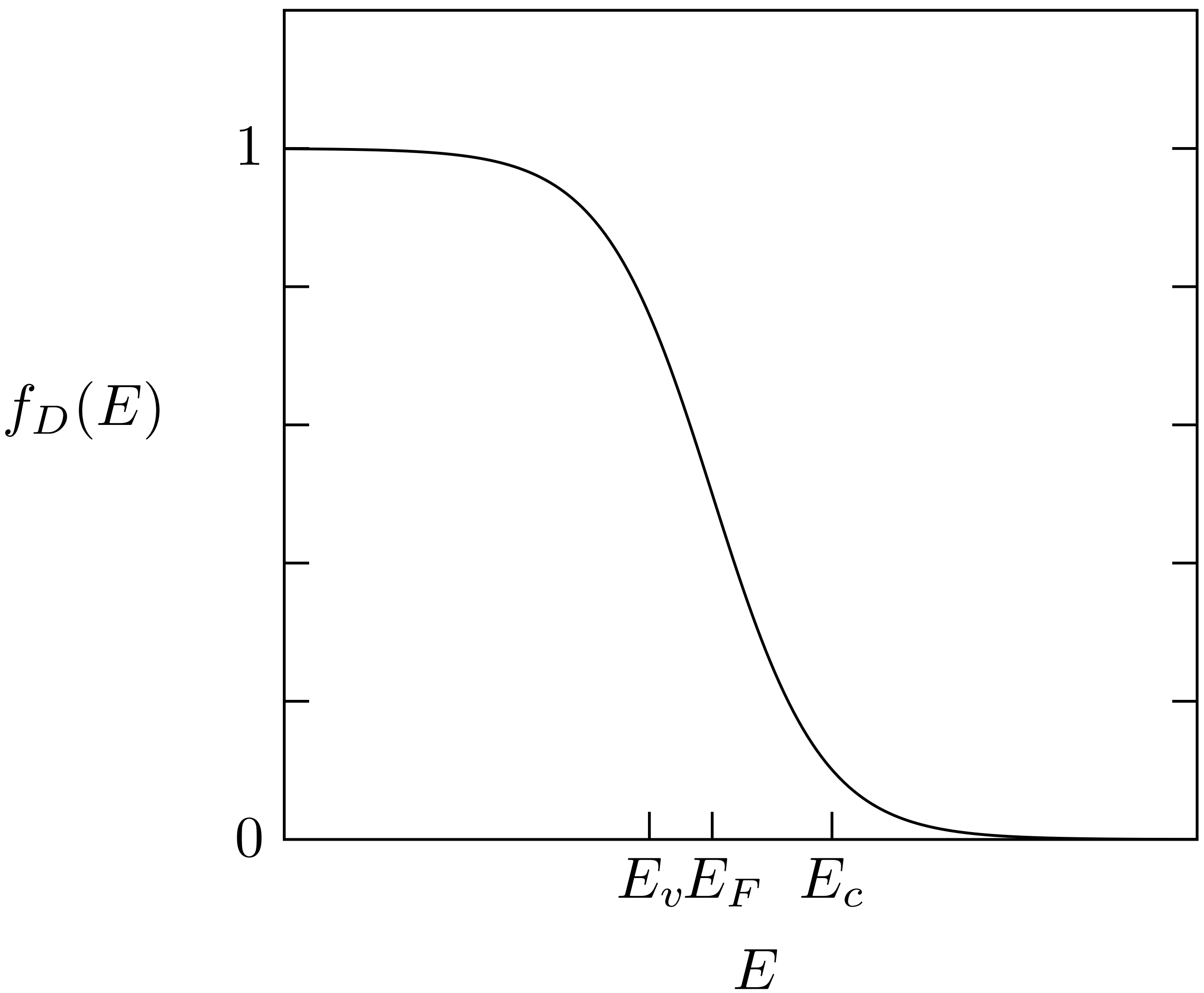


Density of states

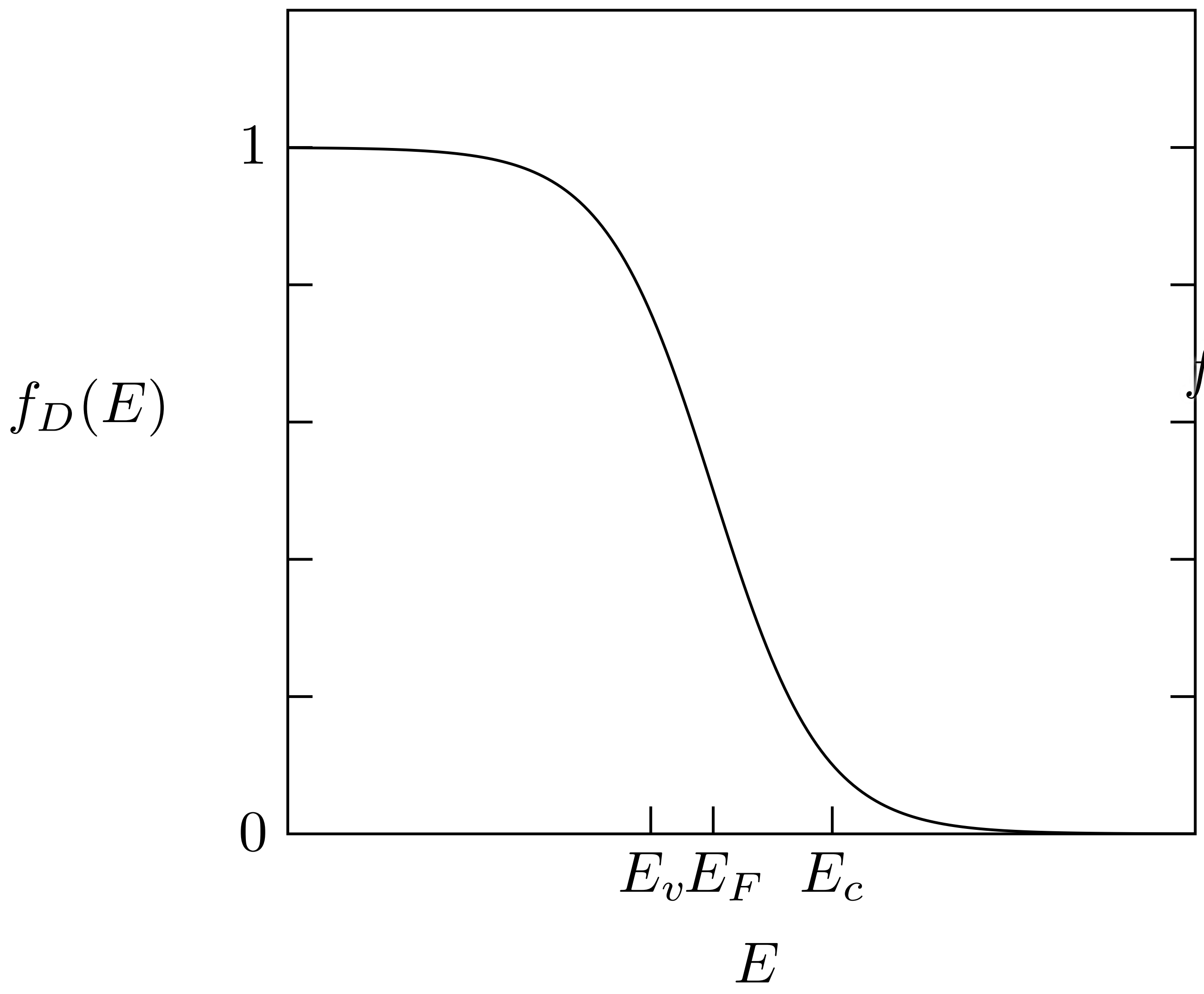
Same as for free electron ?

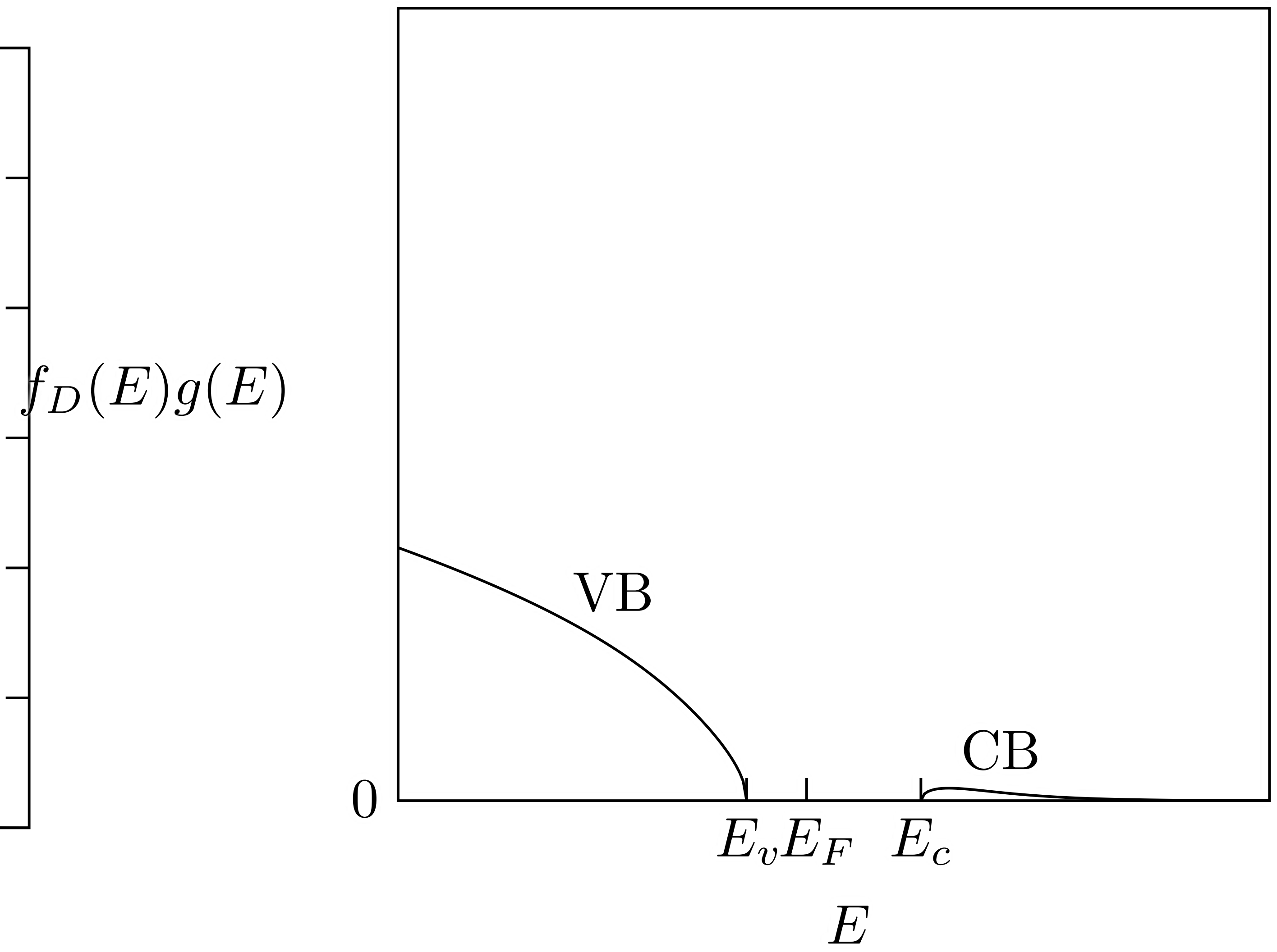


Band occupation at $T \neq 0$



Band occupation at $T \neq 0$





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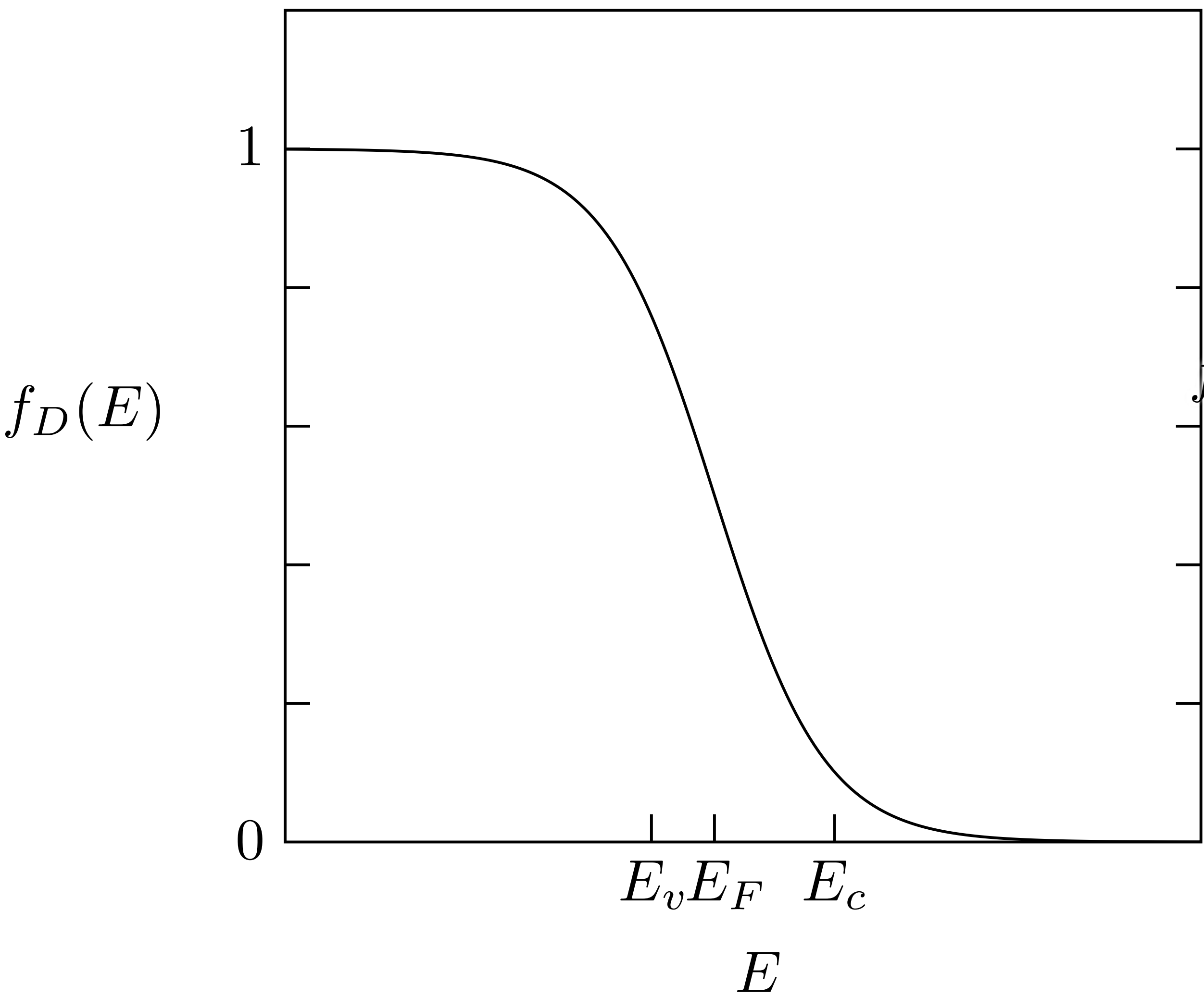

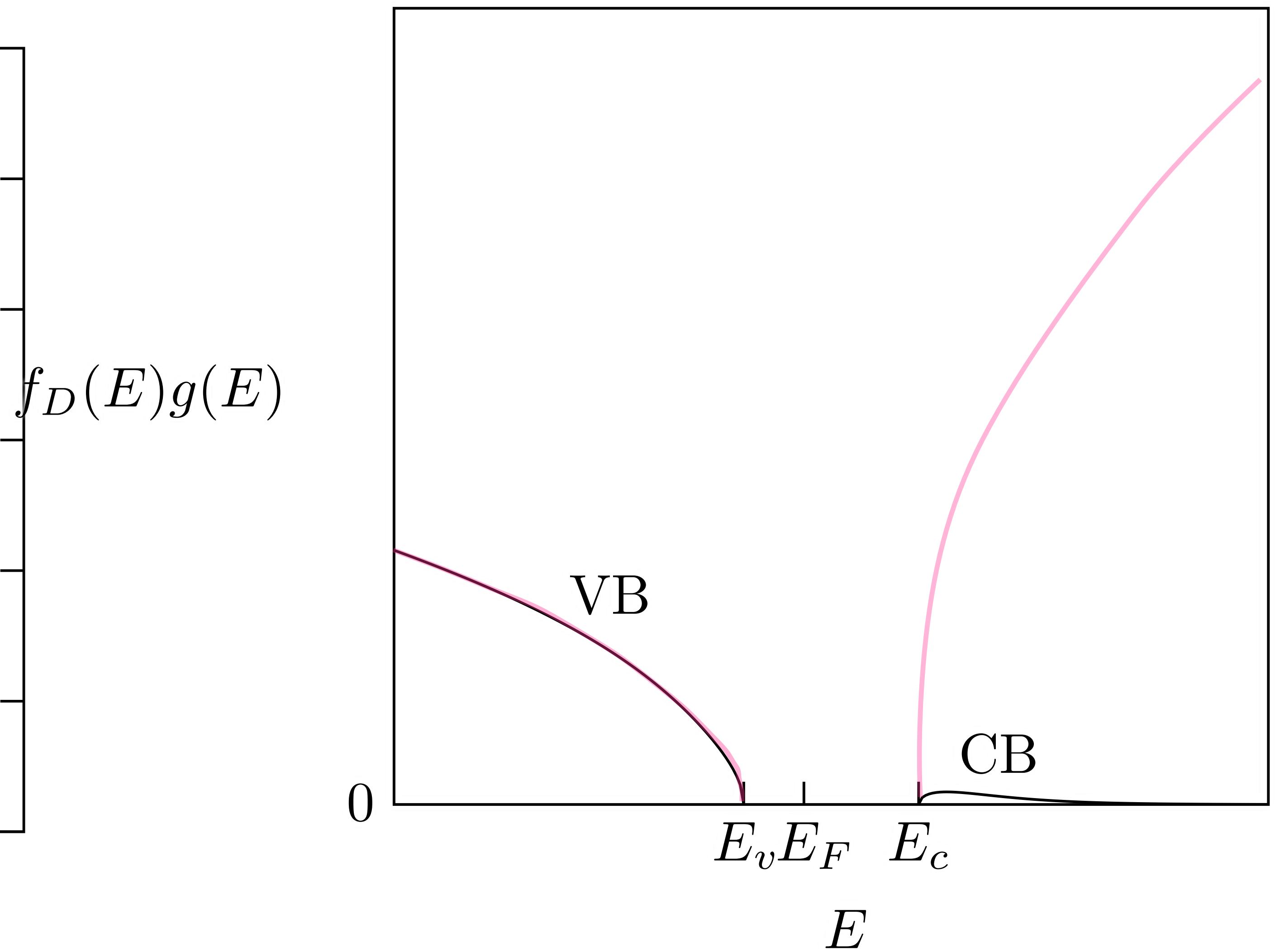

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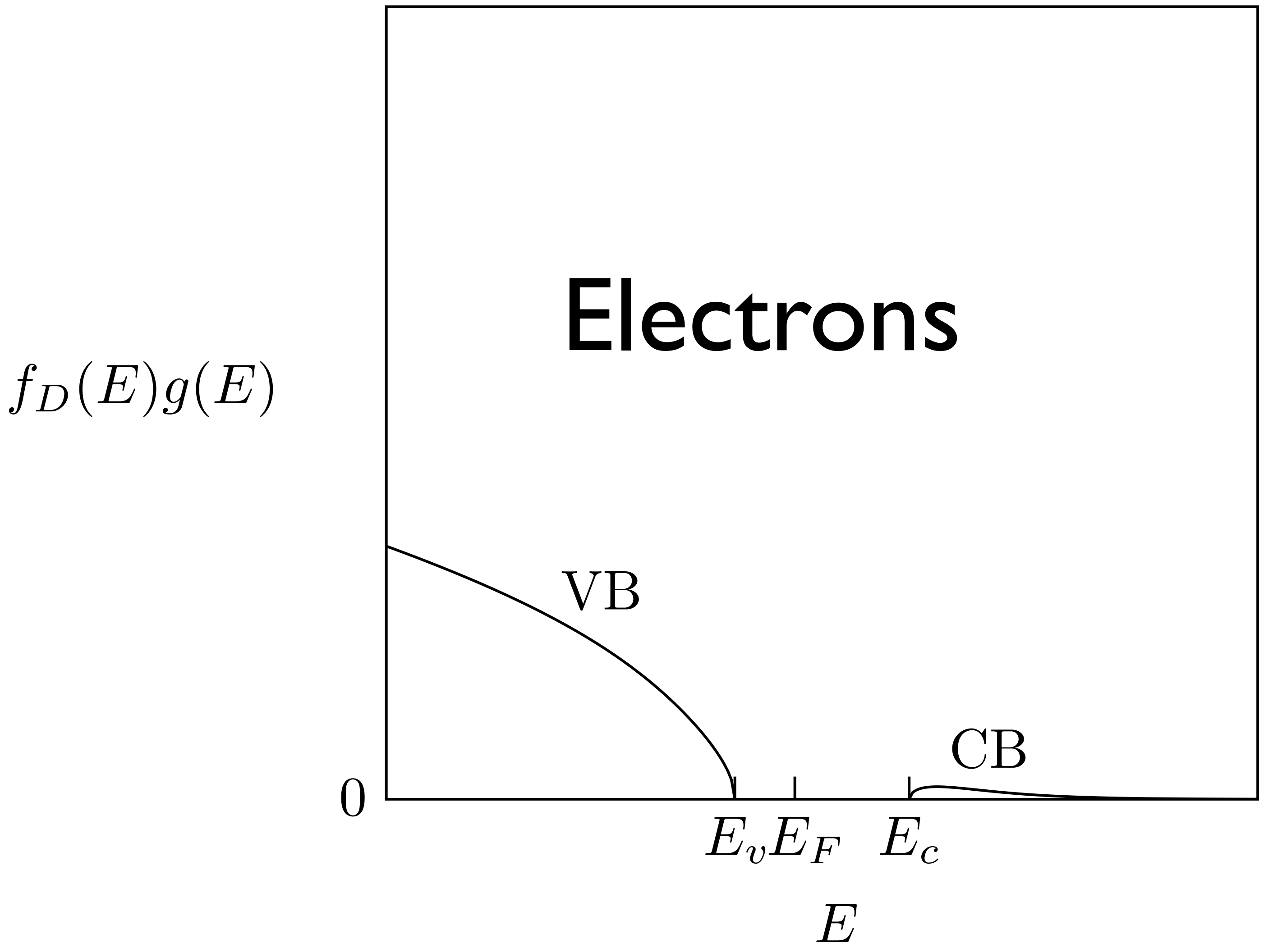

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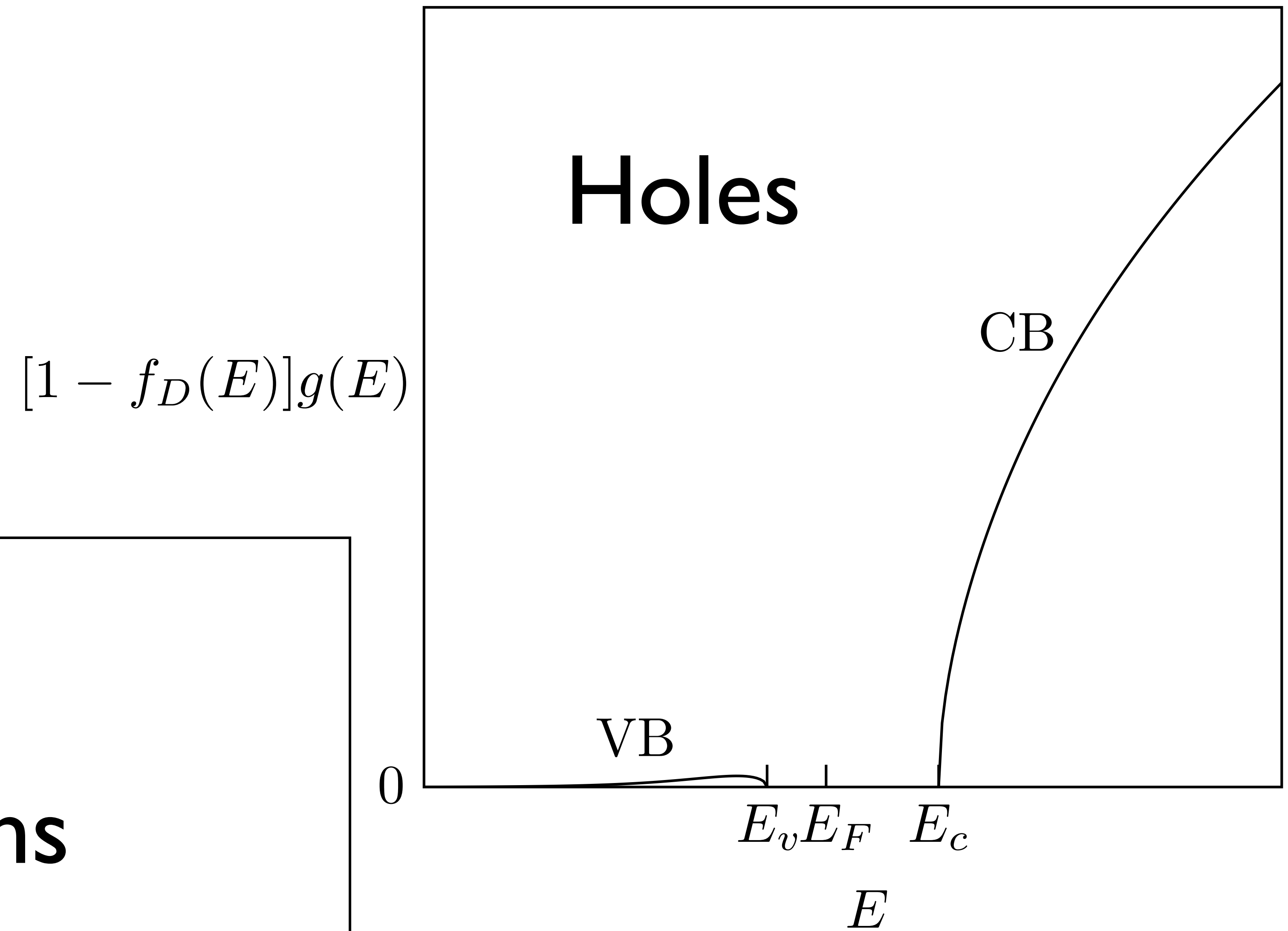
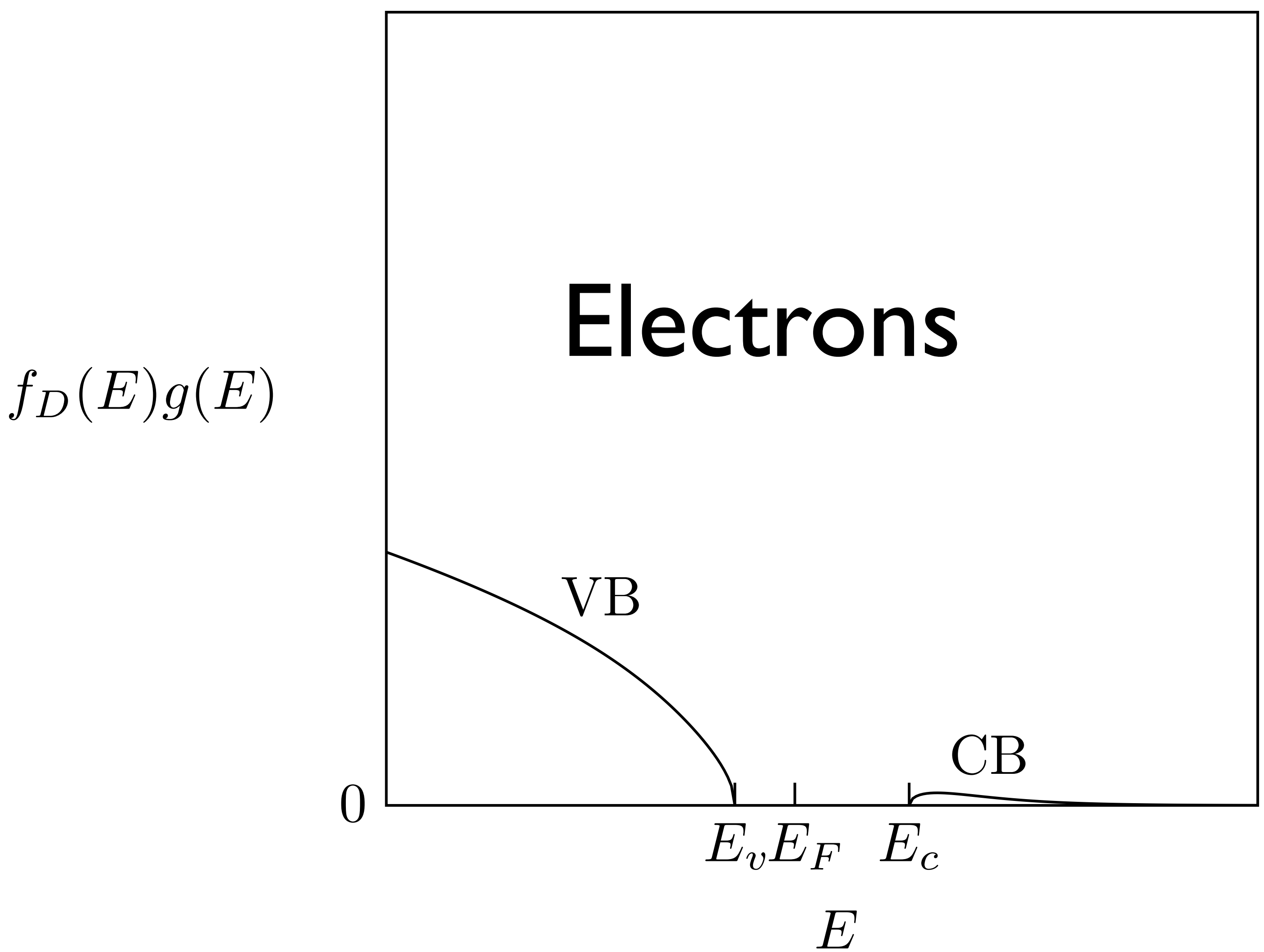
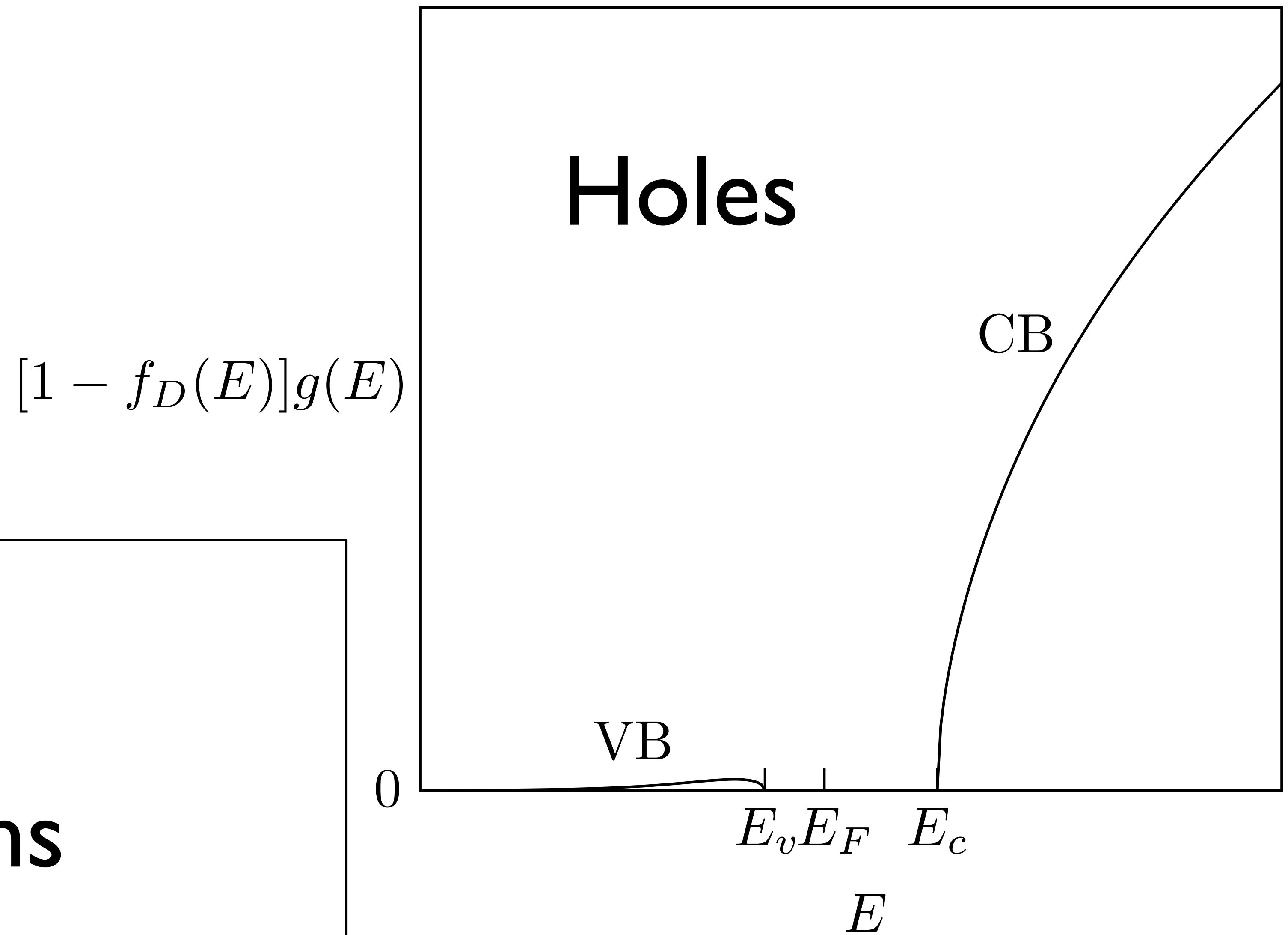
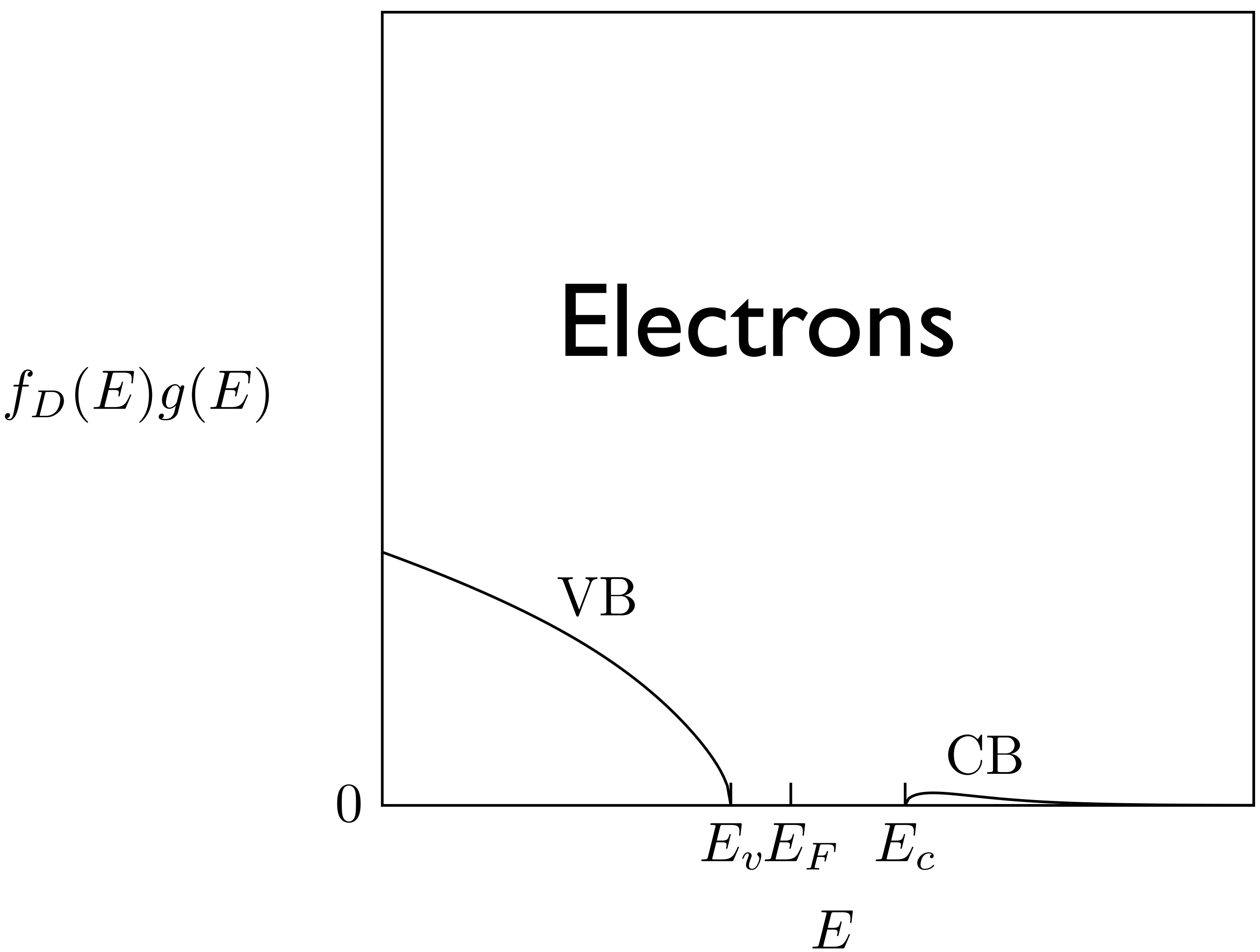




Band occupation at $T \neq 0$

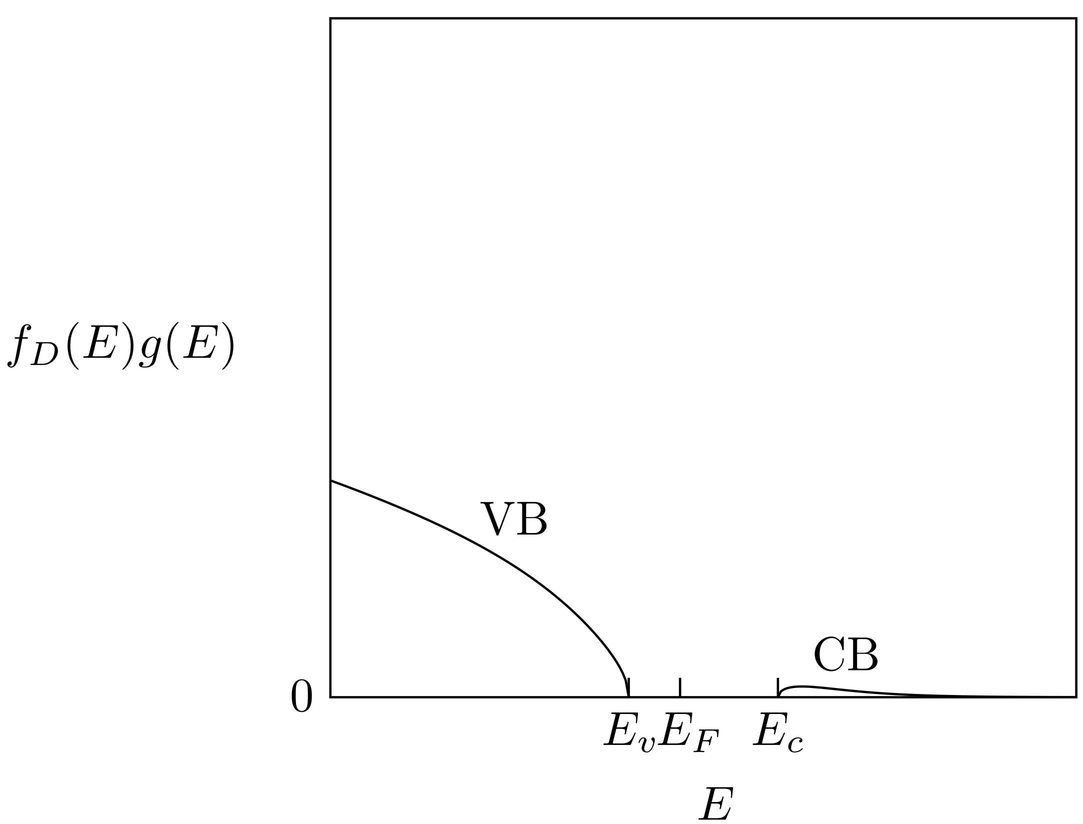
Why $1 - f_D$?

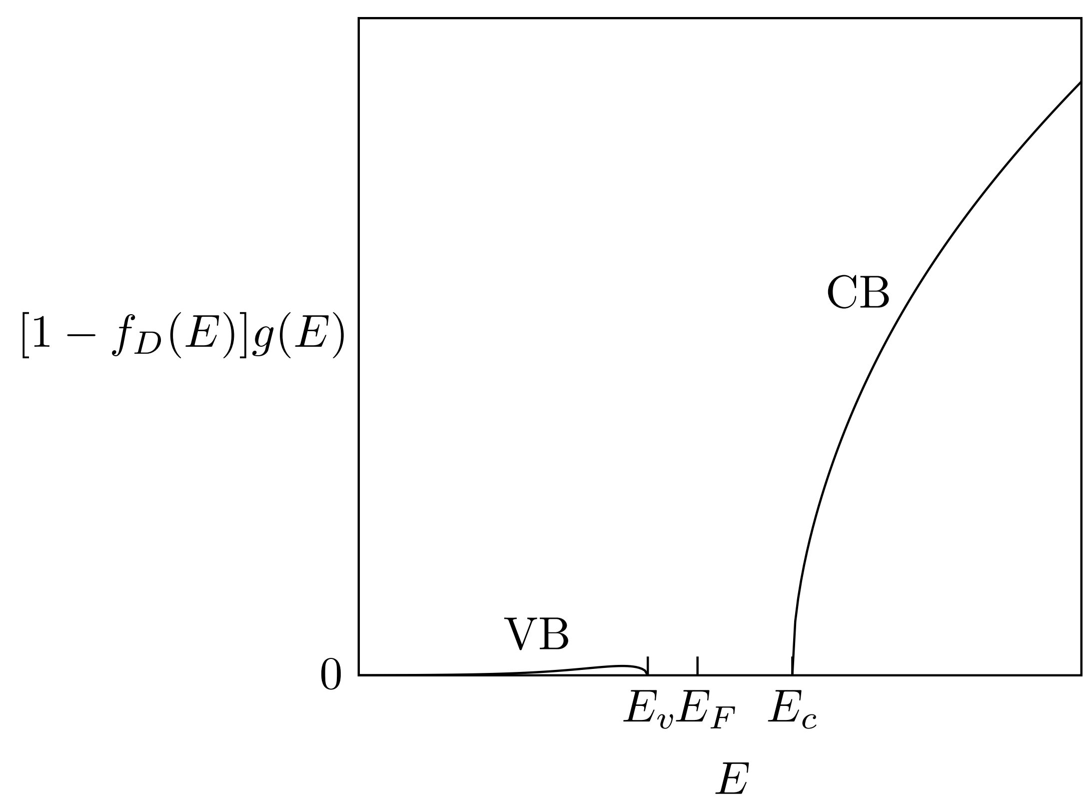




Quiz

In a pure semiconductor, why does the (volume) density of electrons in the conduction band equal the (volume) density of holes in the valence band?





$$n = \frac{1}{V}\int f_D(E)g(E)dE$$

$$= 2\left(\frac{m_n^* k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_c - E_F}{k_B T}\right)$$

$$p = 2\left(\frac{m_p^* k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_F - E_v}{k_B T}\right)$$

Set n = p

$$E_f \approx \frac{1}{2}\left(E_c + E_v\right)$$

$$n_i = \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2k_B T}\right)$$

At 300 K

$$n_i = 9.8 \times 10^{15}$$

At 373 K

$$n_i = 9.5 \times 10^{17}$$

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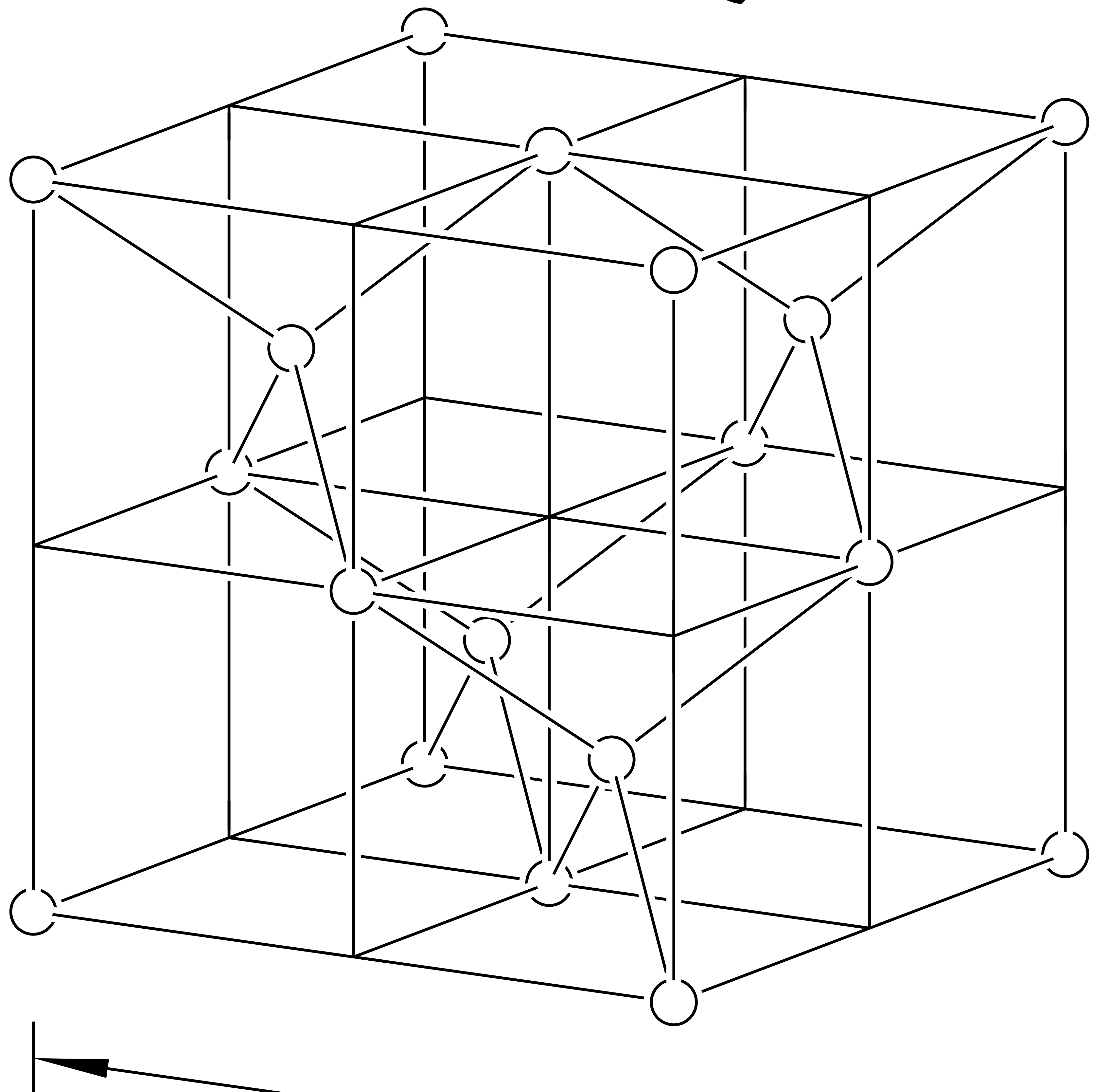
Silicon (Si) has the diamond structure. What is the lattice of the diamond structure?

Question #7

(A) Zincblende
(B) Wurtzite
(C) fcc
(D) bcc
(E) hcp



Silicon (Si) has the diamond structure. How many nearest neighbors does each silicon atom have?

Question #8

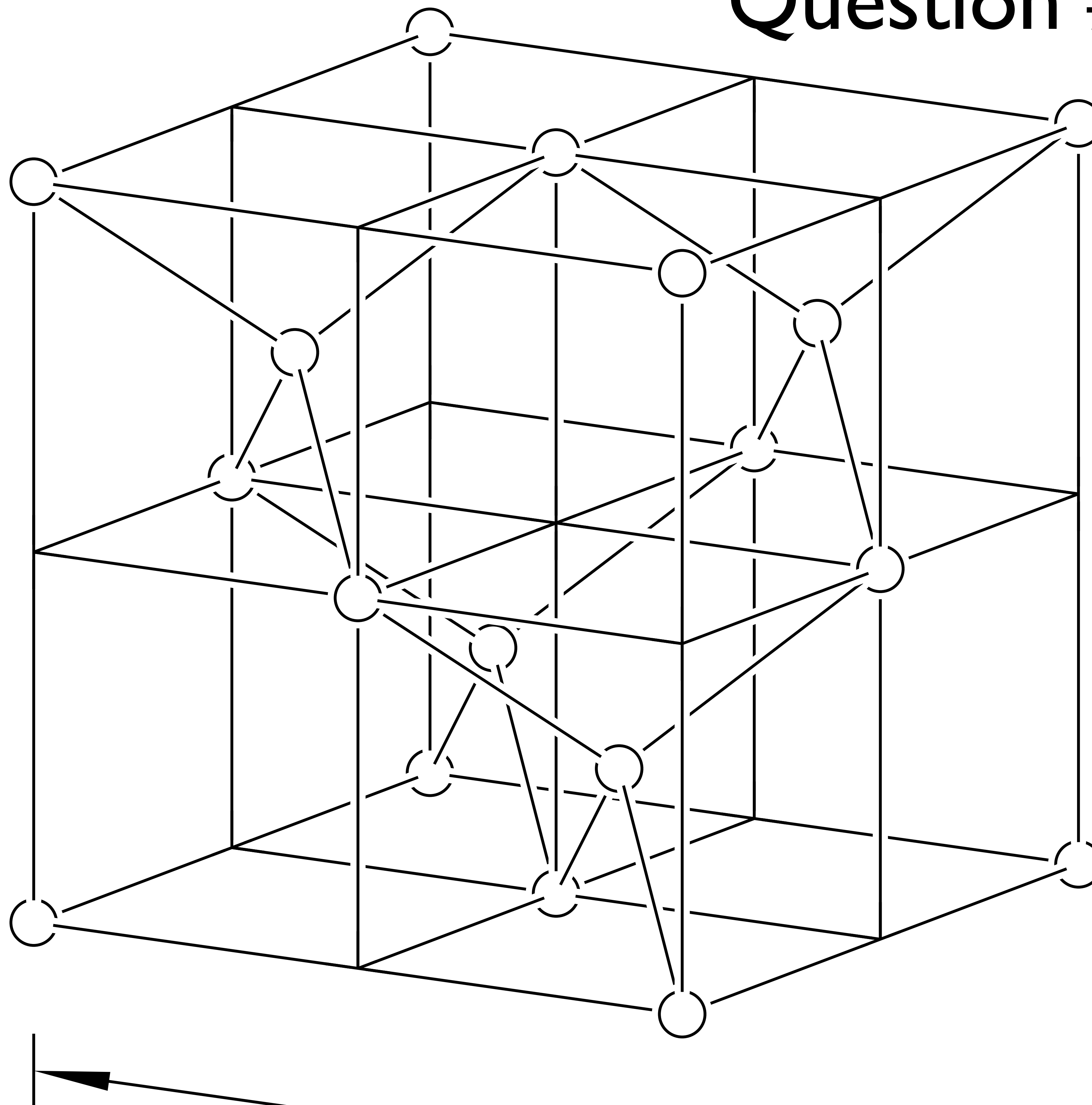
(A) 2

(B) 4

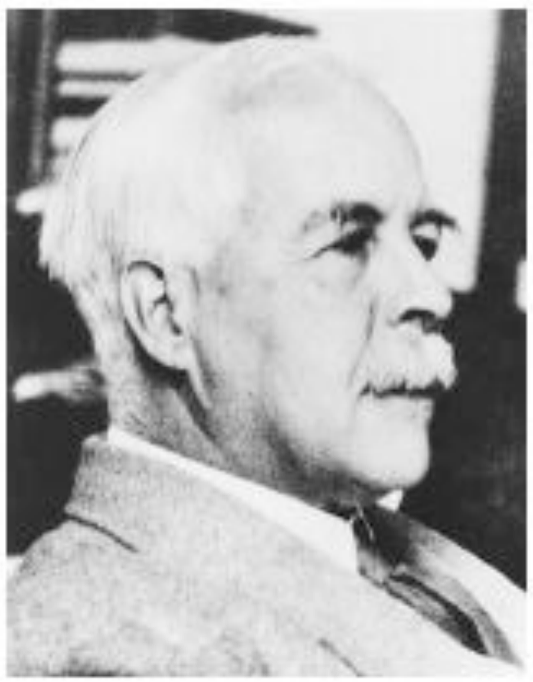
(C) 8

(D) 12

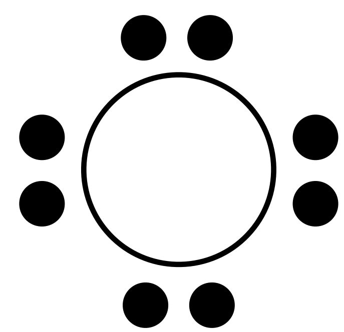
(E) 6



High School Chemistry (do you remember?)

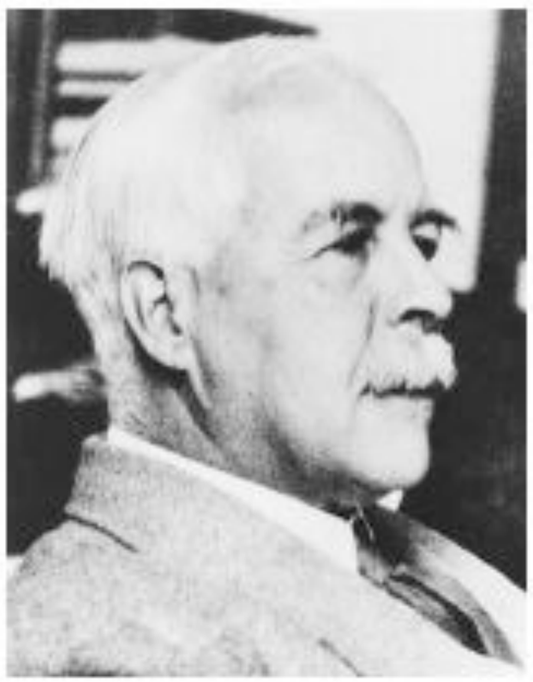


Gilbert Lewis



Lewis diagrams

High School Chemistry (do you remember?)



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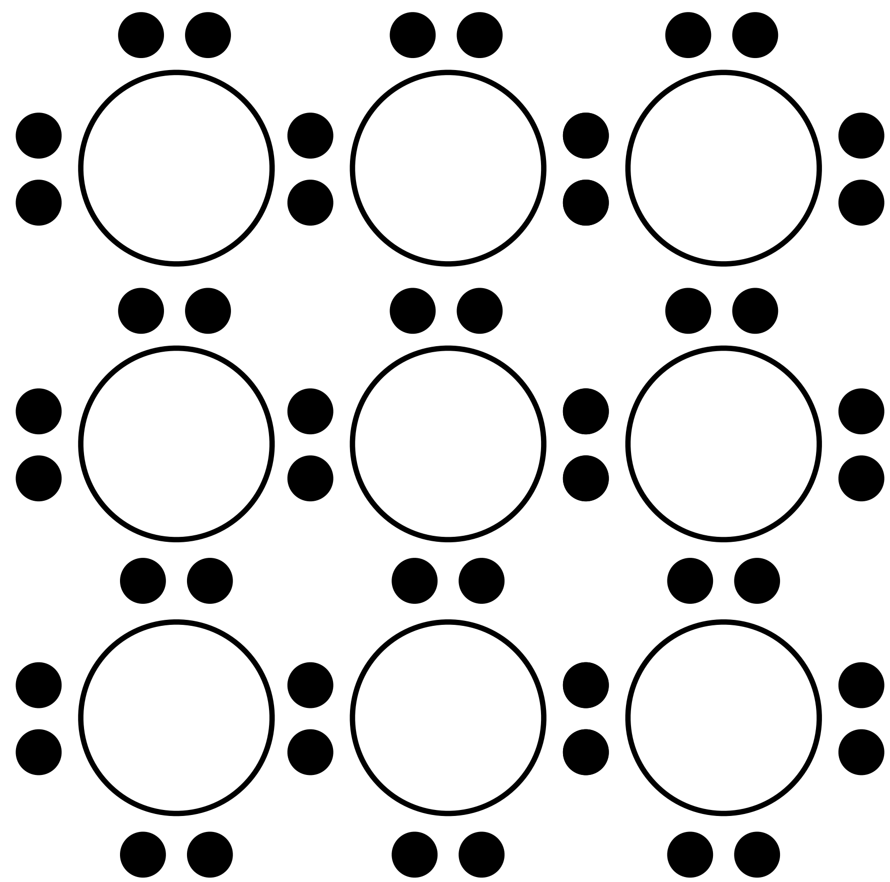

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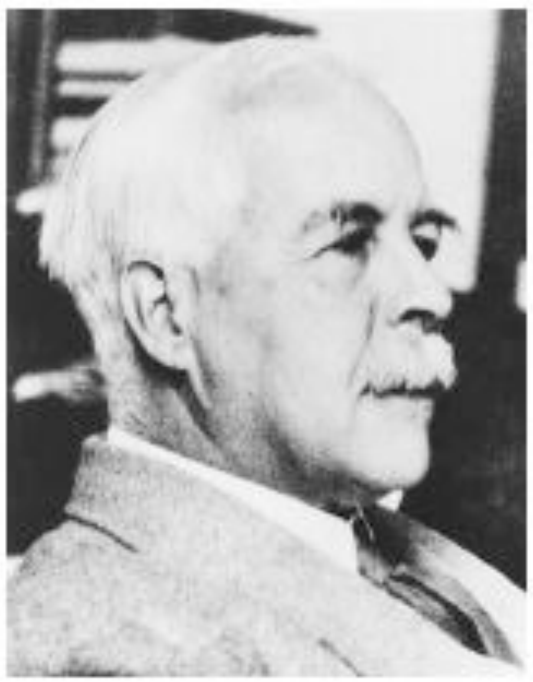
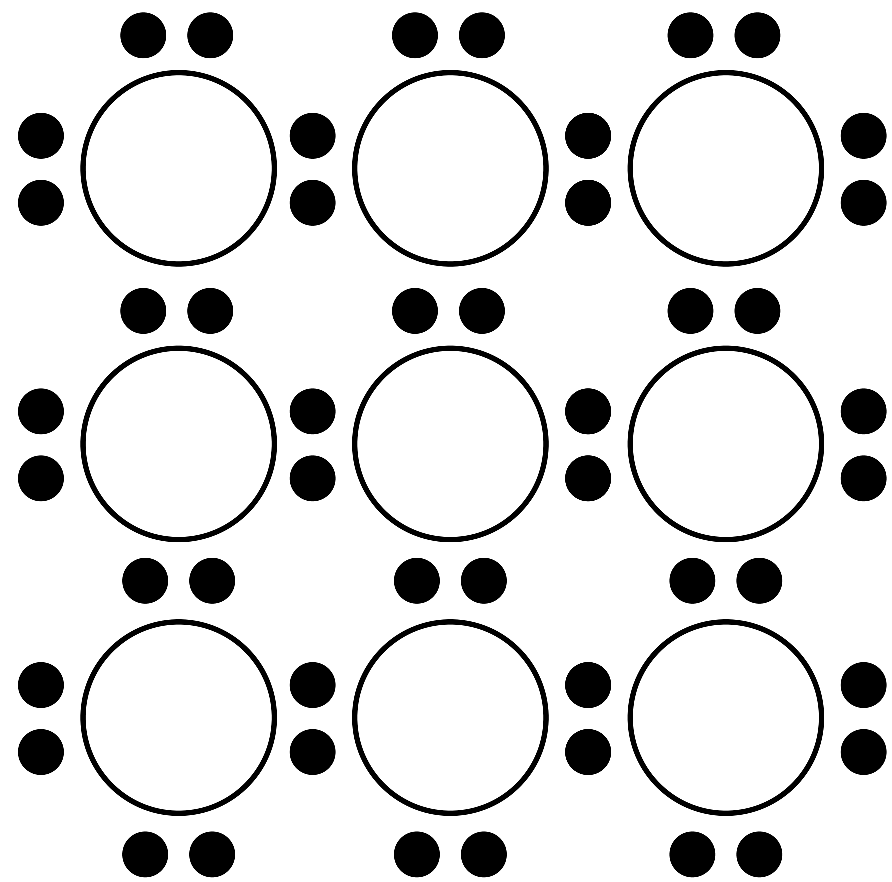
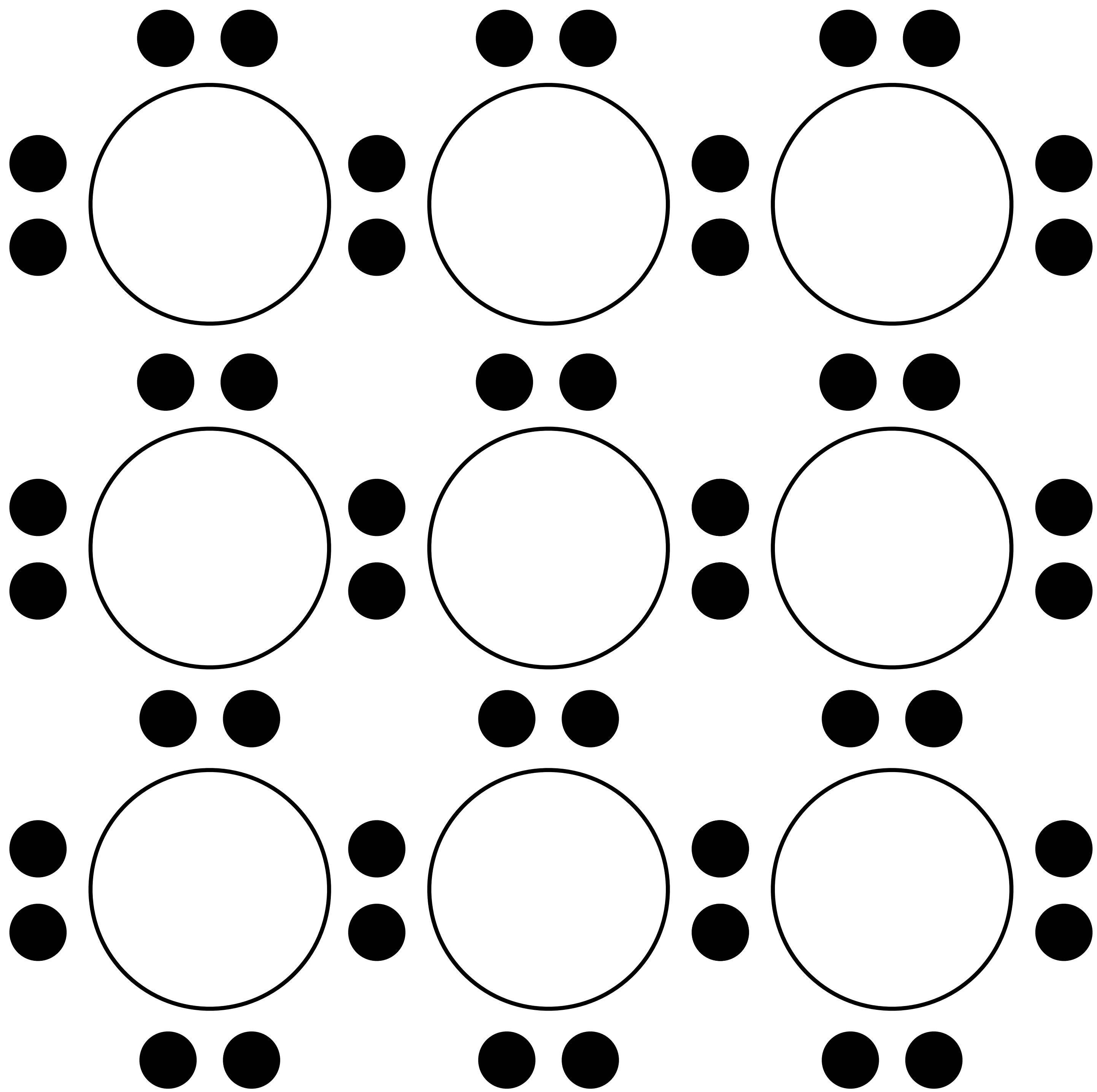


Gilbert Lewis



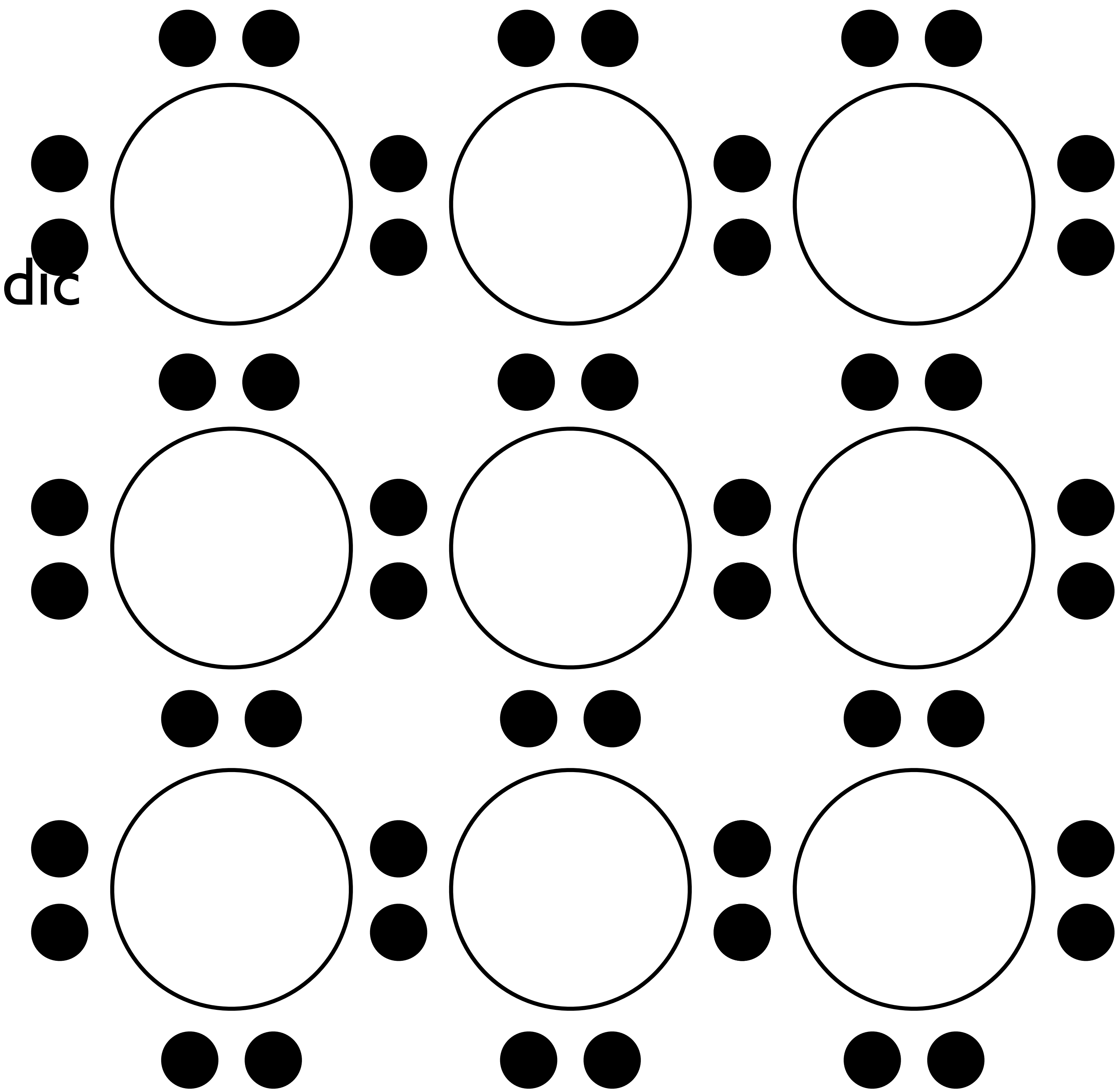
Lewis diagrams

2D Model of a Semiconductor



2D Model of a Semiconductor

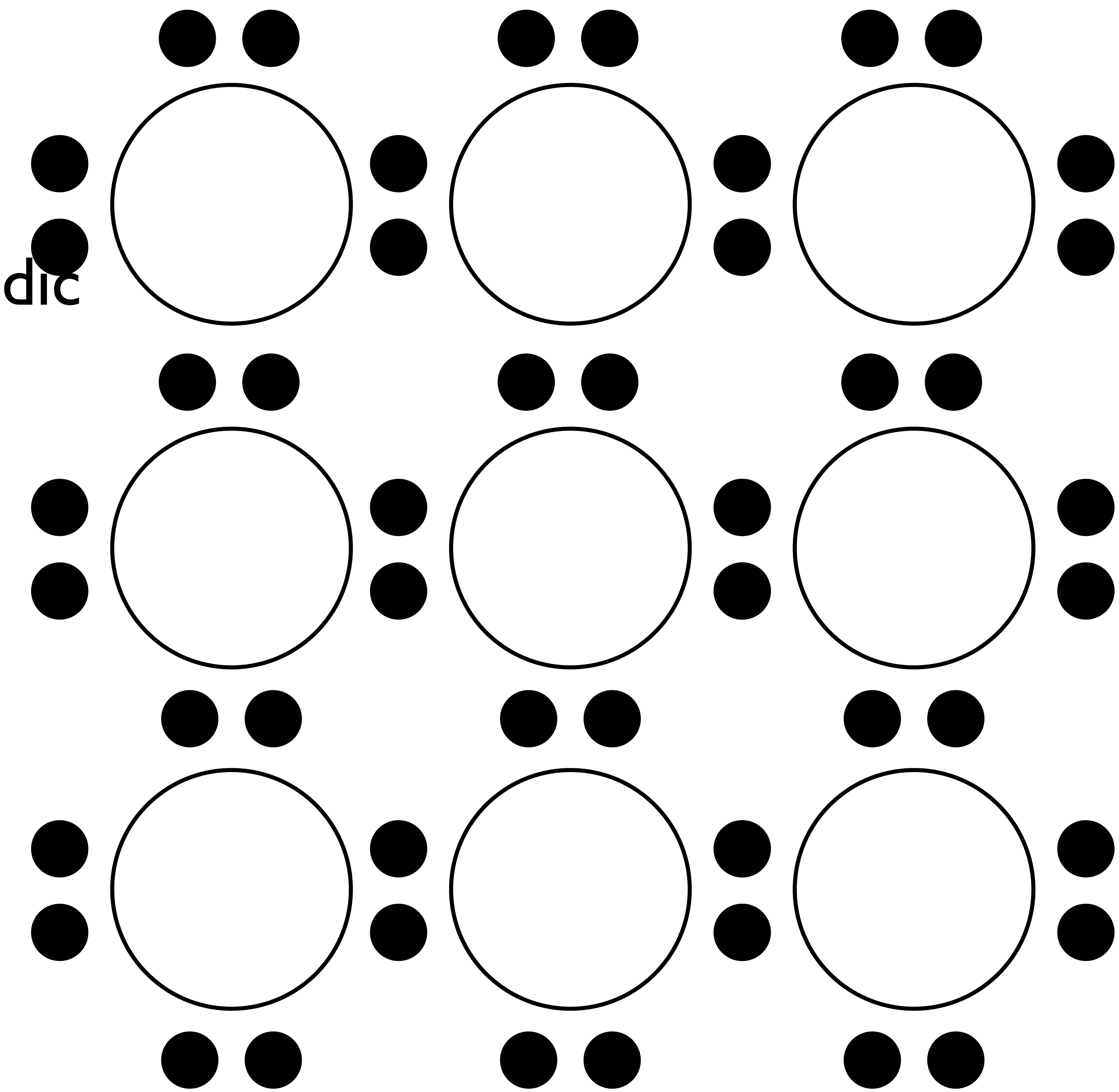
Where is silicon on the periodic table?



2D Model of a Semiconductor

Where is silicon on the periodic table?

Why is that significant?



2D Model of a Semiconductor

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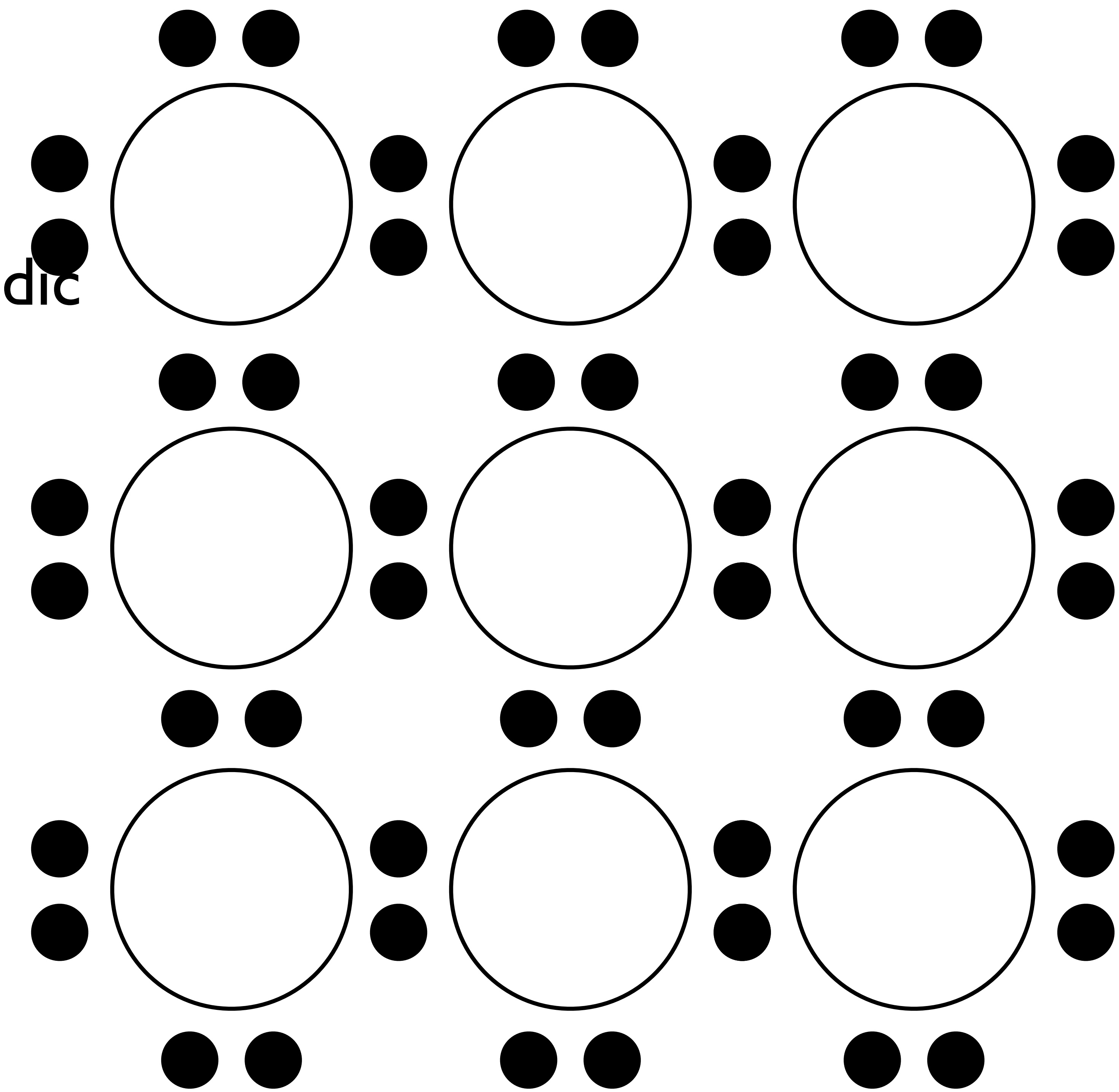
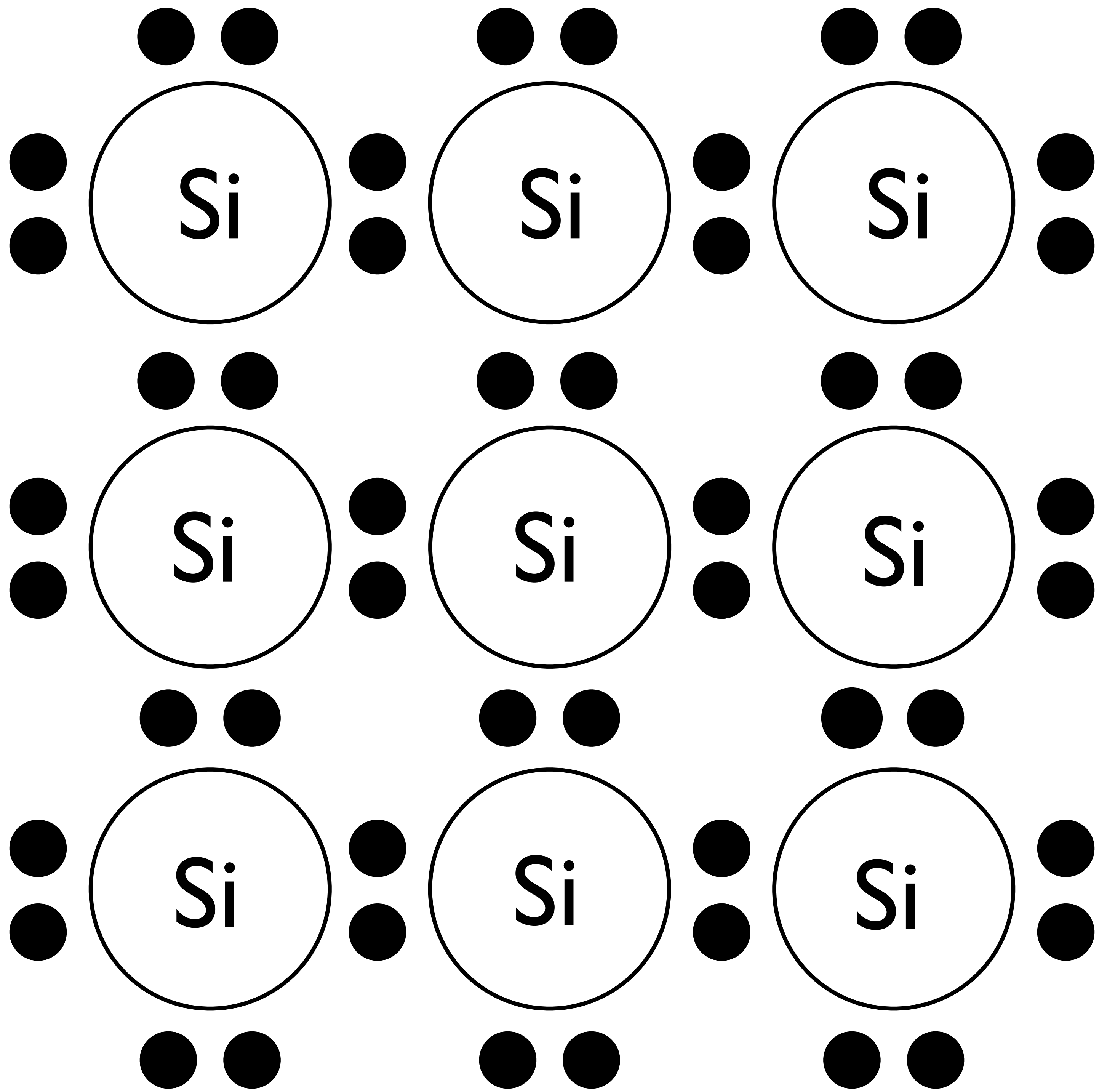
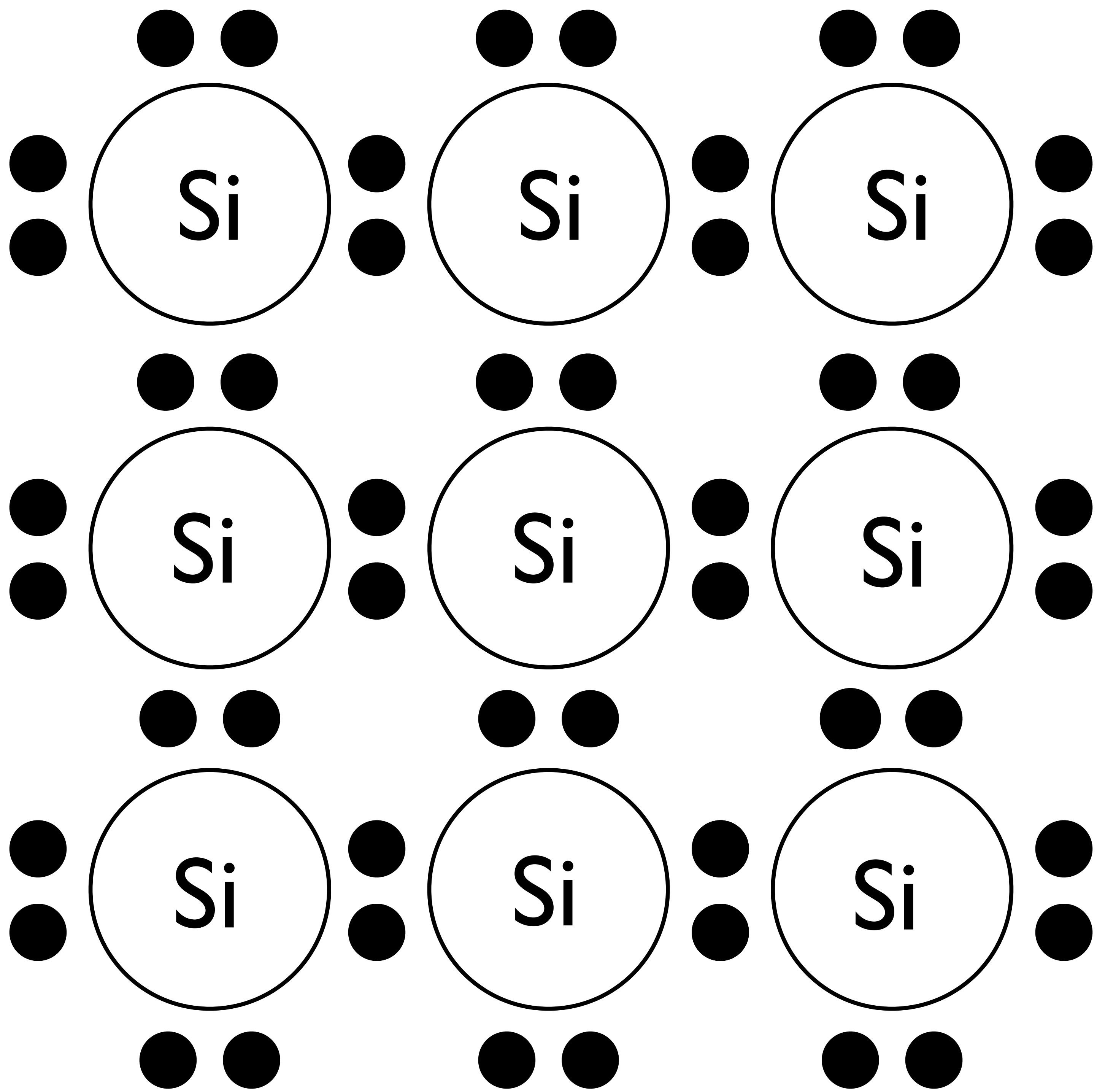


What role does temperature play?

Intrinsic semiconductor

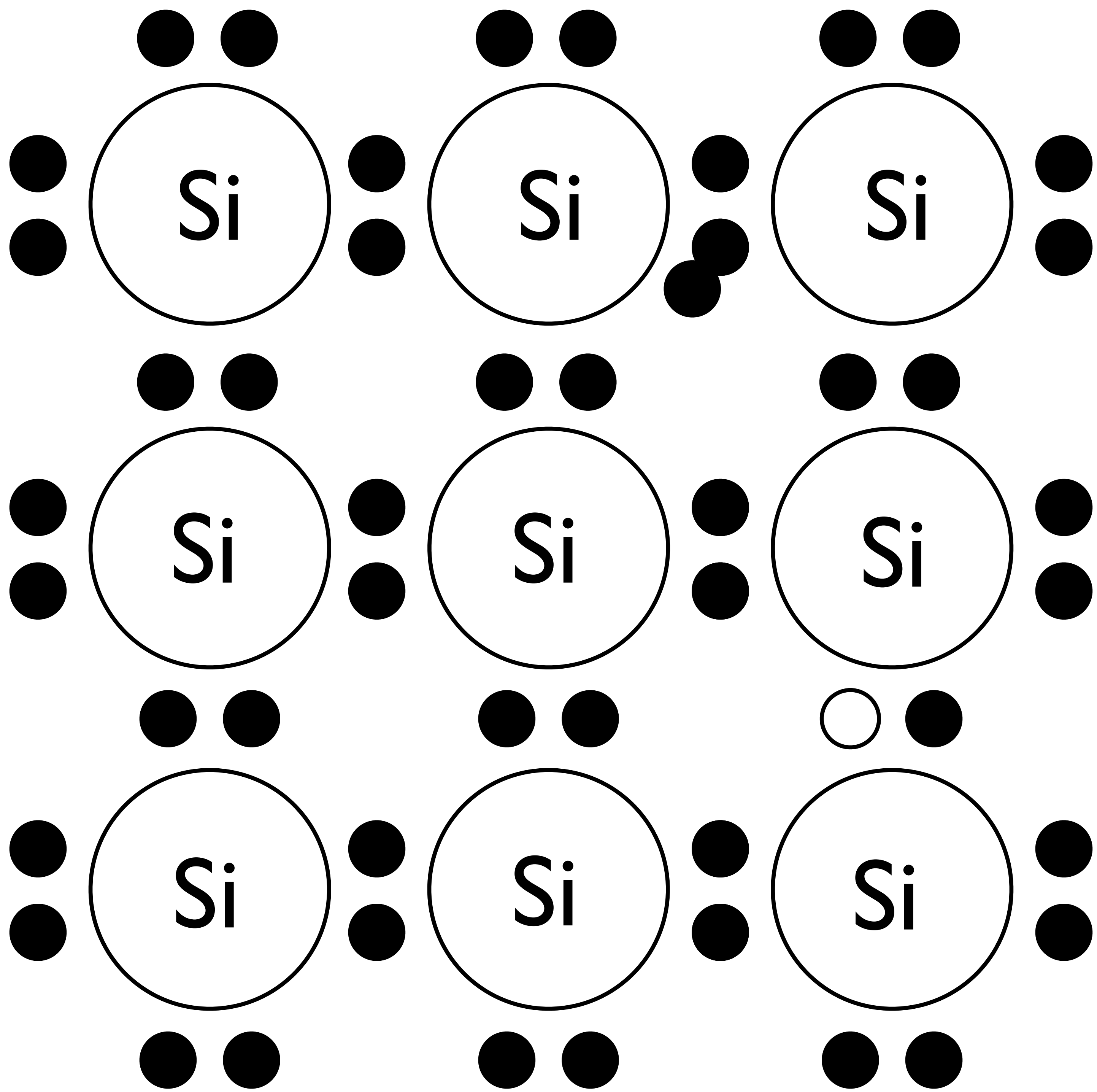


Intrinsic semiconductor



e-h pair creation

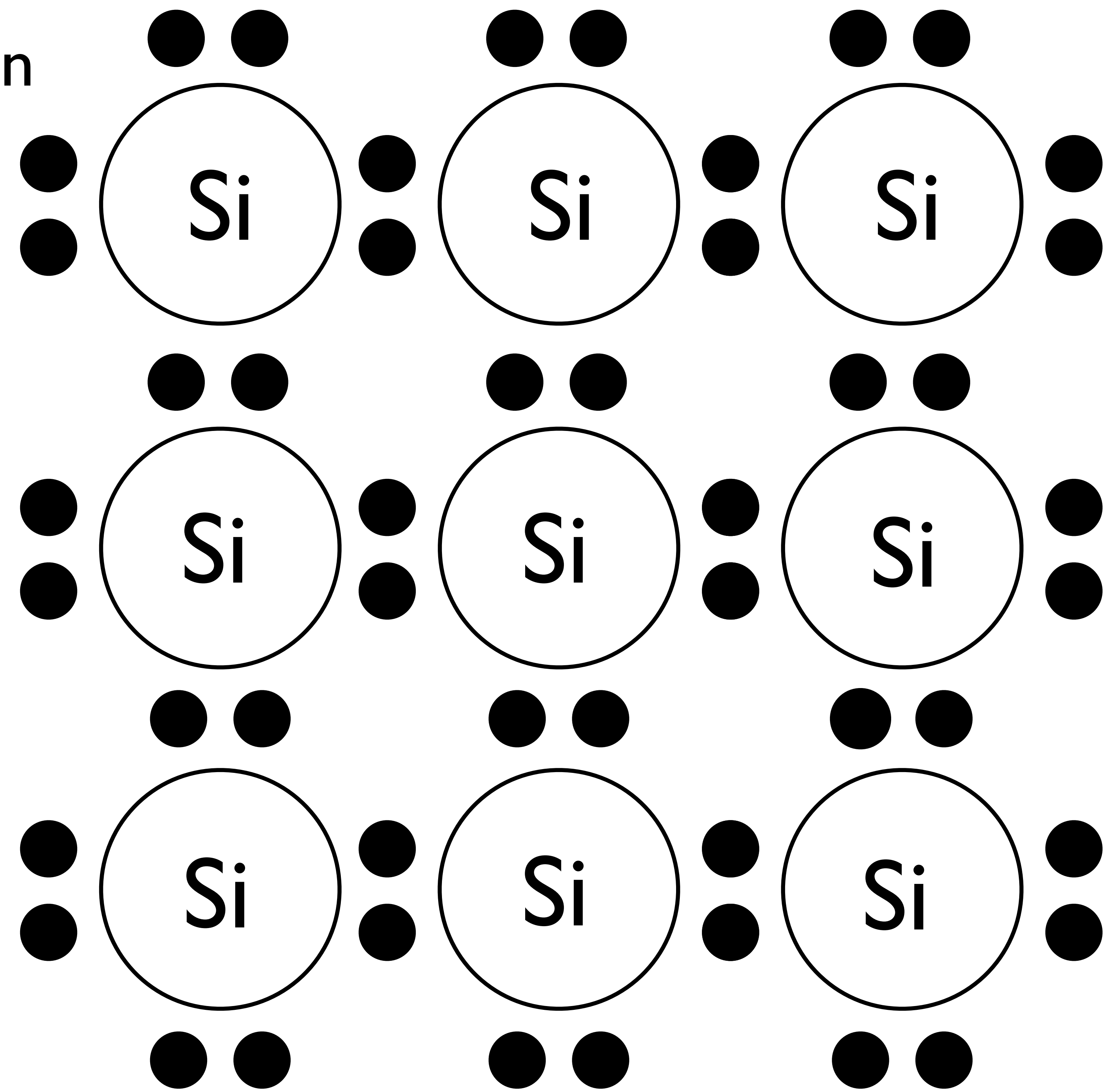
Intrinsic semiconductor



e-h pair creation

Intrinsic semiconductor

Recombination



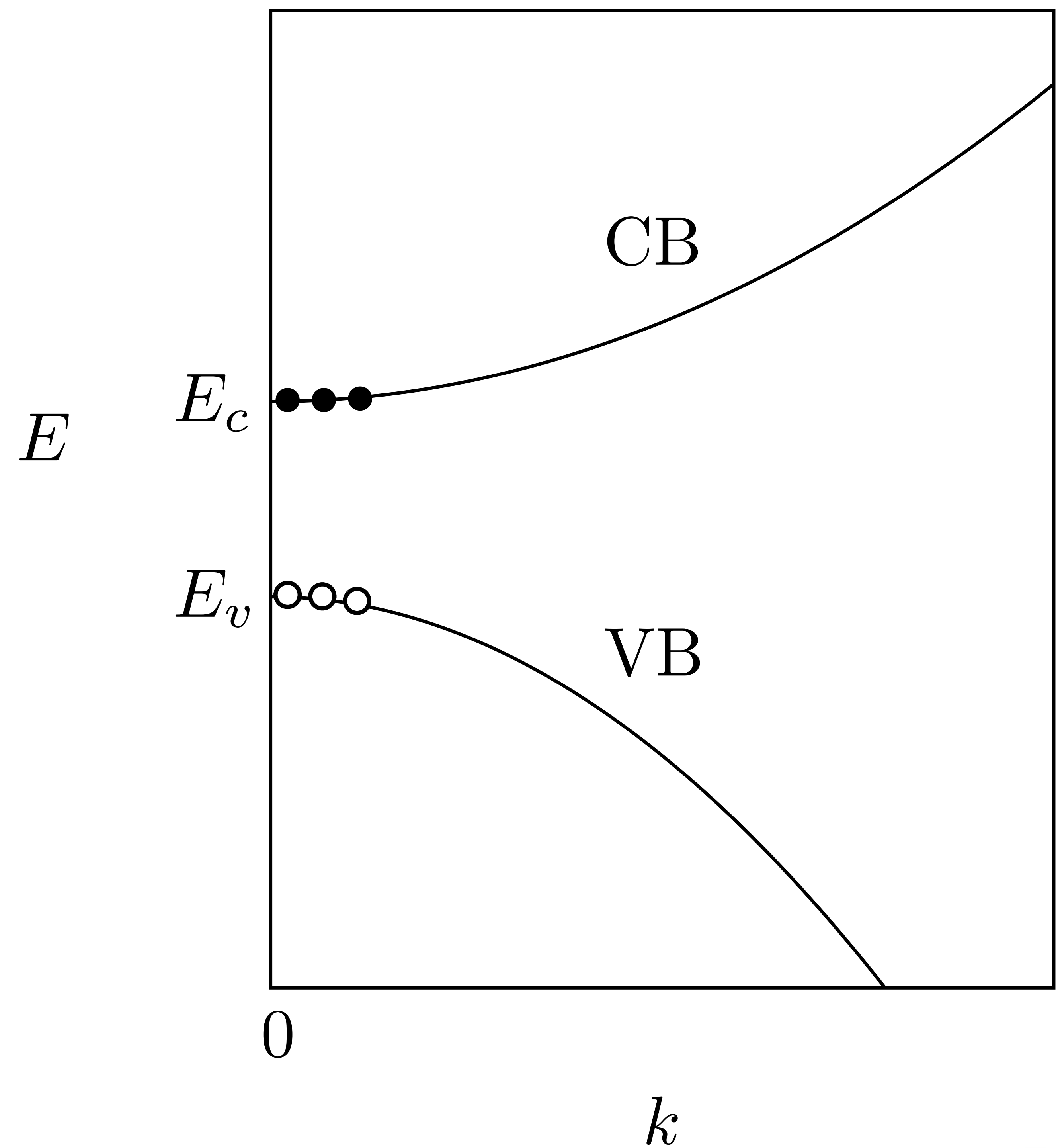
e-h pair creation

Dynamic Equilibrium

$$\mathrm{rate}_{\mathrm{recomb}} = \mathrm{rate}_{\text{e-h creation}}$$

Dynamic Equilibrium

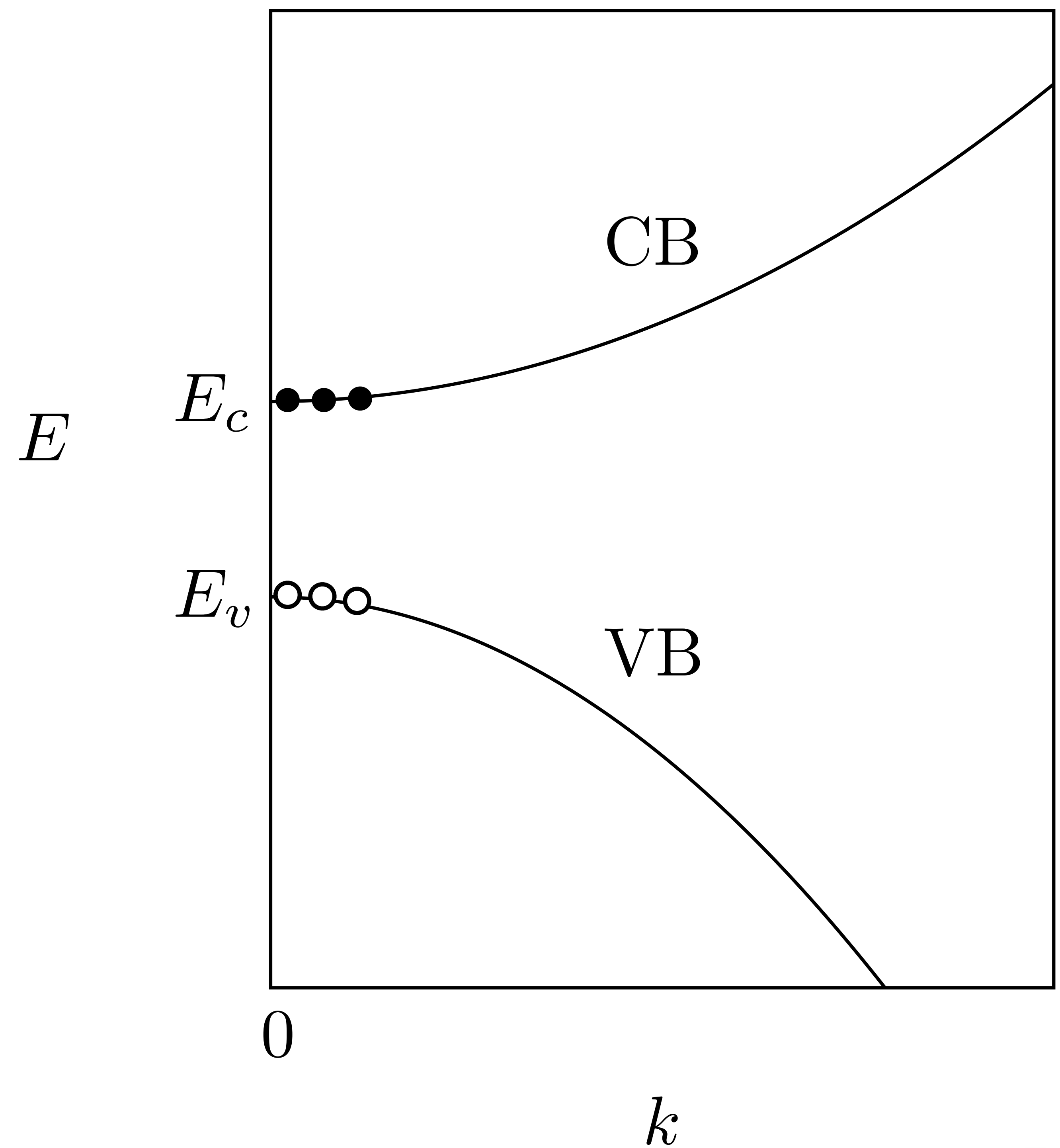
$$\text{rate}_{\text{recomb}} = \text{rate}_{\text{e-h creation}}$$



Dynamic Equilibrium

$$\mathrm{rate}_{\mathrm{recomb}} = \mathrm{rate}_{\text{e-h creation}}$$

Electrons tunnel into the neighboring hole



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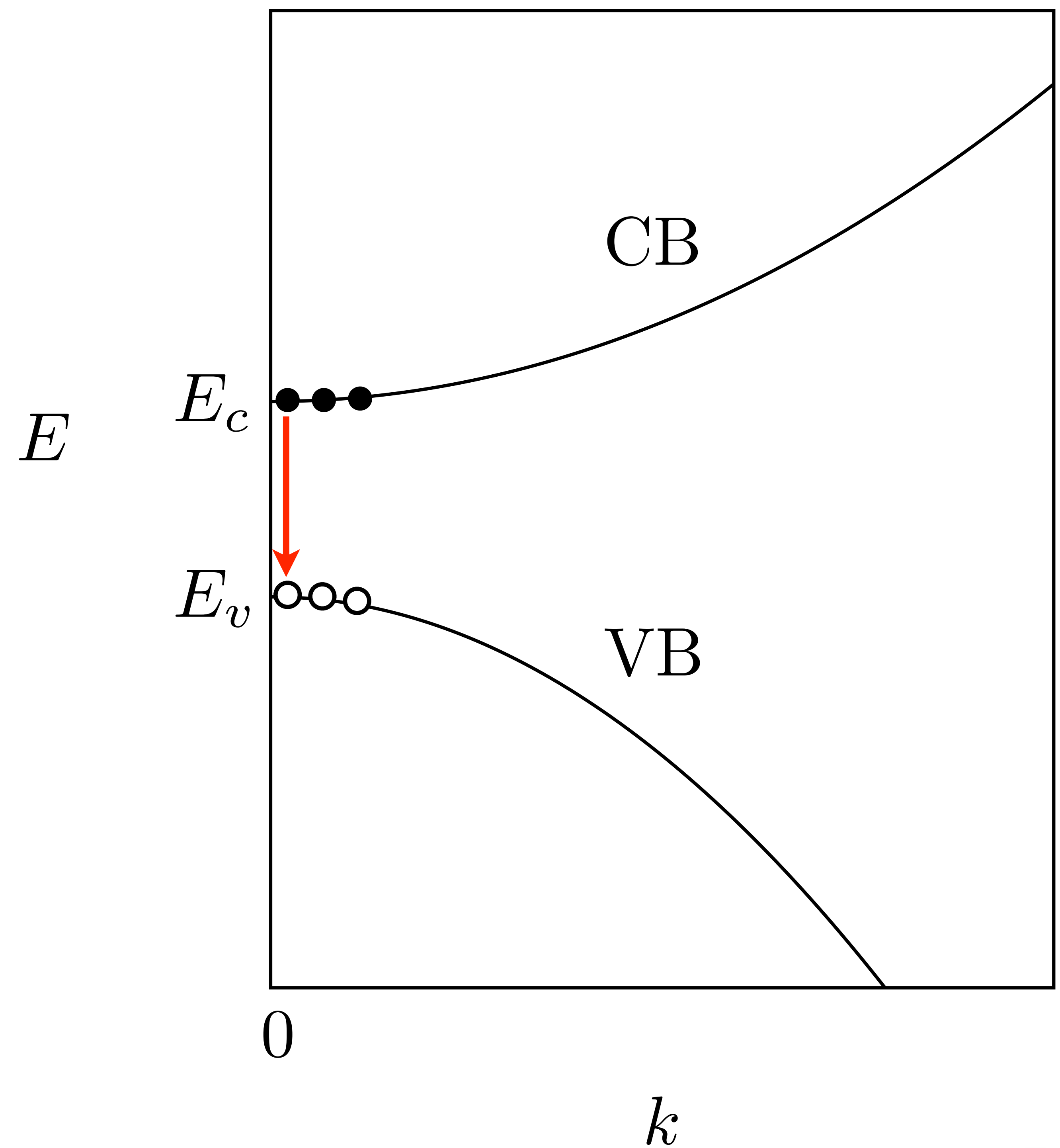

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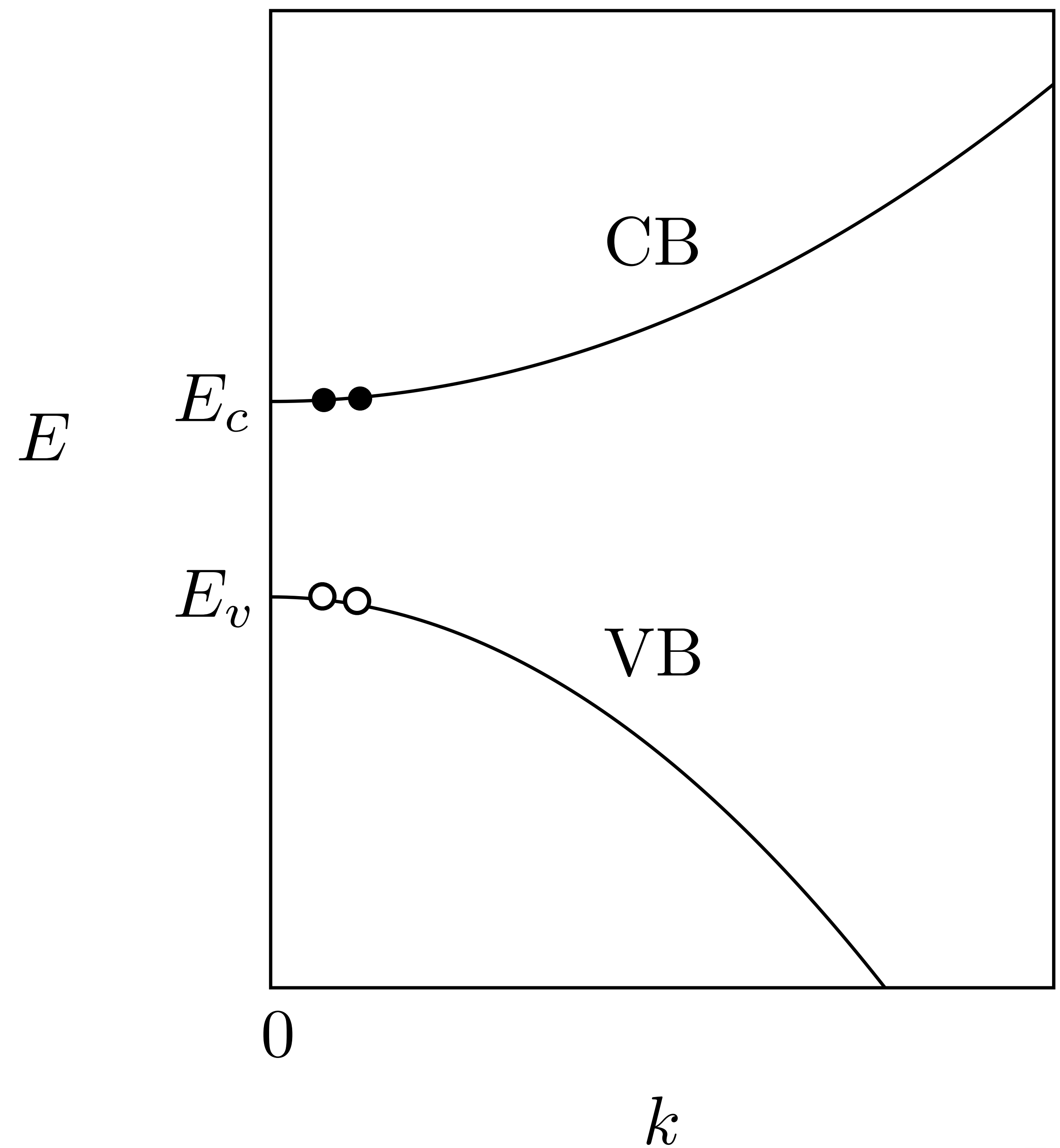
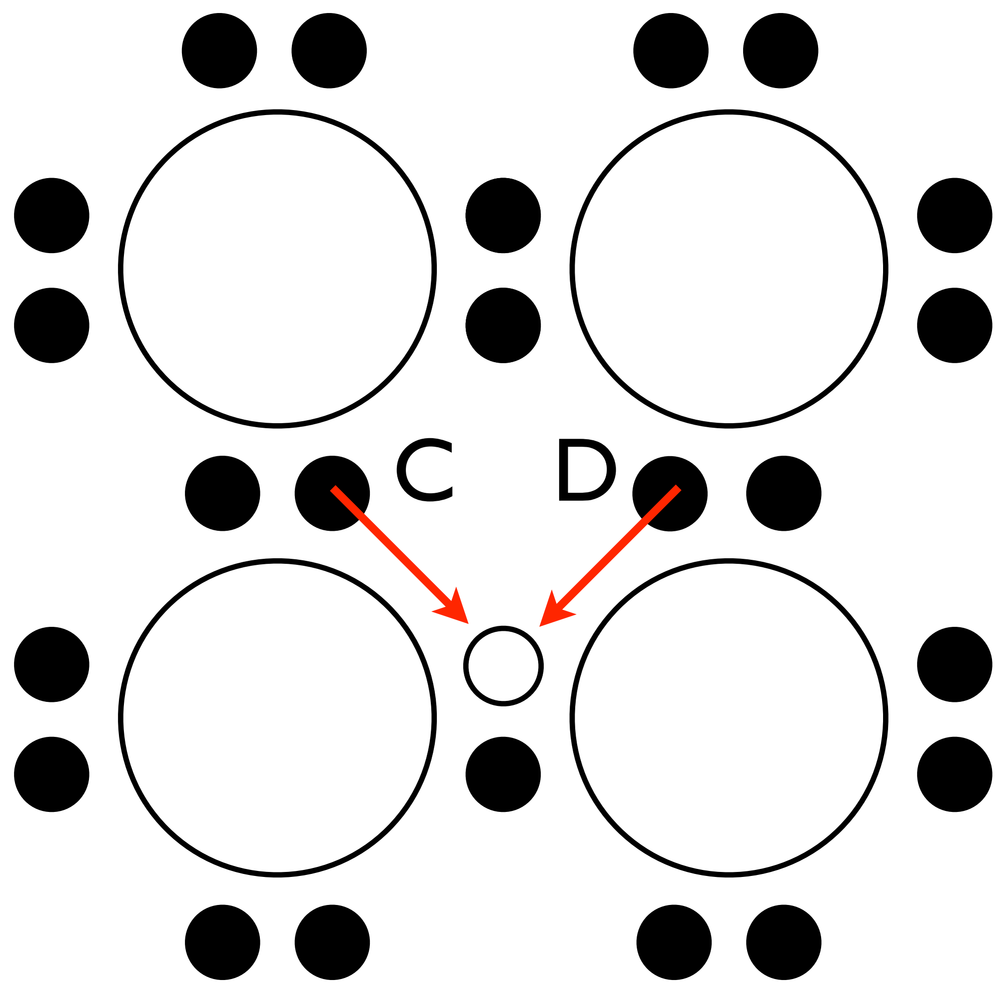


2D Model: hole conduction

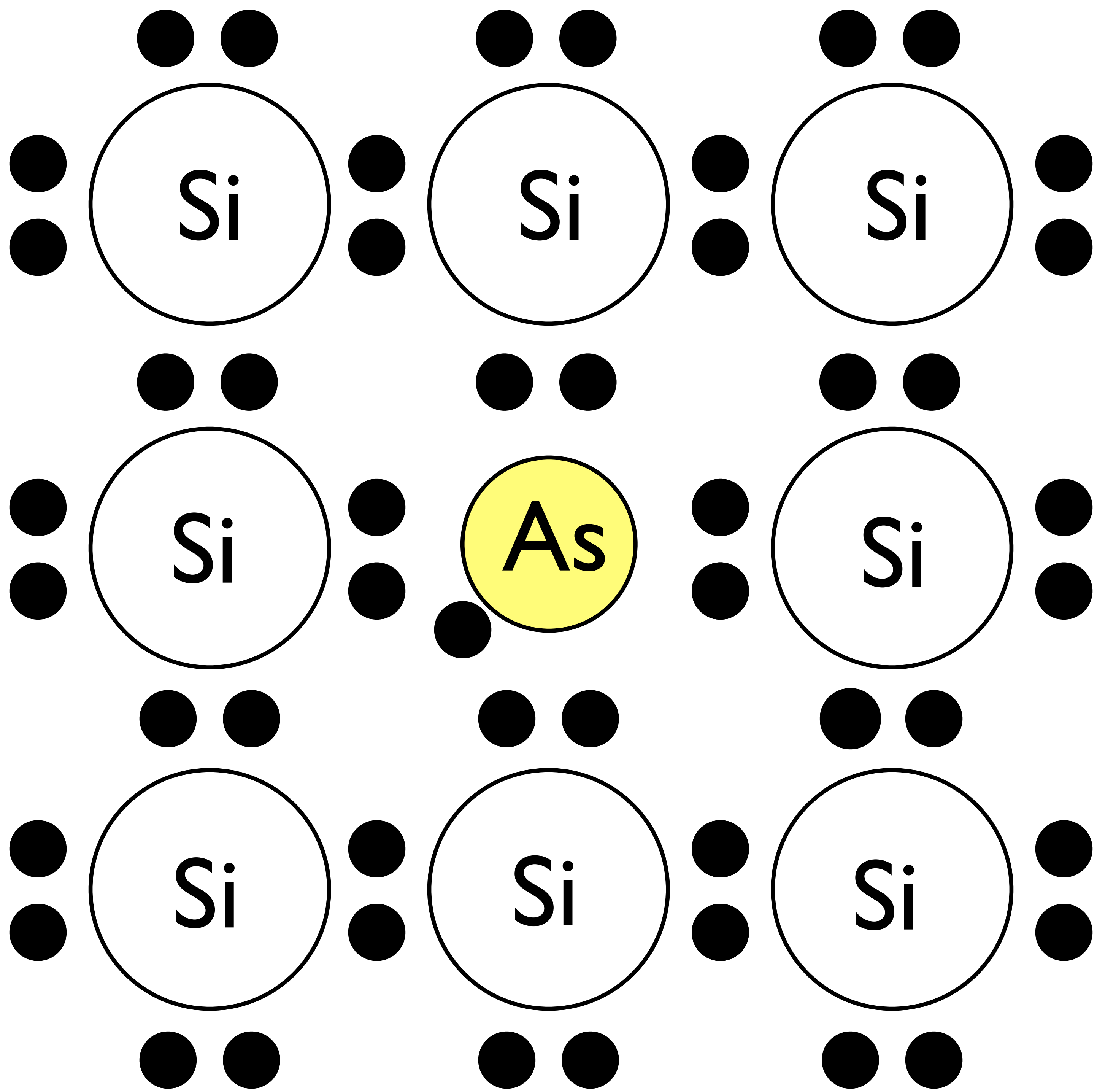
Question #9

$\rightarrow \mathcal{E}$



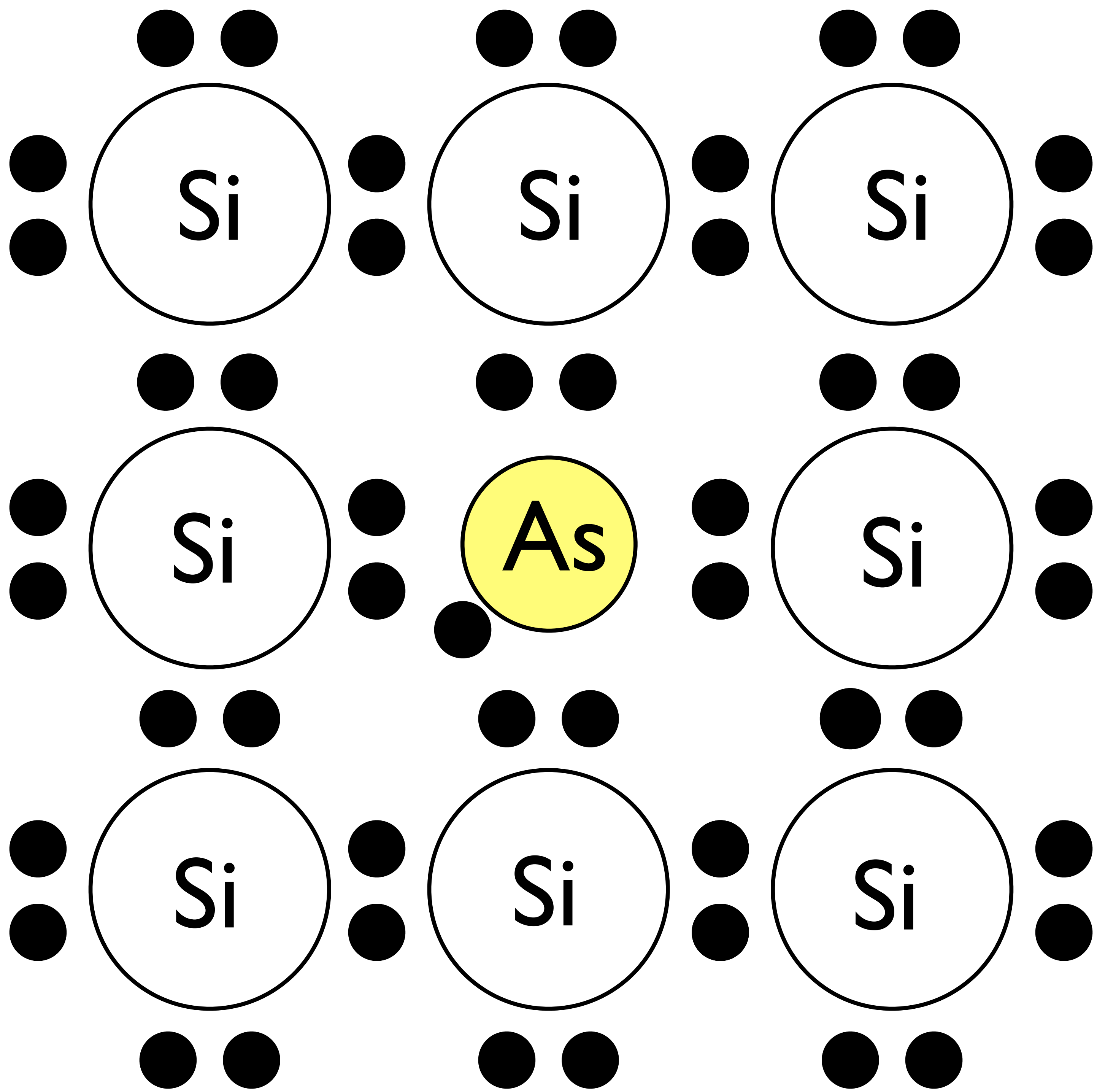
Which electron is more likely to move into the hole?

A doped semiconductor



A doped semiconductor

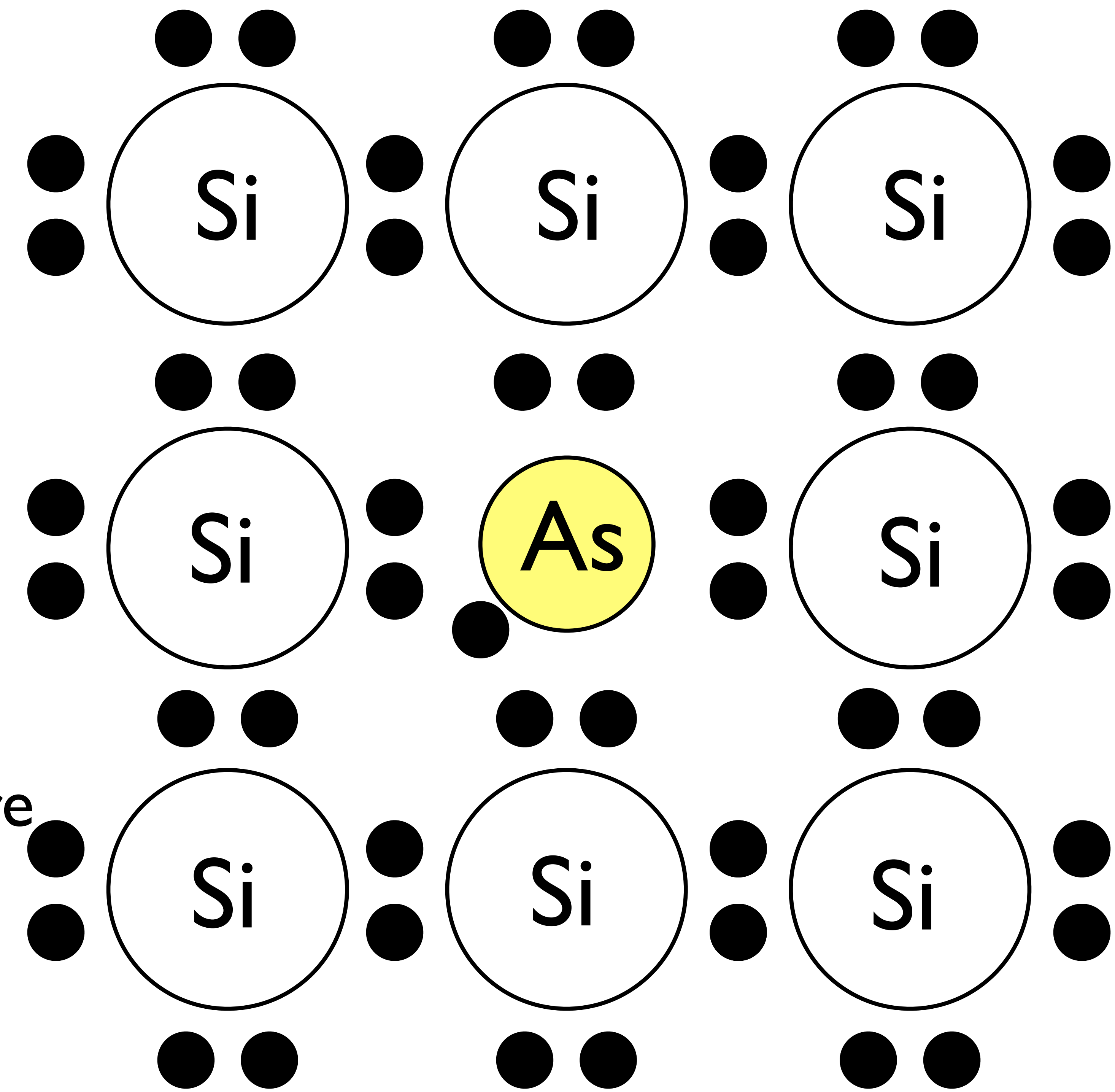
Why is there an “extra” electron?



A doped semiconductor

Why is there an "extra" electron?

Why does it stay by the arsenic atom? (The bonds are full after all...)



A doped semiconductor

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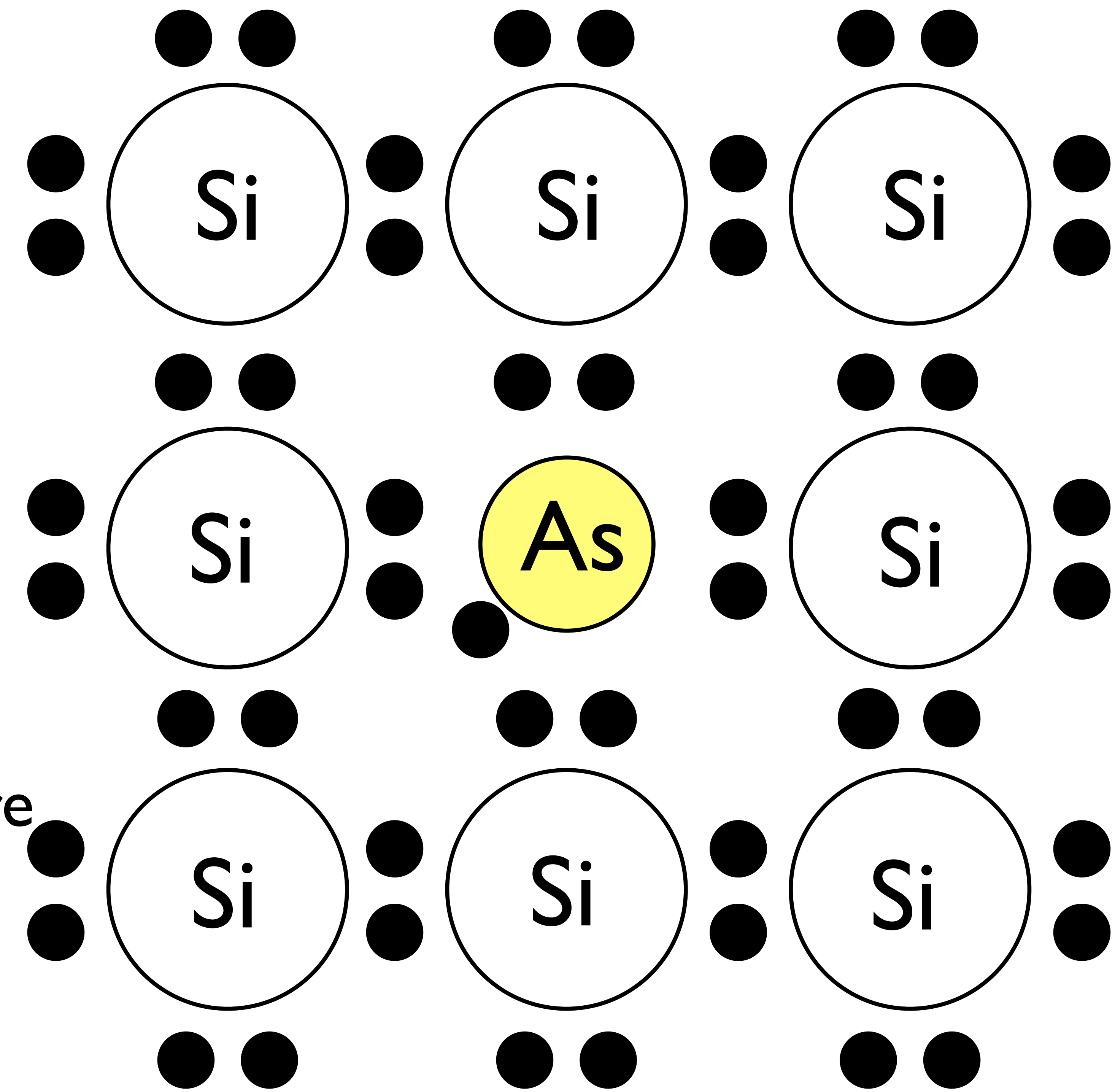

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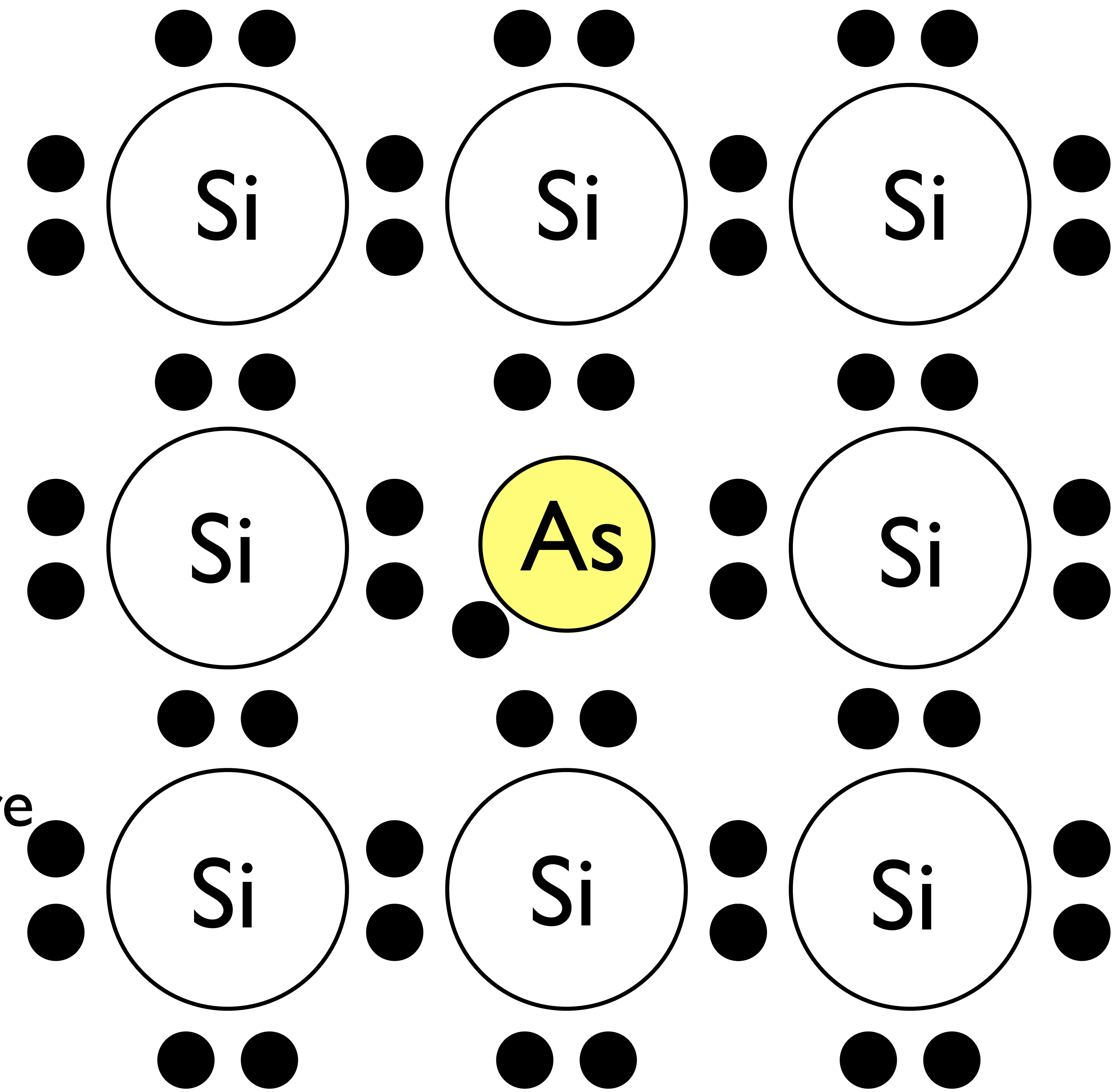

What role does temperature play?

How is this different from the case of pure silicon?

A doped semiconductor

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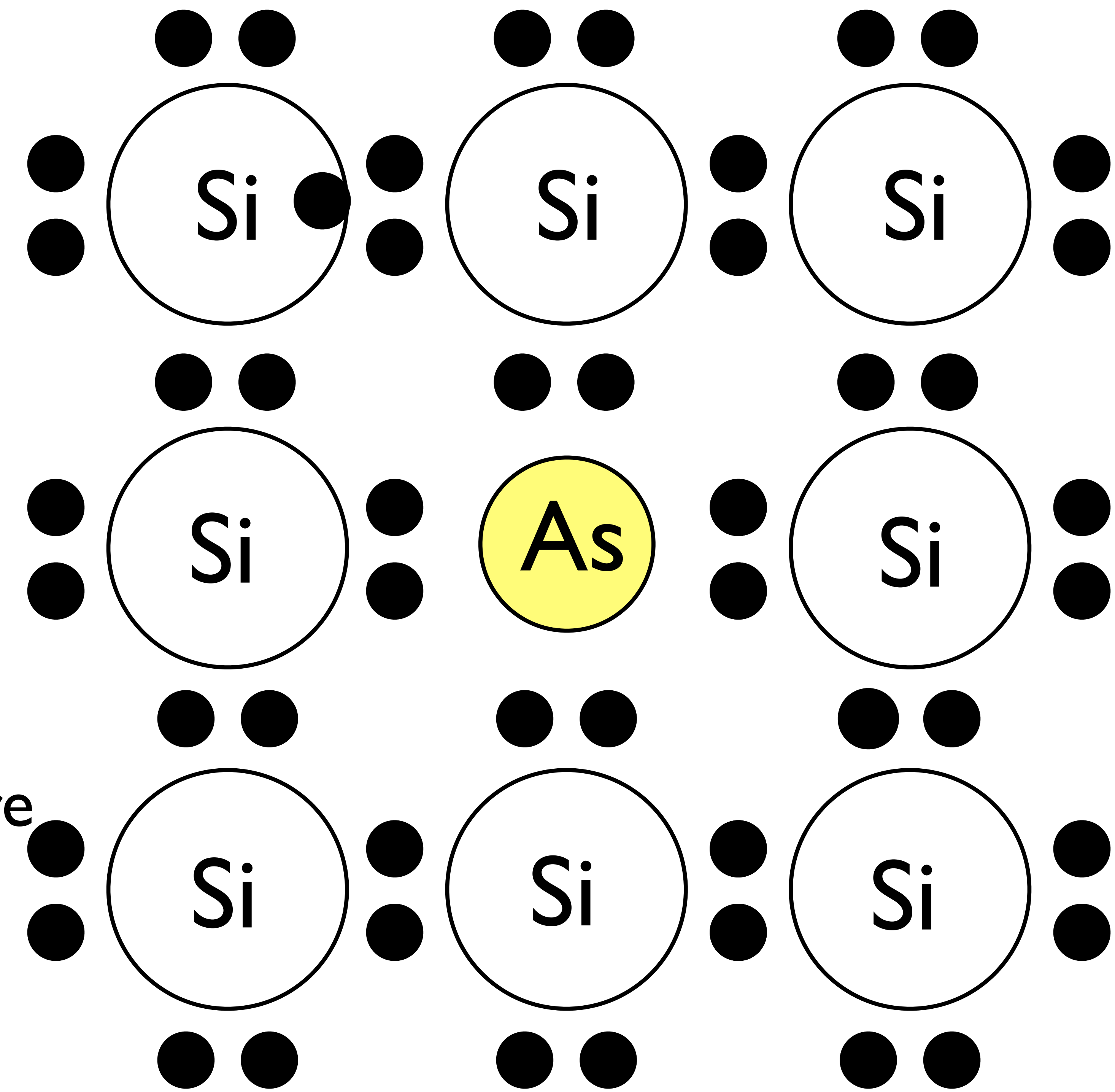

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A doped semiconductor

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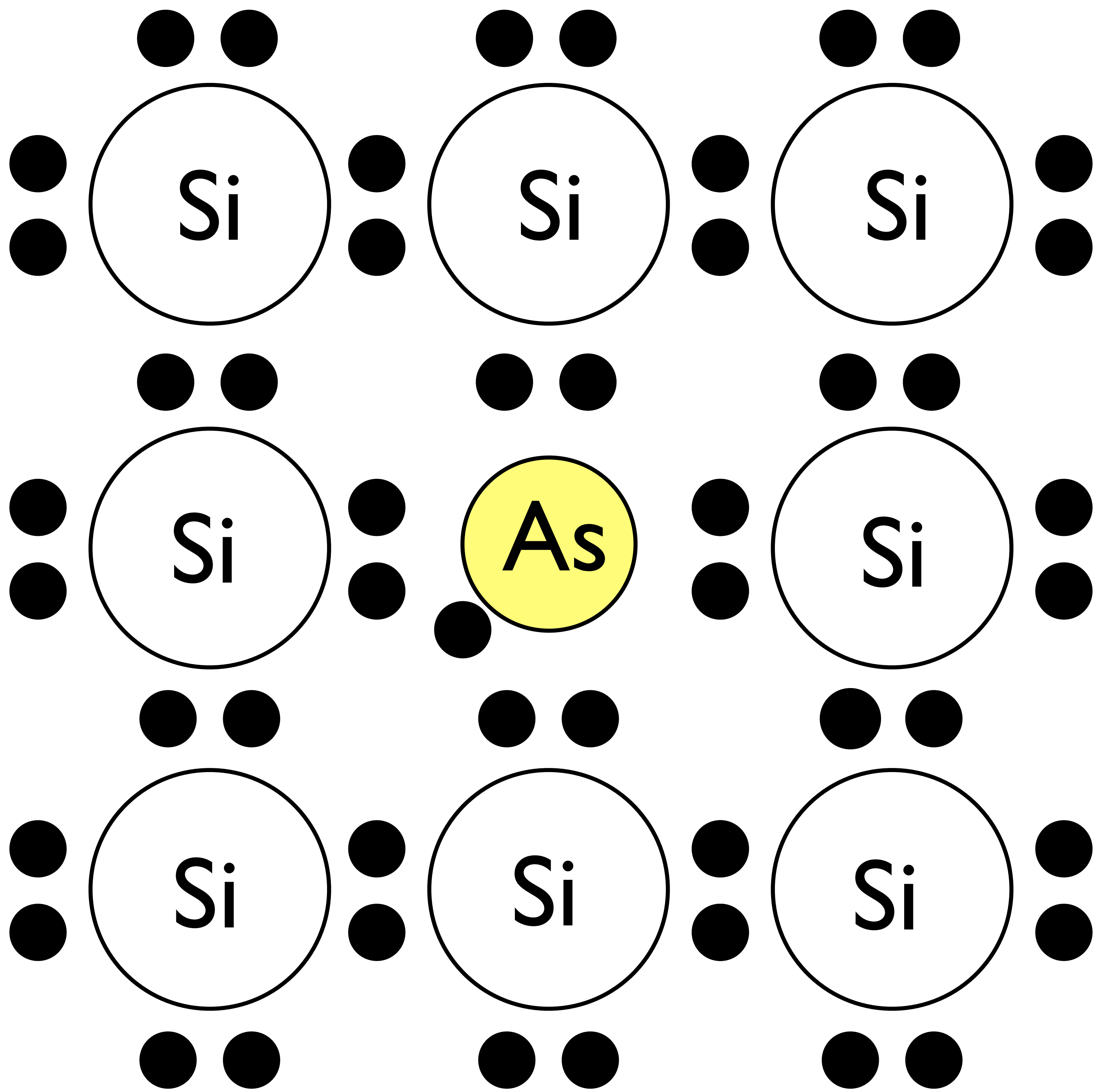

A doped semiconductor

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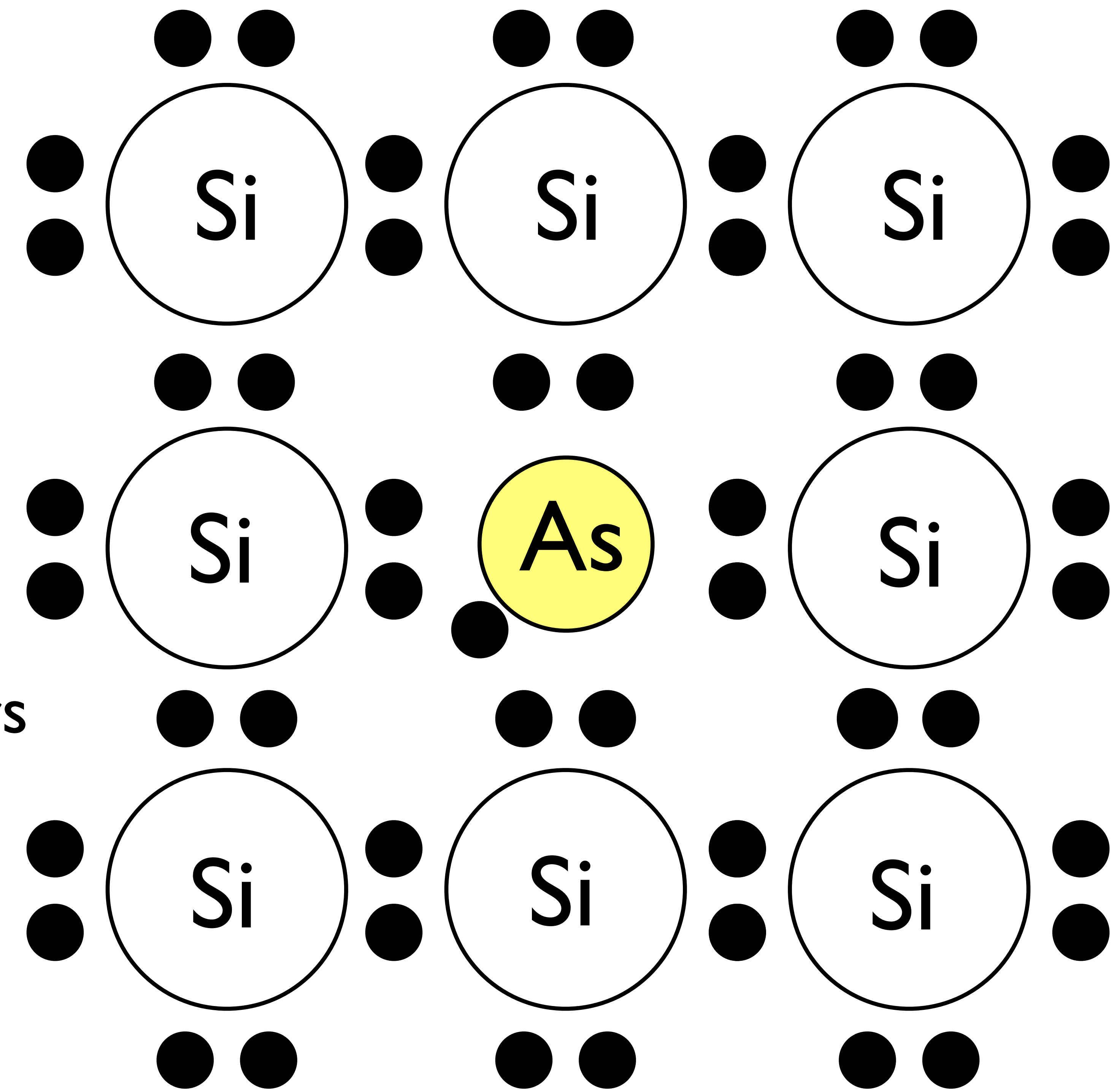
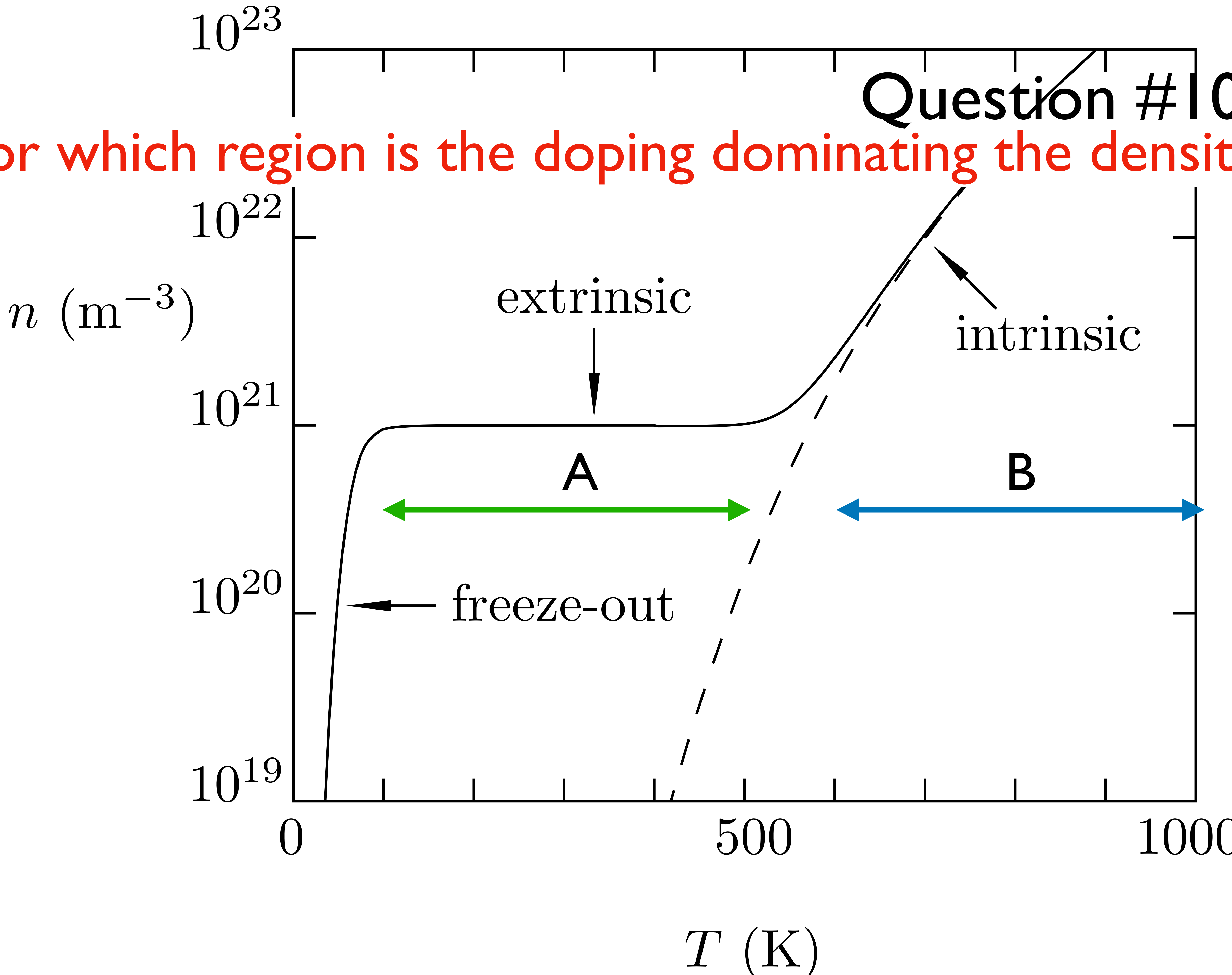


Having donors kills all the holes

Question #10

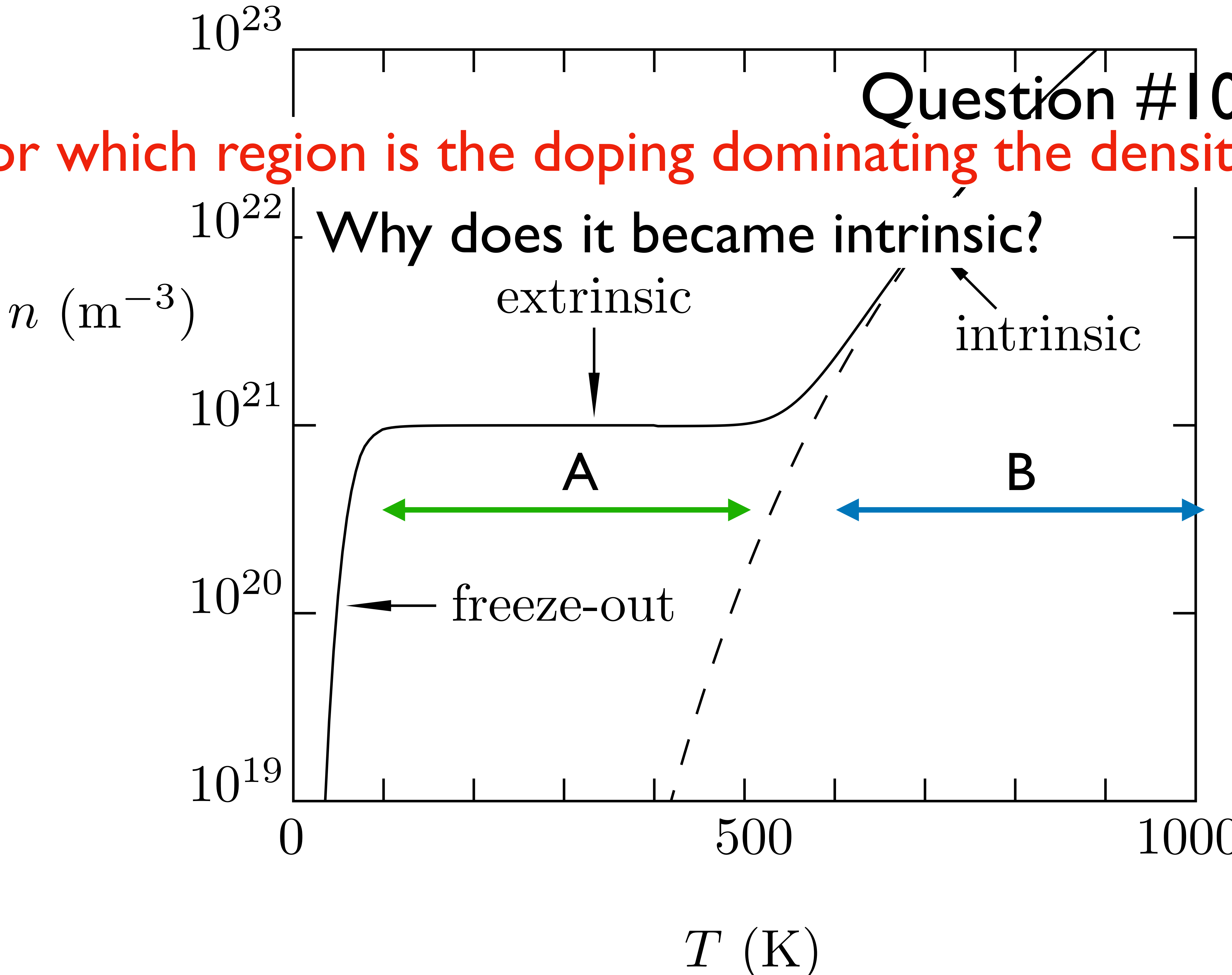
For which region is the doping dominating the density?



Question #10

For which region is the doping dominating the density?

Why does it became intrinsic?



How big of an affect is it?

1 atom in 5×10^7

$n_i = 10^{16}\ \mathrm{m}^{-3} \rightarrow$

How big of an affect is it?

1 atom in 5×10^7

$$n_i = 10^{16}\ \mathrm{m}^{-3} \rightarrow n \approx 10^{21}\ \mathrm{m}^{-3}$$