# BASIC OF ELECTRONICS

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1 Semiconductor Diodes

- The simplest linear circuit element is the resistor. The voltage across this element is related to current through it by Ohm's law. This relationship is graphically depicted by a straight line, as shown in (a). The slope of the line is the conductance of the resistor, i.e., the ratio of current to voltage. The reciprocal of this slope is the resistance in ohms. If the resistor is connected in any circuit, the operating point must fall somewhere on this curve.

a)

b)
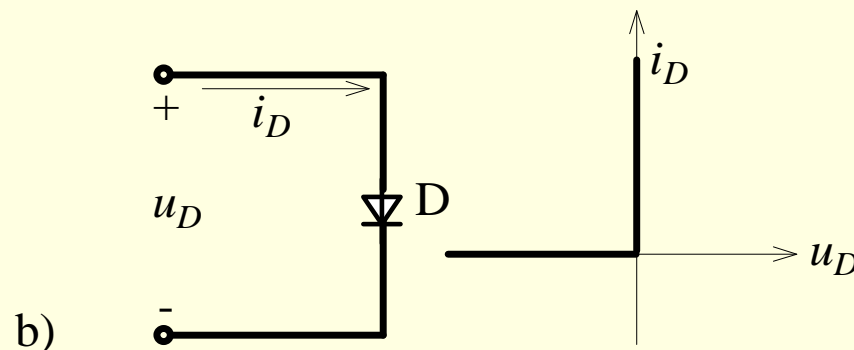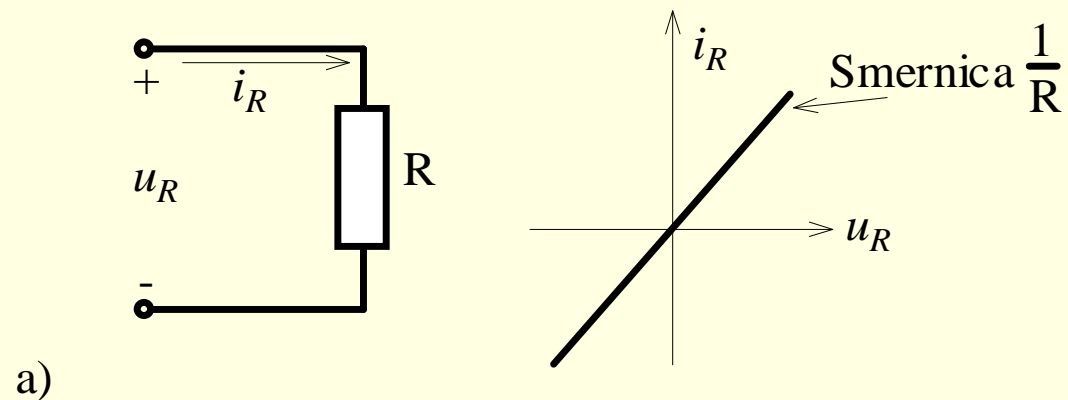
1   Semiconductor Diodes

- The ideal diode is a nonlinear device with a current versus voltage characteristic, as shown in Figure (b). This characteristic is referred to as piecewise linear, since the curve is constructed from segments of straight lines. Note that as we attempt to impose a positive (or forward) voltage on the diode, we are not successful and the voltage is limited to zero. The slope of the curve is infinity. Therefore, under this condition the resistance is zero and the diode behaves as a short circuit. If we place a negative (or reverse) voltage across the diode, the current is zero and the slope of the curve is zero. Thus, the diode is now behaving as an infinite resistance, or open circuit.

a)

b)
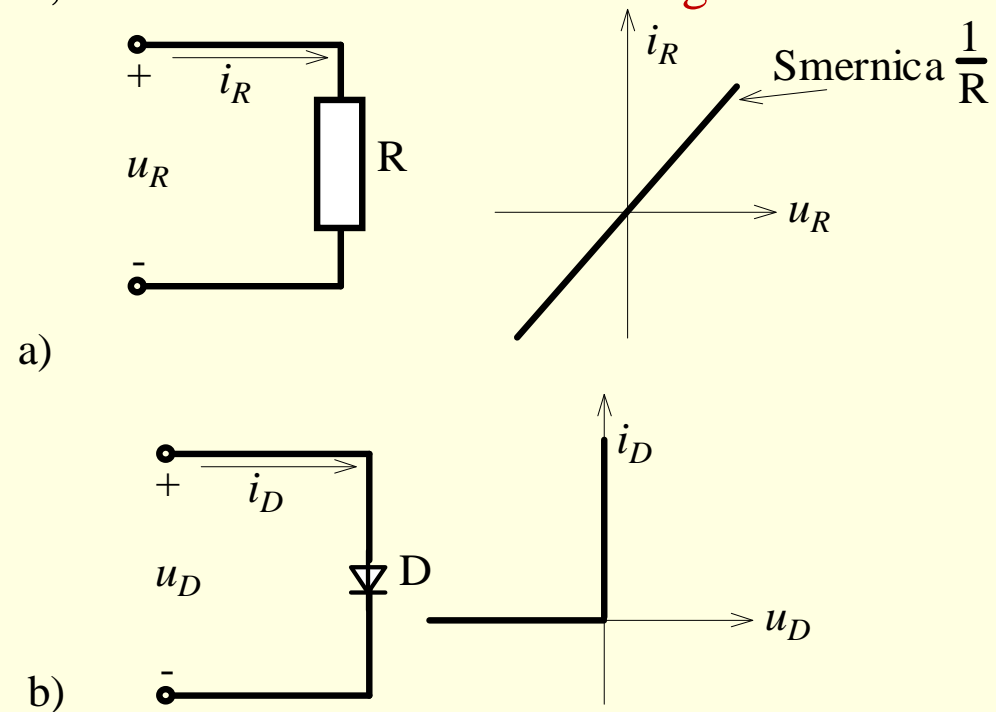
1.1 Diode Construction

- Figure shows a p-type material and an n- type material placed together to form a junction. This represents a simplified model of diode construction. The model ignores gradual changes in concentration of the impurities in the material. Practical diodes are constructed as a single piece of semiconductor material, where one side is doped with p-type material and the other side with n- type material.

Materiál typu P	Materiál typu N

+ -

P N
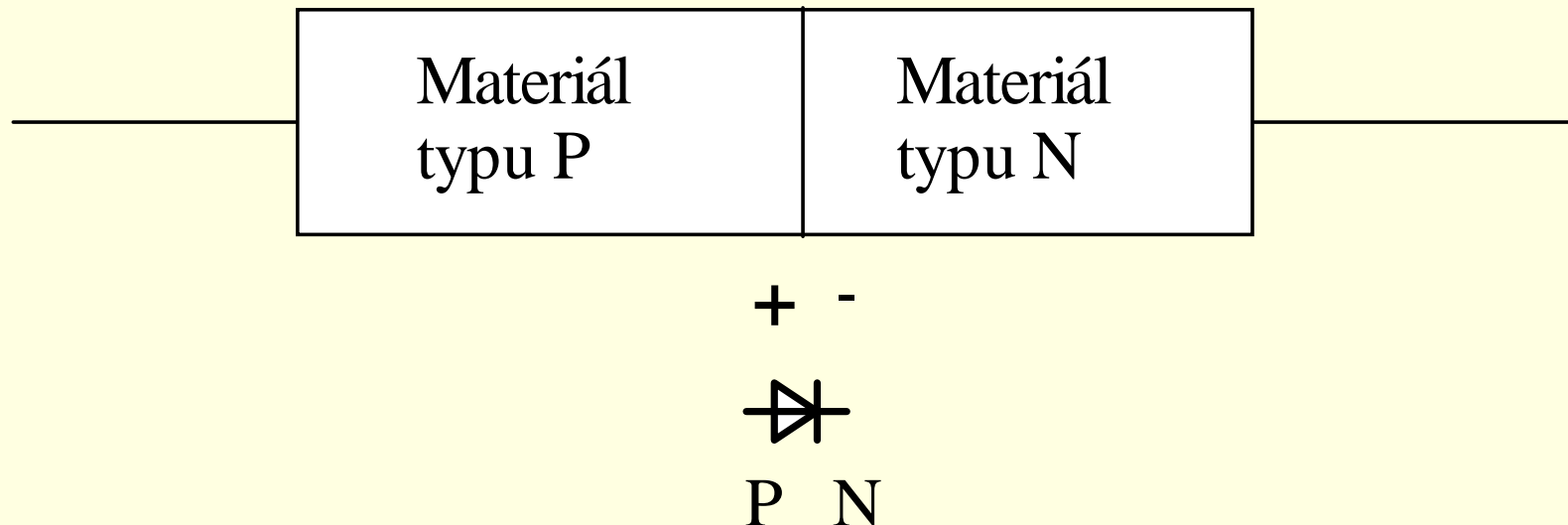
1.1 Diode Construction

- Also shown in Figure is the schematic symbol of the diode. Note that the "arrow" in this symbol points from the p- to the n-type material.

Materiál typu P	Materiál typu N

+ -

P N
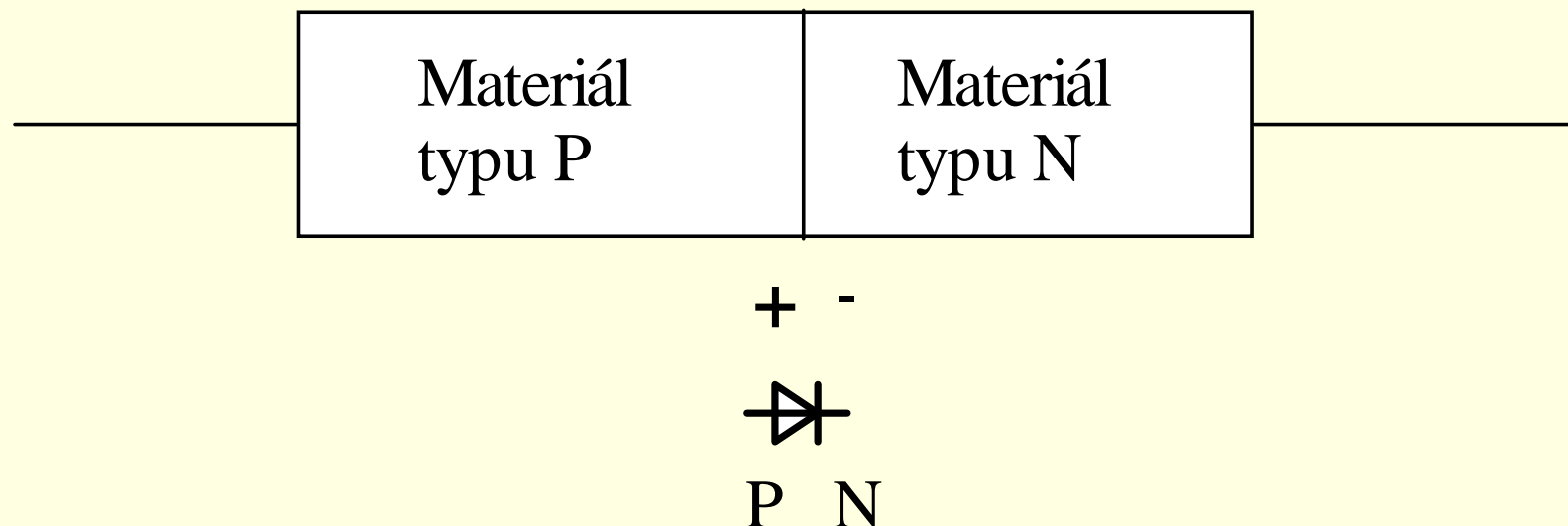
1.1 Diode Construction

- Three different materials are commonly used in the construction of diodes:

  germanium, silicon, and gallium arsenide.

  Silicon has generally replaced germanium for diodes because its larger energy gap allows higher temperature operation, and the material costs are much lower. Gallium arsenide is particularly useful in microwave and high-frequency applications. However, gallium arsenide is more expensive than silicon and the manufacture of gallium arsenide diodes is difficult.

  - germanium (Ge) (energy gap 0,67 eV)
  - silicon (Si) (energy gap 1,1 eV)
 - gallium arsenide (GaAs).

1.1 Diode Construction

- The precise distance over which the change from p- to n-type material occurs within the crystal varies with the fabrication technique.

- The essential feature of the pn junction is that the change in impurity concentration must occur in a relatively short distance. **Otherwise, the junction will not behave as a diode**.

Materiál typu P	Materiál typu N

+   -

P   N
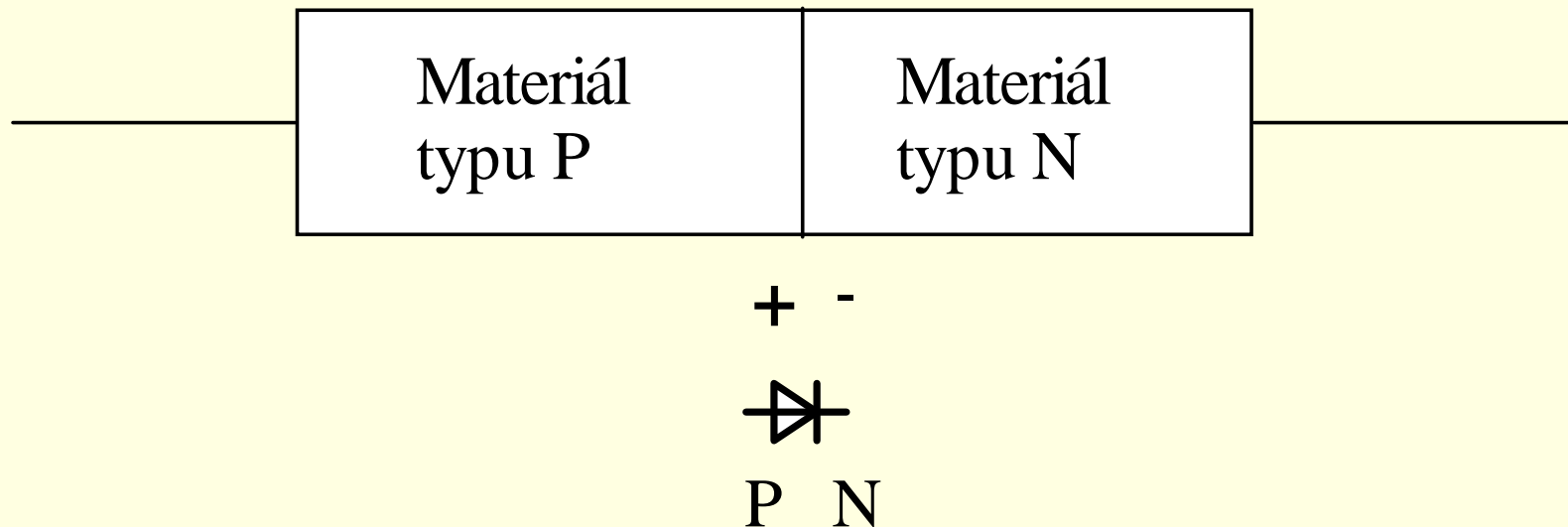
1.1 **Diode Construction**

- A **depletion region** will exist in the vicinity of the junction, as shown in Figure (a). This phenomenon is due to a combination of electrons and holes where the materials join. This depletion region will have few carriers.

- The minority carriers on each side of the depletion region (electrons in the p- region and holes in the n-region) will migrate to the other side and combine with ions in that material. Likewise, the majority carriers (electrons in the n- region and holes in the p-region) will migrate across the junction. However, the two components of the current formed by the hole and electron movements across the junction add together to form the **diffusion current** I_D.

I_D

I_S

| P | | | N |

ochudobnená oblasť

a)
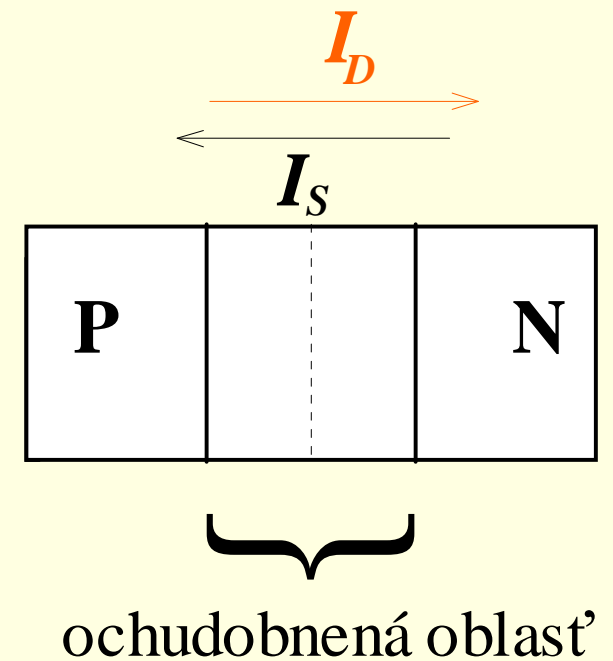
1.1 Diode Construction

- The direction of this current is from the p-side to the n-side.

- In addition to the diffusion current, a current exists due to the minority carrier drift across the junction, and this is referred to as I_S. Some of the thermally generated holes in the n-type material diffuse through the n-type material to the edge of the depletion region.

- There they experience the electric field and are swept across the depletion region into the p-type side. The electrons react in the same manner. The components of these actions combine to form the **drift current** I_S. During open-circuit conditions, the diffusion current is equal to the drift current (at equilibrium).

I_D

I_S

| P | | | N |

ochudobnená oblasť

a)
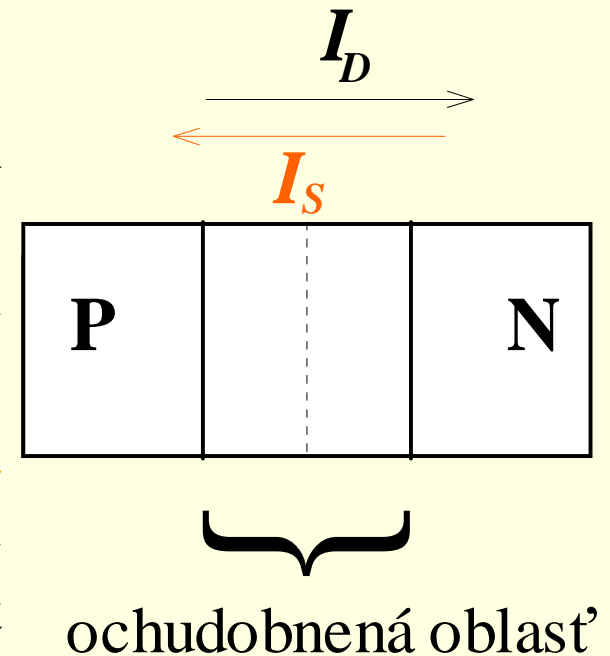
1.1 Diode Construction

- If we now apply a positive potential to the p-material relative to the n-material, as shown in Figure (b), the diode is said to be **forward-biased**. The depletion region shrinks in size due to the attraction of majority carriers to the opposite side. That is, the negative potential at the right attracts holes in the p-region, and vice-versa. With a smaller depletion region, current can flow more readily. When forward-biased, I_D-I_S=I after equilibrium is achieved, where I is the current through the junction.

I_D

I_S

| P | | N |

+ V -

I_D

I_S

| P | | N |

- V+
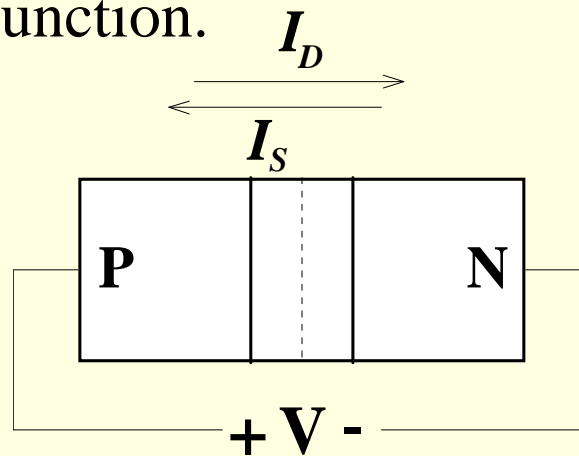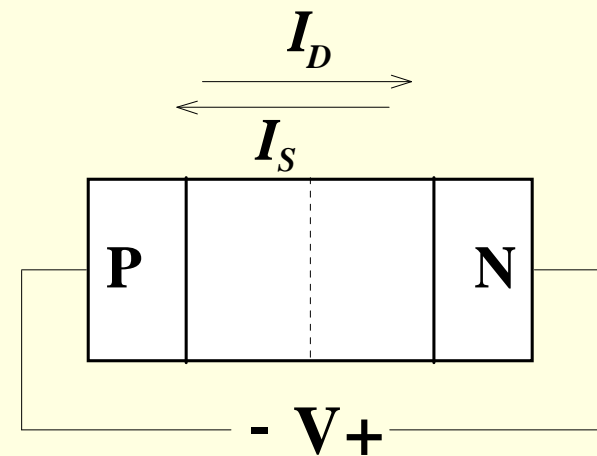
b)   c)

1.1 Diode Construction

- Alternatively, if the applied voltage is as shown in Figure (c), the diode is **reverse- biased**. Free electrons are drawn from the n-material toward the right, and, similarly, holes are drawn to the left. The depletion region gets wider and the diode acts as an insulator. When reverse-biased, $I_S - I_D = I$ after equilibrium is achieved, where I is the current through the junction.

$$I_D$$

$$I_S$$

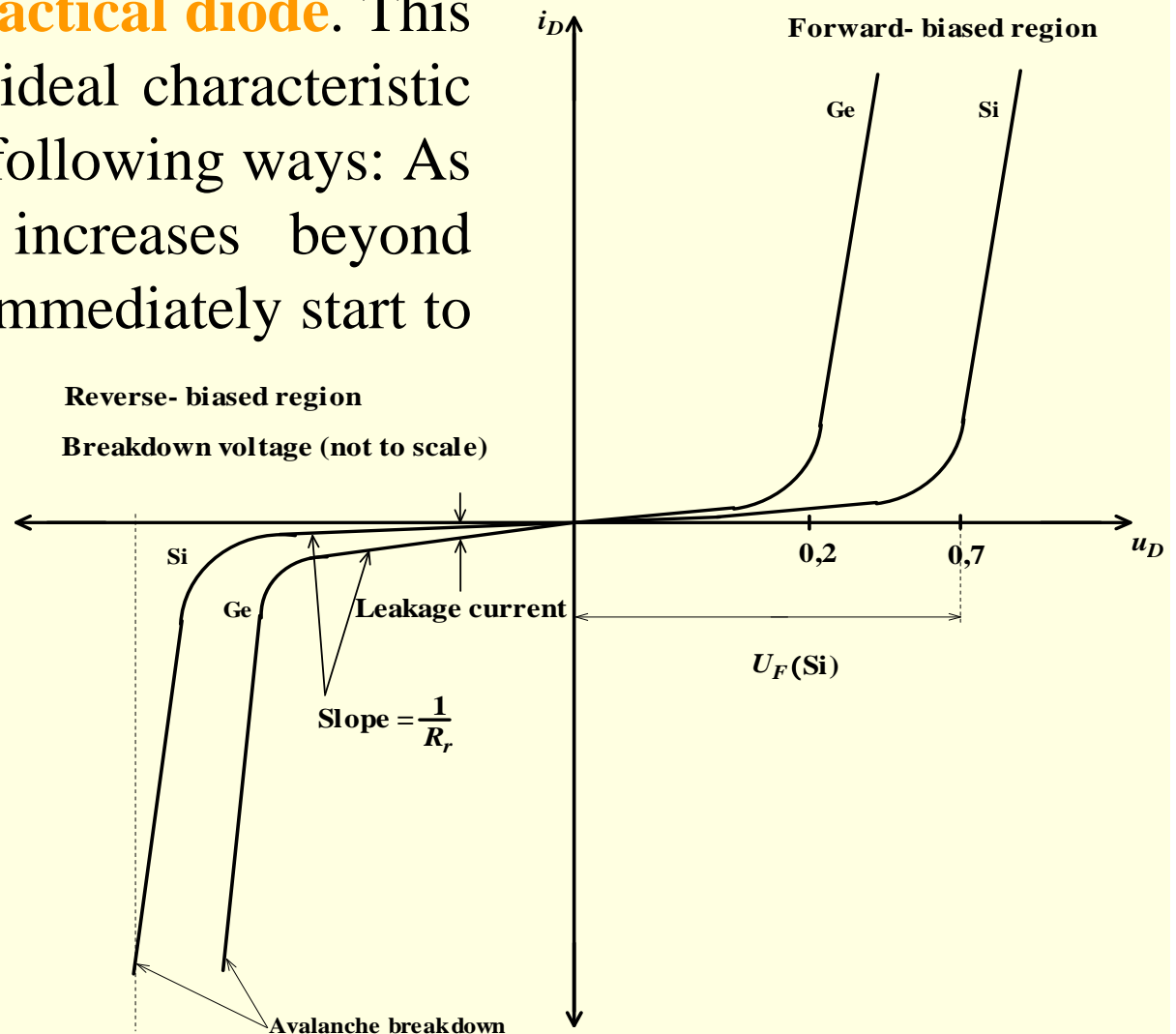| P | N |

$$+ V -$$

b)

$$I_D$$

$$I_S$$
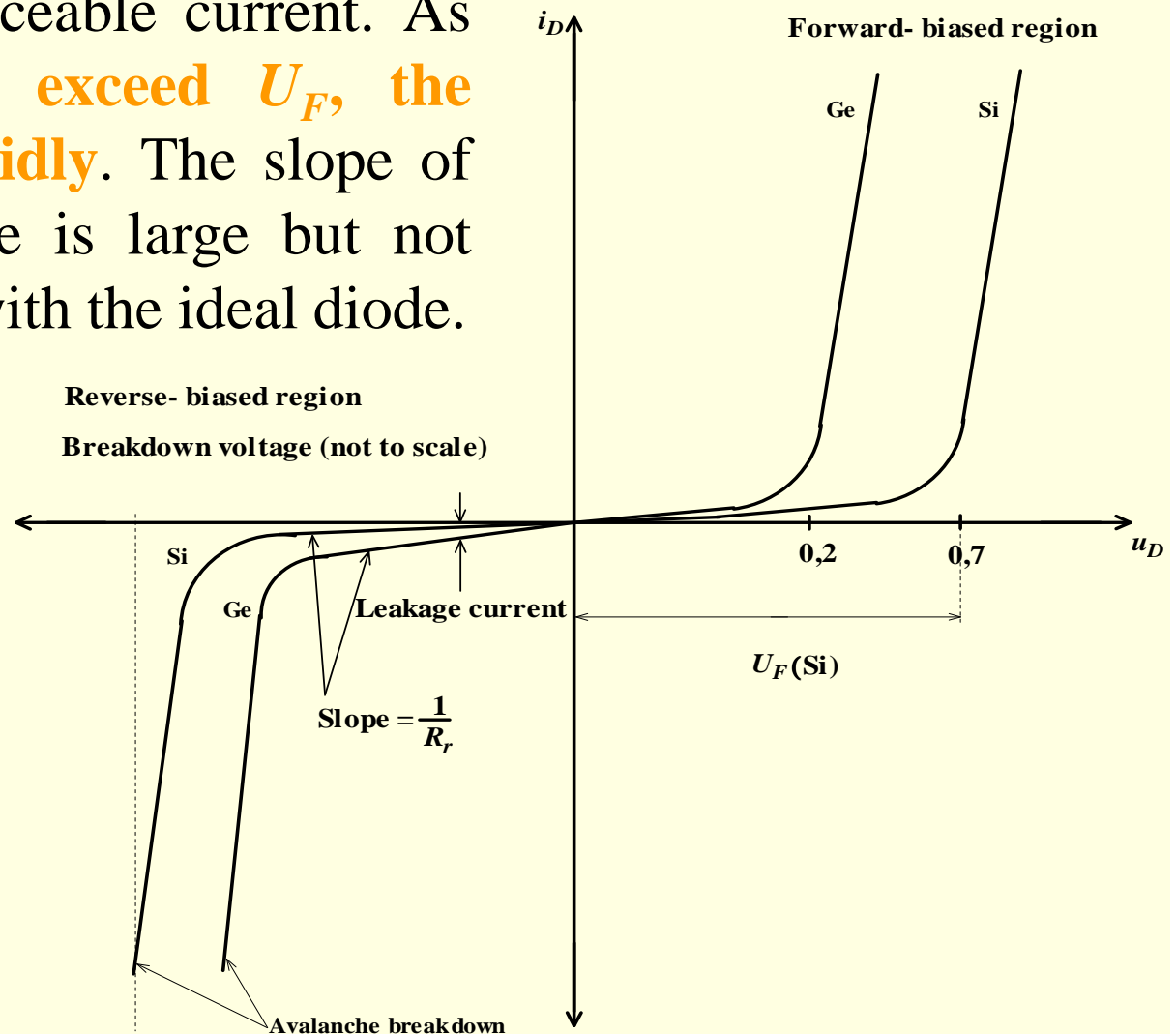
| P | N |

$$- V+$$
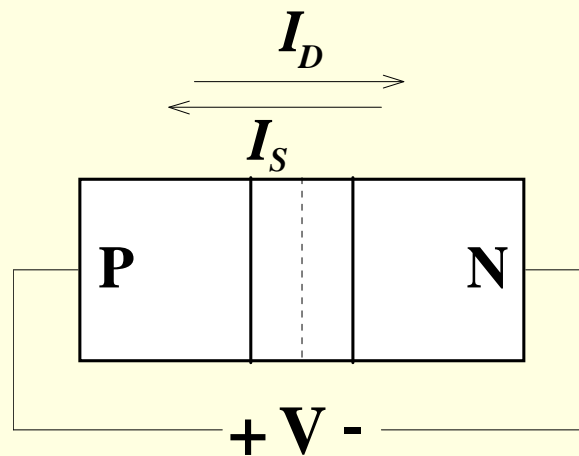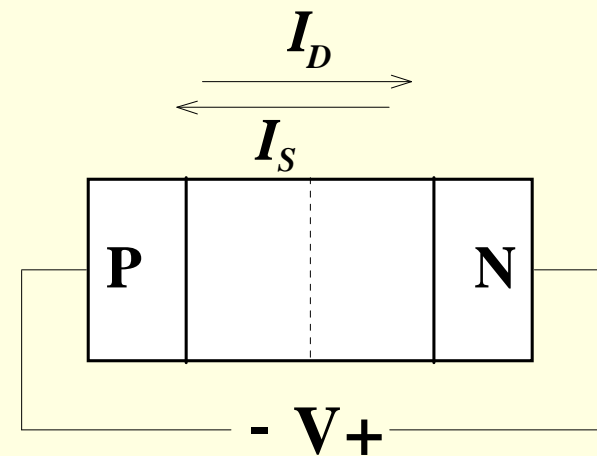
c)

1.2 Diode Operation

- Figure illustrates the **operating characteristics of a practical diode**. This curve differs from the ideal characteristic of Figure 1.9(b) in the following ways: As the forward voltage increases beyond zero, current does not immediately start to flow.

1.2 Diode Operation

V-A Diode operating characteristics

- It takes a minimum voltage, denoted by U_F, to obtain any noticeable current. As **the voltage tries to exceed U_F, the current increases rapidly**. The slope of the characteristic curve is large but not infinite, as is the case with the ideal diode.

i_D

Forward- biased region

Ge **Si**

Reverse- biased region

Breakdown voltage (not to scale)

0,2 **0,7** u_D

Si

Ge **Leakage current**

U_F (Si)

$$Slope = \frac{1}{R_r}$$

Avalanche breakdown

1.2 Diode Operation

V-A Diode operating characteristics

- **The minimum voltage required to obtain noticeable current, U_F,** is approximately 0.7V for silicon semiconductors (at room temperature), 0.2V for germanium semiconductors and for gallium arsenide diodes, U_F is approximately 1.2V.

i_D

Forward- biased region

Ge   Si

Reverse- biased region

Breakdown voltage (not to scale)

Si

Ge

Leakage current

$\text{Slope} = \dfrac{1}{R_r}$

0,2   0,7 u_D

U_F (Si)

Avalanche breakdown
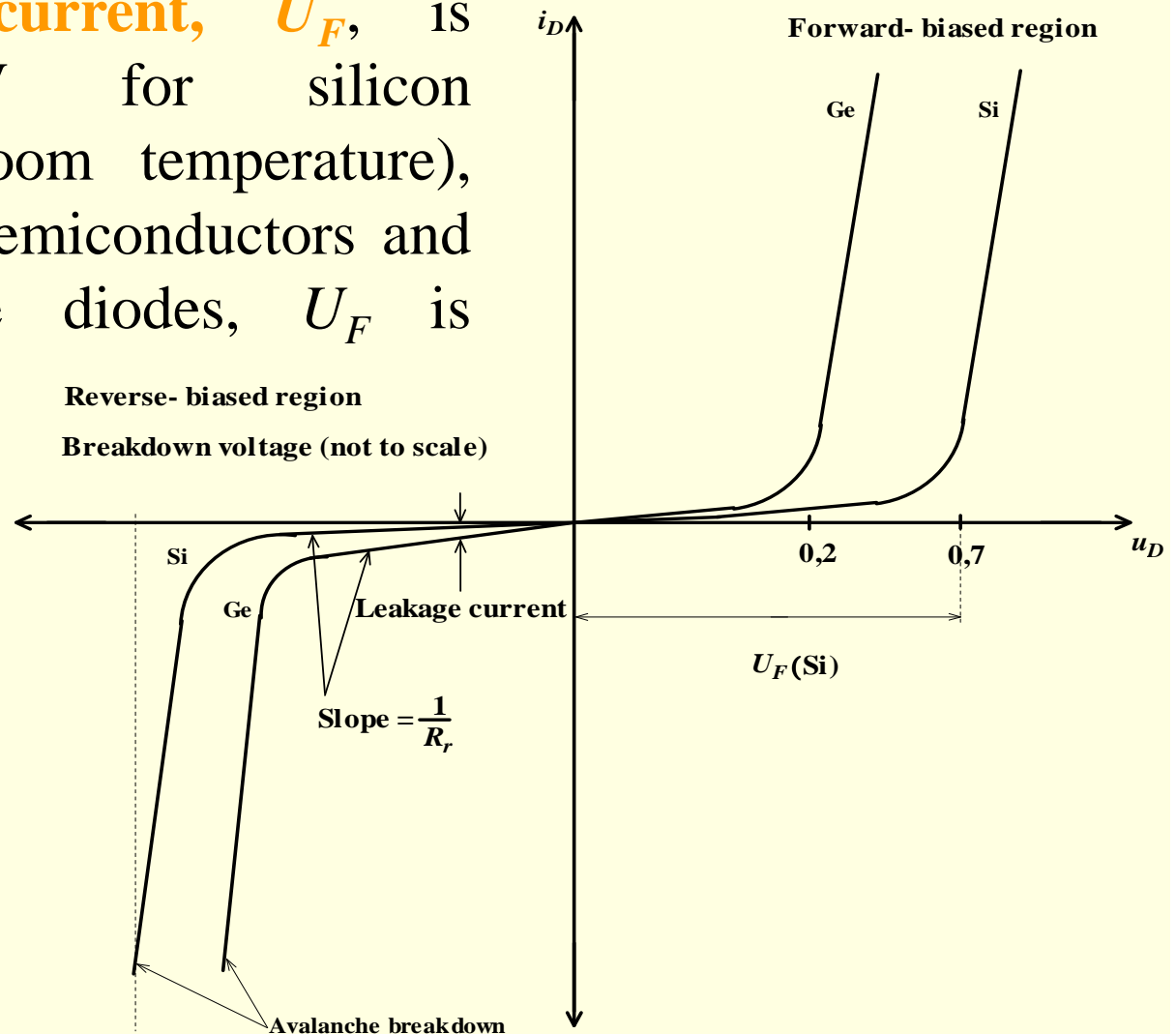
1.2 Diode Operation
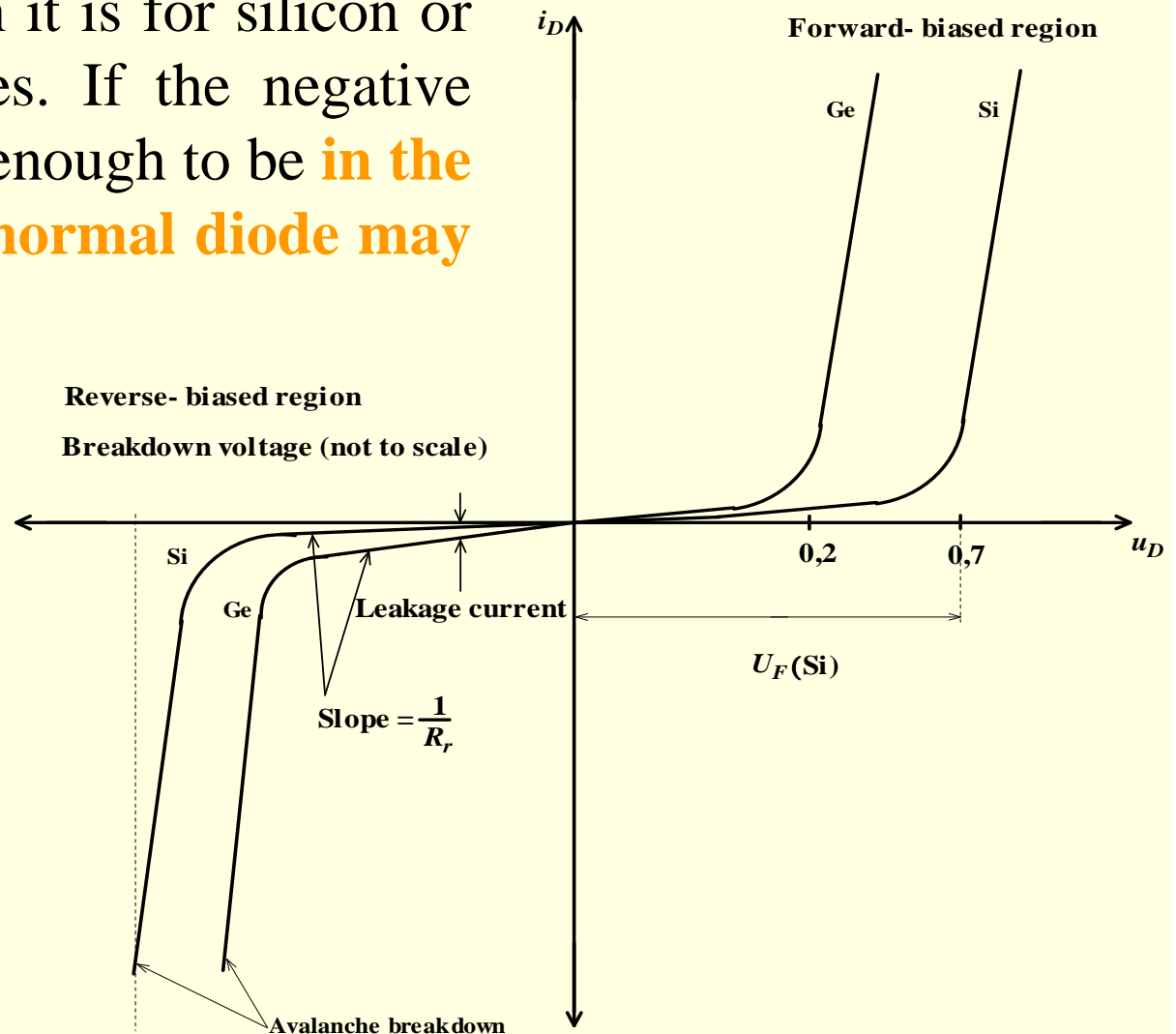## V-A Diode operating characteristics

- When the diode is **reverse-biased, there is some small leakage current**. This current occurs provided that the reverse voltage is less than the voltage required to break down the junction.

i_D

Forward- biased region

Ge   Si

Reverse- biased region

Breakdown voltage (not to scale)

Si

Ge   **Leakage current**

0,2   0,7 u_D

$U_F(Si)$

$\text{Slope} = \dfrac{1}{R_r}$

Avalanche breakdown
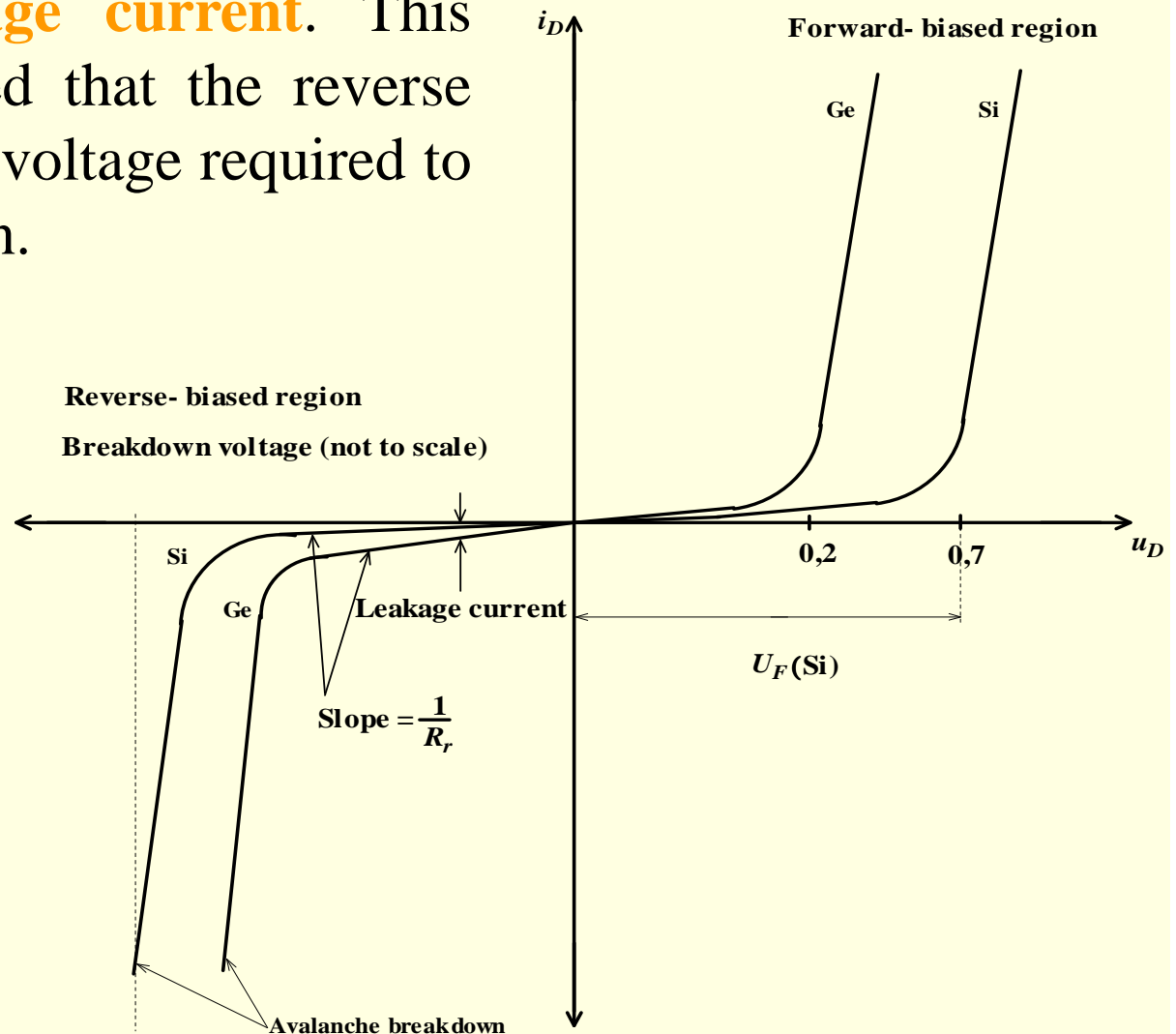
1.2 Diode Operation
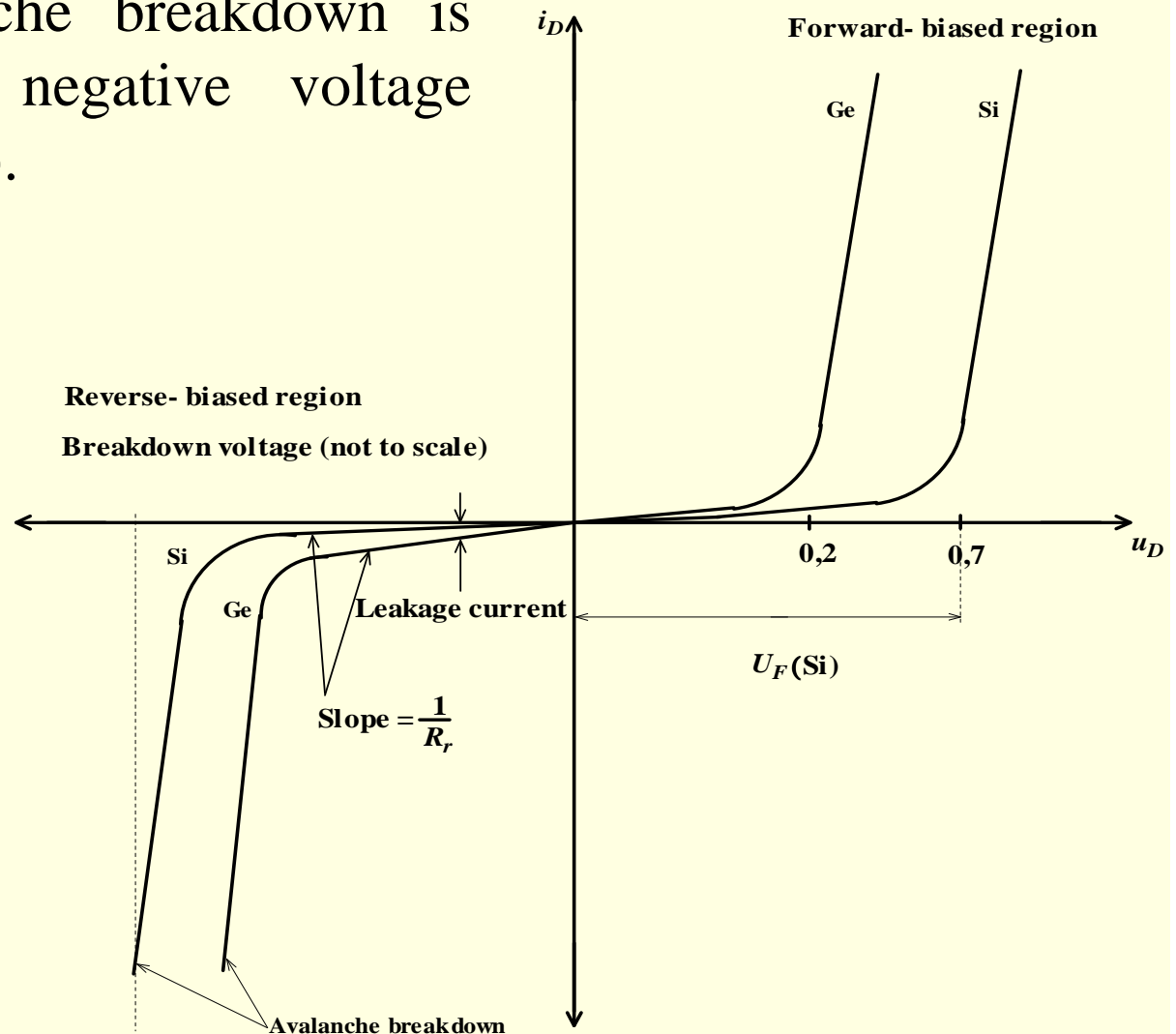## V-A Diode operating characteristics

- The leakage current is much greater for germanium diodes than it is for silicon or gallium arsenide diodes. If the negative voltage becomes large enough to be **in the breakdown region, a normal diode may be destroyed**.

i_D

Forward- biased region

Ge   Si

Reverse- biased region

Breakdown voltage (not to scale)

Si

Ge   **Leakage current**

$\text{Slope} = \dfrac{1}{R_r}$

0,2   0,7 u_D

$U_F\,(\text{Si})$

Avalanche breakdown

1.2 Diode Operation
V-A Diode operating characteristics

- **The curve is not to scale** in the reverse region as the avalanche breakdown is usually at a large negative voltage (typically 50V or more).
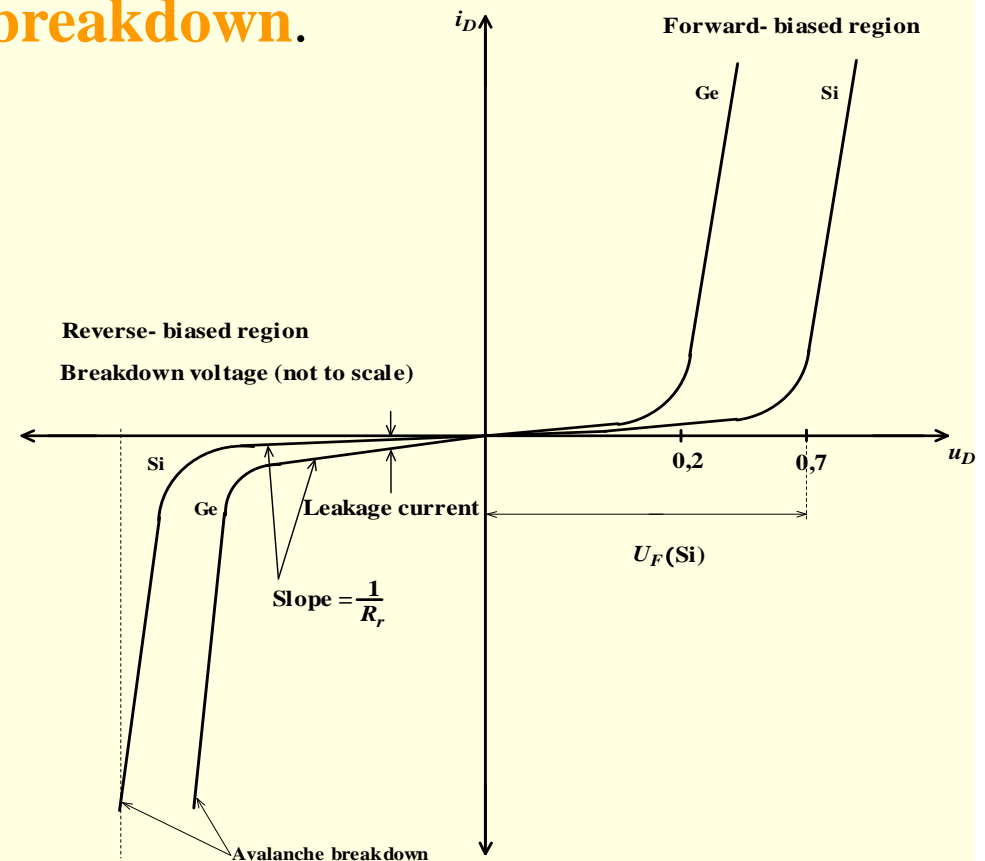
i_D

Forward- biased region

Ge   Si

Reverse- biased region

Breakdown voltage (not to scale)

Si

Ge   **Leakage current**

u_D

0,2   0,7

U_F (Si)

$\text{Slope} = \dfrac{1}{R_r}$

Avalanche breakdown

1.2 Diode Operation

V-A Diode operating characteristics

- The damage to the normal diode at breakdown is due to the avalanche of electrons, which flow across the junction with little increase in voltage. The large current can cause destruction of the diode if excessive heat builds up. This breakdown is sometimes referred to as the **diode voltage breakdown**.

- Diodes can be constructed to utilize the breakdown voltage to simulate a voltage-control device. The result is a **Zener diode**, which will be discussed in next lecture.

i_D

Forward- biased region

Ge   Si

Reverse- biased region

Breakdown voltage (not to scale)

Si

Ge

Leakage current

$Slope = \dfrac{1}{R_r}$

0,2   0,7

u_D

$U_F(Si)$

Avalanche breakdown

1.3   Diode Equivalent Circuit Models

- The circuit shown in Figure (a) represents **dc model-** a simplified model of the silicon diode under both forward and reverse dc operating conditions. The relationships for this model approximate the diode operating curve of the previous Figure.

C_j - *junction capacitor* C_D - *diffusion capacitor* r_d - dynamic resistance

a)   b)   c)
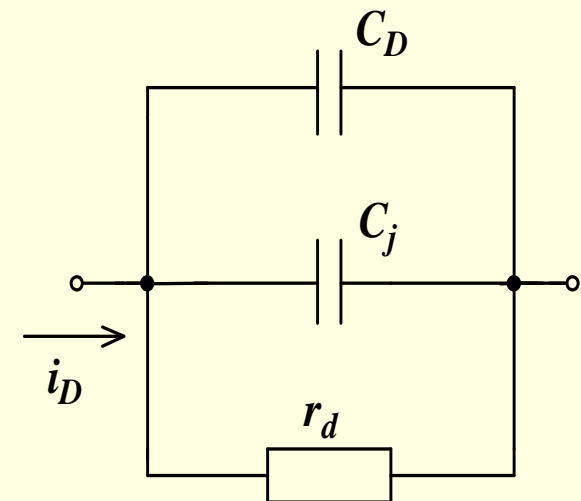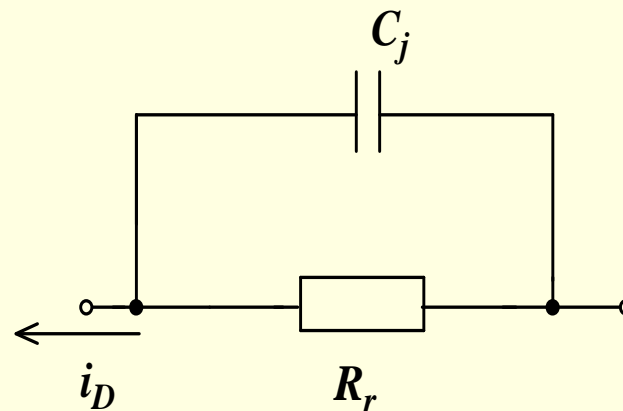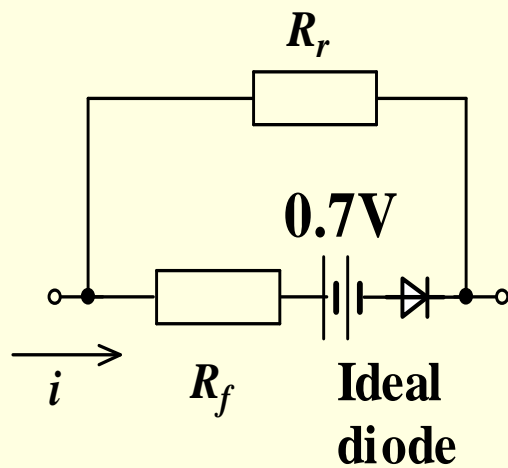
1.3 Diode Equivalent Circuit Models

- The resistor R_r, represents the reverse-bias resistance of the diode and is usually of the order of mega ohms. The resistor R_f represents the contact and bulk resistance of the diode and is usually less than 50Ω. When forward-biased, the ideal diode is a short circuit, or zero resistance. The circuit resistance of the practical diode modeled in Figure (a) is a parallel connection of R_r and $R_f \approx R_f$.

C_j - *junction capacitor* C_D - *diffusion capacitor* r_d - dynamic resistance

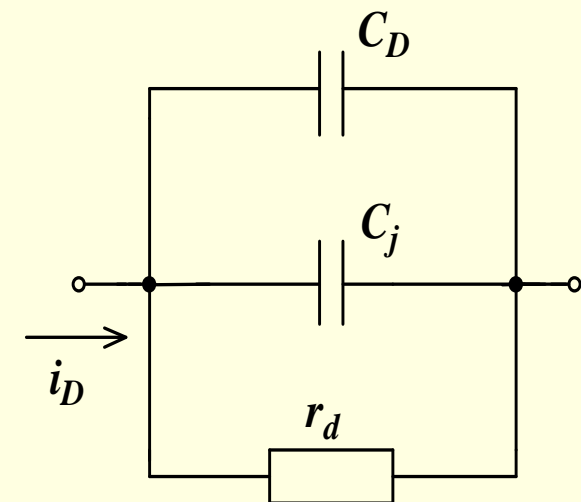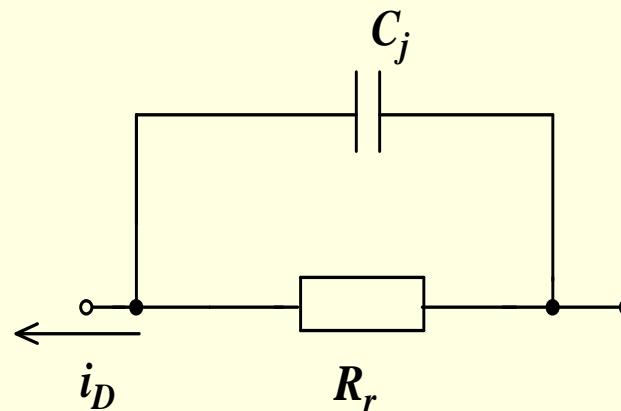a)   b)   c)
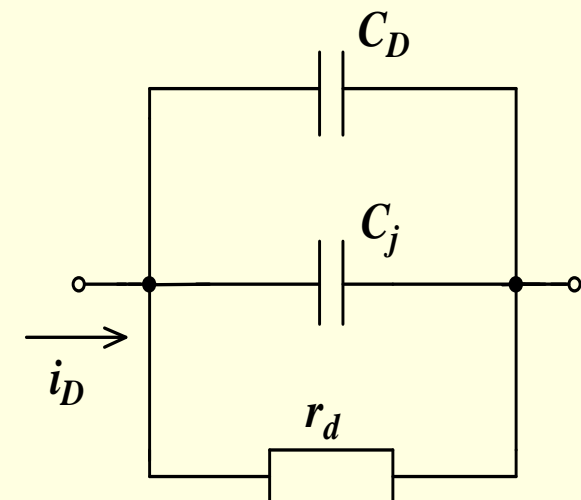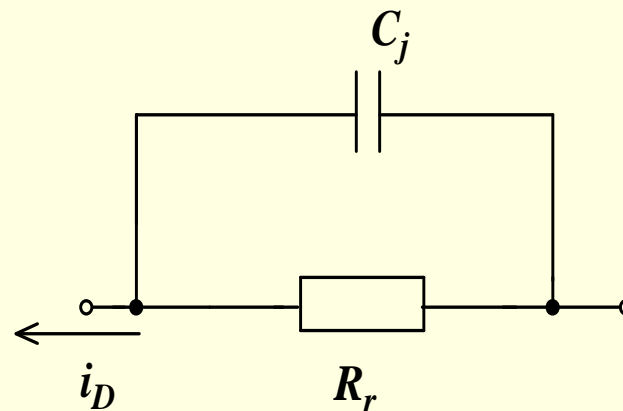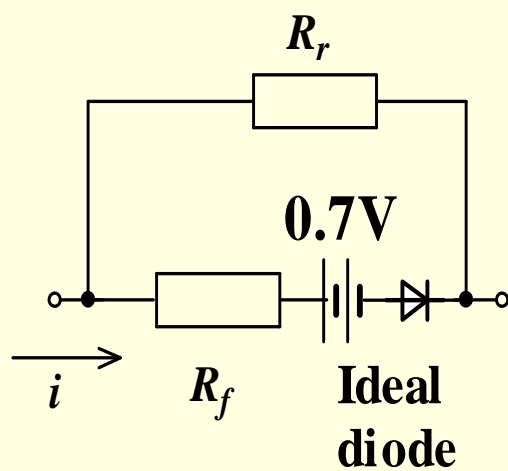
1.3 Diode Equivalent Circuit Models
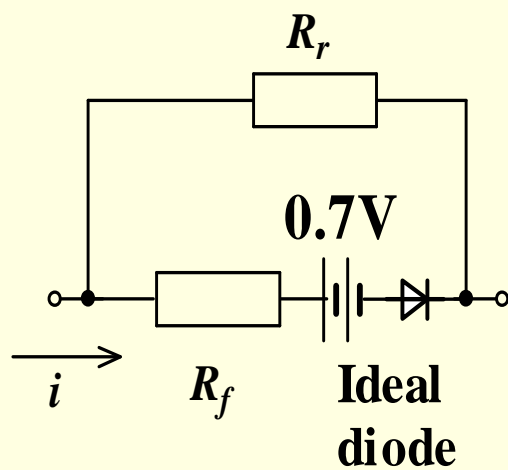
- Under **reverse-bias conditions**, the ideal diode has infinite resistance (open circuit), and the circuit resistance of the practical model is R_r. The ideal diode that is part of the model of Figure (a) is forward-biased when the terminal voltage exceeds 0.7V.

C_j - *junction capacitor* C_D - *diffusion capacitor* r_d - dynamic resistance

a)   b)   c)

1.3 Diode Equivalent Circuit Models

- The **ac circuit** models are more complex because the diode operation depends upon frequency. A simple ac model for a **reverse-biased diode** is shown in Figure (b). The capacitor, C_J, represents the junction capacitance.

C_j - *junction capacitor* C_D - *diffusion capacitor* r_d - dynamic resistance

a)   b)   c)
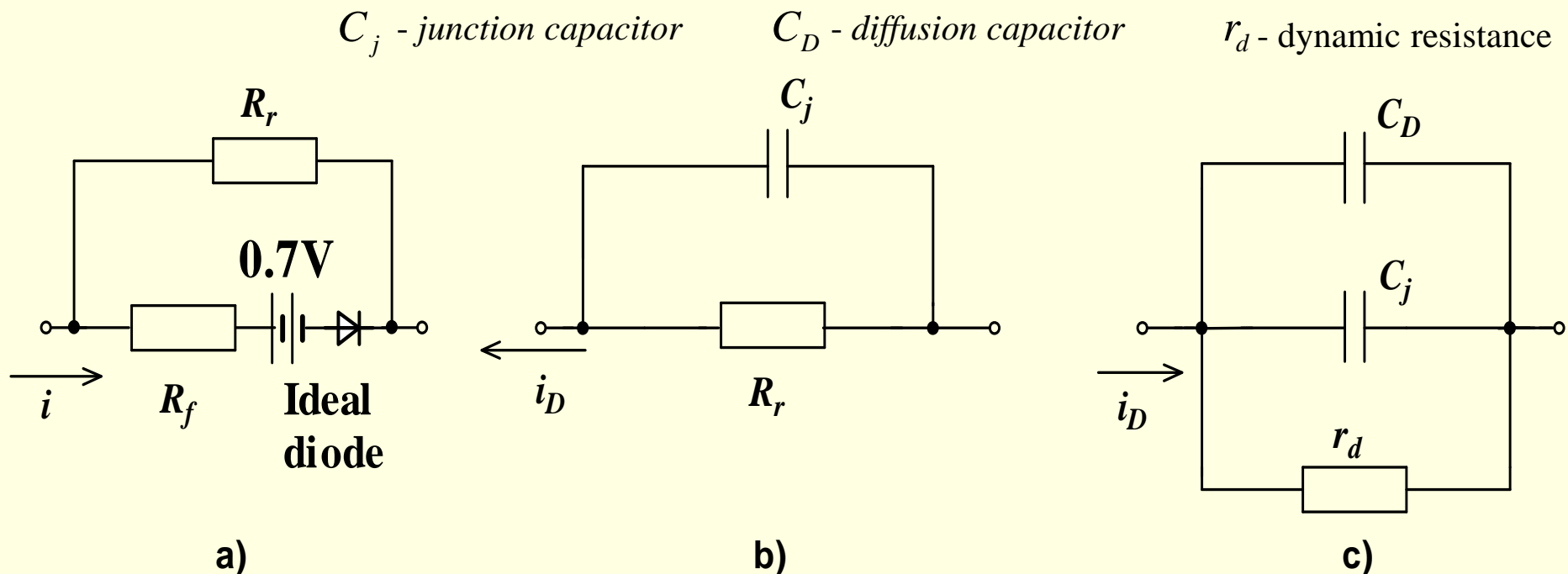
1.3 Diode Equivalent Circuit Models

- Figure (c) shows the **ac equivalent circuit** for a **forward-biased diode**. The model includes two capacitors, the diffusion capacitor, C_D, and the junction capacitor, C_J. The diffusion capacitance, approaches zero for reverse-biased diodes. The dynamic resistance is r_d and it is given by the slope of the voltage-current characteristic. At low frequencies, the capacitive effects are small and r_d is the only significant element..

C_j - *junction capacitor* C_D - *diffusion capacitor* r_d - dynamic resistance

a)   b)   c)
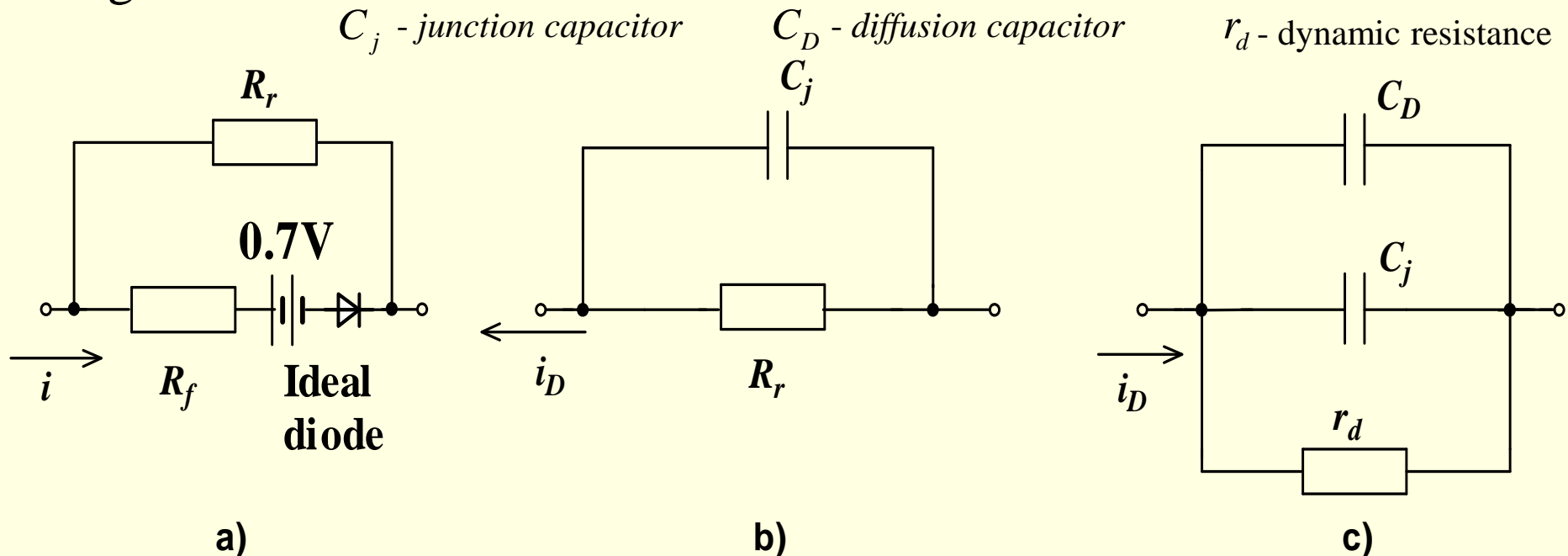
1.4   Physics of Solid- State Diodes
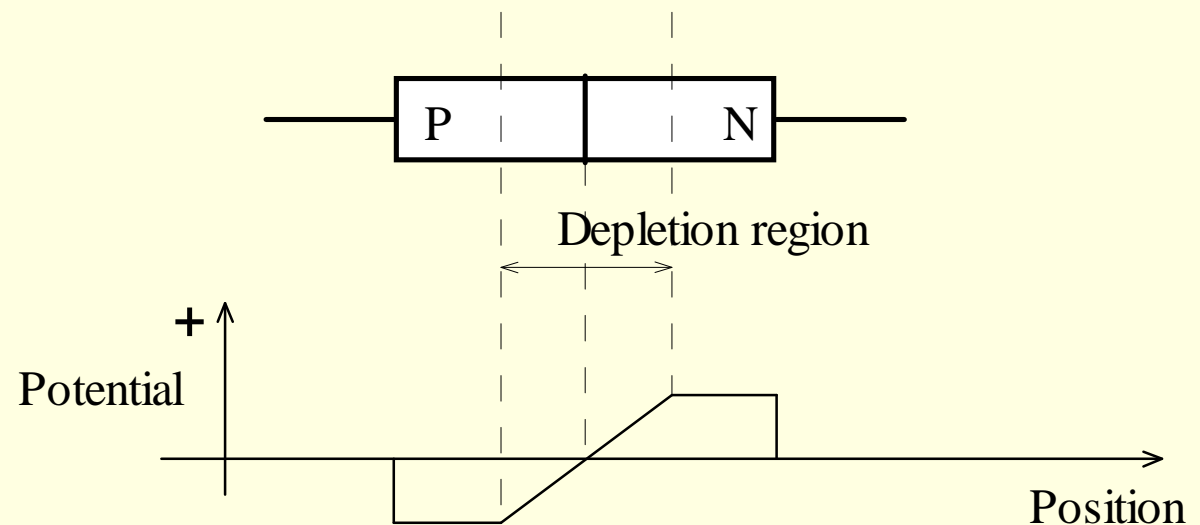
1.4.1 Charge Distribution

Now that we have discussed diode construction and have had a brief introduction to practical diode models, we shall explore some of the more detailed aspects of the differences between practical and ideal diodes.

Diodes can be visualized as a combination of an **n-type semiconductor connected to a p-type semiconductor**. However. in actual production, a single crystal of a semiconductor is formed with part of the crystal doped with n-type material and the other part doped with p-type material.

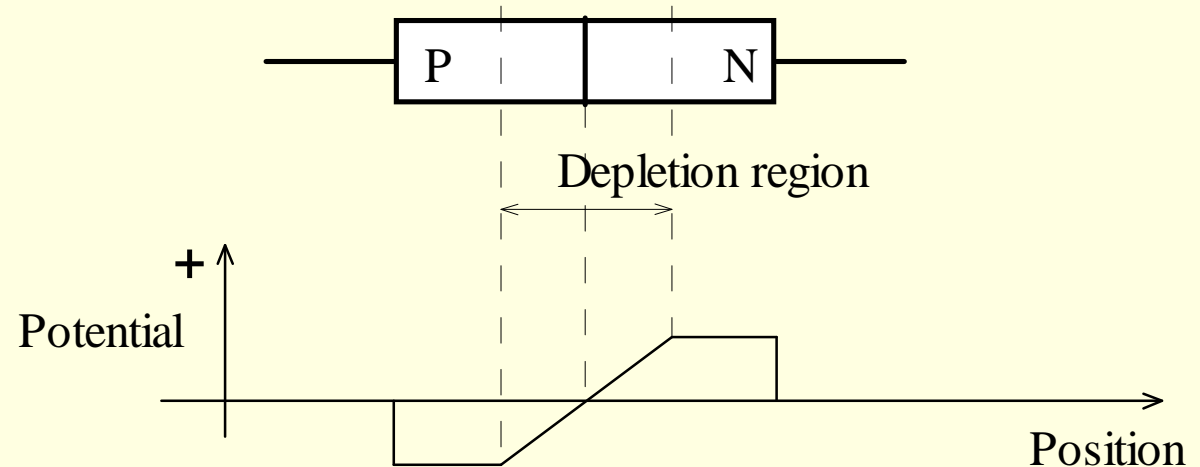# 1.4 Physics of Solid- State Diodes
1.4.1 Charge Distribution

When the p- and n-type materials exist together in a crystal, a **charge redistribution occurs**. Some of the free electrons from the n-material migrate across the junction and combine with the free holes in the p-material.

1.4   Physics of Solid- State Diodes
1.4.1 Charge Distribution

Similarly some of the free holes from the p-material migrate across the junction and combine with free electrons in the n-material. **As a result of this charge redistribution, the p-material acquires a net negative charge and the n- material acquires a net positive charge**. These charges create an electric field and a potential difference between the two types of material that will inhibit any further charge movement.

1.4   Physics of Solid- State Diodes
1.4.1 Charge Distribution

The result is to reduce the number of current carriers near the junction. This happens in an area known as the **depletion region**. The resulting electric field provides a potential barrier, or hill, in a direction that inhibits the migration of carriers across the junction. In order to produce a current across the junction, we must reduce the potential barrier, or hill, by applying a voltage of the proper polarity across the diode.
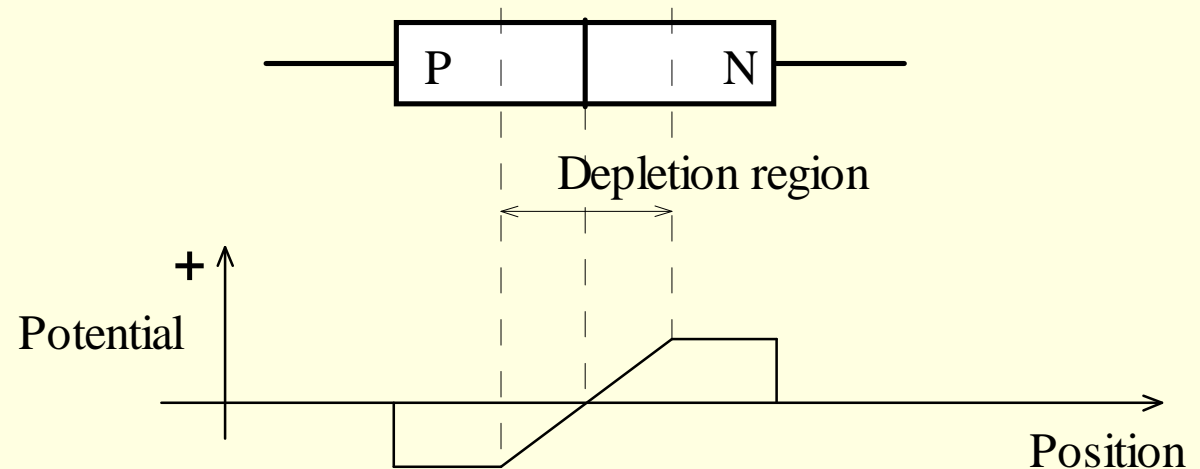
1.4 Physics of Solid- State Diodes

1.4.2 Relationship Between Diode Current and Diode Voltage

An **exponential relationship** exists between diode current and applied potential. It is possible to write a single expression for the current that applies for both the forward- and reverse-bias conditions. The relationship is described by equation:

$$i_D = I_0 \left(\exp\left(\frac{q \cdot u_D}{n \cdot k \cdot T} \right) - 1 \right)$$

i_D = current in the diode

v_D = potential difference across the diode

I_o = leakage current

q = electron charge: 1.6×10^{-19} coulombs (C)

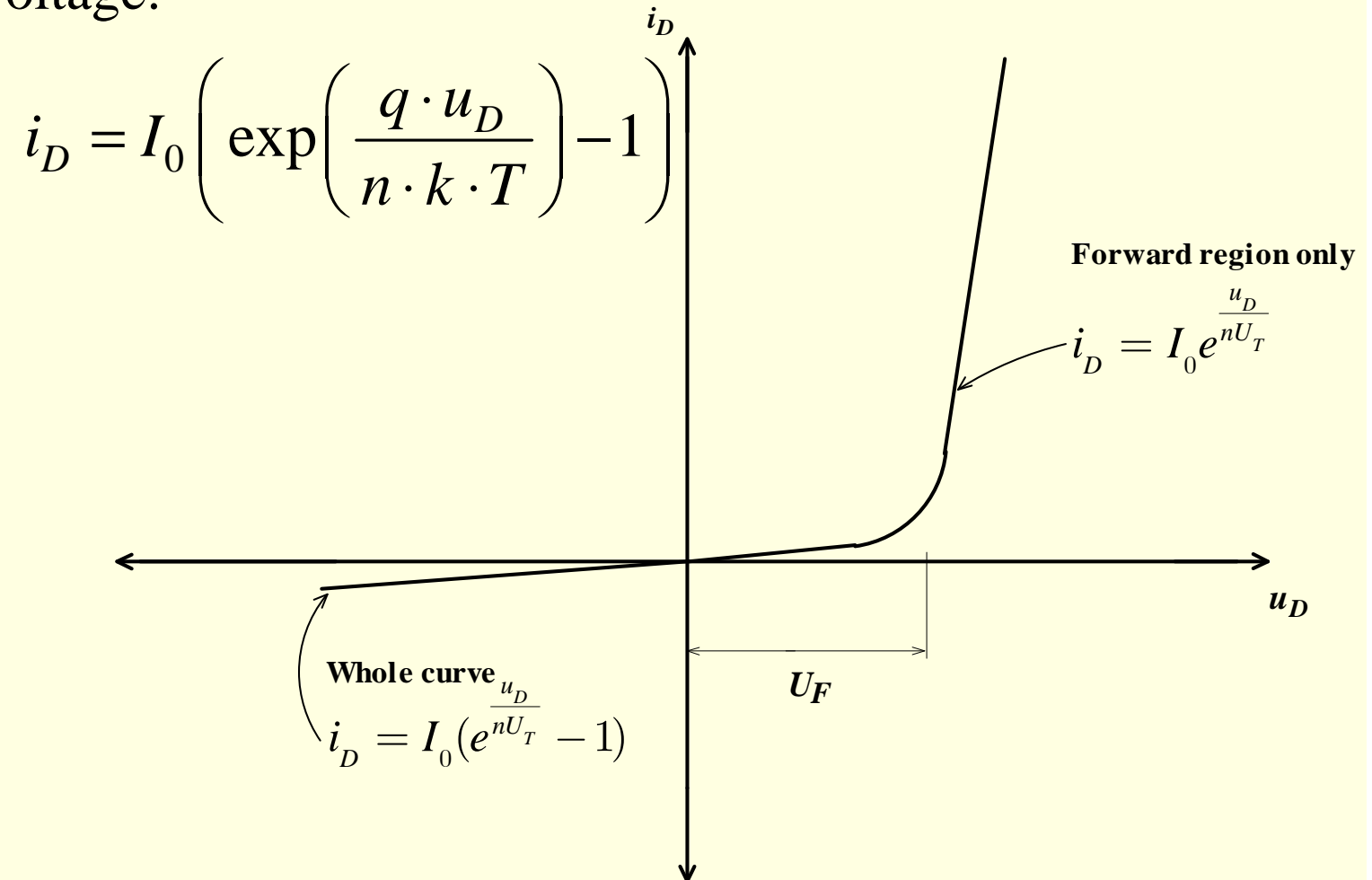k = Boltzmann's constant: 1.38×10^{-23} J/°K

T = absolute temperature in degrees Kelvin

n = empirical constant between 1 and 2, sometimes referred to as the *exponential ideality factor*

1.4 Physics of Solid- State Diodes

1.4.2 Relationship Between Diode Current and Diode Voltage

The expression applies as long as the voltage does not exceed the breakdown voltage:

$$i_D = I_0 \left(\exp\left(\frac{q \cdot u_D}{n \cdot k \cdot T} \right) - 1 \right)$$

Forward region only

$$i_D = I_0 e^{\frac{u_D}{nU_T}}$$

Whole curve

$$i_D = I_0 \left(e^{\frac{u_D}{nU_T}} - 1 \right)$$

U_F

1.4   Physics of Solid- State Diodes

1.4.2   Relationship Between Diode Current and Diode Voltage

Equation (1.1) can be simplied by defining

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

This yields

$$i_D = I_o \left[\exp\left(\frac{v_D}{nV_T}\right) - 1 \right] \tag{1.2}$$

If we operate at room temperature (25°C) and only in the forward-bias region ($v_D > 0$), then the first term in parenthesis predominates and the current is approximately given by

$$i_D = I_o \exp\left(\frac{v_D}{nV_T}\right) \tag{1.3}$$

1.4 **Physics of Solid- State Diodes**

1.4.2 Relationship Between Diode Current and Diode Voltage

These equations are illustrated in Figure:

Forward region only

$$i_D = I_0 e^{\frac{u_D}{nU_T}}$$

Whole curve

$$i_D = I_0 \left(e^{\frac{u_D}{nU_T}} - 1 \right)$$

U_F
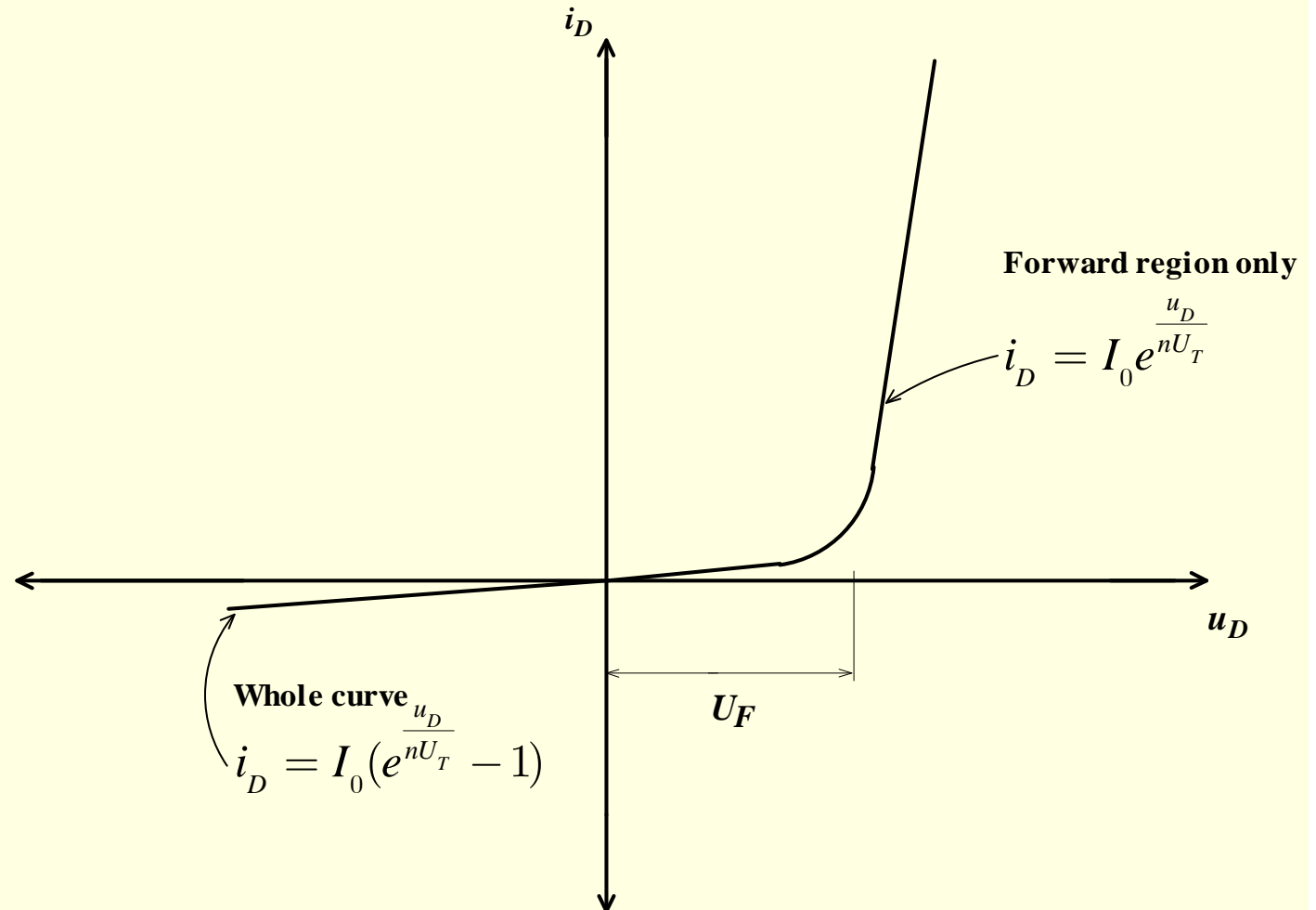
4.4 Fyzika diód v pevnej fáze

4.4.2 Vzťah medzi diódovým prúdom a diódovým napätím

Záverný saturačný prúd I_0 je funkciou
- čistoty materiálu,
- dotovania a
- geometrie diódy.

Empirická konštanta *n* je číslo, ktoré reprezentuje vlastnosť konštrukcie diódy. Môže sa meniť podľa napäťových a prúdových úrovní. Niektoré diódy však môžu pracovať vo veľkom napäťovom rozsahu s pomerne konštantným *n*.

Pre germániové diódy je obyčajne *n=1*.
Väčšina kremíkových diód však pracuje s *n=1,3* až 1,6. Hodnota *n* sa môže meniť aj v konkrétnom procese výroby z dôvodu výrobných tolerancií, čistoty materiálu a úrovne dotovania.

4.4 Fyzika diód v pevnej fáze
4.4.2 Vzťah medzi diódovým prúdom a diódovým napätím

Vzťah medzi prúdom a napätím v pracovnom bode dostaneme ak výraz zderivujeme, nájdeme teda smernicu pre ľubovoľnú hodnotu i_D (pre pracovný bod P):

$$\frac{di_D}{du_D} = \frac{I_0 \exp\left(\dfrac{u_D}{nU_T}\right)}{nU_T} \qquad (4.4)$$

Aby sme vylúčili exponenciálnu funkciu, riešime rovnicu (4.2)

$$\exp\left(\frac{u_D}{nU_T}\right) = \frac{i_D}{I_0} + 1$$

Dosadením tohto výrazu do rovnice (4.4) dostávame

$$\frac{di_D}{du_D} = \frac{\left(i_D + I_0\right)}{nU_T}$$

Dynamický odpor r_d je prevrátenou hodnotou tohto výrazu:

$$r_d = \frac{nU_T}{\left(i_D + I_0\right)} \approx \frac{nU_T}{i_D}$$