Elektronik Elemanlar

Yarı iletken ve diyot (s. 1–20)

Orijinal not: Elektronik-elemanlar-notlarim.pdf

> **UYARI** Bu belge, el yazısı ders notlarından Claude (Anthropic) yardımıyla dijitale aktarılmıştır. Yardımcı kaynak olarak hazırlanmıştır; hata veya eksik içerebilir. Lütfen orijinal notları ve ders kaynaklarını esas alın.
>
> **NOTICE** *This document was transcribed from handwritten lecture notes with the help of Claude (Anthropic). It is meant as a supplementary resource and may contain errors or omissions. Always check against the original notes and official course material.*

orj. s. 1

(Sol üstte okunamayan kısa bir not: ? okunamadı.)

Kitap (ders içeriğine ok ile bağlanmış): *Physics of Semiconductor Devices*, Sze S. M., 2ed edition.

Ders içeriği: Katı yapılar, Elektron ? için hareketleri, yalıtkan, iletkenler, yarı iletken fiziği.

① Diyot → (PN Junction) 

② BJT (Bipolar Junction Transistor) 

③ FET (Field effect transistor) (üstüne küçük harflerle: "Alan etkili transistör")

JFET (altında küçük: "Junction"), MOSFET →  ↗ AC, ↘ DC

Kaynaklar

Ders kitabı: ⋆ *Microelectronic Circuits* → 2016 (Sedra, Smith) — The Oxford Series in electrical and computer engineering

Elektronik → Mehmet Sait Türköz → Birsen Yayınevi, 2004

Değerlendirme

- 1 ödev (~%? 5), 1 proje → LTSpice
- Vize → %30
- Final → %50

orj. s. 2

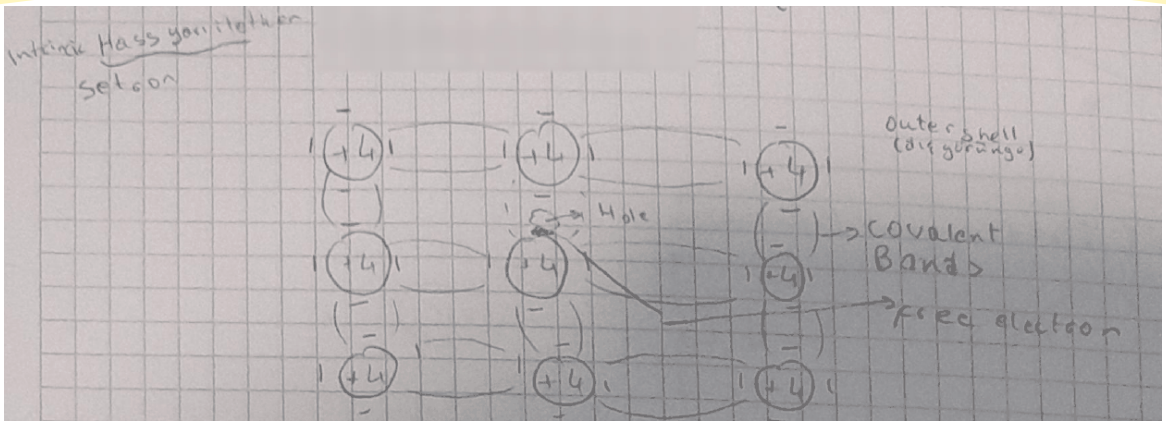
(Sol üst köşede küçük: "Ders 1")

Semiconductors

- Intrinsic Semiconductors (Has yarıiletken)
- Doped Semiconductor (katkılı „)

→ Elemental Semi → Silicon, Germanyum

↪ GaAs → Gallium Arsenide, → compound semi

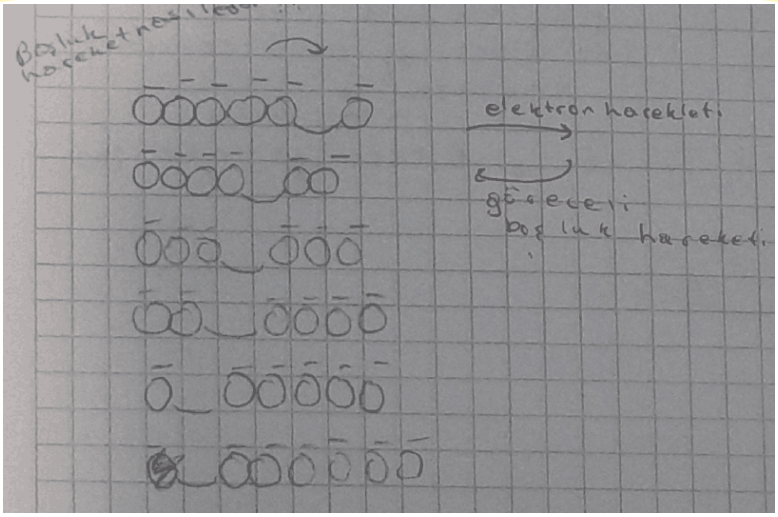


orijinal çizim, s. 2

0°K'de tüm bağlar ?mükemmel → T↑

Hole (Elektron boşluğu)

(Sol kenarda eğik, küçük: "Boşluk hareketi nasıl oluyor?" ?okunamadı.)



orijinal çizim, s. 2

Recombination (Rekombinasyon)

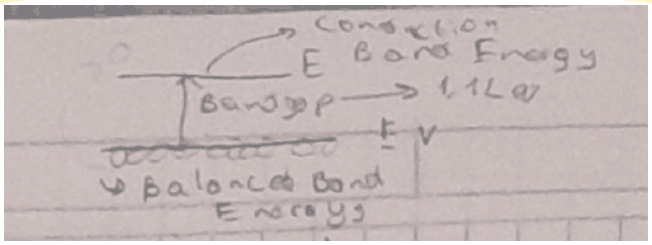


orijinal çizim, s. 2

anhilate: serbest elektronun boşlukla yer değiştirmesi

Termal dengede (Has yarı iletkende)
Thermal generation = Recombination
sıcaklıkla birlikte yeni boş elektron ?oluşması

orj. s. 3



orijinal çizim, s. 3

Free carriers (Serbest Taşıyıcı)

- electrons (Elektron)
- holes (Boşluk)

(Has yarı iletken)

$$n = p = n_i$$

→ (3,1) → sayfa (138)
n: elektron sayısı, p: holes (Boşluk) sayısı

$$n_i = B\,T^{3/2}\,e^{-E_g/2kT}$$

- E_g: Band gap Energy (Band aralığı „)
- B: Parametre (silikon) = $7{,}3 \cdot 10^{15}\ cm^{-3}K^{-3/2}$

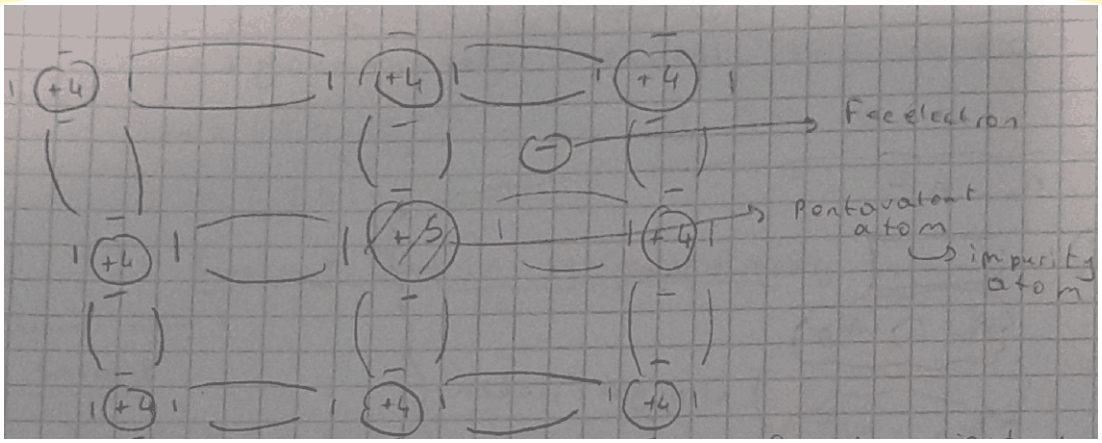
$$T = 300\ K \Rightarrow n_i = 1{,}5 \times 10^{10}\ carriers/cm^3$$

silicon → $5 \cdot 10^{22}\ atom/cm^3$

Doped (katkılı) semiconductor

$$n \cdot p = n_i^2$$

↪ Has yarıiletken ve katkılı yarıiletken için geçerli.



orijinal çizim, s. 3

$$p_n \cdot n_n = n_i^2$$

(Alt indisler daire içine alınmış: n indisleri "yarıiletkenin tipi", i indisi "intrinsic".)

n tipi:

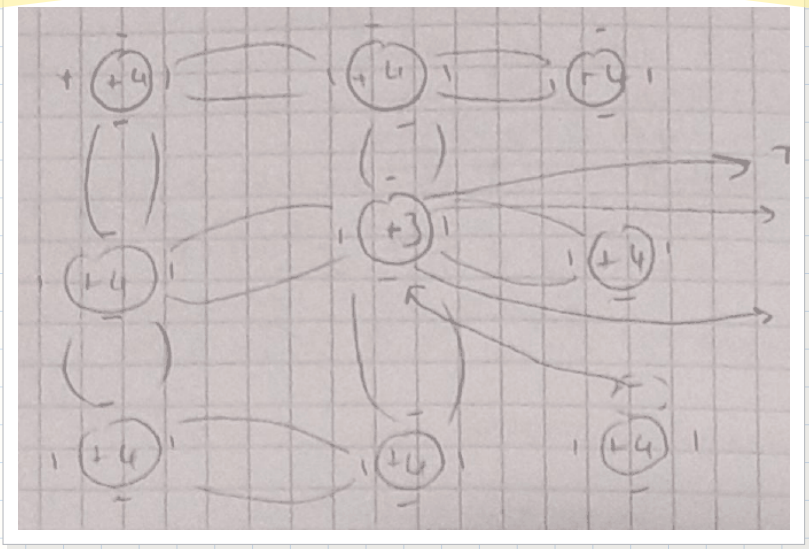
p_n : n-tipi yarıiletkende boşluk sayısı n_n : „ „ elektron sayısı

Doped semiconductor

- n-tipi yarıiletken: çoğunluk taşıyıcıları elektronlar
- p-tipi yarıiletken: çoğunluk taşıyıcı boşluk

orj. s. 4

p tipi



orijinal çizim, s. 4

- Trivalent (Bor)

- impurity Atom
- N_A: Acceptor Atom (+3 valance electron)
  N_A : p tipi yarı iletken
- N_D: Donor Atoms (+5 valance electron)
  ⌞ n tipi yarı iletken

$$n_p \cdot p_p = n_i^2$$

p_p : p-tipi yarıiletkendeki boşluk sayısı
n_p = p-tipi yarıiletkendeki elektron sayısı

$p_n \cdot n_n = n_i^2$
$N_D \rightarrow$ n-tipi yarıiletken
$n_n \simeq N_D$
$\left\{ p_n = \frac{n_i^2}{N_D} \right\}$ n tipi yarıiletken

p-tipi yarıiletken

$p_p \simeq N_A \rightarrow$ Acceptor Atom yoğ.

$$p_p n_p = n_i^2 \Rightarrow n_p \simeq \frac{n_i^2}{N_A} \quad \text{(Elektron sayısı)}$$

orj. s. 5

	n-tipi:	p-tipi:
Çoğunluk taşıyıcıları (Majority carriers)	electrons	holes
Azınlık taşıyıcıları (minority carriers)	holes	electrons

Örnek 3.2

(sayfa 131) n-type silicon, katkı yoğunluğu (dopant concentration) $N_D = 10^{17}/cm^3$, electron ve boşluk yoğunluğunu $T = 300$ K bulunuz.

Çözüm:

$$n_n = N_D \simeq 10^{17}/cm^3$$

$$p_n = \frac{n_i^2}{N_D} \Rightarrow n_i = 1{,}5 \cdot 10^{10}/cm^3$$

$$p_n = \frac{(1{,}5 \cdot 10^{10})^2}{10^{17}} = 2{,}25 \cdot 10^3/cm^3$$

Current Flow in semiconductors

(sürükleme akımı)

Drift Current

$$v_{p\text{-}drift} = \mu_p \cdot E \qquad \text{(Elektrik alanı)}$$

(Küçük notlar: $v_{p\text{-}drift}$ için "hızı"; μ_p için "mobilite hole".)

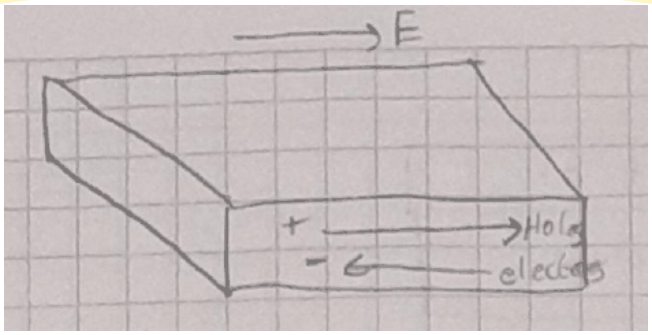
$$\mu_p = 480\ cm^2/V{\cdot}s$$

$v = \mu \cdot E$ (hızı; Elektrik alanı), $\quad \frac{cm}{s} = \mu \cdot \frac{V}{cm} \Rightarrow \frac{cm^2}{V \cdot s}$

$$v_{n\,drift} = -\mu_n \cdot E$$

Elektron mobilitesi ↪ 1350 $cm^2/V{\cdot}s$

orj. s. 6



orijinal çizim, s. 6

in one second:

$$I_p = A\,q\,p\,v_{p\,drift}$$

$A \cdot q \cdot p \cdot v$ $\quad (A:\ cm^2,\ q:\ C,\ p:\ 1/cm^3,\ v:\ cm/s) \rightarrow C$

$$I_p = A\,q\,p\,\mu_p\,E$$

(Soldaki küçük not: "? deliklerin".)

→ J → current density

$$J_p = \frac{I_p}{A} = q \cdot p \cdot \mu_p \cdot E$$

(Soldaki küçük not: "elektronların".)

$$I_n = -A \cdot q \cdot n \cdot v_{n\,drift} \qquad (v_{n\,drift} = -\mu_n E)$$

$$J_n = \frac{I_n}{A} = q \cdot n \cdot \mu_n \cdot E$$

$$J = J_p + J_n = q\,(p\mu_p + n\mu_n)\,E$$

$J = \sigma \cdot E$ $\quad \hookrightarrow$ conductivity (iletkenlik)

$$\rho = \frac{1}{\sigma} = \frac{1}{q\,(p\mu_p + n\mu_n)} \qquad (\rho:\ \text{resistivity})$$

$$\rho = \frac{E}{J}, \qquad \rho = R\,\frac{A}{\ell} \quad (A:\ \text{kesit alanı},\ \ell:\ \text{uzunluk})$$

orj. s. 7

Örnek 3.3

Resistivity = ?
a) intrinsic silicon
b) p-type „ → $N_A = 10^{16}/cm^3$
$n_i = 1{,}5 \cdot 10^{10}/cm^3$
has yarıiletken → $\mu_n = 1350\ cm^2/V{\cdot}s$, $\mu_p = 470\ cm^2/V{\cdot}s$
katkılı yarıiletken → $\mu_n = 1110\ cm^2/V{\cdot}s$, $\mu_p = 400\ cm^2/V{\cdot}s$

Çözüm: a)

$$p = n = n_i = 1{,}5 \cdot 10^{10}/cm^3$$

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)} = \frac{1}{1{,}6 \cdot 10^{-19}(1{,}5 \cdot 10^{10} \cdot 470 + 1{,}5 \cdot 10^{10} \cdot 1350)}$$

$$= 2{,}28 \times 10^{?5}\ \Omega\,cm \rightarrow \text{Has yarıiletken}$$

b) p tipi yarıiletken

$$p_p \simeq N_A = 10^{16}$$

$$n_p = \frac{n_i^2}{N_A} = \frac{(1{,}5 \cdot 10^{10})^2}{10^{16}} = 2{,}25 \cdot 10^4/cm^3$$

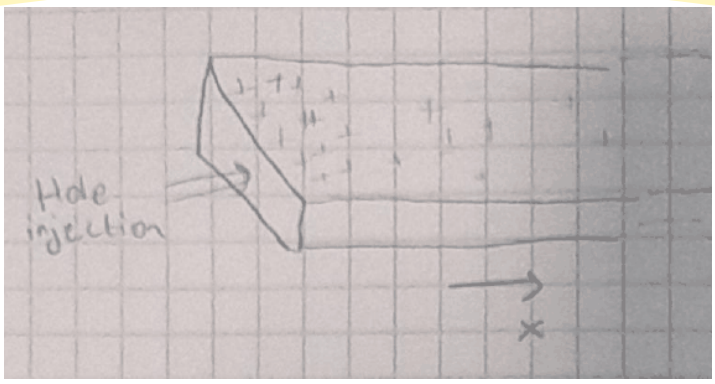
$$\rho = \frac{1}{q(p\mu_p + n\mu_n)} = \frac{1}{1{,}6 \times 10^{-19}(10^{16} \times 400 + 2{,}25 \times 10^4 \times 1110)}$$

$$\simeq \frac{1}{1{,}6 \times 10^{-19} \times 10^{16} \times 400} = 1{,}66\ \Omega\,cm^a$$

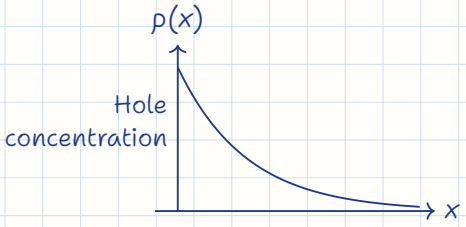
[a] Claude notu: 1/0,64 ≈ 1,56 olduğundan muhtemelen 1,56 Ω cm olmalı.

orj. s. 8

Diffusion Current



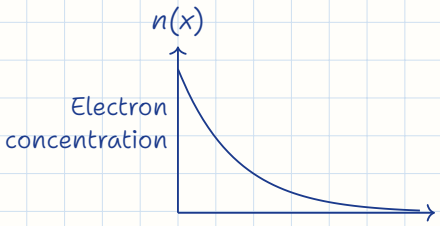
orijinal çizim, s. 8



$$J_p = -q D_p \frac{dp(x)}{dx}$$

D_p: difüzyon sabiti (Boşluk)

$$J_n = q D_n \frac{dn(x)}{dx} \qquad (D_n : \text{elektron difüzyon sabiti})$$



Diffusion constants ↪ $D_p = 12\ cm^2/s$, $D_n = 35\ cm^2/s$

Örnek 3.4

$p(x) = p_0 e^{-x/L_p}$
Find the hole density at $x = 0$.
$p_0 = 10^{16}/cm^3$, $L_p = 1\,\mu m$, $D_p = 12\ cm^2/s$
$I_p = ?$ (Bar cross sectional Area $10\ \mu m^2$)

Çözüm:

$$J_p = -q D_p \frac{dp(x)}{dx}$$
$$= -q D_p \frac{d}{dx}\left[p_0 e^{-x/L_p}\right]$$
$$= q \frac{D_p}{L_p} p_0 e^{-x/L_p}$$
$$J_p(0) = q \frac{D_p}{L_p} p_0$$
$$= 1{,}6 \cdot 10^{-19} \cdot \frac{12}{1 \cdot 10^{-4}} \cdot 10^{16} = 192\ A/cm^2$$
$$I_p = J_p \times A \Rightarrow 192 \cdot 10^{-7} = 19{,}2\ \mu A$$

orj. s. 9

Relationship between D and μ

Einstein relationship

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

$V_T \rightarrow$ Termal Gerilim, Thermal Voltage $\rightarrow$

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

(Çok küçük, silik notlar ok ile: k için "Boltzmann sabiti", T için "sıcaklık", q için "? yük".)

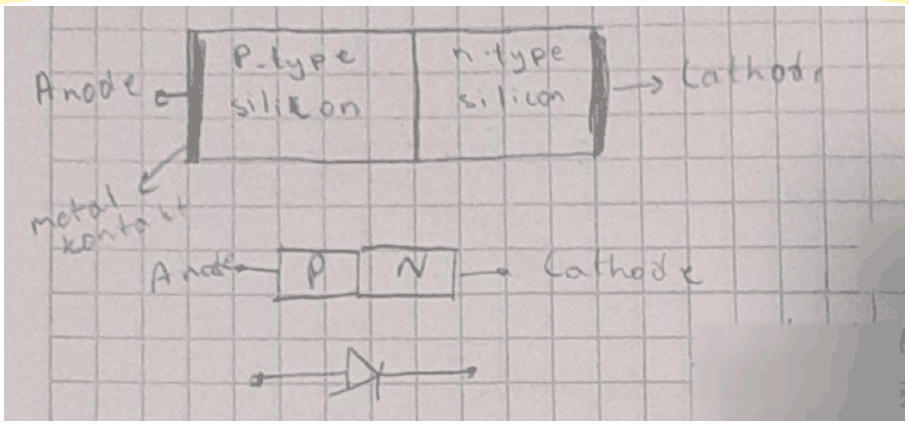
$$T = 300\ \text{K} \Rightarrow V_T \simeq 25{,}9\ \text{mV}$$

$$\simeq 26\ \text{mV},\ 25\ \text{mV}$$

orj. s. 10 (Sol üst köşede küçük: "2. Ders")

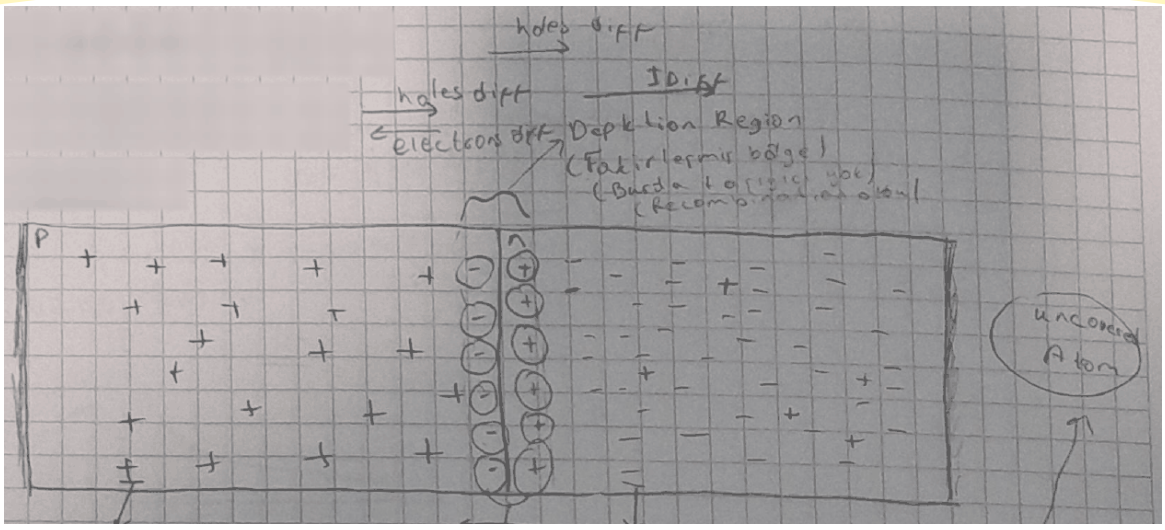
PN Junction

$n_i = 1{,}5 \cdot 10^{10}$ silikonda $\quad n \cdot p = n_i^2$



orijinal çizim, s. 10

Open circuit



orijinal çizim, s. 10

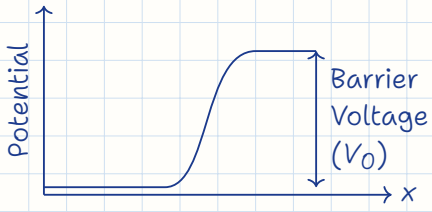
- Depletion Region (Fakirleşmiş bölge) (Burada taşıyıcı yok) (recombination olur)
- Sol bölgenin altında: Majority carriers (çoğunluk T); ilk önce difüzyon gerçekleşir
- Ortada, ok ile E: (Elektrik alan oluşur (difüzyon))

- Sağ bölgenin altında: Çoğunluk T
- Sağda: ← I_S (drift current); ← holes drift; electrons drift →
- Band Charges (Hareketsizdir, sabittir) (ok ile tükenme bölgesindeki yüklere bağlı)

Artıyükler elektrik alanla aynı yönde, eksiler ise ters yönde.

Dengede ⇒ $I_D = I_S$ (I_D: difüzyon akımı; I_S: drift current)

Elektrik alan neticesinde



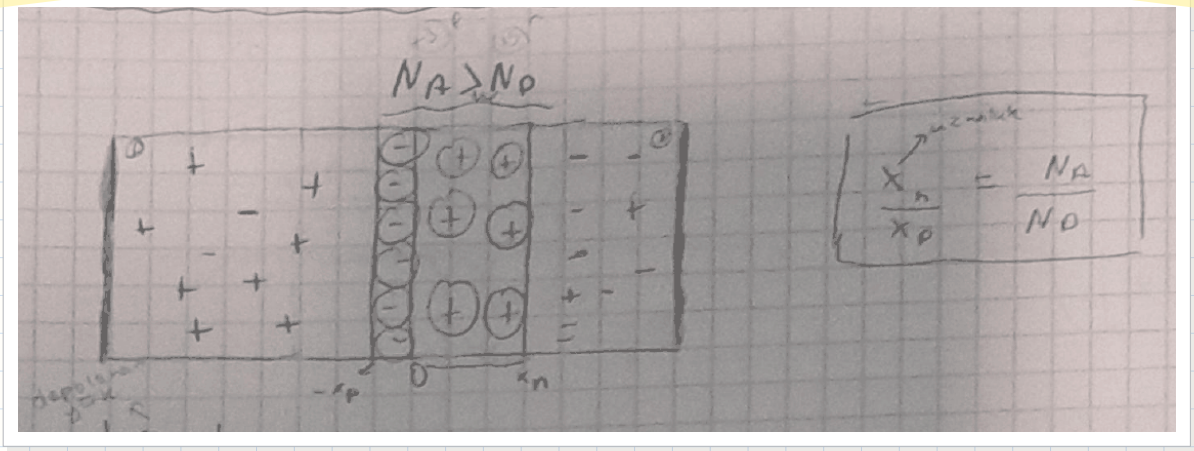
$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

N_A: Acceptor atom (+3) p tipi; N_D: Donor atom (+5) n tipi

orj. s. 11

Farklı katkı yoğunluklarında pn jonksiyonu

$N_A > N_D$



orijinal çizim, s. 11

$$\left.\begin{aligned} |Q_+| &= qAx_nN_D \\ |Q_-| &= qAx_pN_A \end{aligned}\right\} \rightarrow qAx_nN_D = qAx_pN_A$$

$$\frac{x_n}{x_p} = \frac{N_A}{N_D}$$

x_n : n tipi bölgedeki fakirleşmiş bölgenin uzunluğu
x_p : p tipi „ „ „ „

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right) V_0} \qquad (W: \text{ the width of depletion region})$$

$$\varepsilon_s = \varepsilon_r \cdot \varepsilon_0 = (11{,}7)\,(8{,}85 \cdot 10^{-14}\ \text{F/cm})$$

$$\frac{x_n}{x_p} = \frac{N_A}{N_D} \Rightarrow x_p = x_n \frac{N_A}{N_D}$$ [1]

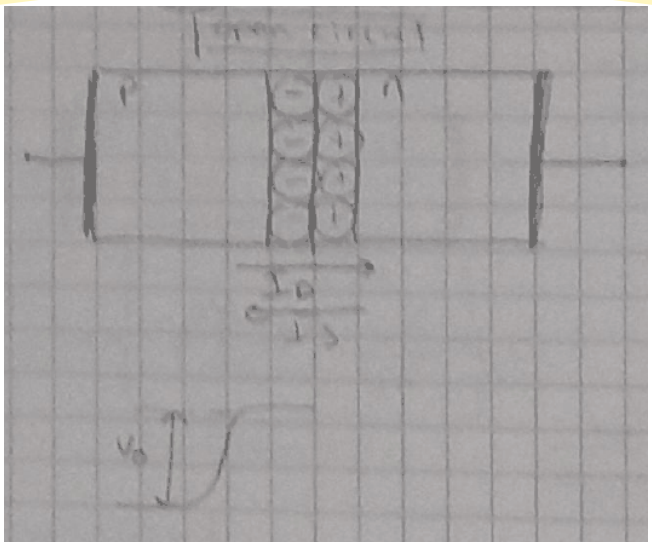
(sağdaki türetme:)

$$x_n + x_p = W$$
$$x_n + x_n \frac{N_D}{N_A} = W$$
$$x_n \left(1 + \frac{N_D}{N_A}\right) = W$$
$$\boxed{x_n = \frac{N_A}{N_A + N_D} W}$$
$$\boxed{x_p = W \frac{N_D}{N_A + N_D}}$$

$$|Q_+| = |Q_-| = Q_J$$
$$Q_J = A\,q \left(\frac{N_A N_D}{N_A + N_D}\right) W$$
$$\boxed{Q_J = A\sqrt{2\varepsilon_s\, q \left(\frac{N_A N_D}{N_A + N_D}\right) V_0}}$$

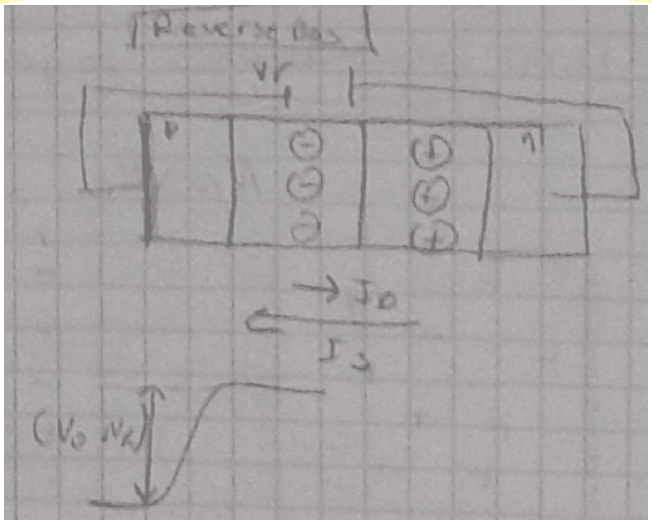
orj. s. 12

The PN junction with an Applied Voltage

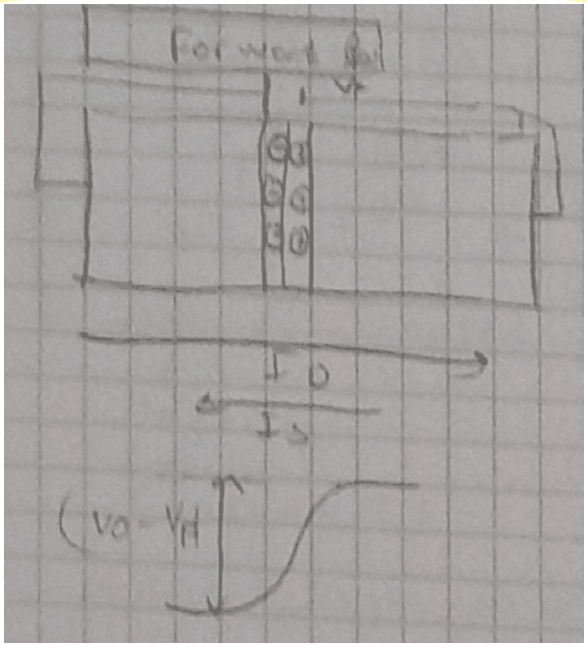


orijinal çizim, s. 12

[1] Claude notu: muhtemelen $x_p = x_n N_D/N_A$ olmalı; sağdaki türetmede de böyle kullanılmış.



orijinal çizim, s. 12



orijinal çizim, s. 12

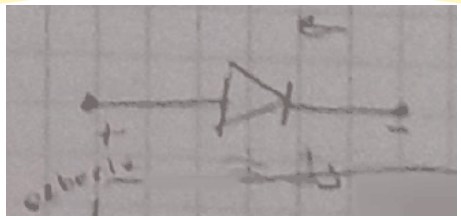
Reverse

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$$

$$Q_J = A\sqrt{2\varepsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right)(V_0 + V_R)}$$

Reverse $\rightarrow I = I_S$

Forward $\rightarrow \boxed{I = I_S\left(e^{V/V_T} - 1\right)}$



orijinal çizim, s. 12

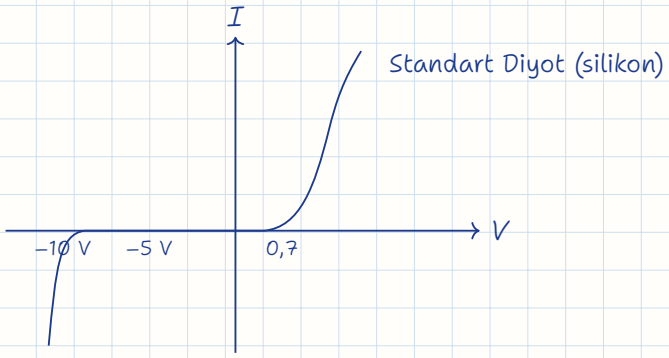
$I_D = I_S e^{V_D/nV_T}$ $V_T = \frac{kT}{q}$? ≈ 25 mV

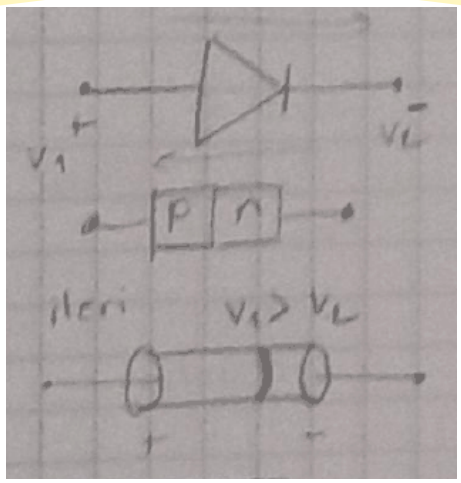
I_S sıcaklıktan çok etkilenir

orj. s. 13

The PN Junction with applied Voltage

(Sol kenarda küçük bir yıldız işareti.)





orijinal çizim, s. 13

Reverse Breakdown

→ Zenner effect → elektrik alanın etkisiyle bağların kopması
→ Avalanche effect

orj. s. 14

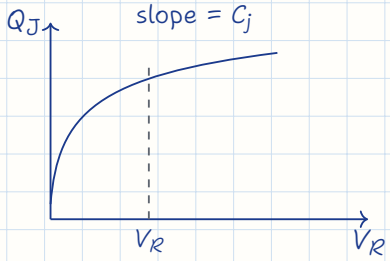
Capacitive effects

→ Depletion or junction capacitance → Reverse region

$$Q_J = A\sqrt{2\varepsilon_s q \frac{N_A N_D}{N_A + N_D}(V_0 + V_R)}$$

$$Q_J = \alpha\sqrt{V_0 + V_R}$$

$$\alpha = A\sqrt{2\varepsilon_s q \frac{N_A N_D}{N_A + N_D}}$$



$$C_j = \left.\frac{dQ_J}{dV_R}\right|_{V_R=V_0}$$

$$\boxed{C_j = \frac{\alpha}{2\sqrt{V_0 + V_R}}} \longrightarrow C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}} \qquad (C_{j0}:\ V_R = 0)$$

(Sağ kenarda küçük: "sayfa 169")

Difüzyon kapasitesi (Diffusion capacitance) → Forward Bias, minority carriers in effect

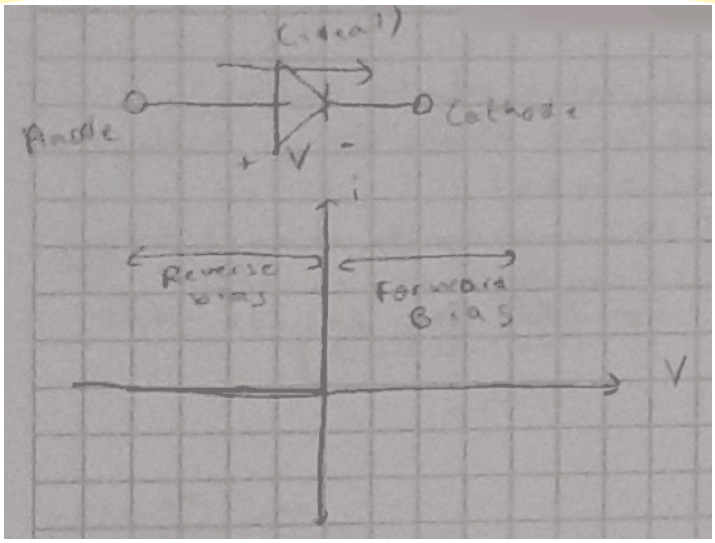
$$C_d = \left(\frac{\tau_T}{V_T}\right) I \qquad (C_d:\ \text{incremental diffusion capacitance};\ \tau_T:\ \text{mean transit time})$$

→ sayfa 169–170 Şekil ? ok.

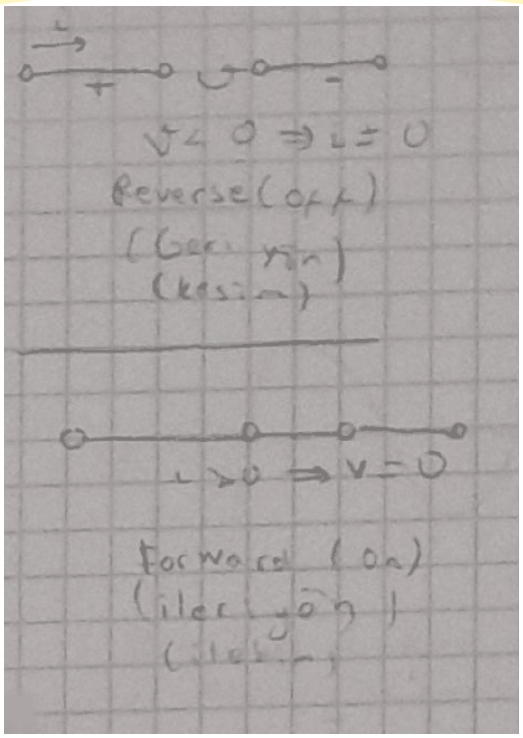
orj. s. 15

(Sol üst köşede küçük: "Ders 3")

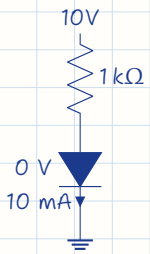
The ideal Diode



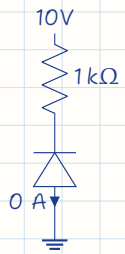
orijinal çizim, s. 15



orijinal çizim, s. 15

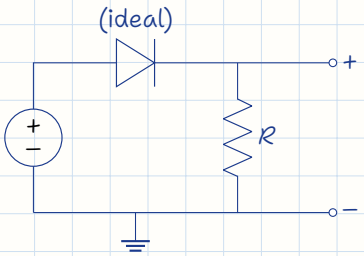


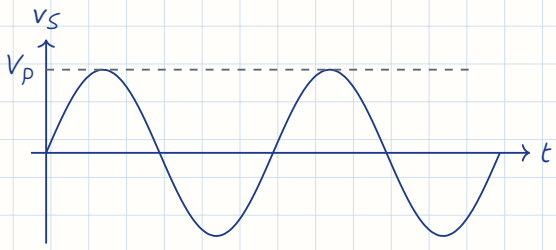
iletim (on)



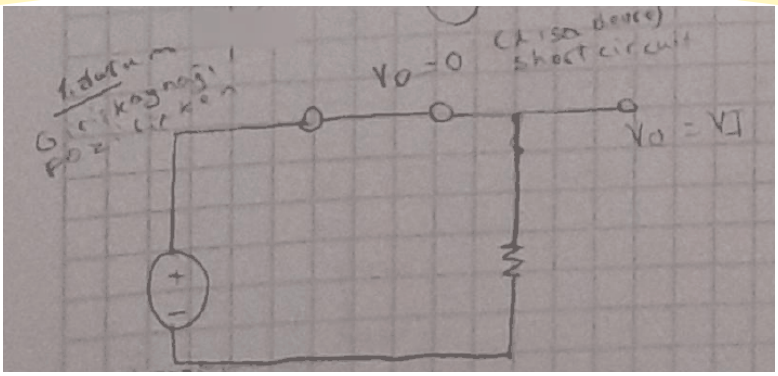
kesim (off)

Yarım dalga doğrultucu (ideal diyot)



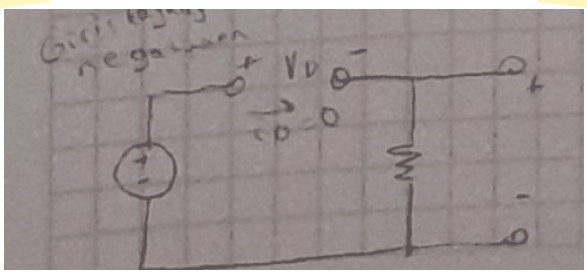


1. durum: Giriş kaynağı pozitifken



orijinal çizim, s. 15

Giriş kaynağı negatifken

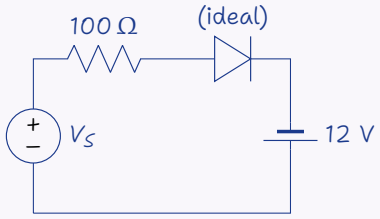


orijinal çizim, s. 15



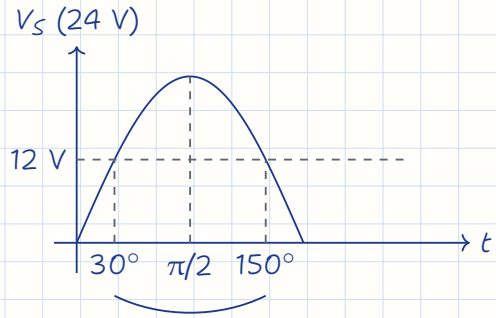
orj. s. 16

Örnek 4.1



V_S: tepe değeri 24 V olan sinüs. a) Peak value of diode current
b) Maximum reverse-bias voltage of the diode?
c) Fraction of each cycle during which the diode conducts (periyodun kaçında diyot iletimdedir?)

Çözüm: c)



$150° - 30° = 120° \rightarrow$ 1/3 cycle

a)

$$I_D = \frac{24 - 12}{100} = 0{,}12 \text{ A}$$

b) Diyot sembolü (anot solda): sol uçta −24, sağ uçta 12 V.

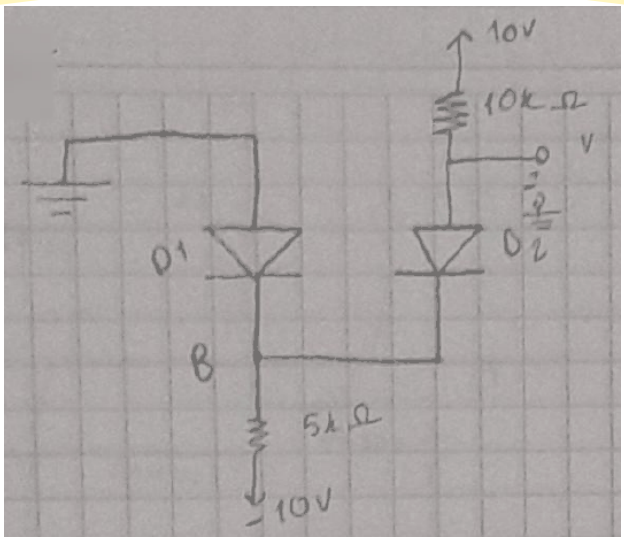
$-24 - 12 = -36$ V (uçlar arasına düşen negatif gerilim)

Lojik kapılar

orj. s. 17

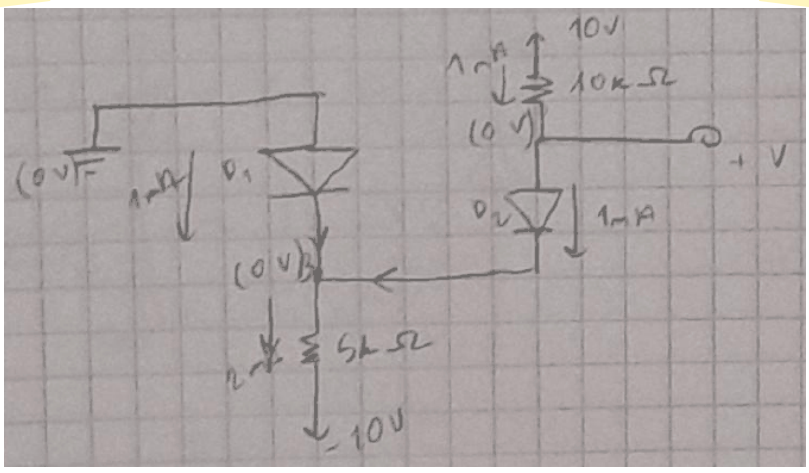
Örnek 4.2

a)



orijinal çizim, s. 17

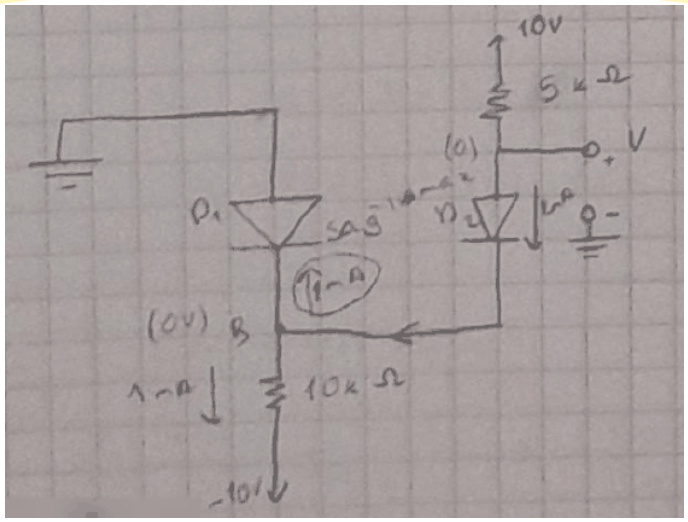
Çözüm: (Sol kenarda: "Çözmek için varsayımda bulunalım")
D_1 is on ve D_2 is on (✓ işaretli)



orijinal çizim, s. 17

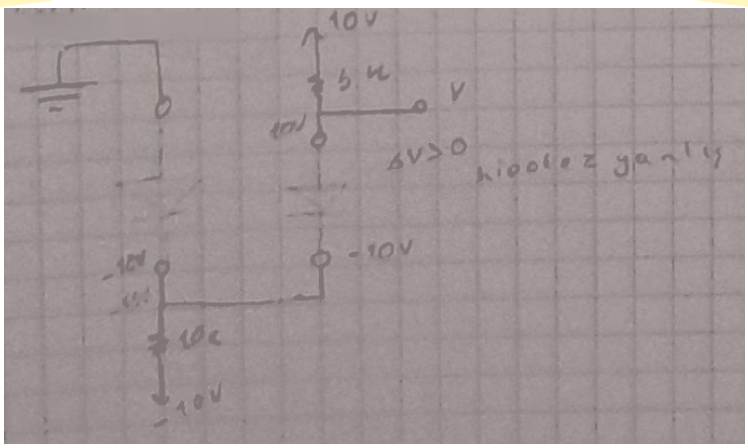
iletimde akım akar ve ?diyot kısa devre gibi davranır.

Örnek 4.2 (b)



orijinal çizim, s. 17

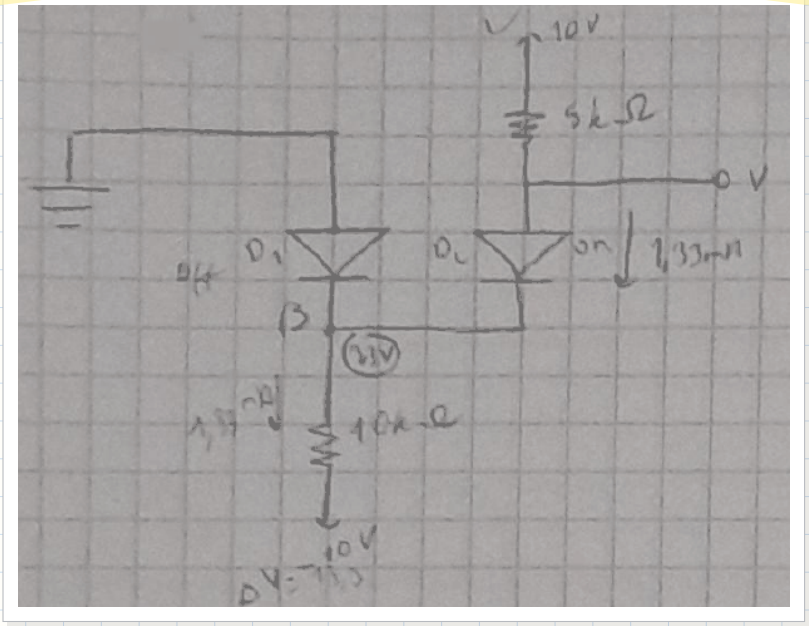
Çözüm: Varsayım: D_1 is on and D_2 is on ⇒ varsayım yanlış
D_1 ve D_2 kesimde:



orijinal çizim, s. 17

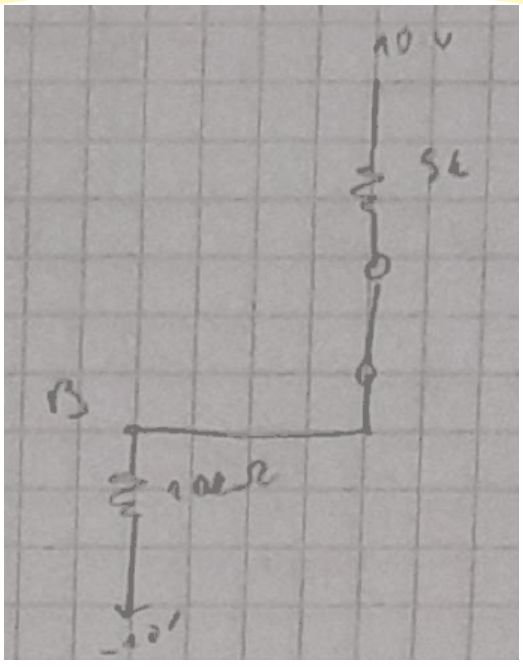
orj. s. 18

D_1 is off and D_2 is on (✓ işaretli)



orijinal çizim, s. 18

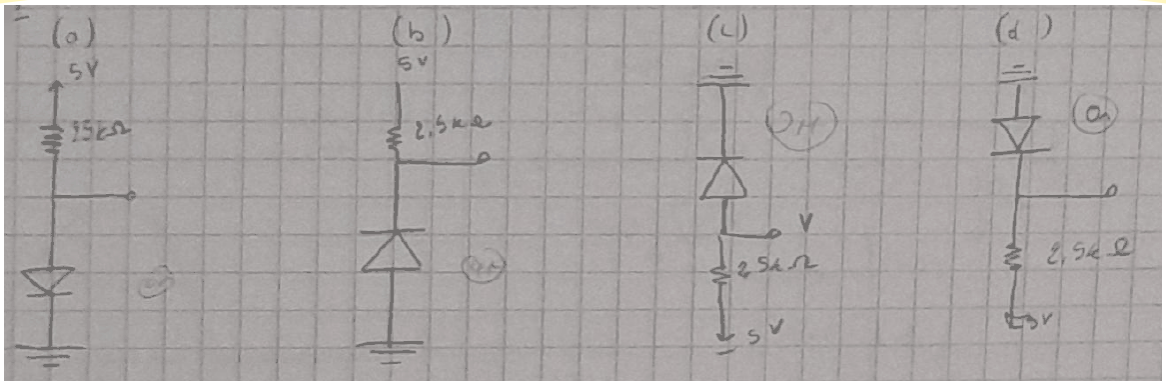
→



orijinal çizim, s. 18

$$I = \frac{20\,V}{15\,k} = 1{,}33\ mA$$

Exercise 4.6 (sf. 183)

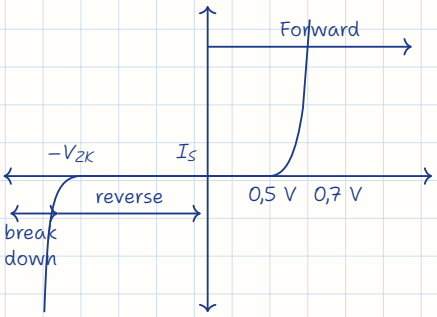


orijinal çizim, s. 18

(Fotoğrafın sağ kenarında bir sonraki sayfanın yarısı da görünüyor; içeriği s. 19'da aktarılmıştır.)

orj. s. 19

4.2 Terminal Characteristics of Junction Diodes



The Forward-Bias Region

$$i = I_S\left(e^{v/V_T} - 1\right)$$



$$i \simeq I_S e^{v/V_T} \qquad V = V_T \ln\frac{i}{I_S}$$

(Solda küçük bir not: "? iki değerin", iki akım için ok.)

$$I_1 = I_S e^{V_1/V_T}$$
$$I_2 = I_S e^{V_2/V_T}$$

$$\frac{I_2}{I_1} = e^{(V_2 - V_1)/V_T}$$

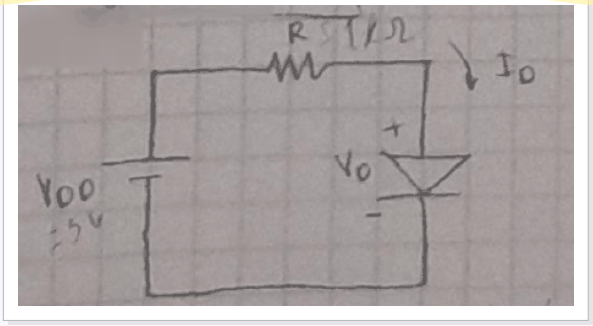
$$V_2 - V_1 = V_T \ln\frac{I_2}{I_1}$$

$$V_2 - V_1 = (\ln 10\ V_T)\log\frac{I_2}{I_1} = \underbrace{(2{,}3\ V_T)}_{60\ \text{mV}}\log\frac{I_2}{I_1}$$

(Soluk, küçük not: "? Wafer, IC process, IC package".)

$i \simeq -I_S$ → Reverse Region

Örnek 4.4



orijinal çizim, s. 19

The diode current is 1 mA @ 0,7 V

Çözüm:

ideal diyot modeli

$V_D = 0$ V

$I_D = \dfrac{5-0}{1} = 5$ mA

constant Voltage drop model (sabit gerilim düşümü modeli)

$V_D = 0{,}7$ V

$I_D = \dfrac{5-0{,}7}{1} = 4{,}3$ mA

orj. s. 20

Exponential model

$$I_D = \frac{V_{DD} - V_D}{R} \quad ① \qquad V_2 - V_1 = 2{,}3\, V_T \log \frac{I_2}{I_1} \quad ②$$

$$I_D = \frac{5-0{,}7}{1} = 4{,}3 \text{ mA}$$

$$V_2 = V_1 + 0{,}06 \log \frac{I_2}{I_1} \implies V_2 = 0{,}738 \text{ (V)}$$

$V_1 = 0{,}7$ V, $I_1 = 1$ mA (ok ile I_1'e), $I_2 = 4{,}3$ mA

Iteration 2nd

$$I_D = \frac{5-0{,}738}{1} = \boxed{4{,}262 \text{ mA}}$$

$$V_2 = 0{,}738 + 0{,}06 \left[\frac{4{,}262}{4{,}3}\right]$$

$$= \boxed{0{,}738 \text{ V}}$$

[2] (Sağda, $V_2 = 0{,}738$ sonucundan kavisli bir çizgiyle bağlanmış not:) "Virgülden sonra 3 basamak aynı olduğundan iterasyonu durduruz"

[2] Claude notu: muhtemelen $0{,}06 \log\left[\frac{4{,}262}{4{,}3}\right]$ olmalı (sonuç ≈ 0,738 V).