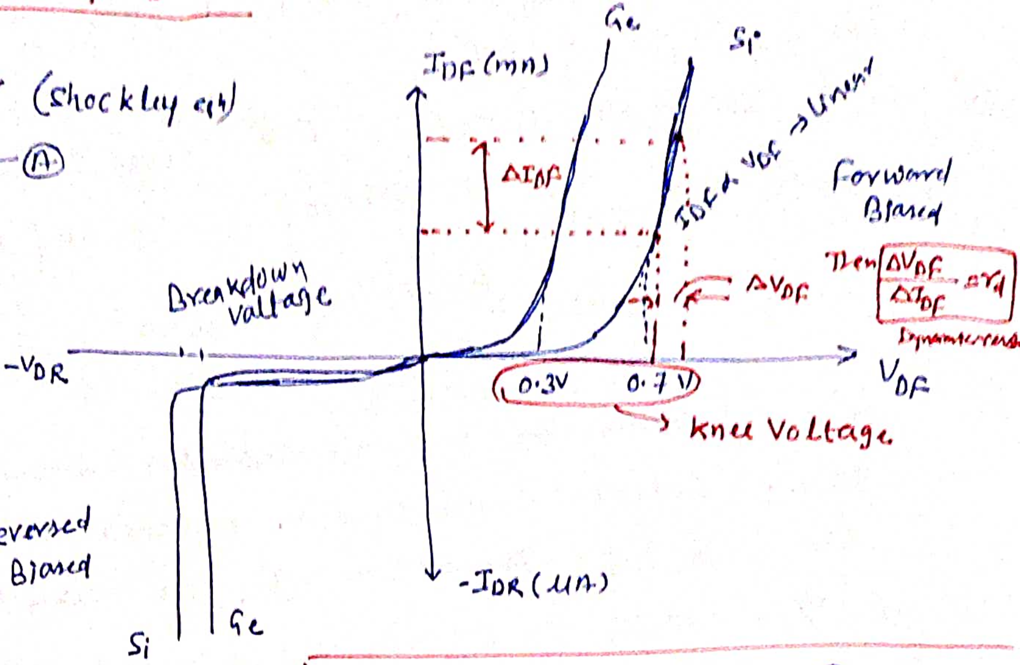
Voltage - current characteristics of Diode

The diode current equation — or (Shockley eqn)

$$I_D = I_0\left[e^{V_D/\eta V_T} - 1\right] \quad \text{— (A)}$$



where
- $I_D \to$ Diode current (mA)
- $I_0 \to$ Reverse saturation current (uA)
- $V_D \to$ Voltage across Diode
- $\eta \to$ constant $1 \to Ge$, $2 \to Si$
- $V_T \to$ Temp. dependent voltage

so $V_T = \frac{KT}{q} = \frac{T}{11600}$

where $K \to$ Boltzman's constant $= 1.38 \times 10^{-23}$

$T \to$ Temp. in kelvin

so at $T = 27°c = 300\,K$, $V_T = 26\,mV$

For forward Biased

$I_D = I_{DF}$, $V_D = V_{DF}$ then

$$\boxed{I_{DF} = I_0\left[e^{V_{DF}/\eta V_T} - 1\right]} \quad \text{— (B)}$$

For Reversed Biased

$I_D = I_{DR}$, $V_D = -V_{DR}$ then

$$\boxed{I_{DR} = I_0\left[e^{-V_{DR}/\eta V_T} - 1\right]} \quad \text{— (C)}$$

$I_{DR} \to$ Negative. $\Rightarrow$ flow of current in opposite direction

Junction Voltage from eqn (A)

$\frac{I_D}{I_0} = e^{V_D/\eta V_T} - 1$

or $1 + \left(\frac{I_D}{I_0}\right) = e^{V_D/\eta V_T}$

Taking log at base e

$\ln 1 + \ln(I_D/I_0) = V_D/\eta V_T$

or $\boxed{V_D = \eta V_T \cdot \ln(I_D/I_0)}$

$\because \ln 1 = 0$

Junction Temp. effects :

For Reverse biased $\Rightarrow$ If I_0 (reverse saturation current) at T_1 Temp ~~and~~ then ~~Temp~~ $I_{0\,new}$ at T_2 i.e

$$\boxed{I_{0(T_2)} = I_{0(T_1)}\left[2^{(T_2 - T_1)/10}\right]} \quad \text{— (D)}$$

NOTE
i.e I_0 approximately doubles for each $10°c$ rise in temp.

For Forward Biased $\Rightarrow$

The Temp coeff. for forward voltage of P-N Junction $\to -1.8\,mV/°c$ for Si, $\to -2.02\,mV/°c$ for Ge

so as a figure at every $°c$ rise in temp. the forward voltage drop of P-N Junction is $\underline{-2\,mV/°c}$.

(1) Determine reverse saturation current at 35°C and 45°C for a Junction which has $I_0 = 30\,nA$ at 25°C. ideal (In

Sol^n Given $I_0 = 30\,nA$, $T_1 = 25°C$, find $I_{0(35°C)}$ and $I_{0(45°C)}$

$$I_{0(35°C)} = I_{0(25°C)}\left[2^{(35-25)/10}\right] = 30\,nA\left[2^1\right] = \underline{\underline{60\,nA}}$$

$$I_{0(45°C)} = I_{0(25°C)}\left[2^{(45-25)/10}\right] = 30\,nA(4) = \underline{\underline{120\,nA}}$$

(2) A Si PN Junction has a reverse saturation current of $I_0 = 30\,nA$ at Temp of 300 K. Calculate the Junction current when the applied Voltage is (a) 0.7 V forward Bias (b) 10 V reverse bias.

Sol^n (a) $V_{DF} = 0.7\,V$, $I_0 = 30\,nA$, $T = 300\,K$

Then $I_{DF} = I_0\left[e^{V_{DF}/\eta V_T} - 1\right]$, $\eta = 2$ {Si}

$$= 30\,nA\left[e^{0.7/2\times V_T} - 1\right]$$

But $V_T = \frac{T}{11600} = \frac{300}{11600} = 26\,mV$

$$I_{DF} = 30\times10^{-9}\left[e^{\frac{0.7}{2\times26\times10^{-3}}} - 1\right] = 30\times10^{-9}\left[e^{13.46} - 1\right] = \underline{\underline{21\,mA}}$$

(b) $$I_{DF} = 30\times10^{-9}\left[e^{-\frac{10}{2\times26\times10^{-3}}} - 1\right] = 30\times10^{-9}\left[e^{-192} - 1\right] = \underline{\underline{-30\,nA}}$$

Diode specification

(1) **Peak Inverse Voltage (PIV) or Peak reverse Voltage (PRV)** ⇒ Maximum reverse Voltage that may be applied across the diode., Beyond this voltage diode will be damaged.

(2) ~~Forward Saturat~~
Steady state forward current ⇒ The maximum current that may be passed continously through the diode.

(3) **Reverse breakdown Voltage** ⇒ The maximum voltage when diode is connected in reverse bias, after which avalanch breakdown takes place

Numericals Based on Diode Current Equation:-

$$I_{DF} = I_0\left(e^{V_{DF}/\eta V_T} - 1\right)$$
$$I_{DR} = I_0\left(e^{-V_{DR}/\eta V_T} - 1\right)$$

where $I_0 \rightarrow$ reverse saturation current at room Temp. i.e $27°C$ or $300K$

V_T = Thermal Voltage $= \frac{T}{11600}$

V_T at room Temp $= 26\,mV$

η = identical const $\eta = 1 \Rightarrow Ge$, $\eta = 2 \Rightarrow Si$

Q1. Calculate reverse saturation current of a diode if the current at 0.2V forward bias is 0.1 mA at a Temp. 25°C and identical factor is 1.5.

Given- $I_0 = ?$

V_{DF} = Forward Bias Voltage = 0.2V

I_{DF} = forward Biased diode current = 0.1 mA = 0.1×10^{-3} A

Temp. = 25°C = 25+273 = 298 Kelvin

$$V_T = \frac{T}{11600} = \frac{298}{11600} = 0.0257 \text{ Volt}$$

$\eta = 1.5$

The Diode eqn for forward Biased- $I_{DF} = I_0\left(e^{V_{DF}/\eta V_T} - 1\right)$

or
$$I_0 = \frac{I_{DF}}{\left[e^{V_{DF}/\eta V_T} - 1\right]} = \frac{0.1\times10^{-3}}{\left[e^{\left(\frac{0.2}{1.5 * 0.0257}\right)} - 1\right]} = \frac{0.1\times10^{-3}}{\left[e^{5.190} - 1\right]}$$

(ln Base)

$$I_0 = \frac{0.1\times10^{-3}}{(179.122055 - 1)} = 5.619\times10^{-4}\times10^{-3}\text{ A}$$

$$\Rightarrow \boxed{I_0 = 5.619\times10^{-7}\text{ A}}$$

Q2. If current of a diode changes from 1 mA to 10 mA, what will be the change in voltage across the diode, $\eta = 1.2$

$$I_{DF_1} = I_0\left(e^{V_{DF_1}/\eta V_T} - 1\right) \Rightarrow \frac{I_{DF_2}}{I_{DF_1}} = \frac{e^{V_{DF_2}/\eta V_T} - 1}{e^{V_{DF_1}/\eta V_T} - 1}$$
$$I_{DF_2} = I_0\left(e^{V_{DF_2}/\eta V_T} - 1\right)$$

Take ln -

$$\ln\left(\frac{I_{DF_2}}{I_{DF_1}}\right) = \frac{\ln(A)}{\ln(B)} = \ln[A - B] = \ln\left[e^{V_{DF_2}/\eta V_T} - e^{V_{DF_1}/\eta V_T}\right]$$

$$\ln\left(\frac{I_{DF_2}}{I_{DF_1}}\right) = \ln\left(e^{V_{DF_2}/\eta V_T - V_{DF_1}/\eta V_T}\right)$$

$$= \frac{V_{DF_2}}{\eta V_T} - \frac{V_{DF_1}}{\eta V_T} = \frac{\Delta V}{\eta V_T}$$

$$\Delta V = \eta V_T \ln\left(\frac{I_{DF_2}}{I_{DF_1}}\right) = 1.5 * 26\times10^{-3} \ln\left(\frac{10\times10^{-3}}{1\times10^{-3}}\right) = 0.0718\,V$$

Q3 A Ge diode is operating at a Temp. 25 °C with reverse saturation current of 1000μA. calculate the value of forward current if it is forward biased by 0.22 V.

Given ⇒ $T = 25°C = 25 + 273 = 298$ kelvin, $\eta = 1$

$I_{o\,25°C} = 1000\mu A$, ① I_o at room temp $= ?$

② find $I_{DF} = ?$, when $V_{DF} = 0.22V$,

I_o at room temp i.e 27°C $= I_{o\,at\,25°C}\left(2^{(T_2 - T_1)/10}\right)$

$= 1000\mu A \left[2^{(27-25)/10}\right]$

$= 1000 * 1.1487$

$\boxed{I_o \text{ at } 27°C = 1148.698\mu A}$

$I_{DF} = I_{o\,\text{at room Temp}}\left(e^{V_{DF}/\eta V_T} - 1\right)$

$= 1148.698\left[e^{\left(\frac{0.22}{1 * 26\times10^{-3}}\right)} - 1\right] = 1148.698\mu A\left[4729.328 - 1\right]$

$I_{DF} = 5431421.254\,\mu A \approx \underline{5.43\ A}$

MOST important Questions for 2-marks.

Submission Date: 8/0?/23 (For your lab internal marks evaluation)

① why si diode is preffered Ge.

② what do you mean by doping? why it is required?

③ why Bridge type full wave rectifier is preferred over center tapped full wave rectifier. State two ~~key~~ reasons.

④ what is difference between avalanch and zener breakdown in P-N Junction diode.

⑤ why Temperature coefficient of resistance of a semiconductor is negative.

⑥ Explain breakdown and knee voltage with its value for Si & Ge.

⑦ The reverse saturation current of a silicon diode is 5 mA at room Temperature. find the diode current at 60 °c and a forward voltage of 0.5 V.

⑧ Discuss the formation of depletion ~~diode~~ layer in diode.

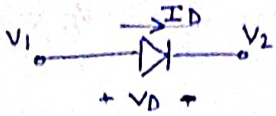
⑨ Explain the effect of Temperature on diode.

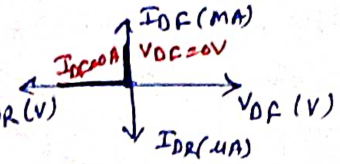
2, 7, 15, 33
35, 46, 47, ~~49~~,
Sub. 60, 62, ~~65~~, 66

Times 25, 27, 28, 39, 56, 58, 63,

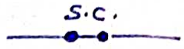
5, 15, 20, 23,
~~35~~, 38, 40, 44,
45, 54, 58,
59, 60, 62,
65, 66, (68 sub)

Ideal Diode



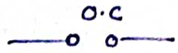


In Forward Biased

If $V_D > 0V$ or $V_1 - V_2 > 0V \Rightarrow V_1 > V_2 \longrightarrow$ ON Condition $\Rightarrow$ 

Then V_D = Voltage across Diode = 0, current through Diode (I_D) = maximum.

In Reverse Biased

If $V_1 - V_2 < 0V$ then $V_1 < V_2 \Longrightarrow$ OFF Condition = 

Then V_D (Voltage Across Diode) = maximum, I_D (Current through diode) = 0A

So in Ideal case it work as Automatic switch.

Practical diodes.

For Ge Diode

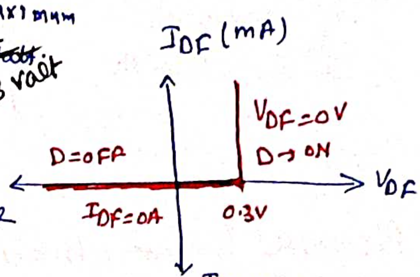
Knee Voltage = 0.3V

If $V_1 - V_2 > 0.3$ Volt, then Diode is ON. $\Rightarrow$ I_{DF} = Maximum, V_{DF} = ~~0 Volt~~ 0.3 Volt

If $V_1 - V_2 < 0.3$ Volt, then Diode is OFF

$I_{DF} = 0A$

V_{DF} = max.

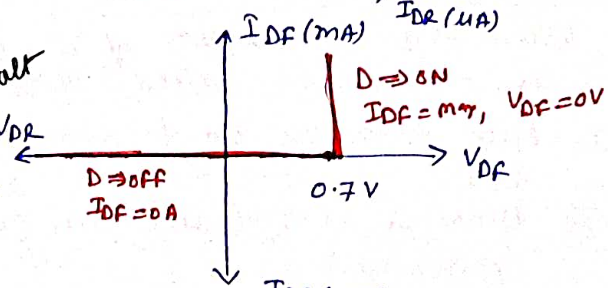


For Si diode

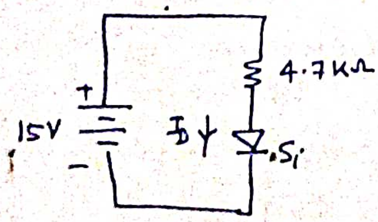
Knee Voltage = 0.7 Volt

If $V_1 - V_2 > 0.7$ V $\Rightarrow$ Diode → ON, I_{DF} → max, V_{DF} = 0.7 Volt

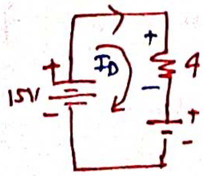
If $V_1 - V_2 < 0.7$ V $\Rightarrow$ Diode → OFF $\Rightarrow$ V_{DF} → max, I_{DF} = 0 A



Example. A Si diode is used in ckt as shown in fig. Calculate diode current



$\Rightarrow$



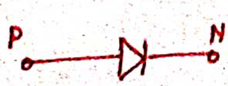
0.7 when Diode is Forward Bias then Voltage Across diode is 0.7V. and in Reverse biased work as open circuit so diode current is 0A.

Accor. to KVL.

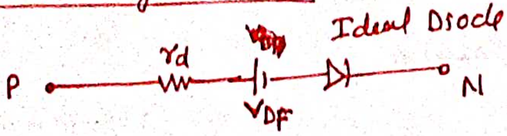
$$15 - I_D * 4.7\times10^3 - 0.7 = 0$$

$$I_D = \frac{15-0.7}{4.7\times10^3} = 3.04 \text{ mA}$$

Piecewise linear equivalent circuit of Diode



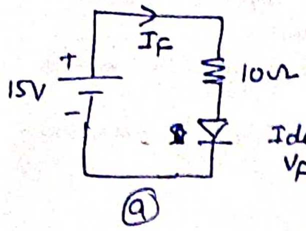
$\Longrightarrow$

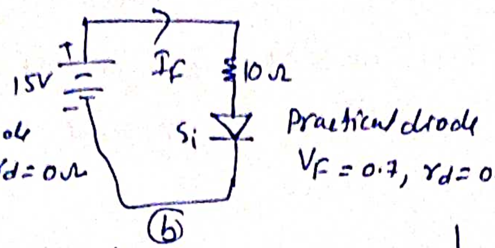


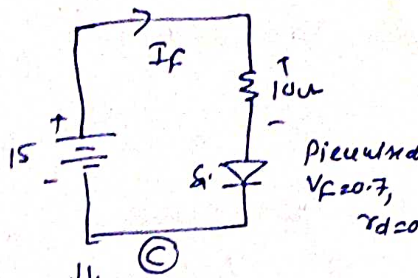
$r_d \rightarrow$ Diode Forward resistance

$V_{DF} \rightarrow$ Voltage Across Diode when Forward Bias.

Eg: Calculate I_F for the diode ckt assume diode has $V_F = 0.7V$, and $r_d = 0\Omega$. Recalculate when ~~$r_d = 0.025\Omega$~~. $r_d = 0.025\Omega$.

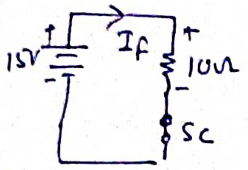






For Fig. (a)

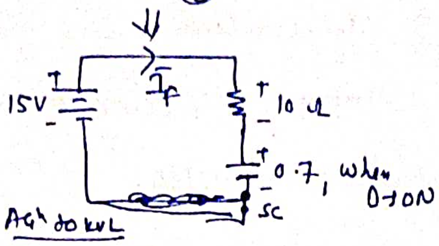
~~when~~ In forward Biased Diode is ON then work as a wire



Acc^n to KVL

$15 - I_F \times 10 = 0$

$I_F = \frac{15}{10} = 1.5A$.

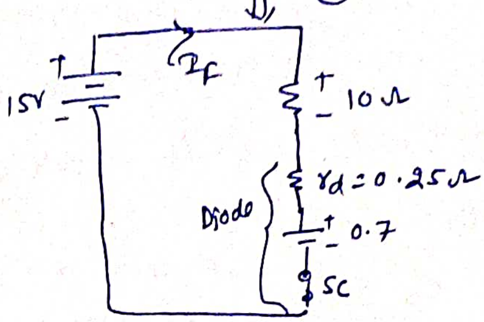


Acc^n to KVL

$15 - I_F \times 10 - 0.7 = 0$

$I_F = \frac{15 - 0.7}{10}$

$I_F = 80mA$



Acc^n to KVL

$15 - 10I_F - 0.25I_F - 0.7 = 0$

$I_F = \frac{15 - 0.7}{10 + 0.25} = 78mA$

Piecewise linear chracteristics

When F.B. chracteristics of a diode is not available then a straight line approximation called Piecewise linear chracteristics.

① First mark the ~~forward~~ forward Valtage (V_{DF}) (0.3 for Ge, and 0.7 for Si) on Horizental axis.

② Draw a stright line from (V_{DF}) point with a slope of the diode dynamic resistance.

Eg: Construct Piecewise linear chracteristics for Si diode, which has a 0.25Ω dynamic resistance and 200 mA max^m forward current.

Sol^n: $V_{DF} = 0.7$ because diode is made by Si

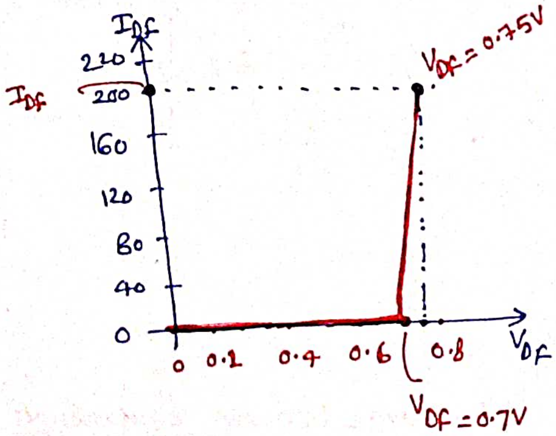
Then dynamic resistance (r_d) $= \frac{\Delta V_{DF}}{\Delta I_{DF}}$

so $\Delta V_{DF} = r_d * \Delta I_{DF} = 0.25\Omega * 200 \times 10^{-3}$

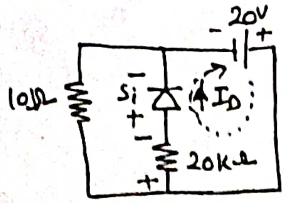
$\Delta V_{DF} = 0.05V \Rightarrow$ change in ΔV_{DF}

so $\Delta V_{DF(new)} \Big|_{at\ \Delta I_{DF} = 200mA} = V_{DF} + \Delta V_{DF} = 0.7 + 0.05$

$= 0.75V$



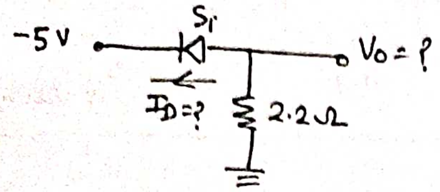
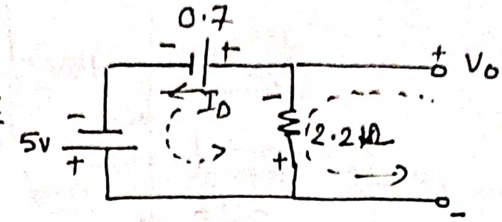
Numericals

① 

Find out $I_D = ?$

Apply KVL ⇒ $-20V + 20\times10^3 \times I_D + 0.7V = 0$

$$I_D = \frac{19.3}{20\times10^3} = \underline{0.96A}$$

②  $\equiv$ 

Apply KVL in Outer loop.

$V_o = I_D * 2.2\Omega$ — ①

Apply KVL in inner loop –

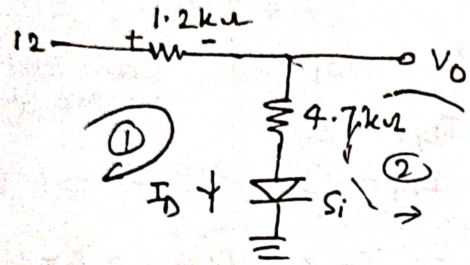
$0.7V - 5V - 2.2\Omega * I_D = 0$

$-4.3 - V_o = 0$

$$\boxed{V_o = -4.3V}$$

and $I_D = \frac{V_o}{2.2\Omega} = \frac{-4.3}{2.3\Omega}$

$$\boxed{I_D = -1.95A}$$

③ 

KVL in loop-①

$12 - 1.2k\Omega\, I_D - 4.7k\Omega\, I_D - 0.7 = 0$

$I_D = \frac{11.3}{5.9\times10^3} = 1.9\,mA$,

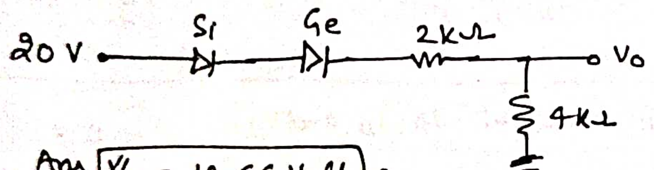
For V_o KVL in loop-②

$V_o = I_D * 4.7k\Omega + 0.7$

$= 1.9\times10^{-3} * 4.7\times10^3 + 0.7$

$V_o = 8.93 + 0.7$

$$\boxed{V_o = 9.63V}$$

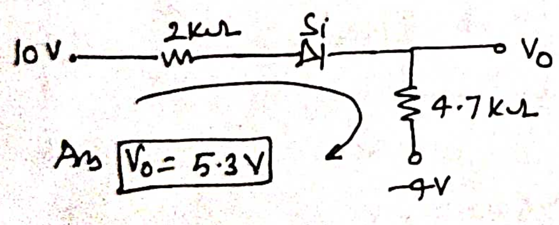
④ 

Ans $\boxed{\cancel{V}_o = 12.66\ Volt}$ ✗

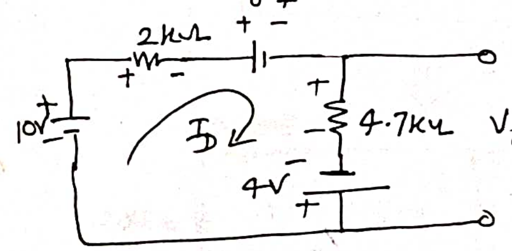
$20 - 0.7 - 0.3 - I(6k\Omega) = 0$

$I = \frac{19}{6k\Omega}$

$V_o = \cancel{4k\Omega * \frac{19}{6k\Omega}}$ 6 0.7

⑤ 

Ans $\boxed{V_o = 5.3V}$

⇒ 

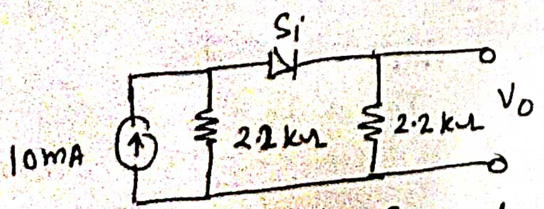
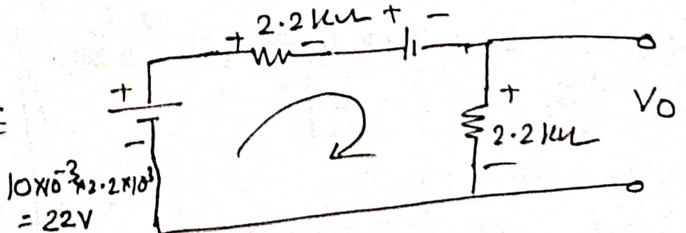
$V_o = I_D * 4.7k\Omega - 4$

$-10 + 2\times10^3 I_D + 0.7 + \underbrace{4.7\times10^3 I_D - 4}_{V_o} = 0$

$I_D = \frac{14 - 0.7}{6.7\times10^3} = \frac{13.3}{6.7\times10^3} = \underline{1.98\,mA}$

and $V_o = 4.7\times10^3 * 1.98\times10^{-3} - 4$

$$\boxed{V_o = 9.306 - 4 = 5.306}$$

⑥  = 

$10\times10^{-3} * 2.2\times10^3 = 22V$

Convert Current source into Voltage source –

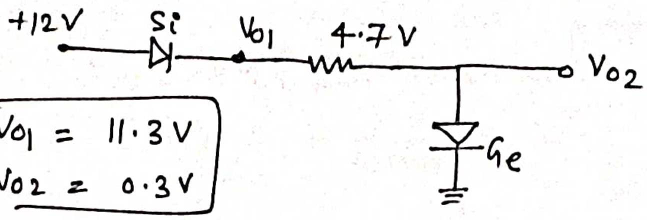
Appl KVL $-22 + 2.2\times10^3 \times I_D + 0.7 + 2.2\times10^3 I_D = 0$

$I_D = \frac{22 - 0.7}{4.4\times10^3} = \frac{21.9}{4.4\times10^3} = \underline{4.8\,mA}$

& $V_o = I_D * 2.2\times10^3$

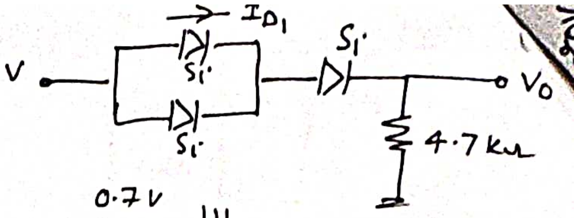
$= 4.8 \times 2.2 = \underline{10.65V}$

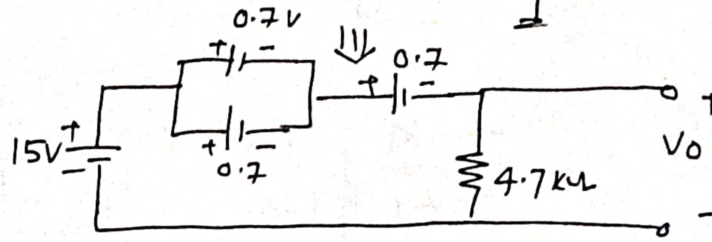
(7) +12V Si V_{o1} 4.7V V_{o2} Ge



$\boxed{V_{o1} = 11.3V \quad V_{o2} = 0.3V}$

(8) 15V Si Si Si 4.7kΩ Vo





Apply KVL

$15 - 0.7 - 0.7 - I_D * 4.7k\Omega = 0$

$I_D = \frac{13.6}{4.7 \times 10^3} = 2.8 mA$

But $I_D = I_{D1} + I_{D2}$, ~~am~~ both diodes are same

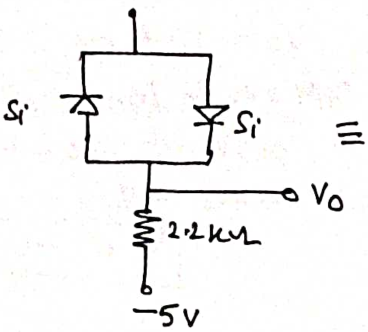
$2 I_{D1} = I_D$

$I_{D1} = \frac{I_D}{2} = \frac{2.8 mA}{2} = 1.6$ mA

$V_o = I_D \times 4.7k\Omega = 2.8 \times 4.7$ Volt

$\Rightarrow$ 13.16 Volt

(9) 15V Si Si Vo 2.2kΩ −5V



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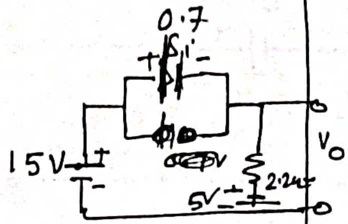


~~$V_o = 15V - 0.7$~~

~~$V_o = 14.3V$~~

KVL

$15 - 0.7 - V_o = 0$

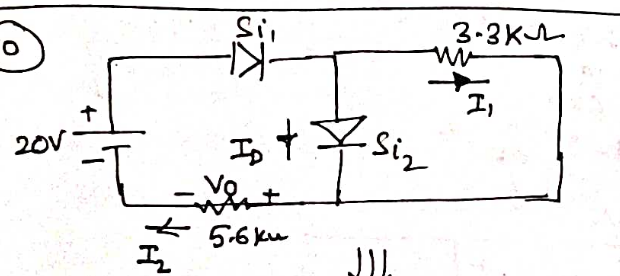
$\boxed{V_o = 14.3V}$

For I_D

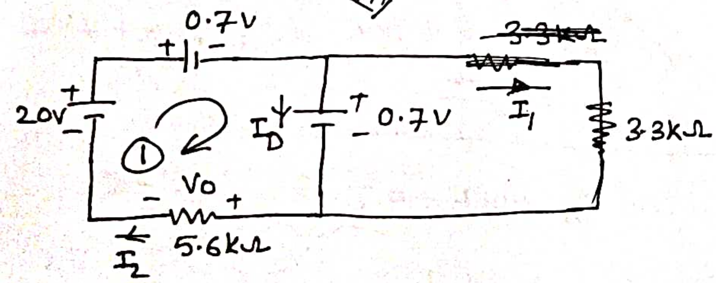
$V_o = I_D * 2.2k\Omega - 5V$

$I_D = \frac{V_o + 5}{2.2k} = \frac{14.3 + 5}{2.2k} = \frac{19.5}{2.2k} = 8.7mA$

(10)



⇓



Diode Si_2 ∥ 3.3kΩ, so Voltage drop across 3.3kΩ is ⇒ 0.7 Volt

ie $0.7 = I_1 * 3.3k\Omega \Rightarrow I_1 = \frac{0.7}{3.3k\Omega}$

$\boxed{I_1 = 0.212 mA}$

Apply KVL in loop (1)

$20 - 0.7 - 0.7 - I_2 * 5.6 \times 10^3 = 0$

$\boxed{I_2 = \frac{18.6}{5.6 \times 10^3} = 3.32 mA}$

$V_o = I_2 \times 5.6 \times 10^3 = 18.6$ Volt

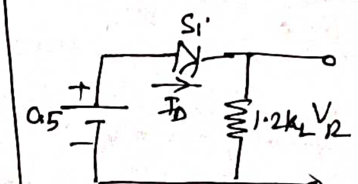
For I_D

$I_D + I_1 = I_2$

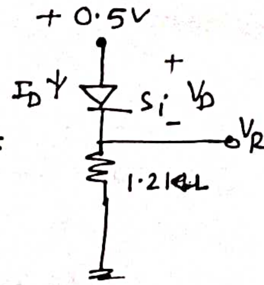
$I_D = I_2 - I_1 = (3.32 - 0.212)$

$\boxed{I_D = 3.11 mA}$

(11) Find out I_D, V_D, and V_R.



⇐



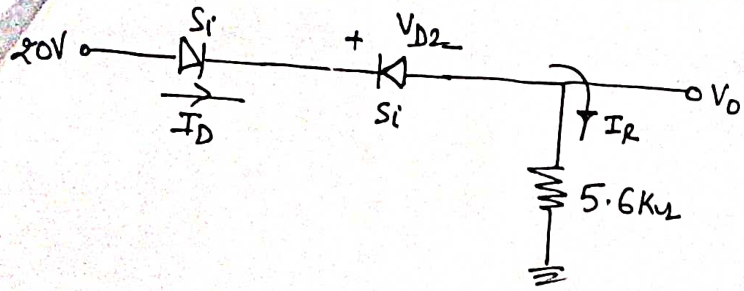
$V_D = 0.7$ V.

$0.5 - 0.7 - V_o = 0$

$V_o = -0.2 \simeq 0V$ { Diode is always off condition

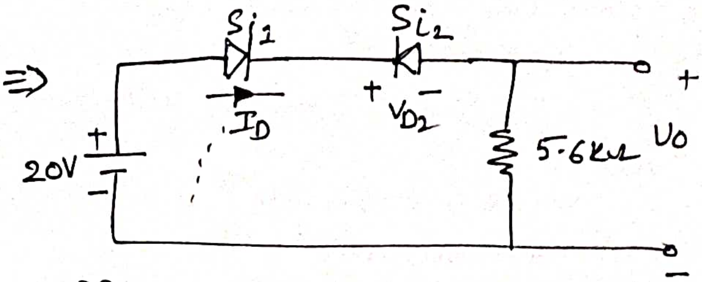
$I_D = 0A$

$\boxed{V_R = 0.5V}$



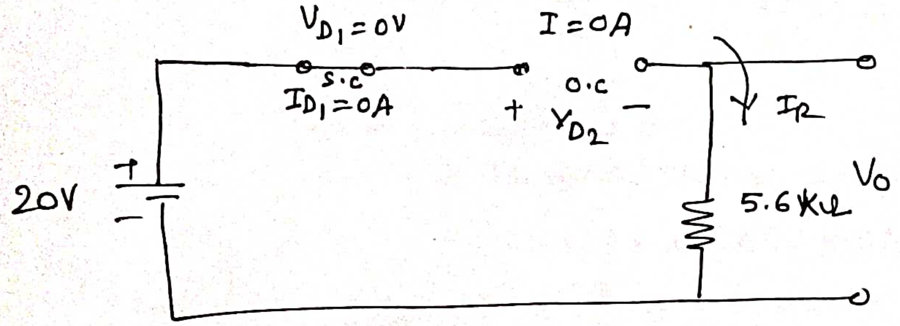
Find Out I_D, V_{D2}, and V_o.

⇒



Diode $Si_1 \rightarrow$ ON, But $Si_2 \rightarrow$ OFF, so series Combination is treated as open circuit. ie Current through Diodes ie $\boxed{I_D = 0A}$

ie $I_{D1} = I_{D2} = I_R = 0A$



ie $V_o = I_R * 5.6K\Omega$

$= I_D * 5.6k\Omega$

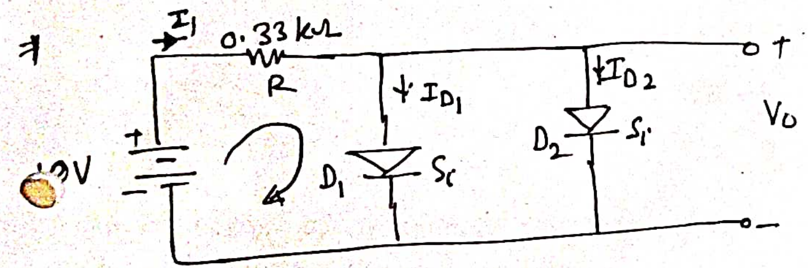
$\boxed{V_o = 0V}$ ∵ $I_D = 0A$

and $V_{D2} = V_{open\ Circuit} = E = 20V$

Apply. KVL ➡

$20 - V_{D1} - V_{D2} - V_o = 0$

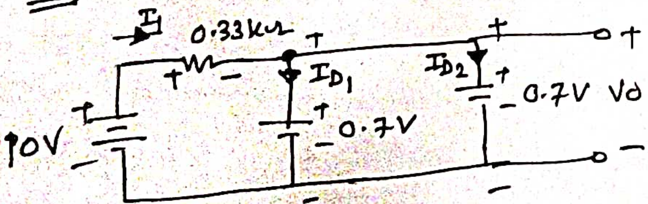
$\boxed{V_{D2} = 20 - 0 - 0V = 20V}$



Find Out V_o, I_1, I_{D1}, I_{D2}, and V_o

V_o = Voltage Across D_2 diode i.e.

$\boxed{V_o = 0.7V}$



For I_1, Apply Branch KVL

$10 - 0.33 \times 10^3 I_1 - 0.7 = 0$

$I_1 = \frac{10 - 0.7}{0.33 \times 10^3} = \underline{28.18 mA}$

For I_{D1} & I_{D2}

$I_1 = I_{D1} + I_{D2}$

But Both diodes are Same

$I_{D1} = I_{D2} = \frac{I_1}{2} = \frac{28.18 mA}{2}$

$= 14.09 mA$