Diodes

* Introduction to semi-conductors

• Silicon & Germanium are two types of semiconducting materials.
Both have 'four' valence electron.

• Intrinsic crystal is one that has no impurities.

• Doping is the process of adding impurities to intrinsic semiconducting materials to increase & control conductivity within the material.

→ n-type is formed by adding pentavalent (5 valence electrons) impurity atoms
eg:- Ph, As, Sb
-- electrons are called majority carriers in n-type material.
-- holes are minority carriers in n-type material.

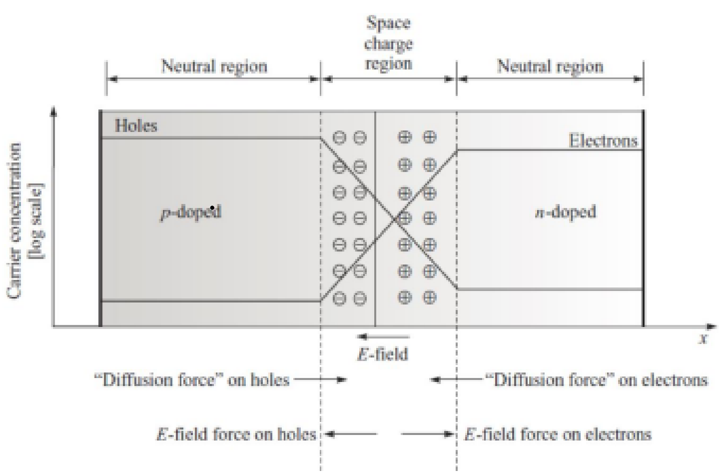
→ p-type material is formed by adding trivalent (3 valence e^-) impurity atoms
Eg:- B, Ga, In, Al
-- holes are called majority carriers in p-type material.
-- electrons are called minority carriers in p-type material.

★ P-N Junction

- It is formed by joining p-type & n-type semiconductors.
- 'Junction' refers to boundary interface where the two regions of the semiconductor meet
- It is created in a single crystal of semiconductor by doping by ion implementation / diffusion of dopants / epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant).

* p-n junc^n in thermal equilibrium: with zero bias voltage applied.

- The region nearby the p-n interfaces lose their neutrality and become charged, forming the space charge region or depletion layer.



- The electric field created by the space charge region opposes the diffusion process for both electrons & holes.

- There are two concurrent phenomena. the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion.

- The space charge region is a zone with a net charge provided by the fixed ions (donors or acceptors) that have been left uncovered by majority carrier diffusion
- When equilibrium is reached, the charge density is approximated by the displayed step funcⁿ.
- The region is completely depleted of majority carriers (leaving a charge density equal to the net doping level), and the edge between the space charge region is quite sharp.
- The space charge has the same charge on both sides of the p-n interfaces, thus it extends farther on the less doped side.

Energy band diagram of PN Junction (under equilibrium)

i) Depletion region width (W):

$$\boxed{W = \sqrt{\frac{2\epsilon_s}{q} V_{bi} \left(\frac{N_A + N_D}{N_A N_D}\right)} \quad \text{cm}}$$

ii) Build-in E-field ($E_{build\text{-}in}$)

$$\boxed{E_{build\text{-}in} = -\frac{2V_{bi}}{W} \quad \frac{V}{cm}}$$

rresponds

iii) Built-in potential (V_{bi})

$$\boxed{V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \quad \text{Volts}}$$

* Forward biasing of p-n junction

- External voltage applied to the junction in such a direction that it cancels the potential barrier, thus permitting current flow is called forward biasing.
- For this, connect +ve terminal of battery to p-type & −ve terminal to n-type.
- The applied forward potential establishes the electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junc^n.
- $\because$ the potential barrier voltage is small, a small forward voltage is sufficient to completely eliminate the barrier.
- Once the potential barrier is eliminated by the forward voltage, junc^n resistance becomes almost zero and a low resistance path is established for the entire circuit.

$\therefore$ current flows in the circuit. This is called forward current.

* Reverse biasing of p-n junction

- External voltage applied to the jun^c is in such a direction the potential barrier is increased it is called reverse biasing.
- For this, connect -ve terminal of the battery to p-type & +ve terminal to n-type.
- The applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant at the jun^c is strengthened & the barrier height is increased.
- The increased potential barrier prevents the flow of charge carrier across the jun^c. Thus, a high resistance path is established for the entire circuit & hence current does not flow.

* VI characteristics of P-N jun^c diode

* I-V relationship in a PN junc diode / diode eqn.

$$\boxed{I_D = I_s\left(e^{\frac{V_D}{\eta V_T}} - 1\right)}$$

↳ Shockley's eqn

↳ Diode current eqn

where, I_D is diode current in mA

V_D is applied diode voltage in volts

I_s is leakage or reverse saturation cur

η is ideality factor ($\eta_{Ge} = 1$ & $\eta_{Si} = 2$)

V_T is thermal voltage at $T = 300K$

$V_T = \frac{KT}{q} = \frac{T}{11600}$; $V_T = 26mV$, $T = 300K$

With zero voltage :-

$V_D = 0, \because I_D = I_s\left(e^{\frac{V_D}{\eta V_T}} - 1\right) = I_s\,(e^0 - 1) = 0$

Forward biased:-

$V_D > 0$

When $V_D >> \eta V_T$ then,

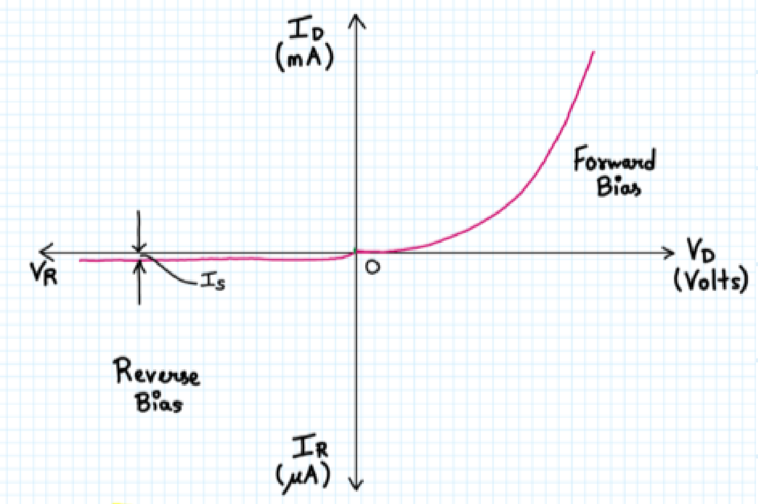
$e^{\frac{V_D}{\eta V_T}} >> 1$ & $I_D \cong I_s e^{\frac{V_D}{\eta V_T}}$

Reversed - biased:

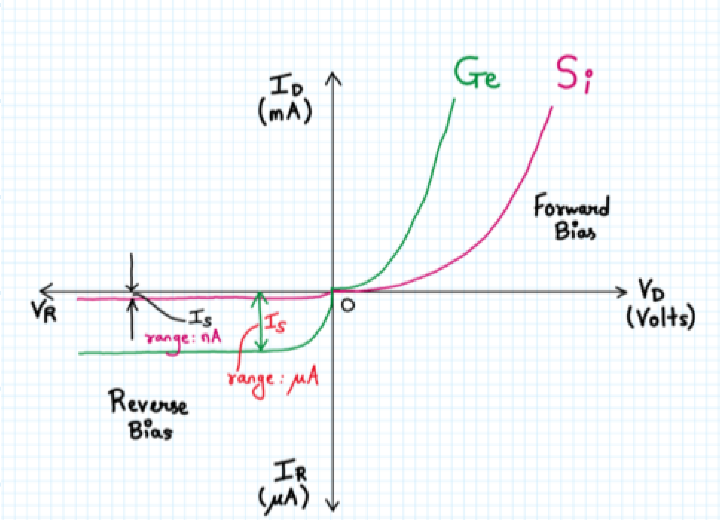
$V_D < 0$

When $V_D << \eta V_T$ then,

$e^{\frac{V_D}{\eta V_T}} << 1$ & $I_D \cong -I_s$ i.e. reverse current saturates to I_s in reverse direction.



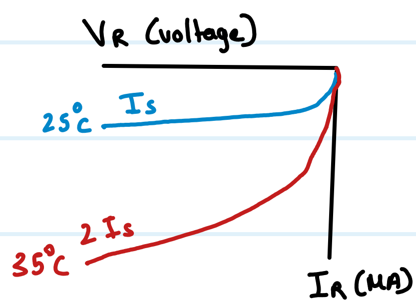
I-V characteristics of diode



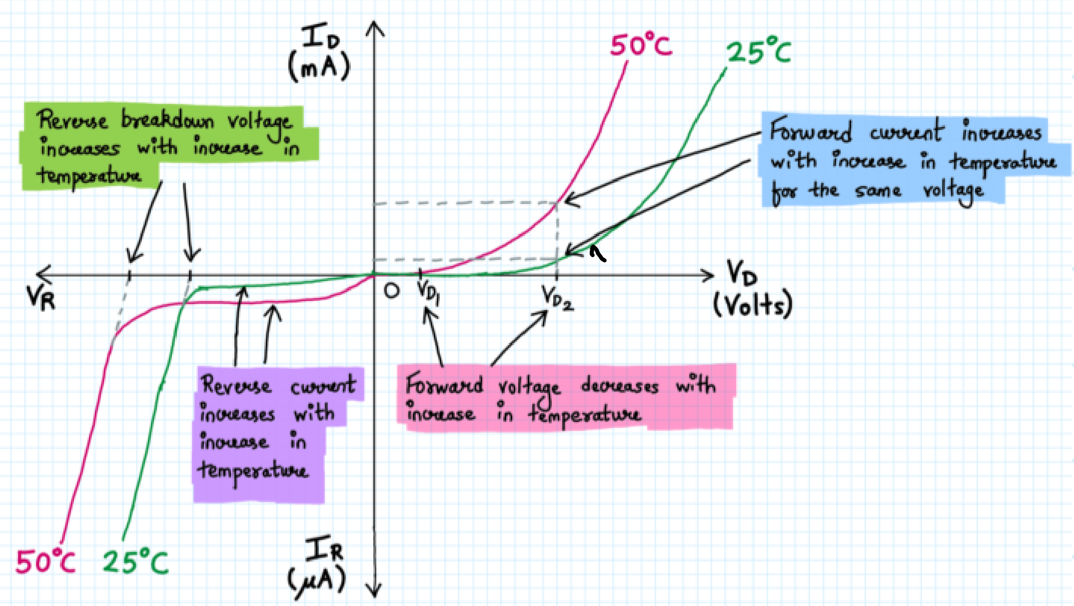
I-V characteristics of Si and Ge diode

* Temp dependence on diode I-V characteristics

- V_T & I_s in diode eqn are temp dependent terms.
- ↑ in temp results in ↑ thermal activity and ↓ diode resistance, which influences both the forward & reverse characteristics of diode.
- Diode forward voltage decreases by 2.5 mV per degree rise in temp.



- Reverse saturation current & breakdown voltage ↑ with ↑ in temp.
- Reverse saturation current gets doubled for every 10°C rise in temp



Effect of temperature on the diode characteristics

Q] * **Numerical 1**

Find the forward current in a Si diode at a forward voltage of 0.6V, reverse saturation current of 0.1 μA and temperature of 27°C $V_D = 0.6V$, $I_s = 0.1\mu A$, $V_T = 26mV$ $I_D = ?$

Now, if a reverse voltage of 10V is applied to the diode $\eta = Si = 2$

Find the reverse current flowing through the diode

→ Diode eqn is

$$I_D = I_s\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$$

$$T = 27^\circ C = 300\,K$$

For Si, $\eta = 2$ & $V_T \approx 26mV$ at $T = 27^\circ C$

$$\frac{V_D}{\eta V_T} = \frac{0.6}{2 \times 26\,mV} = x_1 = 11.53$$

$$I_D = 0.1 \times 10^{-6}\left(e^{11.53} - 1\right)$$

$$I_D = x_2 = 10.172\ mA$$

$\because I_D \approx x_2$ ...... Forward current in a Si diode

→ $V_D = -10V$;

$$I_D = I_s\left(e^{\frac{-10}{2 \times 26mV}} - 1\right)$$

$$I_D = I_s\,(x_3 - 1) \qquad e^{-192.30} \approx 0 \simeq x_3$$

$$\therefore I_D = -I_s = -0.1 \times 10^{-6}$$

$\therefore I_D = -0.1\mu A = x_4$ ...... reverse current in Si diode

Q] ## * Numerical 2

The reverse saturation current of a Ge diode at 27°C is 5μA

Find the forward voltage at which the current is 25 mA

→ Given,

$T = 27°C = 300K$, $I_S = 5 MA$, $I_D = 25 mA$, $\eta = 1$ (Ge), $V_T = 26mV$

$$I_D = I_s\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$$

$$I_D + I_s = I_s \, e^{\frac{V_D}{\eta V_T}}$$

$$e^{\frac{V_D}{\eta V_T}} = 1 + \frac{I_D}{I_s} = 1 + \frac{25 \times 10^{-3}}{5 \times 10^{-6}}$$

$$e^{\frac{V_D}{\eta V_T}} = 5001 = y_1$$

$$\frac{V_D}{\eta V_T} = \ln(5001) = 8.517$$

$$V_D = 8.517 \times 26 \times 10^{-3}$$

$V_D = 0.221 \ V$ .... Forward voltage of Ge diode

★ Diode Applications:-

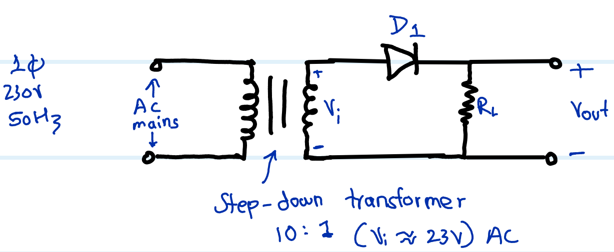
1] Rectifier

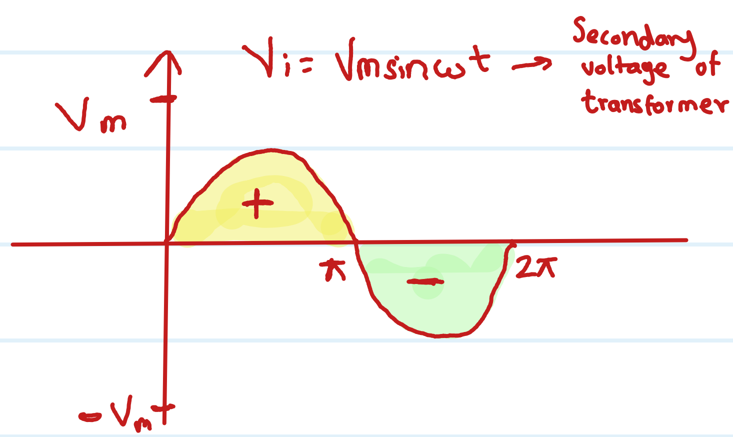
- Half wave rectifier
- Full wave center tap rectifier
- Full wave bridge rectifier

① ckt diagm
② working
③ I/p - o/p wrt time
④ Analysis:-
a) Vout (avg) { Iout avg }
b) Vout (rms) { Iout rms }
c) Rectification eff (η)
d) Ripple factor (r)
e) TUF

Half-wave Rectifier with 'R' load:

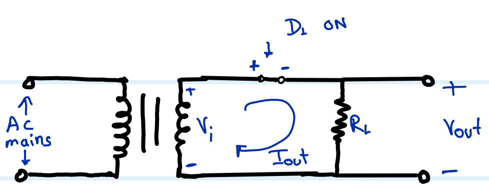
Circuit diagram:-





Case I: During +ve half cycle of $I_p(V_i)$

D_1 is F.B i.e ON



$V_{D_1} \approx 0$

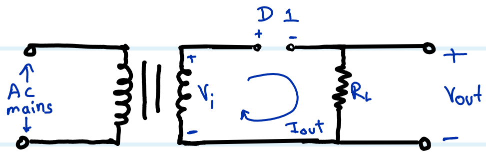
$V_{out} = V_i$

o/p follows ip voltage

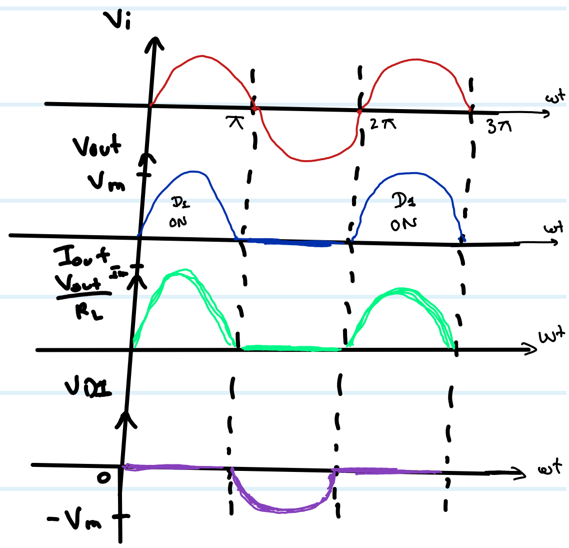
$I_{out} = \frac{V_{out}}{2}$

Case II : During -ve half cycle of I/p (V_i)

D_1 is R.B i.e OFF



$I_{out} = 0$
$V_{out} = 0$
$V_{D1} \neq 0$ ("PIV rating")



HWR I/P & O/P waveforms

Input - output w/fs:-

$$\boxed{\begin{aligned} V_{out} &= V_i \ (V_m \sin\omega t) && \text{if} \quad 0 < \omega t < \pi \\ &= 0 && \text{if} \quad \pi < \omega t < 2\pi \end{aligned}} \quad \text{—}(1)$$

Analysis :- HWR

a)
$$V_{out\,(avg)} = \frac{V_m}{\pi} \quad [\text{i.e. } V_{DC} = 0.318\, V_m]$$

$$I_{out\,(avg)} = \frac{I_m}{\pi}$$

b)
$$V_{out\,(rms)} = \frac{V_m}{2}, \quad I_{rms} = \frac{I_m}{2}$$

c)
Rectification efficiency (η) :⟶ It is ratio of DC power at the O/P to the applied I/P AC power

$$\% \eta = \frac{P_{DC}}{P_{AC}} \times 100$$

$$P_{DC} = V_{DC} I_{DC} = \frac{V_{DC}^2}{R_L} = I_{DC}^2 R_L$$

$$P_{AC} = V_{rms} I_{rms} = \frac{V_{rms}^2}{R_L} = I_{rms}^2 R_L$$

$$P_{DC} = \frac{V_{DC}^2}{R_L} = \frac{\left(\frac{V_m}{\pi}\right)^2}{R_L} = \frac{V_m^2}{\pi^2 R_L} \quad \ldots\ldots\ldots \text{ (a)}$$

$$P_{AC} = \frac{V_{rms}^2}{R_L} = \frac{\left(\frac{V_m}{2}\right)^2}{R_L} = \frac{V_m^2}{4R_L} \quad \ldots\ldots\ldots \text{ (b)}$$

$$\% \eta = \frac{P_{DC}}{P_{AC}} \times 100 = \frac{\frac{\cancel{V_m^2}}{\pi^2 \cancel{R_L}}}{\frac{\cancel{V_m^2}}{4 \cancel{R_L}}} \times 100$$

$$\% \eta = \frac{4}{\pi^2} \times 100$$

$$\boxed{\% \eta = 40.56 \%} \quad \text{HWR}$$

d) Ripple factor (r) : It is ratio of rms value of o/p AC component to the DC component of rectifier o/p

$$r = \frac{I_{AC}}{I_{DC}} \qquad I_{ac} = \sqrt{I^2_{out(rms)} - I_{dc}^2}$$

i.e. $$\frac{I_{ac}}{I_{dc}} = \sqrt{\frac{I_{rms}^2}{I_{dc}^2} - 1}$$

$$\therefore \quad r = \sqrt{\frac{I_{rms}^2}{I_{dc}^2} - 1}$$

For HWR, $I_{rms} = \frac{I_m}{2}$, $I_{dc} = \frac{I_m}{\pi}$

$$r = \sqrt{\frac{\frac{I_m^2}{4}}{\frac{I_m^2}{\pi^2}} - 1} = \sqrt{\frac{\pi^2}{4} - 1}$$

$$\boxed{r = 1.21} \quad \text{HWR}$$

e) Transformer ultization factor: TUF is a quantitative indication of the ulitization of VA rating of tronsformer. The more the value of TUF, the more will be the utilization. In other words, the VA rating of required transformer will be less if TUF is more & vice-versa

$$TUF = \frac{\text{DC Power Output}}{\text{Effective VA rating of transformer}} = \frac{P_{DC}}{\text{Effective VA rating of transformer}}$$

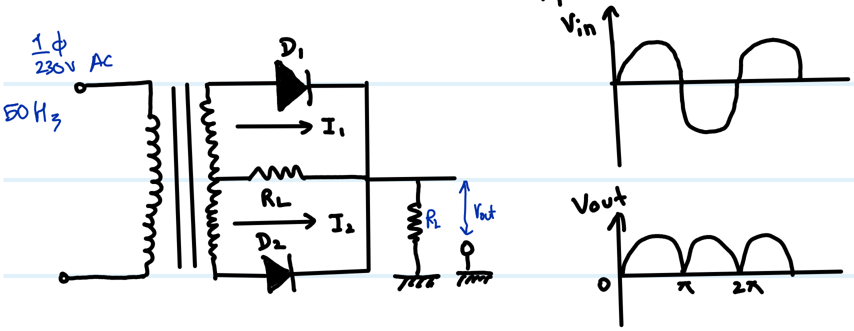
$$P_{DC} = I_{avg} \times V_{avg}$$

$$\therefore P_{DC} = \frac{V_m}{\pi} \times \frac{I_m}{\pi} \quad — ①$$

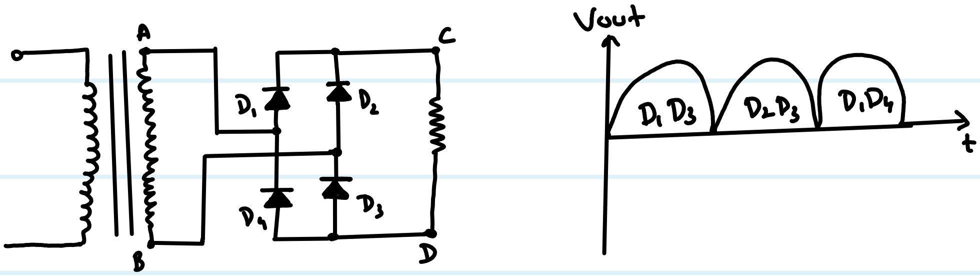
$$VA_{rating} = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{2} \quad — ②$$

$$\therefore TUF = \frac{P_{dc}}{VA} = \frac{2\sqrt{2}}{\pi^2} = 0.285$$

Full wave "Center tapped" rectifier with 'R' load.



Full wave Bridge Rectifier



① $$V_{out\,(avg)} = V_{dc} = \frac{2V_m}{\pi}$$

② $$I_{out\,(avg)} = \frac{V_{avg}}{R_L} = \frac{2I_m}{R_L}$$

③ $$V_{out\,(rms)} = \frac{V_m}{\sqrt{2}} \quad , \quad I_{rms} = \frac{I_m}{\sqrt{2}}$$

④ $$\eta = \frac{8}{\pi^2} \times 100 \approx 81.05\ \%$$

$$\eta_{FWR} > \eta_{HWR}$$

⑤ $$\text{Ripple factor } (\gamma) = \sqrt{\frac{\pi^2}{8} - 1} = \underset{FWCTR}{0.483} \qquad \gamma_{FWR} < \gamma_{HWR}$$

⑥

$TUF = 0.672$ FWCTR

$TUF = 0.816$ FWBR

∴ Comparisons of Rectifiers

Particulars	HWR	FWCTR	FWBR
① No. of diodes	1	2	4
② I_{dc}	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
③ V_{dc}	$\frac{V_m}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2V_m}{\pi}$
④ I_{rms}	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
⑤ η	40.6%	81.2%	81.2%
⑥ PIV	V_m	$2V_m$	V_m
⑦ Ripple factor	1.21	0.48	0.48
⑧ TUF	0.285	0.672	0.812