SGS-THOMSON MICROELECTRONICS

# APPLICATION NOTE

# PARALLEL OPERATION OF POWER RECTIFIERS

B. Rivet

## INTRODUCTION

In parallel operation of several diodes, the current is not split into equal parts because of differences between forward characteristics.
The current through the rectifier having the lowest voltage drop will be higher than the current through the other diodes.

On the other hand the temperature coefficient of the forward voltage is negative and therefore this unbalanced situation at switching ON can become worse up to a stable equilibrium state.

The designer has to be sure that at this final state the diodes operate below the maximum specified limits.

The aim of this study is to calculate the acceptable difference between forward voltage drops of diodes to be paralleled in a given application.

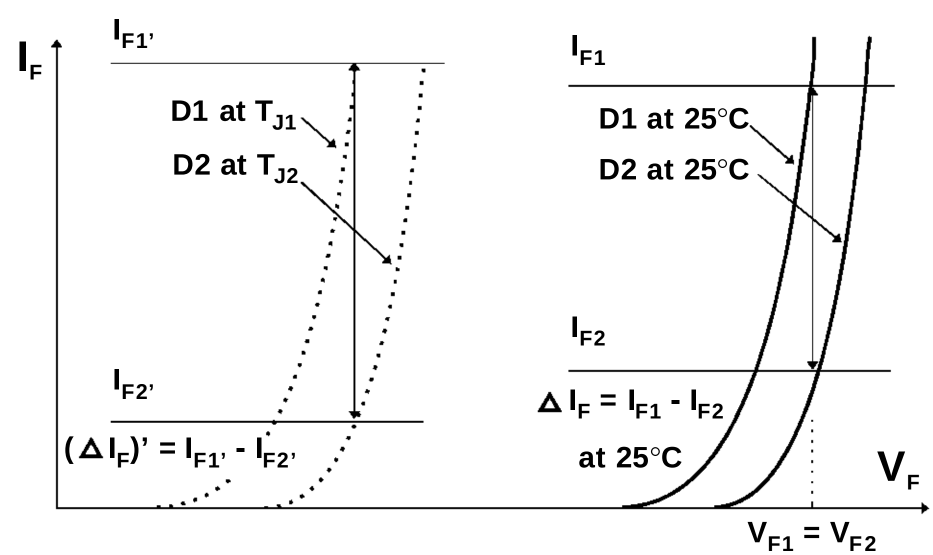
## I - QUALITATIVE ANALYSIS AND LIMITATIONS

Let's assume that we have two diodes D1 and D2 connected in parallel.
The forward characteristics of the two diodes at $T_{J1} = T_{J2} = 25°C$ are shown in fig.1.
The total current $I_T = I_{F1} + I_{F2}$ is not split into equal parts.

The thermal dissipation makes the difference $\Delta I_F = I_{F1} - I_{F2}$ increase.

Indeed, the current through D1 is higher than through $D_2$ so $T_{J1} > T_{J2}$ , and because the forward voltage has a negative temperature coefficient, the difference $\Delta I_F$ increases.

**Fig.1 :** Forward characteristics of two diodes D1 and D2 in parallel




at $T_{J1} = T_{J2} = 25°C$ ————

With $T_{J1} > T_{J2} > 25°C$ : $(\Delta IF)' > \Delta I_F$ -----------

For a safe and reliable operation it is absolutely necessary to remain within the maximum ratings of the devices :

1) $T_{J1}$ lower than the maximum junction temperature

2) Current through D1 compatible with the specified maximum RMS current.

## II - SIMPLIFIED FORWARD CHARACTERISTIC MODEL

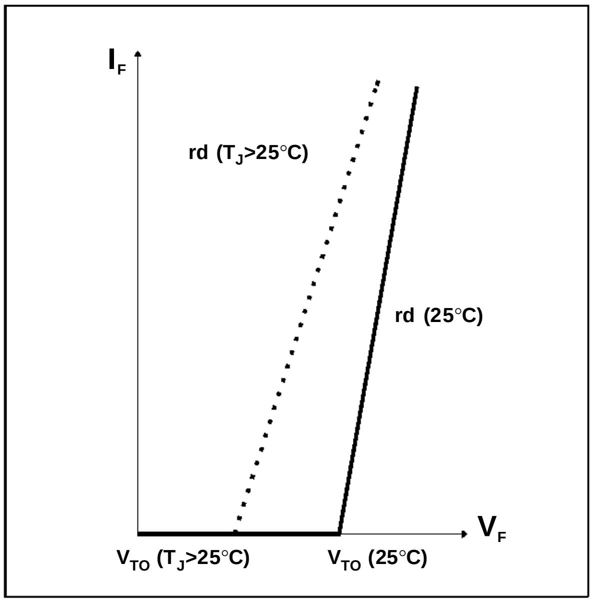
The forward characteristic of a diode may be assimilated to a straight line whose equation is :

$$V_F = V_{TO} + rd \times I_F \qquad \text{(fig.:2)}$$

$V_{TO}$ and rd act as a function of the temperature.

$V_{TO}$ has a negative temperature coefficient ($\alpha_{TO}$) and rd has a positive temperature coefficient ($\alpha$ rd).

**Fig.2 :** Forward characteristics model of rectifier versus temperature

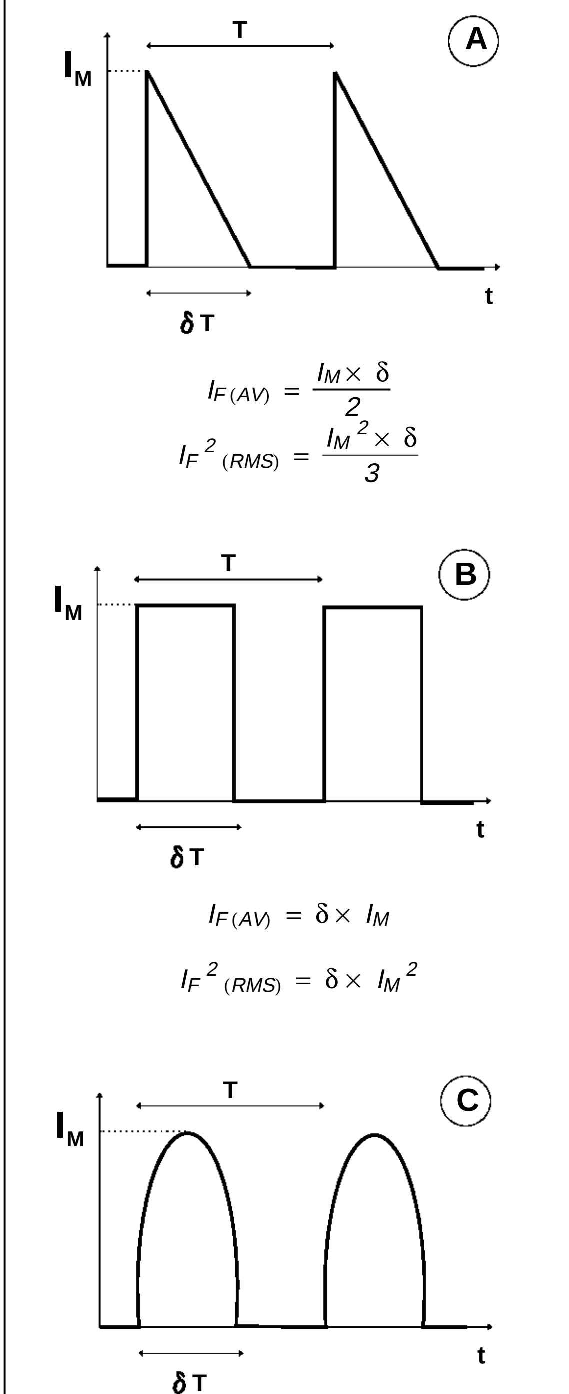



This model allows to easily calculate the operating point ($V_F$, $I_F$) of each diode and to evaluate the power losses due to the conduction.

$$P_{cond} = V_{TO} \times I_{F(AV)} + rd \times I_F{}^2{}_{(RMS)} \qquad (1)$$

In practice the waveforms of current can be assimilated to simple forms (rectangular, triangular, sinusoidal), so $I_{F(AV)}$ and $I_{F(RMS)}$ can be expressed with the peak current ($I_M$) and the duty cycle ($\delta$) (Figure 3)

**Fig.3 :** Average and RMS values for different currents wave forms




A:

$$I_{F(AV)} = \frac{I_M \times \delta}{2}$$

$$I_F{}^2{}_{(RMS)} = \frac{I_M{}^2 \times \delta}{3}$$

B:

$$I_{F(AV)} = \delta \times I_M$$

$$I_F{}^2{}_{(RMS)} = \delta \times I_M{}^2$$

C:

$$I_{F(AV)} = \frac{2 \times I_M \times \delta}{\pi}$$

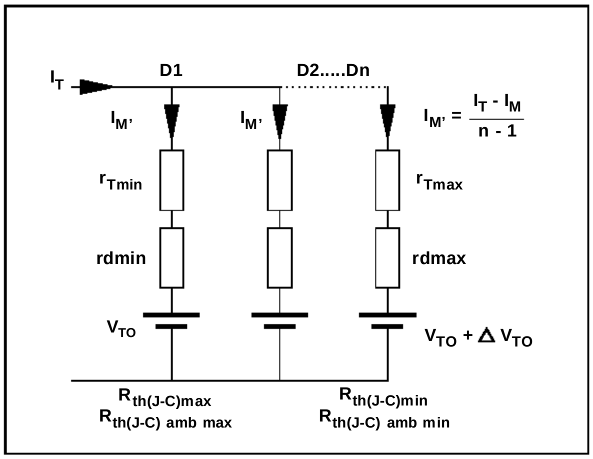
$$I_F{}^2{}_{(RMS)} = \frac{I_M{}^2 \times \delta}{2}$$

## III - OPERATING WITH SEVERAL DIODES IN PARALLEL

Taking into consideration the dispersion of both the diodes parameters as well as the circuit parameters, we can calculate the maximum difference between $V_F$ (measured at 25°C and at the nominal current specified for the device $I_F = I_{F(AV)}$) in order to be sure than no diode will operate out of its specification.

The calculation is based on the worst case situation (Figure 4) : we suppose that D1 has the lowest $V_{TO}$ and rd and the highest $R_{th(j-c)}$ and $T_{CASE}$. This diode supports the highest current $I_M$ and operates at the highest junction temperature.

**Fig.4 :** Worst configuration of several diodes in parallel




As a first step, we have to determine the maximum acceptable peak current ($I_M$) through D1 in these conditions.

### III.1. Thermal limitation : $I_{M1}$

The maximun total power dissipation in the diode is given by :

$$P_T = \frac{T_{J\,max} - T_{CASE\,(max)}}{R_{th\,(j-c)\,max} + R_{th\,(c)}*}$$

The total power dissipation is

$$P_T = P_{COND} + P_{COM}$$

$P_{COND}$ : conduction losses  $P_{COND} = \rho\, P_T$

$P_{COM}$ : commutation losses  $P_{COM} = (1-\rho)\, P_T$

For SCHOTTKY diodes, the commutation losses are negligible ( $\rho = 1$)

(*) Case of double diodes.
$R_{th(c)}$ : Coupling thermal resistance

We can write $P_{COND}$ versus $I_M$ for rectangular waveform :
(For the other waveforms see the annex).

$$P_{COND} = V_{TO}\,(100°C)\,\delta.I_M + rd\,(100°C)\,\delta.I_M^2$$

So

$$I_{M1} = \frac{-\,V_{TO}.\delta + [(V_{TO}.\delta)^2 + 4.P_{COND}.rd.\delta\,]^{+1/2}}{2\,.\,rd\,.\,\delta} \quad (2)$$

### III.2. $R_{MS}$ current limitation : $I_{M2}$

If $I_{F(RMS)}$ is the maximum RMS current specified in the data sheet, the limit in the case of a rectangular waveform will be :

$$I_{M2} = \frac{I_{F\,(RMS)}}{\sqrt{\delta}}$$

It is obvious that we will take the minimum value of $I_{M1}$ and $I_{M2}$

### III.3. Calculation of $\Delta V_F$

* THE DIODES PARAMETERS ARE :

| | |
|---|---|
| $\propto_{TO}$ | Temperature coefficient of $V_{TO}$ |
| $\propto_{rd}$ | Temperature coefficient of rd |
| $V_{TO}$ | Threshold voltage at $T_J$ = 25°C |
| rd | Dynamical resistance at $T_J$ = 25°C and its dispersion (rd min, rd max) |
| $R_{th(j-c)}$ | Junction to case thermal resistance and its dispersion $R_{th(j-c)min}$ , $R_{th(j-c)max}$. |
| $T_{Jmax}$ | max operating junction temperature |

* THE "APPLICATION" PARAMETERS ARE :

| | |
|---|---|
| $I_T$ | Peak current through the diodes and its waveform. |
| $\delta$ | Duty cycle |
| n | Number of diodes |
| $T_C$ | Case temperature and the dispersion $T_C$ min (coldest case) and $T_C$ max (hotest case) |
| $r_{t\,max}$<br>$r_{t\,min}$ | Min and max values of the resistances of wires and various connections. |

By solving electrical and thermal equations corresponding to the circuit of the fig.5 in the case of rectangular waveform , we find :

$$\Delta V_F < \frac{\Delta V_{F1} + \Delta V_{F2} + \Delta V_{F3} - \Delta V_{F4}}{\Delta}$$

**With**

$$\Delta V_{F1} = (r_T\ min + rd\ min)\ I_M - (r_T\ max + rd\ max)\ I_M'$$
$$\Delta V_{F2} = R_{th(j-c)\ max}\ (\alpha_{TO} + \alpha\ rd\ .\ I_M)\ .\ P1$$
$$\Delta V_{F3} = (\alpha_{TO} + \alpha\ rd\ .\ I_M)\ .\ (T_{C\ max} - T_{C\ min})$$
$$\Delta V_{F4} = R_{th(j-c)\ min}\ .\ (\alpha_{TO} + \alpha\ rd\ .\ I_M')\ .\ P2$$
$$\Delta = 1 + R_{th(j-c)\ min}\ [\alpha_{TO} + rd\ .\ I_M']\ \delta\ .\ I_M'$$
$$P_1 = \frac{V_{TO}\ \delta\ I_M + rd\ min\ \delta\ I_M'^2}{\rho}$$
$$P_2 = \frac{V_{TO}\ .\ I_M' + rd\ max\ .\ I_M'^2}{\rho}$$
$$I_M' = \frac{I_T - I_M}{n - 1}$$

### III.4. Information about of diodes parameters

$\alpha_{TO}$ and $\alpha_{rd}$ are given for some part numbers in the following table :

| | BYV255 -xxx | BYT60P -xxx | BYW51 -xxx |
|---|---|---|---|
| $\alpha_{TO}\left(\frac{V}{°C}\right)$ | $-1.6\ 10^{-3}$ | -1.6 10-3 | $-1.6\ 10^{-3}$ |
| $\alpha_{rd}\left(\frac{\Omega}{°C}\right)$ | $+2\ 10^{-6}$ | $+3\ 10^{-6}$ | $+16\ 10^{-6}$ |

* Datasheet gives $V_{TO\ max}$ (100°C) and rd max (100°C)

with these values we can determine $V_{TO}$(25°C) and rd max (25°C) :

$$V_{TO}\ (25°C) = V_{TO\ max}\ (100°C) - \alpha_{TO} \times 75$$

$$rd\ max\ (25°C) = rd\ max\ (100°C) - \alpha_{rd} \times 75$$

* rd min and $R_{th\ (j-c)min}$ can be calculated by :

rd min = k . rd max with k = 0.75

$R_{th(j-c)min}$ = k . $R_{tj(j-c)max}$ with k = 0.75

* We recommande to take $T_{Jmax}$ = 110°C to increase the safety margin for parallel operation.

## IV - EXAMPLES OF APPLICATION

### IV.1. Example of rectifiers in discret package

In this example we look for the maximum peak current $I_T$ versus $V_F$ that can flow in three BYV255 (n = 6) connected in parallel.

The current is rectangular and we consider 3 different duty cycles ( $\delta$= 0.3 $\delta$= 0.5 $\delta$= 0.7).

As a good estimation, the conduction losses can be considered to be 95 % of the total losses ( $\delta$ = 0.95 )

**Application data is**

$T_{C\ max}$ = 80°C
$T_{C\ min}$ = 78°C
$\rho$ = 0.95
rt max = 0.5 m $\Omega$
rt min = 0.4 m $\Omega$

**Diodes data is**

From data sheet of BYV255 we get :

$R_{th(j-c)max}$ = 0.4°C/W
$R_{th(c)}$ = 0.1°C/W
$V_{TO\ max}$ = 0.7 V (at 100°C)
rd max = 1.35m Ohms (at 100°C)
$I_{F(RMS)}$ = 150 A

From the recommandations of § 3.4 we can calculate :

$R_{th(j-c)\ min}$ = 0.3°C/W
$V_{TO}$ at 25°C = 0.82 V
rd max at 25°C= 1.20m $\Omega$
rd min at 25°C = 0.9m $\Omega$

**Calculations :**

**a) $I_{M1}$**

In this example we have to take into account $R_{th(c)}$ because there are two diodes in the package. Thus :

$$P_{COND} = \frac{\rho\ (T_{J\ max} - T_{C\ max})}{R_{th\ (j-c)} + R_{th\ (c)}}$$

$P_{COND}$ = 57 W

The following table gives $I_{M1}$ value for $\delta$ = 0.3 - 0.5 - 0.7 (according to the relation (2) of page 3)

| $\delta$ | $I_{M1}$ [A] |
|---|---|
| 0.3 | 196 |
| 0.5 | 130 |
| 0.7 | 97 |

**b) $I_{M2}$**

$$I_{M2} = \frac{I_{F(RMS)}}{\sqrt{\delta}}$$

The following table gives the $I_{M2}$ limits for $\delta$ = 0.3 - 0.5 - 0.7

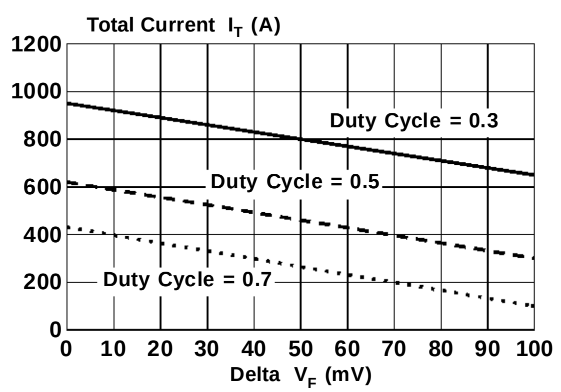
| $\delta$ | $I_{M2}$ [A] |
|---|---|
| 0.3 | 274 |
| 0.5 | 212 |
| 0.7 | 179 |

### c) Results

These two tables show that the $I_M$ current is imposed by thermal considerations ($I_{M1} < I_{M2}$).

Using formulas (5) - (6) - (7) - (8) we can draw the

**Fig.5 :** Peak current $I_T$ versus $\Delta$ $V_F$ for different duty cycles with 3 BY255 in parallel




curve Fig.5 $I_T$ versus $\Delta V_F$ for different duty cycles.

### IV.2 Example of double rectifiers

In this example we consider a BYW51. The two diodes in the same package are connected in parallel. The current is rectangular with $\delta$ = 0.5 . The commutation losses are negligible ( $\rho$ = 1)

Application data is :

$\rho$ = 1

$r_{T\ min}$ = 0.5 m$\Omega$

$r_{T\ max}$ = 0.5 m$\Omega$

Diode data :

From data sheet of BYW51 we get

$R_{th(j-c)}$ = 2.5C/W

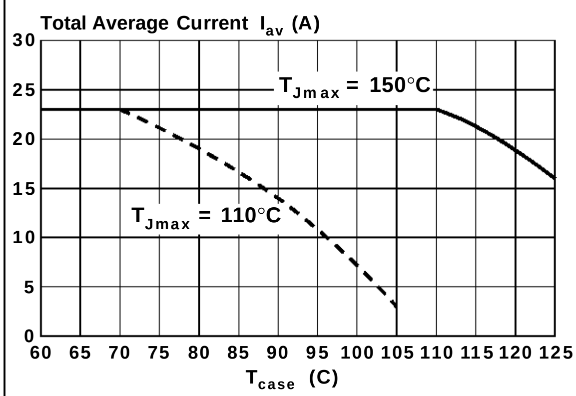
$R_{th(c)}$ = 0.1C/W

$V_{TO\ max}$ = 0.66 V(at 100C)

rd max = 14 m$\Omega$ (at 100C)

Fig.6 shows the total average current versus $T_C$. The flat part of the curves corresponds to the $I_{F(RMS)}$ limitation and the other part corresponds to the thermal limitation. The calculation is done with $\Delta V_F$ = 30 mV.

**Fig.6 :** $I_{AV}$ versus Tc for BYW51 double rectifier in parallel operation ($\delta$ = 0.5)

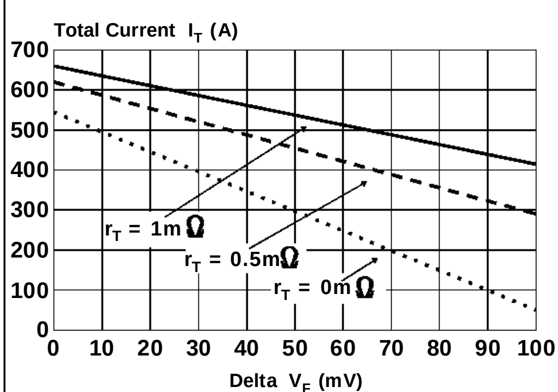



### V - INFLUENCE OF THE WIRING RESISTANCE : rT

When all diodes are connected through the same wiring resistance, the total current is better split into the circuitry.

Fig.7 shows the good influence of the wiring resistance when all diodes are connected through the same $r_T$ (Same conditions as BYV255 example, with $\delta$ = O.5)

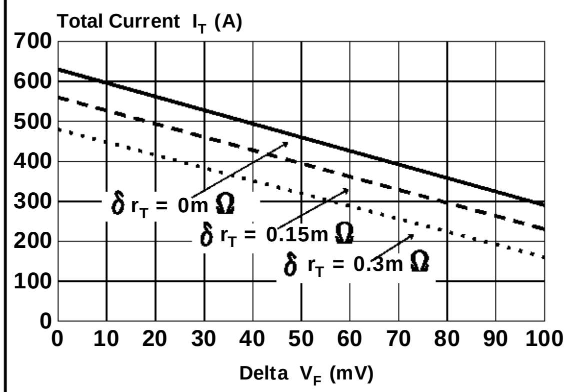
**Fig.7 :** It versus $\Delta$ $V_F$ for different resistances of connections.
(Case of 3 BYV255 with $\delta$ = 0.5)




If diodes are connected through very different wiring resistance, the current imbalance can be important.

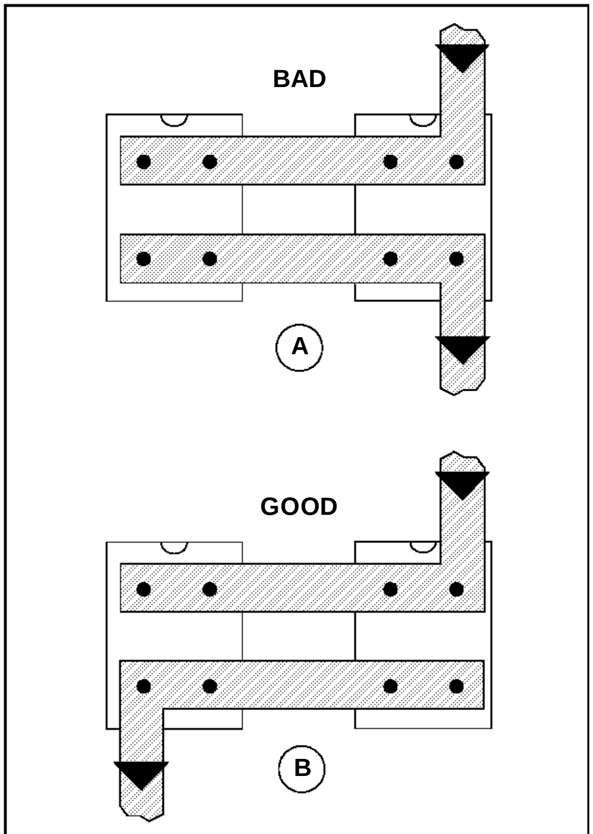
Fig.8 shows $r_T$ influence for different values of $r_T$ tolerance.

**Fig.8 :** It versus Δ $V_F$ for different wiring resistance dispersion.
(Case of 3 BYV255 with δ = 0.5)




Particular care must be taken to connect several diodes in parallel. The assembly must be as symetrical as possible in order to reduce variation of $r_T$ from one rectifier to another (see Fig.9). In the same way it is necessary to mount the packages on a single and efficient heat sink in order to reduce the variation of the case temperatures.

**Fig.9 :** Assembly of 2 ISOTOP packages :
(B) configuration provides a better balance of stray resistances




## VI - COMMENTS ABOUT Δ$V_F$ IN MANUFACTURING

**VI.1** Double rectifiers (*) (2 diodes in the same package) :

These devices house 2 silicon dice coming from the same wafer and the dispersion is low :

90% of the production offers a Δ$V_F$ lower than 30 mV.

**VI.2** Rectifiers in separate packages : (or discrete)

In this case the dispersion is more important and when a Δ$V_F$ lower than 100 mV is needed in the application, a screening is necessary.

## VII - CONCLUSION

Ultra fast rectifiers and power schottky diodes can be easily connected in parallel to provide a reliable high current device if a few simple rules are applied.

This paper shows how we can calculate, for a given application, the maximum value of the forward voltage drop variation (Δ$V_F$) which guarantees that each diode will operate always below its maximum ratings.

This calculation takes into account the dispersion of the diode parameters (given by the manufacturer) and the electrical and thermal characteristics of the circuit.

Thus, it is possible to know if a special selection in term of $V_F$ is needed or if the number of diodes connected in parallel is large enough to allow the use of standard parts without risk of overcurrent for one of the rectifiers.

**(*)** BYT261 - BYV255 - BYW51, ... etc

## ANNEX

### A - TRIANGULAR WAVEFORM

$$I_{M1} = \frac{-V_{TO}\left(\frac{\delta}{3}\right) + \left[\left(V_{T0} \cdot \frac{\delta}{2}\right)^2 + 4 \cdot P_{COND} \cdot rd \cdot \frac{\delta}{3}\right]^{1/2}}{(2/3) \cdot rd \cdot \delta}$$

$$I_{M2} = \frac{I_{F(RMS)}\sqrt{3}}{\delta}$$

$$\Delta V_F < \frac{\Delta V_{F1} + \Delta V_{F2} + \Delta V_{F3} - \Delta V_{F4}}{\Delta}$$

**With**

$\Delta V_{F1} = (r_T\, min + rd\, min) \cdot I_M - (r_T\, max + rd\, max) \cdot I_M'$

$\Delta V_{F2} = R_{th(j-c)\,max}\,(\alpha_{TO} + \alpha_{rd} \cdot I_M) \cdot P1$

$\Delta V_{F3} = (\alpha_{TO} + \alpha_{rd} \cdot I_M) \cdot (T_{C\,max} - T_{C\,min})$

$\Delta V_{F4} = R_{th(j-c)\,min} \cdot (\alpha_{TO} + \alpha_{rd} \cdot I_M') \cdot P2$

$\Delta = 1 + R_{th(j-c)\,min}\,[\alpha_{TO} + rd \cdot I_M'\,]\,(\delta/2) \cdot I_M'$

$$P_1 = \frac{V_{TO}(\delta/2) \cdot I_M + r_{d\,min}(\delta/3) \cdot I_M^{\,2}}{\rho}$$

$$P_2 = \frac{V_{TO}(\delta/2) \cdot I_M' + r_{d\,max}(\delta/3) \cdot I_M'^{\,2}}{\rho}$$

$$I_M' = \frac{I_T - I_M}{n - 1}$$

### B - SINUSOIDAL WAVEFORM

$$I_{M1} = \frac{-2\,V_{TO}\left(\frac{\delta}{\pi}\right) + \left[\left(2\,V_{T0} \cdot \frac{\delta}{\pi}\right)^2 + 2 \cdot P_{COND} \cdot \delta \cdot rd\right]^{1/2}}{rd \cdot \delta}$$

$$I_{M2} = I_{F(RMS)} \cdot \left(\sqrt{2/}\,\delta\right)$$

$$\Delta V_F < \frac{\Delta V_{F1} + \Delta V_{F2} + \Delta V_{F3} - \Delta V_{F4}}{\Delta}$$

**With**

$\Delta V_{F1} = (r_T\, min + rd\, min) \cdot I_M - (r_T\, max + rd\, max) \cdot I_M'$

$\Delta V_{F2} = R_{th(j-c)\,max}\,(\alpha_{TO} + \alpha_{rd} \cdot I_M) \cdot P1$

$\Delta V_{F3} = (\alpha_{TO} + \alpha_{rd} \cdot I_M) \cdot (T_{C\,max} - T_{C\,min})$

$\Delta V_{F4} = R_{th(j-c)\,min} \cdot (\alpha_{TO} + \alpha_{rd} \cdot I_M') \cdot P2$

$\Delta = 1 + R_{th(j-c)\,min}\,[\alpha_{TO} + rd \cdot I_M'\,]\,(\delta/\pi) \cdot I_M'$

$$P_1 = \frac{2\,V_{TO}(\delta/\pi) \cdot I_M + r_{d\,min}(\delta/3) \cdot I_M^{\,2}}{\rho}$$

$$P_2 = \frac{2\,V_{TO}(\delta/\pi) \cdot I_M + r_{d\,max}(\delta/3) \cdot I_M^{\,2}}{\rho}$$

$$I_M' = \frac{I_T - I_M}{n - 1}$$