2.2.1 Fast Recovery Epitaxial Diodes for use in High Frequency Rectification

In the world of switched-mode power supply (S.M.P.S.) design, one of the most pronounced advances in recent years has been the implementation of ever increasing switching frequencies. The advantages include improved efficiency and an overall reduction in size, obtained by the shrinking volume of the magnetics and filtering components when operated at higher frequencies.

Developments in switching speeds and efficiency of the active switching power devices such as bipolars, Darlington and especially power MOSFETs, have meant that switching frequencies of 100kHz are now typical. Some manufacturers are presently designing p.w.m. versions at up to 500kHz, with resonant mode topologies (currently an area of intensive academic research) allowing frequencies of 1MHz and above to be achievable.

These changes have further increased demands on the other fundamental power semiconductor device within the S.M.P.S. - the power rectification diode.

Key Rectifier Characteristics.

In the requirements for efficient high frequency S.M.P.S. rectification, the diode has to meet the following critical requirements:-

- Short reverse recovery time, $t_{rr}$, for compatibility with high frequency use.
- Low forward voltage drop, $V_F$, to maximise overall converter efficiency.
- Low loss switching characteristics, which reduce the major frequency dependent loss in the diode.
- A soft reverse recovery waveform, with a low $dI_R/dt$ rate, reduces the generation of unwanted R.F.I. within the supply.

The Philips range of fast recovery epitaxial diodes (FREDs) has been developed to meet the requirements of high frequency, high power rectification. With many years' experience in the development of epitaxial device technology, Philips offers a comprehensive range of FREDs. Some of their standard characteristics include:-

- A reverse blocking voltage range from 100V to 800V, and forward current handling capability from 1A to 30A. Thus, they are compatible for use in a wide range of S.M.P.S. applications, from low voltage dc/dc converters right through to off-line ac/dc supplies. Philips epitaxial diodes are compatible with a range of output voltages from 10V to 200V, with the capability of supplying a large range of output powers. Several different package outlines are also available, offering the engineer flexibility in design.
- Very fast reverse recovery time, $t_{rr}$, as low as 20ns, coupled with inherent low switching losses permits the diode to be switched at frequencies up to 1MHz.
- Low $V_F$ values, typically 0.8V, produce smaller on-state diode loss and increased S.M.P.S. efficiency. This is particularly important for low output voltage requirements.
- Soft recovery is assured with the whole range of FREDs, resulting in minimal R.F.I. generation.

Structure of the power diode

All silicon power diodes consist of some type of P-I-N structure, made up of a highly doped P-type region on one side, and a highly doped N+ type on the other, both separated by a near intrinsic middle region called the base. The properties of this base region such as width, doping levels and recombination lifetime determine the most important diode characteristics, such as reverse blocking voltage capability, on-state voltage drop $V_F$, and switching speed, all critical for efficient high frequency rectification.

![Fig. 1 Main steps in epitaxial diode process.](image-url)
A high blocking voltage requires a wide lightly doped base, whereas a low \( V_r \) needs a narrow base. Using a short base recombination lifetime produces faster recovery times, but this also increases \( V_r \). Furthermore, in any P-N junction rectifier operating at high currents, carrier injection into the base takes place from both the P and N+ regions, helping to maintain a low \( V_r \).

### Technology

High voltage power diodes are usually manufactured using either double-diffused or an epitaxial technology. High injection efficiency into the base coupled with a narrow base width are essential for achieving a low \( V_r \). High injection efficiency requires the slope of the diffusion profile at the P+ N and N+ N junctions to be very steep. Achieving a minimum base width requires very tight control of the lightly doped base layer. Both these criteria can be met using epitaxial technology.

### Epitaxial process

The epitaxial method involves growing a very lightly doped layer of silicon onto a highly doped N+ type wafer; see Fig. 1(a). A very shallow P type diffusion into the epi layer is then made to produce the required P-I-N structure (Fig. 1(b)). This gives accurate control of the base thickness such that very narrow widths may be produced. Abrupt junction transitions are also obtained, thus providing for the required high carrier injection efficiency. The tighter control of width and junction profile also provides a tighter control of \( Q_s \), hence, the switching recovery times are typically ten times faster than double diffused types.

### Double-diffused process

Double diffusion requires deep diffusions of the P+ and N+ regions into a slice of lightly doped silicon, to produce the required base width. This method is fraught with tolerance problems, resulting in poor control of the base region. The junction transitions are also very gentle, producing a poor carrier injection efficiency. The combination of the two produces a higher \( V_r \) value, and also a poor control of stored charge \( Q_s \) in the base, leading to a relatively slow switching speed.

Figure 2 gives a comparison of the diffusion profiles for the two methods.

### Lifetime control

To achieve the very fast recovery time and low stored charge, \( Q_s \), required for high frequency rectification, it is necessary to introduce lifetime killing (gold doping) into the base of the diode. This produces a lower \( Q_s \) and faster reverse recovery time, \( t_{rr} \). Unfortunately, doping also has the effect of increasing \( V_r \). Fig. 3 shows a graph of normalised \( V_r \) versus the minority carrier lifetime for a 200V and 500V device. It can be seen that there is an optimum lifetime for each voltage grade, below which the \( V_r \) increases dramatically.

Philips has been using gold-killing techniques for well over twenty years, and combining this with epitaxial technology results in the excellent low \( V_r \), \( t_{rr} \) and \( Q_s \) combinations found in the FRED range.

### Passivation

To ensure that the maximum reverse blocking potential of the diode is achieved, it is necessary to ensure that high fields do not occur around the edges of the chip. This is achieved by etching a trough in the epitaxial layer and depositing a special glass into it (Fig. 1(c)). Known as full mesa glass passivation, it achieves stable reverse blocking characteristics at high voltages by reducing charge build-up, and produces a strong chip edge, reducing the risk of assembly damage. This means that the diodes are rugged and reliable, and also allows all devices to be fully tested on-slice.
Finally, Fig. 1(d) shows the chip after it has been diced and metallised. The rectifier is then assembled into a wide selection of different power packages, the standard TO-220 outline being one example.

**Characteristics**

**Forward conduction loss**

Forward conduction loss is normally the major component of power loss in the output rectification diodes of an S.M.P.S. For all buck derived output stages, for example the forward converter shown in Fig. 4, the choke current always flows in one or other of the output diodes (D1 and D2).

The output voltage is always lowered by the diode forward voltage drop $V_f$ such that:-

$$V_V + V_f = V_d D$$  \hspace{1cm} (1)

Where D is the transistor duty cycle. Thus, the resulting power loss due to $V_f$ of the output rectifiers is:-

$$P_{on\text{ loss}} = V_f I_o$$  \hspace{1cm} (2)

where $I_o$ is the output load current of the converter. The loss as a percentage of the output power is thus:-

$$\frac{V_f I_o}{V_o I_o} = \frac{V_f}{V_o}$$  \hspace{1cm} (3)

This loss in efficiency for a range of standard S.M.P.S. outputs is shown in Fig. 5. It is clear that $V_f$ needs to be kept to an absolute minimum particularly for low output voltages if reasonable efficiency is to be achieved.

To accommodate variations in the input voltage, the output rectifiers are usually chosen such that their blocking voltage capability is between 4 and 8 times the output voltage. For the lowest output voltages, Schottky diodes should be the first choice. Unfortunately, the characteristically low $V_f$ of the Schottky cannot be maintained at voltages much higher than 100V. For outputs above 24V, fast recovery epitaxial diodes are the most suitable rectifiers.

Figure 6 shows an example of $V_f$ versus forward current $I_D$ for the Philips BYV32 series, rated from 50V to 200V and with a maximum output current of 20A. This reveals the low $V_f$ values typical of the epitaxial technique.

From Fig. 6 and equation 2, it is possible to estimate the loss due to the output rectifiers in an S.M.P.S. For example, for a 12V, 20A output, a conduction loss of 17W typical and 20W maximum is obtained. This corresponds to a worst case loss of 8% of total output power, normally an acceptable figure.

Philips devices offer some of the lowest $V_f$ values on the market. Maximum as well as typical values are always quoted at full rated currents in the datasheets. However this is not the case with all manufacturers, and care should be taken when comparing Philips devices with those of other manufacturers.
Reverse recovery

a) $Q_s$, $t_{rr}$, and $I_{rrm}$

Following $V_r$, the most important feature of a high frequency rectifier is the reverse recovery characteristic. This affects S.M.P.S. performance in several ways. These include increased diode switching loss, higher peak turn-on current and dissipation in the power transistors, and increased generation of electro-magnetic interference (e.m.i.) and voltage transient oscillations in the outputs. Clearly, the rectifier must have optimum reverse recovery characteristics to keep this catalogue of effects to a minimum.

When the P-N diode is conducting forward current, a charge is built up in the base region, consisting of both electrons and holes. It is the presence of this charge which is the key to achieving low $V_r$. The higher the forward current, the greater is this stored charge. In order to commutate the diode (i.e. switch the device from forward conduction into reverse blocking mode) this charge has to be removed from the diode before the base can sustain any reverse blocking voltage. The removal of this charge manifests itself as a substantial transient reverse current spike, which can also generate a reverse voltage overshoot oscillation across the diode.

The waveforms of the reverse recovery for a fast rectifier are shown in Fig. 7. The rectifier is switched from its forward conduction at a particular rate, called $dI_F/dt$. Stored charge begins to be extracted after the current passes through zero, and an excess reverse current flows. At this point the charge is being removed by both the forcing action of the circuit, and recombination within the device (dependent upon the base characteristics and doping levels).

At some point the charge has fallen to a low enough level for a depletion region to be supported across the base, thus allowing the diode to support reverse voltage. The peak of reverse current, $I_{rrm}$ occurs just after this point. The time for the current to pass through zero to its peak reverse value is called $t_r$. From then on, the rectifier is in blocking mode, and the reverse current then falls back to zero, as the remainder of the stored charge is removed mostly by recombination. The time for the peak reverse current to fall from its maximum to 10% of this value is called $t_b$.

Factors influencing reverse recovery

In practice, the three major parameters $t_{rr}$, $Q_s$, and $I_{rrm}$ are all dependent upon the operating condition of the rectifier. This is summarised as follows:

- Increasing the forward current, $I_F$, increases $t_{rr}$, $Q_s$, and $I_{rrm}$.
- Increasing the $dI_F/dt$ rate by using a faster transistor and reducing stray inductance, significantly decreases $t_{rr}$, but increases $Q_s$ and $I_{rrm}$. High $dI_F/dt$ rates occur in the high frequency square wave switching found in S.M.P.S. applications. (MOSFETs can produce very small fall times, resulting in very fast $dI_F/dt$).
- Increasing diode junction temperature, $T_j$, increases all three.
- Reducing the reverse voltage across the diode, $V_r$, also slightly increases all three.
Specifying reverse recovery

Presently, all manufacturers universally quote the $t_{rr}$ figure as a guide. This figure is obtained using fixed test procedures. There are two standard test methods normally used:

**Method 1**
Referring to the waveform of Fig. 7:

$I_F = 1\, A$; $\frac{dI_F}{dt} = 50\, A/\mu s$; $V_r > 30\, V$; $T_j = 25^\circ C$.

$t_{rr}$ is measured to 10% of $I_{rrm}$.

**Method 2**
$I_F = 0.5\, A$, the reverse current is clamped to 1A and $t_{rr}$ is measured to 0.25A.

This is the Electronics Industries Association (E.I.A.) test procedure, and is outlined in Fig. 8.

The first and more stringent test is the one used by Philips. The second method, used by the majority of competitors will give a $t_{rr}$ figure typically 30% lower than the first, i.e. will make the devices look faster. Even so, Philips have the best $t_{rr}$, $Q_s$ devices available on the market. For example, the Philips BYW29 200V, 8A device has a $t_{rr}$ of 25ns, the competitor devices quote 35ns using the easier second test. This figure would be even higher using test method 1.

Reverse recovery is specified in data by Philips in terms of all three parameters $t_{rr}$, $Q_s$ and $I_{rrm}$. Each of these parameters however is dependent on exact circuit conditions. A set of characteristics is therefore provided showing how each varies as a function of $dI/dt$, forward current and temperature, Fig. 9. These curves enable engineers to realise what the precise reverse recovery performance will be under circuit operating conditions. This performance will normally be worse than indicated by the quoted figures, which generally speaking do not reflect circuit conditions. For example, a BYW29 is quoted as having a $t_{rr}$ of 25 ns but from the curves it may be as high as 90 ns when operated at full current and high $dI/dt$. Similarly a quoted $Q_s$ of 11 nC compares with the full current worst case of 170 nC.

In the higher voltage devices (500V and 800V types) $t_{rr}$ and $Q_s$ are much higher, and will probably be the most critical parameters in the rectification process. Care must be taken to ensure that actual operating conditions are used when estimating more realistic values.

**Frequency range**

Figure 10 compares the recovery of a Philips 200V FRED with a double diffused type. The FRED may be switched approximately 10 times faster than the double diffused type. This allows frequencies of up to 1MHz to be achieved with the 200V range.

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**Fig. 9** Reverse recovery curves for BYW29.
In the higher voltage devices where the base width is increased to sustain the reverse voltage, the amount of stored charge increases, as does the trr. For a 500V device, 500kHz operation is possible, and for 800V typically 200kHz is realistic.

**Fig. 10** Comparison of reverse recovery of FRED vs double diffused.

(a) Philips 200V FRED.
(b) Double-diffused diode.

**Effects on S.M.P.S operation**

In order to analyse the effects of reverse recovery on the power supply, a simple non-isolated buck converter shown in Fig. 11 is considered. The rectifier D1 in this application is used in freewheel mode, and conducts forward current during the transistor off-time.

The waveforms for the diode and transistor switch during the reverse recovery of the diode when the transistor turns on again are given in Fig. 12.

As the transistor turns on, the current ramps up in the transistor as it decays and reverses in the diode. The dI/dt is mainly dependent on the transistor fall time and, to some extent, the circuit parasitic inductances. During the period t_s the diode has no blocking capability and therefore the transistor must support the supply voltage. The transistor thus simultaneously supports a high voltage and conducts both the load current and the reverse recovery current, implying a high internal power dissipation. After time t_b the diode blocking capability is restored and the voltage across the transistor begins to fall. It is clear that a diode with an I_rm half the value of I_F will effectively double the peak power dissipation in the transistor at turn-on. In severe cases where a high I_rm / t_rr rectifier is used, transistor failure could occur by exceeding the peak current or power dissipation rating of the device.

**Fig. 12** Reverse recovery diode and transistor waveforms.

There is also an additional loss in the diode to be considered. This is a product of the peak I_rm and the diode reverse voltage, V_r. The duration of current recovery to zero will affect the magnitude of the diode loss. However, in most cases the additional transistor loss is much greater than the diode loss.

**Diode loss calculation**

As an example of the typical loss in the diode, consider the BYW29, 8A, 200V device as the buck freewheel diode, for the following conditions:-

\[ I_F = 8A; \quad V_r = 100V; \quad \text{d}I/F/\text{d}t = 50A/\mu s; \]
\[ T_j = 25^\circ C; \quad \text{duty ratio} \quad D = 0.5; \quad f = 100kHz. \]

The diode reverse recovery loss is given by:

\[ P_{rr} = \frac{1}{2} \cdot V_r \cdot I_{rm} \cdot t_r \cdot f \]

From the curves of Fig. 7, t_r=35ns, I_{rm} = 1.5A. Assuming I_b = I_r/2 gives:

\[ P_{rr} = \frac{1}{2} \cdot 100 \cdot 1.5 \cdot 17.5 \cdot 100k = 132mW \]
This is still small compared to the diode $V_F$ conduction loss of approximately 3.6 W. However, at $T = 100^\circ C$, $dI/dt = 100 A/\mu s$ and $f = 200 kHz$, the loss becomes 1.05W, which is fairly significant. In the higher voltage devices where $t_c$ and $I_{rrm}$ are significantly worse, then the frequency dependent switching loss will tend to dominate, and can be higher than the conduction loss. This will limit the upper frequency of operation of the diode.

The turn-on current spike generated in the primary circuits due to diode reverse recovery can also seriously affect the control of the S.M.P.S. when current mode control is used (where the peak current is sensed). An RC snubber is usually required to remove the spike from the sense inputs. Good reverse recovery removes the need for these additional components.

**b) Softness and $dI/dt$**

When considering the reverse recovery characteristics, it is not just the magnitude ($t_c$ and $I_{rrm}$) which is important, but also the shape of the recovery waveform. The rate at which the peak reverse current $I_{rrm}$ falls to zero during time $t_c$ is also important. The maximum rate of this slope is called $dI/dt$ and is especially significant. If this slope is very fast, it will generate significant radiated and conducted electrical noise in the supply, causing R.F.I. problems. It will also generate high transient voltages across circuit inductances in series with the diode, which in severe cases may cause damage to the diode or the transistor switch by exceeding breakdown limits.

A diode which exhibits an extremely fast $dI/dt$ is said to have a "snap-off" or "abrupt" recovery, and one which returns at a relatively smooth, gentle rate to zero is said to have a soft recovery. These two cases are shown in the waveforms in Fig. 13. The softness is dependent upon whether there is enough charge left in the base, after the full spread of the depletion region in blocking mode, to allow the current to return to zero smoothly. It is mainly by the recombination mechanism that this remaining charge is removed during $t_c$.

Maintaining $t_c$ at a minimum would obviously give some reduction to the diode internal loss. However, a snappy rectifier will produce far more R.F.I. and transient voltages. The power saving must therefore be weighed against the additional cost of the snubbers and filtering which would otherwise be required if the rectifier had a snappy characteristic.

The frequency range of R.F.I. generated by $dI/dt$ typically lies in the range of 1MHz to 30MHz, the magnitude being dependent upon how abrupt the device is. One secondary effect that is rarely mentioned is the additional transformer losses that will occur due to the extremely high frequencies generated inside it by the diode recovery waveform. For example, core loss at 10MHz for a material designed to operate at 100kHz can be significant. There will also be additional high frequency loss in the windings due to the skin effect. In this case the use of a soft device which generates a lower frequency noise range will reduce these losses.

### Characterising softness

A method currently used by some manufacturers to characterise the softness of a device is called the softness factor, $S$. This is defined as the ratio of $t_b$ over $t_a$.

$$ S = \frac{t_b}{t_a} $$

An abrupt device would have $S$ much less than 1, and a soft device would have $S$ greater than 1. A compromise between R.F.I. and diode loss is usually required, and a softness factor equal to 1 would be the most suitable value for a fast epitaxial diode.

**Fig. 14 Different diode $dI/dt$ rates for same softness factor.**

Although the softness factor does give a rough guide to the type of recovery and helps in the calculation of the diode switching loss, it does not give the designer any real idea of the $dI/dt$ that the rectifier will produce. Hence, levels of R.F.I. and overvoltages could be different for devices with the same softness factor. This is shown in Fig. 14, where the three characteristics have the same softness factor but completely different $dI/dt$ rates.

In practice, a suitable level for $dI/dt$ would be to have it very similar in magnitude to $dI/dt$. This would keep the noise generated to a minimum.
At present there is no universal procedure used by manufacturers to characterise softness, and so any figures quoted must be viewed closely to check the conditions of the test.

**Comparison with competitor devices**

Figure 15 compares a BYV32 with an equivalent competitor device. This test was carried out using an L.E.M. Qs test unit.

The conditions for each diode were identical. The results were as follows:

BYV32:  
- \( S = 1.2 \), \( \frac{dI}{dt} = 40\text{A}/\mu\text{s} \)  
- Voltage overshoot = 5V

Competitor:  
- \( S = 0.34 \), \( \frac{dI}{dt} = 200\text{A}/\mu\text{s} \)  
- Voltage overshoot = 22V

For the Philips device, apart from the very low \( Q_s \) and \( I_{rrm} \) values obtained, the \( S \) factor was near 1 and the \( \frac{dI}{dt} \) rate was less than the original \( \frac{dI}{dt} \) of 50A/\( \mu \)s. These excellent parameters produce minimal noise and the very small overshoot voltage shown. The competitor device was much snappier, the \( \frac{dI}{dt} \) was 4 times the original \( \frac{dI}{dt} \), and caused a much more severe overshoot voltage with the associated greater R.F.I. The diode loss is also higher in the competitor device even though it is more abrupt, since \( Q_s \) and \( I_{rrm} \) are larger.

The low \( Q_s \) of the Philips FRED range thus maintains diode loss to a minimum while providing very soft recovery. This means using a Philips type will significantly reduce R.F.I. and dangerous voltage transients, and in many cases reduce the power supply component count by removing the need for diode snubbers.

**Forward recovery**

A further diode characteristic which can affect S.M.P.S. operation is the forward recovery voltage \( V_f \). Although this is not normally as important as the reverse recovery effects in rectification, it can be particularly critical in some special applications.
Forward recovery is caused by the lack of minority carriers in the rectifier p-n junction during diode turn-on. At the instant a forward bias is applied, there are no carriers present at the junction. This means that at the start of conduction, the diode impedance is high, and an initial forward voltage overshoot will occur. As the current flows and charge builds up, conductivity modulation (minority carrier injection) takes place. The impedance of the rectifier falls and hence, the forward voltage drop falls rapidly back to the steady state value.

The peak value of the forward voltage is known as the forward recovery voltage, \( V_{fr} \). The time from the forward current reaching 10% of the steady state value to the time the forward voltage falls to within 10% of the final steady state value is known as the forward recovery time (Fig. 16).

The magnitude and duration of the forward recovery is normally dependent upon the device and the way it is commutated in the circuit. High voltage devices will produce larger \( V_{fr} \) values, since the base width and resistivity (impedance) is greater.

The main operating conditions which affect \( V_{fr} \) are:
- \( I_f \), high forward current, which produces higher \( V_{fr} \).
- Current rise time, \( t_r \), a fast rise time produces higher \( V_{fr} \).

**Effects on S.M.P.S.**

The rate of rise in forward current in the diode is normally controlled by the switching speed of the power transistor. When the transistor is turned off, the voltage across it rises, and the reverse voltage bias across the associated rectifier falls. Once the diode becomes forward biased there is a delay before conduction is observed. During this time, the transistor voltage overshoots the d.c supply voltage while it is still conducting a high current. This can result in the failure of the transistor in extreme cases if the voltage limiting value is exceeded. If not, it will simply add to the transistor and diode dissipation. Waveforms showing this effect are given in Fig. 17.

Table 1 outlines typical \( V_{fr} \) values specified for rectifiers of different voltage rating. This shows the relatively low values obtained. No comparable data for any of the competitor devices could be found in their datasheets. It should be noted that in most S.M.P.S. rectifier applications, forward recovery can be considered the least important factor in the selection of the rectifier.

<table>
<thead>
<tr>
<th>Device type</th>
<th>( V_{br} ) (Volts)</th>
<th>( I_f ) (Amps)</th>
<th>( dI/dt ) (A/( \mu )s)</th>
<th>typ ( V_{fr} ) (Volts)</th>
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<td>BYW29</td>
<td>200</td>
<td>1.0</td>
<td>10</td>
<td>0.9</td>
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<tr>
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<td>500</td>
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<td>10</td>
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<tr>
<td>BYR29</td>
<td>800</td>
<td>10</td>
<td>10</td>
<td>5.0</td>
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Table 1. \( V_{fr} \) values for different Philips devices.

**Reverse leakage current**

When a P-N junction is reverse biased, there is always an inherent reverse leakage current that flows. In any piece of undoped semiconductor material there is a thermally generated background level of electron and hole pairs. These pairs also naturally recombine, such that an equilibrium is established. In a p-n junction under reverse voltage conditions, the electric field generated will sweep some of the free carriers generated out of the device before they can recombine, hence causing a leakage current. This phenomenon is shown in Fig. 18.
The reverse leakage current is greater still in the killed, fast rectifier. Since the pairs are generated thermally, it is obvious that raising the junction temperature will increase the leakage significantly. For example, the leakage current of a FRED can increase by up to 20 times by raising the junction temperature, $T_j$, from 25°C to 100°C. This increase can be far greater in other diode technologies.

Many S.M.P.S. designers have a misconception about leakage current, and believe that it renders the rectifier poor quality, giving high losses, and is unreliable. This is not so. Leakage is a naturally occurring effect, and is present in all rectifiers. The leakage in an S.M.P.S. diode is normally extremely small and stable, with very little effect on the rectification process. Some manufacturers have over-emphasised the benefits of very low leakage devices, claiming that they have great advantages. However, this will be shown to be groundless, since any reduction in the overall diode power loss will be minimal.

In practice, the reverse leakage current only becomes significant at high operating temperatures (above 75°C) and for high reverse blocking voltages (above 500V), where the product of reverse voltage and leakage current (hence, power loss) is higher. Even then, the leakage current is still usually lower than 1mA.

Table 2 lists the maximum leakage currents for some of the devices from the Philips range (gold killed), revealing low levels, even in the higher voltage devices, achieved through optimised doping.

<table>
<thead>
<tr>
<th>Device type</th>
<th>$V_{BR(max)}$ (Volts)</th>
<th>max $I_r$ (mA)</th>
<th>max $I_r$ (µA)</th>
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<td></td>
<td></td>
<td>$T_j=100^\circ C$</td>
<td>$T_j=25^\circ C$</td>
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<td>BYW29</td>
<td>200</td>
<td>0.6</td>
<td>10</td>
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<td>10</td>
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<tr>
<td>BYR29</td>
<td>800</td>
<td>0.2</td>
<td>10</td>
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Table 2. Maximum reverse leakage currents for Philips devices.

The power dissipation due to leakage is a static loss and depends on the product of the reverse voltage and the leakage current over a switching cycle. A worst case example is given below where the data sheet leakage current maximum is used at maximum reverse blocking voltage of the diode.

**S.M.P.S example: Flyback converter**

Consider first the BYV29-500 as the output rectifier in the discontinuous flyback converter (Note: the reverse blocking occurs during the transistor on time, and a minimum duty of 0.25 has been assumed.) The BYV29-500 could generate a possible maximum output voltage of 125V. The maximum leakage power loss is:

$$P_L = 500V \times 0.35mA \times 0.25 = 43.75mW$$

Alternatively, for the BYR29-800, maximum rectified output is approximately 200V, and by similar calculations, its maximum loss is 40mW. Lower output voltages would give leakage losses lower than this figure.

These types of calculation can be carried out for other topologies, when similar low values are obtained.

**Conclusion**

Philips produces a comprehensive range of Fast Recovery Epitaxial Diodes. The devices have been designed to exhibit the lowest possible $V_f$ while minimising the major reverse recovery parameters, $Q_s$, $t_{rr}$ and $I_{rrm}$. Because of the low $Q_v$, switching losses within the circuit are minimised, allowing use up to very high frequencies. The soft recovery characteristic engineered into all devices makes them suitable for use in today’s applications where low R.F.I. is an important consideration. Soft recovery also provides additional benefits such as reduced high frequency losses in the transformer core and, in some cases, the removal of snubbing components.