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Application **Note**

Fast Recovery Epitaxial Diode Characteristics and Application Examples

Objectives

This document outlines the main characteristics of the Littelfuse Fast Recovery Epitaxial Diode (FRED) family, and highlights typical applications and examples. FREDs are utilized across various power electronic systems such as electric vehicle (EV) chargers, residential photovoltaic (PV) inverters with battery storage, and industrial motor or pump drives, as illustrated in Figure 1. These devices typically operate at switching frequencies up to several kHz. For optimal operation and high efficiency of the converter, the switching behavior of these diodes must be closely matched to the characteristics of the actively switching transistor.

This document provides an in-depth analysis of the physical mechanisms governing diode reverse recovery. Additionally, the influence of different Littelfuse process technologies on these characteristics is highlighted. Finally, typical application examples are presented to assist in selecting a FRED and to illustrate the effects of reverse recovery behavior on the application.

(a) EV charging

(b) Residential photovaltic inverter with battery storage and EV charger

(c) Industrial water pumping station

Figure 1. Example illustrations

Applications

- Switched-mode power supplies (SMPS)
- Power factor correction (PFC)
- EV-battery charging
- Renewables (for example, PV-inverters)
- Industrial drives

Target Audience

This document is intended for design and development engineers, system architects, and test engineers of power electronics systems.

Contact Information

For more information on FRED characteristics and their applications, contact the Littelfuse Power Semiconductor team of product and applications experts at PowerSemiSupport@Littelfuse.com

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1. Introduction

The Littelfuse Silicon (Si) Fast Recovery Epitaxial Diode is utilized in several types of power electronic systems, as illustrated in Figure 1, in which the operating frequencies range from several kHz up to the MHz range. The primary goal in power electronics development is to reduce energy losses caused by the switching and conduction losses of power transistors and diodes. Therefore, not only must the conduction losses be reduced, but the switching losses, as well. Thus, the switching speed of almost every new generation of metal-oxide field-effect transistors (MOSFET) and insulated gate bipolar transistors (IGBT) is increasing with regard to voltage and current transitions, dv/dt and di/dt, respectively. To select the best diode for each application, development engineers must understand the underlying principles of their behavior.

Despite recent developments in the field of Schottky Barrier Diodes (SBD) in the range exceeding 650 V that are based on wide bandgap materials like Silicon Carbide (SiC), the bipolar Si FRED remains the preferred choice for a vast majority of applications. This is due to its cost-efficiency, mature technology, and satisfactory performance for most applications. It provides reliable operation with low reverse recovery loss and reduced EMI, making it ideal for moderate switching frequencies and cost-sensitive designs.

To further optimize the performance of Si FREDs, several methods are available to control the switching characteristics of diodes. Each method leads to a different set of characteristics of forward voltage drop, V_F, blocking voltage, V_{RRM}, and reverse recovery time, t_{rr}. The most critical parameters influencing the turn-on and turn-off behavior of a diode in the application are peak forward voltage, V_{FR}, forward voltage drop, V_F, maximum reverse recovery current, I_{RM}, and reverse recovery time, t_{rr}, and are shaped by different manufacturing processes.

1.1 Switching Behavior of PIN Diodes

Power diodes used in a range exceeding 650 V and high-current applications are predominantly PIN diodes, which consist of a heavily doped p+ region, a lightly doped n– drift region, and a heavily doped n+ substrate, as illustrated in Figure 2.

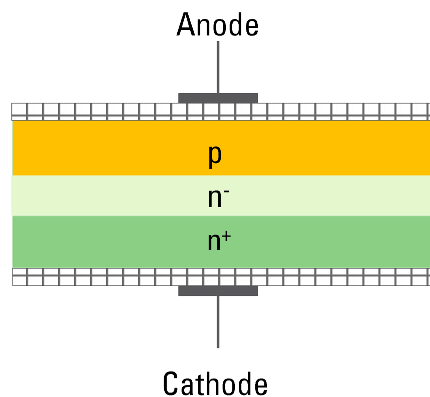

Figure 2. Cross-sectional view of a PIN diode

The n– region sustains the reverse blocking voltage and, during forward conduction, becomes conductivity-modulated by excess minority carriers, significantly reducing its resistivity and enabling low forward voltage drop. When the diode is forward-biased, the injected carriers accumulate in the drift region, and the diode conducts efficiently. However, when the current is commuted to another switching device, such as a MOSFET or IGBT, the diode cannot immediately block reverse voltage because the stored charge in the drift region must first be removed. This removal occurs through carrier recombination and reverse current sweep-out, a process known as reverse recovery.

During reverse recovery, a transient reverse current flows, reaching a peak value denoted as I_{RM}, before decaying to zero. The time interval from the zero crossing of the forward current to the point where the reverse current falls to a specified threshold is defined as the reverse recovery time, t_{rr}. The total recovered charge, Q_{rr}, is the integral of the reverse current over this interval. The shape of the reverse recovery waveform strongly influences circuit performance. A soft recovery, characterized by a gradual decay of reverse current, minimizes voltage overshoot and electromagnetic interference (EMI), whereas a snappy recovery, with an abrupt current decay, can induce high di/dt and large voltage transients across parasitic inductances. These transients are given approximately by $\Delta v = L_\sigma \cdot di/dt$, where L_σ is the commutation loop inductance. Consequently, the diode's recovery softness is a critical parameter for EMI compliance and device ruggedness.

The reverse recovery characteristics depend on several factors, including the diode's technology, the forward current at turn-off, the commutation rate $|di_F/dt|$, and the junction temperature, T_{vj}. Higher commutation rates and forward current increase the peak reverse recovery current, I_{RM}, while higher temperatures generally increase carrier lifetime, leading to longer recovery tails. In addition to reverse recovery, the diode exhibits forward recovery during turn-on, where a temporary overvoltage, V_{FR}, appears as the depletion region collapses and conductivity modulation builds up. This overvoltage increases with $|di_F/dt|$ and contributes to switching losses in the complementary device.

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Figure 3 illustrates a typical current and voltage waveform of a PIN diode during a switching event, highlighting the forward conduction phase, reverse recovery current, and the transition to the blocking state.

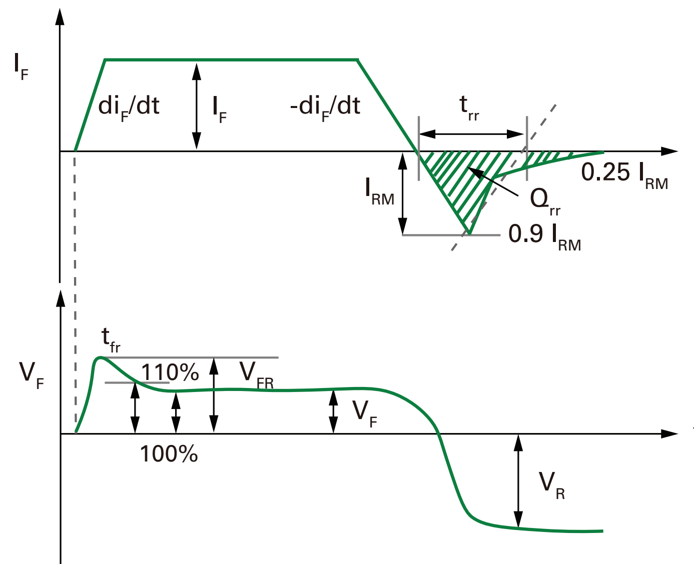

Figure 3. Typical switching current and voltage waveform for a PIN diode

In contrast to a PIN diode, SBDs, shown in Figure 4, are majority-carrier devices with negligible stored charge and can be switched very quickly, similar to a MOSFET. The observed reverse current in SBD is only due to the charging of the metal barrier-silicon capacitance, which is independent of temperature. Until recently, Si SBDs have only been used for applications with low blocking voltages, typically less than 300 V. For applications requiring ultrafast diodes with blocking voltages higher than 300 V, bipolar FREDs are now accompanied by SiC SBDs to some extent but continue to be the major device of choice.

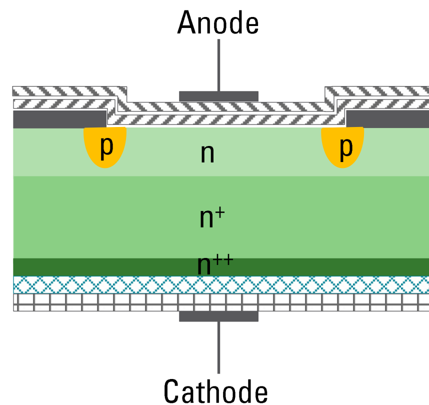

Figure 4. Cross-sectional view of a Schottky diode

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1.2 FRED Technology and Process Enhancements

FRED technology is derived from epitaxial PIN diodes, which is one of the two main types of PIN diodes, the other being diffused PIN diodes. In epitaxial PIN diodes, the intrinsic region is created by an epitaxial growth process. This approach allows for more accurate control over material properties, resulting in improved diode performance. It also enhances reverse recovery characteristics and switching speed.

FRED diodes, outlined in Figure 5, leverage epitaxial technology to enhance reverse recovery characteristics, switching speed, and efficiency.

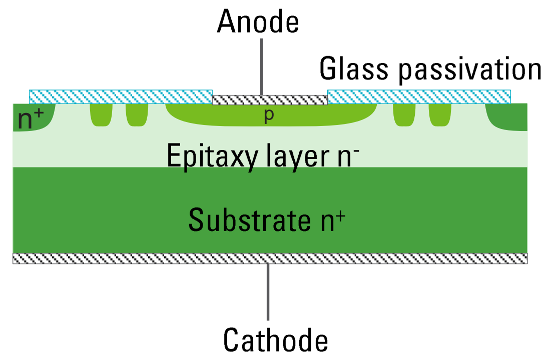

Figure 5. Cross-sectional view of a FRED with planar passivation

To further accelerate the recombination of stored charge and reduce reverse recovery losses, recombination centers are introduced into the n-epitaxial layer. Techniques such as gold or platinum doping and electron irradiation are commonly used to enhance recombination by increasing the recombination rate of minority carriers, which results in improved turn-off performance.

For ultrafast diodes, the n- layer that supports blocking the voltage should be as thin as possible. This minimizes both the forward voltage drop and the amount of stored charge within the pn-junction, further improving switching speed. To balance mechanical strength with the need for a thin epi-layer, the epitaxial process uses a thick n^+-doped substrate for strength, while the thin monocrystalline n-layer (epi-layer) is grown on top. The thickness and resistivity of the epi-layer are adjusted based on the desired blocking voltage capability of the FRED diode, ensuring it meets the required performance regarding blocking voltage and operating frequency.

1.3 Enhanced FRED Types

FREDs are designed for high-speed switching applications and are thus integral in various power electronics systems. Over the years, Littelfuse has developed multiple variants of ultra-fast diodes to address specific performance and application requirements, leveraging advancements in semiconductor processing technologies. These innovations optimize key characteristics such as reverse recovery behavior, leakage current, and temperature stability.

The passivation of the pn-junction uses planar technology, which is similar to the manufacturing process of transistors. Guard rings reduce the electric field strength to prevent voltage break-down and the surface is coated to ensure blocking voltage stability. As mentioned earlier in Section 1.2, recombination centers are introduced to the n-epitaxial layer to improve the recombination of stored charge and minimize reverse recovery losses. To improve the turn-off behavior, either gold or platinum atoms can be diffused interstitially into the n-epitaxial layer. These atoms function as trapping sites, in which the excess holes can recombine with electrons. Another way to create recombination centers is electron irradiation. Here, silicon atoms are displaced from their normal crystalline lattice sites. However, at elevated temperatures, some of these displaced atoms can return to their lattice sites, so the irradiation process is typically followed by a controlled annealing step to stabilize the desired defect structure. When irradiation energy and annealing temperature are carefully optimized, the defect distribution and minority carrier lifetime become stable, ensuring consistent and reliable reverse recovery characteristics. These measures result in a well-suited diode for high-frequency applications.

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The characteristics and explanation of multiple FREDs based on different diffusion/implantation materials are summarized in two complementary tables. Table 1 provides the comparative overview of various ultrafast diode technologies based on different process technologies. It compares the structural design and expected electrical behavior of standard (Std.) FRED, HiPerFRED™, Sonic FRD™, and HiPerDyn™ FRED types. The table provides insights into the diffusion/implantation material, their usage, leakage current at high temperatures, temperature coefficients, and forward voltage drops. As can be seen, Std. FRED diodes are gold doped and offer rapid switching but at the expense of higher leakage current. The HiPerFRED™ diodes are platinum doped and are ideal for high-frequency applications with low leakage. Table 2 presents the key electrical parameter values of different FRED variants. It includes parameters such as reverse recovery time, t_{rr}, forward voltage, V_F, charge stored, Q_{rr}, maximum reverse recovery current, I_{RM}, and reverse leakage current, I_R. From the table, it can be concluded that the FRED variant DSEI30-12A has a reverse recovery time of 220 ns and a forward voltage of 2.4 V, while the HiPerFRED™ variant DSEP30-12B has a reverse recovery time of 480 ns and a forward voltage of 2.6 V @ 125 °C.

Table 1. Comparison of different ultrafast diodes by process technologies

	Diffusion/Implantation Material	Usage	Leakage Current I_R at High Temperature	Forward Voltage Temperature Co-efficient	Forward Voltage Drop
Standard FRED	Gold doped	Fast switching	High I_R	Negative	Low
HiPerFRED™	Platinum doped	Very fast, good for high frequency output rectifiers	Low I_R	Negative	Medium
Sonic FRD™	Helium implanted and electron irradiation	Hard and fast switching	Low I_R	~ Constant	Very low
HiPerDyn™ FRED	Series connection of diodes	Very fast switching	Medium I_R	Negative	High

Table 2. Key electrical parameters and values of FREDs

Variant	Model	t_{rr}	V_F	Q_{rr}	I_{RM}	I_R
FRED	DSEI30-12A[2]	220 ns	2.4 V @ 100 °C	3000 nC	26.5 A @ 100°C	7 mA
HiPerFRED™	DSEP30-12B[3]	480 ns	2.6 V @ 125°C	290 nC	17.5 A @ 125°C	0.5 mA
Sonic FRD™	DHG30I1200HA[4]	410 ns	1.9 V @ 125°C	3250 nC	23.5 A @ 125°C	0.5 mA
HiPerDyn™	DSEP30-12CR[5]	85 ns	3.4 V @ 100 °C	380 nC	9 A @ 100°C	2 mA

Any manufacturing process for ultrafast diodes presents both advantages and disadvantages. The Standard FRED diodes, which are gold doped, offer fast switching and a low forward voltage drop but have higher leakage current at high temperatures and a negative temperature coefficient. HiPerFRED™ diodes are platinum doped and ideal for high-frequency applications due to their very fast switching and low leakage current, though they have a medium forward voltage drop and a negative temperature coefficient. Sonic FRD™ diodes, enhanced with helium implantation and electron irradiation, are suitable for hard and fast switching, exhibit very low forward voltage drop, and low leakage current, maintaining a nearly constant temperature coefficient. HiPerDyn™ FRED diodes offer very fast switching but come with medium leakage current, high forward voltage drop, and a negative temperature coefficient.

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2. FREDs as Freewheeling Diodes

Topologies working with an inductive load, such as inductors in a boost or buck converter, transformers, and motors require the use of freewheeling diodes. FREDs are perfectly suited for this scenario. Due to the inductive load, the current must continue to flow via a dedicated circuit frequently. In the event of turning on the transistor, the freewheeling path must block the input voltage to prevent a short circuit. The typical interaction between the power transistor and the freewheeling diode is illustrated in Figures 6 and 7. Figure 6 depicts the simplified circuit of a buck converter. This circuit provides an output voltage, V_{out}, which is lower than the supply voltage, V_{in}. Figure 7 illustrates the control signals for T1, as well as the voltage and current waveforms of T1 and D1.

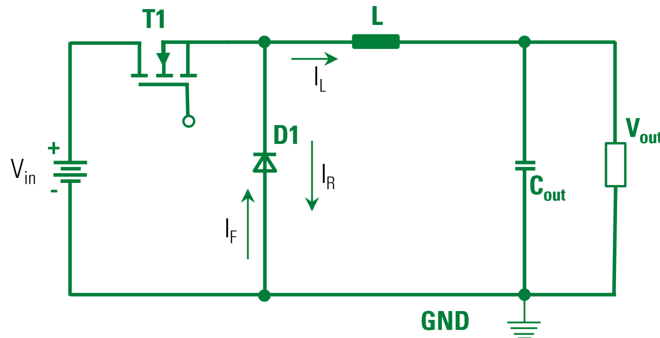

Figure 6. Buck converter circuit diagram

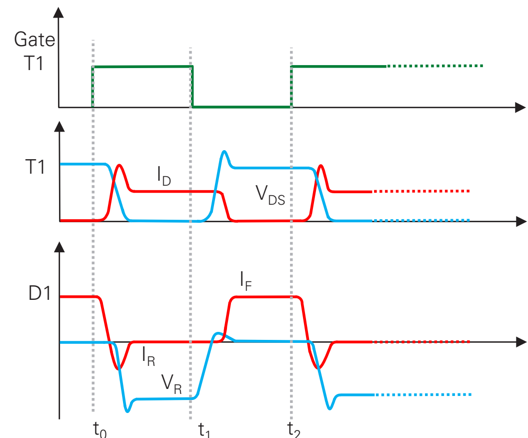

Figure 7. Transistor gate signals, current, and voltage waveforms along with the diode current and voltage waveforms for one switching cycle of the buck converter

The conducting and blocking phases of the two active elements T1 and D1 are described in distinct operation steps.
At a specific time, t_0, the controller switches on T1. The series circuit of L and C_{out} is connected to the supply voltage, V_{in}, and makes the current, I_L, increase linearly. The magnitude of this current change depends on both the difference $V_{in} - V_{out}$ and the inductance L. After a certain time, fixed by the controller, T1 is switched off again. In the discontinuous mode of operation, a part of the energy stored in the inductance, L, $E_L = ½ \cdot L \cdot I_L^2$, is transferred via the freewheeling path into the capacitor, C_{out}, because the inductor forces a current to continue flowing. Constant current through a capacitor leads to a voltage build-up according to UC=1/C Integral ic(t)dt.

At a specific time, t_2, T1 is switched on again and the whole procedure is repeated. The switching action of Diode D1 is characterized by four important phases:

A. the diode blocks while T1 is in the on-state,
B. the transition from blocking to conducting mode: turn-on,
C. the diode conducts forward current while T1 is turned off,
D. the transition from conducting to blocking mode: turn-off.

A. Blocking Mode: While the MOSFET T1 is conducting, the supply voltage, V_{in}, appears as reverse voltage at diode D1. As with all semiconductors, a small leakage current, I_R, flows from the cathode to the anode of the diode. The leakage current is influenced by factors such as blocking voltage capability, the temperature of the diode chip, and most importantly, the diode's technology. The reverse power loss, considering the applied reverse voltage, is given by:

$$P_{SP} = V_{in} \cdot I_R$$

B. Turn-On: With the transistor T1 switched off, the current, I_L, in the inductor must keep on flowing. The voltage across the diode drops down and the diode takes over the current of the inductor. The current rise time in D1 equals the current fall time in T1. The volume charge accumulated in the pn junction of the diode during the blocking phase is neutralized by carriers, resulting in a change in the resistance of the pn-junction during current rise time. This turn-on of the diode is accompanied by a short overvoltage in forward direction which is called forward-recovery and depends on the chip temperature, on the $-di_F/dt$, and again on the diode technology.

Compared to the blocking voltage, the overvoltage is relatively low and for most applications, does not significantly impact the operation of the diode, as represented by waveform D1 in Figure 7. However, this dynamic turn-on voltage of the diode contributes to the peak voltage that appears across the transistor T1, thereby increasing its turn-off losses. The overvoltage, V_{FR}, primarily influences the diode's turn-on losses.

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C. On-State: Once the turn-on phase is over, the diode conducts the forward current, I_F. There is a forward voltage drop, V_F, due to the threshold voltage of the pn-junction and the resistance of the semiconductor. This voltage drop depends on the chip temperature, the forward current, I_F, and the semiconductor technology.

To indicate the forward voltage drop at different currents and consequently, to calculate the on-state losses, the parameters V_{TO} and r_T often appear in datasheets. A simplified model for the forward voltage drop is represented in Figure 8 and calculated using:

$$V_F = r_T \cdot I_F + V_{T0}.$$

The on-state power dissipation can then be calculated accordingly:

$$P_D = V_{T0} \cdot I_F + r_T \cdot I_F^2$$

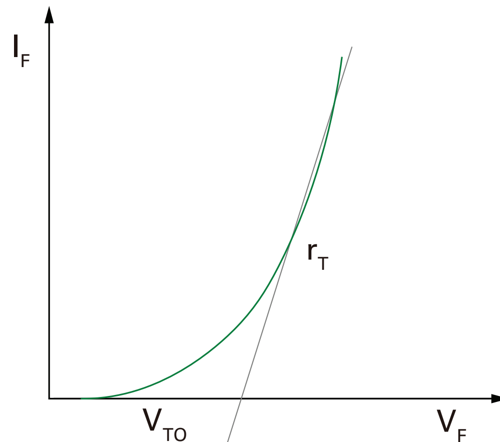

Figure 8. Typical forward voltage drop V_F versus current, its model $r_T \cdot I_F + V_{TO}$

The calculated losses, however, are only approximate values, as V_{T0} and r_T depend on the temperature and are only given for a certain virtual junction temperature, T_{vj}. Since this temperature can differ from the actual operating temperature, the calculated losses are only valid for the given temperature.

D.Turn-off: Apart from the on-state characteristic, the turn-off behavior is the most important parameter in determining the suitability of the diode for a high frequency application. When the current, I_F, is commutated to the transistor, it decreases linearly with the di/dt, at which the transistor turns on the current. In power MOSFETs and IGBTs, current change rates exceeding 1000 A/µs can easily be achieved. During this process, the carriers which have flooded the pn-junction during the on-state must be removed before the diode can begin blocking the reverse voltage. This removal leads to the reverse recovery current, I_{RM}, with the waveform affected by factors such as chip temperature, forward current, I_F, current change rate, $-di_F/dt$, and the diode's technology.

Figure 9 (a) and Figure 9 (b) portray how the reverse recovery current depends on the chip temperature of a gold doped– and platinum doped epitaxial diode of the same forward characteristic, respectively.

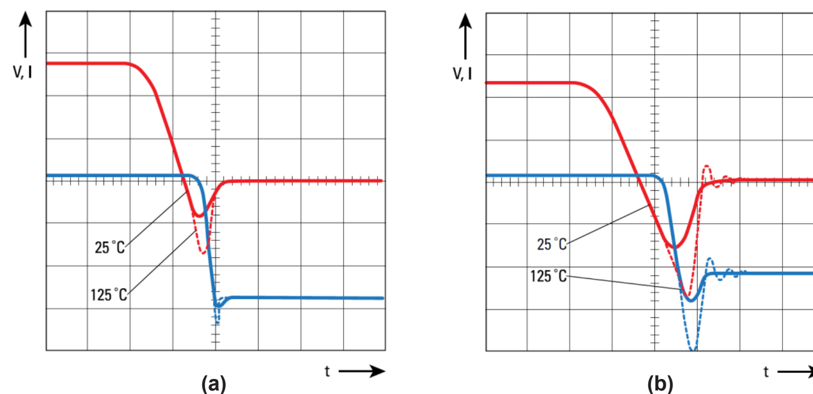

Figure 9. Reverse recovery current and voltage for two FRED diodes at T_{vj} = 25 °C and 125 °C: (a) gold doped diode, and (b) platinum doped diode

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The difference between the two technologies is particularly evident when comparing the recovery behavior at various current change rates $-di_F/dt$ and the same temperature. The gold-doped diodes with controlled minority carrier reduction maintain their soft recovery behavior, even at high $-di_F/dt$ values as demonstrated in Figure 10(a). For platinum-doped diodes, the decrease rate of the recovery current increases with increasing $-di_F/dt$-values as denoted in Figure 10(b), making the diode "snappy". The faster the recovery current decreases, the higher the overvoltage caused by the stray inductances of the circuit layout. If the maximum voltage exceeds the maximum blocking voltage of the transistor, it is preferable to design the circuit to reduce stray inductance. Snubbers could also be used as an option to ensure the safe operation of the equipment. Additionally, excessively high dv/dt values can lead to increased EMI.

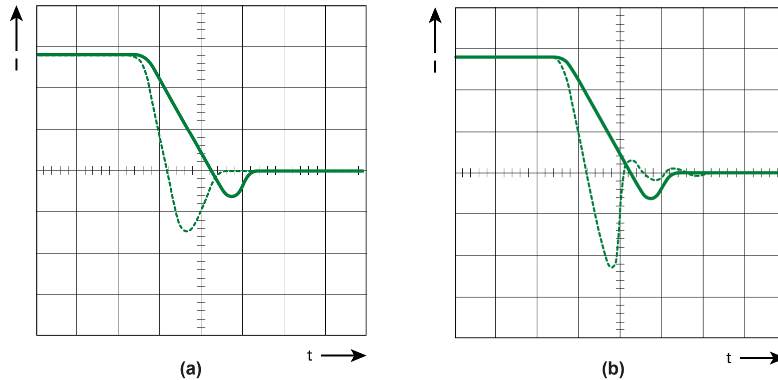

Figure 10. Reverse recovery currents for different $-di_F/dt$ values at T_{vj} 125 °C: (a) gold doped diode, and (b) platinum doped diode

The reverse recovery current of the diode not only influences the overall switching losses, but also significantly impacts the turn-on losses of the transistor, as the transistor must conduct both the diode's reverse recovery current and the inductor current during turn-on. This additional current increases the energy dissipated in the transistor. The reverse recovery current combines with the inductor current, resulting in a higher peak current during the transistor's turn-on period. Furthermore, the turn-on time of the transistor is effectively extended by a portion of the diode's reverse recovery time, t_{rr}, as presented in Figure 12 (a) and (b).

Figure 11(a) and Figure 11(b) emphasize the significance of a low peak recovery current accompanied by soft recovery behavior. First, the soft recovery behavior of the gold doped diodes entails a small overvoltage and a low reverse recovery current. Therefore, the diode is marked by low turn-off losses. Secondly, the low reverse recovery current leads to essentially reduced turn-on losses in the transistor. Thus, the choice of the diodes decisively influences the power losses in both devices.

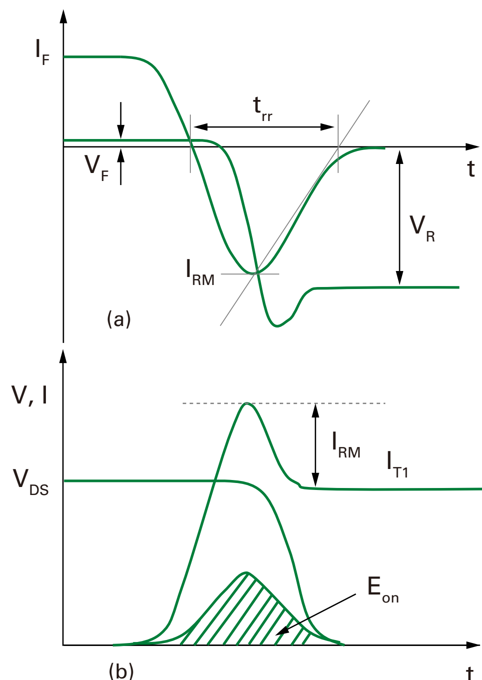

Figure 11. (a) Reverse recovery waveforms for a freewheeling diode and (b) its impact on transistor current and voltage waveform during commutation

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3. Buck-Converter Application Example

The buck-converter application depicted in Figure 6 is used to illustrate how to exemplarily calculate the power losses of the utilized FRED as a freewheeling diode D1. The epitaxial diode, type DSEI30-10A [6], is described in the datasheet, along with the respective data to calculate the power losses. Table 3 lists the selected operating conditions of a buck-converter for calculating power losses.

Table 3. Operating conditions of the buck-converter

Parameter	Value
DC-link voltage, V_{in}	600 V
Current fall time of MOSFET, t_f	60 ns
Output voltage, V_{out}	300 V
Switching frequency, f_{sw}	50 kHz
Inductor current, I_L	15 A
Duty cycle of the MOSFET, d	0.5
Max. junction temperature, $T_{vj(max)}$	125 °C

A. Maximum Blocking Losses: The blocking losses of the diode are calculated using the reverse current specified in the datasheet:

I_R	Reverse current, drain current	V_R = 1000 V	T_{vj} = 25 °C	750 µA
		V_R = 800 V	T_{vj} = 125 °C	7 mA

Here $V_R \approx V_{in}$ = 600 V. Using the value I_R = 7 mA at T_{vj} = 125 °C, V_R = 800 V, the blocking losses are calculated as given in equation (1).

$$P_{blocking} = V_{in} \cdot I_R | T = T_{vjmax} \cdot d \quad (1)$$

Assuming the worst-case scenario using the datasheet's maximum value at 125 °C, the result is equation (2).

$$P_{blocking} = 600\,V \cdot 7\,mA \cdot 0.5 = 2.1\,W \quad (2)$$

This 2.1 W is conservative because the 7 mA specification is given at 800 V; at actual 600 V, the leakage current is expected to be less than or equal to this value, resulting in a slightly lower blocking loss.

B. Turn-on Losses: The calculation of the actual turn-on losses is much more difficult than the calculation of the blocking losses or on-state losses. There is no static operation, the current and the voltage of the diode are functions of time and can only be calculated approximately by using exponential and hyperbolic equations.

To estimate the diode turn-on losses, the turn-on waveform is given in a simplified form in Figure 12. This simplification provides a margin of safety, ensuring that the calculated turn-on losses are slightly higher than those experienced in actual operation. By using this approach, calculations can be made directly from datasheet values with greater confidence.

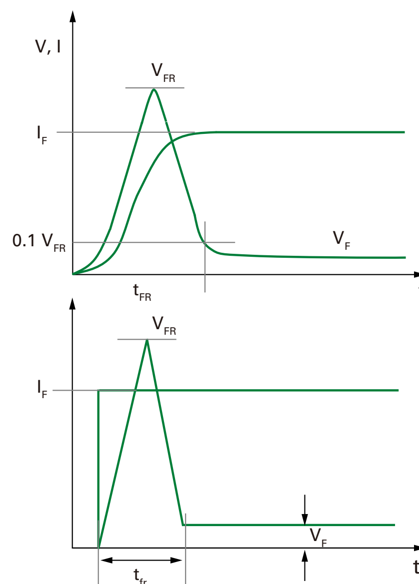

Figure 12. Actual diode turn-on V/I waveforms and their linearized approximations to simplify turn-on power loss calculations

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The current rise time is determined by the turn-off time of the MOSFET and the load current, as calculated in equation (3).

$$di_F/dt = I_F/t_F = (15\ A)/(60\ ns) = 250\ A/\mu s \quad (3)$$

The diagram in Figure 13 taken from the datasheet illustrates the relationship between the current change rate and both the turn-on recovery time (t_{fr}) and the peak forward voltage (V_{FR}) for $-di_F/dt = 250\ A/\mu s$, these values can then be used in the subsequent calculations of turn-on losses.

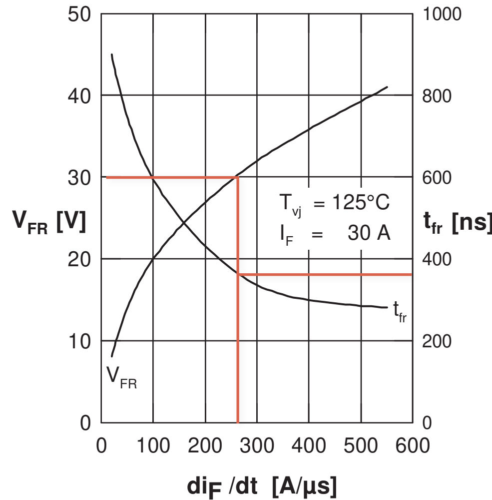

Figure 13. Peak forward voltage V_{FR} and t_{fr} as a function of di_F/dt from the DSEI30-10A datasheet

Reading the values reveals V_{FR} = ~29.5 V and t_{fr} = ~360 ns. To calculate the turn-on energy, the current, I_F, which is assumed to be constant, is multiplied by the triangle waveform of the overvoltage, V_{FR}, and by the time, t_{fr}, to obtain equations (4).

$$E_{on} = I_F \cdot V_{FR} \cdot t_{FR} \cdot 0.5$$
$$E_{on} = 15\ A \cdot 29.5\ V \cdot 360\ ns \cdot 0.5 = 79.650\ \mu J \quad (4)$$

The turn-on power losses can be calculated by multiplying the pulse energy E_{on} by the switching frequency, as seen in equations (5).

$$P_{on} = E_{on} \cdot f_{sw}$$
$$P_{on} = 79.650\ \mu J \cdot 50\ kHz = 3.982\ W \sim 4\ W \quad (5)$$

C. On-state Conduction Losses: Figure 14 from the datasheet depicts how to estimate the on-state forward voltage at I_F = 15 A and T_{vj} = 125 °C. Based on the V_F curve for T_{vj} = 100 °C, the forward voltage at 15 A is approximately 1.77 V.

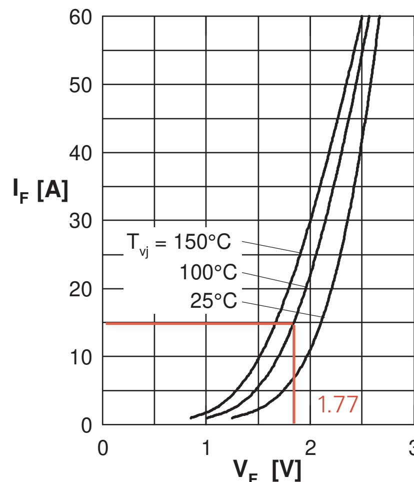

Figure 14. Forward current I_F as a function of the forward voltage drop V_F from the DSEI30-10A datasheet

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Thus, the on-state losses can be calculated, as shown in equations (6).

$$P_{cond} = V_F \cdot I_F \cdot d = 1.77\,V \cdot 15\,A \cdot 0.5 = 13.3\,W$$

When the on-state losses are calculated using the formula:

$$P_{cond} \approx (V_{T0} \cdot I_F + r_T \cdot I_F^2)(1\text{-}d), \text{ and with } V_{T0} = 1.5\,V \text{ and } r_T = 12.5\,m\Omega,$$

it results in a slightly smaller value: $P_{cond} \approx (1.5\,V \cdot 15\,A + 12.5\,m\Omega \cdot (15\,A)^2) \cdot 0.5 = 12.7\,W$ (6)

D. Turn-off Losses: Similar to the turn-on losses, the turn-off losses can only be calculated approximately using the datasheet values. Once again, the waveforms of the voltage and of the current are simplified in Figure 15.

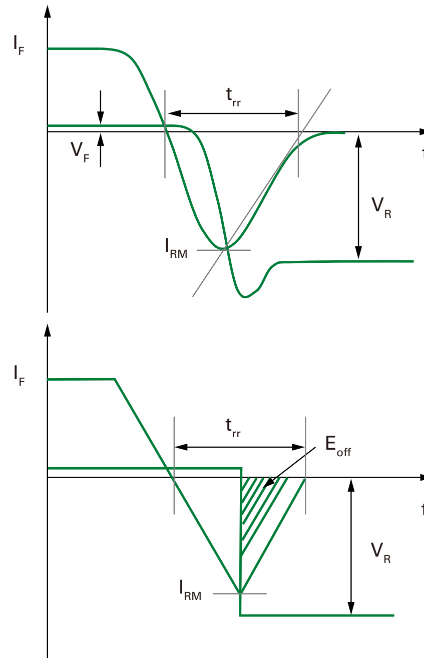

Figure 15. Actual diode reverse recovery I/V waveforms and their linearized approximations

Assuming the same di_F/dt as specified for turn-on, Figure 3 and Figure 5 of the datasheet indicate I_{RM} = 15 A and t_{rr} = 100 ns. These data are valid for T_{vj} = 100 °C and must be multiplied by a factor adjusting these data for T_{vj} = 125 °C. This factor K_f is given in the datasheet, as illustrated in Figure 16.

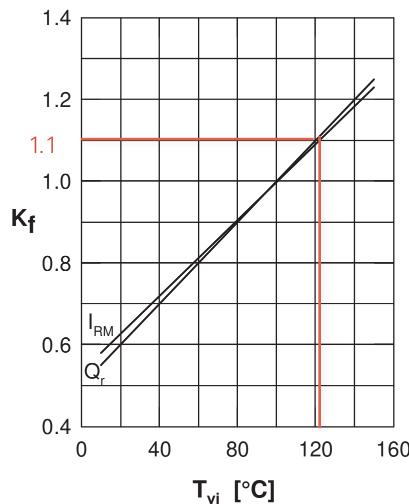

Figure 16. Dynamic parameter, I_{RM} versus T_{vj}

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For T_{vj} = 125 °C, the data for I_{RM} are to be multiplied by 1.1. This simplified calculation of the turn-off behavior results in a turn-off energy, as listed in equations (7).

$$E_{off} = I_{RM} \cdot K_f \cdot V_R \cdot (t_{rr}/2) \cdot 0.5$$
$$E_{off} = 15\,A \cdot 1.1 \cdot 600\,V \cdot 50\,ns \cdot 0.5 = 248\,\mu J \qquad (7)$$

Equations (8) shows that the multiplication by the switching frequency results in a turn-off power loss.

$$P_{off} = E_{off} \cdot f_{sw}$$
$$P_{off} = 248\,\mu J \cdot 50\,kHz = 12.4\,W \qquad (8)$$

E. Total Diode Losses: The total losses of the diode in the buck converter are calculated in equations (9).

$$P_{tot} = P_{blocking} + P_{on} + P_{cond} + P_{off}$$
$$P_{tot} = 2.1\,W + 4\,W + 13.3\,W + 12.4\,W = 31.8\,W \qquad (9)$$

The loss distribution of the free-wheeling diode in this example is illustrated with the diagram in Figure 17. In this example, the dynamic and static losses are very well balanced, where the percentage of dynamic loss contribution $P_{on} + P_{off}$ is approximately 52 %.

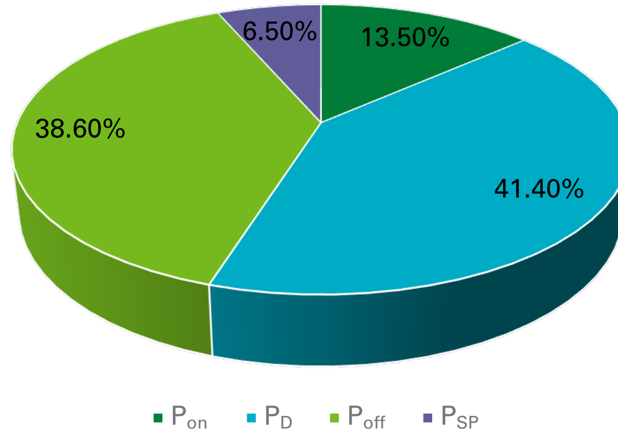

Figure 17. Loss distribution of the free-wheeling diode D1 in the buck-converter application

Both the thermal resistance values $R_{th(j-c)}$ = 0.9 K/W and $R_{th(c-h)}$ = 0.25 K/W are specified in the datasheet. Using these values, the chip temperature is calculated to be 29 °C higher than the case temperature. With a chip temperature limit of 125 °C, the maximum allowable heatsink temperature is, therefore, 88.2 °C, as determined by equations (10).

$$T_{Hmax} = T_{vjm} - (R_{th(j-c)} + R_{th(c-h)}) \cdot P_{tot}$$
$$T_{Hmax} = 125\,°C - (0.9+0.25)\,K/W \cdot 32\,W = 88.2\,°C \qquad (10)$$

While this example is based on a buck-converter circuit, the same approximations and calculations can be used for the boost-converter or other hard switching topologies.

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4. Additional Applications

The FRED technology is best suited for all kinds of free-wheeling functions, as detailed in the previous section with the buck-converter example. However, this functionality is hidden in many other applications as well.

4.1 Rectifier Diodes

When considering ultrafast epitaxial diodes for use as rectifier diodes, it is essential to evaluate specific application requirements such as the expected switching frequency and the necessary blocking voltage. Ultrafast epitaxial diodes are suitable for rectification only when the switching frequency exceeds 1 kHz and the blocking voltage requirement exceeds 200 V. These conditions are quite common in the output rectifier stage of switch-mode power supplies (SMPS), as illustrated exemplarily in Figure 18. SMPS generally operate with a Pulse Width Modulation (PWM) controller. Therefore, the mode of operation of the epitaxial diode used as a rectifier is very similar to that of a freewheeling diode. Since the current and voltage waveforms are rectangular, the power loss calculations can be performed using the same approach as in the case of the freewheeling diode, described in Section 2.

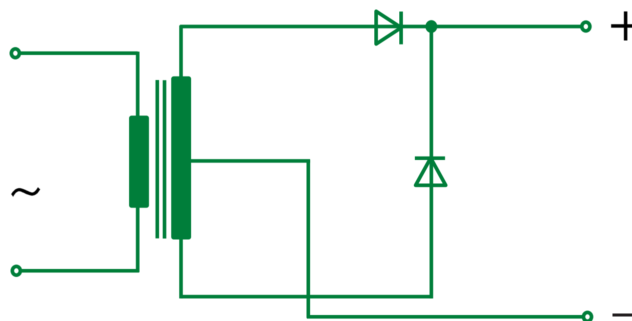

Figure 18. Center-tapped DC output circuit with common-cathode diode connection

4.2 Anti-parallel Diodes

An anti-parallel diode is a diode connected to a switching device, such as MOSFET or IGBT, represented in Figure 19, allowing for current flow in the opposite direction. This means the anode of the diode is connected to the emitter of the switching device, and the cathode of the diode is connected to the collector/drain of the switching device. Anti-parallel diodes are frequently used in inverters and DC-AC conversion circuits, where they provide a path for the reverse current when the switching device is turned off, thereby preventing voltage overshoot across the switch. Fast Recovery Epitaxial Diodes (FREDs) are particularly suitable for this purpose, as their fast and soft reverse recovery characteristics minimize switching losses and thermal stress in the complementary device, improving overall circuit efficiency and reliability.

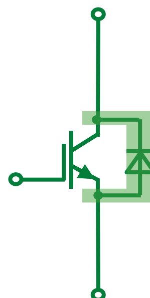

Figure 19. FRED as anti-parallel diode

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4.3 Snubber Diodes

Snubber circuits are used to protect power semiconductors from being destroyed by transient overvoltage spikes. The di/dt values of more than 1000 A/µs, which can be reached with MOSFETs or IGBTs, cause an overvoltage due to the parasitic stray inductances of the circuit wiring. The equation

$V_{ind} = L\sigma \cdot di/dt$ underlines how high these overvoltages can be, even at very low stray inductances. For example, a -di/dt of 1000 A/µs during a turn-off event with a stray inductance of 100 nH generates a voltage spike calculated in equation (11).

$$V_{ind} = 100\ \text{nH} \cdot 1000\ \text{A/µs} = 100\ \text{V} \qquad (11)$$

This 100 V spike, when added to the DC bus voltage, may or may not exceed the voltage rating of the switching device, depending on the system's operating voltage. For example, in a system with an 800 V_{DC} bus, a 100 V overshoot results in 900 V, which is well within the margin of a 1200 V-rated device. However, in a 100 V_{DC} system, the same overshoot could push the total voltage to 200 V, potentially exceeding the safe operating limit of a 200 V-rated device. In such cases, either a higher-rated device must be used, or the overshoot must be mitigated using a snubber circuit.

Snubber circuits can limit the generated overvoltage by transferring the energy stored in the stray inductances to a capacitor. Apart from its capacitance, the turn-on behavior of the diode determines the remaining overvoltage. The DSEI30-10A datasheet provides the forward recovery voltage, V_{FR}, that can be expected, and the forward recovery time, t_{fr}, for various di_F/dt values, as depicted in Figure 20.

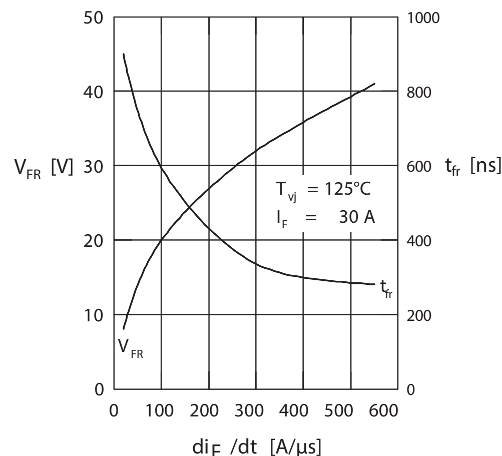

Figure 20. Typical peak forward voltage V_{FR} and t_{fr} versus di_F/dt of DSEI30-10A

Once the forward recovery characteristics are determined, the next step is to select and dimension an appropriate snubber circuit. The choice of snubber topology — RC, RCD, or DC clamp — depends on the switching frequency, energy dissipation requirements, and the nature of the voltage transients.

- RC snubbers are typically used in low-frequency applications to dampen oscillations and limit voltage spikes.
- RCD snubbers are more suitable for high-frequency switching environments, where they absorb and dissipate the energy stored in parasitic inductances.
- DC clamp circuits are employed when energy recovery is desired, improving overall efficiency.

The choice of the diode in the snubber circuit is equally important. Key parameters to consider include t_{rr}, V_{FR}, and softness factor. Diodes with fast and soft recovery characteristics reduce switching losses and minimize EMI, improving overall circuit efficiency. FRED diodes, with their epitaxial structure, offer low t_{rr} and soft recovery behavior, making them ideal for snubber applications in high-speed switching environments. Their predictable forward recovery behavior also helps limit voltage overshoot during turn-on, ensuring reliable clamping action. When designing snubber circuits, selecting a FRED diode with suitable voltage and current ratings, along with low V_{FR} and t_{rr}, is essential for optimal performance.

The component values for the snubber (R, C, and D) can be calculated based on the peak overvoltage, switching frequency, and the energy stored in the stray inductance. For detailed design methodology and practical examples, refer to [7] [8] [9], which outlines snubber dimensioning techniques for various power semiconductor configurations.

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5. Summary

As described in detail in this application note, ultrafast diodes have distinct characteristics, depending on the manufacturing process. These characteristics should be carefully considered in terms of their performance in various applications. For instance, replacing standard FREDs in an existing circuit with DSEI diodes can significantly reduce the power losses of both the diode and the transistor. Additionally, the soft recovery behavior of all DSEI diodes helps protect the transistor from excessive dv/dt or overvoltage spikes, while also minimizing conducted or radiated EMI.

The market for ultrafast diodes is constantly expanding. Apart from their standard application as freewheeling diodes in inverters, these diodes are also increasingly used in snubber circuits and in rectifier circuits in switch-mode power supplies. All FREDs delivered by Littelfuse are characterized by very low reverse recovery currents, even at high $-di_F/dt$. Simultaneously, they show a soft decrease of the reverse recovery current, thus avoiding inductive over-voltages with very high dv/dt. These over-voltages could cause a malfunction or even the destruction of an active switching device like MOSFET or IGBT.

The buck converter example shows that when selecting an ultrafast diode, all operating conditions should be considered together rather than evaluating individual parameters in isolation. In general, the diode losses are mainly determined by the forward voltage drop, V_F and reverse recovery characteristics.

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Revision History

Date	Revision	Changes
November 2025	1.0	Initial Release

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