C-Class Ultra Fast Recovery Diodes for High Speed Switching Applications

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Abstract

In this paper, a new family of planar ultra fast recovery diodes is introduced in the 300V to 1200V voltage range. The (3rd Gen.) *C-class* fast diodes were developed using a combination of modern design techniques to achieve very low switching losses along with the softest recovery characteristics to date. The C-class diodes ensure high immunity against common failure modes and reliable performance under all operating conditions. The new diodes also maintain low on-state voltages, a positive temperature coefficient during on-state, and low values of reverse leakage current at high temperatures. These performance advantages makes the C-class diodes very attractive for modern high frequency applications where a fast and rugged switching performance accompanied with low levels of Electromagnetic Interference (EMI) are essential.

Introduction

Fast recovery diodes play an important role in most power electronic circuits as freewheeling and/or snubber components. In modern high frequency applications, many design features are required for the diode in order to reduce the overall losses of the circuit, and to prevent any failure mechanisms that might occur during the diode switching transients. As a result, significant progress in the development of fast power diodes has been achieved in recent years with optimum trade-offs between the static and dynamic parameters matched with the requirements of the specific application. However, in spite of such progress, the diode is still considered by many circuit designers as the weak component in the application limiting the ability to increase the operating frequency and subsequently increasing the system's efficiency. Therefore, the development of new design techniques continues with the aim to further enhance the diode performance especially with regard to the dynamic performance while taking into account the manufacturing costs and process capabilities.

The most important features of modern fast recovery diodes are

a)*Low on-state voltage and positive temperature coefficient for optimum parallel diode operation.*
b)*Stable reverse blocking characteristics with low leakage current at elevated temperatures.*
c)*Low reverse recovery losses, soft recovery, and ruggedness against dynamic avalanching.*

Other features are also important in many applications such as surge current capability, avalanche energy withstand capability, and a low overshoot voltage during the diode turn-on transient period.

In this paper, a new range of ultra fast recovery diodes is introduced offering significant improvements in static and dynamic parameters. The new C-class diodes are primarily aimed at high speed switching applications as freewheeling components and fast rectifiers. The paper also outlines state of the art design techniques employed in the new range of diodes along with the resulting performance advantages. Experimental test results are included in order to verify the performance of the new diodes in modern applications.

Fast Diode Design Techniques

The P^+IN^+ epitaxial structure has usually been the favoured choice for diodes operating in low to medium voltage applications 300-1200V. Diodes are normally classified as P^+IN^+ depending on the drift region doping level. The P^+IN^+ diode is also referred to as the punch-through diode where under reverse bias, the depletion layer reaches the N^+ region before avalanche breakdown occurs. The conventional epitaxial diode shown in figure (1) with a highly doped and relatively deep diffused emitters has major drawbacks, exhibiting poor switching characteristics with a long reverse recovery time and a large reverse recovery charge. In addition, these diodes have also suffered from several failure mechanisms during reverse recovery due to snappy recovery and dynamic avalanching [1].Therefore, snubber protection circuits are usually used to achieve a softer diode recovery. However, these circuits are costly and bulky. Therefore the achievement of softer recovery by improving the diode structure is highly desirable especially in high frequency applications

As a result of modern process, new lifetime killing techniques and planar junction termination designs, rapid steps were introduced in the design of modern fast diodes. Three major design techniques brought about this improvement:

(1) Emitter Efficiency Control Techniques.
(2) Axial Lifetime Killing Control Techniques.
(3) Deep Diffusion Control Techniques.

By implementing the above techniques, high performance conventional and novel hybrid structures were introduced and implemented on an industrial scale (2)(3)(4). However, no structures has been reported combining the three methods especially in the low to medium voltage range. The C-class diodes reported in this paper are the first diodes to exploit this technology for diodes rated at less than 1200V.

C-class Diode Technology

The new C-Class range of ultra fast recovery diodes were designed by combining the three diode design control methods. Each technique contributes towards the control of the CHARGE DYNAMICS dominating the diode static and dynamic performance. Through subtle optimisation of the combined methods, a Triple Charge Control action was achieved as shown in Figure (1) when compared to previous generations of diodes using only one or two of the above techniques.

The first technique utilises a low P- emitter efficiency to control the gradient of the excess carrier concentrations. The shape and distribution of the stored charge in the drift region is a very important factor affecting the reverse recovery characteristics of the diode. The increasing carrier distribution profile towards the NN^+ interface is preferred for achieving softer recovery characteristics and lower reverse recovery losses compared to a flat or decreasing carrier profile (5). The low emitter efficiency also contributes to the achievement of a positive temperature coefficient on-state characteristics which is essential for parallel operation of diodes.

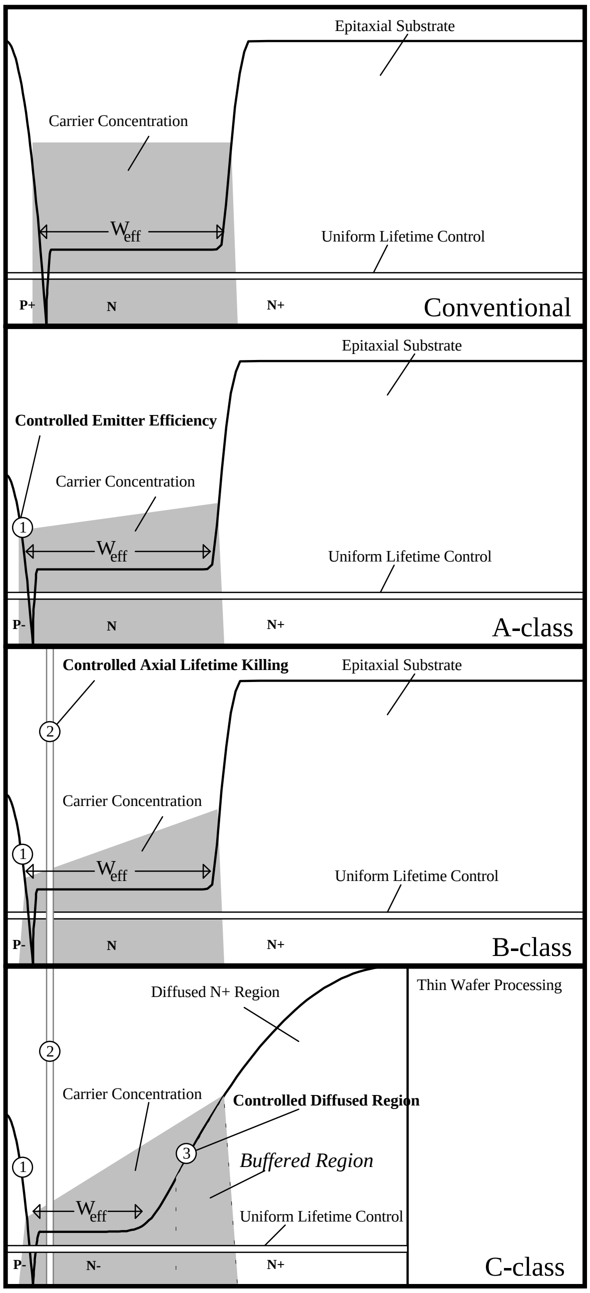


Figure (1) Evolution of Ultra Fast recovery Diodes using Combined Control Techniques.

Further control of the gradient charge profile is achieved by the use of controlled local lifetime in the drift region nearer the PN junction. The use of local lifetime killing processes such as Proton or Helium implantation have enabled the control of the axial carrier lifetime profile. This method allows a recombination layer with low lifetime values near the PN junction to effectively reduce the reverse recovery parameters and generate a softer recovery without increasing the forward voltage drop. The high lifetime value near the NN^+ interface will provide the additional residual charge for softer recovery. In addition, by adding a uniform lifetime killing using electron irradiation, we can control the softness of the diode during reverse recovery. Also, this method of carrier lifetime control will not increase the leakage current substantially when compared to other techniques such as gold diffusion.

However, the control of the gradient of the carrier concentration has still proved ineffective. Under certain combinations of forward current, commutating di/dt, circuit inductance, and junction temperature, it is likely that the diode can be made to produce excessive voltage spikes due to snappy recovery (6). Snappy recovery is normally caused by the sudden disappearance of the minority carriers stored in the drift region. This often occurs when the depletion layer reaches the N^+ region in punch-through epitaxial structures during the recovery phase, resulting in a current chop-off, and extremely high di/dt's, and hence large voltage spikes as shown in figure (2).

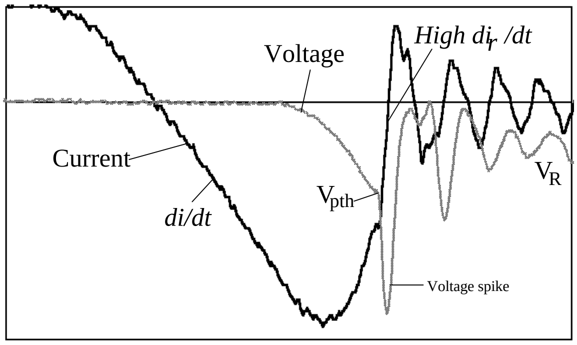


Figure (2) Typical reverse recovery current and voltage waveforms showing hard snappy recovery behaviour due to punch-through.

In order to prevent snappy recovery in epitaxial structure, N-Buffer layers were introduced with higher doping levels in front of the N^+ substrate. This region reduces the spreading out of the depletion layer, providing the extra charge needed for softer recovery. The doping level of the buffer layer should be high enough to prevent the depletion layer from reaching the NN^+ junction but low enough to allow for conductivity modulation. However, these designs, in addition to the extra cost of a second epi-layer, can still exhibit snappy recovery under certain extreme conditions.

By adopting a controlled deep diffused N^+ layer combined with the controlled graded stored charge profile, a 'progressive punch-through' action is achieved in the NN^+ interface which practically resembles a buffer region. Hence, the effective drift region width W_{eff}, doping and the punch-through voltage can be reduced safely without the device becoming snappy. Also, by using thinner wafers, the forward voltage drop can be reduced to levels approaching those of an epitaxial structure. This technique ensures that the stored charge remains at the NN^+ interface at the latter stages of the recovery period, whilst the deep diffused N^+ layer prevents the depletion layer from sweeping out the remaining carriers ensuring soft recovery characteristics under extreme conditions. Rugged performance was also achieved by having a suitable excess carrier profile in the drift region and maintaining clean and uniform processes with optimum edge termination and contact designs as shown in figure (3).

Finally, oscillations occurring during reverse recovery when operating at high switching speeds were also taken into account. This type of behaviour is widely mistaken for snappy recovery and is due to a low level of stored charge remaining during reverse recovery. Although oscillatory recovery characteristics do not normally lead to destructive voltage overshoots, it can cause high electromagnetic interference EMI which is highly undesirable in modern power electronics applications. The new C-Class diodes maintain ultra soft recovery characteristics with minimum EMI levels under all conditions.

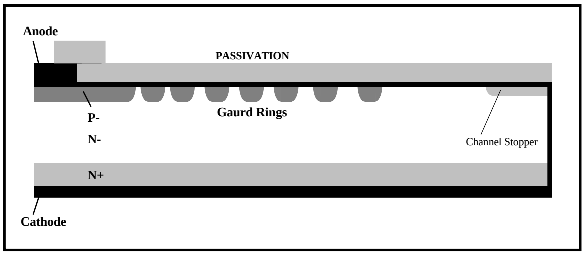


Figure (3) Planar Junction termination design of C-class diodes.

Experimental results are presented in the following section showing the performance advantages of the 600V - 1200V C-class diodes both for the static and dynamic parameters.

Reverse Recovery of C-class diodes

In order to confirm and verify the performance of the new C-class diode range, a number of tests under different operating conditions were carried out using an inductive load test circuit shown in figure (4). Results were obtained for a number of 600V and 1200V C-class diodes and compared with state of the art ultra fast diodes using conventional technologies.

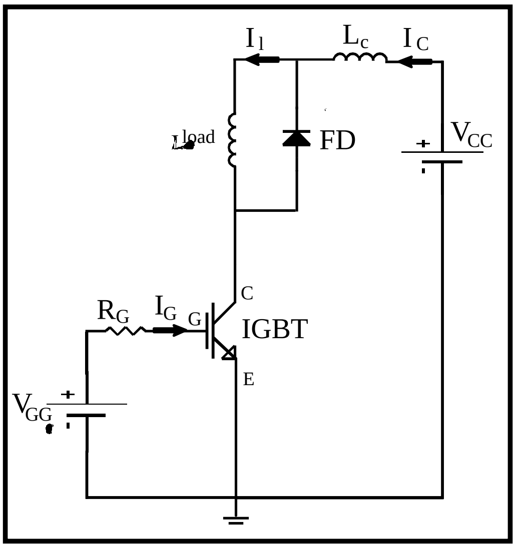


Figure (4) IGBT and freewheeling diode in an inductive load test circuit.

Figure (5) shows the reverse recovery current waveforms for a 30A/1200V C-class diode compared with a 30A/1200V ultra fast conventional diode. The test was carried out at a forward current of 5A to verify the device performance at low currents. The figure clearly indicates that the C-class diode maintains soft recovery characteristics compared to the conventional diode even at low currents and high di/dts.

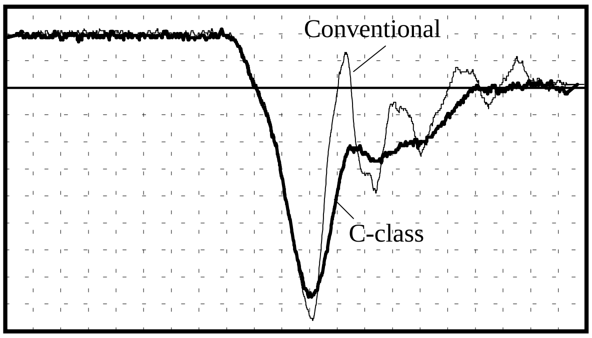


Figure (5) Experimental results showing the reverse recovery current waveforms for 1200V/30A fast diodes. (V_{cc}= V_R=600V, I_c=I_F=5A, di/dt=500A/us, 25^{o}C) [2.5 A/div, 25 nsec/div]

Figure (6) shows the reverse recovery current waveforms for both diodes at two different temperature (25^{o}C & 125^{o}C). The waveforms show that the C-class diode is less temperature dependent with regard to the switching performance. While the C-class diode peak recovery current increases by 23% at 125^{o}C, the conventional diode increases by 40%. The C-class diodes ensures lower losses in the system when operating at higher temperatures.

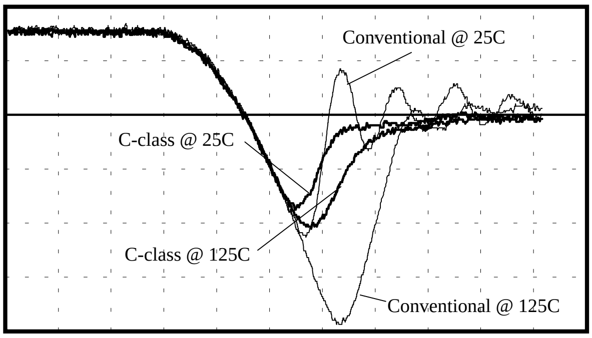


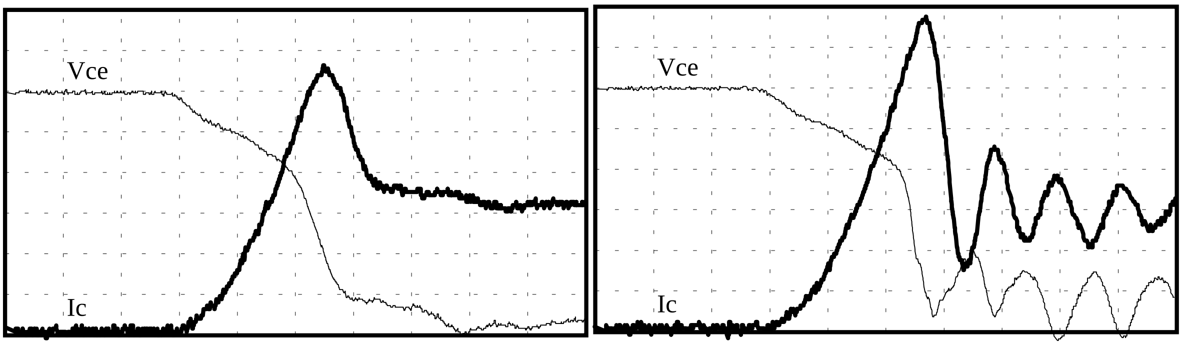
Figure (6) Experimental results showing the reverse recovery current waveforms for 1200V/30A fast diodes. (V_{cc}= V_R=600V, I_c=I_F=30A, di/dt=800A/us, 25^{o}C & 125^{o}C) [20 A/div, 50 nsec/div]

Figure (7) and (8) shows experimental results for the IGBT and freewheeling diode current and voltage waveforms during IGBT turn-on. The results confirm that the C-class diode has lower losses and very soft recovery characteristics compared to the high oscillatory recovery of the conventional ultra fast diode even at a voltage level routinely encountered in applications. The power losses curves shown in figure (9) also confirm a lower peak power loss in both the IGBT and C-class diode.

The diodes then were tested under higher stress condition at a rail voltage of 1000V (i.e. 83% of the breakdown voltage) and at a high commutating di/dt of 1600A/usec. The C-class diode survived these conditions as shown in figure (10), although the current waveforms clearly shows the diode in a dynamic avalanche mode represented in a current bump during the recovery phase. However, figure (10) also shows that the conventional ultra fast diode failing under these conditions. It can be concluded that, by employing a C-class diode in the system, a further reduction in the IGBT losses can be realised by operating the circuit at higher switching speeds without risking a diode failure or generating high levels of diode electromagnetic interference.

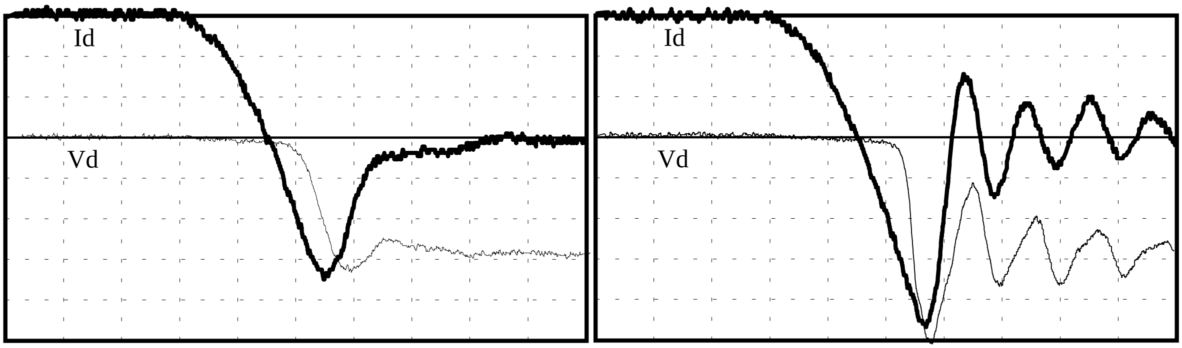
Similar results were also obtained for a 30A/600V C-class diode when compared to a 30A/600V ultra fast conventional diode as shown in figure (11). The C-class diode shows soft recovery characteristics while the conventional ultra fast diode exhibits oscillatory recovery characteristics, a higher peak recovery current and a larger overshoot voltage.

The 600V C-class diode also survived when tested under high stress condition at a rail voltage of 550V (i.e. 90% of the breakdown voltage) as shown in Figure (12).



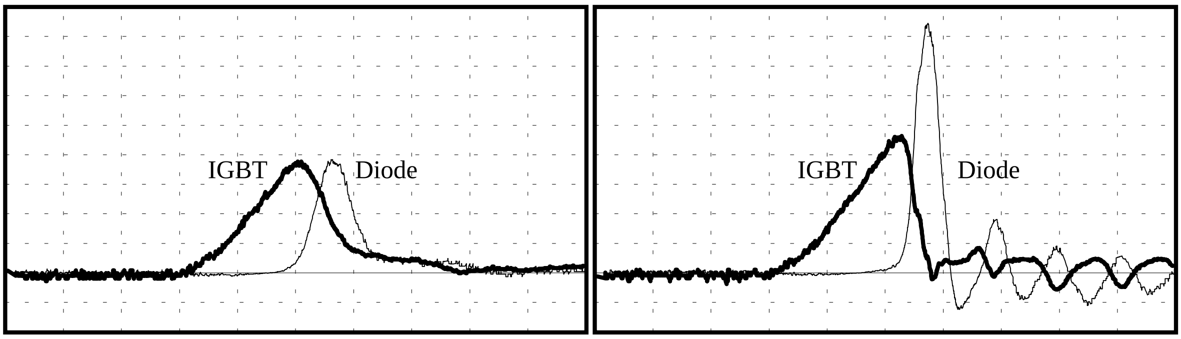
C-class Diode **Ultra Fast Conventional Diode**

Figure (7) Experimental results showing the IGBT current and voltage waveforms during IGBT turn-on for 1200V/30A fast diodes. (V_{cc}= V_R=600V, I_C=I_F=30A, di/dt=800A/us, 25^{o}C) [10 A/div, 100 V/div, 50 nsec/div]



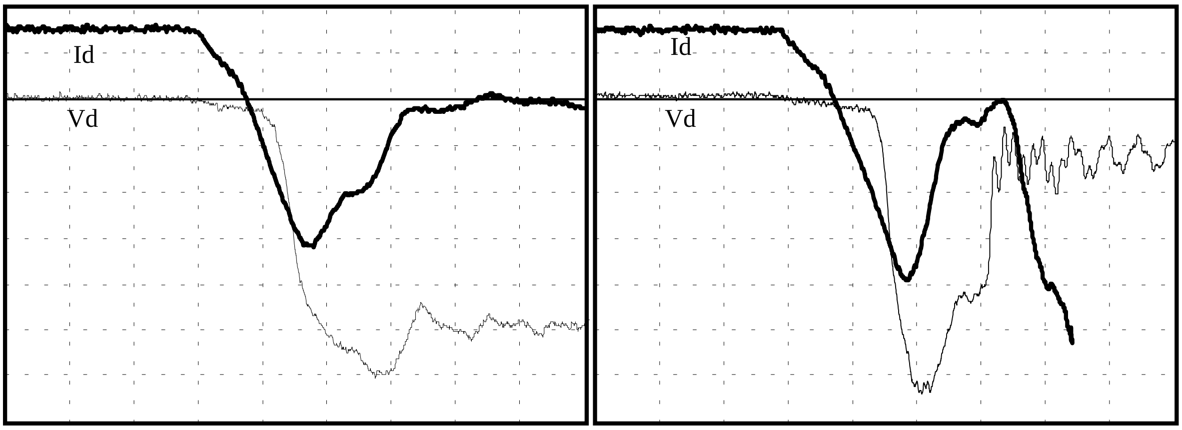
C-class Diode **Ultra Fast Conventional Diode**

Figure (8) Experimental results showing the freewheeling diode current and voltage waveforms during IGBT turn-on for 1200V/30A fast diodes. (V_{cc}= V_R=600V, I_C=I_F=30A, di/dt=800A/us, 25^{o}C) [10 A/div, 200 V/div, 50 nsec/div]



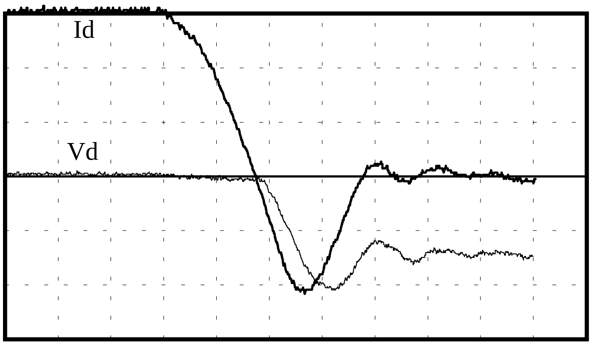
C-class Diode **Ultra Fast Conventional Diode**

Figure (9) Experimental results showing the IGBT and freewheeling diode power losses curves during IGBT turn-on for 1200V/30A fast diodes. (V_{cc}= V_R=600V, I_C=I_F=30A, di/dt=800A/us, 25^{o}C) [5 kW/div, 50 nsec/div]

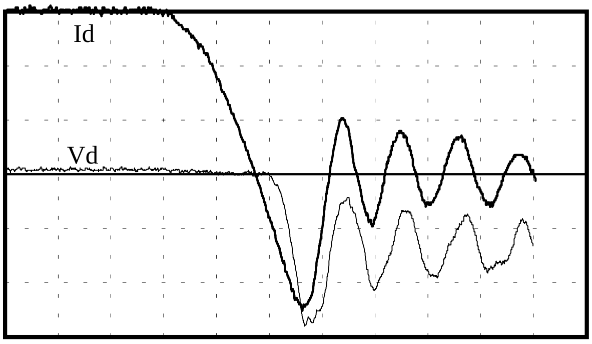


C-class Diode **Ultra Fast Conventional Diode**

Figure (10) Freewheeling diode current and voltage waveforms during IGBT turn-on for 1200V/30A fast diodes. (V_{cc}= V_R=1000V, I_C=I_F=30A, di/dt=1600A/us, 25^{o}C) [20 A/div, 200 V/div, 50 nsec/div]

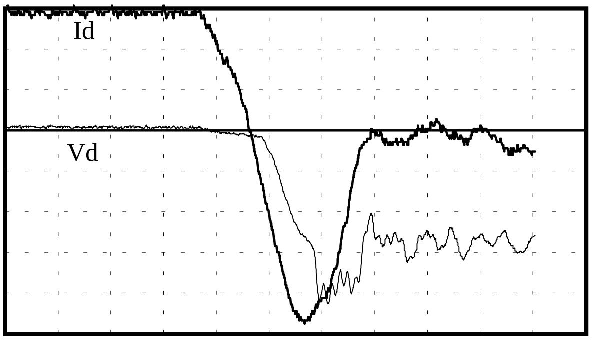


C-class Diode



Ultra Fast Conventional Diode

Figure (11) 30A/600V Freewheeling diode current and voltage waveforms during IGBT turn-on. (V_{CC}= V_R=300V, I_C=I_F=30A, di/dt=600A/us, 25^{O}C) [10 A/div, 200 V/div, 50 nsec/div]



(12) C-class 30A/600V diode current and voltage waveforms during IGBT turn-on. (V_{CC}= V_R=550V, I_C=I_F=30A, di/dt=1200A/us, 25^{O}C) [10 A/div, 200 V/div, 50 nsec/div]

Static Performance of C-class diodes

All C-class diodes have a positive temperature coefficient for the on-state characteristics. The 1200V diode has a forward voltage drop at its rated current of 2.2V at 25^{O}C and 2.3 at 125^{O}C. Also, the 600V diode has a forward voltage drop at its rated current of 1.75V at 25^{O}C and 1.82 at 125^{O}C. In addition, the leakage current for both the 1200V and 600V C-class diodes does not exceed 1mA hot (i.e. 125^{O}C) at the breakdown voltage.

The C-class diode range is also avalanche energy rated with surge current withstand capabilities and will be available in the 300V-1200V voltage range and with current ratings from 10A to 200A.

Conclusion

A new family of ultra fast power diodes in the 300V - 1200V voltage range is introduced. This paper outlines the design techniques used for optimising the new range of diodes. The main three techniques are based on optimising the diode structure parameters including emitter efficiency control, local lifetime control and controlled deep diffused N^+ layers. Optimum performance is achieved by adopting each of these methods in the diode design. High immunity against common failure modes along with low static and dynamic losses was achieved by controlling both the stored charge gradient and the NN^+ interface doping profile.

References

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