Optimized diode design for IGBT's and GCT's switching circuits.

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Abstract
In a modern power converter, the high performance of semiconductor switches, like IGBTs and GCT's, imposes hard turn-off to diodes, with fast current gradients resulting in undesirable and dangerous overvoltages. A new family of optimized diodes has been developed as well as a new test circuit able to evaluate the diode behavior under real operation conditions.

Introduction

The technological trend in high power converters pushes towards the use of active semiconductor devices having low switching losses and reduced need of auxiliary circuits (snubber/clamp). In this regard, the most interesting devices are high voltage IEGTs [1] / IGBT s [2], [3], and IGCTs [4] having the following common features:
they allow high switching speed at both turn-on and turn-off;
they are press-pack mounted, for easy series connection;
they are, in most cases, asymmetrical, so that the free-wheeling diode has to be provided externally;
The dI/dt limit at turn-on is due to the reverse-recovery features of the free-wheeling diode; therefore, the availability of a fast and soft-switching, high-voltage (e.g., 4.5-6.5 kV) free-wheeling diode may enable a relevant reduction of turn-on snubber inductance, with consequent cost, power loss, and weight reduction.
Overvoltage clamps, to reduce overvoltage at turn-off, and full turn-off snubbers for overall losses reduction [5], are also frequently adopted. For both voltage clamp and snubber circuits, it is necessary to employ high voltage diodes having low forward recovery voltage and fast and soft reverse recovery characteristics.
For the reasons outlined above, fast-recovery diodes play a key role as freewheeling, snubber or clamp diodes in topical power converters, where the excellent switching performance of new power semiconductor switches imposes them very hard turn-off condition, with fast current gradients that may result in large overvoltages [6]-[9]. Optimal diode design for these applications should therefore offer a satisfactory trade-off among features such as:
soft recovery, which limits overvoltages and oscillations;
low reverse-recovery current (Irr), to allow a high dI/dt diode capability at turn-off
low energy loss during recovery.
The first requirement is particularly important, since PIN fast-recovery power diodes must typically be protected by snubber circuits that limit the dangerous overvoltages caused by steep current ramps, which can damage the diode and the surrounding elements. Due to the complexity and cost of snubber circuits and the lack of uniformity of the solutions adopted by the manufacturers, PIN power diodes able to withstand snubberless operation are extremely desirable. In this respect, the problem is that of
designing diode structures ensuring self-limitation of the peak reverse voltage at the moment of current switch-off [10]-[13].
The aim of this contribution is therefore to present a new family of optimized diodes for snubber-free operation, as well as a new test circuit able to evaluate the diode switching behavior under realistic conditions.

Diode features

To evaluate the performance of different technologies and designs, a complete set of press-packed PIN diodes (φ = 56 mm, 4500 V) have been designed and fabricated by POSEICO with the following features:
different values of the base width
different values of the base resistivity
uniform reduction of base lifetime through electron irradiation (EI)
axial control of base lifetime through proton irradiation (PI)
The qualitative results are reported in Table I where are summarized the electrical effects of the process variation.

Table I

	Increase of base width	Increase of base resistivity	Uniform lifetime reduction (EI)	Axial lifetime control (PI)
Recovery softness	↑	↑	↓	↑
Oscillation during recovery	↓	↑	↑	↓
Snap-off voltage	↑	↓	↓	↑
Reverse-recovery current	↓	-	↓	↓
Energy loss during reverse recovery	↑	-	↓	↓
Energy loss during forward recovery	↑	↑	-	-
Forward voltage drop	↑	-	↑	-
On-state energy loss	↑	-	↑	-

The arrows show the effects on the diode electrical characteristics of more important process options reported on the first line.

Testing

A new test set-up has been designed and built up with the purpose of:
reproducing the hard switching conditions encountered by the diodes in their operating life (i.e., current gradients up to 2000 A/s, peak voltages up to 3200 V, temperatures in the range 25 ?150C).
measuring diodes with different designs in order to extract optimization criteria.
A schematic picture of the equipment, which uses a high-current, high-voltage, press-packed IGBT as a switching element, is shown in FIG. 1.
By using this circuit, it is possible to measure the diode under test (DUT) under typical operating conditions (FIG. 2) and under limit conditions as well (FIG. 3). During the test, the diode is not protected by any snubber circuit, in order to allow possible overvoltages and dangerous oscillations to show up.

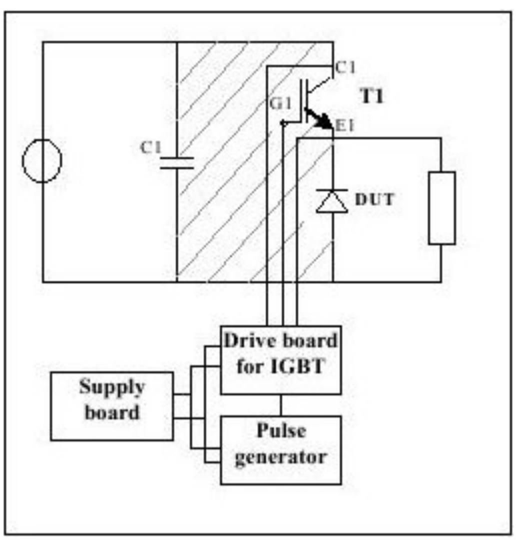

FIG. 1 - Schematic picture of the equipment for diode testing under high-dI/dt and high-voltage switching condition. T1 is a high-current,

high-voltage press-packed IGBT.

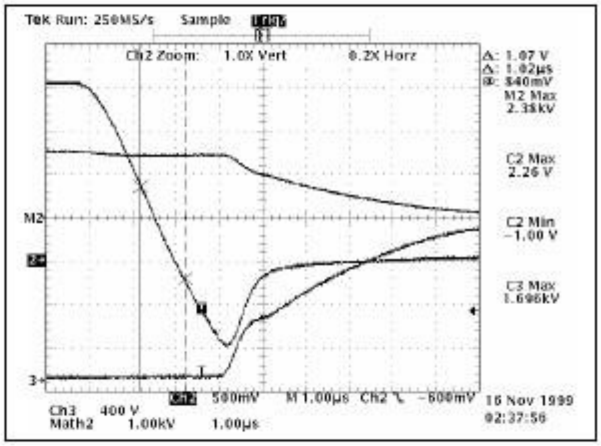

FIG. 2 Diode reverse recovery characteristics under typical switching conditions: IF = 2100 A, dI/dt = 1100 A/s, VR = 1800 V, Tj = 125 C.

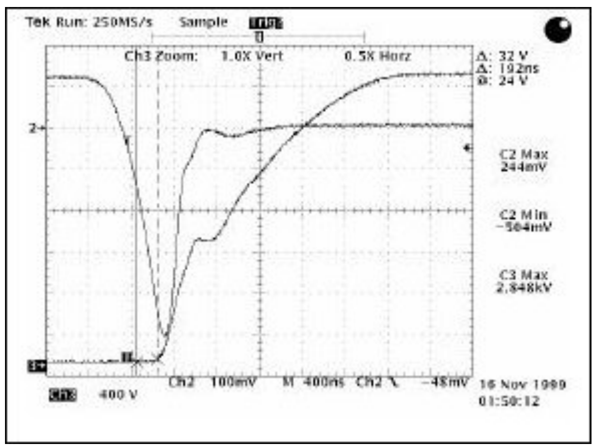

FIG. 3 Diode reverse recovery characteristics under limit switching conditions: IF = 100 A, dI/dt = 1700 A/s, VR = 2800 V, Tj =25 C.

Numerical simulations

The experimental study was complemented by the use of a commercial numerical tool, able to simulate the diode behavior under realistic conditions. This tool uses a mixed-mode simulation technique, whereby the diode is simulated by a finite-element method and a drift-diffusion model, whereas the rest of the circuit is treated in a SPICE-like fashion.

We simulated several diode structures, with different intrinsic base width, resistivity and carrier lifetime [10]. For each structure we simulated the reverse-recovery transient with different values of the forced dI/dt. These simulations allowed to extract the softness factor and the maximum reverse voltage (snap-off voltage) that the diode can withstand without experiencing spurious oscillations, dangerous for the device and the surrounding circuit. Moreover, the simulations allowed us to study the behavior of diodes switching under conditions (very high dI/dt and reverse voltage > 3200 V) that lie beyond our experimental set-up capability.

FIG. 4 shows the simulated reverse recovery of samples D9 (ρ = 260 Ωcm, W = 110 m, electron dose = 15 KGy) and E8 (ρ = 260 Ωcm, W = 235 m, electron dose = 15 KGy), both with dI/dt = - 80 A/s, while FIG. 5 shows the simulated behavior of samples E8 (ρ = 260 Ωcm, W = 235 m, electron dose = 15 KGy) and G10 (ρ = 360 Ωcm, W = 235 m, electron dose = 15 KGy), both with dI/dt = - 490 A/s.

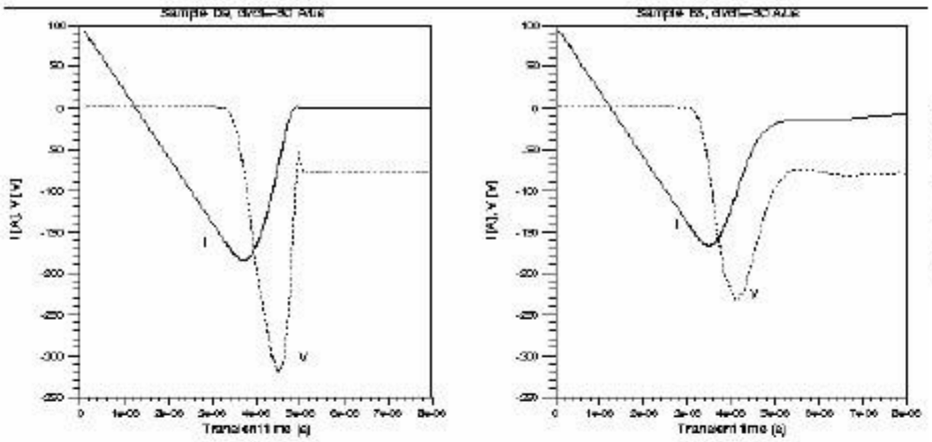

FIG. 4
Simulated reverse recovery for two diodes with different base width.

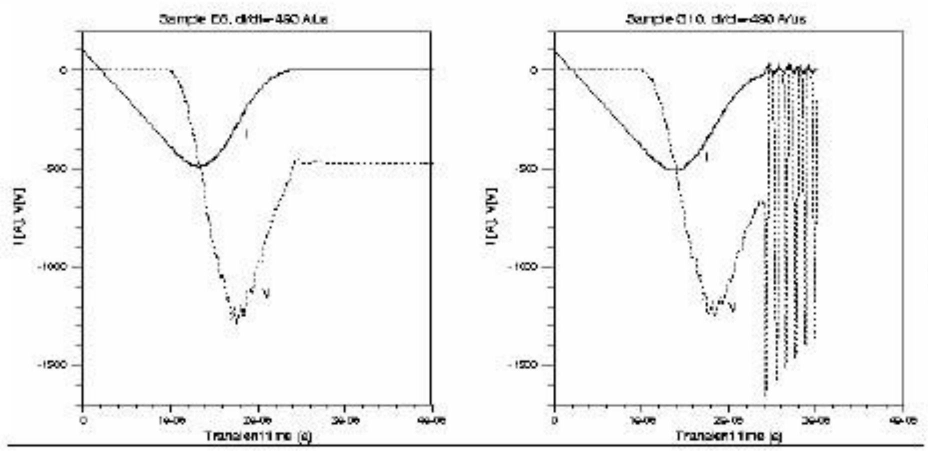

FIG. 5
Simulated reverse recovery for two diodes with different base resistivity.

Applications
The amount of data collected by measures and by numerical simulations, have been used for the design and realization by POSEICO of a new diode family optimized for IGBT and GCT circuit. The blocking voltage are 3.3 - 4.5 and 6.5 KV and the range of current is 250 ?1500 A.
The diodes of this new family have been employed as free-wheeling and snubber diodes for the half-bridge assembly developed by AnsaldoBreda [14] and based on press-pack IGBT/IEGTs (4500 V / 3000 A), for use in traction power converter for locos, high-speed trains and double-deck trains.
As part of the assembly, the diodes were submitted to a full testing cycle, including electrical (FIG. 6) and thermal test and a full power endurance test on inductive load. Finally, the assemblies have been successfully tested in the field. A high-speed train ETR 500 P (FIG. 7), equipped with a 2.2 MW IEGT converter has been extensively tested on the test track of Velim (Czech Republic). The IEGT/IGBT converter will shortly be in commercial operation.
Another application using POSEICOs optimized diodes is a NPC inverter leg for industrial motor control shown in FIG. 8. In this case the switch devices are press packed GTC cooled with a heat pipe system. This 3.8 MW circuit works at Vdc=5600 V, the diodes can withstand a current gradient of about 500 A/s without oscillations due to their recovery features.

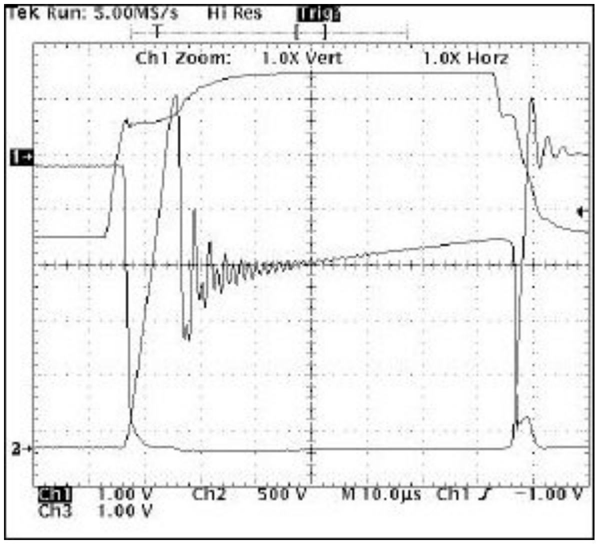

FIG. 6 Double pulse test on IEGT half-bridge assembly: Turn-off current = 2000 A, V dc-link = 2800 V. The overcurrent waveform at turn-on corresponds to free-wheeling diode reverse recovery.

FIG. 7 High-speed train ETR 500 P

FIG. 8 leg for industrial motor control

Conclusion

A complete analysis, based on protoypes testing and numerical simulation has been performed with the aim to obtain optimized diodes for application in IGBT and GCT high power circuits A new family of diode has been developped and successfully tested in real condictions both for traction (inverter for high speed trains) and industrial application (inverter for industrial motor control).

References

[1] H. Matsuda et al. High power /4.5 kV, 4 kA turn-off IEGT, in Proc. 8th European Conf. Power Electronics and Applications (EPE'99), 1999.

[2] F. Auerbach et al. 6.5 kV IGBT modules, in Proc. PCIM99, Nuremberg (D), 1999 [3] Y. Takahashi et al. 4.5 kV, 1200 A Power Pack IGBT, in Proc. PCIM99, Nuremberg (D), 1999

[4] P. K. Steimer et al. IGCT - a new emerging technology for high power low cost inverter, in IEEE.IAS Annual Meeting, 1997

[5] R. Marquardt et al: Advanced IGBT converters using 4.5, 6.5 kV devices, in Proc. 8th European Conf. Power Electronics and Applications (EPE'99), 1999.

[6] M. Beuermann, D. Westerholt, Turn-off capability of GTO snubber diodes, in Power Conversion, June 1997 Proc., pp. 29-33.

[7] A. Weber, N. Galster, E. Tsyplakov, A new generation of asymmetric and reverse conducting GTOs and their snubber diodes, in Power Conversion, June 1997 Proc., pp. 475-485.

[8] M. T. Rahimo, W. J. Findlay, L. Coulbeck, An improved design for ultra soft-fast recovery diodes suitable for (600-1200V) IGBT applications, in Power Conversion, May 1998 Proc., pp. 409-417.

[9] N. Galster, H. Vetsch, M. Roth, E. Tsyplakov, E. Carroll, The design, application and production-testing of high-power fast recovery diodes, in Power Conversion, May 1998 Proc., pp. 55-65.
[10] M. Pasqualetti, M. Portesine, R. Scicolone, B. Zerbinati, R. Menozzi, A. Bellini, P. Cova, Effect of the physical structure on the recovery softness of PIN diodes: experimental and numerical analysis, in Proc. 7th European Conf. Power Electronics and Applications (EPE'97), pp. 4.013-4.017, 1997.
[11] H. B. Assalit, L. O. Eriksson, S. J. Wu, High power controlled soft recovery diode design and application, in Proc. Industrial Applications Symp. (IAS), pp. 1056-1061, 1979.
[12] M. T. Rahimo, N. Y. A. Shammas, Optimisation of the reverse recovery behaviour of fast power diodes using injection efficiency and lifetime control techniques, in Proc. 7th European Conf. Power Electronics and Applications (EPE'97), pp. 2.099-2.104, 1997.
[13] R. Barthelmeß , M. Beuermann, N. Winter, New diodes with pressure contact for hard-switched high power converters, in Proc. 8th European Conf. Power Electronics and Applications (EPE'99), 1999.
[14] L. Fratelli, G. Bocchetti , Press-pack IGBT converter for heavy locos and high-speed trains: International Conference on Railway Traction Systems, Capri, Italy 15-17 May 2001.

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