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A comparison of charge dynamics in the Reverse-Conducting RC IGBT and Bi-mode Insulated Gate Transistor BiGT

Liutauras Storasta, Arnost Kopta and Munaf Rahimo
 ABB Switzerland Ltd, Semiconductors
 Lenzburg, Switzerland
 e-mail: liutauras.storasta@ch.abb.com

Abstract—In this paper we present the analysis of charge dynamics in the reverse conducting (RC)-IGBT and the Bi mode Insulating Gate Transistor (BiGT). The differences and similarities between the two device concepts are analyzed with the aid of 2D device simulations using a realistic 3.3kV device model. The influence of the anode shorts dimensioning and buffer design on the on-state characteristics and the snap-back effect is discussed and the advantages of the hybrid BiGT structure are demonstrated. It is shown that the application of the BiGT structure decouples the conventional RC-IGBT design trade-offs with respect to the diode and IGBT areas in relation to the snap-back effect. Main design principles for optimal IGBT and diode performance are outlined.

I. INTRODUCTION

Reverse conducting devices offer an attractive solution for increasing power density in IGBT modules. As the same chip is utilized in IGBT and free-wheeling diode modes, the required area for achieving the same power is decreased. In addition, the temperature oscillations of the chips are greatly reduced which leads to improved reliability of the power modules. Despite many advantages, until recently reverse conducting devices did not offer comparable performance to the traditional two chip approach. Difficulty to optimize the same silicon for both modes usually limited the employment of these devices to soft-switching applications [1]. It has been recently demonstrated, that the BiGT concept, consisting of a hybrid structure comprising an RC-IGBT and a standard IGBT, offers a significantly improved on-state characteristics compared to the state-of-the-art RC-IGBT [2].

Fig.1 shows a comparison between the measured on-state I-V characteristics of different reverse conducting devices. The voltage snap-back, a typical negative differential resistance region is observed in RC-IGBTs [1-3]. This part of the I-V characteristics could have a negative impact when the devices are paralleled, especially at low temperature conditions. The peak voltage before the snap-back is significantly reduced or even eliminated in a BiGT device designs. However, further studies with regard to the design

principles of the BiGT will enable better understanding of the device behavior and continuous optimization. Until now, simulation and experimental investigations have been focused on RC devices [3] while hybrid BiGT structure adds another dimension of complexity to the design. In addition, the BiGT device is required to operate under hard-switching conditions in both IGBT and diode modes and fulfill the rigorous robustness standards set on power devices today. For that reason, the trade-offs between the diode and IGBT modes must be carefully considered. The above topics are addressed in this paper.

II. DEVICE SIMULATION STRUCTURES

The device structures used in the simulations are presented in Fig. 2. As a basis, a 3.3 kV 62.5 A Enhanced-Planar SPT IGBT structure was utilized. For simulations of the on-state characteristics in the IGBT mode, large device structures measuring up to 2.5 mm were modeled in order to give a realistic representation of the BiGT concept. With the aim to reduce the number of mesh points, the MOS cell was replaced with equivalent n+ source emitters located with the same periodicity on the front emitter-side. On the device collector side, the n+ diffusions (anode shorts) were distributed

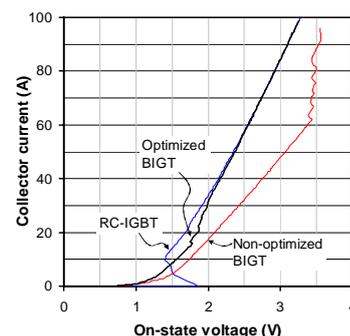


Figure 1. On-state I-V characteristics of an RC-IGBT (blue curve) compared to two different designs of the BiGT (red and black curves)

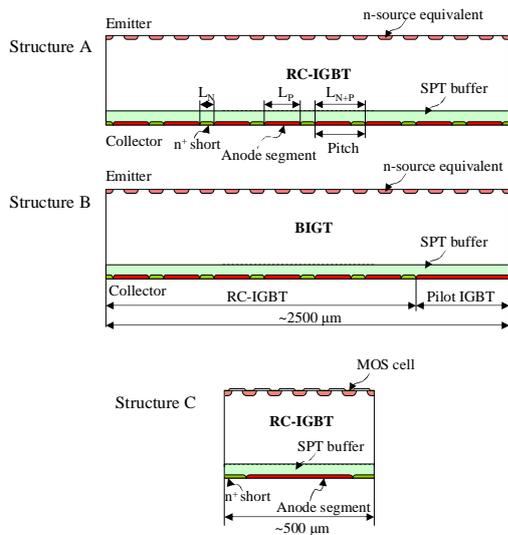


Figure 2. RC-IGBT and hybrid BiGT structures used in device simulations: A) RC-IGBT structure with equally distributed anode shorts B) BiGT structure with a pilot IGBT area C) RC-IGBT structure with full MOS cells

periodically to form anode segments, as shown in Fig. 2, structure A. The sum of the anode segment and the n+ short length L_{N+P} is referred to as pitch and the structure is called RC-IGBT. For the BiGT simulation, some of the shorts were omitted thus creating increased anode areas called pilot IGBTs embedded inside the RC-IGBT (Fig. 2, structure B).

To simulate diode characteristics a structure with several full MOS cells on the emitter side and 1/2 to 4 anode segments at the collector side, was used (Fig. 2, structure C). This allowed us to build reverse conducting structures with a varying L_{N+P} length up to 1 mm. The same structure was also used for the switching simulations. In this case, no pilot IGBT was included in modeled structure.

To simulate I-V characteristics with negative differential resistance regions, the device simulation was performed using a time dependent technique. A current ramp from 0 A to 62.5 A was applied to the semiconductor device at a constant rate of 0.6 A/ms.

III. RESULTS

A. Snap-back in IGBT mode

Fig. 3 shows the simulated on-state I-V characteristics of an RC-IGBT compared to the characteristics of a standard IGBT, simulated using the large structure A as shown in Fig. 2 with a backside pitch L_{N+P} of 240 μm . The curve exhibits a typical negative resistance region or snap-back at low currents, after the on-state voltage reaches 20 V. This behavior is similar to previously reported lateral segmented anode IGBTs and reverse-conducting structures [3-5]. The current flow is initially unipolar from the emitter to the n+ shorts in the collector. The lateral flow of electrons through the buffer above the anode segments forward biases the anode junction at the point where the voltage drop is the largest. The hole concentration in the drift region is increasing thus reducing its resistivity by conductivity modulation, causing the on-state voltage to snap-back.

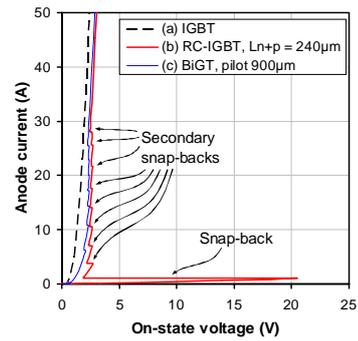


Figure 3. Simulated on-state I-V characteristics of RC-IGBT with shorts/anode ratio of 1/4 and pitch 240 μm (curve (b)) compared to standard IGBT (curve (a)) and BiGT (curve (c))

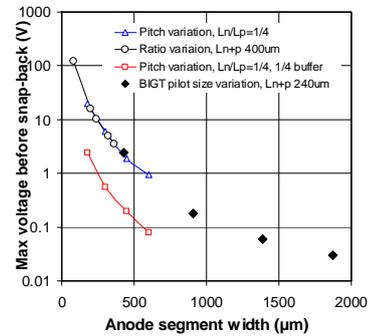


Figure 4. Maximum voltage before the snap-back as a function of the anode segment size for different n widths

Increasing the width of the anode regions (L_P) increases the resistive path for the electrons above the anode and effectively reduces the peak voltage before the snap-back as well as the current density for the on-set of carrier injection. The width of the n+ shorts (L_N) was found to have no influence on the maximum voltage peak, but an increased L_N length reduced the current density at which the snap-back occurs. In Fig. 4 the maximum voltage drop before the snap-back is plotted as a function of the anode segment width. The snap back voltage depends solely on the anode segment width for the same SPT buffer design and is independent from the conditions on how the width of the n+ shorts L_N was chosen (see triangle and round symbols). By reducing the buffer doping by a factor of 4, the resistive path above the anode is increased, thus forward biasing the junction at a lower current. As a result, the voltage peak is reduced by an order of magnitude (Fig. 4, square symbols). Nevertheless, the buffer design can not be freely adjusted for minimum snap-back in a punch-through device, as it strongly affects other device properties such as blocking capability, leakage current and short circuit capability.

As it will be shown later, increasing the anode segment widths has a negative impact on the diode characteristics. To overcome such limitations, the size of only one anode segment can be increased to form a pilot IGBT similarly to the hybrid BiGT structure. The maximum voltage before the snap-back can be efficiently reduced by this approach, as shown in Fig. 4

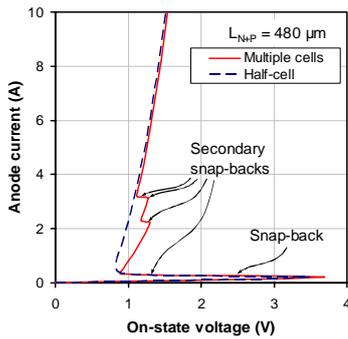


Figure 5. Comparison of the on-state I-V characteristics of an RC-IGBT obtained with a large multi-cell structure containing many anode segments (solid line), and a structure with only one anode segment. The dimensions of the anodes and shorts are the same for both structures.

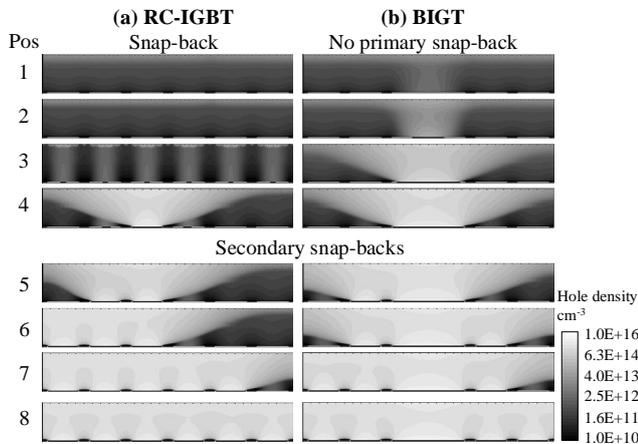


Figure 6. Hole density distributions in an RC-IGBT and BiGT during the primary snap-back and secondary snap-backs. Positions 1 to 4 correspond to equal current densities in both devices.

in diamond symbols. These points were obtained on a large structure with 240 μm pitch, which would cause a snap-back voltage in excess of 20 V without the pilot IGBT. One of the anodes was enlarged in steps up to 1.9 mm. At a pilot IGBT width of 1.5 mm, the snap-back drops below 100 mV. A full I-V curve of the 0.9 mm large pilot IGBT area is plotted in Fig. 3 curve (c).

B. Secondary snap-backs

After the initial snap-back, a series of secondary snap-backs are observed in the RC-IGBT as well as in the BiGT (marked with arrows in Fig. 3) in agreement with the experiment (Fig. 1, non-optimized BiGT curve). These small voltage variations continue up to one half of the nominal device current. However, when simulations of the same design are performed using a single-cell structure (Fig. 2, structure C), it leads to different characteristics. Comparison of a 480 μm pitch on-state simulation using structures A and C (see Fig. 2) is shown in Fig. 5. The maximum snap-back voltage is the same in both cases, but the secondary snap-backs are not visible in the one-cell simulation. The same behavior is also sometimes observed in the large structure if

the anode shorts are perfectly aligned with the MOS cells in the front.

Simulation of a single cell corresponds to the case when all anode segments start injecting simultaneously. Figure 6 a shows the current distribution in the large multiple cell structure during the I-V sweep-up. Due to irregularities of the mesh (which is actually closer to the realistic conditions), the injection is slightly different between the anode segments, which causes the initial homogeneous current to concentrate at one anode segment (6 a, positions 3 and 4). Consequently, the turn-on of the other cells is delayed and the device has a larger on-state voltage drop compared to the ideal single cell case. As the current is flowing through one anode segment, the required conditions for forward biasing the anode pn-junction will develop initially at the neighboring anode segment. The positions of the secondary snap-backs coincide with the times where the anode areas become forward biased sequentially and start injecting holes into the drift region, until all anode segments are injecting (Fig. 6, pos. 5-8). If the anode segments are very narrow, some areas of the device might remain inactive even in the nominal current range.

A side by side comparison of the anode forward biasing with the BiGT hybrid structure is shown in Fig. 6 b. Positions 1 to 4 correspond to the same current density in both devices. In the BiGT, the wider anode (pilot IGBT) starts to inject immediately at relatively lower current densities, which reduces the peak voltage and ensures a controlled location of the initial electron hole plasma. As the current rises, injection of the neighboring anode segments sets on. However, it is seen from the comparison of Fig. 3 curve (b) and (c), that the RC-IGBT and BiGT has the same performance in respect to secondary snap-backs. Increasing the widths of the anode segments helps in reducing the required current to forward bias the full anode area.

Recently, heavily paralleled 3.3kV modules containing 24 BiGTs from the optimized design version (shown in Fig. 1) with small secondary snap-backs were subjected for the first time to a PWM frequency test in an H-bridge configuration [6]. The test was carried out at a DC link voltage of 2.1 kV up to stabilization for a junction temperature of 140°C for approximately 30 minutes. Operational frequencies up to 1500 Hz and peak currents up to 800 A were achieved during the tests. The frequency test results provide a first insight into the feasibility of a single BiGT chip operating in both IGBT and freewheeling diode modes successfully under hard-switching conditions with no clear impact of the secondary snap-back effect.

C. Diode area trade-off

In the previous sections it was concluded that for the IGBT mode the preferred design is with the anode segments designed as wide as possible. However, this improvement occurs at the cost of the integrated PIN diode conduction losses, as the separation between the n+ diffusions grows and current distribution is more localized and the loss of effective area utilization. We analyzed the on-state characteristics of the built in diode to understand the design constraints implied by the diode losses.

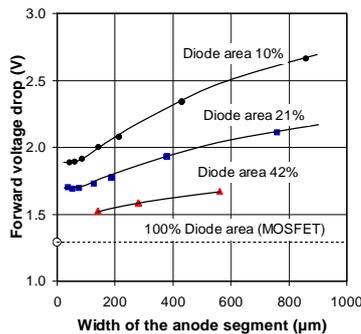


Figure 7. Diode forward voltage drop as a function of the anode segment width for different L_N/L_P ratios.

Fig. 7 shows the dependency of the diode on-state voltage (V_F) drop as a function of the anode segment width for three different L_N/L_{N+P} ratios, which can also be considered as the effective diode area. The simulations were performed using a structure with full MOS cells (Structure C in Fig. 2). The diode on-state simulation with the fully n+ covered backside (MOSFET structure) is included for comparison. The diode on-state value for the MOSFET equals 1.29 V and is shown by a dashed line in Fig. 7.

The V_F shows a complex dependency on the separation between the anode shorts even for the same diode area. At very high L_P length, the n+ regions, which act as cathodes for the diode, interact less and the V_F is higher. However, the V_F is much lower than could be expected from simple scaling of the effective diode area. As the length L_P is decreased, the plasma density between the n+ cathodes increases rapidly which causes the V_F to drop. At L_P around 100 μm the V_F reaches a minimum value with no further improvement at lower L_P values.

D. Switching characteristics

Turn-off simulations in diode and IGBT modes were performed using the structure employing a full set of MOS cells (structure C in Fig. 2). Fig. 8 shows the comparison of turn-off simulation in MOSFET and RC-IGBT body diodes. The $L_N/(L_N+L_P)$ ratio of the RC-IGBT was set to 21% and an anode segment length of 380 μm . Although the two body diodes have largely different on-state voltages, the MOSFET's internal diode exhibits a clear current snap-off at 2.3 μs , whereas the RC-IGBT shows a very soft current tail. This effect is attributed to the field charge extraction (FCE) phenomenon [7]. Indeed, the anode segments turn the MOSFET diode into the FCE diode. At the end of the reverse recovery phase, the anode segments start to emit holes, which support the reverse recovery current and prevent a snap-off from occurring. Similar behavior has been observed experimentally for the BiGT in both diode and transistor modes [2]. However, the improvement of the turn-off softness in IGBT mode is not clearly pronounced in the simulation. The detailed understanding of the anode and shorts dimensioning for optimum softness performance is under investigation.

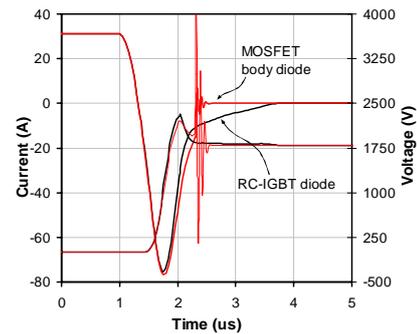


Figure 8. Comparison of reverse recovery waveforms of the built in PIN diodes in the MOSFET and RC-IGBT. $I=31\text{ A}$, $V_{DC}=1800\text{ V}$, $L_c=3500\text{ nH}$

IV. CONCLUSIONS

2D numerical analysis of the on-state I-V characteristics of the 3.3kV BiGT and RC-IGBT has been presented. The examination of the RC-IGBT characteristics has shown that the peak voltage before the snap-back depends solely on the anode segment widths for a specific buffer design and can be considerably reduced by introducing a BiGT hybrid IGBT/RC-IGBT structure with one wide anode region. The wide anode area in the BiGT starts to inject holes at much lower current densities, which in turn reduces the peak voltage and provides a location for the initial electron hole plasma. The pilot IGBT width of 1.5 mm reduces the snap-back voltage to below 100 mV. Although the initial snap-back is eliminated, a series of secondary snap-backs occur in the BiGT. Careful choice of the buffer and anode segment width is required to ensure that the device is utilizing the full anode area. Diode mode operation sets additional limits on the dimensioning of the anode segments. The preferred width lies below 200 μm for minimum on-state losses of the diode. Both diode and IGBT mode show the improved softness of the turn-off characteristics as a result of the FCE action.

REFERENCES

- [1] H. Takahashi, A. Yamamoto, S. Anon, T. Minato, "1200V Reverse Conducting IGBT", Proc. ISPSD'04, p 133, 2004.
- [2] M. Rahimo, A. Kopta, U. Schlapbach, J. Vobecky, R. Schnell, S. Klaka; "The Bi-mode Insulated Gate Transistor (BiGT) A potential technology for higher power applications" Proc. ISPSD'09, p 283, 2009.
- [3] A. Bourennane, J-L. Sanchez, F. Richardeau, E. Imbernon, M. Breil, "On the integration of a PIN diode and an IGBT for a specific application" Proc. ISPS'06, Czech Rep., p 145, 2006.
- [4] J.K.O. Sin, S. Mukherjee, "Analysis and characterization of the segmented anode LIGBT", IEEE Trans. Electron. Dev., vol. 40, no. 7, pp. 1300-1306, July 1993.
- [5] M. Gärtner, D. Vietzke, D. Reznik, M. Stoisiek, K.-G. Oppermann, W. Gerlach, "Bistability and hysteresis in the characteristics of segmented-anode lateral IGBTs", IEEE Trans. Electron. Dev., vol. 45, pp. 1575-1579, July 1998.
- [6] A. Kopta, M. Rahimo, R. Schnell, M. Bayer, U. Schlapbach, J. Vobecky, "The next generation 3300V BiGT HiPak modules with current ratings exceeding 2000A", Proc. PCIM2010, in press.
- [7] A. Kopta, M. Rahimo, "The field charge extraction (FCE) diode a novel technology for soft recovery high voltage diodes" Proc. ISPSD'05, pp. 83-86, 2005.