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OPTIMIZATION AND ADVANTAGES OF THE BIMODE INSULATED GATE TRANSISTOR

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Abstract. *The Bi-mode Insulated Gate Transistor BIGT is a single chip reverse conducting IGBT concept, which is foreseen to replace the standard IGBT / Diode two chip approach in many high power semiconductor applications. Therefore, it is important to understand in detail the design challenges and performance trade-offs faced when optimizing the BIGT for different application requirements. In this paper, we present the main conflicting design trade-offs for achieving the overall electrical and thermal performance targets. We will demonstrate experimentally how on one hand, the BIGT provides improved design features which overcome the restrictions of the current state of the art IGBT/diode concepts, while on the other hand, a new set of tailoring parameters arise for an optimum BIGT behavior.*

Key words: *Power Semiconductors, IGBT, Diode, BIGT*

1. INTRODUCTION

In modern power electronics applications employing IGBT modules, the diode presents a major restriction with regard to losses reductions and maximum surge current capability. Both issues are a result of the typically limited diode area available in a given package footprint design. In particular, these limits were further restricted after the introduction of modern low-loss IGBT designs. Therefore, the simple approach of increasing the diode area is not a preferred solution and in any case remains constrained by the package standard footprint designs. Nevertheless, the clear demand for increased power densities of IGBT and diode components has led to the focus on an IGBT and diode integration solution, or what has been normally referred to as the Reverse Conducting RC-IGBT. The key RC-IGBT feature has been the introduction of the anode shorts for the diode integration [1][2]. However, a number of process and design constraints related to the integrated diode structure have hindered the development of RC-IGBTs for hard switching applications and recent development efforts were aimed at tackling these issues. Hence, resulting in an advanced RC-IGBT concept referred to as the Bi-mode Insulated Gate Transistor (BIGT) [3].

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In addition to the modern miniaturized IGBT MOS cell designs, the second main design enabler for the BIGT realization is the Soft-Punch-Through (SPT) buffer concept [4]. Almost all of today`s IGBT structures are based on the Soft Punch Through or Field Stop lowly doped buffer concept combined with low injection efficiency p-type anodes for providing very low on-state and switching losses when compared to previous generations. However, this design approach has some limits for delivering optimum overall performance due to the difficulty to control the bipolar gain of the IGBT. The bipolar gain has a critical dependency on the finely controlled design parameters of the buffer and anode especially when compared to typical Non-Punch-Through NPT devices. It was also clear that these design restrictions become even more challenging for IGBTs with higher voltage ratings [5]. The main requirements affected by the Soft-Punch-Through (SPT) IGBT structure are illustrated in Fig. 1 and listed below:

1. Reverse blocking leakage current which is critical for device stability during high temperature operation
2. Short Circuit withstand capability at low temperatures and high gate emitter voltages
3. Turn-off softness under high inductance, low currents and temperatures
4. Safe operating area under dynamic avalanche and Switching-Self-Clamping-Mode SSCM
5. Static and dynamic losses trade-off point selection due to (1-4) restrictions

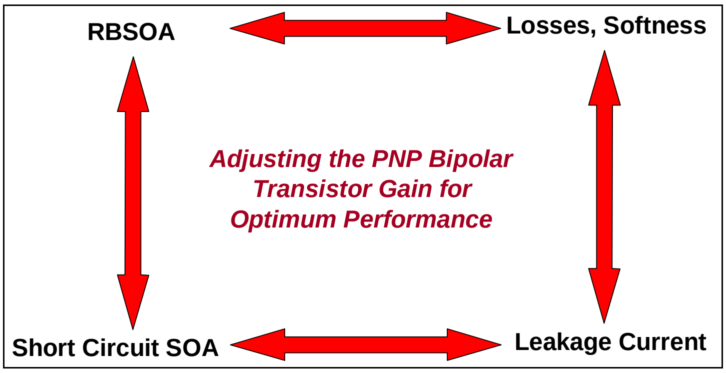

Fig. 1 The trade-offs for SPT design in IGBTs.

As mentioned previously, when compared to IGBTs the RC-IGBT in principle also benefits greatly from the SPT design, and more importantly, it has been shown that the above performance and associated design trade-offs are strongly minimized by the introduction of the anode shorts. Thus, the anode shorts not only enable diode conduction but are also are fundamental for the functionality of the whole device concept [6].

However, conventionally for RC-IGBTs, the IGBT/diode integration and the introduction of the anode shorts for high voltage and hard switching applications has also resulted in a number of performance drawbacks and a new set of trade-offs as summarized below:

- Snap-back in the IGBT on-state I-V characteristics (the shorting effect)
- IGBT on-state versus diode recovery losses trade-off (the plasma shaping effect)

- Safe Operating Area SOA (the charge uniformity effect)
- IGBT versus diode softness trade-off (the silicon design effect)

In this paper, we will discuss the above mentioned topics and provide an overview of the required BIGT optimum design features to obtain good overall electrical performance while targeting main stream hard switching power electronics applications.

2. THE BIGT DEVICE CONCEPT

The development of the BIGT was aimed at solving the above issues by following two integration steps. The first integration follows the standard approach for an RC-IGBT. A cross section is shown in Fig. 2 combining both an IGBT and diode in a single structure. At the collector side, alternating n+ doped areas are introduced into an IGBT p+ anode layer, which then act as a cathode contact for the internal diode mode of operation. The area ratio between the IGBT anode (p+ regions) and the diode cathode (n+ regions) determines which part of the collector area is available in IGBT or diode modes, respectively. During the RC-IGBT conduction in diode mode, the p+ regions are in-active and do not directly influence the diode conduction performance. However on the other hand, the n+ regions act as anode shorts in the IGBT mode of operation, strongly influencing IGBT conduction mode.

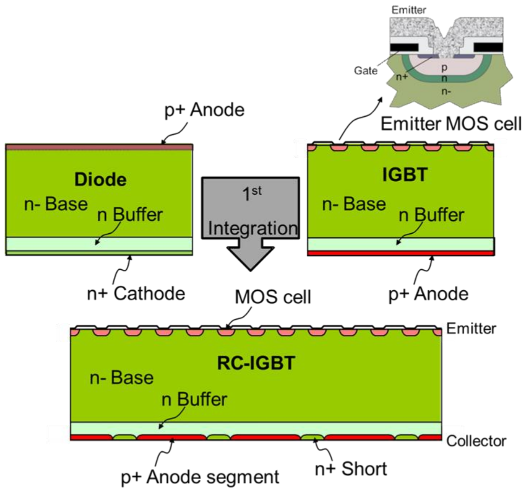

Fig. 2 First integration step: the reverse conducting RC IGBT.

One of the implications of anode shorting is the voltage snapback a referred to previously which is observed as a negative resistance region in the device IGBT mode I-V characteristics. This effect will have a negative impact when devices are paralleled, especially at low temperature conditions. To resolve this issue, a second integration step was required. It has been shown that the initial snap-back can be controlled and eliminated by introducing wide p+ collector/anode regions into the device, also referred to as a pilot-IGBT. This approach resulted in the BIGT concept which is in principle a hybrid structure consisting of an RC-IGBT and a standard IGBT in a single chip as shown in Fig. 3.

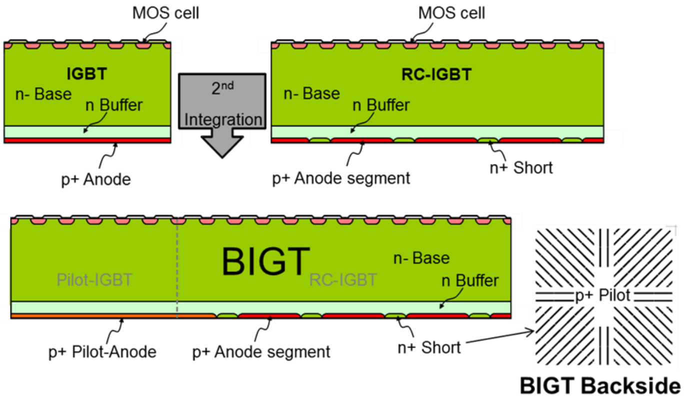

Fig. 3. Second integration step: the bimode insulated gate transistor BIGT.

3. THE BIGT DESIGN TRADE-OFF CHALLENGES

3.1. The BIGT snapback effect

Despite the fact that the n-type shorting regions have contributed to many advantages as explained earlier, the major drawback is related to the snap-back effect in the forward IV characteristics. Nevertheless, this effect has been minimized strongly with the BIGT hybrid design with the introduction of the p+ collector/anode pilot region. The main target of this combination is to eliminate snap-back behavior at low temperatures in the BIGT transistor on-state mode by ensuring that hole injection occurs at low voltages and currents from the p+ pilot region in the IGBT section of the BIGT. Nevertheless, further optimization was still required with relation to the shorting layout design. A radial shorting layout in relation to the pilot region [7] has shown optimum on-state curves with a more smooth increase in the current when compared to a stripe shorting design in parallel to the p+ pilot region as shown in Fig. 4 for a 4.5kV/50A BIGT device.

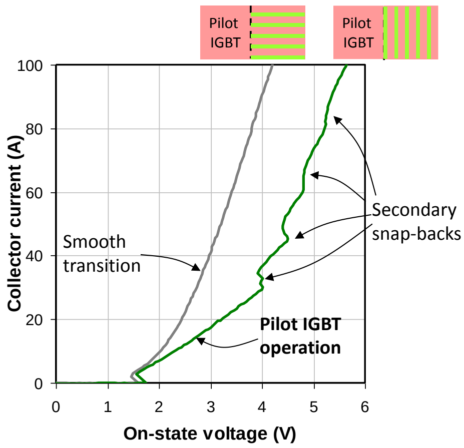

Fig. 4 Reducing the snap-back with the BIGT hybrid design and radial shorting layout.

3.2. IGBT mode versus diode mode losses

For the BIGT losses optimization, the main challenge was to enable low diode mode recovery losses while not having a considerable effect on the transistor mode on-state losses. A three step approach is utilized to achieve this target. The first step is the fine control of the doping profiles of the emitter p-well cells and collector/anode short regions. As shown in Fig. 2, the enhanced planar cell technology exhibits low injection levels and a compensation effect due to the enhancement n-layer. These two features provide the BIGT with a fine pattern p-well profile for obtaining low injection efficiency for a better diode performance. The second optimization step employs a Local p-well Lifetime (LpL) control technique utilizing a self-aligned and well-defined particle implantation which further reduces the diode recovery without degrading the transistor losses trade-off curve and blocking characteristics. The final adjustment of the reverse recovery losses is achieved with a uniform local lifetime control employing proton irradiation. Further reductions in diode recovery losses can be obtained by applying a MOS gate control during Diode-mode conduction and switching [6].

3.3. The BIGT charge uniformity

The structured collector/anode of a BIGT with p+ and n+ areas introduces non-uniformities in the lateral charge distribution which have been studied with the aid of device simulation. While the fine patterning of the RC-IGBT region (see Fig. 2) does not bring much changes to the overall charge distribution, the pilot-IGBT region significantly modifies the BIGT charge and current distribution compared to an IGBT. During the IGBT conduction mode, the p+ pilot acts as a large non-shorted region having very strong anode injection, therefore the electron-hole plasma and the current density is the highest in the pilot region as shown in Fig. 5 [8]. The junction temperature distribution is also affected by this and is highest in the region of the pilot-IGBT, which is placed in the middle of the device for this reason. Conversely, the pilot region has the lowest carrier plasma density during diode conduction.

During the IGBT mode turn-off, the high plasma concentration in the pilot region triggers early dynamic avalanche at the MOS cells located above the same region. The described charge inhomogeneity is mainly pronounced at lower temperatures and low device currents. At the critical SOA conditions, the difference between the RC-IGBT and Pilot-IGBT regions is reduced which results in a similar dynamic avalanche behavior as for the corresponding IGBT.

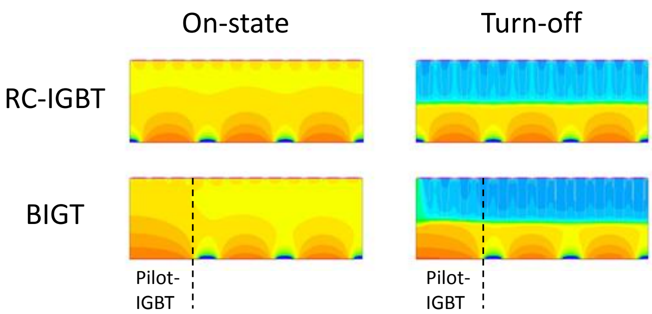

Fig. 5 Hole density during IGBT on-state conduction and turn-off of a Reverse-Conducting IGBT compared to the BIGT, showing the effect of carrier plasma un-uniformity and the occurrence of dynamic avalanche.

3.4. The BIGT diode mode softness

The diode softness challenge is mainly due to the fact that generally the diode silicon does not match the IGBT silicon for obtaining soft recovery performance. Thus, such conflicting requirements could result in diode mode snappy behavior in an integrated structure. To resolve this critical issue, the anode shorts have inherently a switching behavioral feature which provides the BIGT with very soft turn-off characteristics as described in the following section.

4. THE BIGT TRADE-OFF ADVANTAGES

4.1. Reverse bias and leakage current

The presence of the n-type shorts in the BIGT has a large impact on lowering the leakage current. The n-type areas provide a direct path for electrons during reverse blocking conditions, therefore no or very little hole injection occurs. Fig. 6 shows thermal stability comparisons at different temperatures for 6.5kV rated IGBTs and BIGTs with two anode designs. The BIGT clearly demonstrate improved thermal stability at higher temperatures when compared to the IGBT even with very high anode injection efficiencies [9]. The anode shorts remove the influence of the bipolar gain on the leakage current to a large extent. As a result, the leakage current is suppressed and the increment with the temperature is reduced. In addition, the anode strength does not influence the leakage current in the BIGT in contrast to an IGBT structure. However, it can still occur that holes are injected due to the lateral voltage drop when a high leakage current is flowing over large/wide p-doped anode areas, but this was not observed in practical designs even with a pilot IGBT region occupying around 20% of the collector area.

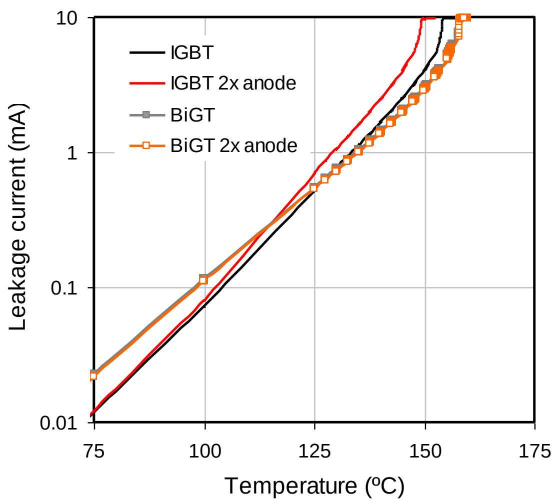

Fig. 6 6.5kV BIGT and IGBT thermal stability curves.

2.2. IGBT and diode mode turn-off softness

As mentioned in the previous section, with regard to the BIGT softness in diode as well as IGBT turn-off modes, an inherent effect in the BIGT similar to the Field Charge Extraction FCE diode [10] has ensured soft performance under all operating conditions. Due to the presence of anode shorts in the BIGT, the lateral current flowing above the large pilot-IGBT area forward biases the p-n junction and additional hole injection produces a small tail current providing the required softness and causing only a minimal increase of the switching losses. As a typical example, for the IGBT mode of operation, this approach means that stronger anode injection is not anymore required to provide only softer performance at the expense of higher losses, higher leakage currents and strong dynamic avalanche conditions as is the case with IGBTs. Fig. 7 shows the IGBT mode turn-off for 6.5kV devices. The BIGT exhibits clearly a soft tail with no abrupt drop in the current during the later stages of the turn-off event as for the IGBT.

The same effect is also present in the diode mode. Here it is of more importance due to the fact that the n-base region design of the BIGT is similar to the IGBT and is not optimized for diode operation. A standard diode using an IGBT n-base region design with a low punch through voltage would be very susceptible to snappiness even under nominal conditions. Because of the FCE effect induced by the anode shorts, the diode is turning off softly and without any visible snap-off. Fig. 8 shows diode turn-off waveforms at the most critical conditions at a low current and low temperature (-40ºC).

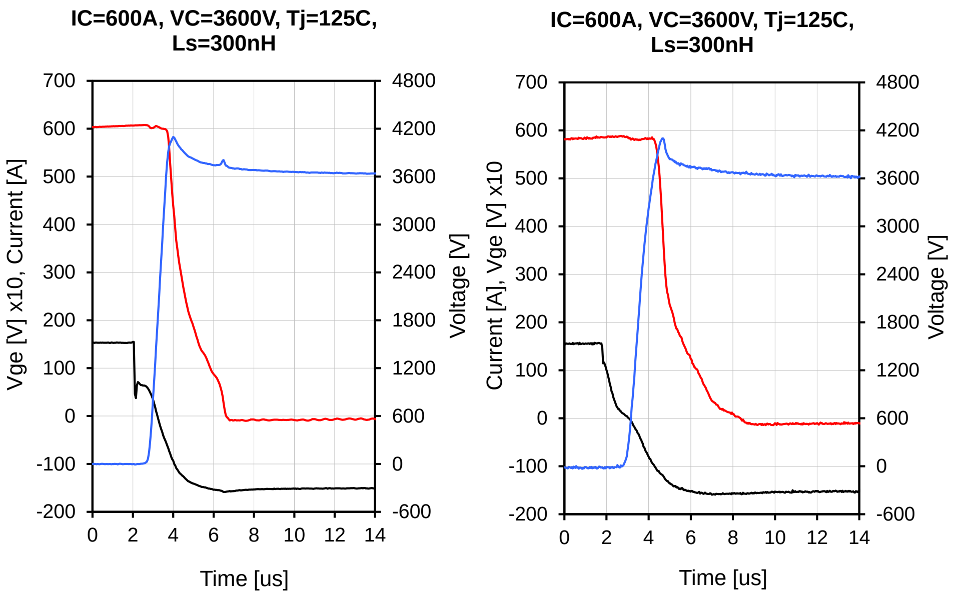

Fig. 7 6.5kV/600A IGBT (left) and BIGT (right) module turn-off waveforms under nominal conditions.

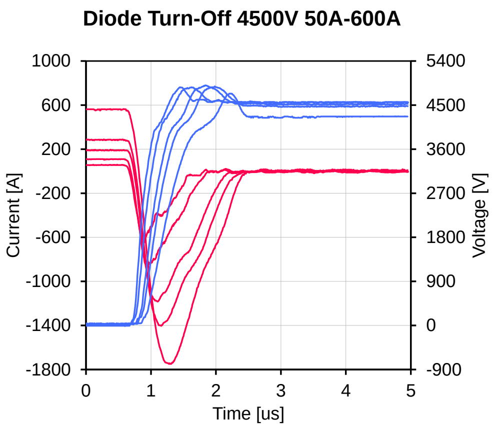

Fig. 8 6.5kV/600A BIGT module diode-mode turn-off waveforms at critical low current conditions at -40ºC.

2.3. The BIGT Short Circuit

In addition, the BIGT shows that the high local anode injection levels needed with the presence of n-types shorts have brought about improvements on the short circuit SOA capability. The BIGT will normally require higher anode p-region doping concentrations compared to an IGBT anode for obtaining the same over-all injection efficiency and hence on-state voltage drop and turn-off losses. During short circuit, an important current dependent failure mode occurs during the short circuit current pulse in SPT designs which is mainly dependent on the charge compensation effect near the buffer region of the IGBT which in turn is dependent on the anode and buffer design [11]. Under high Vge and/or lower operating temperatures, the resulting higher short circuit current will limit the short circuit SOA (SCSOA) capability. In a BIGT, the higher anode p-region doping provide improved charge compensation and hence higher SCSOA. Fig. 9 shows the short circuit test of a 3300V/50A BIGT and reference IGBT chips at 25°C, and a gate voltage of 18V.

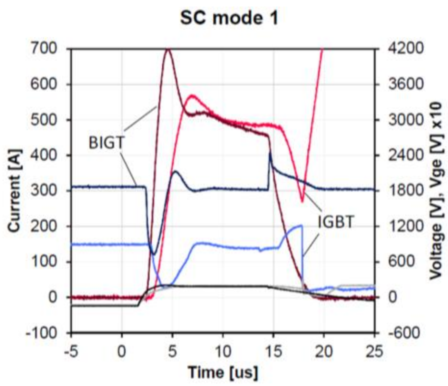

Fig. 9 3.3kV IGBT and BIGT single chip Short Circuit type 1 waveforms at room temperature.

Both devices are designed for the MOS cell, anode and buffer to have similar short circuit current and turn-off losses. While the BIGT has a faster turn-on behavior resulting in a higher overshoot current, it is still capable of withstanding this test at a DC-link voltage of 1800V compared to the IGBT which fails already at 900V. The BIGT chip is also capable of passing the test for higher gate voltages up to 19.5V. In addition to the advantages discussed previously, this feature in the BIGT design provides further flexibility for design trade-offs required to tailor the BIGT for improved overall performance.

5. CONCLUSIONS

The BIGT concept is foreseen to play an important role in many future power electronics applications. Hence, it is important to understand the design trade-off improvements and challenges presented by the BIGT device concept when compared to state of the art IGBTs and diodes. This paper has presented a comprehensive review of these design aspects based on published and newly obtained results for a high voltage BIGT.

REFERENCES

[1] H. Takahashi, A. Yamamoto, S. Anon, T. Minato, "1200V Reverse Conducting IGBT", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`04, Kitakyushu, Japan, p. 133.

[2] S. Voss, F-J. Niedernostheide, H-J. Schulze, "Anode design variations in 1200V Trench Field-Stop RC-IGBTs", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`08, Orlando, USA, 2008, pp. 169-172.

[3] 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", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`09, Barcelona, Spain, 2009, pp. 283-286.

[4] S. Dewar, S. Linder, C. von Arx, A. Mukhitinov, G. Debled, "Soft Punch Through (SPT), Setting new Standards in 1200V IGBT", In Proc. PCIM`00 Conference, Nurnberg, Germany, 2000.

[5] J. Vobecky, M. Rahimo, A. Kopta, S. Linder, "Exploring the Silicon design Limits of Thin wafer IGBT Technology: The Controlled Punch Through (CPT) IGBT", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`08, Orlando, USA, 2008, pp. 76-79.

[6] M. Rahimo, U. Schlapbach, A. Kopta, J. Vobecky, D. Schneider, A. Baschnagel, "A high current 3300V module employing RCIGBTs setting a new benchmark in output power capability", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`08, Orlando, USA, 2008, pp. 68-71.

[7] L. Storasta, A. Kopta, M. Bellini, M.T. Rahimo, U. Vemulapati, N. Kaninsky, "The Radial Layout Design Concept for the Bi-Mode Insulated Gate Transistor", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`11, San Diego, USA, 2011.

[8] D. Wigger, D. Weiss, H-G. Eckel, "Impact of inhomogeneous current distribution on the turn-off behaviour of BIGTs", In Proc. PCIM 2013, pp. 860-867.

[9] L. Storasta, S. Matthias, M.T. Rahimo, A. Kopta, "Bipolar Transistor Gain Influence on the High Temperature Thermal Stability of HV-BiGTs", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`11, Bruges, Belgium June 2012, pp. 157-160.

[10] A. Kopta, M. Rahimo, "The Field Charge Extraction (FCE) Diode, a novel technology for soft recovery high voltage diodes", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`05, Santa Barbara, USA, 2005, pp. 83-86.

[11] A. Kopta, M. Rahimo, U. Schlapbach, N. Kaminski, D. Silber, "Limitation of the Short-Circuit Ruggedness of High-Voltage IGBTs", In Proc. Int. Sym. on Power Semiconductor Devices & IC's ISPSD`09, Barcelona, Spain, 2009, pp. 33-36.