EVS27
Barcelona, Spain, November 17-20, 2013

Optimized IGBT technology for mild hybrid vehicles

Dr. Carlos Castro [1], Laurent Beaurenaut [1]
[1]*Infineon Technologies AG, Am Campeon 1-12, D-85579, Neubiberg, Germany*

Abstract

A new IGBT (Insulated-Gate Bipolar Transistor) technology with a blocking voltage capability of 400V was developed in order to further increase the improvements of hybrid vehicles in terms of fuel efficiency. Conduction and switching losses are significantly reduced by means of using an ultra-thin wafer technology (approximately 40µm thickness) having a direct impact on the overall efficiency. A complete inverter prototype was designed and used to compare the performance of state of the art 650V IGBTs and the new 400V technology. The results showed a significant decrease of the power losses using 400V IGBTs, which could be used to increase the efficiency (less fuel consumption), reduce cost (less chip area or cooling efforts) or/and increase the power density of the system (under same conditions, higher output power possible). Due to its reduced blocking voltage, this new IGBT is mostly suitable for mild hybrid vehicles with working voltages up to approximately 200V.

Keywords: IGBT, Mild hybrid vehicles.

1 Introduction

Oil prices, limitations of the reserves and the needs for reducing current CO2 emissions are forcing governments all around the world to introduce new regulations for improved fuel efficiency. In North America OEMs will be limited to 35 mpg in 2016 and in the European Union to CO2 emissions of 95 g/km by 2020. The only way for all car manufactures to fulfill such regulations is the introduction of hybrid and electric vehicles in their portfolio [1].

Looking at the current market figures, a logical development can be observed: after having explored further saving in conventional combustion systems, the next step is in mild hybrids, then full hybrids and finally electric vehicles.

Unlike a full hybrid system, a mild hybrid system cannot propel a vehicle on electric power alone. The electric motor is used to start the combustion engine (start stop function), to offer a boost function during acceleration or to enable for regenerative braking to recuperate energy. Such a system offers a highly cost-effective way to increase fuel efficiency. Some models show 15 to 20% better fuel economy with a cost adder of only a couple hundred dollars more than similar conventional models.

As the electric motors used in mild hybrid vehicles have a limited power (less than 20kW), the required voltage from the battery can be reduced compared to full hybrid or electric vehicles in order to reduce costs of the different components (battery, switches, capacitors…). Nowadays, mild hybrids vehicles are designed with battery voltages up to 200V while full hybrids or electric vehicles work up to 450V battery voltage (or even higher with booster). However, all of them share a common technology for the switches used in the main inverter: the insulated-gate bipolar transistor (IGBT).

Due to its characteristics, the IGBT has been proven as the best semiconductor switch concept in terms of cost and performance. In order to achieve the highest effectiveness (lowest electrical losses) it is necessary to optimize the inverter DC-Link voltage (i.e. reducing the overall stray inductance in the system) and reduce the gap to the blocking voltage capability of the IGBT. Unfortunately, there was up to now no IGBT technology available with blocking voltages below 600V. That means, for working voltages in the range of 100-200V (mild hybrids), a very large gap and therefore a decrease of the performance offered by the inverter leads to reduced fuel efficiency.

2 400V IGBTs on 40µm wafers

The Trench and Field-Stop technology minimizes at the same time the steady-state and switching losses in the IGBT. A trench cell [2] is combined with a field stop vertical concept.
The trench cell reduces on state losses due to an increased carrier concentration near the emitter (cathode). The field stop concept is an evolution of the NPT concept and consists of an additional n doped layer which is implanted into the backside of the wafer (Figure 1). Combining this field stop region with an increased resistivity of the substrate wafer, the thickness of the device can be reduced by approximately one third maintaining the same blocking voltage. With the reduced wafer thickness a further reduction of the on state losses and also of the turn-off losses can be reached. The field stop layer is lowly doped, so it does not influence the low dose p-emitter which is also implanted from the back side.

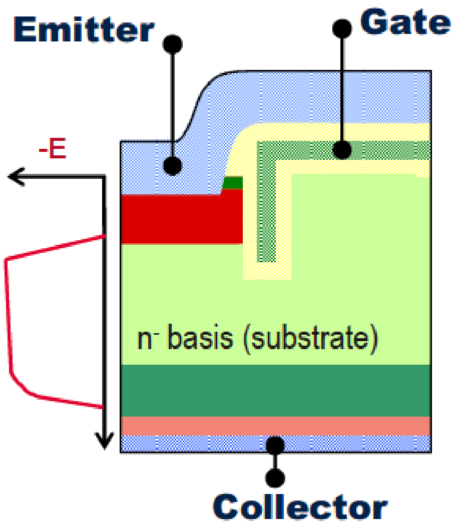

Figure 1: trench and field-stop IGBT cell

The field stop concept implies ultra-thin wafer technologies and therefore a challenge in terms of manufacturability. On the other hand, the power losses of the IGBT are roughly quadratically proportional to the wafer thickness and therefore a reduction of thickness implies a better performance of the system. For these reasons, a ~70µm ultra-thin wafers for 650V class family is used, which is approximately 30% less thickness than state-of-the art. Reducing the voltage to 400V means a ~40µm ultra-thin wafer and therefore a significant technological challenge as many processes (i.e. annealing, metallization, passivation, lithography and etching) are done when the wafers are already thinned.
A sophisticated wafer handling, including very special equipment for ultra-thin wafers in combination with a controlled wafer bow by an optimized backside metallization is essential. The thinning of the wafers itself is done by a combined process of wafer grinding and wet chemical etching [3].

3 Electrical performance

The first product based on this new 40µm IGBT technology was developed on a HybridPACK™ 1 package (Figure 2).

Figure 2: HybridPACK™ 1 package

HybridPACK™ 1 is a proven and well established power module package, used in the 650V range and other platforms. It is designed for Mild and Full HEV applications for a power range up to 30 kW. Designed for a junction operation temperature at 150°C, the module accommodates a Six-Pack configuration being suitable for air or low temperature liquid cooled inverter systems. The flat copper base plate combined with high-performance ceramic substrate and Infineon's enhanced wire-bonding process provides unique thermal cycling and power cycling reliability for Mild HEV inverter applications.

A direct comparison with the state of the art 650V IGBT/diode chipset shows that the 400V IGBT/diode indeed not only reduces significantly conducting losses at lower DC-link voltage but switching losses as well. The losses of 400V and 650V chipset were compared by simple exchanging of the 400V IGBT3/Emcon4 chipset with the 650V IGBT3/Emcon4 at nearly the same die size (400V/216A and 650V/200A). The measurements of both chipsets were performed under the same conditions (test bench setup, PCB, current rating).

The total conduction losses of 400V IGBT/diode chipset are reduced about 15% in comparison to 650V IGBT/diode chipset as it can been seen in the Table 1Table 1.

The total switching losses of 400V IGBT/diode chipset are reduced about 12% in comparison to 650V IGBT/diode chipset in FS215R04A1E3D module (Table 2).

Table 1: Comparison of the conduction losses at 215A IGBT and at 430A diode per switch for 25°C and 150°C (Vce=120V, Ic = 215A / 200A).

	Vce_sat [V] @25°C	Vf [V] @25°C	Vce_sat [V] @150°C°C	Vf [V] @150°C
conduction losses 650V [mJ]	1.45	1.55	1.70	1.45
conduction losses 400V [mJ]	1.30	1.35	1.45	1.20
Reduction conduction losses [%]	10.3	12.9	14.7	17.2

Table 2: Comparison of switching losses at the same Rg (Tj = 150°C, Vce = 120V, IC = 215 / 200A).

	E_{off}	E_{on}	E_{rec}	E_{sum}
Switching losses 650V [mJ]	**3.95** at Rg = 1.8 Ω	**1.0** at Rg = 1.8 Ω	**3.0** at Rg = 1.8 Ω	**7.95**
Switching losses 400V [mJ]	**3.75** at Rg = 1.8 Ω	**0.75** at Rg = 1.8 Ω	**2.5** at Rg = 1.8 Ω	**7**
Reduction switching losses [%]	5%	25%	17%	12%

4 System measurements

In order to analyse the impact of the reduced losses of the switches on a real application, a complete 3 phase inverter system was designed and evaluated (see Figure 3).

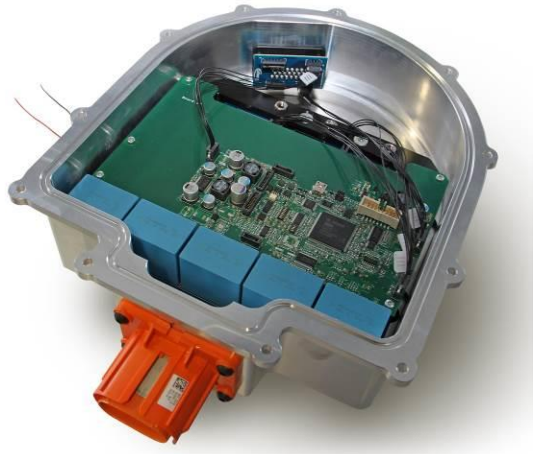

Figure 3: complete 3-phase inverter system used for comparison of 650V and 400V IGBTs technologies

As it was proved that 400V IGBT technology reduced both conducting and switching losses in the application, the chip area used was shrunk. In the 650V inverter two IGBTs of 99.5mm^2 and two diodes of 50.1mm^2 area were implemented for each switch while 86.9mm2 IGBTs and 46.1 diodes were used for the 400V inverter version. That is, IGBT chip area was reduced in 13% and diode chip area in 8%.

Each leg of the inverter was implemented using an Easy 2B package (see Figure 4)

Figure 4: Easy 2B Package

The system specifications are identical for both versions (650V and 400V) of the inverter (see Table 3)

Table 3: System parameters

DC Voltage	125V
Modulation method	SPWM
Switching frequency	10kHz
Phase current	95A

The overall power losses of the inverter were measured using a power analyzer (Yokogawa WT1800) and the results are shown in Table 4.

Table 4: Inverter efficiency comparison

	650V Inverter	**400V Inverter**
Efficiency (%)	93,8	95,2

The improvement in the inverter efficiency with the new 400V IGBT technology and reduced chip area offers significant benefits for system designers:

- Overall cost can be reduced as less chip area is required in order to achieve the same output power. Furthermore, less cooling effort and cost will be necessary in order to fulfill same system specifications.
- The power density and/or the maximum power rating of the inverter can be increased due to the higher efficiency of the semiconductors.

5 Conclusion

A new IGBT technology for lower working voltages (up to 200V) as used in mild hybrid vehicles was presented. By means of using ultra-thin wafers with thickness of just 40µm, not only the conducting but as well the switching losses could be significantly reduced. The direct impact of such reduced power losses on a real application (inverter) was evaluated using system prototypes. The overall efficiency could be increased even using significant less silicon area for the power switches. Such a result can be used by system designers in order to reduce cost and/or increase power density or the maximum power rating of the inverter. After overcoming the technological challenges, the introduction of such devices will have a direct impact on the further improvement of fuel consumption on hybrid vehicles.

Acknowledgments

Special thanks to Omar Vanegas and Tom Röwe for supporting this paper with measurements on a system level.

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Authors

Dr. C. Castro received the M.Sc. ('02) and Ph.D. ('06) in electrical engineering from the University of Granada, Spain and the University of Dortmund, Germany. Since 2006 he is working for Infineon Technologies, first as automotive system engineer and since November 2009 he took over a position as Senior Manager heading the Application Engineering department at the Electric Drive Train business of Infineon Technologies.

Laurent Beaurenaut received in 1999 the M.Sc. in electrical engineering from the Ecole Nationale Superieure d'Electronique, Electrotechnique, Informatique, Hydraulique et Telecommunications,Toulouse, France. He is working as Senior Staff Application Engineer at the Electric Drivetrain business of Infineon. In 2012, he received the title "Fachingenieur Elektromobilität" from the German VDI (The Association of German Engineers).