Characterization of Power Modules by 3D EMC Simulation for the Avoidance of RF Transit-Time Oscillations

R.Siemieniec [(1)], M.Netzel [(2)] and P.Mourick [(3)]

[(1)] Technical University of Ilmenau / Infineon Technologies Austria AG
[(2)] Technical University of Ilmenau
[(3)] Engineering Consultant, Oberscheidental
GERMANY

Abstract

3D EMC simulation, based on the solution of the Maxwell Equations, is used for the characterization of power modules with respect to possible resonance points. It is shown that under certain conditions RF oscillations may occur during the turn-off of the single power device chips which are related to the plasma extraction transit-time (PETT) effect. 3D EMC simulation is used to investigate changes of the power module layout which result in a shift of the modules resonance point and therefore effectively suppress the unwanted RF oscillations.

Keywords: EMC simulation, power module, resonance point, RF oscillation, pett oscillation

INTRODUCTION

Pett (plasma extraction transit time) oscillations are high-frequency oscillations which may occur during the turn-off of bipolar power devices. This phenomenon is a recently discovered effect [1]. Pett oscillations were first found in power modules with paralleled IGBT chips [1], but they also occur in modules with paralleled freewheeling diodes (FWD) or even in case of single IGBT chips [2]. Recent work shows that these oscillations should be avoided due to their adverse influence regarding EMC issues [3].

The analysis of this type of oscillation shows that the occurrence of this effect is related to complex dependencies between the power semiconductor devices as well as the power module layout [4]. In this work, the complete power module is characterized by means of 3D EMC simulation to find resonance points which are necessary preconditions for the occurrence of the Pett oscillation. Changes of the module layout are proposed and their influence with respect to resonance points is investigated.

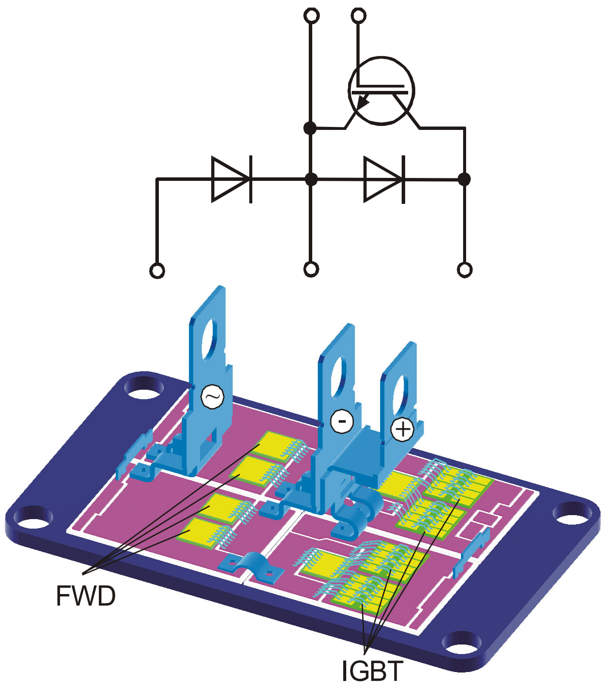

Fig. 1: Internal circuit and layout of the power module

SIMULATION SYSTEM

The analysis of the power modules was performed using the 3D EMC Simulator FLO/EMC [5]. The system solves the complete Maxwell equations:

$$\mathrm{rot}\vec{E} = \frac{-\delta\vec{B}}{\delta t} = -j\omega\mu\vec{H} \quad (1)$$

$$\mathrm{rot}\vec{H} = \vec{J} + \varepsilon\frac{\delta\vec{E}}{\delta t} = \kappa\vec{E} + j\omega\varepsilon\vec{E} \quad (2)$$

$$\mathrm{div}\vec{D} = \rho \quad (3)$$

$$\mathrm{div}\vec{B} = 0 \quad (4)$$

FLO/EMC uses a Transmission Line Matrix (TLM) for an efficient solution in the time domain. In the TLM method, space is divided into cells modeled as the intersection of orthogonal transmission lines. The simulation proceeds in time from an initial field or voltage excitation.

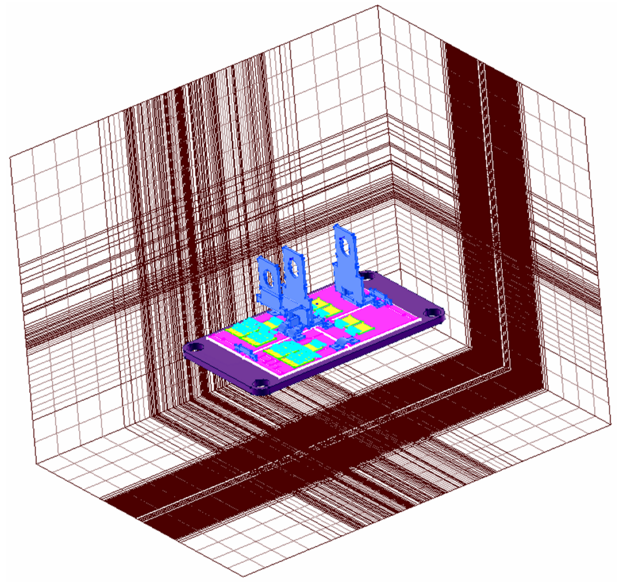

Fig. 2: Grid for 3D EMC Simulation

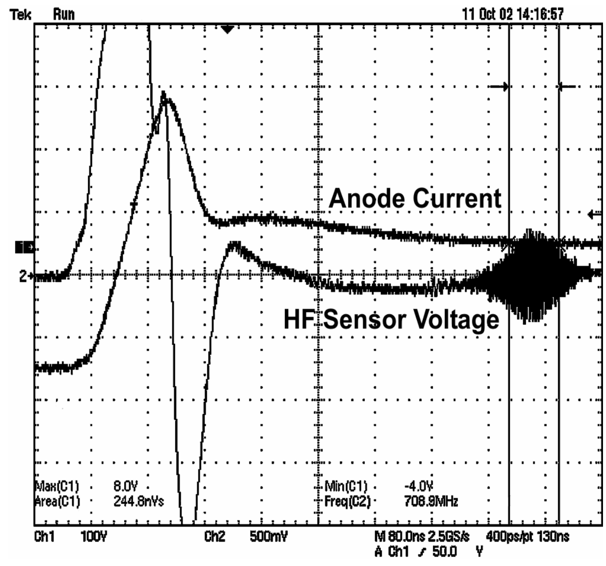

Fig. 3: Measurement of a Pett oscillation in 1200V/600A power module

Voltage pulses are transmitted and scattered at each cell, the electric and magnetic fields are calculated from voltages and currents on the transmission lines at each time step.
FLO/EMC offers the possibility to apply an excitation at several ports inside the model. For the characterization of the power modules, the excitation in form of a delta pulse was applied across a freewheeling diode. In this way can be calculated the scattering parameters, namely the input impedance [5].
There is no possibility to include real semiconductors into FLO/EMC. Therefore, a simplified model is used which reproduces the correct junction capacitance or on-state resistance of the devices (IGBT and FWD).
Figure 1 shows the complete 3D-Model of the characterized power module, a 1.2kV/600A high-side switch. In this power module, two FWDs as well as two IGBTs are paralleled into a group at one single DCB (direct copper bonding) substrate, while again two such groups are paralleled in the module to gain the desired current capability. Figure 2 shows the simulation grid provided for the calculations presented in this work.

THE PETT OSCILLATION

Oscillation Mechanism

The mechanism of Pett oscillation, which occurs in the tail phase of turn-off as shown on example of figure 3, is related to the oscillation mechanism of the Baritt diode [6]. In contrast to the Baritt effect, the carrier injection into the space charge region is caused by the stored excess carriers in the remaining plasma of the device during the turn-off process (see figure 4). Basically, the hole flow through the already formed space charge region has an almost constant drift velocity v_d. The hole density is

$$p = \frac{j}{q \cdot v_d}$$

and increases the effective doping to

$$N_{eff} = N_D + p$$

Consequently, the gradient of the electrical field dE/dw is changed. The discontinuous hole flow in form of packets increases the dE/dw in the location of the carrier packet and decreases the de/dw in the remaining part of the middle region as schematically shown in figure 3. Thus, the transition of a carrier packet results in a small negative voltage which causes a negative differential resistance. Oscillations occur if this negative differential resistance is larger than all other positive resistances in

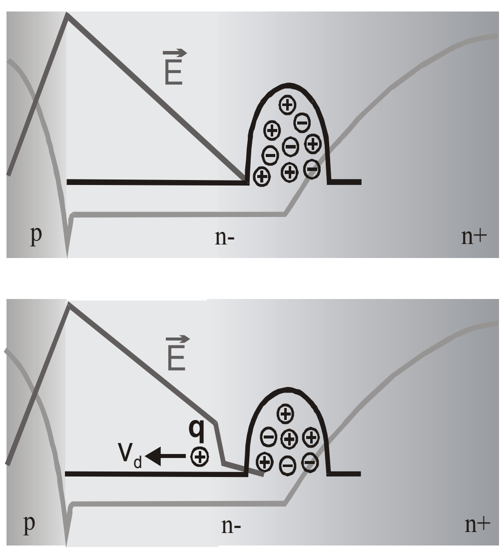

Fig. 4: Origin of the Pett oscillation

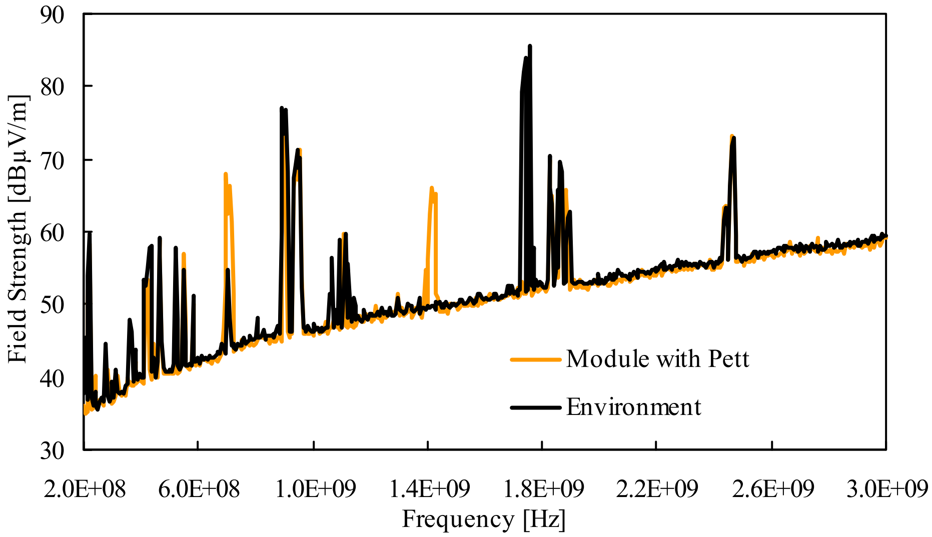

Fig. 5: EMC measurement of a power module showing Pett oscillations in comparison with environment

the complete circuit. The oscillation frequency is then given by

$$f_T = \frac{v_d}{w_{sc}}$$

where w_{sc} is the width of the space charge region.

EMC Compatibility Issues

Figure 5 shows the result of the measurement of electromagnetic emission of a power module showing Pett oscillation during turn-off of the freewheeling diodes (FWDs), compared with the signal of a module which does not show this effect. This measurement was done in a usual, unshielded laboratory, therefore a number of interfering signals are shown which result mainly from broadcast and telecommunication equipment [3].

Here, the Pett oscillation causes two sharp peaks in the frequency spectrum, appearing at 700MHz and 1.4Ghz, respectively, which are assigned to the fundamental frequency and the first harmonic. The emitted power is large enough to cause a violation of EMC limits as set by international standards [7].

If taken into account that in usual power electronic equipment a large number of power switches is used, the necessity to avoid these oscillations becomes clear.

RESULTS

Unchanged Power Module

First, the unchanged power module was characterized using 3D EMC simulation. Figure 6 shows the layout of one of the two FWD groups in detail. Figure 7 shows the simulation results for the impedance of the power

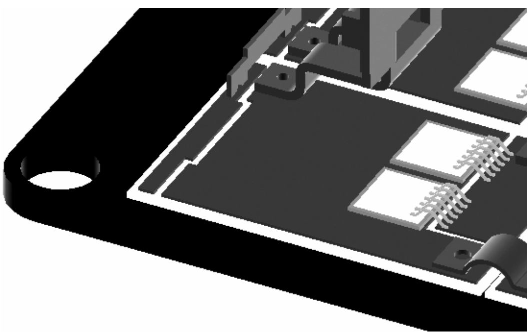

Fig. 6: Module layout for one FWD group, unchanged module

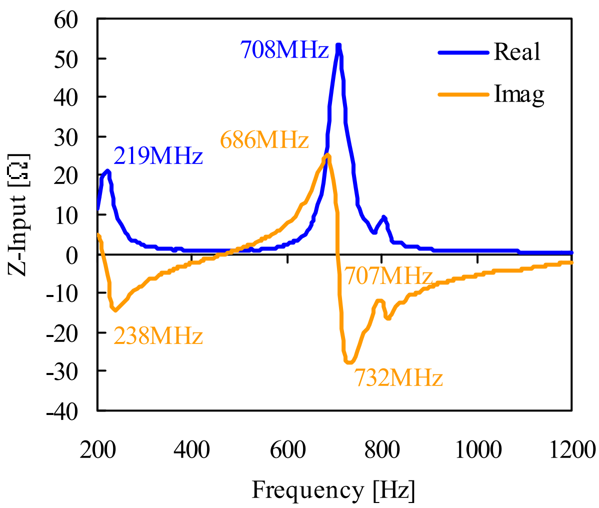

Fig. 7: Impedance of the unchanged module as shown in figure 1

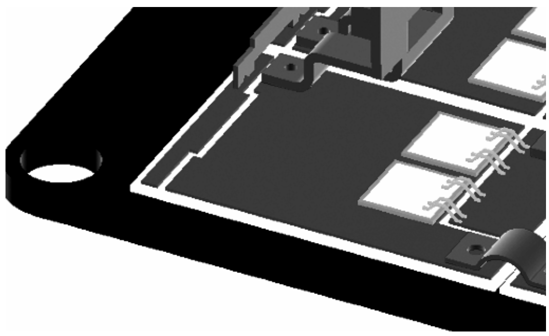

Fig. 8: Module with removed bond wires

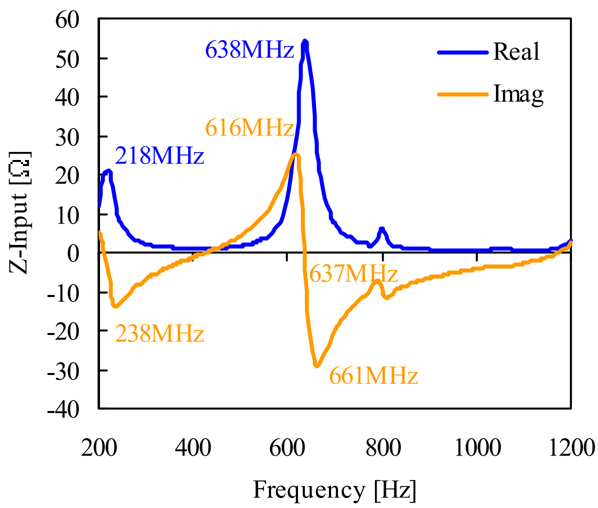

Fig. 9: Impedance of the module with removed bond wires as shown in figure 8

module as shown in figure 1. The module has a resonance point at a frequency of about 700MHz which is in accordance with the oscillation frequency as given by the transit-time of the FWD. Therefore, this simulation explains why Pett oscillation can occur in this power module.
To prevent the occurrence of this effect, the resonance point of the power module should be different from the transit-time frequency. Chances for a realization are given by changes in the module layout or by a change in the parasitic inductance formed by the bond wires.

Influence of Bond Wires

As first, two of the bond wires are removed as shown in figure 8. Due to the increase of the total inductance of the bond wires, the resonance point is shifted towards a lower frequency (see figure 9). Consequently, an increased number of bond wires should result in a lower inductance and therefore in a higher resonance frequency.
An obvious and efficient way for realizing a low inductance is given by providing additional shorts between the anode contact areas as shown in figure 10. This results in a clear suppression of the module resonance (figure 11) and is in accordance with comparable results published previously [8].
Figure 12 shows another module variation, where additional bond wires are placed only at one FWD. As to be seen in figure 13, this is much less efficient compared to the application of direct connecting bond wires.
An interesting alternative is to provide additional bond wires for both FWD, which are connected via a separate small area of the DCB as shown in figure 14. This moves the resonance point to a frequency of approximately 900MHz (see figure 15).
The area which connects the bond wires can also be

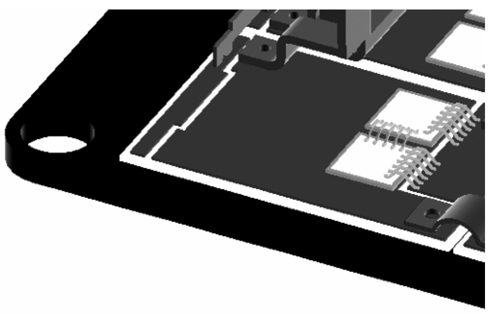

Fig. 10: Module with additional bond wires shorting the anode contact areas of the two FWDs

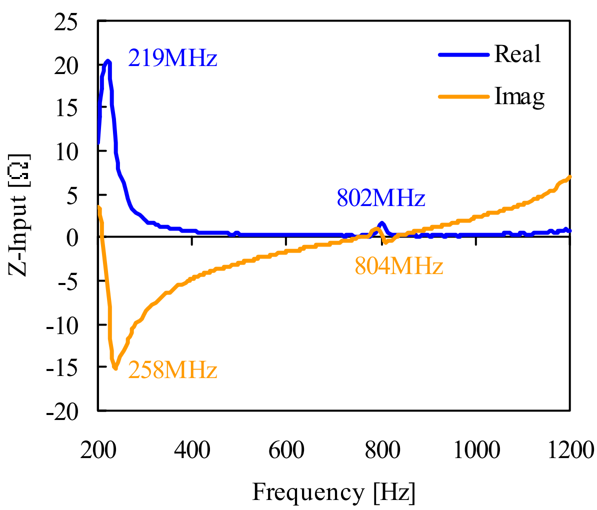

Fig. 11: Impedance of the module with connecting bond wires as shown in figure 10

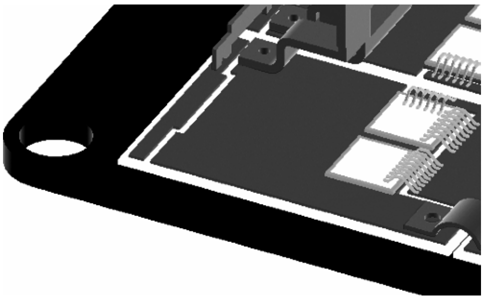

Fig. 12: Module with additional bond wires for one FWD only

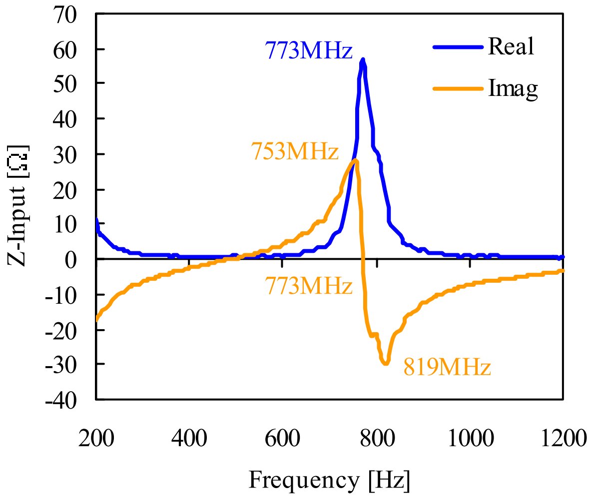

Fig. 13: Impedance of the module with additional bond wires as shown in figure 12

connected with the anode area of the DCB as depicted in figure 16. In this case, the impedance over the frequency range of the module remains almost unchanged as before (compare with figure 17).

Influence of Power Module Layout

Another interesting question is how the impedance of the module depends on the capacitance which is formed by the module itself.
For this investigation, a part of the copper metallization of the DCB carrying the FWDs is separated. Figure 18 shows the resulting layout in detail. According to the simulation results the separation of a part of the copper area of the DCB does not cause any significant change of the resonance point (see figure 19).
Moreover, also the complete removal of the whole area does not show any effect. This means, that the capacitance provided by the DCB areas take almost no influence on the resonance frequency which is a rather unexpected result.
As a last example, figure 20 shows a module with a completely changed layout. This layout allows to double the number of the bond wires and therefore to clearly decrease the inductance. It is expected that this results in a shift of the resonance point to higher frequencies.
The EMC simulation shows that the expectations were not met. The changed layout results in more resonance points, shown in figure 21, and therefore the properties are substantially deteriorated.
The best way for suppression of the unwanted oscillations was found in providing additional anode shorts between the anode contacts of the FWD in one separate group as shown in figure 10. This clearly reduces the inductance of the bond-wires and shifts the resonance point of the complete module into a higher frequency range.

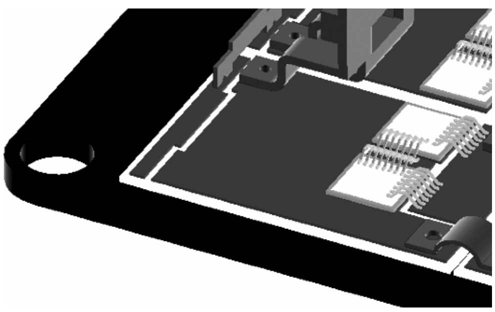

Fig. 14: Module with additional bond wires connecting the anode contacts of the two FWDs via a separate area

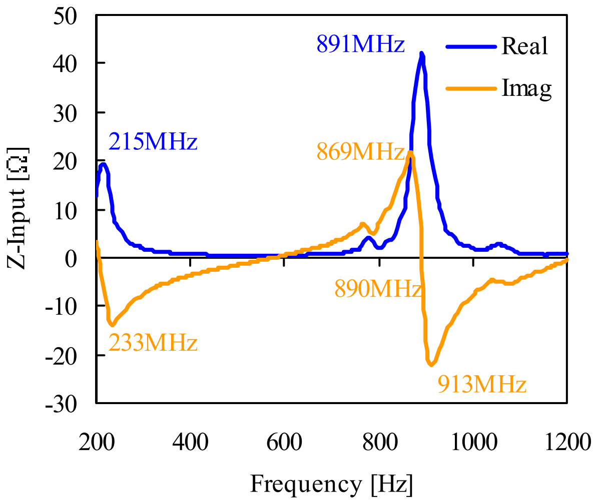

Fig. 15: Impedance of the module with as shown in figure 14

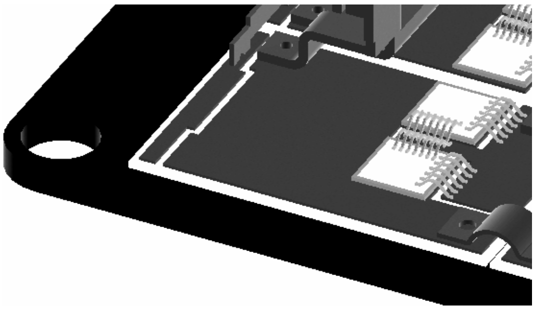

Fig. 16: Module with additional bond wires connecting the anode contacts of the two FWDs via an anode-connected area

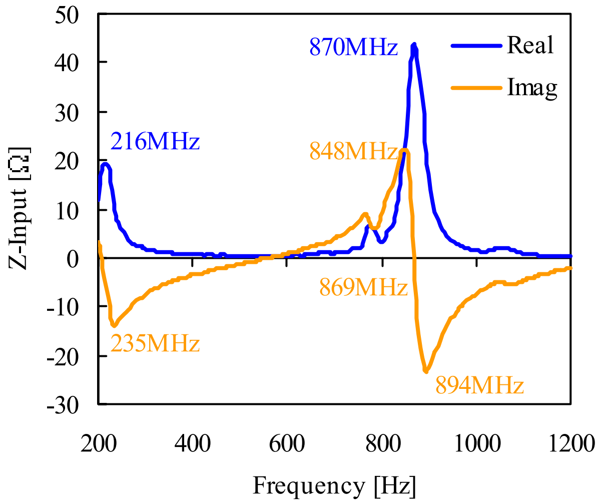

Fig. 17: Impedance of the module as shown in figure 16

CONCLUSION

High-frequency transit-time oscillations in bipolar power semiconductor devices may occur during the tail current phase of the turn-off process. The oscillations investigated in this work are caused by carrier packets extracted from the remaining excess carrier region, which are transported through the already formed space-charge region and which result in oscillations due to interaction with parasitic LC circuits. Resonance frequency of the power module and transit-time of the carriers have to match to effect oscillations.

The use of a 3D EMC simulation tool for the analysis of the power module itself provides a means of detecting the resonance frequency and allows to introduce changes to the module layout.

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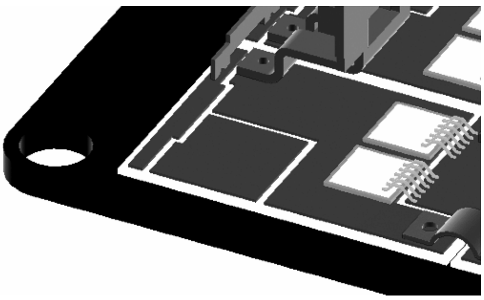

Fig. 18: Module with changed capacitance of DCB

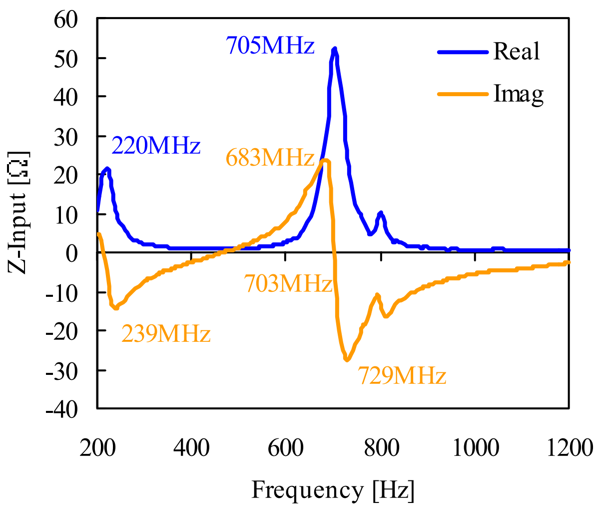

Fig. 19: Impedance of the module with changed capacitance of the DCB as shown in figure 18

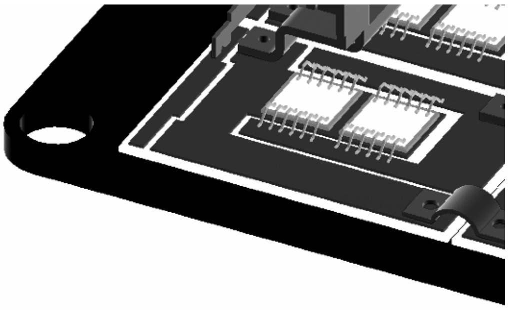

Fig. 20: Module with changed layout and increased number of bond wires

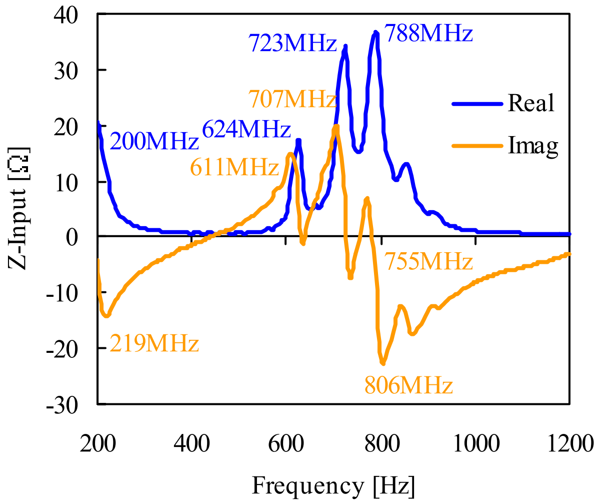

Fig. 21: Impedance of the module with changed layout and increased number of bond wires as shown in figure 20

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Addresses of the authors

Ralf Siemieniec, Infineon Technologies Austria AG, Siemensstraße 2, A-9500 Villach, Austria, e-mail: ralf.siemieniec@infineon.com

Mario Netzel, Technical University of Ilmenau, Dept. of Solid-State Electronics, P.O. Box 100565, D-98684 Ilmenau, Germany, e-mail: mario.netzel@tu-ilmenau.de

Paul Mourick, Engineering Consultant, Auerbacher Weg 12, D-69427 Oberscheidental, e-mail: mourick.p@debitel.net