Proceedings of the 26th International Symposium on Power Semiconductor Devices & IC's
June 15-19, 2014 Waikoloa, Hawaii

Virtual Testing of High Power Devices at the Rim of the Safe Operating Area and Beyond

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Abstract—**The development of high-performance power devices is increasingly supported by predictive computer simulations on the basis of well-calibrated physical device models. Today´s challenge is to make virtual experiments and tests on the computer, which are qualitatively reliable and quantitatively accurate even for device structures that have never been built before, and under operational conditions that very rarely occur as long as the device is kept within the "safe operating area (SOA)". What we are interested in is to explore the rim of the SOA and even to go beyond it in order to study failure and, eventually, destruction mechanisms with a view to improving robustness and reliability of the devices. In particular in the field of high power electronics, predictive high-fidelity computer simulations of "virtual desctruction" are of utmost importance. We will illustrate today´s state of the art with reference to selected real-life examples.**

I. Introduction and Motivation

The continuous progress in power device technology is increasingly supported by power-specific modeling methodologies and dedicated simulation tools. These do not only enable the visualization of fabrication processes and operational principles, but also the detailed analysis of the device and system operation of competing design variants in a very early stage of the development process. Virtual fabrication, virtual experimentation and virtual test by computer simulations have become an integral part of the design methodology for electronic power devices and systems in order to realize cost-efficient and time-economizing development cycles.

A successful virtual design strategy requires modeling methodologies on different levels of abstraction and computational expense. Among the most important aspects to be focussed on, we identify the consistent treatment of electro-thermally coupled fields and coupled domains required for setting up physically-based models for high-fidelity computer simulations. Equally crucial is the reliable validation and accurate calibration of the models, which is the indispensable prerequisite for predictive simulation, in particular for "virtual experiments" at the rim of the safe-operating area close to the destruction of a device.

The high relevance of virtual prototyping is reflected in today´s most crucial problem areas (cf. Fig.1):

- thermal design & management/cooling
- high-temperature operation
- packaging, housing, and interconnects
- vibrational design
- reliability/failure analysis
- robustness ("ruggedness") and stability (even against unlikely, but catastrophic events)
- EMC/EMI and signal integrity
- full system behavior w.r.t. mission profiles

Hence, nowadays the most challenging task of high power device modeling and simulation consists in exploring the safe-operating area and this means the detailed analysis of irregular operating states and failure mechanisms.

II. General Aspects of Power Device and Module Modeling

In today´s power electronics, we basically face the same problem as in micro-electronics, namely that the concept and design of a state-of-the-art power device consisting of some 10,000 microstructured cells, which work in parallel in a cell array for a specified action in a power circuit or module, is essentially governed by intricate trade-off considerations. Therefore a systematic improvement of the performance is hardly possible without being equipped with a profound expertise in the details of the operation of single power device cells and their collaborative interaction as part of a large scale power device with co-integrated additional functionalities such as state monitoring, overload detection

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and protection against overvoltage, overcurrent, or overheating including error detection and compensation by a smart control circuitry, as it is, for example, realized in smart power technologies (SPT) or in high-voltage integrated circuits (HVICs). Using predictive simulation, the required expertise can be gained faster and cheaper than by experimental investigations.

Evidently this requires the availability of efficient simulation platforms, which fit in with today's far advanced design environments used in the semiconductor industry and, in particular, are conform with the widely accepted bottom-up and top-down modeling hierarchies. Moreover, optimal prototyping of power modules requires the concurrent co-optimization of the active and passive electronic elements of a power component and their electrical and thermal interconnection by wire bonds, bus bars, base plate etc. as defined by the packaging and housing of the complete module. To this end, a comprehensive methodology for setting up physically-based (self-)consistent power device and full system models has been developed to enable the effort-economizing and yet accurate numerical co-simulation of individual power devices and full power modules built up of them. This modeling framework [1,2] includes the consistent treatment of electrothermally [3,4,5], thermo-mechanically [6], and electromagnetically [7] (inductively and capacitively) coupled fields and coupled energy and signal domains ("multi-physics" models, cf. Fig.°1) required for deriving electro-magneto-thermo-mechanical macro-models from the continuous field level, and it also provides a solid basis for the reliable validation and calibration of the models.

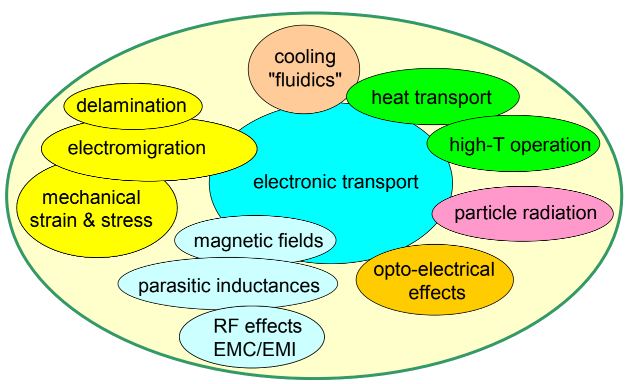

Figure 1. Problem areas in the optimized design of power devices and their interrelation in coupled energy domain ("muliphysics") modeling.

The key to the predictive simulation of entire power modules is the use of model reduction techniques, as they allow for setting up physically-based system-level models, which are tailored in the sense that the descriptive complexity is largely reduced, but without losing the scalability and quantitative accuracy required for predictive simulation. The adequate formal representation of the full system description is provided in terms of a generalized ("coloured") Kirchhoffian network description in combination with an appropriate analog hardware description language such as SPICE, SABER, or VHDL-AMS. This makes it possible to code the models of all the individual system components in a generic and uniform way and to assemble the full power module model by linking the constituent parts on the same descriptional level.

As already stated, the complexity of power modules originates primarily from the complicated coupling between different energy and signal domains (Fig. 1) which, on the one hand, is the inherent property of any controllable electronic device, sensor element or other constituent part of a power module and, on the other hand, is an undesired detrimental property, when it occurs as parasitic cross-coupling between the power system components. Hence the accurate analysis of all relevant kinds of physical coupling effects has a major impact on the optimization of power devices and modules and is, thus, one of the most crucial issues that has to be tackled in the computer-aided design of microdevices and microsystems. In this sense, the physically-based, but yet computationally tractable modeling of power devices and power modules is widely recognized as key technology and necessity, even though it may easily become quite involved. Therefore the computational effort as well as the time spent into model development, validation, calibration, and parameter extraction have to be carefully adjusted to the actual needs, as it has been proposed by the concept of "tailored modeling" [6,8]. Powerful user-friendly commercial power device simulation platforms are already available and enable an efficient and time-economizing computer-aided power device and system development.

III. Model Calibration aided by virtual Experiments

The predictiveness of physical device models is decisively determined by the requirement of being "transparent", which means that all numerical model parameters allow for an intuitive interpretation as physical quantities such as geometrical dimensions, material properties, or other technologial data, and that the values of all these parameters have been extracted from test samples or prototypes by experimental characterization. Usually this process of "model calibration" is restricted to the analysis of the electrical terminal behavior, while the "innerelectronic" behavior is amenable to theoretical analysis or computer simulation only. Hence, the internal physical parameters can be determined by "inverse modeling" only and, therefore, their accuracy is often questionable. But with a view to optimizing the device properties a detailed and precise view into the interior of the real devices under real operation conditions is highly desirable.

This gives the impact to set up an experimental platform for the direct space- and time-resolved measurement of the basic state variables in the electrothermal semiconductor transport equations [1,5], namely the carrier distributions and the temperature profile. To this end, a laser-aided probing technique has been developed [9], which exploits the plasma-optical and thermo-optical effect, i.e. the sensitivity of the complex refractive index to the carrier concentrations and lattice temperature. The correct interpretation of the measured light absorption and deflection signals is quite involved and requires an accurate physical model of the measurement process itself [10,11]. Equipped with that, virtual numerical experiments have to be performed consisting of three parts (Fig. 2): electrothermal device simulation, calculation of the light propagation through the device under test (DUT), and simulation of the detector responses. Comparing the results of real and virtual experiment allows one to correctly evaluate the measured raw data and, at the same time, to calibrate

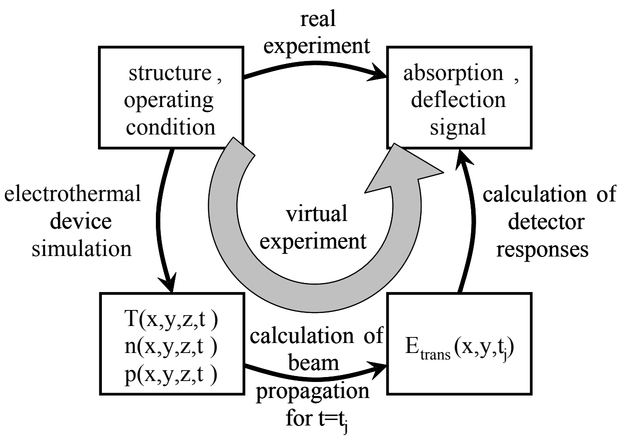

Figure 2: Interrelation between real and virtual experiment, consisting of three parts.

the underlying physical device models. The latter is of particular interest in the case of "unusual" semiconductor material like silicon carbide (SiC), which serves as industrial basis for high-temperature power devices. Therefore, devices made of SiC have been in the focus of the power device experimentalists [12] as well as in that of the theoretical analysts [5] for two decades of years; but nevertheless many material parameters like mobilities and carrier lifetimes are still not very reliable.

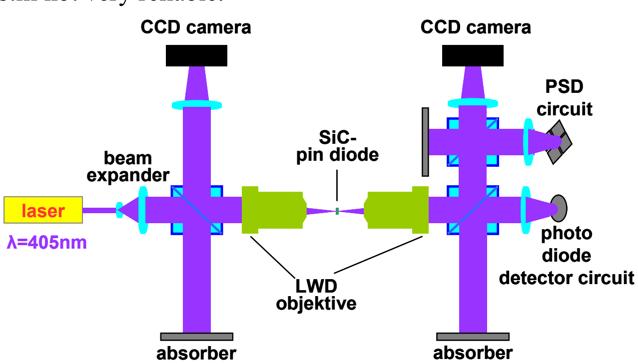

Figure 3: Schematic view of the experimental setup: optical path, electrical lighting, and imaging cameras.

The real experimental setup (Fig. 3) comprises a laser source, an optical set-up with the device under test, and two detector units for light absorption (photo-diode) and beam deflection ("PSD"). The device under test (SiC pin-diode) is biased by strong current pulses with variable pulse height. This drives the DUT in high injection conditions, under which the electron and hole distributions form a quasi-neutral plasma ($n(x) \approx p(x)$) in the low-doped n^--region. According to the Drude model, the local light absorption coefficient is proportional to a weighted sum of the electron and hole densities. In addition, the spatial gradients in the carrier and temperature profiles lead to a deflection of the laser beam (Fig. 4), which complicates the correlation between measured absorption signals and real carrier profiles in the intrinsic layer. For retrieving the carrier profiles from the measured raw data, the virtual experiment is essential (Fig. 2).

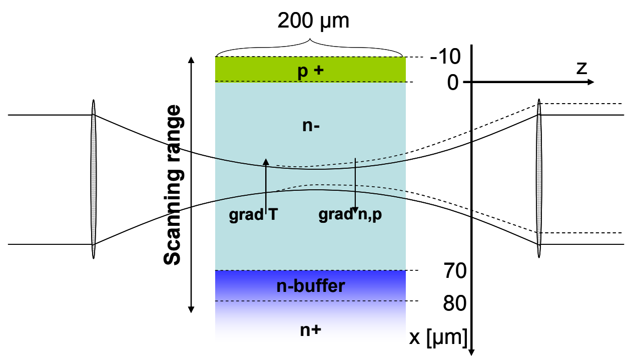

Figure 4: Plasma-optical and thermo-optical effect causing the attenuation and deflection of a coherent light beam, which traverses a semiconductor region under high injection conditions perpendicularly to the direction of current flow.

Typical exemplary real and virtual detector responses in the absorption sensor are displayed depicted in Fig. 5; they are in good overall agreement with each other. This clearly demonstrates that, after a careful readjustment of uncertain device parameters, the real experiment is properly represented by the virtual one. The latter, in turn, makes it possible to reveal the origin of the qualitative differences

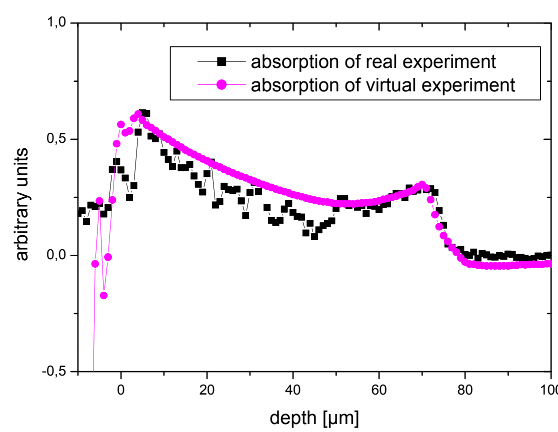

Figure 5: Absorption detector response in the real and in the virtual experiment. The pn-junction is located at 0 µm.

between the light absorption profile and the charge carrier profiles, in particular in the intrinsic region close to the pn-junction and close to the n-buffer. These can be attributed to an enhanced deflection of the laser beam caused by the gradients of carrier density and temperature.

IV. Virtual Testing along the Rim of the Safe Operating Area and Beyond

Achieving the largest possible ruggedness of high power devices against harsh operating conditions is one of the optimization targets during design. Its quantitative description is based on the concept of the (static or dynamic) safe-operating area (SOA), which is defined by the maximum set of (voltage, current) pairs for which the device operates without failure. Determining the boundaries of the SOA is a major concern in industrial applications, as there is an increasing demand for power devices which can be controlled even at the rim of the SOA and where the transient occurrence of dangerous states such as, e.g., avalanche multiplication is tolerated, as long as it does not become destructive. A common approach are experimental stress tests, but these have the obvious disadvantage that they end with the destruction of the device under test in most cases. Therefore one attempts to replace the real stress tests by “virtual tests” based on predictive high-fidelity computer simulations. However, this poses a big challenge to the simulation methodology, because the operating states to be modelled are typically unstable and amenable to a full field-theoretical electrothermally coupled treatment only.

As an illustrative example, we consider cell arrays comprising many thousands of parallel IGBT cells, which are encompassed by an edge termination structure to attain the maximum breakdown voltage also along the boundary of the cell array, since IGBT cell arrays tend to break down at their periphery. Therefore a detailed functional understanding and an optimum design of the edge termination are crucial to achieve the largest possible safe-operating area.

We studied the behavior of two alternative edge termination structures, “junction termination extension” (JTE) [13] and “variation of lateral doping” (VLD) [14,15], in the avalanche regime by numerical simulations and measurements with a view to assessing their ruggedness against such harsh operating conditions. The analyzed parts of a cell array consist of a pn^+n^-p-layered structure and a subsequent JTE or VLD region (Fig. 6). JTE or VLD, respectively, is a p-doped region, with uniform or with gradually decreasing doping towards the right border.

We investigated the time-dependent internal device behavior in the vicinity of the VLD and the JTE edge termination, repectively, under avalanche breakdown conditions. The device region considered (Fig. 6) is a cylindrical ring, where the radius of curvature is chosen in accordance with the real structure. Actually, it represents one of the four corners of the IGBT cell array, which constitute the weakest parts of the cell array as confirmed by experimental findings. The virtual stress test consists in ramping the blocking voltage up to a level slightly above the breakdown voltage and, then, keeping it constant for approximately 100 μs. The response of the two device variants is completely different.

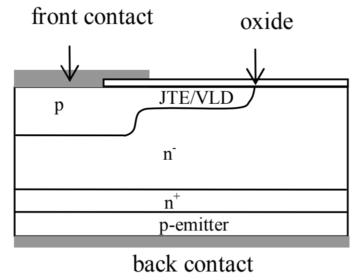

Figure 6: Simplified schematic structure of the edge terminations of an IGBT cell array. JTE or VLD, respectively, is a p-doped region, with uniform or with gradually decreasing doping towards the right border.

In the JTE structure we find an uninterrupted current flow through the device (Fig. 7). Impact ionization occurs localized in the JTE region near the surface and, consequently, the current rises due to avalanche multiplication. A vertical current filament develops underneath the location of avalanche muliplication. However, by the special design of the JTE structure, the profile of the electric field is, throughout the device, only slightly distorted by the avalanche-generated

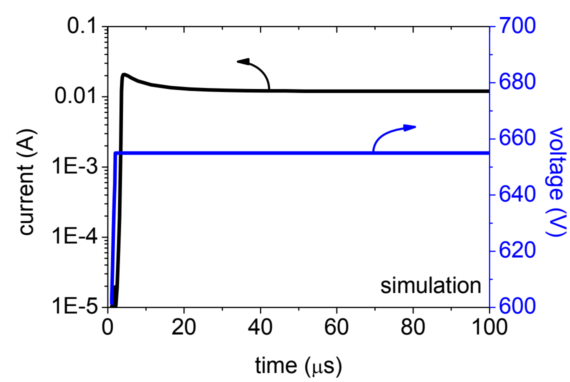

Figure 7: Current transient as obtained from the JTE structure after ramping the blocking voltage up to a level slighty above the avalanche breakdown voltage.

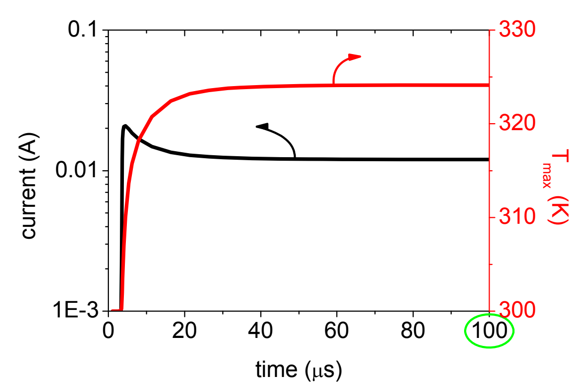

Figure 8: Correlation between temperature transient and current transient as obtained from the JTE structure under avalanche breakdown conditions.

electrons and holes. The power dissipation in the filament leads to an increase of the local temperature which, in turn, reduces the impact ionization rate; as a consequence, the current slightly decreases with time (Fig. 8) and stabilizes at a constant stationary value. Hence, the current filament eventually arrives at a stable stationary state, staying at the same location and carrying a constant current.

A completely different behavior is observed in the VLD structure: we find time-periodic peaks in the avalanche-generated current flowing through the VLD structure (Fig. 9), the period of which decreases with increasing applied voltage .

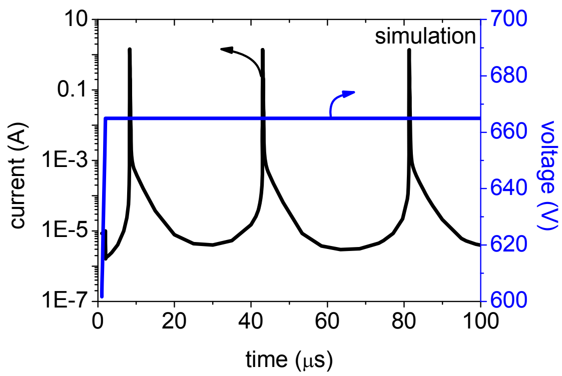

Figure 9:Current waveform as obtained from the VLD structure, exhibiting sharp periodic current peaks after it is driven into the avalanche regime (the bias voltage is kept constant in the simulation).

These current peaks are caused by periodically evolving and self-extinguishing current filaments: In the VLD structure, avalanche multiplication occurs at the bending of the p-body. The avalanche-generated electron-hole pairs and additional holes injected from the p-emitter at the rear side distort the static profile of the electric field drastically. In particular, we observe a local steepening of the peak of the electric field (not shown here) which, in turn, causes a strong localized increase of the avalanche-driven current. The result is a current filament again, for which we find the following time-periodic mechanism: Because of the nearly abrupt onset and steep rise of the avalanche-driven current, the current attains its maximum without a significant change of temperature in the filament (see Fig. 10). But since the maximum current is by a

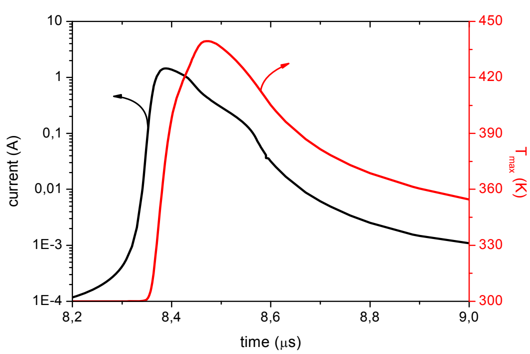

Figure 10: Detailed view of the initial current peak in Fig. 9 (VLD structure), together with the evolution of the maximum temperature in the device.

factor of 50 higher than in the JTE structure and stronger localized, the dissipated power density increases by the same amount, which leads to a subsequent very rapid rise of the filament temperature up to a level (440 K) that is much higher than that reached in the JTE structure (320 K). As a consequence, the impact ionization rate falls very quickly below the multiplication threshold and the filament is destabilized and decays. After a certain period during which the hot spot around the filament cools down, the process of filament formation will restart again. Thus, in contrast to the JTE structure, the VLD structure does not run into an asymptotic stationary state, but orbits in a periodic limiting cycle (Fig.11). By this periodic sequence of short heating and long cooling the dissipated heat is quite effectively distributed in the bulk of the device and, thus, it is protected from running into destruction.

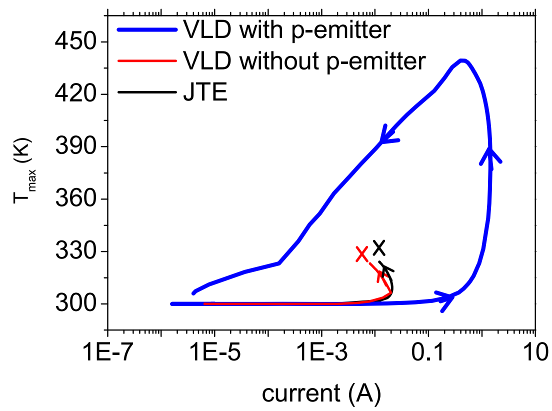

Figure 11: Current-temperature trajectories of the time-variant operating points for the VLD and JTE structure.

Based on our computer simulations we could prove that the completely different transient behavior of the two structures under avalanche breakdown conditions is the result of electrothermal interaction effects. In [15] it is discussed in detail that it is sufficient to consider the temperature dependence of the static I-V-characteristics (cf. Fig. 12) in order to explain the qualitatively different transient behavior and, thus, may be used as a-priori criterion which transient behavior can be expected.

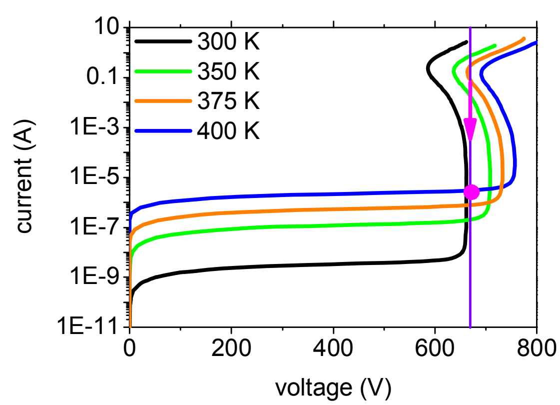

Figure 12: Temperature-dependent blocking characteristics for the VLD structure, showing pronounced negative differential resistance (NDR) behavior.

V. Conclusions

Coupled energy-domain, continuous-field device modeling and coupled-domain system simulation have proven to be indispensable for the development of highly optimized power devices, modules, and systems with competitive performance. Computer-aided design is reducing the number of costly trial-and-error steps and decreases the turn-around times of development cycles. Easy-to-use predictive "TCAD tool boxes" for power devices and systems have today become an integral part of design methodology. Including the functionality for automated parameter identification by closed-loop simulation and, thus, the capability of easy model calibration as well as providing the capability of high-fidelity simulation of irregular operating states at the rim of the safe-operating area is largely desired, already attempted, and in part realized. To this end, we developed a comprehensive and consistent modeling strategy for setting up physics-based “transparent” models, model calibration, device and system analysis, design optimization, reliability and robustness analysis etc. The practicability and efficiency of such a comprehensive, but modular and hierarchical approach has already been demonstrated in the power electronics community by numerous examples.

Now continuing efforts must be made to transform these results in robust, easy-to-use software packages, which are ready for use in existing professional TCAD environments. This implies that, on the device level, software tools must be developed which allow for the efficient interfacing of different single-domain simulators in such a way that - with a view to the specific problem areas of high power technology - new advanced, “tailored” coupling schemes can be realized by a flexible control of the solution process.

Acknowledgment)

The author would like to acknowledge the scientific and technical assistance from his research group and staff, in particular the contributions from Dipl.-Ing. M. Aigner, Dipl.-Phys. F. Hille, Dr. U. Knipper, cand. Ing. A. Korzenietz, Dipl.-Ing. J. Oberndörfer, Dr. G. Schrag, Dr. D. Werber, and Dr. F. Wittmann.

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