Global Electro-thermal CAD of Complex Non Linear 3-D Systems Based on a Fully Physical Time-Dependent Compact Thermal Model

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Abstract— **An original spectral domain decomposition approach is presented for the time-dependent thermal modelling of complex, non linear, 3-dimensional systems. This fully analytical approach immediately gives rise to compact models of non linear distributed thermal subsystems, without requiring approximation by a lumped element RC network, or nodal reduction. In combination with any thermally self-consistent models of analogue, digital, RF and microwave, micro-electromechanical or photonic devices, it supplies a CAD timescale description of mutual thermal interaction between power dissipating and temperature sensitive elements. It therefore has the potential for thermal description of the whole system-in-package. In combination with microwave circuit simulator, Transim (NCSU), the thermal model is applied, for the first time, to the self-consistent global electro-thermal harmonic balance simulation of a spatial power combining power FET array. The model is validated by comparison of electro-thermal simulation of a power HEMT against experimentally obtained thermal images.**

I. Introduction

Self-consistent electro-thermal modelling of the system-in-package (SIP) requires solution of the electrical problem for active and passive devices, analogue, digital, RF and microwave, and for micro-electromechanical systems (MEMS) and photonic components, with simultaneous solution of the thermal problem describing mutual thermal interaction between power dissipating and temperature sensitive elements, including the effects of packaging. This paper describes construction of such a thermal solution and its application in circuit level CAD of complex non linear 3-dimensional systems.

The thermal problem for SIP requires solution of the time-dependent heat diffusion equation for a complex 3-dimensional hybrid structure. Whilst standard numerical techniques such as finite volume, finite element, finite difference, boundary element and transmission line methods have all been used in solution of the heat diffusion equation, these methods require volume or surface discretisation and are computationally intensive. Such solutions are slow and unsuitable for electro-thermal descriptions of complex structures.

For this reason a number of faster thermal descriptions have been explored. The simplest of these consist of thermal resistance descriptions of varying degrees of complexity. However, these descriptions are incapable of describing explicitly complex device structure such as surface metallisation, air bridges, vias and partial substrate thinning, known to be essential, for instance, in electro-thermal descriptions of power transistor operation. Until recently, the state-of-the-art for thermal simulation of heatsink mounted power FETs and MMICs was the hybrid Green's function finite element approach of Bonani *et al.*, [1], which treated all these features. However, this description applied only to the time-independent case. For circuit level CAD, fast 3-dimensional thermal descriptions have been more basic and limited to simple rectangular multilayers. Such models are best exemplified by the work of Szekely *et al.*, who have been using semi-analytical double Fourier series solutions for over 20 years, providing rapid thermal descriptions in programme THERMAN for a range of ICs, MCMs and microsystem elements [2]. Szekely *et al.* have also produced optimised (but necessarily slower) sparse finite difference solutions in programme SUNRED (Successive Network Reduction), for treatment of irregular and arbitrarily inhomogeneous 3-dimensional geometries [3]. However, even with fast 3-dimensional thermal solutions such as these, circuit level models generally require lumped element, thermal RC-network extraction and model reduction, to make possible explicitly coupled electro-thermal simulation on CAD timescales [4]. For intrinsically distributed thermal systems, this necessarily involves approximation and can require substantial preparation and pre-computation time, prior to coupled electro-thermal solution. Furthermore, such solutions generally assume

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that the time-dependent heat diffusion is linear, simply neglecting the non linear effects of temperature dependent material parameters. Finally, thermal solutions often neglect or treat only approximately, the effects of surface radiation and convection. Description of the non linearity of surface fluxes does not appear to have been treated in the electro-thermal CAD literature.

II. Thermal Impedance Matrix Model

The thermal impedance matrix model proposed by the authors for the treatment of the global electro-thermal modelling problem is now described [5]–[11].

A key feature of the proposed approach is that it transforms exactly a non linear, volumetric problem, into a fully linear problem defined only at power dissipating and temperature sensitive device elements, and at interfaces between subvolumes. These subvolumes are most generally N-level rectangular multilayers, with arbitrarily distributed volume heat sources, which can be treated fully analytically using original techniques developed by the authors [10], [11]. This fully analytical thermal solution immediately takes the form of a compact model for electro-thermal CAD, without requiring any explicit model reduction. It provides major reductions in computational expense, making possible explicitly coupled electro-thermal simulation for complex structures on CAD timescales. The structure of this thermal solution is indicated below:

- make exact (*not* small signal) transformations of variable to transform the non linear time-dependent heat diffusion equation into a fully linear equation [7];
- solve the fully linear equation exactly analytically, in complex frequency space (Laplace transform s-space), in rectangular N-layer subvolumes with general (linear) surface boundary conditions [5], [6], [10], [11];
- describe the now linear relation between temperature and flux at discretised interfaces and at power dissipating and temperature sensitive elements, in terms of thermal impedance matrices, with matrix elements generated from the fully analytical subvolume solutions as simple, rapidly convergent, series expressions;
- interpret the thermal impedance matrices as analytically exact, generalised thermal Z-parameters, for the distributed (originally non linear) thermal subsystems;
- implement these thermal Z-parameters as frequency domain or time domain N-port netlist elements within microwave circuit simulator, Transim (NCSU), and solve the coupled electrical-thermal problem by simultaneous iteration (quasi-Newton solutions) [8], [9], [11];
- treat non linear surface fluxes, numerically exactly, as imposed forcing terms about the linear thermal solution (giving the complete non linear solution as the limit of a sequence of fully linear problems [5], [12]).

This approach gives a comprehensive description of the explicitly coupled electro-thermal problem, with full treatment of all thermal non linearities, both material and surface flux, for arbitrarily complex 3-dimensional systems, on CAD timescales. The key advantages of this approach are now outlined.

Firstly, the fully analytical thermal solution in rectangular subvolumes, totally eliminates all volume and surface meshes, discretising only power dissipating and temperature sensitive elements, and interfaces between subvolumes. This approach therefore goes beyond the boundary element method, which uses Green's function techniques to reduce 3-dimensional volume problems to a corresponding 2-dimensional surface description. It is more closely related to the Unsteady Surface Element (USE) method of Beck *et al.*, [13], which discretises only interfaces between subvolumes. However, the USE method has only been applied to simple composite solids and is explicitly time-domain, whereas the thermal impedance matrix approach proposed here can describe arbitrarily complex 3-dimensional geometries, and allows both time domain and frequency domain formulations. Fig. 1 illustrates the thermal impedance matrix description of a complex 3-dimensional volume.

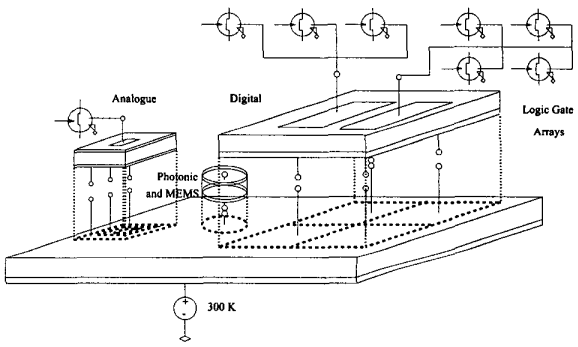

Fig. 1. Analytical thermal impedance matrix description of a complex 3-dimensional thermal system. Rectangular multilayers are described exactly by analytically obtained thermal Z-parameters. The composite solid is described thermally by matching of temperature and flux at the interfaces between thermal N-ports. Only thermal nodes corresponding to power dissipating and temperature sensitive elements, and to the discretised interfaces are required. The thermal model is therefore compact, unlike the network description obtained from numerical volume or surface discretisation.

Secondly, the model produced by the fully analytical, s-space, thermal impedance matrix solution in subvolumes, is minimal. It constitutes a boundary condition independent compact model [14]. Thermal impedance matrix elements represent 'thermal links' which have no direct correlation with physical structure, but which

generalise readily to arbitrary numbers of nodes, unlike thermal network descriptions based on direct subvolume discretisation, which can get increasingly convoluted with increase in size.

This compact description goes beyond most previous compact models, in that it treats both the time-dependent case and thermal non linearity. Compact time-dependent models in the form of RC ladder representations, *e.g.* [4], can only ever be a finite pole-zero approximation to the distributed thermal subsystems. Lumped element approximations describe only the dominant time constants, and represent the continuum for the distributed system by a finite number of poles. By contrast the thermal Z-parameter approach provides an essentially exact description of time-dependent 3-dimensional heat flow in subvolumes, retaining an infinite number of poles.

The matrix formulation of the thermal subvolume solutions allows direct analytical construction of minimal thermal solutions for complex systems, such as metallised MMICs, by simple matrix manipulations on thermal subvolume matrices. Both vertical matching and horizontal matching at subvolume interfaces can be imposed, by appropriate construction of the double Fourier series analytical subvolume solutions. This allows a simpler construction of thermal solutions for complex systems than that based on the hybrid Green's function finite element description of Bonani *et al.* In fact, the approach described here allows fully analytical expressions for the heat flow problem in a complex structure, such as a metallised power FET. It returns the exact heat flow description as a compact model represented by a thermal resistance matrix containing all metallisation effects. The order of this matrix, $N \times N$, is determined only by the small number of heating elements (gate channels or channel subsections), N, no matter how complicated the metallic superstructure. Combined with numerical Laplace inversion, which is very cheap, accurate and easy to implement algorithmically, the compact analytical thermal impedance matrix technique represents a full, and totally original, spectral domain decomposition approach to the time-dependent heat diffusion problem in complex 3-dimensional systems such as entire SIP.

Combination of original, fully analytical, Fourier solutions for arbitrarily distributed volume (rather than surface or interface) heat sources and sinks, with original Fourier solutions for subvolumes having arbitrary flux density prescribed on all faces, gives a method for thermal impedance matrix description of complex inhomogeneous packages. These approaches compare favourably for speed and flexibility with programmes such as THERMAN and SUNRED, and give minimal compact models for electro-thermal CAD directly, without the need for explicit model reduction.

Thirdly, the thermal impedance matrix approach described here has the potential to treat all thermal non linearities, both due to temperature dependence of material parameters, and due to non linear surface fluxes. It therefore differs from most reduced thermal model descriptions, which ignore temperature dependence of material parameters in order to generate a linear thermal network. The proposed approach constitutes the only model in the electro-thermal CAD literature to treat temperature dependent diffusivity, which is essential for accurate calculation of thermal time constants (as opposed to treatment of temperature dependent conductivity alone, for accurate calculation of steady-state temperature, which is more routinely achieved by use of the Kirchhoff transformation [7]).

III. Results

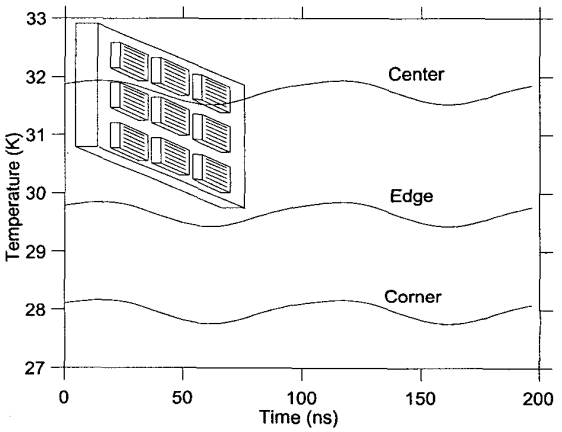

Fig. 2. Single-tone harmonic balance simulation of a power FET array (inset) representative of one kind of spatial power combining architecture. The global simulation is electro-thermally self-consistent. Non linear thermal matching is applied at interfaces between power FET die and substrate. Heat loss is entirely by linearised radiation and convection into free space, with no heatsink mounting.

Fig. 2 illustrates calculated temperature response of a power FET array (inset) obtained from self-consistent electro-thermal simulation by implementing the thermal impedance matrix approach in microwave circuit simulator, Transim (NCSU) [15]. This single-tone harmonic balance (HB) simulation represents a fully coupled, global electro-thermal simulation, of a highly complex and non linear system. The thermal description includes non linearity due to temperature dependence of material parameters, with non linear

matching at interfaces between power FET die and substrate. Heat loss is purely by linearised radiation and convection from the substrate, with no heatsink mounting. The thermally self-consistent electrical description is provided by the Curtice Ettemberg cubic model of the MESFET, with symmetric diodes and capacitances, embedded in a simple amplifier circuit.

For model validation, fully physical electro-thermal simulations of a 24 mm gate length power HEMT were compared against thermal images obtained with an Inframetrics ThermaCam, Fig. 3. Agreement was good.

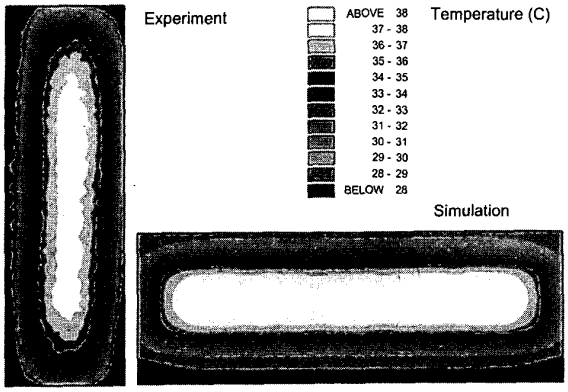

Fig. 3. Measurement and electro-thermal simulation of surface temperature in a 60-finger power HEMT. Bias (V_{DS}, V_{GS}) = (8 V, -1.5 V) and power dissipation is 3.2 W.

IV. Conclusion

Global electro-thermal modelling of complex systems has been outlined. The fully analytical thermal impedance matrix approach to the description of mutual thermal interaction between power dissipating and temperature sensitive elements has been presented. In combination with thermally self-consistent models of device performance, this method has the potential to provide global simulations of large and highly complex systems on CAD timescales. The method was illustrated by HB simulation of a power FET array representative of one kind of spatial power combining architecture. The model was validated by comparison of electro-thermal simulation against measured thermal images for a power HEMT.

V. Acknowledgement

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References

[1] F. Bonani, G. Ghione, M. Pirola and C.U. Naldi, "Thermal CAD for power III-V devices and MMICs," *Proc. SBMO/IEEE MTT-S Internat. Microwave and Optoelectronics Conf.*, vol. 1, pp. 352-357, 1995.

[2] A. Csendes, V. Szekely and M. Rencz, "An efficient thermal simulation tool for ICs, microsystem elements and MCMs: the μS-THERMANAL," *Microelectron. J.*, vol. 29, pp. 241-255, 1998.

[3] V. Szekely, A. Pahi, M. Rencz, "SUNRED, a new field solving approach," *Symp. Design, Test and Microfab. MEMS and MOEMS*, SPIE vol. 3680, no. 1, pp. 278-288, 1999.

[4] V. Szekely, "THERMODEL: a tool for compact dynamic thermal model generation," *Microelectron. J.*, vol. 29, pp. 257-267, 1998.

[5] W. Batty, A.J. Panks, R.G. Johnson and C.M. Snowden, "Electro-thermal modelling and measurement for spatial power combining at millimeter wavelengths," *IEEE Trans. Microwave Theory Tech.* vol. 47, no. 12, pp. 2574-2585, 1999.

[6] W. Batty, A.J. Panks, R.G. Johnson and C.M. Snowden, "Electro-thermal modelling of monolithic and hybrid microwave and millimeter wave IC's," *VLSI Design*, vol. 10, no. 4, pp. 355-389, 2000.

[7] W. Batty and C.M. Snowden, "Electro-thermal device and circuit simulation with thermal non linearity due to temperature dependent diffusivity," *Electron. Lett.*, vol. 36, no. 23, pp. 1966-1968, 2000.

[8] W. Batty, C.E. Christoffersen, S. David, A.J. Panks, R.G. Johnson and C.M. Snowden, "Steady-state and transient electro-thermal simulation of power devices and circuits based on a fully physical thermal model," *Proc. 6th THERMINIC Workshop*, pp. 125–130, Budapest, September 2000.

[9] W. Batty, C.E. Christoffersen, S. David, A.J. Panks, R.G. Johnson, C.M. Snowden and M.B. Steer, "Predictive microwave device design by coupled electro-thermal simulation based on a fully physical thermal model," *Proc. 8th IEEE Internat. Symp. on High Performance Electron Devices for Microwave and Optoelectronic Applications (EDMO 2000)*, pp. 111-116, 2000.

[10] W. Batty, C.E. Christoffersen, S. David, A.J. Panks, R.G. Johnson, C.M. Snowden and M.B. Steer, "Fully physical, time-dependent compact thermal modelling of complex non linear 3-dimensional systems for device and circuit level electro-thermal CAD," *Proc. 17th Annual IEEE SemiTherm Symp.*, San Jose, March 2001.

[11] W. Batty, C.E. Christoffersen, A.J. Panks, S. David, C.M. Snowden and M.B. Steer, "Electro-thermal CAD of power devices and circuits with fully physical time-dependent compact thermal modelling of complex non linear 3-d systems," *IEEE Trans. Components Packaging Technology*, (to be published).

[12] R.M.S. da Gama, "A linear scheme for simulating conduction heat transfer problems with nonlinear boundary conditions," *Appl. Math. Modelling*, vol. 21, no. 27, pp. 447–454, 1997.

[13] J.V. Beck, K. Cole, A. Haji-Sheikh and B. Litkouhi, "Heat conduction using Green's functions," Hemisphere Publishing Corp., Washington DC, 1992.

[14] C.J.M. Lasance, "Two benchmarks for the study of compact thermal modelling phenomena," *Proc. 6th THERMINIC Workshop*, pp. 235–243, Budapest, September 2000.

[15] C.E. Christoffersen, U.A. Mughal, M.B. Steer, "Object oriented microwave circuit simulation," *Int. Journal of RF and Microwave CAE*, vol. 10, no. 3, pp. 164–182, 2000.