The Effect of Polyimide Fixation on Thermal Performance of GaAs Cantilever Based MEMS: A 3D Numerical Analysis with DEETEN

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We refer of novel simulation technology DEETEN based on spatial domain decomposition, capable of efficient multi-million-point 3D simulations on a conventional PC. The technology has been successfully applied to 3D thermal analysis of a GaAs Micromechanical Thermal Converter microsystem.

1. Introduction

Modeling and simulation becomes inevitable in design of novel microelectronic devices. However, with rising interest in 3D devices, like MEMS, complex heterostructure systems or 3D integrated circuits, the amount of machine resources needed for simulation rises more rapidly, than in devices with 2D topology. We want to address this issue by novel simulation technology we call DEETEN – it stems for Differential Equation Efficient Treatment by Eliminative Nesting – where machine resources are taken in more efficient way, following the complexity of the topology of the target device, as well as complexity of the investigated physical property. This method enabled us to analyze thermal properties of a GaAs Micromechanical Thermal Converter device in 3D on a conventional PC within a couple of hours.

The core of DEETEN technology is a structure of complexity-concerning, automatically created, binary-chained, overlapped and overloaded domain-based meshes for 3D modeling and simulation, with primary application to partial differential equation treatment by method of finite differences. It is intended to two goals: to overcome the unnecessary fine mesh structure in areas of smooth (close-to-linearly dependent) fields and so to substantially decrease the memory usage, and to speed the numerical solution by a more-than-proportional factor over the conventional methods.

DEETEN domain structure is homogenous which means that each 3D domain consists of 1000 mesh points (spatial resolution is 1:10). This is of course too raw for describing properties of the simulated system, hence in areas where necessary, one or more other, smaller domains (child) are generated to describe the situation more precisely. This process of chaining of domains goes further and further till the desired spatial resolution is reached or machine resources are exhausted. The deeper the process goes, the more domains exist in a layer of specific nesting level. The distribution of domains at a layer then follows complexity of the modeled system (material characteristics changes or larger gradient of the inspected physical quantity). The most important fact is that creation and annihilation of domains (a domain can be found unnecessary in process of simulation) is “by definition” automatic. There is no need to “tell” the simulator there and there is something to look on – it knows it and focuses its attention in the right places.

The parent and child domains are matched so that the inner volume of a child matches perfectly with one octant of inner volume of the parent. This condition assures that two child domains (sibs) are overlapped so that a part of the boundary of one sib covers with the first plane of inner points of the other sib. Inner volumes of two sibs create smooth unitary volume but *they do not overlap*. This is the necessary condition for sequential (domain-by-domain) solution to PDEs, which are treated by finite difference method. Its relative simple discretization and field relaxation algorithms that mostly lead to global convergence are bless for research workers who will see results without being too much involved in program writing and tuning. We believe, FDM with DEETEN can be as effective as FEM is, if not even more. So we decided to study DEETENs efficiency practically in a case of thermal analysis of MEMS.

2. Studied MEMS

In first, we studied a cantilever-based Micromechanical Thermal Converter developed as key part of Microwave Transmitted Power Sensor (MTPS) [1,2]. This MTC consists of two GaAs cantilevers with two HFET heaters at each. To ensure mechanical stability of the 1-2μm thin cantilever substrate, the system has been enhanced with 2μm thin polyimide membrane with low mechanical stress and thermal conductivity. Our effort was then concerned to estimate the thermal properties of the MTC with and without the PI membrane, and to verify proposed minimal influence of PI membrane to thermal properties of MTC in order to give key data for developers of the MTPS.

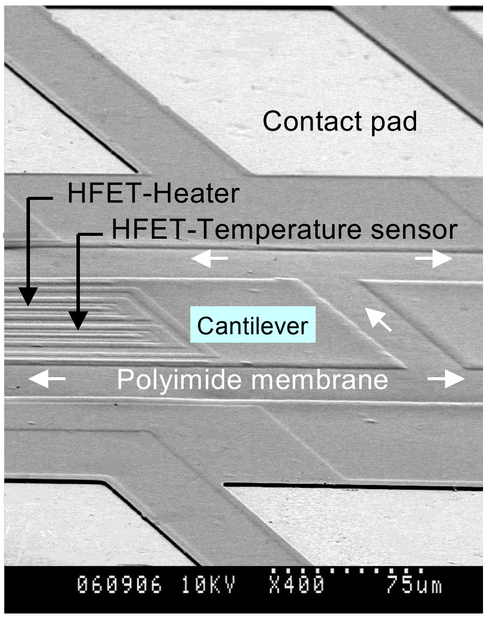

Fig. 1. Micrograph of the simulated MEMS device.

Secondly, we investigated thermal properties of a membrane-like MTC design with isolated GaAs 1μm thin sensing element, "floating" by means of a 1μm thin PI membrane, with two resistive (Pt meander) sensing elements placed on PI membrane. In both simulations, Au/Ti metallization as well as sensing elements have been involved to obtain realistic thermal model of the MTC.

Fig.1 shows a real front-side view of the cantilever MTC device. It consists of two HFETs monolithically integrated on the cantilever structure fixed by 2 μm-thick polyimide membrane. In this integrated approach, one of the HFETs is designed to serve as a heater and the second one is used for the temperature sensing.

Simulated MTCs are kept in air and ambient temperature is 300 K. The air thermal conductance is also included in model. A slight thermal non-linearity of GaAs has not been accounted so far. Power dissipation in the HFET heaters was set to 1 mW.

3. Results of DEETEN simulations

For our purposes, the dimensions of the main domain for cantilever MTC simulation were 1.6x1.6x0.16mm, and the limit of level in the automated creation of domains has been set to 5, i.e. a spatial resolution of 1:256 could be achieved. Typical amount of created domains did not exceed 1500, which gives 1.5 million DEETEN mesh points, in comparison to 256^3 = 16.7 million points of regular rectangular mesh with the same effective spatial resolution. More than memory savings are important savings in simulation time, which for a 400MHz Pentium-II-based PC is approx 3 hours. For the membrane-like, isolated GaAs MTC, we had 1x1x0.1mm main domain, with maximal level of nesting 6, i.e. with achieved spatial resolution up-to 1:512. DEETEN converged to approx. 2.5M points (in comparison to 512^3 = 134M points in a system with regular mesh distances) in about an hour, powered by 1.1GHz Celeron PC with 256MB SDRAM.

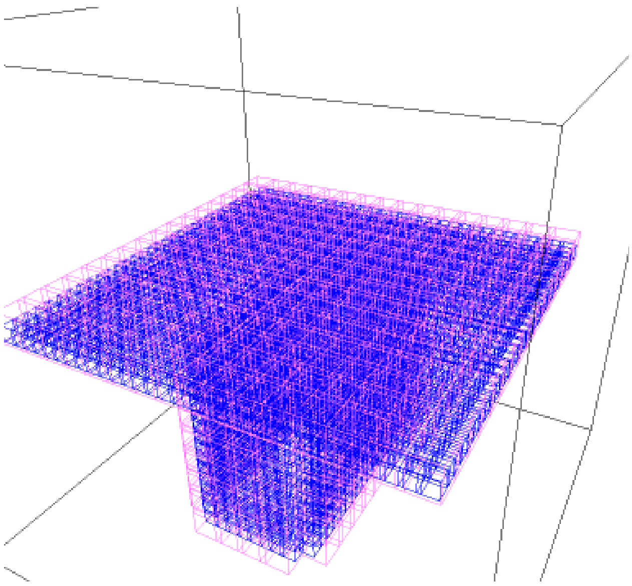

Fig. 2. Domain mesh structure for polyimide-fixed cantilever. Each cubic domain consists of 1000 points with simulation data.

In Fig.2, the automatically created domain mesh structure is depicted for the polyimide-fixed cantilever. Only domains of the two most deeper levels (level 4 and level 5) are depicted. Domains of those orders are situated near material interfaces and big temperature gradients, as is the hole in GaAs bulk or GaAs-polyimide-air boundary. Edges of the base domain of level 0 are also partially visible.

Simulated temperature fields in GaAs and polyimide membrane in a 3D-view are depicted in Fig.3 and Fig 4. The temperature field is encoded in color saturation, thus the hottest regions are white. There is a very small degradation of performance of the MEMS through polyimide fixation: the maximal temperature of the non-fixed MEMS is T_{MAX}=10.11 K over ambient, and for the fixed MEMS, maximal temperature is T_{MAX}=9.96 K over ambient, so the degradation of 0.15 K does not exceed 2 % of overall performance. Much more of importance are metallic leads, which result in about 7 K, or about 40 % degradation. Based on the thermally linear system, the effective thermal resistance of the investigated MEMS can be evaluated as T_{MAX}/P_{HEAT} which is approx. 10 K/mW. The simulated temperature fields of the membrane-like, isolated MTC are depicted in Fig. 3 and Fig. 4. Resulting thermal convergence factor for this design of MTC is approx. 13 K/mW.

4. Conclusions

In thermal investigations of two designs of a Micromechanical Thermal Converter MEMS, DEETEN has been proven as viable and promising technology. However, more effort – and probably, wider research work – is needed. DEETEN joins numerical methods for PDE treatment with modern, object-based software technologies, and uses both in a more sophisticated way. To get even more form it, a joined research effort involving experts from diverse scientific areas is affordable. We hope we can wake the interest in the people there.

Our next plans involve more detailed thermal investigations of MEMS by DEETEN with details in 100-10nm range, more visualization and data-extraction methods, and working on a complex simulator for thermal, electronic and mechanic phenomena in microsystems.

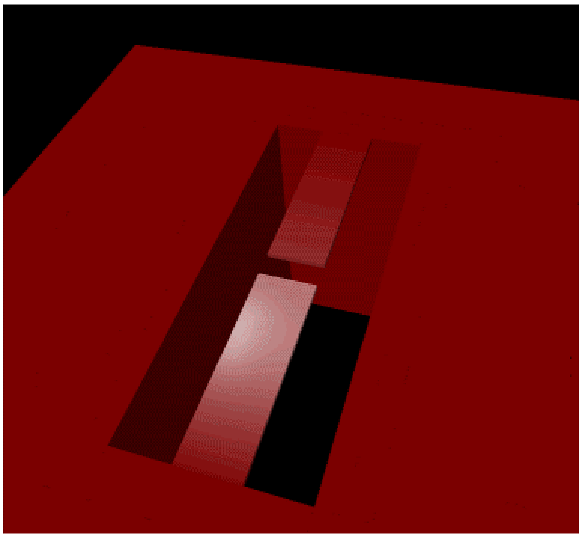

Fig. 3. 3D view of simulated temperature distribution on a GaAs cantilever MTC.

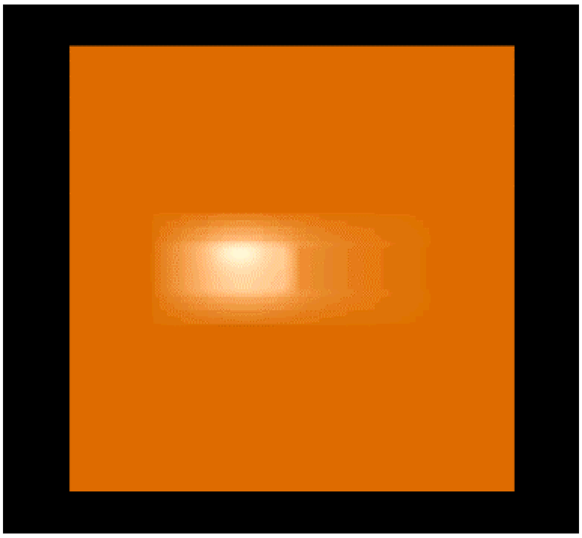

Fig. 4. Simulated temperature field in polyimide membrane in a top view.

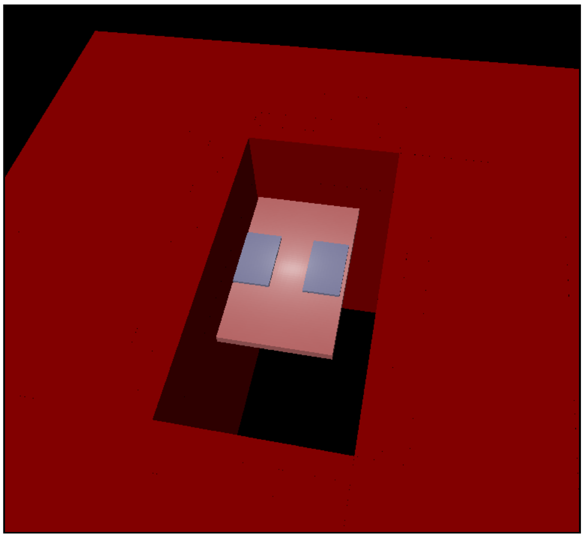

Fig. 5. Temperature field in membrane-like, isolated GaAs MTC. Polyimide membrane, as well as metallization are excluded.

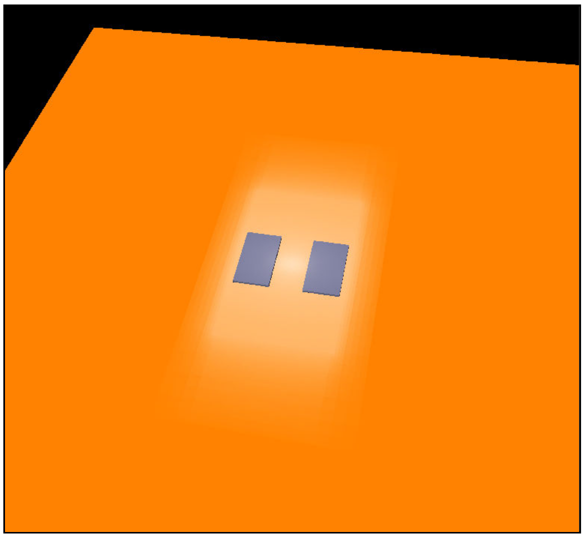

Fig. 6. Temperature field polyimide membrane of the membrane-like MTC. Two Pt resistive temperature sensors are situated on the PI membrane.

References

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