Mixed-Technology CAD for Integrated Systems--
a confluence of electrical and mechanical perspectives

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The history of the integrated circuit (IC) industry over the past three decades has been unparalleled in technical achievement, creating new concepts in support of industrialization and benefits to society. The ubiquitous use of IC technology in virtually every aspect of modern society is a remarkable fact that supports and shapes an information revolution that is now unfolding. Particularly, the areas of communications, computation and industrial/commercial electronics each drive major market segments and are simultaneously supportive of still broader changes in global economic development. At the same time, just as with Amdahl's Law which reveals the limits of computer performance, there are other basic (Newtonian) laws that reflect other systems challenges. Namely, Amdahl's Law says that the slowest path will limit logic speed (or memory access) which in turn controls computer performance. From a broader systems perspective, the size and mass of any system will pose basic limits on its range of application. Hence, the focus of this paper is aimed at considering the parallels and potential synergism between Technology Computer-Aided Design (TCAD) that has leveraged IC design and new domains of CAD that are emerging and shaping the physical (and behavioral) aspects of systems, coming in large part from the perspective of computational mechanics.

The genius and potency of IC technology is the ability to repeatedly, and with nearly atomic-scale precision, change material properties of a silicon wafer, using processing such as deposition, etching, ion implantation and a range of reactive steps. The result is the simultaneous creation of millions (approaching billions) of device components on a single die that measures about one square centimeter in active surface area. The ongoing reduction of minimum feature size and resulting increase in functional density have followed the semi-logarithmic straight line growth predicted by Gordon Moore two decades ago. Yet, this “scaling law” is rapidly approaching limits imposed by fundamental materials properties at the atomic scale. Hence, there is increasing efforts to both measure the results and control IC fabrication processes on this scale. Moreover, the cost of the manufacturing technology, including stringent environmental protection requirements, have necessitated both re-thinking and re-engineering many of the approaches to IC manufacturing. It is in both of these areas--atomic scale technology and achieving more efficient manufacturing--that the synergistic connections between TCAD for ICs and opportunities in computational mechanics will most certainly grow and flourish in the future.

After briefly reviewing the present status of IC scaling, the underlying technology base and the capabilities of existing TCAD tools to support design and manufacturing, specific examples of new challenges for future IC developments will be presented. The impact of micro-machined structures, created using much of the IC fabrication infrastructure in a bootstrapping fashion, on both the sensing and control aspects of manufacturing will be used as driving examples. The atomic force microscope (AFM) and a number of related derivative instruments are revolutionizing metrology for ICs. In-situ monitoring of mechanical and chemical changes to IC wafers has also benefited from new sensors that are micro-machined. Finally, the use of miniaturized gas and fluid controllers is having a major impact on manufacturing, including the possibilities to dramatically reduce materials (and waste) required for the processing.

The overview of TCAD for IC technology development and examples of how micro-machined structures are helping to reshape the manufacturing process itself provide motivation for considering the larger potential synergism of CAD for electronics (defined quite broadly) and computational mechanics. The field of micro-electro-mechanical systems (MEMS) has emerged as the "second coming" of a micro-industrial revolution, now leveraged by both micro-machining as a technological vehicle and micro-electronics with the ability to imbed intelligence deeply and abundantly in such systems. While this paper will not attempt to review the broad field of MEMS, there are essential links between the emerging fields of CAD that will support MEMS and TCAD that continues to support mainstream IC technology development. It is in this area of overlap and especially in the consideration of fabrication processes that recent progress and prospects for future research will be outlined.

Moreover, there are physical effects in the fabrication process that are not important for circuit behavior but critical for MEMS operation and reliability, such as residual stress gradients in thin films and interface stress. Traditional TCAD needs to be enhanced to include better computational mechanics and flexible definition of stress-strain relations for MEMS fabrication prototyping. Also for MEMS behavior modeling, in addition to the Poisson and carrier transport equations, multi-physics system of equations including solid mechanics that treats large stress and deformation, microfluidic and electro-magneto dynamic models may be necessary. These tightly coupled systems pose new research challenges in understanding the numerical stability and adaptability. There is also a rich set of computational geometry utilities such as gridding that can be shared in the mixed-technology software system. Owing to the possible large geometry (in the scale of 50 to 200 μm) and high aspect ratio of MEMS devices in comparison with the microelectronic devices (in the scale of 0.1 to 1 μm), geometry hierarchy in dimensionality and lumping is much more important for the mixed-technology CAD system.

There are two fundamental changes that are now occurring in mainstream IC technology that directly map into the domain of MEMS. First, the limitations of functional density that can be achieved within the silicon wafer have pushed technologists to: a) use trench etching of silicon for both isolation and in creating functional devices (i.e. DRAMS) and b) create more exotic structures on top of the wafers involving a range of conventional (i.e. poly silicon, aluminum...) as well as non-traditional (low- and high-dielectric constant...) materials. Second, many of the performance issues facing future ICs--achieving higher speed and dealing with greater amounts of heat dissipation--have mandated more careful considerations of packaging. Both of these issues and perspectives provide fertile ground for developing stronger links between the TCAD and computational mechanics communities. The range of non-planar structures (trenches, bridges, beams...) that are being imbedded within mainstream IC technologies offers a wealth of opportunities for new research across traditional disciplinary boundaries of engineering. Moreover, the growing breadth of materials that are being used, combined with the fact that their thin film properties often differ mechanically by many orders of magnitude from their macroscopic counterparts, open still broader horizons for essential research and computational prototyping.

In summary, this talk will use the area of IC technology and the strategic use of TCAD in its development as the motivation for a longer-range perspective on growing synergism for future research across the boundaries in engineering and especially linking to computational mechanics. The recent trends in creating MEMS using mainstream IC technology and in applying them for improved manufacturing processes is also briefly reviewed. Both of these themes in turn support the ongoing needs for new computational models of micro-machined silicon technology that exploits thin-films with new materials properties.