MEMS Computer-aided Design

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Abstract

A major hurdle in manufacturing MEMS is reducing the expensive and long product development cycles. Adequate design and fabrication software tools have not been available until recently. Previously, manufacturers were forced to undertake many trial-and-error iterations when manufacturing devices since it was difficult to model accurately the physical behavior of three dimensional microdevices. IntelliSense developed IntelliCAD™ to address the need for predictive MEMS development. IntelliCAD™ is an integrated software system which assists designers in optimizing MEMS devices by providing them with needed manufacturing databases and by allowing them to model the entire device manufacturing sequence and to simulate behavior without having to enter a manufacturing facility. IntelliCAD™ has predicted the behavior of complex structures to within 10% accuracy by utilizing fully coupled thermo-electromechanical analysis. Its use has resulted in device designs that are more manufacturable and in reduced development time and cost.

An opportunity for efficient MEMS manufacturing

Efficient manufacturing of MEMS and other silicon micro-machined devices can be achieved by reducing the expensive and lengthy product development cycle times. The cycle time varies based on the particular application and its complexity, however the most common cause of long development times stems from an industry-wide inability to predict the effects of manufacturing on the device and its performance. Specifically, it has been very difficult to model accurately the behavior of three-dimensional microstructures and to predict thin-film property behavior as a function of the many manufacturing parameters. Iterative design-fabrication-testing procedures proved to be extremely time consuming and expensive.

The recent accumulation of manufacturing information and better computer-aided design tools are two resources that are presently helping to overcome these fabrication setbacks- a welcome relief to manufacturers that were forced to rely solely on trial-and-error when manufacturing devices. IntelliCAD™ was developed to address the need for predictive MEMS development, and it has been the leader in the revolution of CAD for MEMS. IntelliCAD™ provides designers with manufacturing databases and simulators which allow them to model the entire device manufacturing and load simulation without ever having to enter a manufacturing facility. The result is decreased development time and reduced cost for the user.

IntelliCAD™ architecture

Databases:

IntelliCAD's has three extensive Fabrication, Design, and Material databases collected and documented from respected sources. These databases are seamlessly integrated in IntelliCAD™, and users can easily add custom information to any of them. The databases are discussed in more detail as they pertain to device design and simulation.

Device design:

IntelliCAD™ uses a process sequence builder to emulate the actual process steps that go into building a device in a fabrication facility. For example, the steps in a typical MEMS process, including laying down a silicon

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substrate, cleaning, deposition, mask layout, implantation, and etching steps, are incorporated within the IntelliCAD™ Fabrication Database. The process parameter information for each of these steps is automatically transferred from IntelliCAD's Fabrication database to the process builder. Custom user processes can be easily incorporated in the Fabrication Database.

Instead of building a process sequence one step at a time, the user can access the IntelliCAD™ Design database to obtain standard MEMS processes including Bulk Micromachining, Surface Micromachining, LIGA, High Aspect Ratio Micromachining, and others. Once these standard process templates are opened in IntelliCAD™, users can make the desired mask changes or other process changes to suit their needs. The process sequence builder uses a layout editor in which the user can edit design mask layouts or import /export to GDS-II, DXF, and CIF formats.

Once the user inputs a process sequence or uses a process template, an expert system process checker debugs the process to ensure completeness and continuity of the defined steps.   IntelliCAD's solid modeler will then create a three dimensional structure upon combining the fabrication information from the process sequence builder (one dimensional) and planar geometry information from the mask layout editor (two dimensional). Figure 1 shows a typical IntelliCAD™ process sequence and resulting solid model. An architecture such as this, incorporated with a customized solid modeler tailored for MEMS, is a notable departure from pre-cursors to the IntelliCAD™ system [1,2]. IntelliCAD's solid modeler is capable of conformal deposition, etching, and three-dimensional animation and display of the geometry at any given fabrication step.
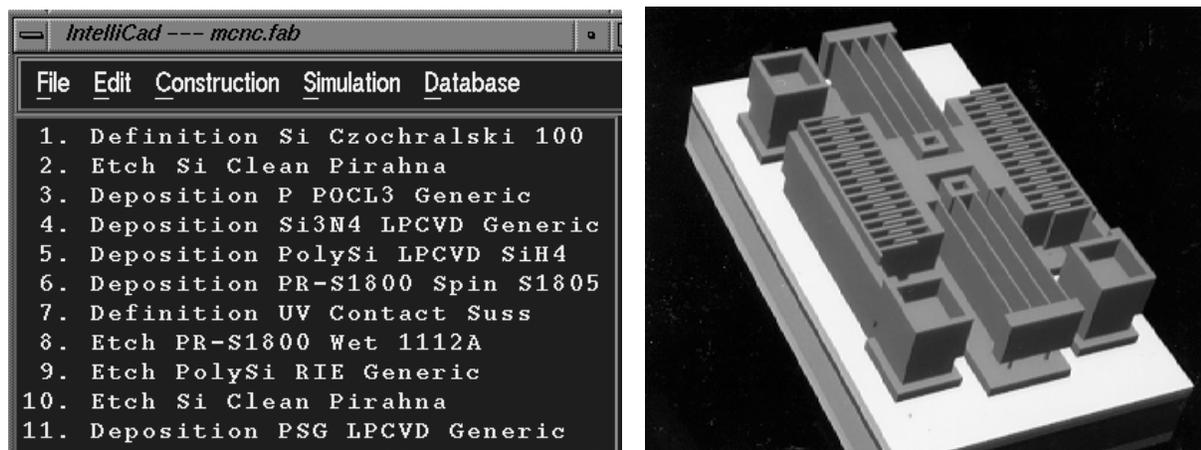
Figure 1: IntelliCAD™ Process Table (partially shown) and Resulting Three-dimensional Comb-drive Solid Model

Performance simulation:

For device performance simulation purposes, an automatic surface and volume mesher has been developed and integrated into the solid modeler. Recently, new algorithms unique to IntelliCAD™ have been developed which locally refine the mesh. This new meshing technique results in increased numerical accuracy for a given computation time when compared to common techniques used in other CAD systems for MEMS.

Once discretized, the geometries are transferred automatically to IntelliCAD's performance simulators for thermomechanical, electrostatic, and fully coupled thermo-electromechanical analysis. Performance simulation is achieved using finite element analysis (FEA), boundary element analysis (BEA), and coupled FEA and BEA, respectively. The analysis allows the specification of voltage, temperature, mechanical stress, thermal stress, and residual stress into a fully coupled analysis. The IntelliCAD™ analysis engines draw on state-of-the-art commercial analysis tools such as ABAQUS for FEA analysis.

At any process step, developers can access the Material database, MEMaterial®, to investigate the effects of process parameters on the structure. MEMaterial® includes mechanical, electrical, and optical properties of thin film materials used in fabricating MEMS devices. A multivariate estimation routine is used to predict/analyze material properties. These properties are given as functions of the important parameters for a particular process. For example,

the user can investigate the stress of a silicon nitride thin-film by varying parameters such as the temperature and pressure of deposition, the radio frequency and power, and gas partial pressures. Once an acceptable stress is achieved, the material properties and fabrication information are automatically sent to IntelliCAD™ for device performance simulation. In this way, the user links the fabrication of the device to the design and simulation of the device.

By incorporating comprehensive databases with a rapid prototyping and manufacturing optimization system, IntelliCAD™ mimics the manufacturing and testing of a silicon microstructure entirely within a workstation environment. The result is reduced development time and cost for the user.

IntelliCAD™ applications

IntelliCAD™ has been used extensively to develop a wide range of MEMS devices including pressure sensors, microphones, accelerometers, gyros, and linear actuators. Typical applications have included: derivation of applied pressure-capacitance change relationships, collapse voltage determination, resonant frequency analysis of gyro elements, investigation of the thermal processing sequence on MEMS device characteristics (for example, effects of anodic bonding on pressure sensor diaphragms), and calculation of the intrinsic temperature sensitivity of sensors. Recently we reported the ability to perform fully-coupled, integrated thermo-electromechanical analysis of MEMS devices using IntelliCAD™[3]. This is the first reported investigation of thermal, mechanical, multi-conductor, and multi-dielectric effects on the performance of MEMS structures. In the near future IntelliCAD's capabilities will be extended to fluidic analysis and piezoresistive analysis.

Comparisons of IntelliCAD™ models to actual experimental data has shown strong and accurate correlations. For example, IntelliCAD™ was used to analyze a capacitive gas and liquid pressure sensor. The pressure sensor was fabricated using both surface and bulk micromachining. Its characteristics included a diaphragm made of silicon with a square area of 0.25 μm^2 and a thickness of 20 μm. The gap size between the diaphragm and the stationary electrode was 0.7 μm. Experiments were performed to measure the capacitance of the sensors as a function of applied pressure on the diaphragm [4]. The IntelliCAD™ simulation was performed by following the actual manufacturing process steps for the sensor as described in this publication and inputting them into IntelliCAD's process builder. Once the solid modeler created a three-dimensional representation of the structure, normal pressure loads were applied on the diaphragm. After the mesher discretized the structure, a coupled electromechanical analysis was performed. The results for both the IntelliCAD™ simulation and the experimental results are shown in Figure 2. Over the range of tested pressures, the IntelliCAD™ model predicted the behavior of the pressure sensor to within 5%.
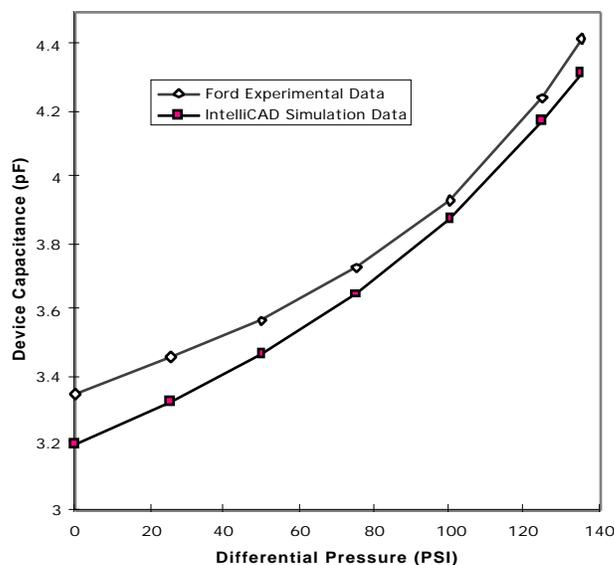
Figure 2: Comparison between IntelliCAD Simulation and Experimental results for Ford Microelectronics Pressure Sensor [4]

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In another example, IntelliCAD™ was used to simulate a surface micromachined Deformable Mirror Display (DMD). Each pixel on the DMD had a dimension of 25.4 µm X 25.4 µm X 0.76 µm. The metallized polymer membrane was 0.1 µm thick and had the following properties: Poisson Ratio of 0.3 and tensile residual stress of 50 MPa. A voltage differential was applied to the device, and the mirror deflection was measured. IntelliCAD's predictions were compared with experimental data. As shown in Figure 3, the IntelliCAD™ simulation of the DMD predicted the mirror deflection as a function of applied voltage to within 10%. A non-linear coupled analysis was used for this IntelliCAD™ simulation.

Such accurate predictions of actual complex modeling situations help users produce optimized designs of their structures. These optimized designs help reduce the number of tedious and costly microfabrication test iterations that are required before a viable device is realized.
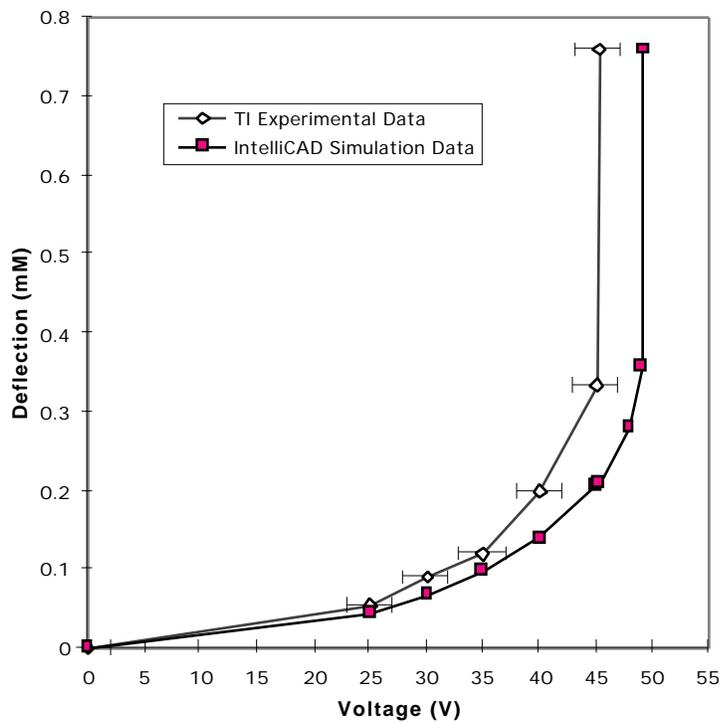
Figure 3: Comparison between IntelliCAD Non-linear Coupled Electromechanical Simulation and Experimental results for Texas Instruments DMD

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