A CAD tool for RF MEMS devices

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Agenda

1. Introduction
2. CAD framework for MEMS devices
3. RF MEMS shunt switch
4. RF MEMS inductor
5. Thermal analysis of RF MEMS shunt switch
6. Summary and Conclusions
7. References

1. Introduction

- MEMS : MicroElectroMechanicalSystems
- a technology that enables the batch fabrication of miniature mechanical structures, devices and systems
- leverages existing state-of-the-art integrated circuit (IC) fabrication technologies
- a complete and smart system-on-a-chip

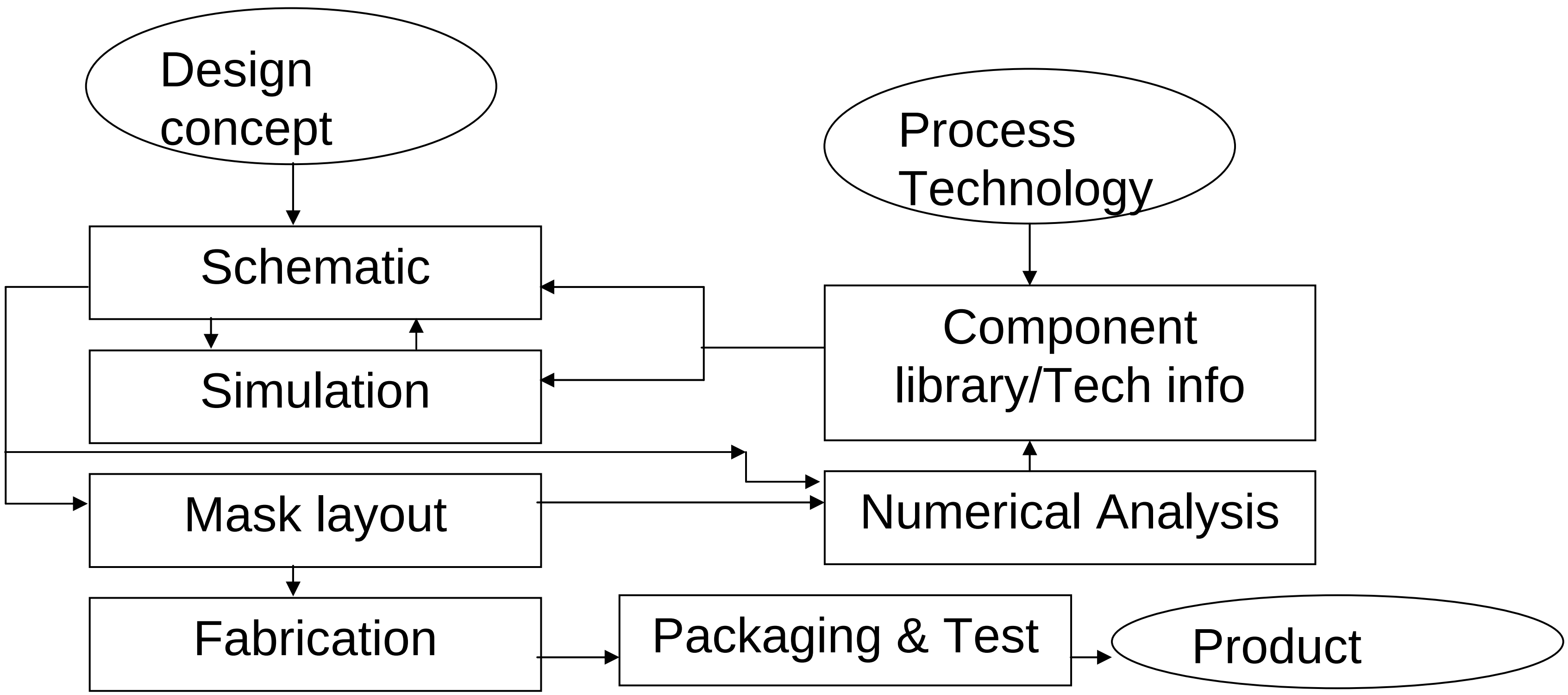
- RF (Radio Frequency) Solid state : Current state-of-the-art circuit designs use a combination of GaAs FET, p–i–n diodes, varactor diodes to achieve the required switching, filtering and tuning functions. High power consumption, reliability issues and high manufacturing cost. Poor RF performances (more than 1–2 dB insertion loss per switching stage)

- RF MEMS improves overall performance

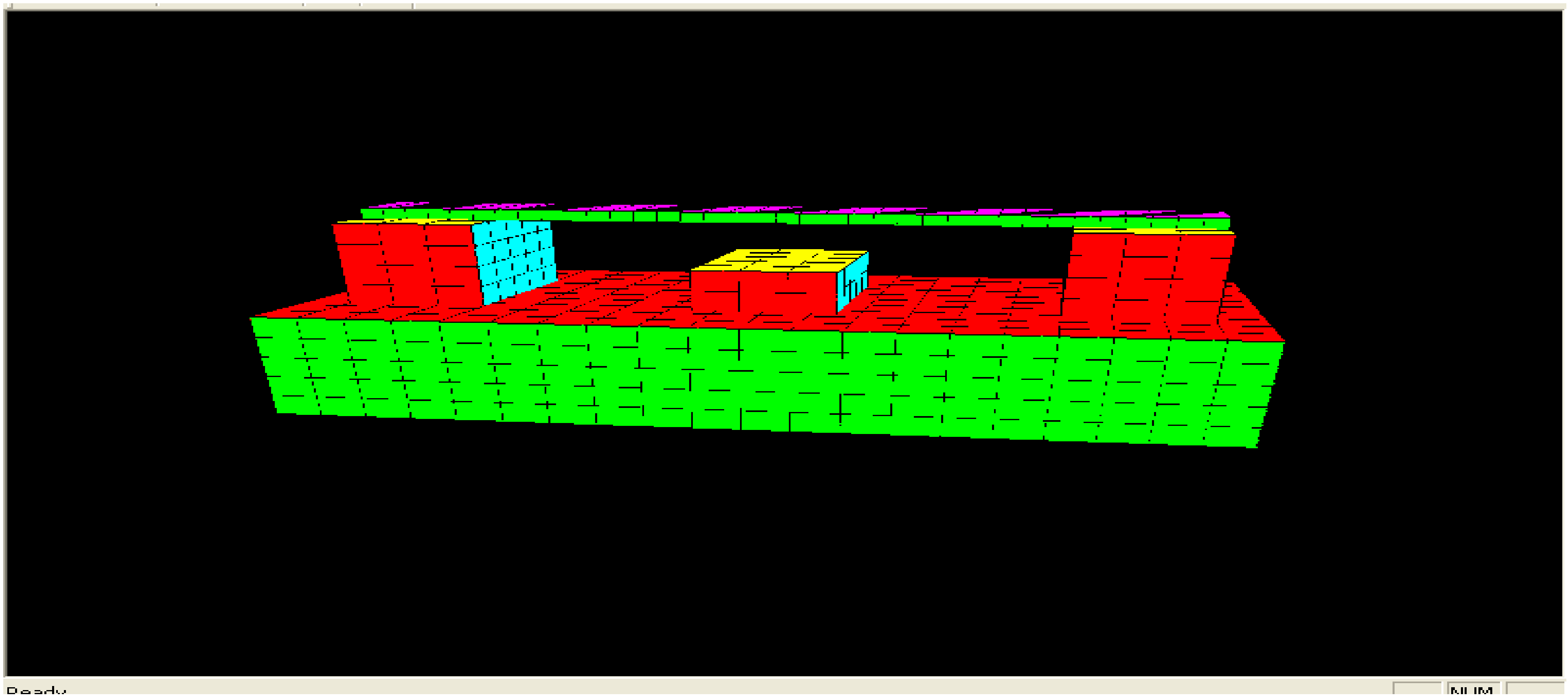
Introduction:
Review and Motivation

- current state-of-the art tools have not yet achieved the maturity what CAD tools have for VLSI.....
- factors such as <u>surface micro roughness</u> are not being addressed in the present tools which are very important to analyze...
- The effect will be dominant due to scaling as <u>surface to volume ratio</u> increases
- focus of MEMS design is now a days at the device level...
- Performance improvement by MEMS...

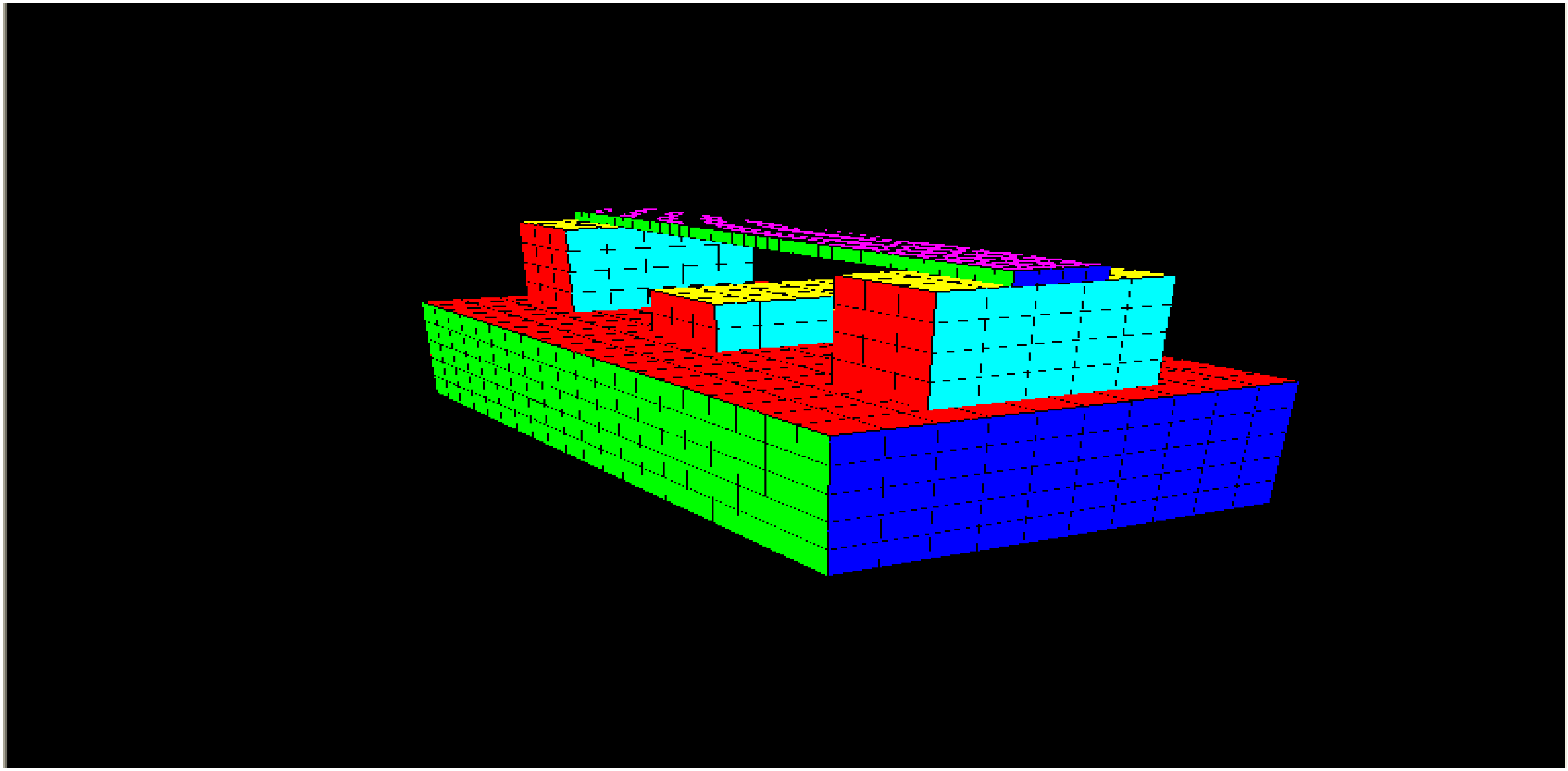
2. CAD framework for MEMS devices (Desirable structured methodology)



3-D, out-of-plane, multi-degree-of-freedom RF MEMS structures with meshing



3-D visualization of RF MEMS shunt switch with meshing



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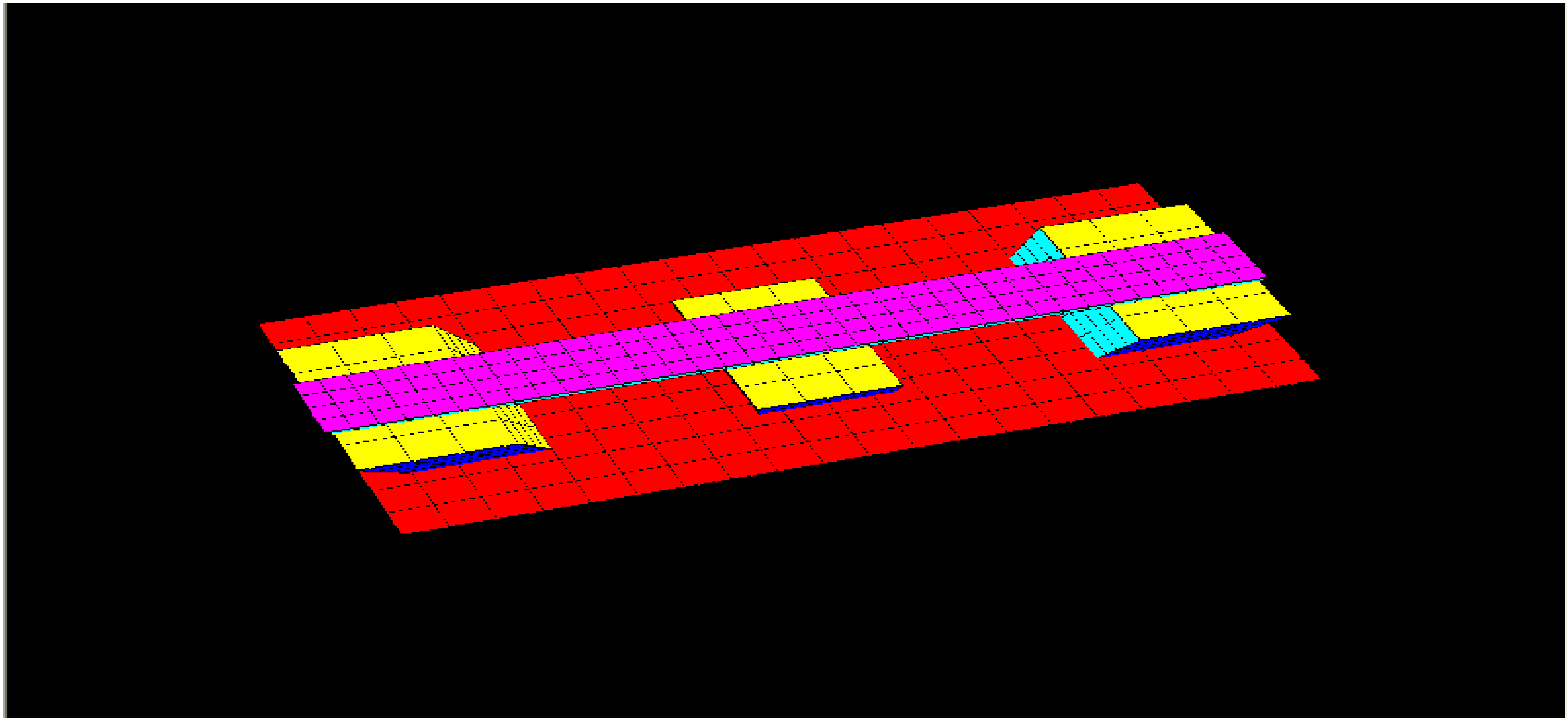
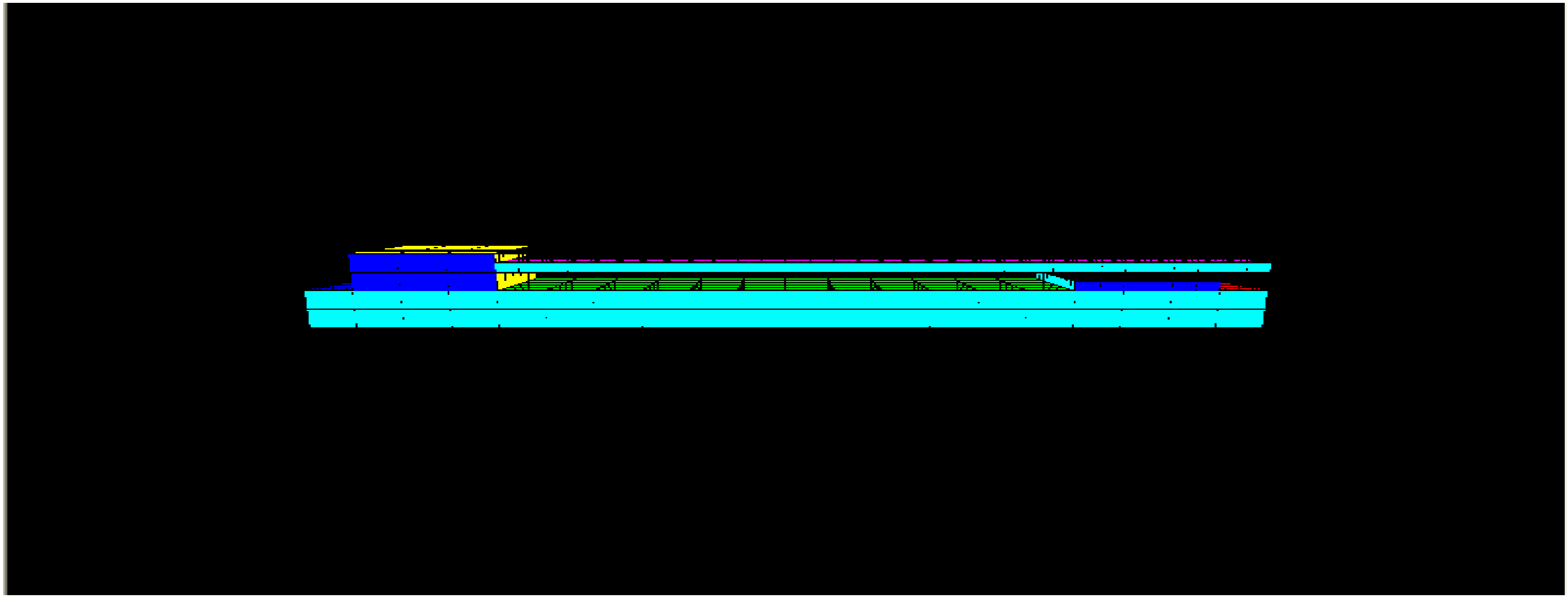
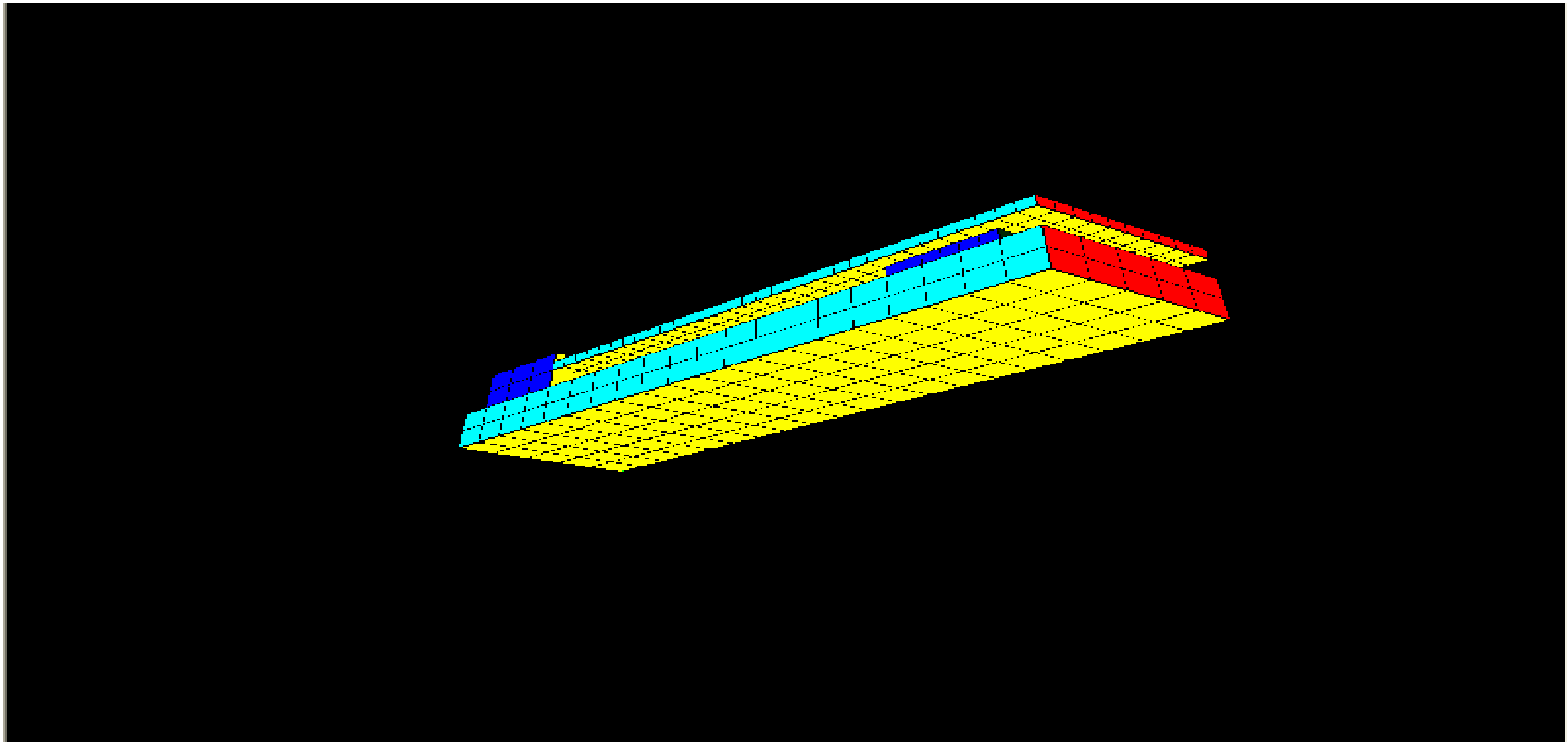


3-D visualization of RF MEMS cantilever switch



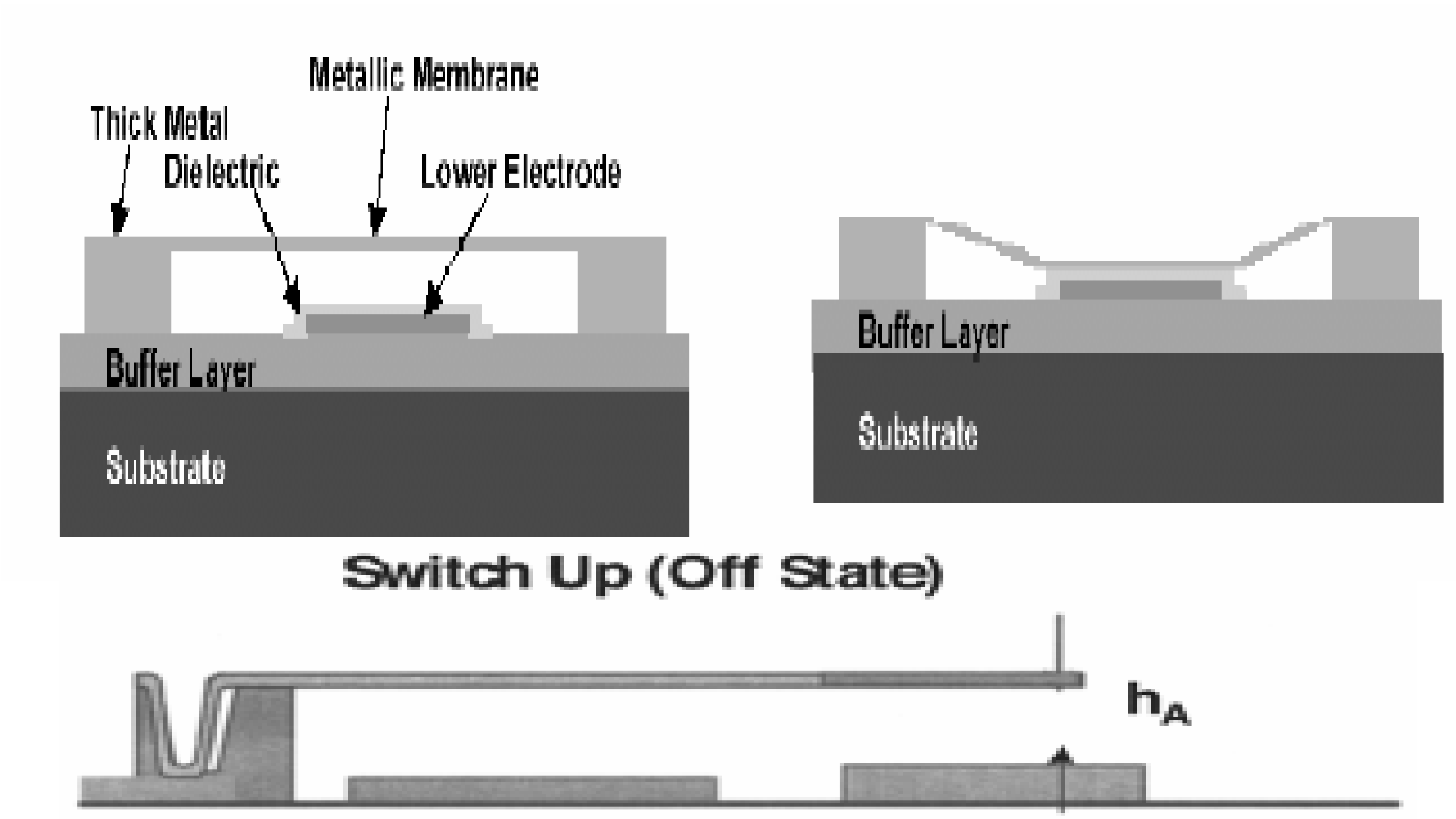
3-D, out-of-plane, multi-degree-of-freedom RF MEMS structures with meshing



Modeling and Simulation of MEMS passive components

- RF MEMS shunt switch
- RF MEMS Inductor

3. Modeling of RF MEMS shunt switch
(Electrical and Mechanical)



Modeling of RF MEMS shunt switch
(Electrical and Mechanical)

Electrical Analysis:

capacitance, electric field

Mechanical Analysis:

stress-strain

RF MEMS shunt switch: Electrical parameters

- Extraction of Electric field

  Solution of Laplace equation by finite difference method

  [Two dimensional electric field contours

  are obtained.]

- Extraction of capacitance

  [Laplace equation is solved to calculate the potential.

  The capacitance per unit area is calculated with Gauss law .The capacitance for the desired area is obtained.]

RF MEMS shunt switch: Electrical parameters

- Surface roughness affects :

capacitance, electric field, resistance , noise ......

- Various ways to model surface roughness :

Mandelbrot-Weierstrass function

[scale independent concept of self-similar fractals is used to model and generate the rough surface]

Mandelbrot-Weierstrass function

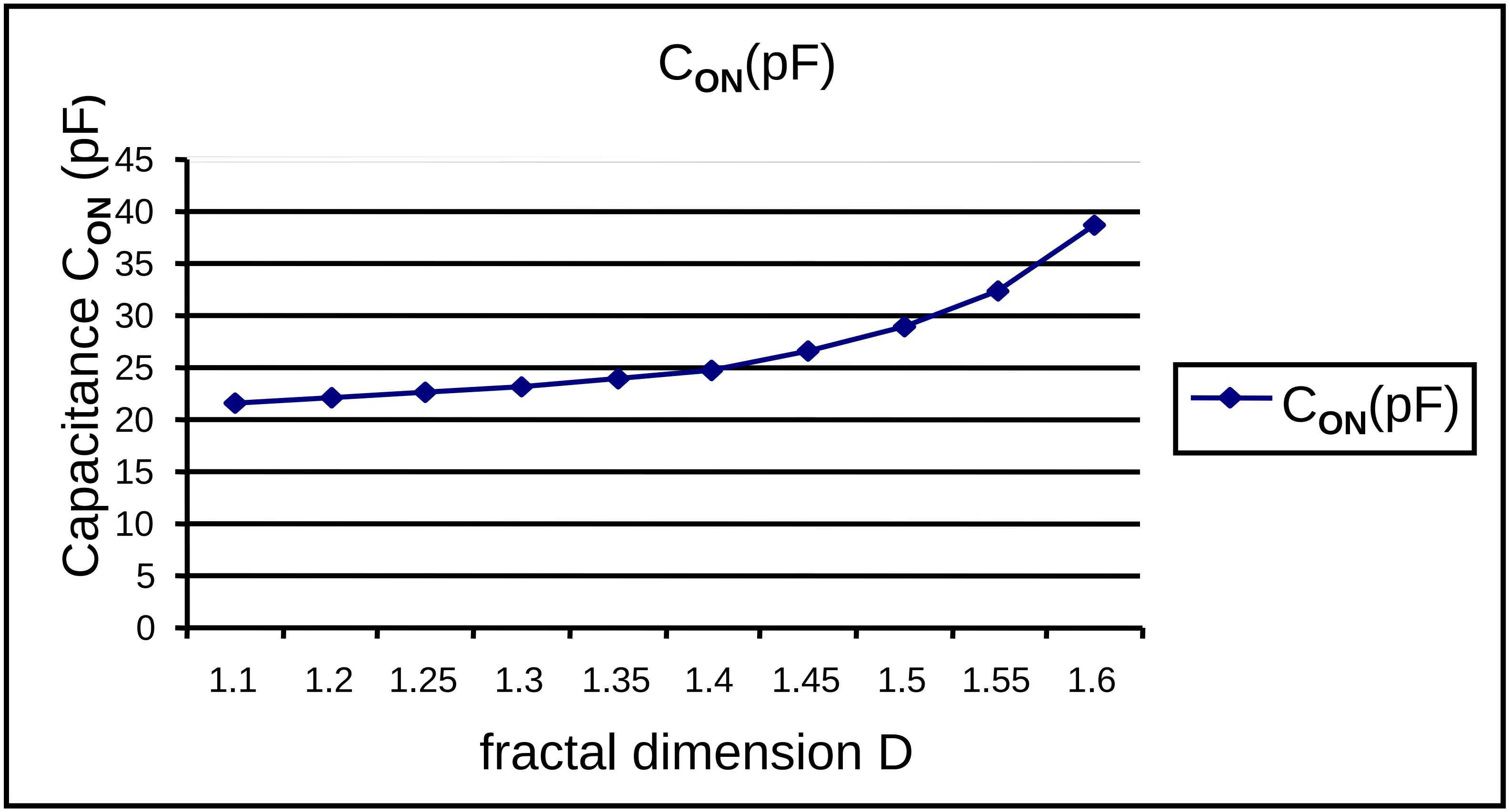
$$f(x) = \sum_{n=-\infty}^{n=\infty} b^{-n(2-D)}[1-k\cos(b^n x+\phi)]$$

fractal dimension, D =log(N)/log(1/r)

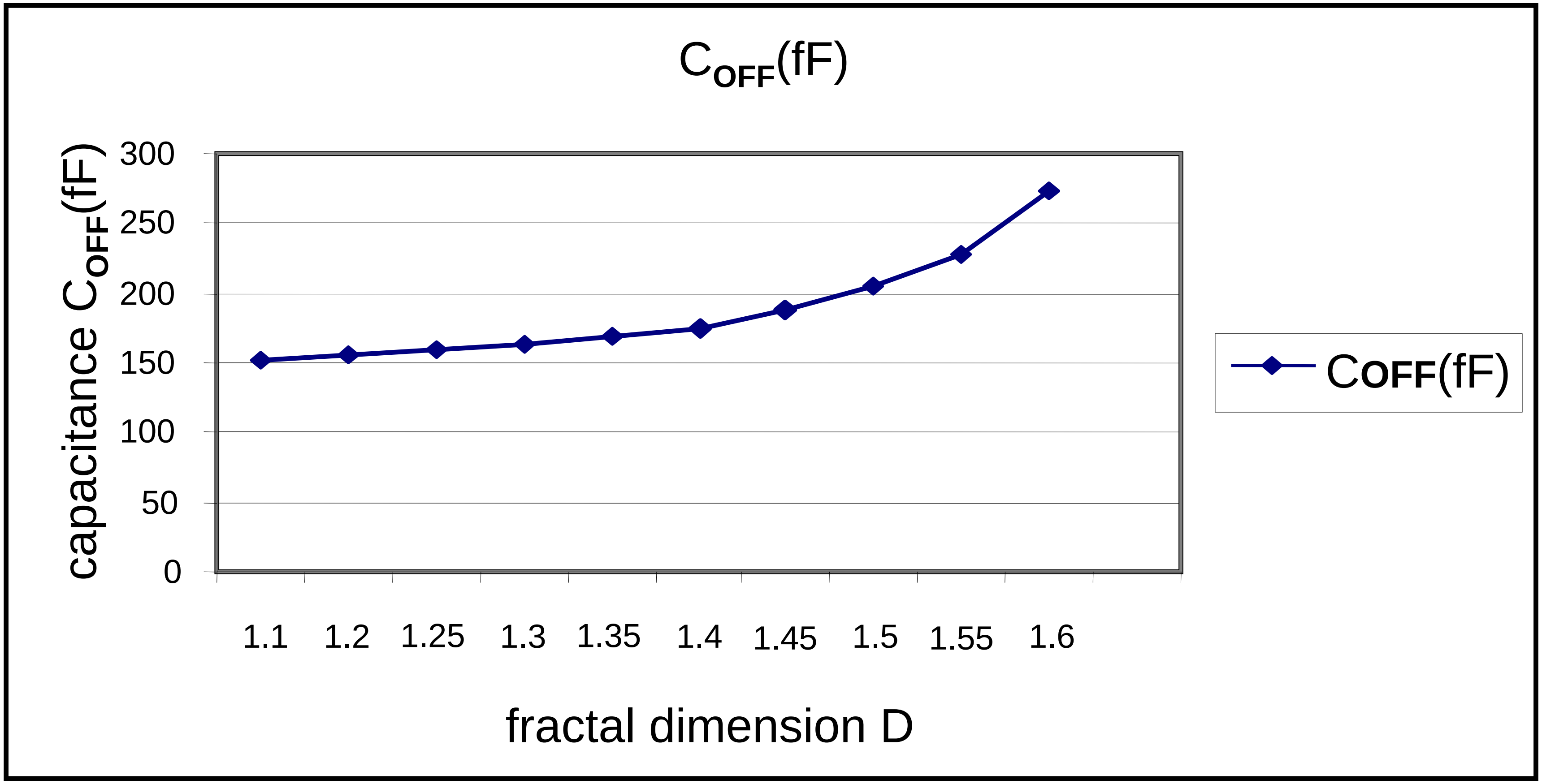
r is the ratio of N parts scaled down from the whole. b is the frequency multiplier value (varies between 1.1 to 3.0), D is non integer (varies between 1 to 2) and ϕ is randomly generated phase. The parameter k can be used to alter the profile. By varying D and k any profile can be generated. The value of fractal dimension D for a surface can be obtained from Atomic Force Microscopy (AFM) measurements.

Roughness also represented by – value of rms roughness

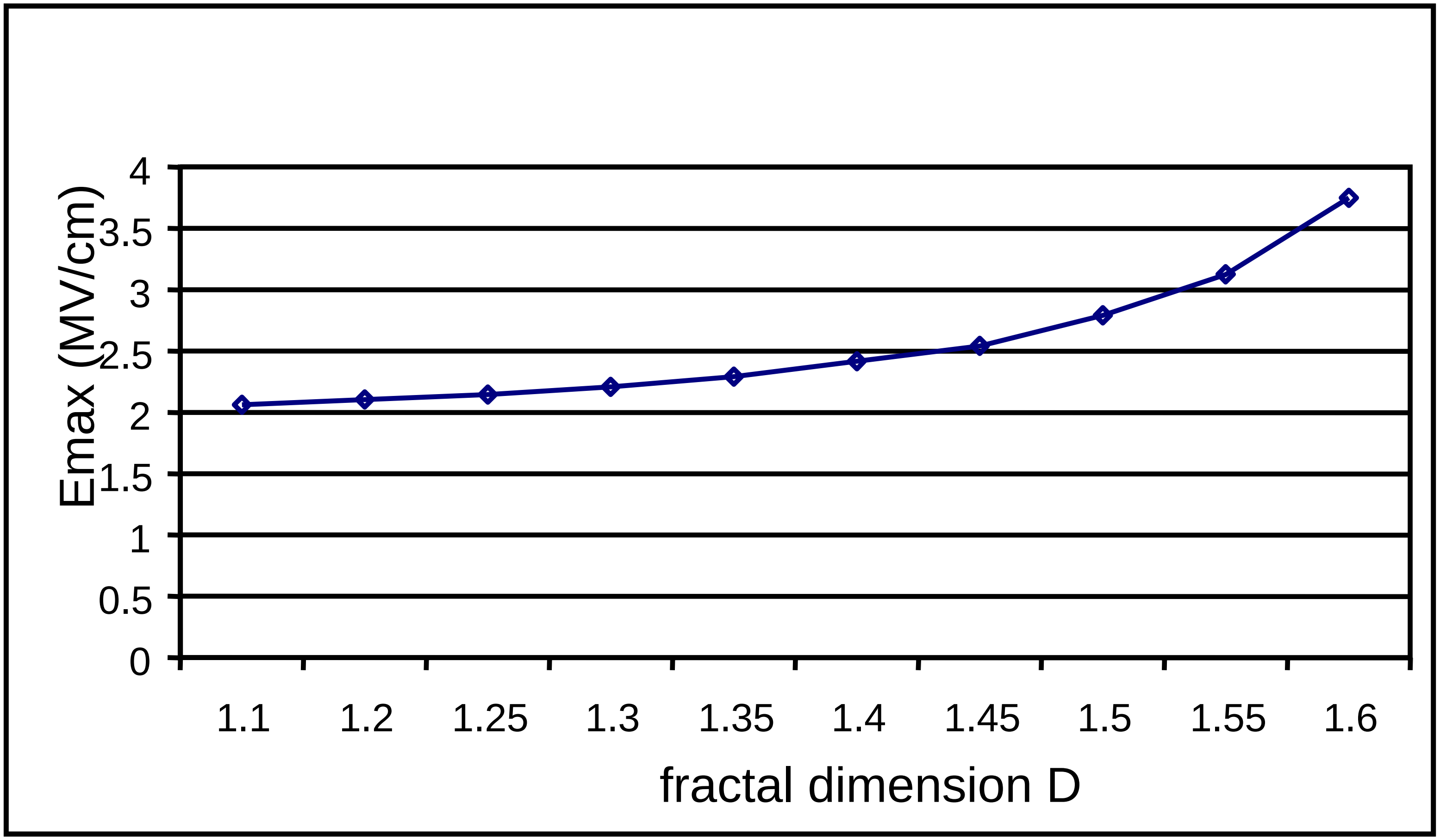
Effect of surface roughness on C_{ON}



Effect of surface roughness on C_{OFF}



Effect of surface roughness on Max. Electric field



Effect of surface roughness

•Capacitance increases with increase in roughness.

•The increase in $C_{\mathbf{OFF}}$ will result in higher insertion loss.

•Maximum Electric field will increase due to roughness due to reduction of distance between two plates at many points.

•The electric field may also increase due to electric field crowding if the surface is very rough.

Mechanical analysis:

FEM analysis: RF MEMS shunt switch

- Discretizing the solution region [triangular elements]
- Governing equations for an element
- [**Plane Strain Analysis**]
- Interpolation polynomial : linear triangular element
- Element shape function [N]

$$[N] = \begin{bmatrix} Ni & 0 & Nj & 0 & Nk & 0 \\ 0 & Ni & 0 & Nj & 0 & Nk \end{bmatrix}$$

"Galerkin's method"

FEM analysis: RF MEMS shunt switch

Calculation of Element stiffness matrix [k]

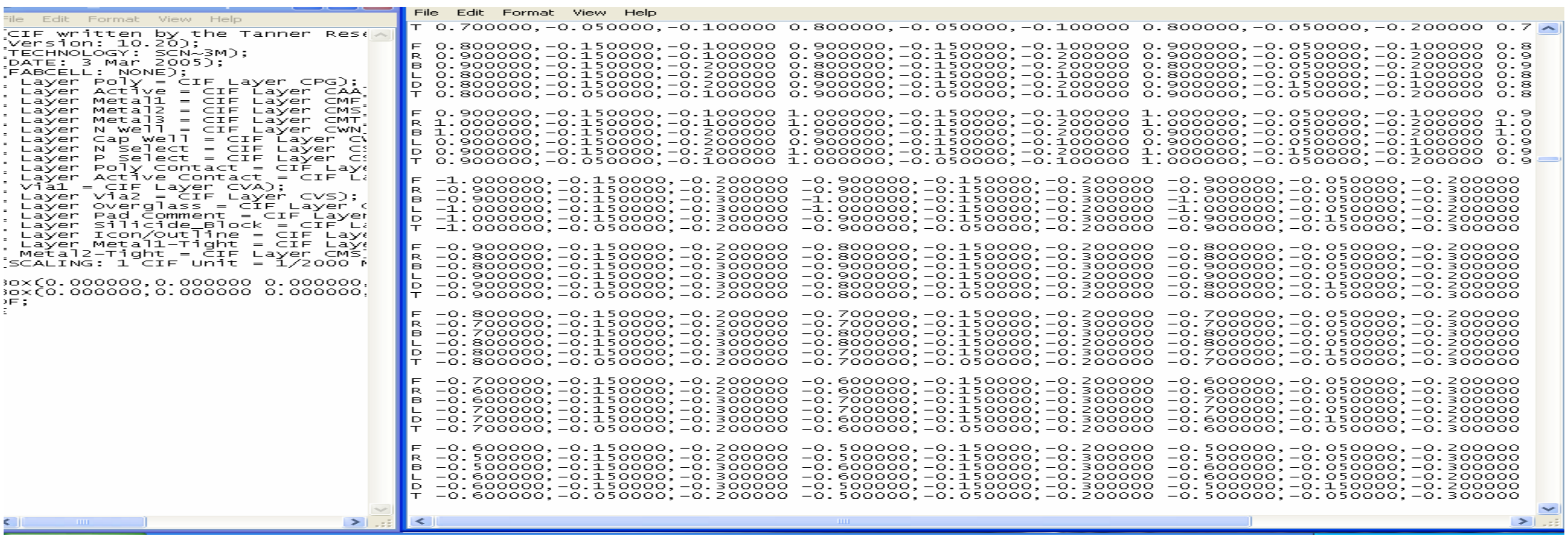
$$[k] = [B]^T [D] [B] \, t \, A$$

- Calculation of Global Stiffness Matrix
- Calculation of displacement vector (considering boundary conditions)
- Calculation of Stress for elements
- The force on the membrane changes with downward displacement
- Modifying force at each iteration, till boundary condition is reached
- At 30 V the membrane goes down for the typical structure
- Ton to toff << Toff to Ton
- Temperature rise adds initial strain reducing actuation

Modeling of RF MEMS shunt switch [contd..]

• tool enables to generate CIF net list [information regarding layers and 2D geometrical dimensions] necessary for planar mask lay out from schematic

•<u>CMOS fabrication process accepts the CIF file to build masks.</u>



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4. Modeling of RF MEMS Inductor

- still many functions that cannot be implemented using conventional integrated circuit (IC) technology, in particular, components with high Quality factor Q [>25]
- analysis of inductors at RF Integrated circuits is increasingly challenging
- computing inductances using conventional techniques and formulae is no longer accurate
- highly accurate techniques such as a fine-grained Finite Element Method may not be feasible due to the large computation time

Inductance extraction process

Tetrahedral Meshing [3-D]

↓

Extraction of voltages[FEM]

↓

Current Density distribution

↓

Energy of Magnetic Field

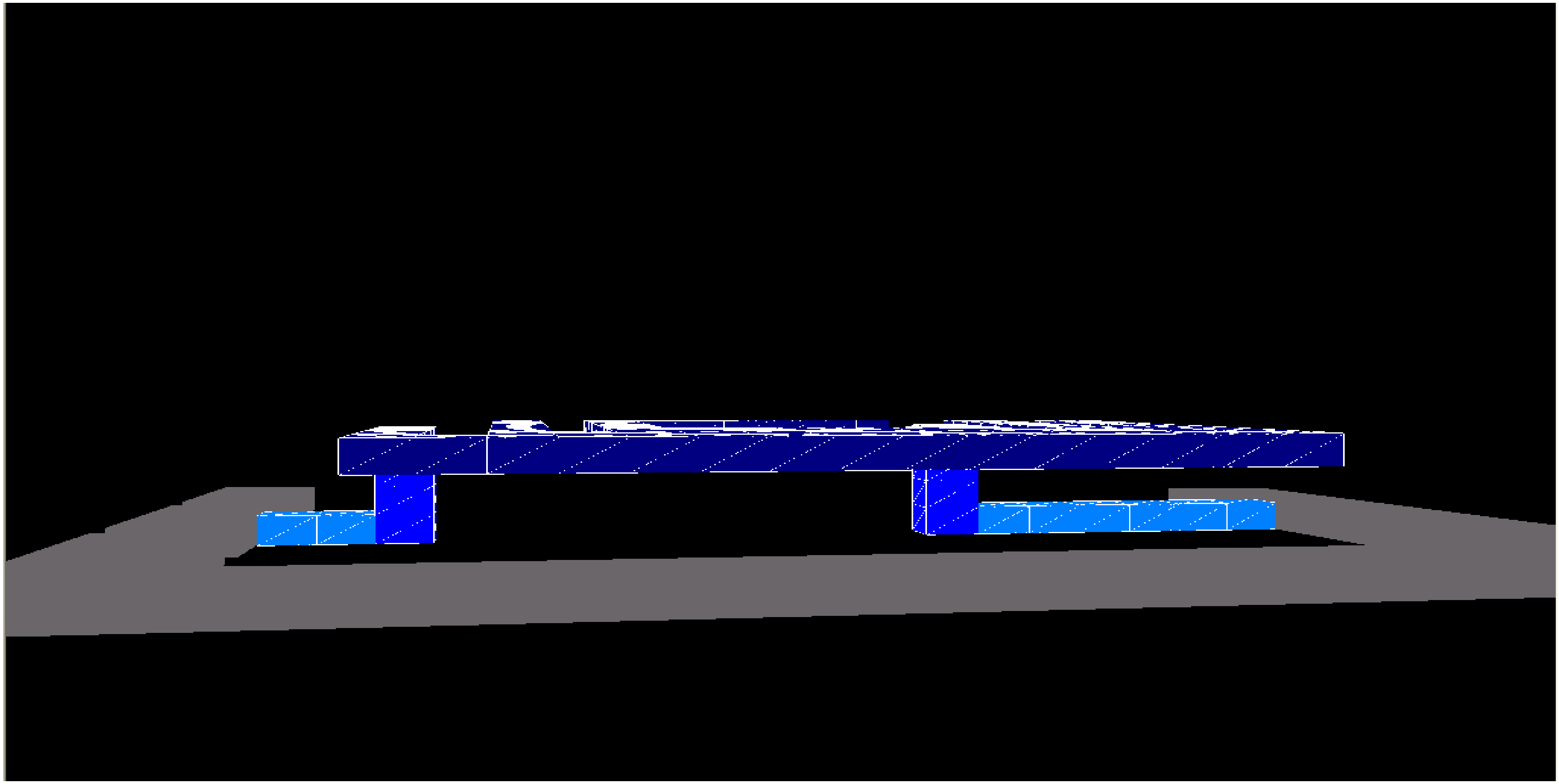
↓

Monte-Carlo Sampling

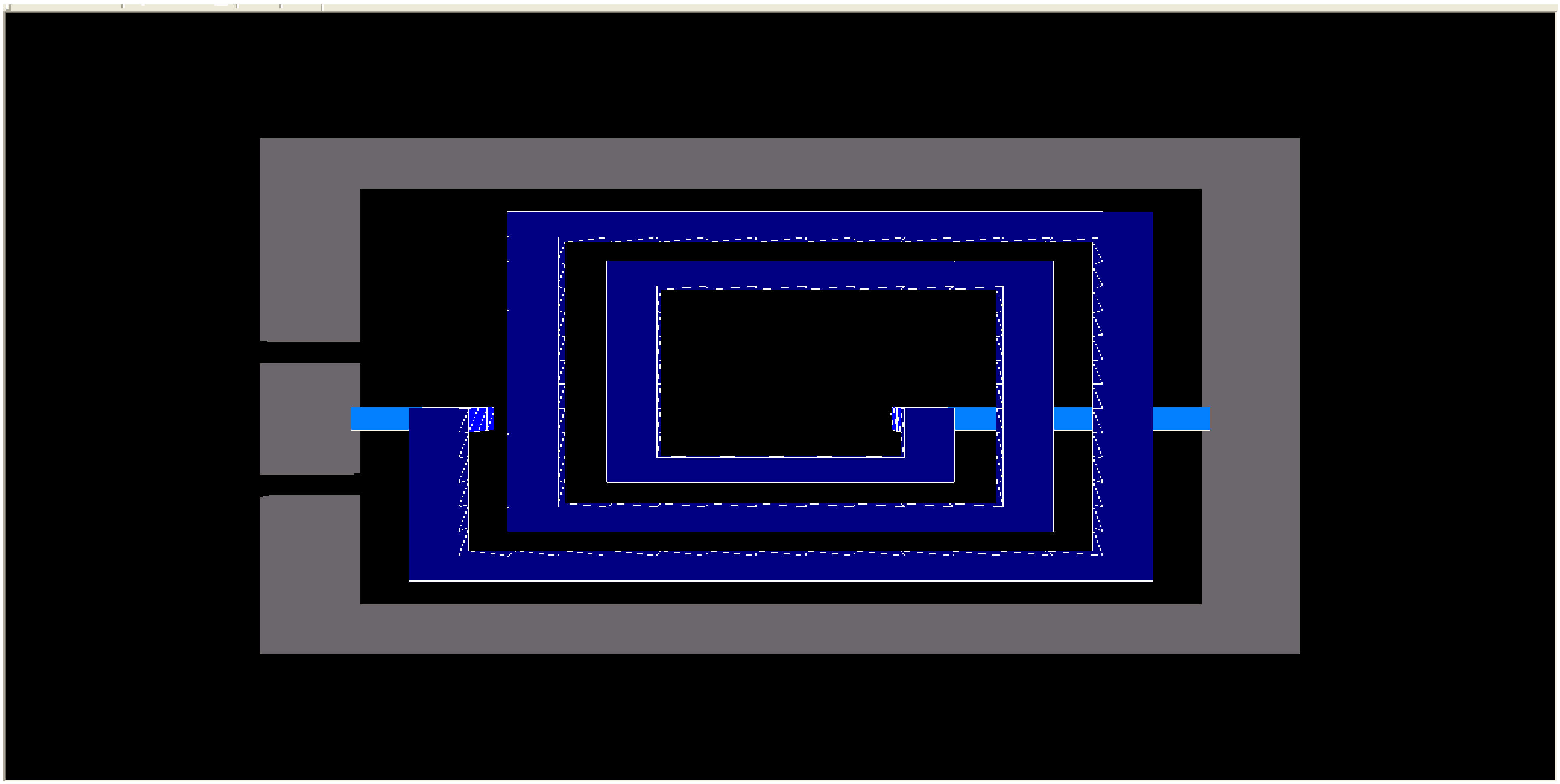
Extractor for MEMS inductor [3-D FEM with Monte-Carlo]

- Physical Approach is adopted
- Tetrahedral meshing of Inductor
- Solution of Laplace equation by FEM
- Current density computations
- Estimation of resulting magnetic field by Monte-Carlo sampling

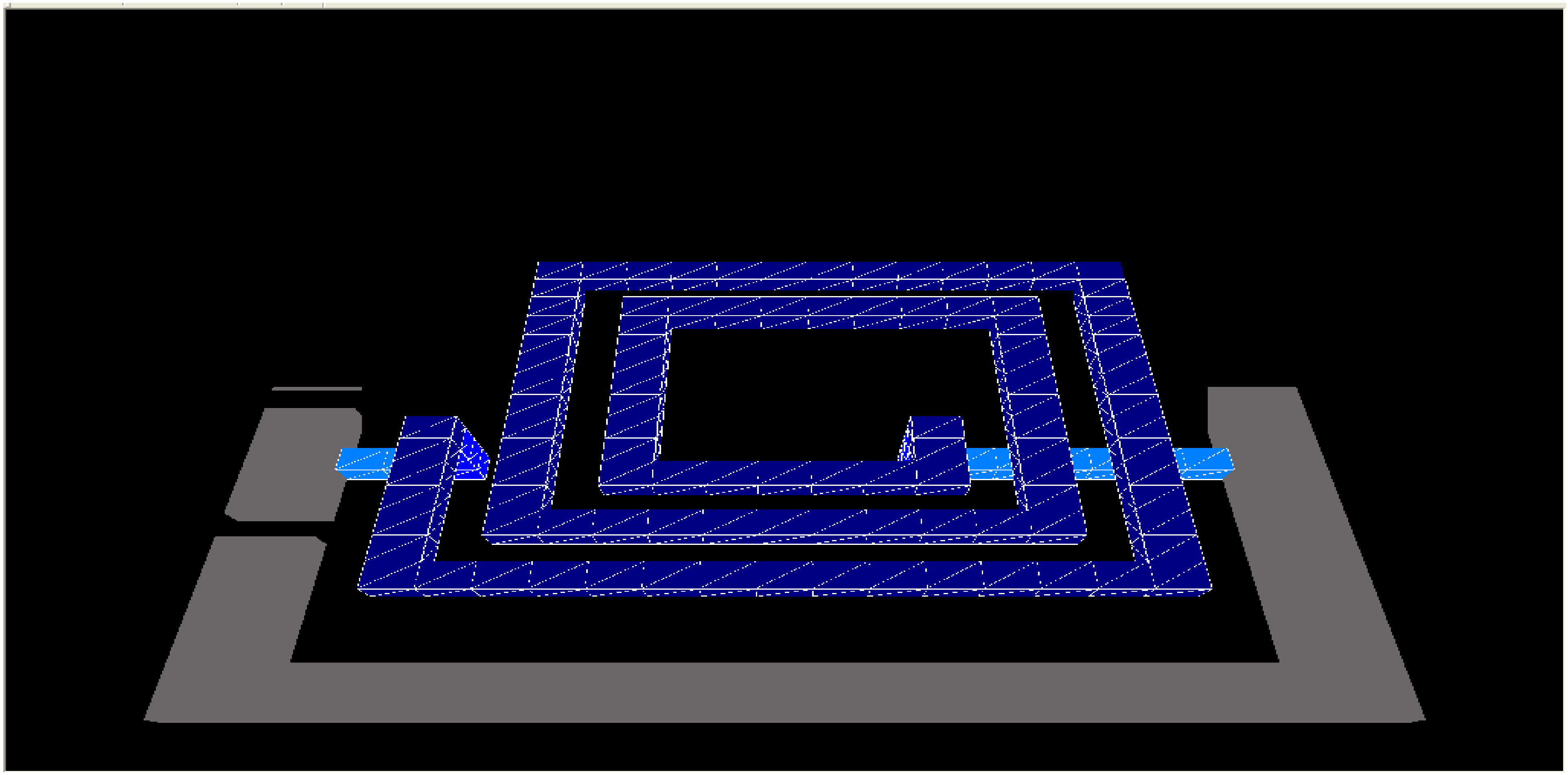
3-D visualization and meshing



3-D visualization and meshing



3-D visualization and meshing



Extractor for MEMS inductor [contd..]

In physical approach – Numerical solution of Neumann's formula for Pre calculated current density distributions

$$L_{ik} = \frac{\mu}{4\pi I j I k} \int_{Vi} \int_{Vk'} \frac{\vec{J}i(r) \, . \, \vec{J}k(\vec{r}\,')}{\left|\vec{r} - \vec{r}\,'\right|} \, dV \;\; dV\,'$$

Extractor for MEMS inductor [contd..]

Solution is carried out by Monte-Carlo sampling

$$W = \frac{1}{2} L I^2$$

$$W = \frac{\mu}{8\pi} \int_v \int_v \frac{\vec{J}(\vec{r}) \cdot \vec{J}(\vec{r}\,')}{\left|\vec{r} - \vec{r}\,'\right|} d^3r' \, d^3r$$

$$W \approx \frac{1}{N} \frac{\mu}{8\pi} \sum_i \frac{\vec{J}(\vec{r}) \cdot \vec{J}(\vec{r}_i\,')}{\left|\vec{r}_i - \vec{r}_i\,'\right|} \frac{1}{p^2\,(\vec{r}_i\,, \vec{r}_i\,')} = \frac{1}{N} \sum_i W_i$$

[W – energy of magnetic field]

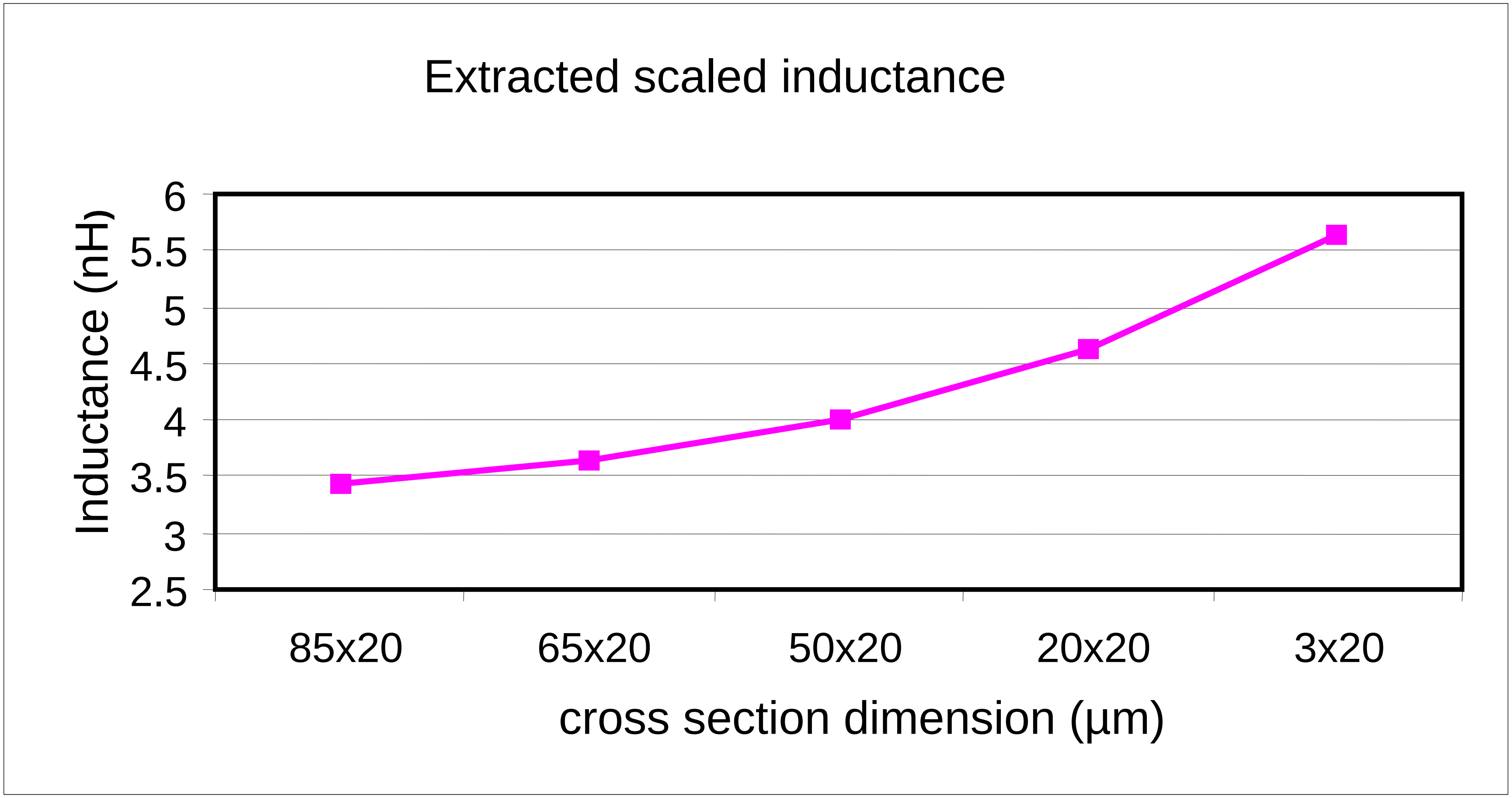
Extractor MEMS inductor [contd...]

- a typical surface micro machined air core with air gap Microsystem Aluminum inductor structure is considered.
- three-turn inductor extracted has 20 μm x 85 μm cross section and spacing (geometric mean distance) 85 μm is suspended over substrate at a height of 100 μm.
- Inductance extracted 3.44 nH for smooth topology with fractal dimension D unity i.e. with zero rms roughness.
- The results are validated.

Extractor for MEMS inductor [contd..]

- for scaled inductors ....
- cross sections 85 μm x 20 μm, 65 μm x 20 μm, 50 μm x 20 μm, 20 μm x 20 μm and 3 μm x 20 μm keeping geometric mean distance same
- the extracted inductance increases with reducing cross section for equal length of inductor
- [$L = 0.002 * A [\log_e ((2* A)/B+C)+0.5-\log_e e]$] validated..

Extractor MEMS inductor :

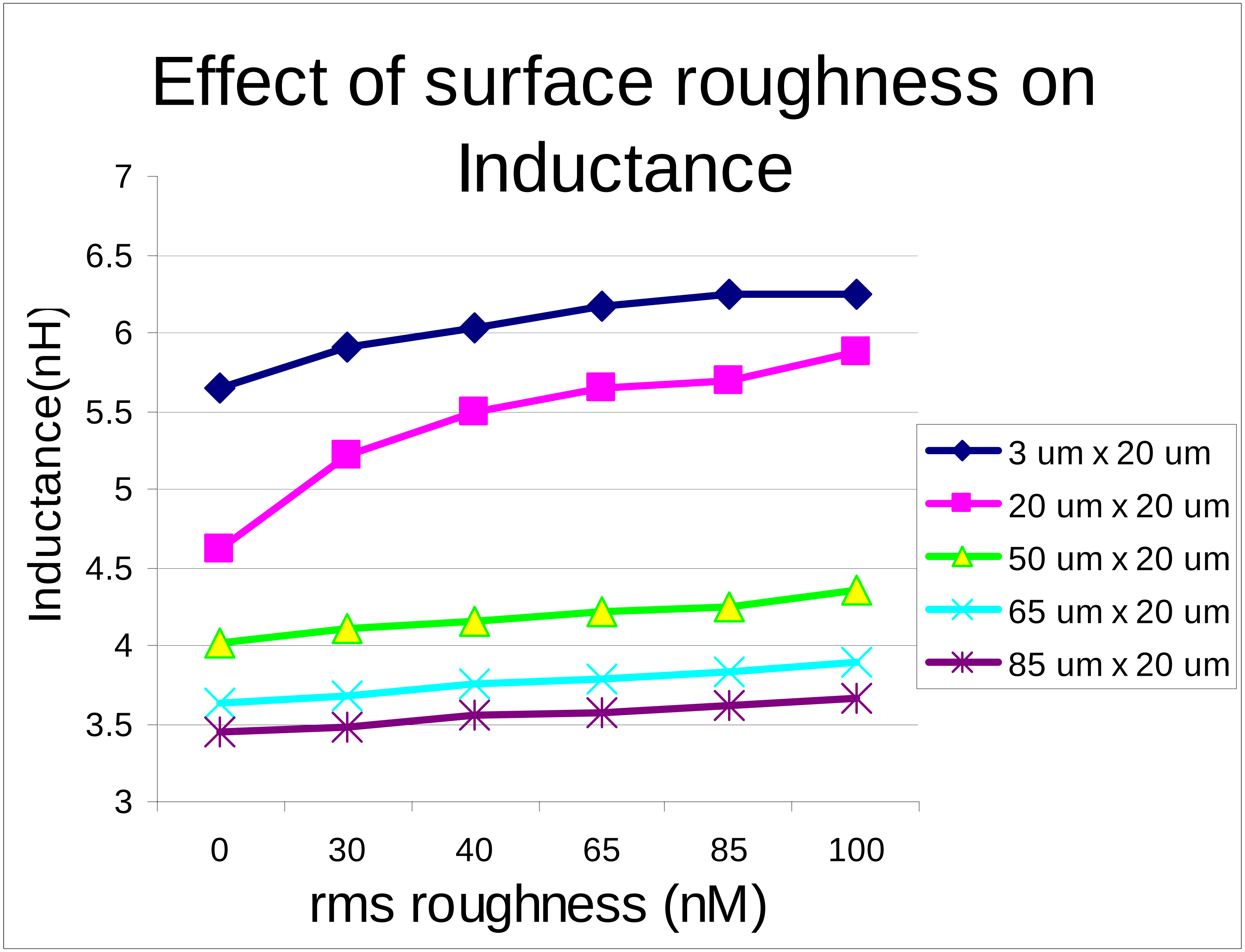


Extractor for MEMS inductor [contd..]

- Effect of surface roughness

- Surface micro roughness modeled at all surfaces of inductor

- Inductance extracted for different values of Fractal dimension D=1.43(rms roughness 30 nm),D=1.53(40nm), D=1.58 (65 nm), D=1.64 (85 nm), D=1.68 (100 nm) for cross sections 85 μm x 20 μm, 65 μm x 20 μm, 50 μm x 20 μm, 20 μm x 20 μm and 3 μm x 20 μm keeping geometric mean distance same



Effect of surface roughness on Inductance
7
6.5
6
5.5
5
4.5
4
3.5
3
Inductance(nH)
0
30
40
65
85
100
rms roughness (nM)
3 um x 20 um
20 um x 20 um
50 um x 20 um
65 um x 20 um
85 um x 20 um

MEMS inductor extractor

“ It can be seen that the value of inductance increases logarithmically. This was confirmed by fitting these characteristics with logarithmic equations.

There is more pronounced change in inductor for smaller values of cross section than higher values.

This is due to higher surface to volume ratio of the inductance”

- As the roughness increases there are many magnetic field components with circular path. Some of them counteract each other, resulting less net magnetic field, which contribute to inductance.
  Another factor is increased current flow due to surface roughness.
  These two counteracting effects; surface roughness (increases the value of inductor) and resultant increased cross section (reduces the value of inductor) giving rise to logarithmic law.

Impact of defect on Inductance values

- single defect of size 40 micrometer was introduced in the structure of 50 μm x 20 μm cross-section
- value of inductance was at 4.01nH, which increases to 5.26 nH because of this single defect

“ The current density obtained in defect is more due to increased circular current paths, leading to increased inductance. The crowding of magnetic energy associated with surface current flow causes the addition in inductance offered.”

5. Thermal analysis of RF MEMS shunt switch

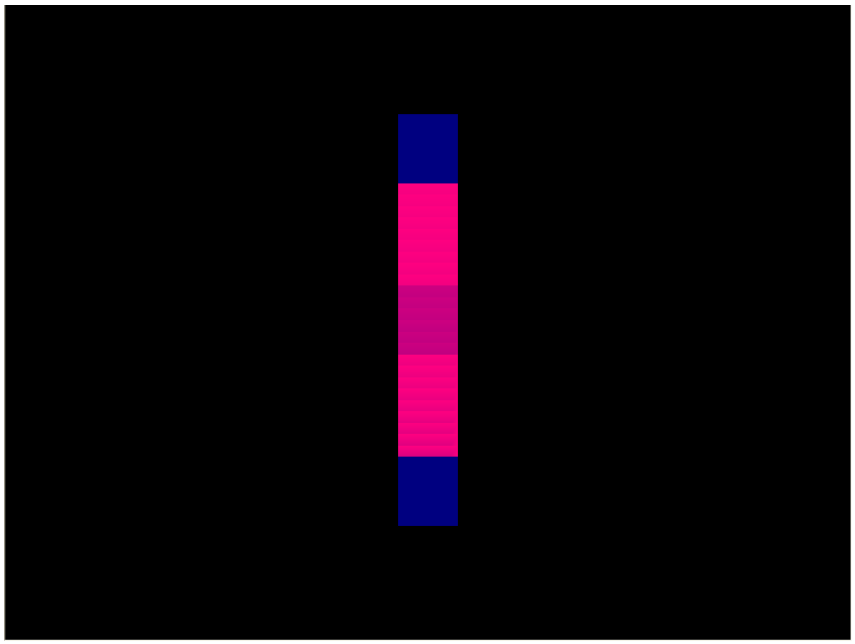
- long-term reliability of MEMS switches is of major concern.
- primarily due to stiction between dielectric and metal layer.
- stiction occurs due to dielectric charging in Silicon Nitride layer.

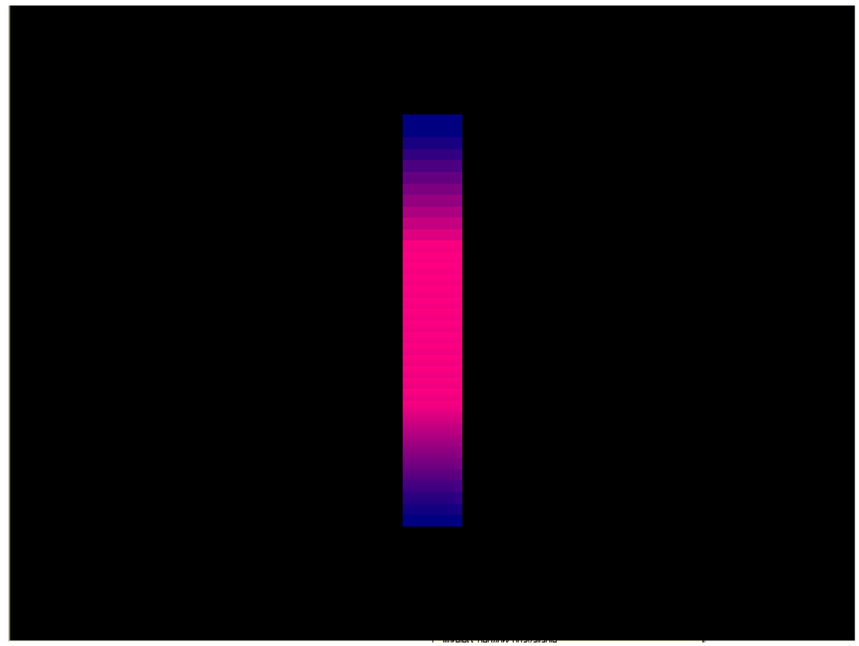
Thermal analysis of RF MEMS shunt switch

- electric field can be as high as 3-5 MV/cm in the dielectric layer, which results in a Frankel-Poole charge injection mechanism [depends on temperature].
- thermal heating plays important role...
- main mode of heat transfer is due to conduction
- T is the temperature of the MEMS bridge (degree Celsius), ***g*** is the rate of heat generated per unit volume (W/m^3), and ***k*** is the thermal conductivity of the bridge

$$\nabla^2 T + \frac{\dot{g}}{k} = 0$$

Thermal analysis of RF MEMS shunt switch





Temperature variation
"down" position

Temperature variation
"up" position [red-hot]

Thermal analysis

- Thermal analysis explains the other failure mechanisms which is also observed in these devices. The other failure is due to latching and self actuation. Self-actuation failure occurs when the signal voltage carried by the switch generates sufficient electrostatic force to pull the beam down.
- It has been observed that this failure mode depends strongly on temperature because compressive thermal strains generated at elevated temperature drastically reduce the pull-in voltage. The heating causes the metal to expand, relaxing the bridge, and thus lowering the pull-in voltage.

6. Conclusion and Remarks

- As product volume grows and as the time-to-market becomes more crucial, there will be an increasing need for effective design tools that permit experimentation before costly fabrication of MEMS.
- Performance analysis and failure mechanisms can be addressed by considering effects such as surface roughness, thermal analysis. As the devices are miniaturized the surface micro roughness will play a major role since surface to volume ratio will increase considerably.
- Useful in design optimization, rapid computational prototyping.

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Thanks a lot