From Theory to Development: Role of Multiphysics Modeling and its Effect on Education in Electronics

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***Abstract*—Electronics engineering is a very rapidly growing field, as the time passes the requirement of more advance technologies increase. There are a lot of institutions and universities around the world that provide quality education to different fields of engineering. The courses that electronics engineers study need practical exposure as well to cope up with industrial demands. In this paper, the role of multiphysics modeling and its impact on engineering education is demonstrated. Finite element modeling (FEM) tools are very powerful tools and due to there huge advantages, electronics graduates should study these tools in their course curriculum to know how to tackle various types of physics problems and through examples it is demonstrated that how these tools can help shift from just theory to development process.**

***Index Terms*—Multiphysics modeling, FEM, electronics engineering, education sector, development.**

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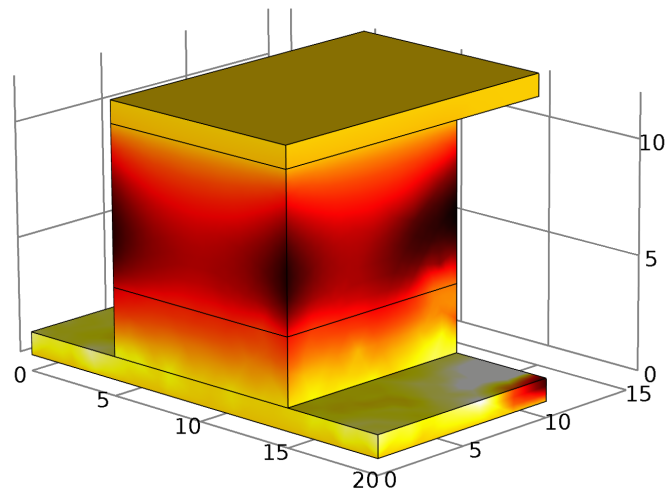

Fig. 1. Joule heating phenomena in memristor is demonstrated by thermal plot. The maximum joule heating problem in memristor can be clearly seen. It is due to the fact that when oxygen vacancies drift with mobility μ_v throughout length D of memristor, it generates heat in the undoped area.

I. Introduction

GRADUATE engineering or graduate research students usually face emerging class of challenges in designing that are vast in multiple disciplines of engineering and sciences. Streamlined computational methods and techniques that combine the can handle physics of various engineering domains, are required to precisely model the problems and accurately predict results before manufacturing or fabrication. Most of the engineering programmes offer field specific simulation and modeling courses on a very limited basis [1]. But as the requirement of engineers in different fields there is a need of one generic tool that can tackle multiphysics problems. As an example; electronics engineering graduates after their education choose an electronics industry [2]. Most of the industries have developed their own tools to train fresh graduates and to work upon. But with the high demand of advanced technologies, various physics solutions are required to design one specific solution, hence, companies are now opting for multiphysics modeling or finite element modller (FEM) to save costs and to reduce computing resources [3]. One tool can handle various physics problems. Instead of teaching very specific tools to electronics engineers, universities should focus and add multiphysics modeling in the course curriculum of graduate engineering students.

Basically, multiphysics environment or simply multiphysics modeling require the basic knowledge of the problem that one is going to solve as a prerequisite. Once, the basic equations of the problem is provided, then using finite element computation, the multiphysics modeller, thus ask for boundary conditions and finally computes those equations for specified boundary conditions. It takes a very less time if the basics are clear. Hence, the name of the paper: From theory to development perfectly suits for multiphysics modeling. These tools takes the theoretical inputs and do all the simulation and testing in between the frame of theory to actual development.

Few engineering curricula in some universities offers design and research experiences of multiphysics environment. An electrical or electronics graduate student may require finite element techniques to solve electric field problems as well as overall device level problems like mechanical stresses or chemical process if the system is on same chip/device. This paper presents the need of multiphysics modeling in electronics engineering graduate course curricula that should covers the most of the methods and techniques of multiphysics modeling.

Post-graduate students become active participants in multiphysics modeling than their theory counterparts because of the analysis by being challenged to tackle variety of physics problems that are related to high priority technological areas.

II. Multiphysics Modeling

Multiphysics handles various simulations that involve multiple simultaneous physical phenomena or multiple physics

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models. As an example; combining stress with RF electrical signals or combining fluid physics with electrical currents. Multiphysics modeling usually involves solving coupled physics systems of partial differential equations. In simple words, multiphysics environment computed partial differential equations for the given boundary conditions of a coupled physics problem of joule heating problem in memristor as shown in Fig. 1. Various modeling and simulations involves multi–coupled systems viz. magnetic and electric fields for electromagnetic circuits, fluid and gas for electronic sensors, or Ion drift or temperature rise in electronic components due to its continuous operation. Another example is the approximation of mean field for the electronic structure of various atoms, in the given example the electron wave functions and electric field are coupled.

A. Core Technologies

Multiphysics modeling or finite element modeller as the name suggests, computes partial differential equations for finite elements. Hence, to solve a problem, first the geometry is designed with proper material selection and then physics problem is selected. After applying boundary conditions to the geometry as per the chosen physics study, The modeller then perform *Meshing* of the geometry.

Meshing is one of the main process for any finite element modeller in which the modeling environment carefully creates very small finite elements of the geometry where the solution can be approximated. Fine or coarse meshing is as per users concerns. Higher the mesh elements, appropriate the result will be with the trade-off in computation speed because more finite elements need more degree of freedom to solve.

B. Studies

Different multiphysics modellers have almost similar material library and the type of studies. The basis of FEM is to solve equations as per the boundary conditions. Various physics modules are available in almost any FEM like: *Acoustic Wave modeling, Semiconductor physics, Fludic Flow, RF, MEMS, Structural Mechanics* and many more.

Physics modules are different from the study it will perform. The study basically depends on the chosen physics module and problem. Studies are basically: *Stationary, Time dependent* or *Frequency dependent*.

III. Importance in Education

As per the discussed benefits and technologies of multiphysics environment, it is required that multiphysics modeling should be included in the curriculum of electronics engineering, so that even fresh engineers when apply their knowledge in industry, they should know how coupled physics work and how to solve such kind of problems [4]. Further two case studies are presented, both are new technologies in the field of electronics. These case studies demonstrate that without multiphysics modeling it would be impossible to compute the parameters mathematically.

Case study I is on recently discovered memristor in which the current distribution, V–I characteristics and temperature effects are studied using multiphysics modeling and in case study II, RF performance, eigenfrequencies and stress distribution is analysed for RF MEMS switch.

IV. Case Study – I: Modeling of Memristor

Memristor is the recently discovered fourth missing circuit element. This case study is chosen because it perfectly links the aim of this paper with actual scenario. Memristor is theoretically postulated in 1971 by Leon Chua [5]. From 1971 till 2008 no–one discovered this missing circuit element, but in 2008 HP labs published a paper in *Nature* [6] that they have discovered the memristor, which shows the results as published by Leon Chua.

They have used multiphysics modeling to first design and test the theory and after the successful attempts, HP labs fabricated the memristor. After that the author of the original papers, studied the intrinsic constrains like temperature dependancy on memristor in which again they used FEM analyses [7].

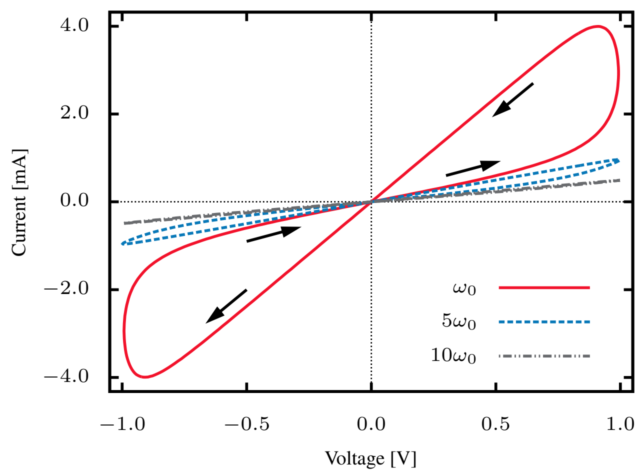

Fig. 2. Hysteresis loop of linear–ion drift memristor for frequencies: ω_0, $5\omega_0$ and $10\omega_0$ under the applied voltage bias of 1.0 V. The maximum current flows through the memristor at ω_0 is 4.0 mA

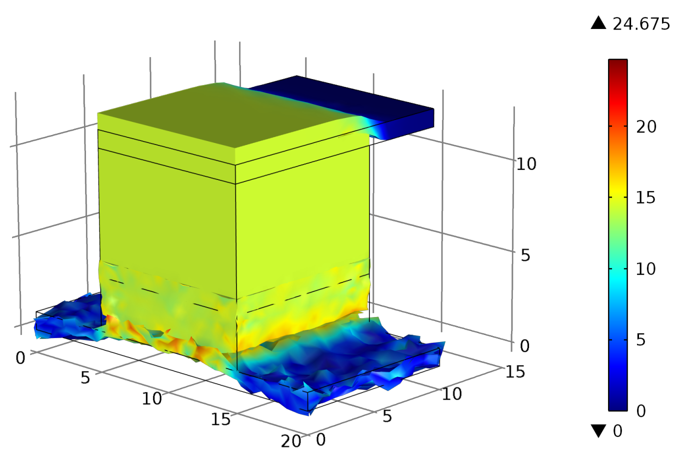

Fig. 3. Normalized current distribution in memristor due to the applied bias. The maximum current flows through the memristor is 24.675 A/m. Bottom deformed electrode is the positive electrode near doped region.

Linear–ion drift memristor is designed in multiphysics modeling with top and bottom plates are of platinum material and TiO_2 material is sandwitched in between. Its current distribution, temperature variation and V–I characteristics are extracted using FEM. Fig.2 shows the extracted V–I characters of designed memristor. Joule heating physics is used to determine the maximum temperature in memristor which is shown in Fig. 1. The darker the areas of the image, maximum temperature affects that areas. Thus from the analysis one can change material or other parameters to ensure the quality performance. Current distribution in memristor is shown in Fig. 3. In which current when bias is applied to memristor, current passes through it. The amount of current passes is shown in Fig. 3. The deformation of the surface depicts the normalised current distribution.

The solution for temperature distribution in the thin films can be computed using solving the Poisson equations as [7]:

$$\Delta T(r,z) = -Q/k_M, \qquad r \leq R, \quad -H/2 \leq z \leq H/2 \tag{1}$$

where, k_M is th thermal conductance of the metallic cylinder, that is assumed to be isotropic, q is the heat source density generated in the uniform metal rod.

The external bias of voltage with respect to time $v(t)$ when applied across the device will move the internal boundary between the two regions viz. doped and undoped by causing the charged dopants to drift from positive to negative terminal [8]. The ohmic conduction and linear ion drift in a uniform field of length D with an average ion mobility μv, the voltage across it can be characterised by using

$$v(t) = \left(\mathcal{R}_{ON}\frac{w\,(t)}{D} + \mathcal{R}_{OFF}\left(1 - \frac{w\,(t)}{D}\right)\right) \tag{2}$$

$$\frac{\mathrm{d}w\,(t)}{\mathrm{d}t} = \mu_v \frac{\mathcal{R}_{ON}}{D} i\,(t) \tag{3}$$

which further yields the following equation for $w(t)$:

$$w(t) = \mu_v \frac{\mathcal{R}_{ON}}{D} q\,(t) \tag{4}$$

By plugging the equation (4) into (2) we can obtain the memristance of system, which is further $\mathcal{R}_{OFF} \gg \mathcal{R}_{ON}$ reduces to:

$$M(q) = \mathcal{R}_{OFF}\left(1 - \frac{\mu_v \mathcal{R}_{ON}}{D^2} q(t)\right) \tag{5}$$

In equation (5) the charge $q(t)$ is crucial to memristance. it becomes larger in value for higher dopant mobilities μ_v and quite smaller for thin–film thicknesses D.

V. Case Study – II: Modeling of RF–MEMS Switch

RF–MEMS (Microelectromechanical) switches are highly regarded for their excellent RF performance in microwave region. RF–MEMS switches have huge advantage as: compact structure, high RF performance, low–cost to manufacture over their semiconductor counterparts. RF–MEMS consists of a micro movable membrane for its switching operation under electrostatic force applied. Multiphysics modeling helps to determine the stress gradient in micro movable membrane to ensure its reliable operation, eigenfrequency analysis to determine its basic modes of frequency, RF performance and many other parameters in a single modeling environment.

RF–MEMS suffer from failures during switching due to fracture of membrane due to high stress prone areas if the stress distribution exceeds about 70% of its material's ultimate tensile strength [9], [10]. In this case study all the above said parameters are analysed using multiphysics modeling. The final design is the outcome of receptive testing and simulation of initial designs. Multiphysics modeling really saved a lot of time in designing and estimating the parameters, which seems

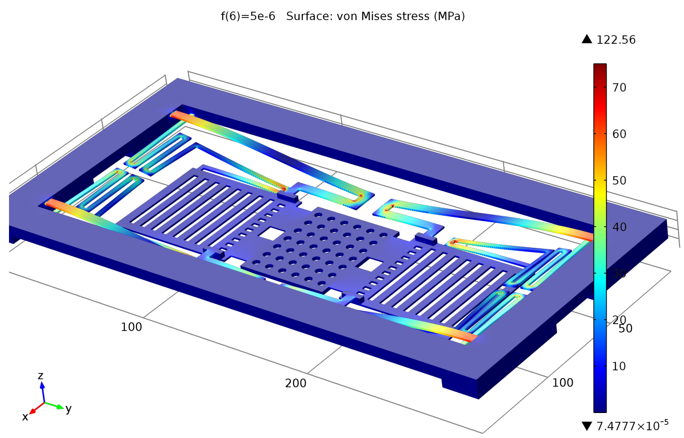

Fig. 4. Stress analysis in micro–membrane designed for RF–MEMS multiport switch. The analysis is done using multiphysics environment with structural physics module. The simulation is shown demonstrating the deflection corresponds to force applied in vertical -Z–direction. The results shows that the maximum stress of 122.5 MPa on the edges of flexures for 5 μN force applied.

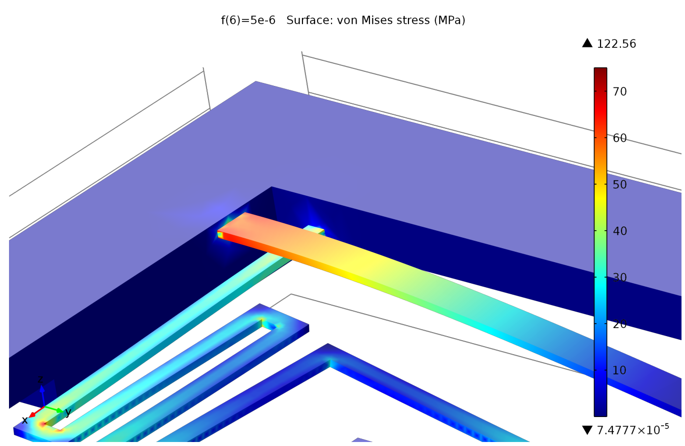

Fig. 5. Close–up view of stress prone area of Ti membrane. The flexures show maximum stress and thus the design can be further improved if required for different materials. The actual deformation is also shown in flexures.

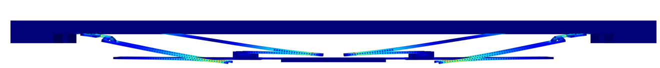

Fig. 6. Vertical deflection of micro membrane in -Z–direction is demonstrated. Results shows that the flexures handle the inner movable membrane well. The design is made to reduce the bending of membrane from middle and after applying force, multiphysics modeling supports the arguments and the result can be seen from deflection and straight inner moveable membrane.

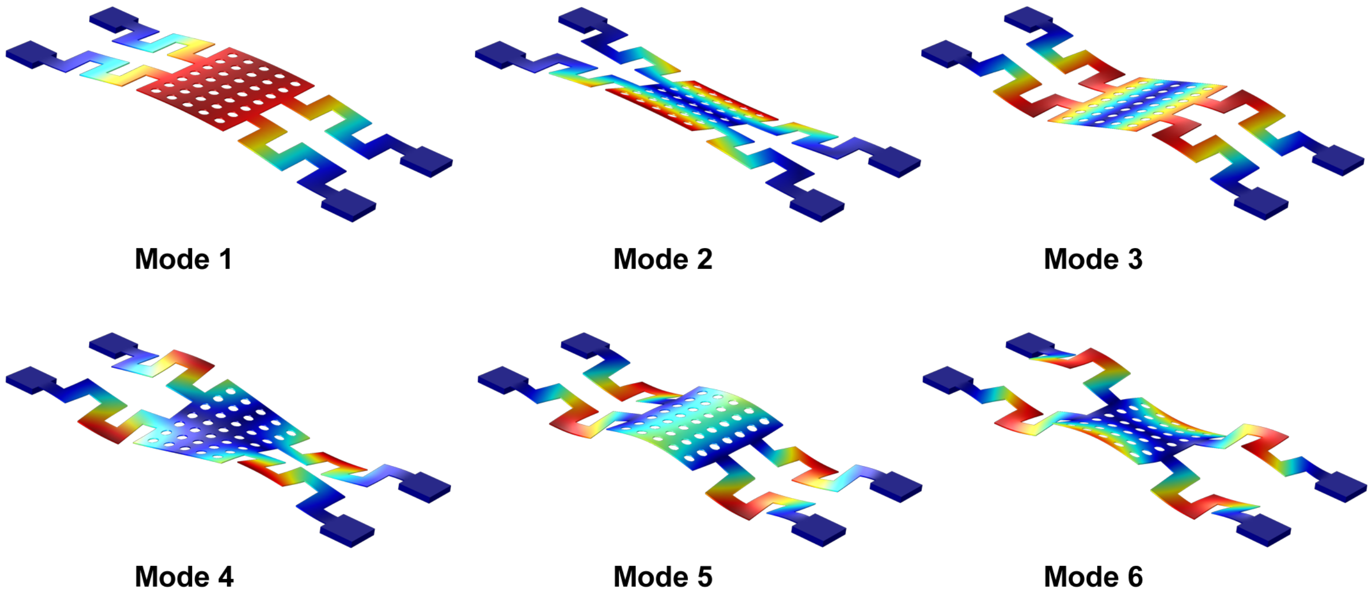

Fig. 7. First six modes with deformation of Au membrane is demonstrated that results from Eigenfrequency analysis in multiphysics environment.

impossible with mathematical analysis [11]. Fig. 4 shows the stress distribution in a Ti based micro membrane. Due to the complex, estimation of spring constant seems unfeasible and for multiphysics modeling its just a matter of few minutes.

Fig. 5 shows the close–up view of stress prone area of the membrane. Fig. 4 demonstrates the maximum stress is in the corners of membrane, while Fig. 5 shows the actual distribution of stress. During actuation, the middle part connected with flexures displaces to turn the switch ON or OFF according to the configuration. The vertical displacement of membrane in -Z direction or in downward direction towards electrodes is shown in the front view as given in Fig. 6. The RF performance is estimated in both ON and OFF state of switch that is given in Fig. 8. The membrane shows nominal stress and great RF performance over a range of frequencies in GHz. The insertion loss and return loss is also plotted. The eigenfrequencies or first six modes are shown in Fig. 7 are shown which is computed for a slightly different membrane designed for millimeter–wave frequencies [12].

The natural frequency of the membrane depends on the equivalent spring constant and the effective mass, the natural frequency f_0 is given as

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_{\text{eff}}}{m}} \tag{6}$$

To determine the first mode of eigenfrequency f_1 for hybrid membrane, the component need to be computed first for Au and then for Poly-Si. Then the addition of these two factors can give best estimate of the desired frequency. The first mode of frequency f_1 can be determined by

$$f_1 = \frac{1}{2\pi}\left[\frac{15.418}{L^2}\right]\sqrt{\frac{EI_x}{\rho}} \tag{7}$$

To compute the parameters in ON state, Y_{11-x} will be used,

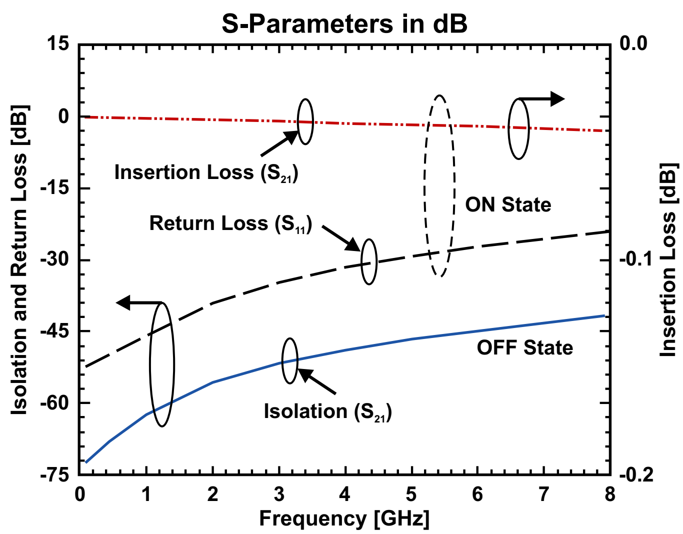

Fig. 8. RF performance measurements using the computation of S–parameters for the membrane shown in Fig. 4 results in isolation of 58 dB in OFF state of switch, insertion loss of 0.012 dB and return loss of 43 dB in ON state at 2 GHz.

where $x = 1$ for ON state and $x = 0$ for OFF state.

$$S_{11-x} = \left(\frac{Y_z^2 - Y_{11-x}^2 + Y_{21-x}^2}{(Y_{11-x} + Y_z)^2 - Y_{21-x}^2}\right) \tag{8}$$

where S_{11-x} is the return loss on ON or OFF state depending on the variable x, $Y_z = 1/Z_0$, $Y_{11-x} = j\omega C_{down}$ for $x = 0$ i.e., in OFF state and $Y_{11-x} = j\omega C_{up}$ for $x = 1$ i.e., in ON state. $Y_{21-x} = -j\omega C_{down}$ for $x = 0$ and $Y_{21-x} = -j\omega C_{up}$ for $x = 1$ i.e., in OFF and ON state respectively. To estimate isolation S_{21-0} and insertion loss S_{21-1}, plug the values in

$$S_{21-x} = \left(\frac{-2Y_{21-x}^2 Y_z}{(Y_{11-x} + Y_z)^2 - Y_{21-x}^2}\right) \tag{9}$$

Equation (8) and (9) helps determining the RF performance at specific frequency. For numerical calculations, frequency sweep seems unfeasible.

VI. Conclusion

From the case studies, it is clear that the capabilities of multiphysics modelling is tremendous for any cross–coupled physics problems. Although multiphysics environment provides a lot of modules to handle various problems, hence to learn different type of problem solving, there is need to put careful attention while learning the modeling methods. The learn curve might be steep for some, but once mastered it cam drastically reduce the designing and testing time. Electronics graduates can take huge advantage if multiphysics modeling is taught in their curricula. It can help fresh graduates to tackle numerous real world problems as they enter in the industry. As only engineers can develop better and advanced products that can serve the technical needs of humanity and it can all be possible with the quality education.

Acknowledgement

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