Introducing Undergraduate Research Results in RF Microelectronics into the Undergraduate ECE Curriculum

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Abstract -- Smart communications technology is currently implemented in a variety of applications ranging from smart antennas to wireless LANs. Microelectronics technology is the only means available to fit the ever-increasing amount of system functionality in a smaller physical footprint. This paper will present how current research being done by undergraduates in silicon technology is being integrated into an EE electromagnetics course to provide a look at a contemporary technology. Information on obtaining course materials is provided.

I. Introduction

Smart communications technology is currently implemented in a variety of applications ranging from smart antennas to wireless LANs. The current research in this area encompasses many aspects of antenna, receiver and system design. Microelectronics technology is the only means available to fit the ever-increasing amount of system functionality in an increasingly smaller physical footprint. An understanding of microelectronics components for use in a mixed signal environment (analog, digital, RF) will be required for undergraduate engineers to design the complex circuits that will ultimately be a part of smart communications systems on a single chip. These new technologies are also excellent motivational tools to help students put theoretical concepts into a current context. This is especially true in required undergraduate courses like electromagnetics (EM) that are heavily mathematics based.

The integration of contemporary topics into EM courses is fundamentally different than the use of multimedia assets that help students visualize EM concepts that are quite mathematically complex [1-3]. Contemporary topics that faculty introduce are frequently based on their research or consulting activities. Increasingly, undergraduate students are involved in research under the direction of faculty and bring a unique perspective to the research process. The experiences faculty mentors gain by observing undergraduate research students learn new material can be leveraged into providing unique lecture material for undergraduate classes.

This paper explores two issues: first, the undergraduate research program in microelectronics at the university; and secondly, some of the benefits undergraduate research students bring in helping faculty introduce research material into classes. The undergraduate student selection and mentoring processes are presented. An example of how undergraduate research results can be brought into the EM classroom, focusing on passive RF microelectronic components such as inductors and capacitors, is discussed. These circuit components are introduced early in the student's academic career, but usually only as ideal circuit elements. Concepts such as resistive

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loss, Q, device coupling (electric and magnetic) and fringing become much more important at the integrated circuit level than at the more ideal “macro” or discrete device level. Component layout, choice of conducting material and device size are more easily discussed in an EM course, with the added positive of the components being a topic of contemporary importance. The paper indicates locations in the EM course where these microelectronic component topics can be introduced. Information on how to obtain sample course materials is found in the paper conclusion.

II. Undergraduate Student Research in Silicon RF Microelectronics

IIa. Background

Many universities have undergraduate students involved in faculty research projects, with some universities having institution-wide programs (MIT’s UROP, for example [4]), although smaller institutions have successful undergraduate research programs as well. While these undergraduate students may not have the mathematics skills of their graduate counterparts, they do have the interest and enthusiasm to engage in open-ended work that is out of the mainstream of the typical structured undergraduate electrical engineering program. Undergraduate student researchers can make contributions to faculty research if the faculty mentor carefully specifies and defines the research problem that the student will address.

While the undergraduate research student receives many benefits from being engaged in the research effort, their research work can also benefit the faculty member's educational enterprise. To keep engineering courses relevant, faculty often bring in current topics to their undergraduate classes. In the ideal world (or department), faculty engaged in research will teach undergraduate courses in the same discipline area. Bringing in research work performed by undergraduate students into undergraduate courses has the important benefit that the coursework is still fresh in the undergraduate student's mind. The key benefit a faculty member has when integrating research results from undergraduate students is by observing how the undergraduate research students learn the necessary research material based on the foundation concepts originally used in the classroom. From these observations, the faculty mentor can determine the course topical areas that need further emphasis. This linkage between course content and research skills is best determined from undergraduate research students at the home institution since they are closer (in time) to the course material. Observing the learning process of the research students illustrates possible conceptual pitfalls and provides the information needed to modify and course lectures accordingly. At the same time, research students have insight into what material or exercises they would have liked to see while learning the course material and have useful ideas on how to approach developing the extra material. Simple courseware tools to help in the related undergraduate course can be developed by the undergraduate students, based on the research tools developed by the students.

IIb. Undergraduate Research Program

One of the conceptually most difficult courses in the undergraduate curriculum is electromagnetics because of the mathematic complexity. Only simple examples and structures can be analyzed while still keeping the mathematics reasonable. In addition, these simple examples are frequently not of a contemporary nature but are traditional problems and therefore not as high of value for student motivation. Integrated circuit structures, however, are good candidates for examples because the structures to be analyzed are mathematically straightforward (at least to first order). These structures can complement the first areas covered in undergraduate electromagnetics courses, electrostatics and magnetostatics. The fundamental Maxwell's Equations (ME) is mathematically decoupled and easier for students to understand and utilize. The application of ME to various classical problems includes resistance, capacitance and inductance, which link electromagnetics to circuit concepts used in other courses. Indeed, it can be mentioned that equivalent circuit modeling of complex structures is a key part of engineering and that rapid circuit simulation requires modeling efforts based on electromagnetics principles. This classical linkage can be updated easily to showcase the microelectronics world by using these same circuit elements but instead in an RF/communications integrated circuit context.

A means to address this need for microelectronics examples in the undergraduate EM course came out of the author's current research in silicon RF microelectronics design. In addition, the work on passive circuit elements lent itself well to an undergraduate research project.

During the spring term (EM is a junior level spring required course), promising research students were identified based on both test performance in the class as well as interest in pursuing a research project. These two issues are key elements since one wants motivated students as well as those intellectually prepared for open-ended projects. During this same time period, the students were also exploring topics for their senior capstone design project and the undergraduate research project provided added synergism.

The undergraduate research phase of the project began in earnest late in the spring semester and carried through the summer and fall terms. The students were presented the foundational material using a variety of methods including in-person tutorials on the subject by the faculty mentor, on-line tutorials on the foundational material, and readings of relevant technical literature.

Faculty mentoring was a large component of the program. The faculty mentor met individually and in groups with the students several times per week to gauge progress and assess worked performed to date. The mentoring load was heaviest during the initial summer month while the students learned the foundational material, with a lessening of the mentoring load as the students became more self-sufficient and confident in their research abilities. The undergraduate students also had the opportunity to work with an entering graduate student during the duration of the summer research experience that had a similar undergraduate research experience the previous spring.

Based on past experience, it was noted that electrical engineering students perform well with research tasks requiring a large degree of computer usage. Part of the research effort involved the creation of sophisticated computer models for analysis and design of the microelectronic circuit elements, but the closing of the design-simulate-test loop required that students also be versed on modern on-wafer RF measurements. For this task, students were mentored in the usage of a Cascade Microtech Probe Station and an HP-8510B Vector Network Analyzer (part of the Villanova University Microwave Laboratory) as a means of verifying their analysis and design tools. For the initial phase of the research project, students were asked to analyze previously fabricated RF microelectronic circuit elements as a way to verify their models. Then, based on these modeling efforts, the students designed several new test structures to a set of stringent specifications.

The material presented in the next section shows how passive IC components such as capacitance, resistance and inductance can be introduced into an electromagnetics course based on what was learned from the undergraduate research experience. The emphasis on various areas has been gleaned from noting problem areas that undergraduate research students initially had in understanding the research literature.

III. Implementation Example: Passive IC elements in Electromagnetics

The examples described in the following section were developed from work done on a National Science Foundation CRCD (Combined Research and Curriculum Development) grant in the area of Smart Communications. The research focus for the undergraduate students was in modeling the frequency response of passive integrated circuit elements using CMOS technology.

Most programs have courses where the IC fabrication process is covered to some extent. However, a short review of the resulting IC structure is important since the passive IC elements are based on parameters such as layer and material (metal and polysilicon layers as shown in Figure 1). Horizontal and vertical dimensions as well as typical layer and material parameters can be introduced at this time, based on widely available information [5]. Cross-sections and top views with appropriate dimensions are illustrated as part of the review.

III.a Integrated circuit resistance

The classical model for integrated circuit resistance is based on the resistive slab where the standard resistance equation $R=\rho L/Wt$ is used. This equation is an ideal one to derive from ME and the constitutive relations:

$$I = \oint \vec{J} \bullet d\vec{S} \quad V = -\int \vec{E} \cdot d\vec{l} \quad V = RI \tag{1}$$

The designer usually only knows the so-called sheet resistance, $R_{sh} = \rho/t$ in Ohms/square because the vertical dimensions are set by the fabrication process. The standard resistance equation is then modified slightly to show $R=R_{sh}\,L/W$. It should be pointed out that in ICs, the sheet resistance of metal layers typically decreases with increasing height above substrate since thicker metals are used to minimize the effects of uneven dielectric layers [5]. It is also interesting for students to note that the L/W ratio is dimensionless and it doesn't matter whether microns or miles are used for L and W. As an integrated circuit design exercise, students are asked to derive the dimensions of a 50Ω resistor (a standard impedance for RF work) based on a sheet resistance of 15 Ω/square. The students are also told L and W are only available in units of 0.75. Once the value of L and W are found, the layout and a photograph of a 50Ω resistor are shown.

Measurements, however, indicate a resistance of 55Ω, so students are asked to determine the actual sheet resistance of the structure and explain possible causes.

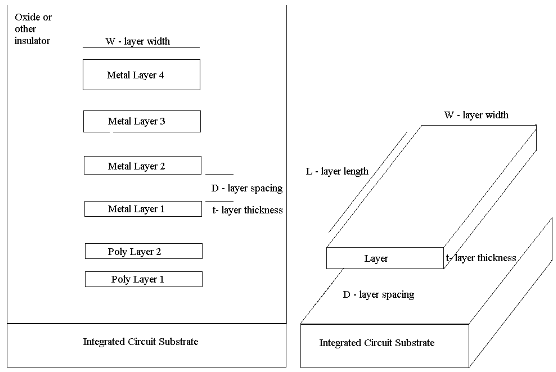


Figure 1. Idealized integrated circuit view showing layers and layer spacings.

III.b Integrated circuit capacitance

The classical model for parallel plate capacitance is also widely used in estimating capacitance in a RF integrated circuit. The capacitor is an ideal element to start with because of the need to use Maxwell's Equations (ME) and the appropriate constitutive relations:

$$Q = \oint \vec{D} \bullet d\vec{S} \quad V = -\int \vec{E} \cdot d\vec{l} \quad Q = CV \tag{2}$$

which yields the classic C=εWL/D relation. In IC design work, however, only the horizontal dimensions are under designer control; the vertical dimension is determined by the fabrication process. The IC context gives rise to the concept of capacitance per unit area where the horizontal dimensions W and L set the area. The instructor can discuss not only the desired capacitance, but also the capacitance between the plates and the integrated circuit substrate (top and bottom plate capacitance; equivalent circuit model in Figure 2.). In this example, C1 is the desired capacitance, C2 and C3 are the top and bottom plate capacitance with the resistance of the top and bottom plate calculated as above (R1 and R2). A note about classical SiO_2 dielectrics can be made, also mentioning new work in low-k, low dielectric materials) [6].

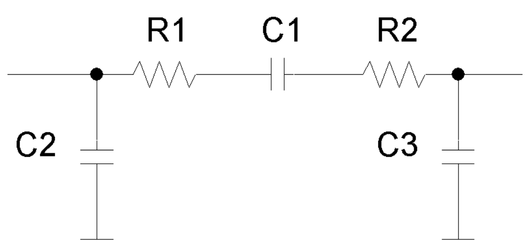


Figure 2. Equivalent circuit model of the integrated circuit capacitor, including parasitic elements.

The resistance material, when combined with integrated circuit capacitance material, can be used to estimate digital timing delays (rise and fall times related to RC) or the frequency response of various sizes of integrated circuit layers for interconnects. In addition to the RC computations, concept of lossy plate capacitance can be reviewed, showing the circuit models of IC capacitors with high sheet resistance (polysilicon material) and low sheet resistance (metal layers). These are good laboratory exercises.

III.c Integrated circuit inductance

The classical approach to covering inductance is based on the magnetostatic ME and constitutive relations. Traditionally, inductance relationships for such inductive elements as single wire, solenoid and toroids are derived. Keeping with the RF integrated circuit theme, inductors can be implemented using a variety of spiral types (rectangular and octagonal to name a few). Rectangular structures are the easiest to derive and the derivation is primarily based on the self-inductance of a rectangular section of metal.

$$\psi = \oint \vec{B} \bullet d\vec{S} \quad I = \int \vec{H} \cdot d\vec{l} \quad \psi = LI \tag{3}$$

An interesting issue arises with IC inductor modeling, arising not only from the inductance itself but also from the materials making up the inductor. The layer capacitance must be included in any equivalent circuit model along with the resistance of the layers. These two equivalent circuit elements can be quite large since an inductor of useful value must be physically large, as Equation 4 shows [7].

$$L = \frac{1.27 \mu N^2 d_{avg}}{2} \left(\ln \frac{2.07}{\rho} + 0.18\rho + 0.13\rho^2 \right) \tag{4}$$

where d_{avg} is the average dimension of the inductor and ρ is the inductor fill factor. While the actual expression shown in Equation 4 above is for the rectangular spiral inductor, the self-inductance of a wire can be derived; the form of both equations can be discussed. As part of a possible laboratory exercise for this unit, students can be provided software that allows them to calculate inductance values from physical dimensions and to determine the frequency response of their inductor. In the equivalent circuit shown in Figure 3, students can be asked to calculate all circuit parameters (R, L, C_i) based on a provided geometry. Students can be asked to model the transfer function of the inductor with and without the model parasitics (R, C) to observe actual upper frequency limits on inductor operation.

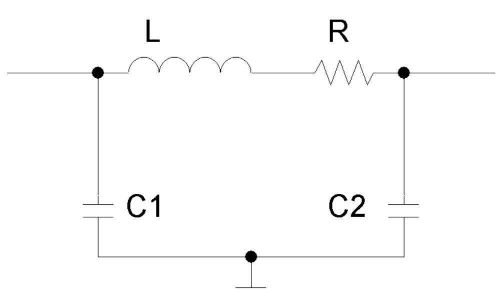
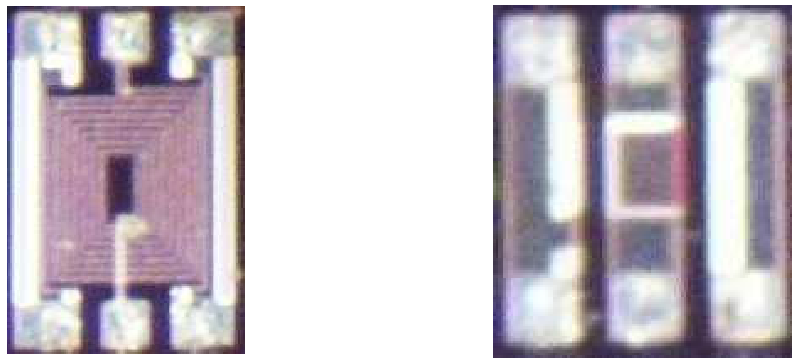


Figure 3. Equivalent circuit model for integrated circuit inductor, including parasitic elements.

Finally, students find actual photographs or even samples of integrated circuits beneficial to understanding, and hence motivation. Shown in Figure 4a is a photomicrograph of a nominal 10 nH inductor in 1.5 micron CMOS technology. A photograph of a double polysilicon capacitor of nominal 2.0 pF is illustrated in Figure 4b.



(a) (b)

Figure 4. a) photomicrograph of student designed 10 nH (nominal) inductor and b) nominal 2.0 pF capacitor in 1.5 micron CMOS technology. RF measurement structures are also shown.

IV. Conclusion

The material presented in the paper has shown some of the benefits in observing how undergraduate students learn research material and using these observations when introducing contemporary topics into undergraduate engineering courses. These observations have yielded insight into better examples for class use and exercises students can use to explore issues in microelectronic components. Since this linkage between undergraduate research and the EM class is a new endeavor, no assessment of the practice has been done. This assessment will be looked at in the future. The exercises and supporting material for the examples presented in this paper are available at http://rcaverly.ee.vill.edu/crcd/em/index.htm .

V. Acknowledgement

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VI. References

[1] "Special Issue on RF and Microwave Tutorials", Gupta, K.C. and Gupta, M.S., ed., *IEEE Trans. Microwave Theory Tech.*, vol. (51), April, 2003.
[2] "Microwave and RF Education - Past, Present and Future", Gupta, K.C., Itoh, T., Oliner, A.A., *IEEE Trans. Microwave Theory Tech*., vol. 50(3), pp. 1006-1014, March, 2002.
[3] "Technology-based Electromagnetic Education", M. Iskander, *IEEE Trans. Microwave Theory Tech*., vol. 50(3), pp. 1015-1020, March, 2002.
[4] MIT UROP Program, http://web.mit.edu/urop
[5] The MOSIS Service, http://www.mosis.org.
[6] "Fast films [IC Interconnect Insulation]", A.S. Brown, *IEEE SPECTRUM*, vol. 40(2), pp. 36-40, Feb. 2002.
[7] "Simple Accurate Expressions for Planar Spiral Inductances," S. S. Mohan *et. al., IEEE Journal of Solid-State Circuits*, vol. 34, no. 10, pp. 1419-1424, October 1999.