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Innovations in Engineering Education through Integration of Physics

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Dr. Kanti Prasad is a professor in the department of electrical and computer Engineering and is founding Director of Microelectronics/VLSI Technology Laboratories at the University Massachusetts Lowell. Professor Prasad initiated the Microelectronics/ VLSI program in 1984, and is teaching 16.469/16.502 VLSI Design and 16.470/504 VLSI Fabrication courses since its inception. From the spring of 1986 Professor Prasad developed 16.661 Local Area/Computer Networks, and since 1994 VHDL Based Digital Design and taught up to 2001, till Dr. Terence Kelly (received his doctorate under supervision of Professor Prasad) took over. From spring 1998, Professor Prasad also developed and taught 16.517, MMIC Design and Fabrication course to meet the growing demand of regional semiconductor industries. He is the recipient of Zone I best paper award by American Society of Engineering Education (ASEE) in 2008. He has been appointed as honorable member of IAAB of the MEGHE group of Institution and Shree Baba Ramdeo College of Engineering and Management (Nagpur) in India. He has also received the Best Teaching award for the New England Region, and the Best Campus award for the Zone 1 from ASEE during 2012. He is also coordinator for Graduate Studies in VLSI and Semiconductors certificate program. Professor Prasad already offered Online 16.517 MMIC Design and Fabrication during Spring 2009 and also developing MEMS Design and Fabrication to be offered Online starting from Spring 2013. He is the author of over 150 theses, dissertations and papers published and presented in journals/conferences of national and international repute. In 2013 Professor Prasad was awarded Fellow from the ASEE.

Innovations in Engineering Education through Integration of Physics

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1. Introduction

We are already in the age of information technology revolution. This not only incorporates traditional engineering but all aspects of power of Internet also, culminating into a variety of state-of-art technologies. It is the sublime duty of engineering educators to integrate these technologies into their curriculum as a prime requirement. The class room instructions must prepare the students not only to meet the challenges of the revolution but must enable them to cope with the challenges presented because of perpetual enhancements in technologies.

Presentation of advanced technologies through innovative teaching is of prime importance, but the most important is the comprehension of these technologies by the students. How to accomplish this goal is of paramount importance? My teaching experience of 30+ years at the state-of-art technologies has convinced me that no new information can become knowledge until it is yoked (yoga) with the existing database of the students. The best method to accomplish this is that educator must integrate fundamentals in the state-of-art technologies. We must make sure that we continually connect higher with the lower knowledge to make them wise else they will be otherwise. I repeat this mantra in all my classes so that no student of mine remains in 'otherwise' category.

Presentation of advanced technologies in classroom is of prime importance. In order to demonstrate it, I would like to recite a number of Hi-Tech courses; I am involved in teaching and research at the moment.

2.0 Depiction of Physics Fundamentals in the State-of-Art Technology courses.

Illustration of integration of Physics in my courses namely 1) MMIC Design and Fabrication, 2) VLSI Design, and 3) VLSI Fabrication will be presented through the examples in these courses.

2.1 MMIC Design and Fabrication

Example 2.1: Using Kirchhoff current and voltage laws, derive A, B, C, D matrix and calculate the input VSWR for the circuit shown below. The line is connected to a matched load given

$$S_{11}=\frac{A+BY0-CZ0-D}{A+BY0+CZ0+D}$$

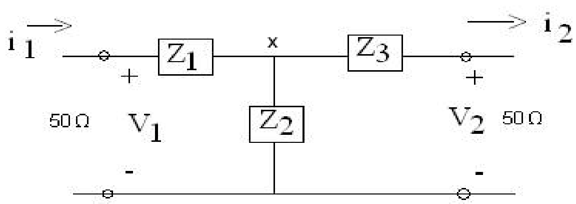


figure 1

where Z_1= 1Ω, Z_2= 2Ω, and Z_3= 4Ω.

Solution:

$v_1 = v_2 - 4i_2 + i_1$ eq(1)

Using KCL @node x,

$i_1 + i_2 = \frac{v1-i1}{2}$ eq(2)

Algebraic simplification leads to

$v_1 = \frac{3}{2}v_2 - 7i_2$ i.e. $A=\frac{3}{2}$; B=-7

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{vmatrix} \frac{3}{2} & -7 \\ \frac{1}{2} & -3 \end{vmatrix}$$

$v_1 = \frac{1}{2}v_2 - 3i_2$ i.e. $C=\frac{1}{2}$; D=-3

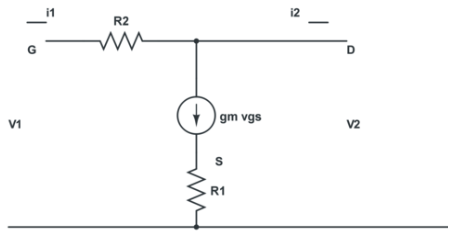
$$T_L=S_{11} = \frac{\frac{3}{2}+\frac{7}{50}-\frac{50}{2}+3}{\frac{3}{2}-\frac{7}{50}+\frac{50}{2}-3} = \frac{-20.64}{23.36} = -0.88356$$

$|T_L| = 0.88356$

$$VSWR = \frac{1+|T_L|}{1-|T_L|} = \frac{1+0.88356}{1-0.88356} = 16.176$$

Example: 2.2

Design a broadband amplifier making use of negative feedback and calculate the S-Parameters for the equivalent circuit of the amplifier given below:
Using again the Kirchhoff's current and voltage laws, the Admittance matrix $\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$ can be derived as,



$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{R_2} & \frac{1}{-R_2} \\ \frac{g_m}{1+g_m} - \frac{1}{R_2} & \frac{1}{R_2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

From the y matrix, the S-matrix can be derived as

$$S_{11} = S_{22} = \frac{1}{D}[1 - \frac{g_m Z_0}{R_2(1+g_m R_1)}]$$

$$S_{21} = \frac{1}{D}[\frac{-2g_m Z_0}{(1+g_m R_1)} + \frac{2Z_0}{R_2}]$$

$$S_{12} = \frac{2Z_0}{DR_2}$$

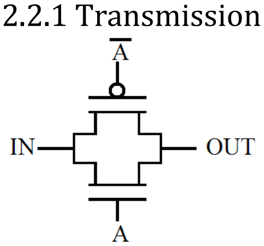
Where $D = 1 + \frac{2Z_0}{R_2} + \frac{g_m Z_0}{R_2(1+g_m R_1)}$

Both these examples, the author has chosen to demonstrate how crucial it is to demonstrate basic circuit principles based on sound physics to solve complex problems in the RF design based on S- parameters.

2.2 VLSI DESIGN

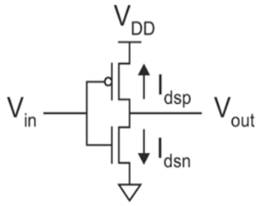
In any Technology, if one understands how to design an inverter and a transmission gate, one can design any complex chip. In CMOS technology, a transmission gate is designed as below:

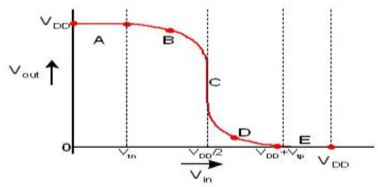
2.2.1 Transmission Gate:



Based on simple electronics, it can easily be proved that NMOS is hard on 1*s* and soft on 0*s*, whereas PMOS is hard on 0*s* and soft on 1s. So the gate transmits input IN from 0 volt and V_{DD} volt at the output as OUT.

Inverter:





Based on NMOS and CMOS characteristics and transposing them, we get a curve for the inverter depicting V_{out} vs V_{in} as below.
In B region NMOS is in saturation, whereas PMOS is in linear region, such that

$I_{dsn} = \beta_n (V_{in} - V_{tn})^2$ and

$$I_{dsp} = -\beta_p ((V_{in} - V_{DD} - V_{tp})(V_{out} - V_{DD}) - (\frac{(Vout - VDD)^2}{2})$$

Adding both these currents and with some algebraic simplification

$$V_{out} = (V_{in} - V_{tp}) + \sqrt{(Vin - Vtp)^2 - 2(Vin - VDD/2 - Vtp)VDD - (Vin - Vtn)^2}$$

In D-Region, the NMOS is in linear region, whereas PMOS is in saturation, such that

$$I_{dsn} = \beta_n (V_{in} - V_{tn} - \frac{V_{out}}{2}) V_{out}$$

And $I_{dsp} = \frac{\beta p}{2}(V_{in} - V_{DD} - V_{tp})^2$

Based current addition and simplification

$$V_{out} = (V_{in} - V_{tn}) - \sqrt{(Vin - Vtn)^2 - (Vin - VDD - Vtp)^2}$$

The equations (1) and (2) are the basis of robust design having determined the noise margins NMs. So that system is always in the deterministic mode. This can be demonstrated very clearly by giving some numeric values to these parameters such as V_{DD}=5V and V_{in}=0.7V and V_{tp}=-0.7V

Substitution of these values in B-region leads to

V_{out} = (V_{in} +0.7)- $\sqrt{-7.2\,Vin + 18}$

Which on partial differentiation with respect to V_{in} gives

$\frac{\partial Vout}{\partial Vin}$ = 1+ $\frac{(1/2)\,(-7.2)}{\sqrt{-7.2\,Vin+18}}$ = -1

i.e. V_{in} = 2.05 =V_{IL}
and therefore V_{out} = 4.55 = V_{OH}

Similarly in D-region
V_{out} = (V_{in} - 0.7)-$\sqrt{7.2\,\mathrm{Vin} - 18}$

Differentiating V_{out} with respect to V_{in}

$\frac{\partial Vout}{\partial Vin}$ = 1- $\frac{(1/2)\,(7.2)}{\sqrt{7.2\,Vin-18}}$ = -1

V_{in} = 2.95V =V_{IH}

And V_{out} = 0.45V = V_{OL}

so NM_L = | 2.05-0.45| = 1.6V

and NM_H = |2.95-4.55| = 1.6V

These examples illustrate how integration of fundamentals lead to the state-of-art technologies which are so essential for succeeding in VLSI chip design technology.

2.3 VLSI Fabrication

During this course, the author covers a variety of topics including Miller Indices, Photolithography, Oxidation, Diffusion, Ion implantation, Metallization, Testing, Characterization, Packaging, and Reliability & Failure Analysis etc. However, demonstrative examples are chosen from Diffusion, and failure analysis.

2.3.1 Diffusion

The basic physics involved here are Fick's laws:

$$J = -D\frac{\partial C(x,t)}{\partial x} \qquad (1)$$

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \qquad (2)$$

The initial conditions @t=0 in C(x,0)=0, and boundary conditions are C(0,t)=C_s, and C(∞,t)=0, culminate into Deposit-On which is given by

$C(x,t)= C_s\ \mathrm{erfc}(\frac{x}{2\sqrt{Dt}})$

Based on initial conditions C(x,0)=0 and boundary conditions $\int_0^\infty C(x,t)dx = Q_T$ and C(∞,t)=0, the solution becomes Drive-In, which is given by

$C(x,t)= \frac{Q_T}{\sqrt{\pi Dt}}\exp(\frac{-x^2}{4Dt})$

These are the basis of calculating p-n Junction depth illustrated by the following examples.

Example 2.3.1 Deposit-On

Calculate junction depth 'x_j' and the total amount of dopant introduced into the n-types substrate with a bulk concentration C_B of $1*10^{15}$ cm^{-3} after boron pre-deposition at 975°C for 60 minutes.

The junction depth is defined by condition $C_{xj}= C_B= 1*10^{15}$ cm^{-3}

The solid solubility of boron in Si at 975°C is $3.5*10^{20}$ cm^{-3} , and diffusivity of boron in Si is $1.5*10^{-14}$ cm^2/s

$C(x_j,t)= C_B = Cs\ \mathrm{erfc}(\frac{x_j}{\sqrt{4Dt}})$

$\frac{x_j}{1.47*10^{-5}} = \mathrm{erfc}^{-1}(2.9*10^{-6}) \approx 3.3$

so $x_j= 0.49\ \mu m$

The total amount of dopant introduces into the substrate Q(t) is given by

$Q_t = \frac{\sqrt{4Dt}}{\sqrt{\pi}} C_s= 2.9 * 10^{15}$ atoms/cm^2

Example 2.3.2 Drive-In

Calculate the junction depth x_j of the sample in example 2.3.1 after Drive-In at 1100°C for 4.5 hours.

$C(x,t)= \frac{Q_T}{\sqrt{\pi Dt}}\exp(\frac{-x^2}{4Dt})$

$Q_t =(\frac{2C_s\sqrt{Dt}}{\sqrt{\pi}})_{predep} = \frac{5.18*10^{15}}{\sqrt{\pi}}$

Where $C_{s'(t)} = \frac{5.18*10^{15}}{\pi\sqrt{(Dt)_{drive-in}}} = 2.5*10^{19}/cm^3$

So $x_j = (-4Dt_{drive-in} \ln\frac{C_B}{Cs'(t)})^{½} = 4.4\ \mu m$

The most exciting aspect of this course is when the students calculate the p-n junction depth theoretically based on physics and then also measure it experimentally in the lab (DSIPL) in a clean room environment through sectioner equipment.

2.3.2 Failure Analysis:

This analysis is based on physics principles such as distribution function F(t), probability density function f(t) , and mean time between failure MTBF, etc.

$F(t) = 0$ for $t < 0$

$0 \leq F(t) \leq F(t')$ for $0 \leq t \leq t'$

and $F(t) \rightarrow 1$ as $t \rightarrow \infty$

$f(t) = \frac{d}{dt}F(t)$, and

$MTBF = \int_0^\infty tf(t)dt$

The failure analysis is vividly illustrated through the example below.

Example 2.3.3

For a median life of $9 * 10^5$ hours and $\sigma = 1.8$, what fraction of device would have failed after 10 years.

Given:

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^t \frac{1}{x} exp[\frac{-1}{2} (\frac{lnx-\mu}{\sigma})^2]dx$$

$$F(t) = \frac{1}{1.8\sqrt{2\pi}} \int_0^{87600} \frac{1}{x} exp[\frac{-1}{2} (\frac{11.38-13.71}{1.8})^2]dx$$

$$F(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-1.294} e^{\frac{-1}{2}} u^2 du$$

$$[F(t)]^2 = \frac{1}{2\pi} \int_\infty^{1.83} rdr \int_{3\frac{\pi}{2}}^{\pi} d\theta$$

$$= \frac{1}{2\pi} \int_\infty^{1.674} e^{-z}dz \int_{3\frac{\pi}{2}}^{\pi} d\theta$$

$$=0.04682564$$

$\therefore F(t) = 0.2164$

i.e., 21.64 devices would fail after 10 years.

3. Correlation Between Fundamentals and Preparing the Workforce for 21st Century.

The technology is evolving all the time, but the fundamental principles hardly change. It is therefore the solemn duty of instructors in the classroom to integrate the fundamentals in any State-of-Art technology. This will ensure that the engineering students who are product of such teaching methodology never become obsolete. During my own teaching tenure I have graduated several hundreds of students who are placed in the high tech industry regionally, nationally, as well as internationally, who are vibrant and dynamic throughout their careers as have been found from the surveys of the alumni office.

In fact I would suggest that engineers in the work environment should even take some advanced technology courses as the time moves. This is a paradigm which is applicable even to the instructors in each discipline of engineering as the technology evolves in that particular discipline. I would also like to further suggest that the instructors who are teaching fundamental courses, they should also point out some of these fundamentals how germane they are in certain State-of-Art technologies.

In my own case, I also teach Circuit theory, which is the most fundamental course in the curriculum of Electrical and Computer Engineering. I have shown in the classroom, how the measurements of Resonant frequency 'f_0', the Quality factor 'Q' and the Voltage gain 'G_V' are the basis of electrostatic assist (ESA) no-shake algorithm used in designing Microeletromechanical sytems(MEMS) which I have been working on for the last ten years. This example excited the students of mechanical engineering to the extent that seven students out of forty made straight A's, especially when I pointed out that the lead engineer of MEMS at Analog Devices is a Mechanical engineer. The 'f_0' and 'Q' are of paramount importance in designing and testing bulk acoustic wave (BAW) filters, a research project I was involved at Skyworks Solutions for seven years. At the moment I am involved as a collaborative research endeavor with the Skyworks at replacing or minimizing the wet processing with dry strip involving advanced plasma techniques. Again the lead Engineer here is a renowned physicist. I would therefore suggest that engineering education innovations should also involve some interdisciplinary approaches.

4. Conclusion:

The technologies are bound to evolve with time based on better modeling techniques. Intricate sound principles are sure to be explored. Therefore, we must teach fundamentals of physics, chemistry and mathematics rigorously and demonstrate continually, how the state-of-art technologies are based on these fundamentals. This is the cardinal philosophy of Innovation in Engineering Education including interdisciplinary approaches to some reasonable extent.

I am convinced however, that innovations in engineering education must be carried out in all disciplines of engineering through integration of fundamentals along with state-of-art technologies for the readiness of the work force development nationally as well as internationally to meet the challenges of emerging technologies of the 21st century.

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