TEACHING MICROELECTRONIC DEVICE COURSES USING MATHCAD

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ABSTRACT

In this paper a technique to teach microelectronic devices utilizing the power of MathCAD program is presented. The design and analysis of an advanced microelectronic device is shown in details. To assess the outcome of this technique, a group of students who finished this course are surveyed and the results of the survey are presented. The survey shows that the majority of the surveyed students feel that the outcome of using MathCAD is very positive.

1. INTRODUCTION

Teaching microelectronic devices presents a challenge to instructors and students alike. The challenge comes from the nature of the material taught and the level of accuracy required for modern devices. Microelectronic courses require a multifaceted background of knowledge, where it is necessary to have a thorough understanding of the physical phenomena related to the subject matter, a knowledge of high level mathematics, and an understanding of the technology practical limitations.

To overcome these difficulties, several approaches are normally used. The first is to address ideal cases only, so simple analytical treatment can be used. The second is to simplify the problems by neglecting secondary effects. The third is to present the final results without deep analysis. The outcome of these approaches is the failure to provide the students with complete up-to-date knowledge or to provide them with a deep understanding of the fundamentals of the subject matter.

The problems mentioned above were addressed by using MathCAD program in teaching this type of courses. This tool is developed by MathSoft (1986-2001). The power of MathCAD allows the instructor to tackle advanced subject matters and to provide the students with a tool to design advanced devices. Microsoft Power Point™ was utilized to deliver the lectures, hence allowing for covering more materials with greater details.

For this type of courses, MathCAD is preferred because structured programming is not necessary, unit conversions are done automatically, and the program instant error messages can provide an easy way of identifying and correcting mistakes. In addition to all these features, all

equations and calculations can be made visible in their actual from, and the effect of any change in the input parameters is instantaneously shown. These are important features that simplify the design procedure.

To explain this teaching technique, an example of how to design advanced devices is presented. The MathCAD program used to solve the example is shown in Appendix (A).

2. COURSE OUTLINES

2.1 Course Description

ELE 335 Theory of semiconductor devices I (3 credit hours): A unified treatment of the theory of operation of semiconductor devices, including p-n junctions, bipolar transistors, and field effect transistors. Topics include doping, band gap, mobility, carrier lifetime, photolithographic techniques, passivation, chemical etching, metallization, and device testing. PRQ: CHEM 210T and CHEM 212 with a grade of C or better, Phys. 260, and ELE 210.

2.2. Objectives of the course

1. Introduce electrical engineering students to semiconductor material properties.
2. Provide the students with a solid knowledge of the theories of modern electronic devices.
3. Ensure that the students can apply semiconductor theories to design electronic devices and investigate their performance.

To satisfy objective 3, it was necessary to find a tool that facilitate the device design and allow for an easy way to investigate the device performance. The tool chosen is MathCAD software.

3. EXAMPLE OF A DESIGN PROBLEM

Using MathCAD, students were able to design advanced devices with high accuracy. An example of how to design a 4H-SiC Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is shown below.

3.1 Example of a Design Problem

Design an Al-gate n-channel 4H-SiC-MOSFET with a structure similar to that of Figure 1. Determine the gate length L and gate width Z that result in a threshold voltage V_T of 1.5V and a saturation current I_{Dsat} of 10 mA at a gate voltage V_G of 5V. Assume that the electron affinity χ_s for SiC is 3.27eV, the work function ϕ_m for the Al gate metal is 4.6 eV, the dielectric constant ε_{ox} of the gate oxide (SiO_2) is 3.9, and the oxide charges Q_f is 10^{10}qC/cm^2. The relationship between the impurity concentration and the mobility for SiC is shown in Fig. 2(a).

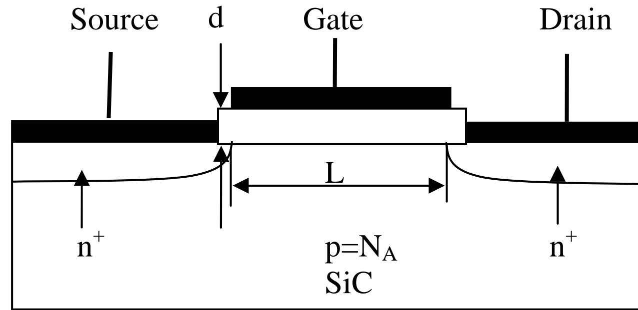

Figure 1: MOSFET structure

3.2 Problem solution

In this problem, it is required to design a MOSFET that has a threshold voltage of 1.5V and provides a saturation current of 10 mA at a gate voltage of 5V. Students are required to determine the doping and the dimensions of the device to achieve these requirements. To obtain the oxide thickness d that gives a threshold voltage V_T of 1.5V, the following equation is used:

$$V_T = \phi_{ms} - \frac{Q_f}{\varepsilon_{ox}/d} + \frac{Q_{SC}}{\varepsilon_{ox}/d} + 2\psi_B\,, \qquad (1)$$

where

$$\psi_B = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right),\ Q_{sc} = 2\sqrt{q\varepsilon_s N_A \psi_B}\ ,\ \text{and}\ \phi_{ms} = \phi_m - \phi_s\,, \qquad (2)$$

q is the electron charge, k is Boltzmann constant, T is the temperature in Kelvins, ϕ_{ms} is the difference between the work function for the metal ϕ_m and that for the semiconductor ϕ_s, ε_s is the semiconductor dielectric constant, Q_{sc} is the depletion region charge per unit area on the semiconductor side, and n_i is the intrinsic carrier density.

In Eq. (1), the oxide charges Q_f and the oxide dielectric constant ε_{ox} are known. The rest of the parameters, except d, can be calculated from Eq. (2). From this equation one realizes that ψ_B depends on N_A and n_i. Here, the doping N_A is not known; therefore, the students need to choose a value for it. The students need also to ensure that the chosen value is a practical value: i.e., not to be less than the intrinsic density nor higher than the saturation value. However, choosing a practical value for N_A may not be the end of the story, since the assumed value must also lead to a realistic and optimized design. This may require running several rounds of trails and errors, where MathCAD can be of a great value.

The doping can be assumed, but the intrinsic concentration should be obtained from the relation

$$n_i = \sqrt{N_C N_V}\,\exp(-E_g/2kT)\,, \qquad (3)$$

where N_C and N_V are the conduction and valence band density of states, E_g is the energy gap. E_g and k are constants that are obtained from the literatures, but N_C and N_V should be calculated from the relations

$$N_C = 2[(2\pi m_n^* kT)/h^2]^{3/2} \text{ and } N_V = 2[(2\pi m_p^* kT)/h^2]^{3/2}. \quad (4)$$

Here m_n^* and m_p^* are the electron and hole effective masses, and h is Planck's constant.

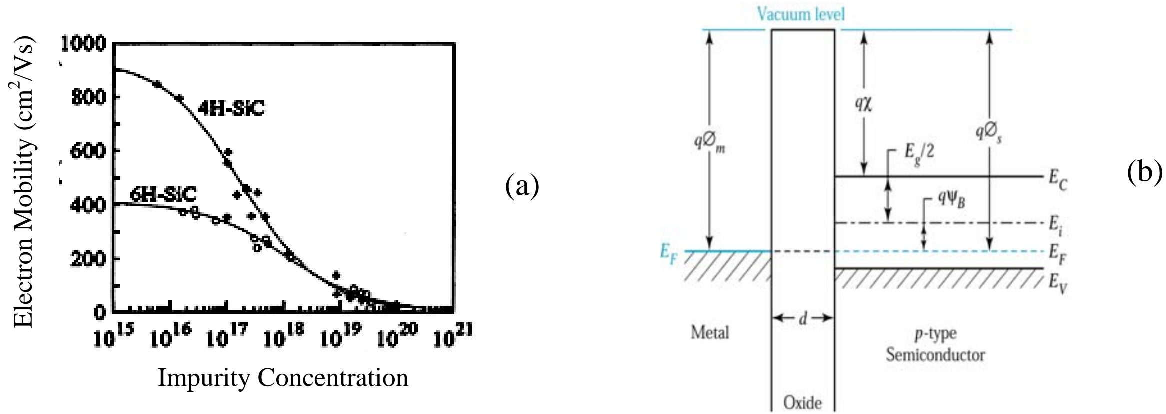

Figure 2: (a) Electron Mobility of SiC as a function of the doping concentration, Shaffer *et al.* (1994); (b) Energy band diagram of metal-oxide- semiconductor (MOS) structure, Sze (2002).

Obtaining n_i from Eqs. (3) and (4), ψ_B and, consequently, Q_{sc} can be obtained. The value of ϕ_m is given, but the value of ϕ_s needs to be calculated. The students need now to use Fig. 2(b), to obtain this value. From the figure it can be seen that

$$\phi_s = \chi_s + E_g / q - \Delta, \quad (5)$$

where $\Delta = E_F - E_V = (kT/q)\ln(N_V / N_A)$. Using the assumed value of N_A and obtaining N_V from Eq. (4), Δ can be obtained. Since χ_s is given and E_g for SiC is known, ϕ_s and, in turn, ϕ_{ms} can be calculated.

All parameters in Eq. (1) are now known, except the value of the oxide thickness *d*, which can be obtained by solving this equation. If the value of *d* is found to be impractical, then a new value for N_A should be assumed and all parameters in equations (1)-(5) should be recalculated to obtain a more practical value for *d*.

The current of the MOSFET is obtained for the linear region from the relation

$$I_D = \left(\frac{\mu_n Z C_0}{L}\right)\left[(V_G - V_T)V_D - \frac{V_D^2}{2}\right], \quad (6)$$

and for the saturation region from the relation

$$I_{Dsat} = \left(\frac{\mu_n Z C_0}{2L}\right)[V_G - V_T]^2 \quad (7)$$

where $C_0=\varepsilon_s/d$ is the gate capacitance/unit area, μ_n is the electron mobility, V_D is the drain voltage, Z is the device gate width and L is the device gate length. I_{Dsat}, V_G, and V_T are given. μ_n is obtained from Fig. 2(a) using the assumed value of N_A. Equation (7) is now a one equation in two unknowns, Z and L. If L is assumed, 1μm for example, Z can be obtained. Here the students will realize that the chosen value of N_A affects μ_n which, in turn, affects the value of Z. Z is also affected by the chosen value of L. If the calculated value of Z is found to be unrealistic (too large or too small) then the value of N_A and L need to be adjusted. If no realistic values for the dimensions can be obtained, the students will realize that a device with these requirements does not exist.

4. SURVEY

To measure the impact of using MathCAD, students enrolling in a senior level microelectronic course were surveyed about ELE 335. The number of the valid respondents is eleven students out of fourteen. Nine students indicated that they spent about 6-10 hours a week studying for ELE 335 while two indicated that they spent close to 11-15 hours/week. This indicates that the average time of studying spent by students on this course is about 8 hours/week, which is reasonable for most engineering courses. In other ways, the use of MathCAD was not a heavy burden on the students. The results of the survey are shown in Table 1.

Table 1: Results of survey.

Question	yes	No
The use of MathCAD helped me understand the fundamentals of semiconductor devices.	81%	19%
The use of MathCAD helped me understand how devices are designed and how their performance is optimized.	91%	9%
The use of MathCAD convinced me to enroll in other semiconductor device courses.	91%	9%
This course gave me deeper understanding of semiconductor devices than other device courses that did not utilize MathCAD	73%	27%

From the survey, more than 80% have indicated that MathCAD helped them understand the fundamentals of the subject matter and more than 90 % indicated that the software helped them in device design. The majority of the surveyed students felt that MathCAD convinced them to enroll in advanced semiconductor devices and gave them a deeper understanding of semiconductor devices than other courses that do not utilize CAD software. This of course is a result of the deeper understanding of the material taught.

We recognize, however, that this survey is a preliminary survey, and to understand the full impact of using MathCAD a more methodical survey needs to be conducted.

5. CONCLUSIONS

Using MathCAD to teach a junior level microelectronic course has transformed the course from addressing basic knowledge of the subject to a design course where advanced devices can be designed and analyzed. This software gave the students the expertise to handle new technologies, even if the devices were not addressed in the course.

REFERENCES

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APPENDIX (A)
Solution of the MOSFET design problem using MathCAD

$m_0 := 9.11\cdot10^{-31}kg \quad m_n := .29\cdot m_0 \quad m_p := 1.25\cdot m_0 \quad h := 6.63\cdot10^{-34}J\cdot s \quad \mu_n := 900\cdot\frac{cm^2}{V\cdot s} \quad N_A := 10^{15}\cdot cm^{-3}$

$V_T := 1.5\cdot V \quad \chi := 3.27\cdot V \quad \phi_m := 4.6\cdot V \quad eV := 1.6\cdot10^{-19}\cdot J \quad T := 300\cdot K \quad \varepsilon_0 := 8.85\cdot10^{-14}\cdot\frac{F}{cm} \quad V_G := 5\cdot V$

$k := 1.38\cdot10^{-23}\cdot\frac{J}{K} \quad q := 1.6\cdot10^{-19}\cdot C \quad \varepsilon_s := 10.1\cdot\varepsilon_0 \quad E_g := 2.9\cdot eV \quad \varepsilon_{ox} := 3.9\cdot\varepsilon_0 \quad I_D := 10\cdot mA$

$N_v := 2\cdot\left(2\pi\cdot m_p\cdot k\cdot\frac{T}{h^2}\right)^{\frac{3}{2}} \quad N_c := 2\cdot\left(2\pi\cdot m_n\cdot k\cdot\frac{T}{h^2}\right)^{\frac{3}{2}} \quad n_i := \sqrt{N_c\cdot N_v}\cdot\exp\left(\frac{-E_g}{2k\cdot T}\right) \quad Q_f := 1\cdot10^{10}\cdot q\cdot\frac{1}{cm^2}$

$\Delta := \frac{k\cdot T}{q}\ln\left(\frac{N_v}{N_A}\right) \quad \psi_B := \frac{k\cdot T}{q}\cdot\ln\left(\frac{N_A}{n_i}\right)$

$\phi_s := \chi + \frac{E_g}{q} - \Delta \quad \phi_{ms} := \phi_m - \phi_s \quad Q_{sc} := \sqrt{2\cdot\varepsilon_s\cdot q\cdot N_A\cdot 2\cdot\psi_B}$

$C_0 := \frac{Q_f - Q_{sc}}{\phi_{ms} + 2\cdot\psi_B - V_T} \quad d_{ox} := \frac{\varepsilon_{ox}}{C_0}$ Assume, $L := 10^{-6}\cdot m$ Then, Z is obtained from:

$V_D := 0\cdot V, 0.1\cdot V .. 10\cdot V$

$Z := \frac{I_D}{\left[\left[\frac{(\mu_n\cdot C_0)}{2\cdot L}\right]\cdot(V_G - V_T)^2\right]}$

$I_{DSAT}(V_G) := \left[\frac{(\mu_n\cdot Z\cdot C_0)}{2L}\right](V_G - V_T)^2$

$I_D(V_G, V_D) := \left[\frac{(\mu_n\cdot Z\cdot C_0)}{L}\right]\left[\left[(V_G - V_T)\cdot V_D\right] - \frac{V_D^2}{2}\right]$

$I_{DD}(V_G, V_D) := \text{if}(V_D \le V_G - V_T, I_D(V_G, V_D), I_{DSAT}(V_G))$

$\Delta = 0.271\ V$ $\quad \psi_B = 1.208\ V$

$Q_{sc} = 2.628\times10^{-4}\frac{s\,A}{m^2}$

$C_0 = 6.428\times10^{-4}\frac{1}{m^2}F$

$d_{ox} = 5.37\times10^{-8}m$

$Z = 2.822\times10^{-5}m$

$L = 1\times10^{-6}m$

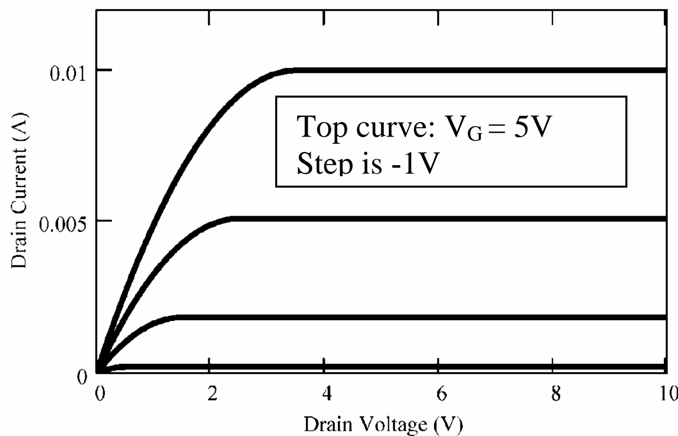

Figure 3: MathCAD simulation for the MOSFET I-V Characteristics