Analog VLSI Design Resource Kit

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PREFACE

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A. Philosophy Behind the Need for These Tutorials

The education of undergraduate electrical and computer engineering students in digital CMOS VLSI design is widespread, thanks to the large number of integrated and sophisticated computer aided design (CAD) packages available to universities. Many undergraduate students can now routinely design, simulate, fabricate and test relatively complex digital integrated circuits. In addition, they enjoy a high success rate in terms of "working parts" due to the level of design automation afforded by the current CMOS digital VLSI design tools, which allows the students to achieve closure on the complete design-test loop. The ability to close the design loop is a powerful educational tool because it seizes the student's imagination by seeing their theoretical work put into practice.

CAD of analog CMOS VLSI circuits at the undergraduate level is not at this time, unfortunately, at the same level of sophistication as CAD of digital VLSI circuits. CAD-based analog synthesis and design tools are still evolving in a process that borrows, to some degree, from the lessons learned in the development of digital CAD tools. In spite of the relatively immature status of analog CMOS VLSI CAD (when compared with digital CAD), there is still a widespread interest in teaching analog VLSI design. Up until quite recently, most analog VLSI courses were to be found only at the graduate level in many universities because of the more experimental nature of the course due to the relative immaturity of analog CAD tool suites. However, a number of books suitable for undergraduate education have appeared that address circuit design concepts pertinent to analog CMOS VLSI design. Many of these books cover the important analog VLSI design topics such as operational amplifier design, sampled data circuits, and data conversion.

In most analog VLSI design courses, students are assigned a course project to reinforce the lecture material. In analog VLSI, there are a great many more component variables that must be considered than in a digital VLSI. Unfortunately, by the time sufficient material has been covered in class to do a significant project, the fabrication turn around time pushes the acquisition of the finished chip out of the course term. What is needed is a means for students to learn the course material and then be able to simulate and test these circuits as soon as possible after the lecture as a method to enhance their understanding. Students can then initiate course projects with a deeper understanding of the underlying circuit design principles. One way to accomplish this task is to provide the students with a "resource kit" containing a set of pre-fabricated analog CMOS VLSI circuits and an accompanying set of tutorials to explain important measurements needed in evaluation of analog circuits. The resource kit would act as a supplement to analog CMOS VLSI design courses, but would not preclude the assignment of individual student projects. Indeed, the students will be able to undertake projects with a greater degree of understanding, which will translate into a more meaningful design experience for them.

The resource kit also provides instructors of analog CMOS VLSI design courses a laboratory-style tutorial manual containing important topics in CMOS analog VLSI design, with an accompanying chip set that covers these topics and allows electronic altering of some system constants to see the effects of parameter variations. The resource kit allows instructors to cover the design methodology of analog CMOS VLSI circuits in lecture and then lets students go into the laboratory to observe actual circuits (using the tutorials and chip set) based on these design principles. As a link to digital VLSI courses, the first tutorial focuses on a circuit common to both digital and analog VLSI. This version of the Resource Kit (Version 2) contains tutorials dealing with simple CMOS inverting amplifiers, current mirrors, operational amplifiers, switched capacitor filters, ring oscillators and digital to analog converters.

B. Notes for Users of the Tutorials

1. The circuits described in the resource kit were chosen for their operational simplicity. This allows undergraduate students the opportunity to design, analyze and simulate simple circuits that will enhance their understanding of the circuit's operation. This understanding becomes the foundation for designing more sophisticated analog circuits based on these underlying principles. By the same token, however, the circuits provided in the Resource Kit are not "high performance" by any means, and their shortcomings become evident during measurements. This lack of "performance" should not be taken as a negative, however. My philosophy about education is that students should receive a thorough grounding in fundamentals before tackling the complex. When the students observe a circuit's shortcomings, the motivation for improving the circuit is passed to them and the reasons for the extra time and effort needed for a more sophisticated design are evident. Commercially available integrated circuits, by definition, must be high performance and hence are not as good at providing the motivation students need in warranting the additional design time required for more sophisticated circuits.

2. There are at least two copies of each circuit (except for the ring oscillator and the digital to analog converter) on the test chip. The reasons for this are two-fold: first, if one of the circuits should somehow become nonfunctional (either by process problems or accidental overvoltage application, for example), there is another copy available to test. Secondly, the multiple circuits provide test opportunities to determine any on-wafer process variability. These extra circuits take up both area and I/O pins, but can be removed by editing the MAGIC file. Your favorite circuit(s) may then be placed on-chip and used in your classes.

3. The technology chosen for the circuits and experiments described in these tutorials is a single polysilicon layer, double level metal scalable CMOS process (both n-well and p-well processes are supported). The single poly layer process was chosen over the double poly layer process because, at the present time, MOSIS offers both processes with 2 micron gate widths.   Capacitors are fabricated using polysilicon-metal overlays, and the pad frame is the MOSIS standard 2 micron Tiny Chip pad frame (with about 1800 by 1800 microns of payload area).   Since single poly circuit designs can be fabricated in the double poly process, but not vice versa, the chip set exhibits a (small) degree of universality from one process to the next. Currently, MOSIS offers the single poly process with VLSI Technology, Inc., and the double poly process (both regular and low noise analog) through Orbit Semiconductor, Inc. The layout has been prepared using the MAGIC (version 6) layout editor on a 1 lambda grid. The standard circuit extractors and simulation file programs available with the MAGIC tool suite (ext2sim, sim2spice, pspice) have been used.

4. Several of the tutorials require the use of a variable DC source for setting bias conditions on various circuit elements. I ***strongly*** recommend the use of a potentiometer (a 10KΩ potentiometer is sufficient), connected to 5 volts and ground, as the bias controller, or a current limited 0 to 5 volt power supply. Earlier versions of the chip set were accidentally destroyed by momentary overvoltage (as little as 6.5 volts!) from an external power source applied to the chip set by eager students. We found that the use of the variable resistor bias controller virtually eliminated any possibility of overvoltage application occurring. This does not eliminate, however, placing a large voltage at the input to the circuits. The tutorials have been written to remind students to **verify** input signal specifications **before** they apply them to the circuits.

5. The simulations described in the tutorials have been tested using SPICE3. The simulation files should also work with SPICE2, but this has not been verified.   The CMOS model definitions in each of the SPICE files were taken from a typical MOSIS run. This set of model definitions should be updated according to the vendor and process to insure simulation accuracy. The circuits described in the tutorials should also simulate using PSPICE® as well as most other analog simulators (such as CAzM).

6. A measurement section can be found at the end of each tutorial. The measurement data illustrated in these sections were obtained using the equipment listed. This specific equipment was needed so that the data could be collected in a form that would be easily inserted into the tutorial. Most undergraduate laboratories have equipment that is functionally similar to that used in collecting the sample data, and therefore should yield similar measurement results.

BIBLIOGRAPHY

***Note by Author*:** The following list of books and journal papers represents but a very small fraction of the extensive literature available on the subject of analog CMOS design, and so by no means is it meant to be exhaustive. This list below contains published material that I have found useful for teaching undergraduate students the fundamentals of analog CMOS VLSI design.

Allen, P., and D. Holberg, *CMOS Analog Circuit Design*, Holt, Rinehart and Winston, Fort Worth, TX, 1987.

Geiger, R., P. Allen and N. Strader, *VLSI Design Techniques for Analog and Digital Circuits*, McGraw-Hill Publishing Co., New York, 1990.

Gray, P. and R. Meyer, *Analysis and Design of Analog Integrated Circuits,* John Wiley and Sons, Inc., New York, 1993 (more geared toward graduate classes, but contains a wealth of information for design of analog integrated circuits).

Gray, P. and R. Meyer, "MOS Operational Amplifier Design-A Tutorial Overview", IEEE J. Solid-State Circuits, vol. SC-17(6), pp. 969-982, Dec., 1982.

Haskard, M. and I. May, *Analog VLSI Design: nMOS and CMOS*, Prentice Hall, New York, 1988.

Shoji, M., *CMOS Digital Circuit Technology,* Prentice Hall, Inc., Englewood Cliffs, NJ., 1988.

Tuinenga, P. *SPICE: A Guide to Circuit Simulation and Analysis using PSpice®*, Prentice-Hall, Inc., Englewood Cliffs, NJ., 1988.

Weste, N., and K. Eshraghian, *Principles of CMOS VLSI Design*, Addison-Wesley, Reading, MA, p.47, 1988.

A more advanced source of analog CMOS VLSI circuit design concepts that is widely referenced in the research literature:

Gray, P, D. Hodges, R. Brodersen, *Analog MOS Integrated Circuits*, IEEE Press, New York, 1980.

Pin Assignment for Chip Set

PIN	*FUNCTION*
1	Gain Controlled Amplifier Output
2	Adjustable Current Mirror Output
3	Non Adjustable Current Mirror Output
4	Switched Capacitor Filter 2 Output
5	NC
6	Switched Capacitor Filter 2 Clock
7	Switched Capacitor Filter 2 Input
8	Inverting Amplifier 3 Output
9	Inverting Amplifier 3 Input
10	GROUND
11	Inverting Amplifier 2 Output
12	Inverting Amplifier 2 Input
13	Inverting Amplifier 1 Output
14	Inverting Amplifier 1 Input
15	NC
16	Control Line
17	Switched Capacitor Filter 1 Output
18	Switched Capacitor Filter 1 Input
19	Switched Capacitor Filter 1 Clock
20	Operational Amplifier 1 Output
21	Operational Amplifier 1 Noninverting Input
22	Operational Amplifier 1 Inverting Input
23	Operational Amplifier 2 Noninverting Input
24	Operational Amplifier 2 Inverting Input
25	NC
26	Ring Oscillator Output
27	Ring Oscillator Frequency Adjust
28	NC
29	Operational Amplifier 2 Output
30	VDD (+5 volts)
31	DAC Clock Input
32	DAC 1 Output
33	DAC 2 Output
34	DAC a0 Input (LSB)
35	NC
36	DAC a1 Input
37	DAC a2 Input
38	DAC a3 Input (MSB)
39	Gain Controlled Amplifier Clock
40	Gain Controlled Amplifier Input