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Using Transistor Roles in Teaching CMOS Integrated Circuits

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Abstract: - CMOS integrated circuit analysis and design is a fast paced field which deals with many advanced technologies and a difficult skill for many students in a comprehensive first course in Microelectronics. New methods and techniques to help novices learn are needed. In this paper the transistor role concept is used and common individual CMOS transistor roles are identified. Typical circuit and block symbols have been used and some new symbols are defined. Roles of transistors capture expert electronics engineers tacit knowledge in a way that can be explicitly taught to students; therefore, roles should be taught to students in order to distinguish different transistor configurations in an integrated circuit. The use of roles and role-based circuit analysis and design is also expected to facilitate the teaching of circuit analysis and synthesis.

Key-Words: - CMOS transistors, CMOS circuits, MOS amplifiers, transistor roles, Microelectronics, Macroelectronics, teaching, engineering education.

1 Introduction

Education in the discipline of Microelectronics requires an adequate combination of strategies such as teaching methods, learning approaches and course design and assessment, in order to achieve better learning results. The Accreditation Board for Engineering and Technology (ABET) Criteria has transformed engineering education into a continuous improvement process [1]. Most studies report effects of curriculum design and new ways of presenting teaching material, while the introduction of new concepts has been far more rare. Conventional approaches to teaching electronics emphasize rather on devices instead of subsystems. An alternative approach in Electronics education termed ‘Macro-Electronics’ [2],[3] shifts the focus from individual devices and elements to the system level. Towards this direction we have recently introduced the concept of ‘Transistor Roles’ and we have identified the most common roles of bipolar transistor configurations in analog integrated circuits [4].

As CMOS integrated technology has dominated analog, digital and mixed-signal electronic systems, undergraduate courses (ought to) place greater emphasis on CMOS transistors. In a CMOS integrated circuit the transistors are used in standard configurations which occur over and over again [5],[6]. For instance:

- Some transistors are used as switches. The requirements for switches are: a very high off resistance, a relatively low on resistance and the absence of offset when they turned on;
- Some transistors are used as amplifiers, in one of the main circuit topologies: common source, common drain or common gate. There are even special amplifier topologies with two or more MOS transistors, such as complementary transistor pairs;
- Others offer a subsidiary role to other devices; for instance, they act like diodes, active loads of other transistors or variable resistors with reasonable range of linearity in certain applications.
- Others are used to implement ideal circuits such as constant-current sources.

When a student faces a complex circuit, he/she has to spend a lot of time in order to realize how each transistor works (the *role* of each transistor in the circuit). Also, during synthesis, a student needs to first capture the circuit in concept and then enter into details; otherwise he/she risks getting lost into the details. The correct top-down process would be to synthesize the circuit using block diagrams and then get into the details. This process would be simplified if a standard library were available with he most common building blocks, such as amplifier circuits, differential pairs, sources etc.

Therefore, the purpose of this work is to:

1. Identify common MOS transistor circuits which are used as building blocks of complex systems such as Op Amps, comparators, voltage regulators, ADCs, DACs, gates, analog multipliers, phase-locked loops etc.
2. Define most common *roles* of single MOS transistor circuits.
3. Recap available symbols for common transistor circuits and define new symbols where not available.

Once these CMOS transistor roles are defined, they may be used for educational purposes:

- In circuit analysis, to make students able to decode the function of a transistor topology in a complex circuit.
- In circuit synthesis, to make students able to build large circuits in block diagrams before getting into details, following a top-down design approach.

This paper is structured as follows: In section 2 we present three representative multi-transistor CMOS-circuits often used in teaching Analog Integrated Circuits: an *operational amplifier*, a *comparator* and *a switched capacitor integrator*. These widely used circuits in mixed analog-digital designs are used to identify common MOS-transistor roles. We also deal with circuit symbols in this section. In section 3 we show how a multi-transistor circuit may be redrawn using the predefined role-symbols to make circuit analysis easier; we also show how the proposed symbol library may be used to synthesize a complex CMOS circuit in a block diagram. Finally, section 4 presents our conclusions and future work.

2 Identifying CMOS transistor roles

CMOS Op Amps and comparators are the most important building blocks of an analog, digital or mixed-signal electronic circuit, and therefore, provide good examples of how simple MOS-circuits [7] are combined to perform a complex system [8],[9]. In Fig. 1 we can see the internal circuitry of a CMOS operational amplifier [10] with 16 MOS-transistors in different roles. In Table 1 we identify these roles and we present a standard symbol where available; where there was no symbol available, we have defined and proposed our own. Table 1 gives also an informal definition for each role, suitable for teaching. We note that a single MOSFET may change role when combined with others in a different configuration.

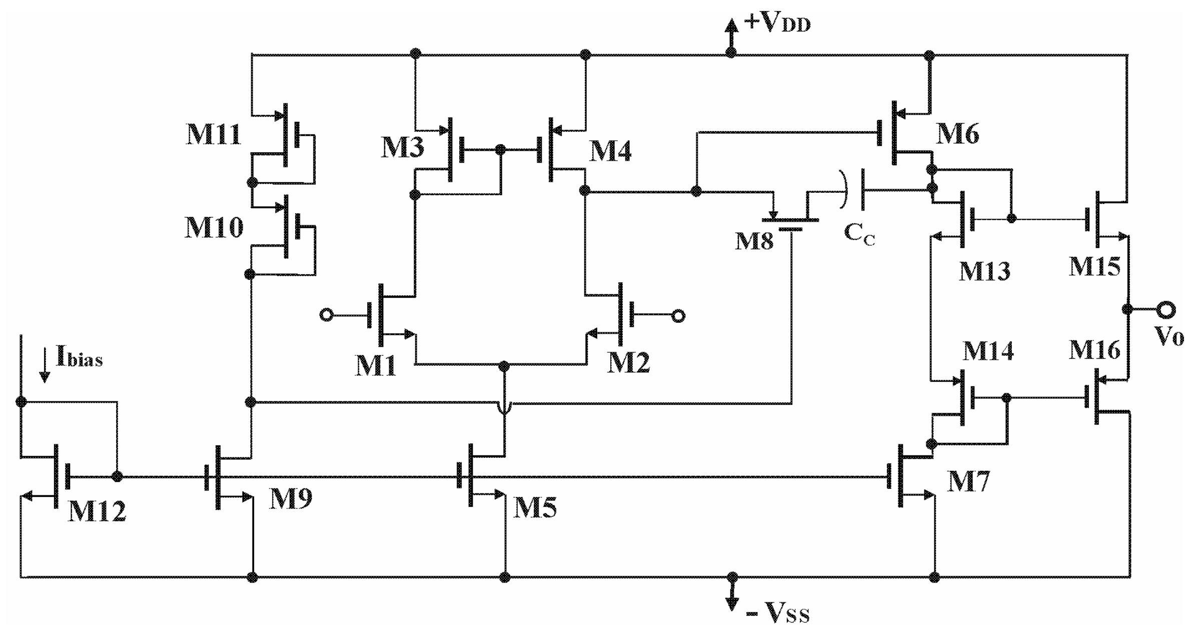


Fig.1: Complete schematic of a CMOS Op Amp with 16 transistors in various roles

Table 1: Transistor roles in the CMOS Op Amp of Fig. 1

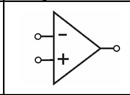
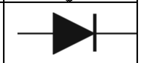
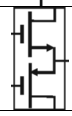
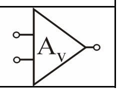
Transistors	Role	Informal description	Symbol
M1-M2	Differential pair	Differential amplifier (Source coupled pair)	
M7, M3-M4	Active load	Source's or Drain's effective load (transistor connected as diode or current mirror load)	
M10,M11,M12 M13,M14	MOS diode	MOS-Transistor with gate short-circuited to drain	
M5, M9-M12	Constant-current source	MOS Current mirror or single MOS as voltage controlled current (sink or source)	
M15-M16	Complementary pair	Series connected gate-source junctions of two transistors or puss-pull configuration	
M8	Active resistor	'Floating' resistor using a single MOS transistor in non-saturated region (voltage controlled resistor)	
M6	Voltage gain amplifier	Common-source amplifier	

Figure 2 shows a typical open loop CMOS comparator (MC 14575) [11]. A comparator is a circuit which compares two analog signals and outputs a binary signal based on the comparison. It consists of ten MOS-transistors in various configurations. The open loop design uses a high-gain differential amplifier and results in a circuit with very low propagation time delay. In Table 2 we identify the roles of these transistors, we present an informal definition for each role and draw the corresponding symbol. The first five transistor roles have already been defined for the CMOS Op Amp circuit of Fig.1; the additional role of the *CMOS inverter* is defined.

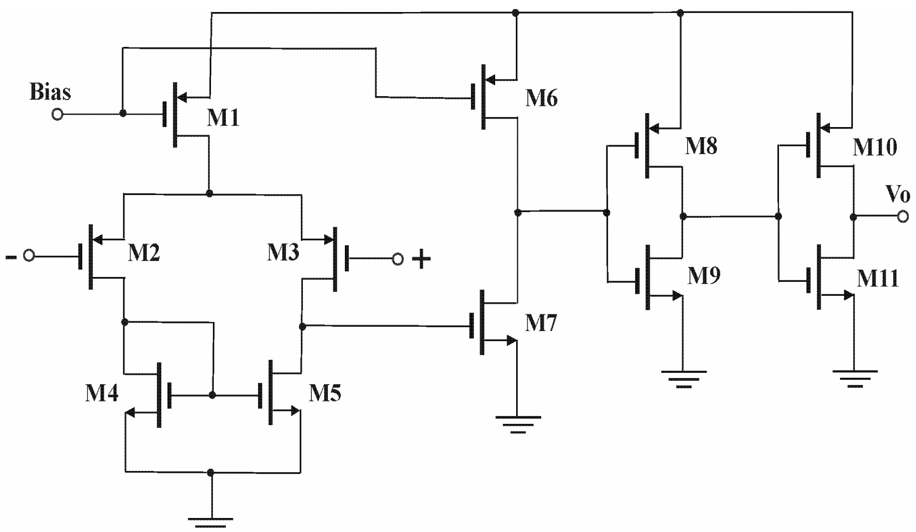


Fig. 2: Complete schematic of a CMOS open loop comparator with 10 transistors in various roles

Table 2: Transistor roles in the CMOS open loop comparator of Fig.2

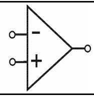
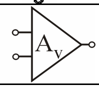
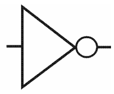
Transistors	Role	Informal Description	Symbol
M1	Constant-current source	MOS Current mirror or single MOS as voltage controlled current (sink or source)	
M2-M3	Differential pair	Differential amplifier (Source coupled pair)	
M4	MOS Diode	MOS-Transistor with gate short-circuited to drain	
M6, M4-M5	Active load	Source's or Drain's effective load (transistor connected as diode or current mirror load)	
M7	Voltage gain amplifier	Common-source amplifier	
M8-M9 M10-M11	CMOS inverter	Complementary pair with both gates connected together and to the input and both drains connected together and to the output	

Figure 3 presents a CMOS switched capacitor integrator [12]. CMOS integrators are used in analog to digital converters, switched capacitor filters and sigma-delta modulators [13]. Table 3 shows two new transistor roles, not defined in the preceding circuits: *the MOS switch* and the *transmission gate*.

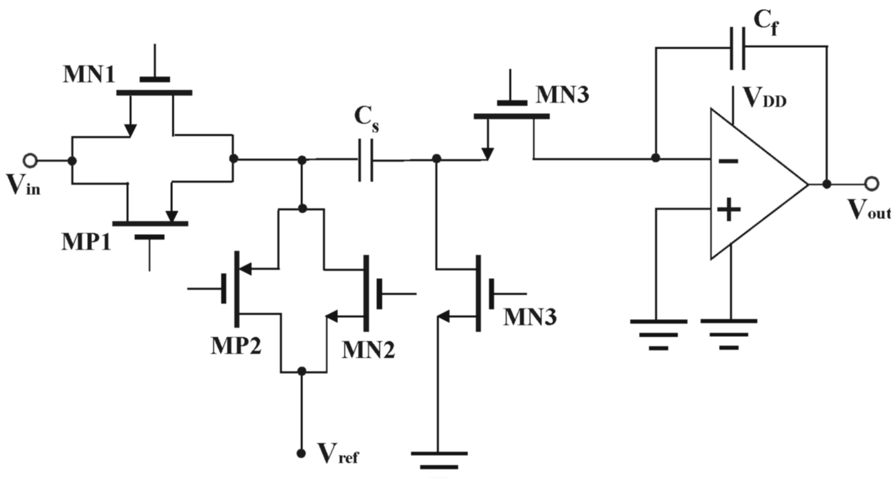
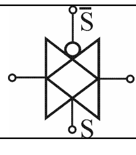
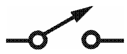


Fig. 3: Complete schematic of a MOS switched-capacitor integrator

Table 3: MOS transistor roles in the switched capacitor integrator of Fig. 3

Transistors	Role	Informal description	Symbol
MN1-MP1 MN2-MP2	Transmission gate	A switch constructing by connecting a p-channel and an n-channel enhancement-MOS in parallel. S is low in the 'on' state , S is low in the 'off' state	
M3-M4	MOS-switch	In the 'on' state the gate is grounded In the 'off' state a constant voltage is applied across the gate to source.	

3 Use of roles in schematic diagrams

In order to show how CMOS integrated circuits can be redrawn using the predefined role symbols, let us first consider the CMOS Op Amp of Fig. 1. Students find Op Amps to be conceptually obvious and are gratified when they discover that they can analyze or synthesize integrated Op Amp circuits. On the other hand, the functionality simplicity of Op Amps is exchanged for a collection of transistors which get combined into different topologies. Figure 4 shows a simplified schematic for the CMOS Op Amp of Fig. 1 taking into account the role symbols of Table 1. It is obvious that the circuit is minimized and its function is now more clear and evident.

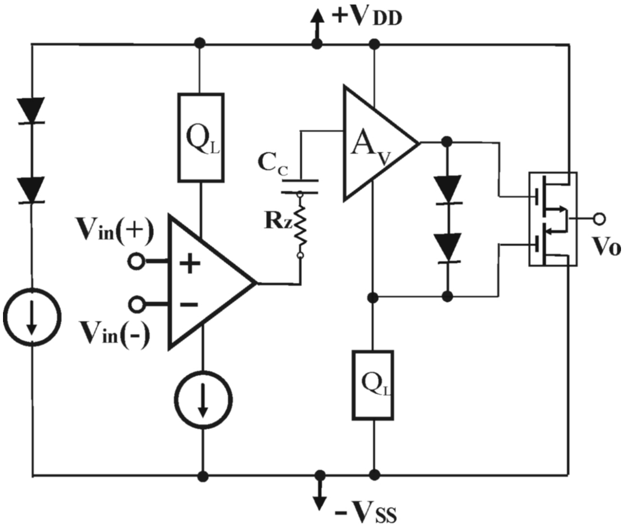


Fig. 4: Simplified schematic of the CMOS Op Amp of Fig.1 using the role symbols

In a lower level of complexity, the Op Amp is a combination of three stages: a *differential input stage*, a middle *high-gain stage* and an output *push-pull (source follower) stage*. In order to avoid level shifting the DC-bias point for the gate of transistor M6, the input transistor of the middle stage needed to be a PMOS transistor with an NMOS active load. The internal capacitor C_c provides feedback frequency compensation and the active resistor R_z (transistor M8) provides a 'nulling' resistance to reduce the effect of that right hand plane zero in the transfer function, and thus, to improve the frequency response of the amplifier. The output stage is a power amplifier class AB since the presence of the series MOS-diodes eliminates much of the crossover distortion inherent to push-pull output stage.

Figure 5 shows a simplified schematic for the CMOS comparator using the predefined transistor role-symbols. The open loop comparator is a combination of a differential input stage, a second gain stage and a pair of inverters. The inverter pair of M8-M9 and M10-M11 are for the purpose of providing an output capability and minimizing the propagation delay.

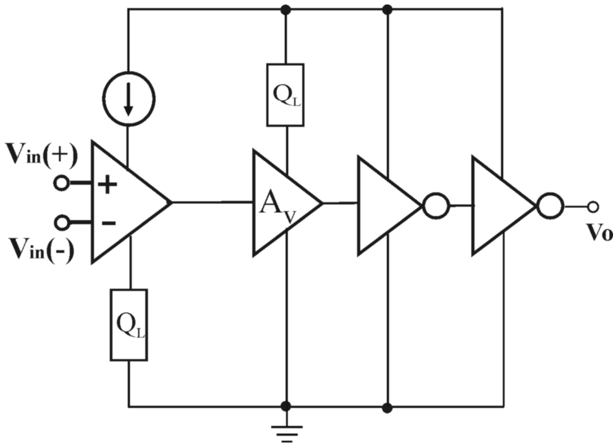


Fig. 5: Simplified schematic of the CMOS comparator of Fig. 2 using the role symbols

Finally, a simplified schematic for the CMOS integrator of Fig. 3 is shown in Fig. 6, where two MOS-switches and two CMOS-switches (transmission gates) have been redrawn using their symbols. Transmission gates produce a strong output voltage level, no matter how strong the input signal is. The main advantage of the transmission gate over the MOS switch is that the dynamic analog signal range in the 'on' state is drastically increased [14].

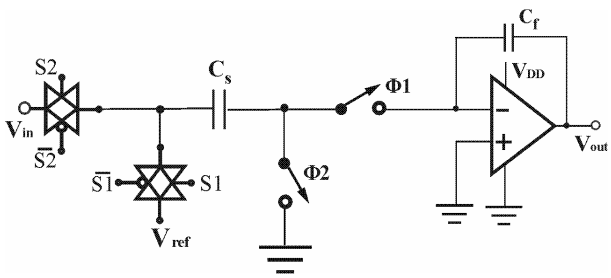


Fig. 6: Simplified schematic of the CMOS switched integrator of Fig. 3 using the role symbols

It is obvious that the above schematic diagrams make the qualitative description of the initial complex circuit easier and help students gain a better understanding of the whole system.

4 Conclusion and future work

In this work we have used the concept of transistor roles defined in [4] in order to identify the most common transistor roles in CMOS integrated circuits. A *transistor role* is introduced by giving its informal definition together with an appropriate role symbol and additional examples of use. Using transistor roles we may redraw complex circuits in terms of a few, well understood blocks, in order to facilitate teaching CMOS circuits. The advantage of this approach in circuit analysis is that the students will be able to easily decode the function of a transistor topology in a complex circuit and draw a much simpler block diagram; also, in circuit synthesis, students will be able to build large circuits in block diagrams before getting into details, following a top-down design approach.

After an intensive study of various CMOS integrated circuits, we have found out that most circuits can be described in terms of the following eleven roles: *differential pair*, *active load*, *MOS diode*, *active resistor*, *constant-current source*, *complementary pair*, *voltage gain amplifier*, *inverter*, *source follower*, *MOS switch*, *transmission gate*. The *cascade transistor pair* is not defined as a new role, because its basic function is equivalent to the function of a transistor. It should be noted here that roles are *not* a collection of *additional* concepts which enlarges the amount of material to be learned; analysis becomes easier when the role of each transistor is identified in a given transistor configuration; synthesis on the other hand becomes easier when we use standard, well understood blocks to build complex circuits using a top-down approach.

It is obvious that a similar teaching approach may be followed with BiCMOS and MESFET composite transistors. BiCMOS technologies combine most advantages of both CMOS and bipolar technologies at the expense of higher manufacturing cost due to required extra processing steps. MESFET semiconductor technology is used mainly in the case of very high speed circuits.

One of our future efforts will be the standardization of the role library. Once this is done, it is clear that this library may be included in a graphical tool for CMOS transistor level analog design software [15]. Another issue is to accomplish the role concept of transistor configu-rations from a *signal-flow* point of view, i.e., to find the corresponding transfer function or input/output relationship for each role. It is our aim to *measure* the effectiveness of roles in teaching. We have to carry out an educational research and compare our approach to the conventional methods of teaching CMOS integrating circuits in the undergraduate level.

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