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Comparative Study Between BJT and MOSFET Implementation of Current-Source Loads Voltage Amplifiers

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Abstract **– This paper presents a comparative study between common-emitter and common-source voltage amplifiers for two types of loads: passive loads and current-source loads. Although BJT and MOSFET have different device equations, some surprising similarities can be highlighted in terms of voltage gain expressions. Actually, in the end it is shown that voltage gain can be calculated using only one relation for both types of transistors and both types of loads.**

Keywords – common-emitter amplifier, common-source amplifier, passive loads, current-source loads, analog electronics, similarity between BJT and MOSFET voltage amplifiers, comparative study, a unified relation for gain calculation .

I. INTRODUCTION

This paper presents a comparative study between passive loads and current-source loads for two configurations of voltage amplifiers: common-emitter (CE stage) and common-source (CS stage). Because the active element is different it is normal to expect different results in terms of gain relations [1], [2], [3] but, in the end, it can be shown that there are some surprising similarities. These similarities are very useful for students in order to speed up the learning process.

At the end of this study, it is highlighted that voltage gain can be expressed as a ratio between equivalent Early voltage and Thermal Voltage (in the case of BJT amplifiers) or a ratio between equivalent Early voltage and half of overdrive voltage (in the case of MOSFET amplifiers).

II. COMMON-EMITTER AMPLIFIERS

This section presents the main characteristics of common-emitter amplifier (CE) implemented with both types of loads: passive load and active load respectively.

A. *Common-Emitter Amplifier with Passive Load*

A typical topology of common-emitter (CE) stage with passive load is presented in Figure 1.

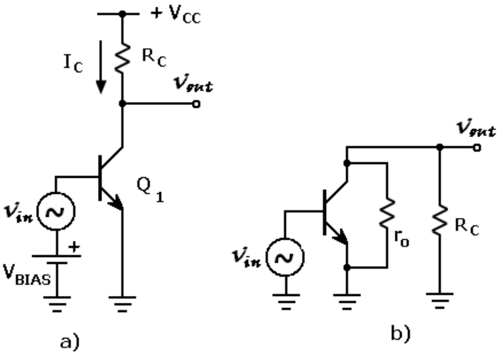

Figure 1. Common emitter stage with passive load [4]

The voltage gain calculated in the absence of external load is given by relation (1):

$$a_{vo} = -g_m R_L = -g_m (r_o \| R_C) . \quad (1)$$

where:

- $g_m = \dfrac{\partial I_C}{\partial V_{BE}} = \dfrac{I_C}{V_T}$ represents the transconductance of the active element Q_1;
- V_T represents the thermal voltage;

In many practical situations of this type of amplifiers, the internal resistance of the transistor is much greater than internal load, ($r_o >> R_C$), therefore the voltage gain can be approximated with relation (2):

$$a_{vo} \cong -g_m R_C = \frac{I_C}{V_T} R_C . \quad (2)$$

Taking into account that the product of I_C and R_C cannot exceed the power supply, V_{CC}, is very important to note that the maximal gain for passive load CE stage cannot exceed an upper barrier given by relation (3), no matter what we try to do.

$$a_{v\,max} \cong \frac{V_{CC}}{V_T} . \quad (3)$$

From the last relation it can be seen that maximal expected gain has no way to exceed $1/V_T \cong 38,46$V/V for each volt of the power supply. For instance, if V_{CC}=5V, the gain cannot be greater than 38,46×5=192,3V/V. Note that, in practice, this value cannot be reached because is calculated in ideal conditions (no external load and ideal transistor).

From relations (2) and (3) it can be seen some drawbacks of this topology: (1) the voltage gain is highly dependent of the supply voltage V_{CC} and has relative low values; (2) the voltage gain is also dependent of bias current I_C. Therefore, this type of amplifier is not used inside integrated circuits.

B. *Common-Emitter Amplifier with Current-Source Load*

By replacing internal load R_C with a current source in the previous diagram it can be obtained a typical topology of CE stage with active load (see Figure 2).

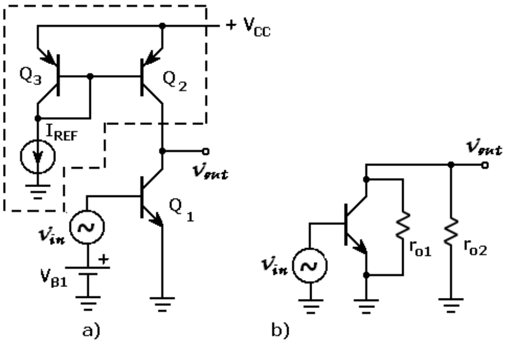

Figure 2. Common-Emitter amplifier with active load (current mirror implemented with Q_2 and Q_3)

For this configuration, under no external load assumption, the voltage gain is calculated using following relations (4):

$$\left.\begin{aligned} a_{vo} &= -g_{m1}R_L = -g_{m1}(r_{o1}\|r_{o2}) \\ R_L &= r_{o1}\|r_{o2} = \frac{r_{o1}r_{o2}}{r_{o1}+r_{o2}} \\ r_{o1} &= \frac{V_{AN}}{I_C};\quad r_{o2} = \frac{V_{AP}}{I_C}; \end{aligned}\right\} \Rightarrow$$

$$a_{vo} = -g_{m1}\frac{V_{AN}\cdot V_{AP}}{(V_{AN}+V_{AP})I_c}. \tag{4}$$

Replacing the transconductance as a function of I_C and V_T, the voltage gain can be rewritten as in relation (5):

$$\left.\begin{aligned} a_{vo} &= -g_{m1}\frac{V_{AN}V_{AP}}{(V_{AN}+V_{AP})I_c} \\ g_{m1} &= \frac{I_C}{V_T} \end{aligned}\right\} \Rightarrow$$

$$a_{vo} = -\frac{V_{AN}\cdot V_{AP}}{(V_{AN}+V_{AP})}\frac{1}{V_T}. \tag{5}$$

In [1], [2], [3] it is shown that the cumulative effect of internal resistances or transistors Q_1 and Q_2 can be modeled using an equivalent Early voltage given by relation (6):

$$V_{Aeq} = \frac{V_{AN}\cdot V_{AP}\cdot}{V_{AN}+V_{AP}}. \tag{6}$$

Using this concept of equivalent Early voltage, the voltage gain from relation (5) can be rewritten as follows:

$$a_{vo} = -\frac{V_{AN}\cdot V_{AP}}{(V_{AN}+V_{AP})}\frac{1}{V_T} = -\frac{V_{Aeq}}{V_T} \tag{7}$$

Note that the last expression of the gain is similar to relation (3), the only difference being that the voltage supply V_{CC} is replaced with the equivalent Early voltage, V_{Aeq}.

From relation (7) it can be seen at least two main advantages of this topology:

- The voltage gain is very high (because V_{Aeq} is much greater than V_{CC}) and no longer depends on how large the power supply voltage is;
- The voltage gain no longer depends on the bias current I_C.

Therefore this topology is very attractive for analog IC because it can be used for low voltage and very low bias currents. The typical gain for this type of amplifier can reach 1500V/V at very low current of 5µA. However, this stage has two drawbacks: it requires very accurate biasing point; the voltage gain drops dramatically when amplifier being loaded with low resistance external loads.

III. COMMON-SOURCE AMPLIFIERS

This section presents the main characteristics of common-source amplifiers (CS) implemented with both type of loads: passive and active load respectively.

A. *Common-Source Amplifier with Passive Load*

A typical topology of the CS stage with passive load is presented in Figure 3.

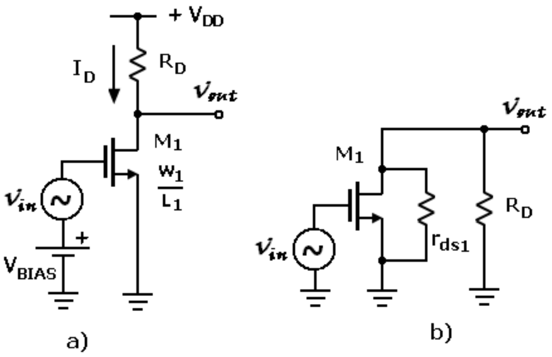

Figure 3. Common-source amplifier with passive load [4]

The voltage gain in absence of external load can be determined with relation (8), [4]:

$$a_{vo} = -g_m R_L = -g_m \left(r_{ds} \| R_D \right). \qquad (8)$$

where:

- $g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{I_D}{0.5 \cdot V_{OV}}$ represents the transconductance of the active element M_1;
- V_{OV} represents the overdrive voltage of the active element M_1 at a bias current I_D;

For this type of amplifier, the condition $r_{ds} >> R_D$ is met in many cases and therefore voltage gain can be rewritten as in relation (9)

$$a_{vo} \cong -g_m R_D = -\frac{I_D}{0.5 \cdot V_{OV}} R_D. \qquad (9)$$

Taking into account that the product of I_D and R_D cannot exceed the supply voltage, V_{DD}, is very important to note that the maximal gain for passive load CS stage cannot exceed the value given by relation (10), [4], no matter what we are trying to do.

$$a_{v\ max} \cong \frac{V_{DD}}{0.5 \cdot V_{OV}}. \qquad (10)$$

The last relation highlights some drawbacks of these amplifiers: (1) the voltage gain is highly dependent of the supply voltage V_{DD} and has low values; (2) the voltage gain is also dependent of the bias current I_D via the overdrive voltage. Therefore, these amplifiers are not used inside integrated circuits.

Note that relation (10) is similar with relation (3), but the differences are: the voltage supply is renamed and the thermal voltage V_T is replaced by half of the overdrive voltage.

B. Common-Source Amplifier with Current-Source Load

A typical topology of CS stage with active load is obtained from previous schematic by replacing the R_D with a current source as presented in Figure 4.

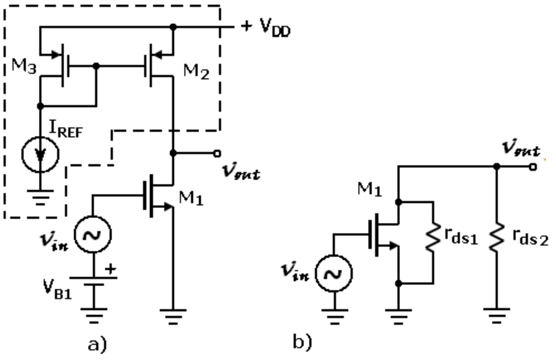

Figure 4. Common-source amplifier with active load (current mirror implemented with M_2 and M_3)

For this configuration, with no external load connected, the voltage gain is estimated using next relations (11), [4]:

$$\left.\begin{aligned} a_{vo} &= -g_{m1} R_L = -g_{m1} \left(r_{ds1} \| r_{ds2} \right) \\ R_L &= r_{ds1} \| r_{ds2} = \frac{r_{ds1} r_{ds2}}{r_{ds1} + r_{ds2}} \\ r_{ds1} &= \frac{1}{\lambda_N I_D};\quad r_{ds2} = \frac{1}{\lambda_P I_D}; \end{aligned}\right\} \Rightarrow$$

$$a_{vo} = -g_{m1} \frac{1}{\left(\lambda_N + \lambda_P \right) I_D}. \qquad (11)$$

Replacing the transconductance as a function of I_D and V_{OV}, the voltage gain can be rewritten as in relation (12):

$$\left.\begin{aligned} a_{vo} &= -g_{m1} \frac{1}{\left(\lambda_N + \lambda_P \right) I_D} \\ g_{m1} &= \frac{I_D}{0.5 \cdot V_{OV1}} \end{aligned}\right\} \Rightarrow$$

$$a_{vo} = -\frac{1}{0.5 \cdot V_{OV1}} \frac{1}{\left(\lambda_N + \lambda_P \right)}. \qquad (12)$$

In [1], [2], [3] it is shown that the cumulative effect of internal resistances or transistors M_1 and M_2 can be modeled using an equivalent Early voltage given by relation (13):

$$V_{Aeq} = \frac{V_{AN} \cdot V_{AP} \cdot}{V_{AN} + V_{AP}} = \frac{1}{\lambda_N + \lambda_P}. \qquad (13)$$

Using this concept of equivalent Early voltage, the voltage gain given by relation (12) can be rewritten as follow [4]:

$$a_{vo} = -\frac{1}{0.5 \cdot V_{OV1}} \frac{1}{\left(\lambda_N + \lambda_P \right)} = -\frac{V_{Aeq}}{0.5 \cdot V_{OV1}} \qquad (14)$$

Note that the last expression of the gain is similar to relation (10), the only difference being that the voltage supply V_{DD} is replaced by equivalent Early voltage, V_{Aeq}.

Relation (14) highlights the main advantage of these amplifiers: the voltage gain is no longer dependent of the supply voltage V_{DD} and has better values. Therefore, these amplifiers can be used for low voltage supply and they are widely used inside integrated circuits.

IV. COMPARATIVE ANALYSIS

Although the functional equations of MOSFET transistor and BJT transistor are quite different, a careful analysis of common-emitter and common-source stages shows surprising similarities, especially in the particular case where current-sources are used as loads. All these similarities are highlighted in table 1.

The most important observations are:

- The thermal voltage V_T, from any relation written for BJT amplifiers can be replaced by half of the overdrive voltage $0.5V_{OV}$, in order to obtain valid and similar relations for MOSFET amplifiers;
- The maximal voltage gain for passive load amplifiers can be expressed as a ratio between two voltages: a) the voltage supply V_{CC} and V_T for BJT; b) the voltage supply V_{DD} and $0.5V_{OV}$ for MOSFET;
- The voltage gain for current-source load amplifiers is also a ratio between two voltages: a) the equivalent Early voltage and V_T for BJT; b) the equivalent Early voltage and $0.5V_{OV}$ for MOSFET;
- The equivalent Early voltage has the same expression for both CS and CE stages;

Parameters Name	BJT	MOSFET	Observations
Transconductance	$g_m = \frac{I_C}{V_T}$	$g_m = \frac{I_D}{0.5 \cdot V_{OV}}$	- V_T is replaced by $0.5V_{OV}$; - I_C is replaced with I_D , but is only a notation, the meaning is the same;
Equivalent Early voltage (amplifiers with current-source loads)	$V_{Aeq} = \frac{V_{AN} \cdot V_{AP} \cdot}{V_{AN} + V_{AP}}$	$V_{Aeq} = \frac{V_{AN} \cdot V_{AP} \cdot}{V_{AN} + V_{AP}}$ $V_{Aeq} = \frac{1}{\lambda_N + \lambda_P}$	- V_{Aeq} has the same expression for both amplifiers with current-source loads ; - For MOSFET common-source stage, Equivalent Early voltage can be also calculated using λ parameters;
Maximal voltage gain for resistive loads (amplifiers with passive loads)	$a_{v\,max} \cong \frac{V_{CC}}{V_T}$	$a_{v\,max} \cong \frac{V_{DD}}{0.5 \cdot V_{OV}}$	- V_T is replaced by $0.5V_{OV}$; - V_{CC} is replaced with V_{DD} , but is only a notation, the meaning is the same;
Voltage gain for current-source loads (amplifiers with current-source loads)	$a_{vo} = -\frac{V_{Aeq}}{V_T}$	$a_{vo} = -\frac{V_{Aeq}}{0.5 \cdot V_{OV1}}$	- V_T is replaced by $0.5V_{OV}$; - Voltage supply (V_{CC} or V_{DD}) from passive load configuration (see previous row) is replaced by equivalent Early voltage V_{Aeq}; - V_T is replaced by $0.5V_{OV}$;

In fact the most interesting aspect of this study is that the gain can be calculated using the same relation for any type of load or active transistor.

V. CONCLUSION

This paper presented a series of surprising similarities between CS and CE stages found by the author over time. Among them two are noteworthy: (1) the thermal voltage V_T and half of the overdrive voltage $0.5V_{OV}$ fulfill similar roles; (2) in absence of external load the voltage gain can be determined using the same relation for both types of loads (active or passive) and both types of transistors (BJT or MOSFET).

The voltage gain is the ratio between the equivalent Early voltage and the thermal voltage or a ratio between the equivalent Early voltage and half of the overdrive voltage. A small trick must be made in the case of passive loads (Figure 1 or Figure 3): here V_{Aeq} is calculated using the same relation (6) but instead of V_{AP} is mandatory to use static voltage across the internal load resistance R_C or R_D.

From the educational point of view all these conclusions are very useful in order to speed up the learning process.

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