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Power Amplifier Output Stage: BJT vs. FET

The bipolar junction transistor (BJT) was invented by Bell Labs in the late 1940's and quickly led to the electronics revolution of the 1950's and 60's. The field-effect transistor (FET) was developed shortly after the BJT, and became practical as an alternative in the early 1970's. The commercial availability of the FET soon brought about a further expansion of the electronics revolution by utilizing their small size, high speed and high efficiency, enabling the full scale integration of complex logic arrays like those in computer microprocessors. (Neamen, [B3]) They are unanimously praised for their superior performance in low power digital circuits, but there is still great debate in some circles as to their superiority in high power analog circuits, specifically power amplifiers, and the debate has long been clouded with misinformation and half-truths promulgated not only by marketing executives, but in some cases by well-intentioned engineering professionals. (Self, [B1]), (Slone, [B2])

The FET offers some noteworthy improvements over the BJT, but despite their similarities, these devices remain fundamentally different in structure and behavior, and each possesses unique advantages and disadvantages that appeal to certain applications. The following report seeks to establish an honest evaluation of these two competing devices by reviewing literature from industry leaders and renowned amplifier designers to compare and contrast some of the defining characteristics of these extremely pervasive technologies.

In the industry of amplifier design, advocates of the FET output stage often point to its unrivaled simplicity of design and low parts-count, a direct consequence of the FET's unique field-effect operation. The FET is a purely voltage-controlled device that induces conduction through its output terminals with the electric field (voltage) applied to its Gate terminal, and has very high impedance such that its input current is virtually zero (neglecting input capacitance). (Neamen, [B3]) Since it draws no input current, an FET power amplifier output stage can be driven directly by the voltage output of the preceding voltage amplifier stage (VAS), coupled simply through small-valued Gate-stopping resistors to prevent an otherwise purely capacitive load from destabilizing the amplifier. (Slone, [B2])

High-power BJTs, on the other hand, can require input currents in excess of 500mA, far more than can be safely supplied by a typical low-power VAS. (Neamen, [B3]) Driving these devices directly from the VAS would cause disastrous large-signal distortion and may even set fire to the small-signal transistors, so BJT power stages are almost always preceded by at least one medium-power predriver stage capable of supplying the BJT input current. In addition to a predriver stage, BJTs also require multi-slope V-I limiting circuitry to prevent the high-power output conditions that can lead to secondary breakdown and thermal runaway. (Slone, [B2]) These are a destructive phenomenon where non-uniformities in junction current can form hot spots of decreasing resistance, initializing a positive feedback loop that further increases current and temperature until the junction may actually melt. (Neamen, [B3]) Adding a necessary V-I limiting protection circuit can easily triple the parts-count of the output stage.

Unlike BJTs which must be carefully monitored and confined to within their safe area of operation (SOA), FETs benefit enormously from a junctionless internal structure, consisting only of a thick channel of silicon buried beneath an insulated slab of semiconductor (Gate) that creates the electric field. The physical nature of the enhancement-mode FET is such that as current and temperature increase, the device's ON-resistance and threshold voltage actually increase along with it and can reduce channel current when the device is overdriven. Thus, the Power FET is naturally current limiting and the only threat of damage it faces is Gate-Source voltage breakdown, for which most devices have internal zener diode protection, and Drain-Source (channel) voltage breakdown, which is usually on the order of several hundred volts since the FET channel is junctionless. This inherent behavior of the FET has earned it a reputation of reliability, durability, and simplicity, since in the absence of predriver stages and protection circuitry, an FET output stage need only be composed of two complementary FETs and two Gate-stopping resistors. (Self, [B1]), (Slone, [B2])

Now the question remains: what then are the benefits of the BJT?

BJTs offer a number of benefits including low cost, very high gain, high linearity, high efficiency, a sharp conduction curve, low threshold voltage and low saturation voltage. The high gain is a fundamental characteristic of the forward-active diode structure, and the higher gain (compared to the FET) allows for more of the output to be fed back to the input as a negative feedback closed loop which very effectively linearizes an otherwise exponential conduction curve. However, there appears to be some confusion within the engineering community regarding the linearity qualification of BJTs versus FETs. The critically acclaimed British amplifier design guru, Douglas Self, demonstrates, in my view quite convincingly, that despite the claims made by some professionals that FETs are naturally more linear than BJTs, the truth is quite the opposite. (Self, [B1]) Self openly admits to his strong preference for BJT output stages, but G. Randy Slone, an equally well-respected author and engineer, argues adamantly in support of FET power stages but declares from the very beginning that BJTs are in fact significantly more linear. (Slone, [B2]) In an article published by Motorola entitled "Power MOSFETs versus Bipolar Transistors," Motorola Staff Engineer, Helge Granberg, appropriately confronts the issue:

> Some literature claims that MOS power FETs are inherently more linear than the bipolar transistors. This is only true up to the point where envelope distortion, caused by saturation, instabilities or other reasons, is not present. It is also a function of bias current (I_{DQ}). The FETs usually require higher idling currents than bipolars to get full advantage of their linearity. Bipolars are usually biased only to get the base-emitter junction into forward conduction. (Granberg, [B4])

In settling the issue of linearity, to which the BJT holds the crown, Granberg also touched on the differing efficiencies of the two transistors. There are a number of factors that lead to the FETs slightly lower efficiency, most notable among them is the relatively high quiescent "idle" current necessary to maintain low crossover distortion in the FET class AB output stage. This is due to the gradually increasing FET conduction curve indicating the sensitivity by which its output current responds to changes in Gate potential near the threshold value. FETs have much lower sensitivity to gate voltage changes so their class AB configuration must be biased pretty far into the channel's conduction zone to encourage a smooth transition between complementary devices near the crossover region. (Self, [B1]) Some FETs achieve optimum performance with idle bias currents as high 250mA. (Huebner, [B5]) This additional power consumption is the strongest reason for the typical FET having roughly five percent less efficiency than its BJT counterparts that require only a few tens of milliamps of idle current. (Slone, [B2])

It is widely accepted that the steep BJT conduction curve allows for their complementary output devices to switch ON and OFF quickly and almost seamlessly when their bias current is properly tuned. This smooth transition is critical to maintaining low crossover distortion and depends entirely on the precision of the fixed bias voltage applied by the VAS between the complementary inputs. Crossover distortion is one of the most audible and unpleasant amplifier distortions and is also one of the most common. It therefore receives a great deal of attention and the BJT's performance in this area is one of the strongest arguments for its continued support. (Slone, [B2])

G. Randy Slone, however, raises an interesting and seemingly valid concern. Their steep conduction curve makes BJTs especially sensitive to fluctuations in bias voltage, the finely tuned parameter that determines crossover distortion. It just so happens that one of the benefits of an FET device is its exceptional temperature stability, while BJT parameters are notorious for their temperature dependence. Slone agrees that BJTs are far superior at achieving an almost flawless crossover transition, but argues that their steep conduction curve, combined with the temperature dependence of their conduction threshold voltage, leads to an almost futile task of attempting to maintain the "flawless" crossover performance amid even subtle temperature changes. He notes:

> "… It is possible to obtain lower levels of crossover distortion with BJT outputs. But unless you like to fiddle with your amplifier on a regular basis, the optimum bias setting will probably drift to the point of exceeding FET crossover levels in a relatively short time." (Slone, [B2])

Clearly both the bipolar junction transistor (BJT) and field effect transistor (FET) provide the analog circuit designer with a rich blend of operational features and behavioral characteristics that can be fitted to any number of applications. Both transistors are obviously well suited for power amplification, and each device appears to have a considerable constituency of supporters who, for one reason or another, have established a preference and are content to stick with it. And with each transistor having uniquely appealing advantages, I expect to see more of the so-called "hybrid" amplifier designs popping up that offer the alluring possibility of having the best of both worlds.

Bibliography

[B1] Self, D., *Audio Power Amplifier Design Handbook*, 4h ed. Great Britain: Newnes, 2006, pp. 109-338.

[B2] Slone, G. R., *High-Power Audio Amplifier Construction Manual*, New York: McGraw-Hill, 1999, pp. 141-288.

[B3] Neamen, D. A., *Microelectronics: Circuit Analysis and Design*, 3d ed. New York: McGraw-Hill, 2007, pp. 119-574.

[B4] Granberg, H. O., "POWER MOSFETs versus BIPOLAR TRANSISTORS," Motorola Inc., Phoenix, AZ, RF Application Reports, 1993.

[B5] Huebner, T., "LM4702 Driving a MOSFET Output Stage," National Semiconductor Corporation, Application Note 1645, May 2007.

BJT advantages

- higher gain – higher linearity
  - very large and constant (flat) vs. temp, except at high power (betadroop) and very reactive
- Z_{in} is low and temp-dependent (diode junctions) → disadvantage
  - uneven VAS loading can cause LF distortion.
  - miller feedback linearizes the VAS at HF.
  - GNFB can correct LF VAS distortion (high gain)
- *sharp turn-ON curve (conduction curve is steep)
  - a finely tuned OPS can have very low crossover → distortion.
  - sensitivity to V_{be} can make this hard to obtain or maintain vs. temp.
- low $V_{CE}(sat)$ – good for low-voltage high-power applications
  - maximum output swing
- more efficient
  - low $V_{CE}(sat)$, low ON-resistance
- low V_{γ} threshold voltage
- lower bias current –
  needs very little I_Q to obtain low crossover distortion.

disadvantages

- betadroop – causes large-signal distortion during high power output.
- requires complicated predriver stage (high input current)
- thermal tracking – BJTs are very Temp-sensitive.
  - V_{bias} requires V_{be} multiplier circuit.
- 2^{nd} breakdown / thermal runaway
- lower bandwidth (especially in power BJTs) ← lower slewrate.
- requires ballast resistors
  - generates IM distortion at HF.
- minority carrier device → charge holding effect
  - switchoff distortion.
- less durable
  - diode junctions have lower breakdown voltage.
  - junctions are susceptable to thermal runaway
- difficult to parallel – must be closely matched b/c of V_{be} sensitivity.
- requires complex protection circuitry.
  - i-v slope limiters.

debates:

- crossover distortion: (support FET) Slone, ~~National Semi~~ neutral, (support BJT): Self.
- linearity: (support FET) Motorola (support BJT) Self, Slone,
- difficult to parallel.
  (FETs are better) Slone, Motorola, National Semi (BJTs are better): Self

FET advantages	disadvantages
• naturally current limiting – as I_D & Temp rise, V_{TN} rises, channel resistance rises. (no thermal runaway)	• less efficient – higher bias current, higher ON-resistance.
• durability – only damaged by overvoltage. – High channel breakdown voltage (no junctions), V_{gs} has internal protection (zeners) -(no 2nd breakdown)	• higher $V_{DS(sat)}$ – reduces OPS output swing.
• high Z_{in} – only input current is for capacitance. -Z_{in} is constant with temp.	• much lower gain – less NFB possible, reduced linearity.
• maintains gain during high power output – no betadroop	• large internal capacitance – not a problem if R_G is used.
• Fast – no switchoff distortion (no charge storage)	• high V_{TN} (threshold) – reduces voltage efficiency of VAS.
• wide bandwidth – good for switching amps – even RF.	• high cost – requires larger die than a similar BJT
• less sensitive to V_{bias} fluctuations – (square-law conduction) - simpler bias circuit, no thermal tracking.	★ may have greater crossover distortion.
• can be easily paralleled	
• can drive low-Z loads w/out LSD (beta droop)	
• simpler drive circuit & protection circuit - no predriver BJTs, no complicated i-v slope limiters.	
• no ballast resistors – reduces higher-order IMD - FETs can operate at RF.	