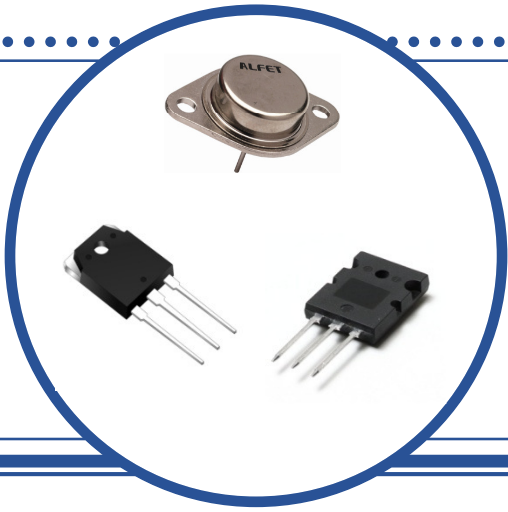
APPLICATION NOTE

AUDIO BIPOLAR TRANSISTOR PARAMETER CONSIDERATIONS



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Introduction

When comparing the parameters of bipolar junction transistors (BJTs) for audio power amplifier applications there are a number of key parameters that need to be carefully considered. In addition it is important to understand how these parameters are measured to determine both how the device will perform in a real world amplifier as well as judging devices against each other.

For audio applications the typical key parameters that are important are:

- Power rating (thermal resistance)
- Safe operating area (SOA)
- Current gain - h_{FE}
- Linearity
- Transition frequency - f_T

The purpose of this application note is to firstly understand these parameters and how they manifest themselves in an audio power amplifier but also to understand how they are specified on device datasheets

Safe Operating Area (SOA) and Power Rating

The amount of power that a transistor can deliver and handle in a class-AB power amplifier is determined by 2 main parameters: The P_{DISS} power rating and the safe operating area (SOA).

The power rating figure is directly linked to the thermal resistance of the device and the maximum allowable operating temperature. The following equation demonstrates this relationship:

$$\theta_{jc} = \frac{T_{j(\max)} - T_a}{P_{DISS}}$$

Where T_a is the ambient temperature and is assumed to be 25°C. Therefore, for a 150W transistor:

$$\theta_{jc} = \frac{150 - 25}{150} = 0.833^{O}C/W$$

This parameter tells us the heat transfer capabilities of the device in how much the junction temperature will rise in temperature when power is dissipated if it were perfectly mounted on an infinite heatsink. Obviously, in the real world, this figure has to be de-rated for practical heatsinks, etc. Unfortunately things are never as simple as this and there are a number of additional factors that need to be considered in our design. Firstly we need to understand the desired operating curve. With a purely resistive load this is quite straightforward but once we start allowing for an inductive load things start to look much worse.

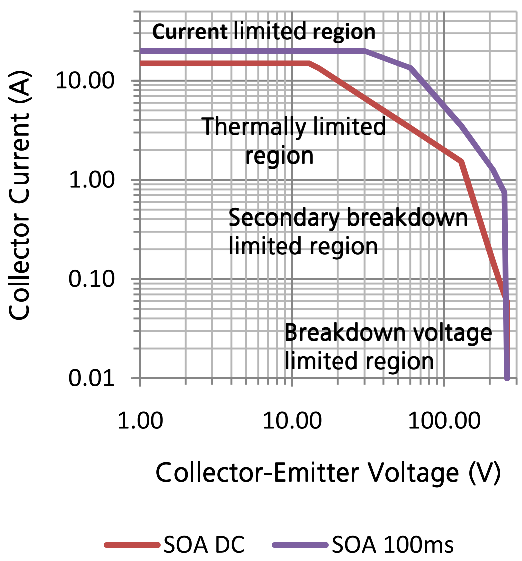

Fig. 1: Typical BJT Safe Operating Area (SOA) Curve - DC

There are 4 distinct regions to the safe operating area characteristic that need to be understood. Linear audio power amplifiers use a wide part of this area, particularly when driving inductive loads and it is important that devices stay within this area. Figure 1 shows a typical 200W BJT curve for SOA with DC operation (red) and 100ms pulsed conditions (purple).

Current Limited Region: In this area the continuous current is limited by the capability of the internal bond wires and it can be seen that the device will delivery higher current under pulsed operation.

Thermally (Power Limited Region): This region is at a slope equal to the devices power dissipation rating and represents the point at which the junction is at it's maximum temperature (usually 150°C) on an infinite heatsink with perfect thermal coupling. It can also be seen that for pulsed signals the device can effectively handle much more transient power in this region.

Secondary Breakdown Region: Power BJTs are subject to a failure mode called secondary breakdown, in which excessive current and normal imperfections in the silicon die cause portions of the silicon inside the device to become disproportionately hotter than the others. The doped silicon has a negative temperature coefficient, meaning that it conducts more current at higher temperatures. Thus, the hottest part of the die conducts the most current, causing its conductivity to increase, which then causes it to become progressively hotter again, until the device fails internally. The thermal runaway process associated with secondary breakdown, once triggered, occurs almost instantly and may catastrophically damage the transistor package. This region is perhaps the most significant for audio power amplifier designers as the power capability of the device is most severely limited and the potential consequences of exceeding the devices capabilities are most catastrophic and difficult to protect against. The capabilities of the device do improve under transient conditions but the mechanism can still occur under pulsed conditions. Semelab's bipolar audio transistors are particularly capable in this respect.

Breakdown Voltage limited region: This is where the BV_{CEO} point of the device is reached and very large currents will flow resulting in fast destruction of the device. This region must *always* be avoided and appropriate derating of power supply rails is important. In addition, inductive loads can elevate supply rails because of back EMF and clamp diodes from the output to the power supply rails are always recommended.

Typical Amplifier Operation Within the SOA & Device Number Selection

Understanding the areas to avoid are the first step to ensuring a design will be reliable but in high power designs where voltages are high and multiple parallel devices are employed there are a number of issues to consider. To decide how many devices are required for a given power output generally comes down to the regions of thermal limiting and secondary breakdown. Thermal limiting is a more difficult one to lay down hard and fast rules for as the area of the SOA curve will be derated depending on the heatsink thermal resistance, device insulator thermal resistance and the specified duty cycle of the audio signal. For information on heatsink selection guidelines please refer to Semelab application note: *Lateral Mosfet Design Recommendations For Audio Amplifiers.* This is important in device number selection to ensure that maximum junction temperature ratings are not exceeded prior to thermal protection and that the amplifier can deliver sustained power output without shutdown. The MG devices demonstrate extremely high power handling capabilities due to their low thermal resistance which mean that less devices can be used for a given power from this thermal aspect (or the same number of devices and a smaller heatsink).

Avoiding secondary breakdown is far more critical in real world designs to ensure a balance between reliability and a cost-effective number of output devices. This is because the BJT's power capability is reduced in this region as previously explained. Semelab's new range of MG bipolar power transistors are optimised for secondary breakdown characteristics which typically do not come into play until around 130V. Many of the industry standard audio power devices start exhibiting secondary breakdown at as low as 50V. Figure 2 shows the SOA for the Semelab MG6330 when compared to the industry standard 2SC5200 that is extensively used in audio applications.

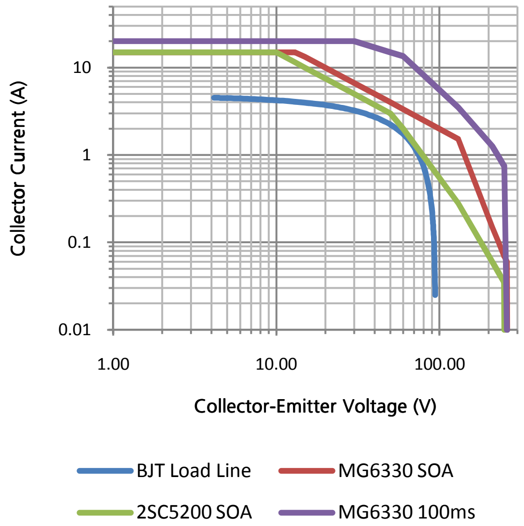

Fig. 2: Comparison of power devices with overlaid output device load line

Figure 2 shows the load line swinging across it's output range for a single device in an amplifier with +/- 100V rails and delivery around 1kW rms output power into a 4 ohm resistive load. This example has 5 devices in parallel where the device is driven to 4.5A pk.

We can quickly see that the current rating of the device is not significant in linear audio applications because it will always be greater in it's rating than we could use because of the other limiting factors It can be seen that with 2SC5200 devices we would be right on the limits of secondary breakdown whereas with the MG6330 we are comfortably inside. In addition the thermal resistance of the Semelab devices is 0.625 versus 0.833^{o}C/W – 25% lower. What this is intended to demonstrate is that devices that may *appear* to be of similar power and capabilities can perform radically differently in a real world audio amplifier when reviewing the characteristics in detail. Typically this means a reduction in output devices resulting in a solution that is smaller, lighter, more cost effective and potentially more reliable.

When performing this kind of SOA analysis it is also important to take worst case considerations into account. Therefore we should look at what happens with the restive load of the previous example replaced with a load that includes inductance and represents a real loudspeaker. Looking at the curve for a commercially available

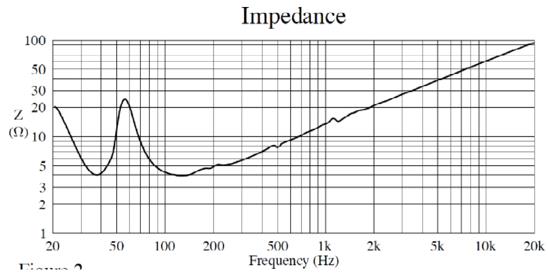

Fig. 3: Typical Professional Speaker Cabinet Impedance Curve

We can see that this 2 x 18" sub cabinet is clearly quite inductive and although nominally 4 ohms, the impedance does drop to 3.8 ohms. Looking at typical drive units we can see that a 6.5 Ohm and 4mH series inductance can be typical. If we ignore the resonance and look at a load with this impedance at 100Hz we get the following load curve:

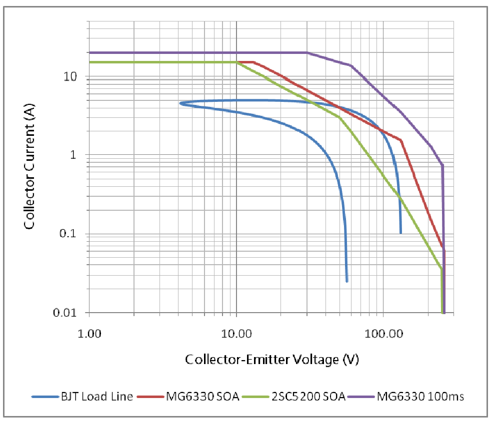

Fig. 4: Inductive load driven at 100Hz

This is still with our 5 pairs of output devices and we can clearly see that the 2SC5200 devices spend a large amount of time in the secondary breakdown. It is also interesting to note that although the MG6330 are clearly pushed beyond limits, they are not pushed into the secondary breakdown region. At 200Hz the situation looks like this:

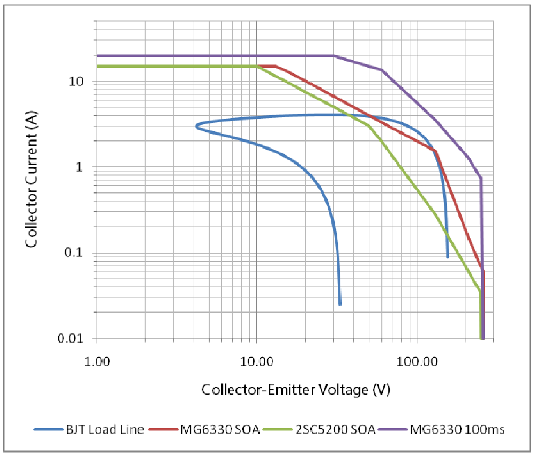

Fig. 5: Inductive load driven at 200Hz

The increased phase shift is further coming in to effect and although the peak current is lower the dissipation situation has become worse. Figure 6 shows the operation with 12 pairs of output devices. The 2SC5200 devices are still entering the secondary breakdown region but it must be remembered that these curves are for continuous dc operation and the curves do extend for pulsed operation. This can certainly be taken into account when considering the device count but bear in mind that a full output 20Hz audio signal represents a significant time and we therefore recommend not working outside the 100ms curve. This will allow for low frequency operation and any degradation of these parameters at elevated temperatures (all datasheet SOA curves are at a 25^{o}C junction temperature).

Once a minimum number of devices has been selected based on this SOA capability it is then important to look at the thermal analysis to ensure that the chosen number combined with the application heatsink will manage to keep the junctions temperatures within safe limits. It is better to analyse the thermal performance with dissipation curves and the thermal techniques that are outlined

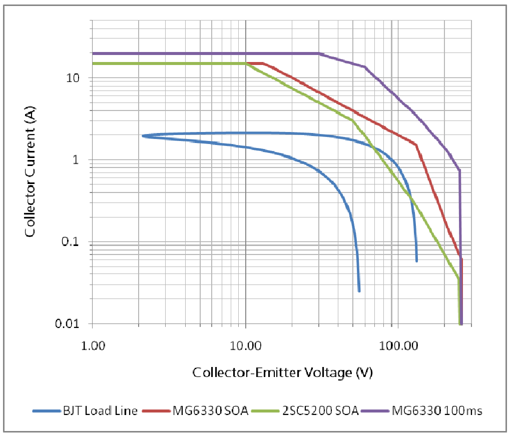

Fig. 6: 100Hz with 12 output pairs

Ultimately it is up to the designer and the product specifications to weigh up the required number of output devices but these examples do clearly demonstrate how large the advantageous impact of having extended SOA parameters is. By extending the secondary breakdown point to around 130V, Semelab's audio BJTs offer a significant benefit in usable power capability. This is why simply comparing voltage & current ratings against cost can prove to be a false economy from both a total solution cost point of view and the added costs of resolving failed products in the field.

The MG6330 & MG9410 from Semelab that have been used so far for comparison are not the highest power capability device within Semelab's range but offer the most cost competitive alternative solution. The MG6331 & MG9411 within the same range are higher power devices in the same TO3P package. They utilise a much thinner die structure resulting in significant improvements in the power dissipation capability and associated thermal resistance. This extends the safe operating area further and Figure 7 shows the 200Hz curve with 6 output pairs response overlaid:

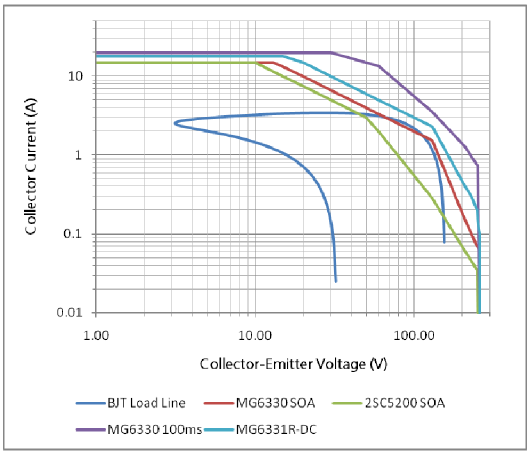

Fig. 7: Advantages of using higher performance transistors

Here we can see that even with only 6 pairs of this device and an inductive load that we are still inside the SOA. The significant improvement here is that the power capability part of the curve has increased from 200 to 300W and this also lifts up the secondary breakdown area too, even though the effect starts at around the same 130V point. Obviously our thermal calculations for a given heatsink still need to be worked through to ensure that this might be a feasible solution at this power.

One further possibility is to use Semelab's MG6332 family of devices which feature matched double die in a TO264 package. The die is the same as the MG6330 & MG9410 but with 2 packaged together and matched. Thus 2 devices can be replaced with one and this cuts down on board area, emitter resistors and mounting labour, etc. Very high power amplifiers can now be made in a very compact board area. Figure 8 shows our same sample amplifier with 4 pairs of this device:

Gain (h_{FE}) Specification

The gain of the output stage device is very important in audio power amplifiers. This parameter is specified as h_{FE} (also often referred to as beta) and represents the gain of base current to collector current and is measured at DC. This parameter should always be measured at a specified collector current and it is very important when comparing devices to be sure that they are compared at the same current. All BJTs exhibit what is referred to as *beta droop* where the gain falls off as current increases. Therefore, it is important to always evaluate the h_{FE} at the maximum design working current. Figure 8 illustrates the phenomena through a datasheet h_{FE} vs. I_C curve.

The value of this parameter is important in power amplifiers primarily because it determines the size and power rating of the output driver stage. Generally speaking, designers consider the 'higher the better' of this parameter. However, it is probably worth adding that this is only good if it is consistently high across devices.

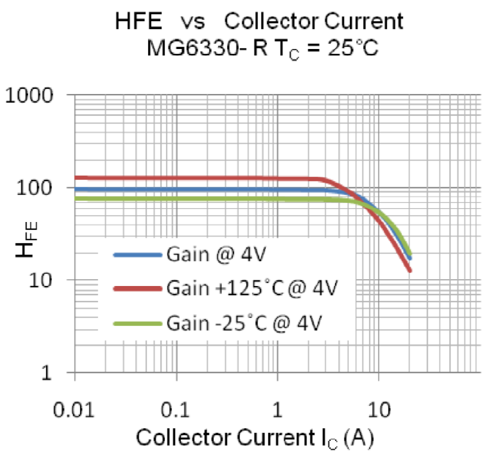

Fig. 8: Bipolar transistor gain curve

In addition to the driver stage considerations the flatness of this curve also determines the linearity of the device. The flatter this curve is and the more it holds up at higher current, the lower the open loop distortion (and therefore also the closed loop by implication) of the amplifier. It is this beta droop characteristic that is largely responsible for the increase in distortion as you lower load impedance in bipolar transistor power amplifiers. Distortion is often twice that at 4 ohm load when compared to the 8 ohm load figure.

A device which looks attractive because of high gain at lower currents may have exactly the same (or worse) drive requirements as one with apparently lower gain if it exhibits a lot of beta droop. There are a number of audio devices on the market that will yield gains of 150+ at lower currents but at 10A the gain may only be 20. The conclusion of this is to always look at the curves and understand the true h_{FE} at the currents you intend to operate at.

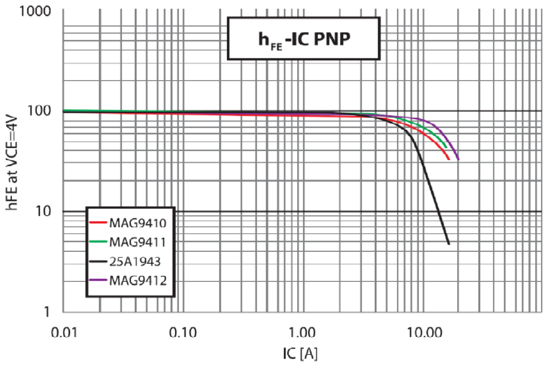

Fig. 9: h_{FE} linearity comparison

Figure 9 illustrates a comparison between the Semelab audio bipolars and the industry standard device in terms of the gain linearity. First observations show that the Semelab devices demonstrate a better hold-up of the gain at high currents which results in both easier drive and lower distortion (particular when contrasting 4 & 8 Ohm figures).

Transition Frequency (f_T)

The transition frequency is also important in any audio power amplifier design in that it will affect both the open-loop bandwidth that can be achieved as well as the placement of dominant poles. Both of the parameters will affect the resulting distortion of the amplifier and will be most prominent at higher frequencies. The f_T is the frequency at which the gain has dropped to unity (0dB) and the gain will increase at a slope of 6dB/octave as frequency reduces until to h_{FE} of the particular transistor is reached.

Clearly, a higher f_T results in more usable gain across a wider bandwidth and therefore lower exhibited distortion in the amplifier closed loop because of this higher feedback factor. In addition it will generally be easier to stabilise an amplifier design with wide closed loop bandwidth with a power transistor with higher f_T. This is because the power BJT will introduce less phase shift in the loop response for a given dominant pole frequency. A higher transition frequency will generally result in being able to increase this dominant pole frequency which makes more gain available in the audio bandwidth and therefore results in lower distortion across the audio band.

When changing one transistor for another in an existing design, moving over to one with higher f_T will generally not impact the amplifiers closed loop stability. In fact it is likely that stability will be improved through a potentially improved loop phase margin.