Shot Noise-Suppressed Operation of Bipolar Junction Transistors.

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Abstract. Recent work in quantum optics on the generation of sub-shot noise "quiet" light [1] with laser and light-emitting diodes has refocused attention on shot noise in electronic and photonic devices. In the course of this work, we have successfully modeled the small signal operation of bipolar junction transistors and photon transport transistors [2] using a common conceptual methodology. This methodology highlights the close parallels between electronic and photonic shot noise and reveals a number of common misconceptions concerning shot noise in bipolar transistors which have become entrenched in the professional literature. In this paper we present noise measurements for several BJT configurations and we interpret those measurements in terms of base-emitter diode shot noise suppression using a photon transport transistor [2] as a model.

1. Introduction

It has become customary to refer to the "base current shot noise" and the "collector current shot noise" of a BJT as if these were generated by corresponding physical processes and can be represented by corresponding physical current or voltage noise generators [3,5].

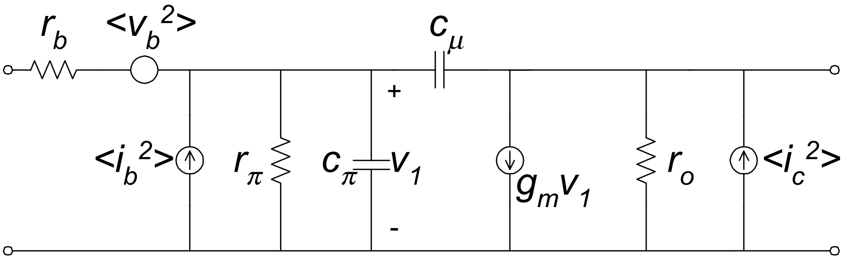

Figure 1 Gray and Meyer Bipolar Transistor Model.

For example, Gray and Meyer [3] present the model shown in Figure 1 in which the base current shot noise and the collector current shot noise are represented by current noise sources at the base and collector respectively. This model suggests that the collector current noise must be at least equal to full shot noise. However, as we shall show, this is not generally true.

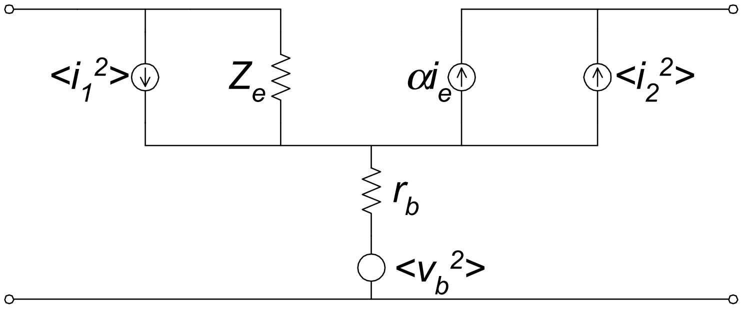

Figure 2 Van der Ziel Bipolar Transistor Model.

Van der Ziel [4] presents the model shown in Figure 2 which shows current noise sources at the emitter and collector and identifies these to be base-emitter shot noise plus partition noise in the collector circuit. At low frequencies, when the emitter is open circuited, his model predicts sub-shot noise current at the collector.

In fact, the equivalent current noise sources of Figure 1 are fictitious entities which have been incorporated into the literature on the basis of convenience and have acquired a spurious physical reality. For example, the so-called collector shot noise is actually composed of two components, (a) shot noise current flowing in the base-emitter diode and transferred to the collector circuit, plus (b) independent base-collector current partition noise, as shown in Figures 3, 5 and 7. Consequently the full collector current shot noise flows only under very restricted conditions. A high impedance base-emitter circuit will result in suppression of the base-emitter shot noise current. A convincing demonstration of this suppression of base-emitter diode current shot noise, now well understood in laser and light-emitting diodes, occurs when a BJT is operated with high impedance emitter input in the common base configuration.

2. Grounded Base/Open Emitter Model

In the grounded base/open emitter model shown in figure 3, the shot noise is represented by a voltage source (v_{esn}) at the emitter and partition noise by a current source (i_p) at the collector.

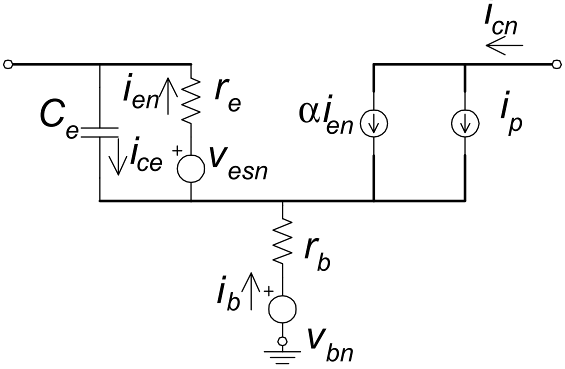

Figure 3 Grounded Base/Open Emitter Model.

Because the emitter is open circuit, there is no emitter current ($i_e = 0$) and therefore $i_{ce} = i_{en}$ and the current (i_{en}) through the emitter resistance (r_e) is given by:

$$i_{en} = \frac{v_{esn}}{\left(r_e + \frac{1}{sC_e}\right)} \qquad (1)$$

The noise current through the emitter resistance is zero at low frequencies but tends towards the full shot noise current as the frequency rises and the diffusion capacitance C_e closes the current loop.

Since the current at the collector is $i_{cn} = \alpha i_{en} + i_p$, and the two terms are uncorrelated, the mean square current in unit bandwidth (current noise spectral density) at the collector is given by:

$$< i_{cn}^2 > = \alpha^2 < i_{en}^2 > + < i_p^2 > \qquad (2)$$

$$= \frac{\alpha^2 < i_{esn}^2 > \gamma^2}{\left[1+\gamma^2\right]} + < i_p^2 > \qquad (3)$$

where $< i_{esn}^2 > = < v_{esn}^2 > / r_e^2$ is the full mean square emitter shot noise current in unit bandwidth and $\gamma = f/f_\alpha$, where f is the frequency at which the current noise spectral density is measured and f_α is equal to $1/2\pi C_e r_e$.

At low frequencies, the current noise spectral density is mainly due to partition noise and is equal to $(1-\alpha)2eI_c$. This is a fraction (the Fano factor) of the full shot noise level $2eI_c$, and is approximately equal to $1/\beta$ times full shot noise, where β is the common emitter current gain.

At high frequencies, the current noise spectral density tends to the full shot noise.

Experimental data were obtained for the type MJE3055T NPN power transistor. The experimental data were obtained using a system constructed at the University of Canberra [7]. This system comprised the transistor under test, a thermionic diode (CV2171) shot noise reference source, a low noise amplifier, swept frequency spectrum analyser and PC-based data acquisition facility.

Figure 4 shows the theoretical and experimental plots for the grounded base/open emitter configuration. The Fano factor is evidently much less than unity at low frequencies with shot noise suppression in close agreement with that predicted from Equation 3. However the agreement is evidently less satisfactory at higher frequencies.

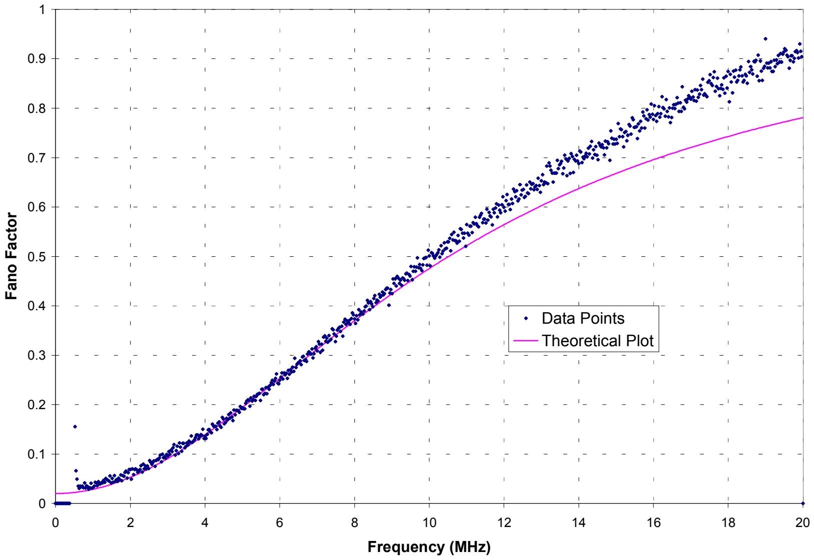

Figure 4 Measured and Model Fano Factors for the Grounded Base/Open Emitter BJT.

Unlike some contemporary models [3,5], this model does not include a shot noise source at the collector and the collector noise never exceeds full shot noise. At low frequencies the collector shot noise is suppressed by a factor of more than 50 (17dB), in clear contradiction to the statements often found in contemporary textbooks [3].

3. Open Base/Grounded Emitter Model

The open base/grounded emitter circuit model is shown in figure 5.

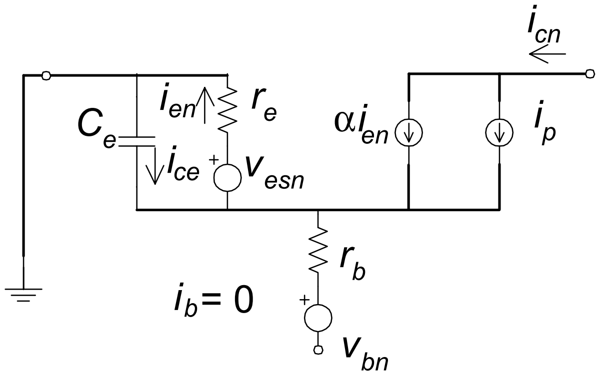

Figure 5 Open Base/Grounded Emitter Model.

The current noise spectral density at the collector includes both a shot noise component and a partition noise component, and is given by:

$$< i_{cn}^2 >= \frac{\alpha^2 < i_{esn}^2 > \gamma^2}{\left[(1-\alpha)^2 + \gamma^2\right]} + < i_p^2 > \frac{\left[\alpha + \sqrt{(1-\alpha)^2 + \gamma^2}\right]^2}{\left[(1-\alpha)^2 + \gamma^2\right]} \qquad (4)$$

At low frequencies, the collector current Fano factor is $1/(1-\alpha)$, where the only significant noise is amplified partition noise, approximately β times full collector shot noise.

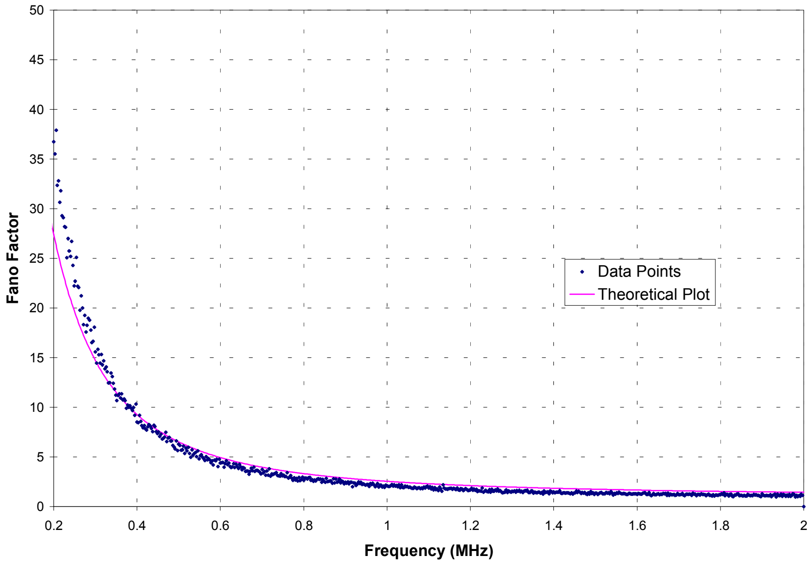

Figure 6 Measured and Model Fano Factors for Open Base/Grounded Emitter BJT.

Figure 6 shows the theoretical and experimental plots for the Open Base/Grounded Emitter case. Again, the experimental results support the suggested model. At high frequencies, the current noise spectral density approaches full shot noise.

4. Grounded Base/Grounded Emitter Model

The grounded base/grounded emitter model is shown in Figure 7.

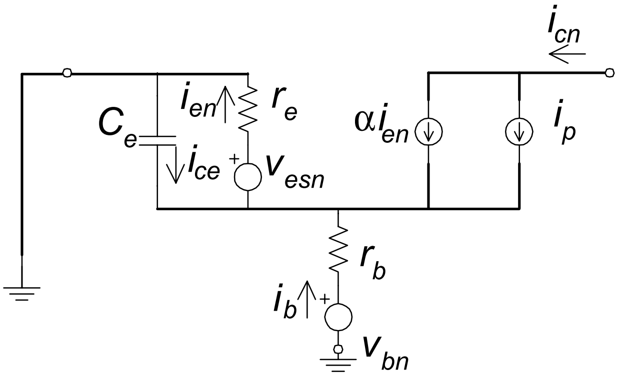

Figure 7 Grounded Base/Grounded Emitter Model.

Again the current noise spectral density at the collector includes a shot noise component and a partition noise component and is given by:

$$< i_{cn}^2 > = \frac{\alpha^2 < i_{esn}^2 > \left[\gamma^2 + \rho^2\right]}{\left[(\rho + 1 - \alpha)^2 + \gamma^2\right]} + < i_p^2 > \frac{\left[\alpha + \sqrt{(\rho + 1 - \alpha)^2 + \gamma^2}\right]^2}{\left[(\rho + 1 - \alpha)^2 + \gamma^2\right]} \qquad (5)$$

where $\rho = r_e/r_b$.

At low frequencies, the current noise spectral density is given by:

$$< i_{cn}^2 > = \frac{\alpha \rho^2 < i_{csn}^2 >}{(\rho + 1 - \alpha)^2} + \frac{(1 - \alpha)(\rho + 1)^2 < i_{csn}^2 >}{(\rho + 1 - \alpha)^2} \qquad (6)$$

which, for the given transistor, is marginally above full shot noise $(< i_{csn}^2 >)$ at the collector.

At high frequencies, the current noise spectral density tends to the full shot noise level.

Figure 8 shows the theoretical and experimental plots for the grounded base/grounded emitter case. The figure includes theoretical plots for the shot and partition noise component (lower plot), the theoretical thermal noise component (middle plot) and the total theoretical noise (upper plot). Thermal noise is significant for this case because of the low impedance base emitter circuit, unlike the previous cases.

Again, the experimental results compare well with the theoretical results and support the suggested model.

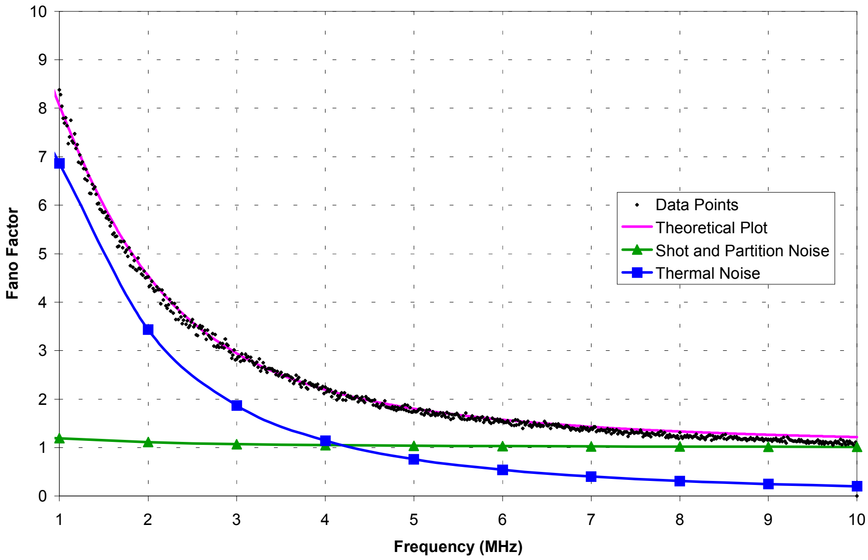

Figure 8 Measured and Model Fano Factors for Grounded Base/Grounded Emitter.

5. Conclusion

Our measurements support the Van der Ziel model and the conceptual physical models we have presented in this paper. They do not support those equivalent noise source models which include a (non-physical) full shot noise source in the collector circuit. Such models are specific to particular configurations and can be easily misinterpreted [3]. We demonstrate that the shot noise in a BJT originates at the emitter-base junction. We also show, in Equations (3) and (4) and Figures (4) and (6), that emitter shot noise can be easily suppressed, as in a light-emitting junction, by raising the impedance of the emitter-base circuit. Its physical origin is best represented by a full shot noise voltage source located at the emitter-base junction. The much weaker partition noise can be represented by a current noise source at the collector as in a photon coupled transistor [2,5,6].

References

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