Low Frequency Noise in Bipolar Transistors

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OUTLINE

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- Noise Basics
- Measurement Setup
- Popcorn noise Plots
- Typical 1/f noise Plots
- Noise scaling
- Methods of reducing noise
- Conclusion

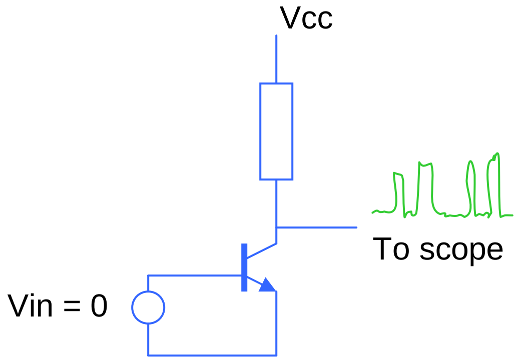
INTRODUCTION

- Noise sets the lower limit on the minimum detectable signal.
- LF Noise is very important for analog & mixed signal circuits
- LF noise has a wide impact from DC to high frequencies.
- LF noise is detrimental to performance of DC coupled systems:
  - Operational and Instrumentation Amplifiers
  - Oscilloscope Vertical Amplifiers
  - A/D and D/A converters
- Oscillators and Mixers (AC coupled systems):
  - LF noise is converted into Phase Noise
  - Broadens the output spectrum of an oscillator
  - Introduces time jitter in a digital system

- HF noise affects the performance of Communication Systems
- Improving S/N ratio allows wider repeater spacing
- Less transmitted power
- 1dB increase in cell phone Noise Figure results in:
  - 26% more base stations and increased system cost

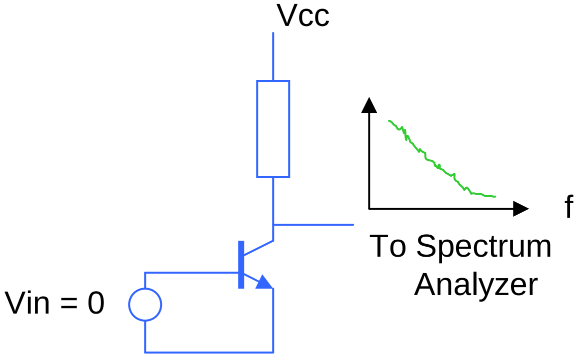
POPCORN NOISE

- Popcorn Noise appears as sudden spurts of current in time domain.
- It was first observed in audio amplifiers as “pops” in the speaker.
- This is due to the traps in the EB space charge region which gets charged and affects the flow of adjacent carriers.
- This is believed to be due to metallics at the EB junction.
- Other names for Popcorn noise:
  - Burst Noise
  - Generation-Recombination Noise (G-R Noise)
  - Random Telegraph Signal (RTS)
- There are very few papers on popcorn noise.



FLICKER or 1/f NOISE

- In frequency domain, it shows a 1/ f behavior.
- 1/f noise due to distribution of traps with different time constants
- 1/f noise is due to:
  - carriers tunneling through an oxide barrier at the emitter
  - recombination at the EB periphery due to surface states
  - generation-recombination due to implant damage etc
- 1/f noise is also observed in:
  - carbon resistors and poly silicon resistors
  - absent in metal film resistors !
- Other names for 1/f noise:
  - Flicker Noise
  - Pink Noise
- More publications on 1/f noise



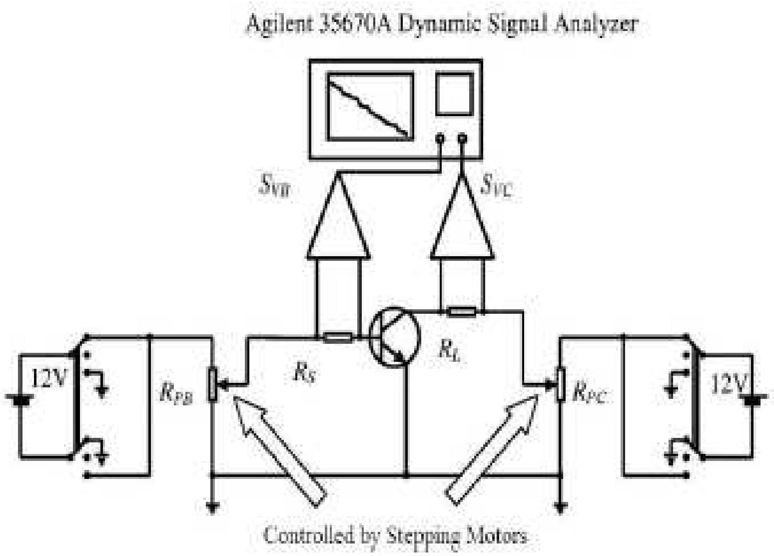
SHOT NOISE

- It is due to fast movement of carriers through the depletion region
- This is similar to shot being fired from a gun
- It is independent of frequency
- It depends only on the current in the device
- It appears as a baseline noise floor

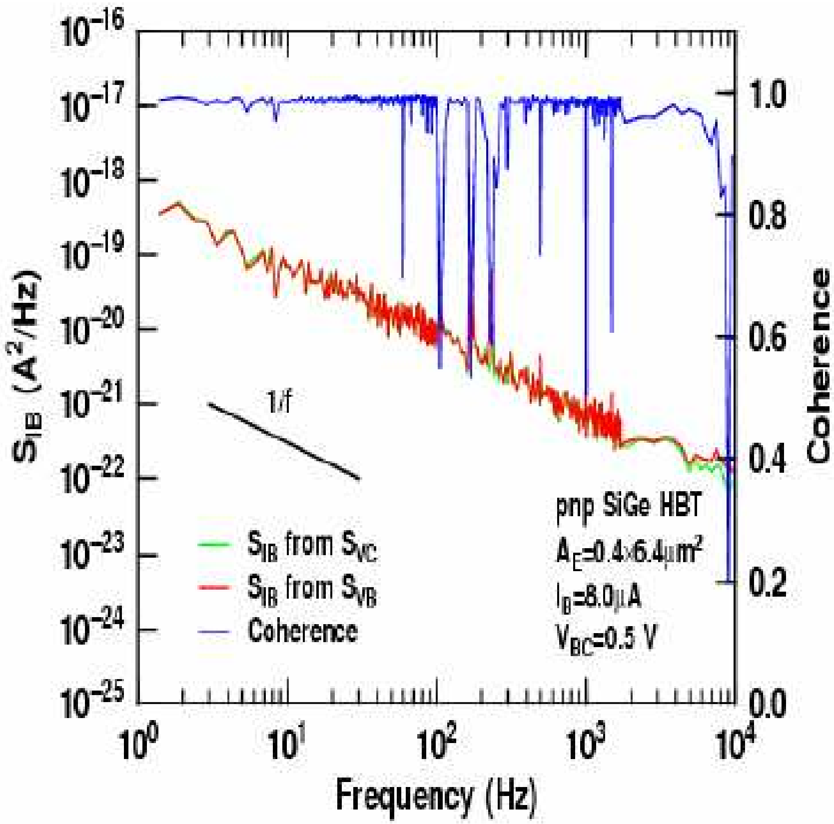
THERMAL NOISE

- Due to thermal energy causing electrons to move randomly in a resistive material
- Evaluated by Johnson in 1928 (also called Johnson noise)
- Depends on temperature and resistor value
- R_B and R_E contribute to thermal noise
- It appears as a baseline noise floor

POPCORN & 1/f NOISE MEASUREMENT SYSTEM - I



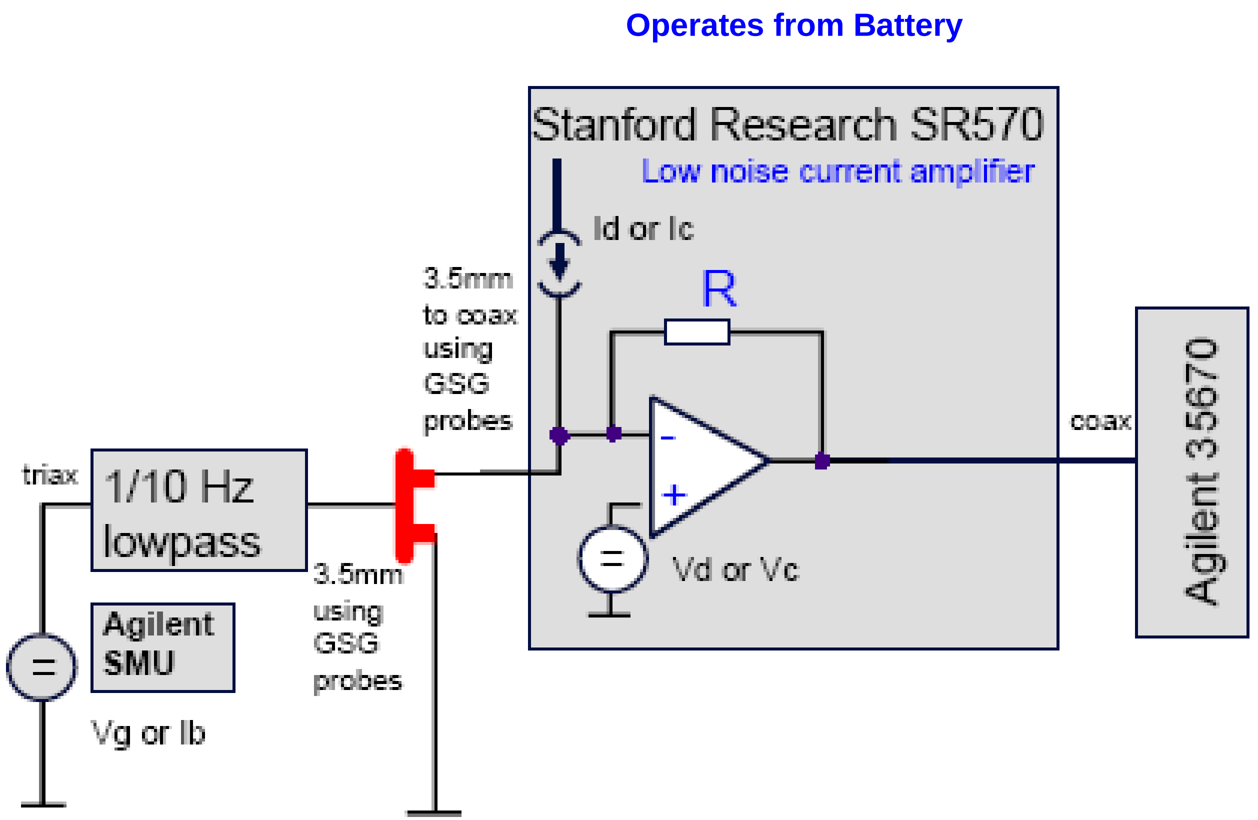
$$S_{IB} \approx \frac{S_{VC}}{\beta^2 \cdot R_L^2}$$



- **Run from battery to avoid power supply interference**
- **EG&G Model 5113 Low Noise Amplifiers**
- **Rs should be large for Sib measurement**
- **Dual channel allows coherence measurements**

Instead of SA, use Tek TDS 5034 20MHz Scope to capture Popcorn waveform

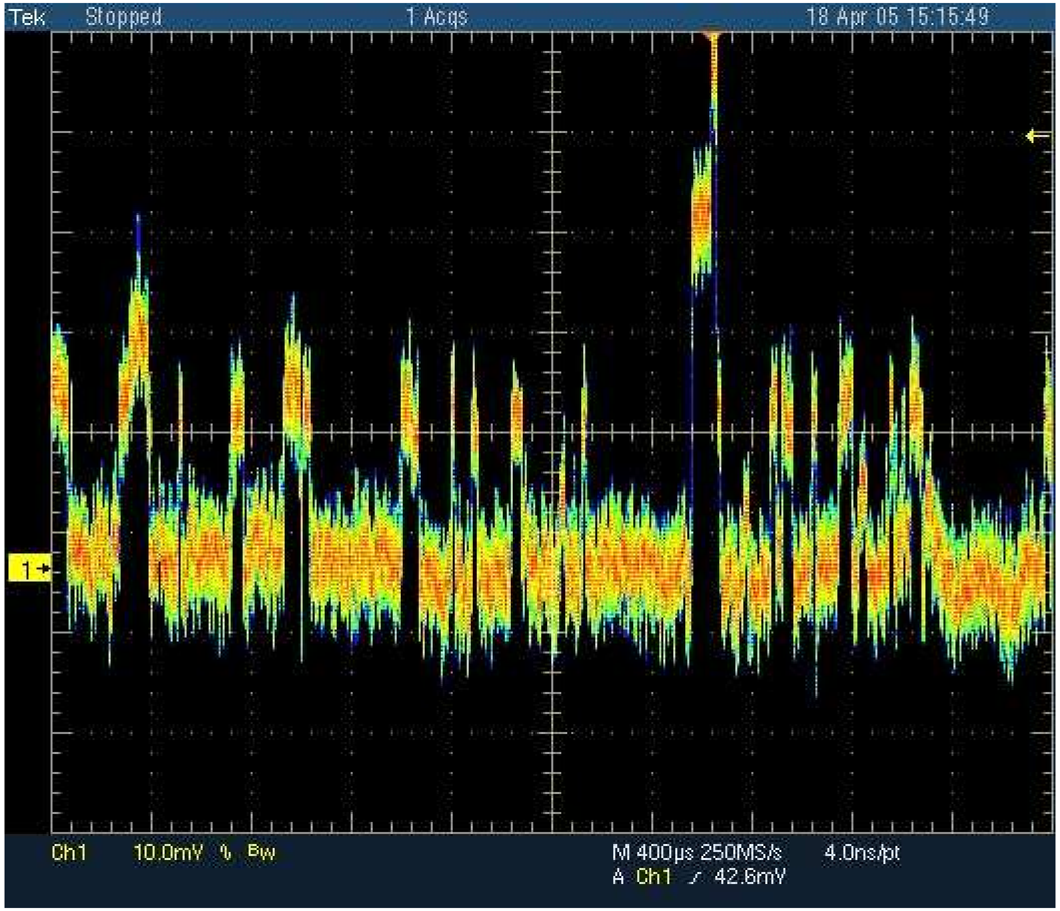
POPCORN & 1/f NOISE MEASUREMENT SYSTEM - II



The LP filter should contain a large R for Sib measurement

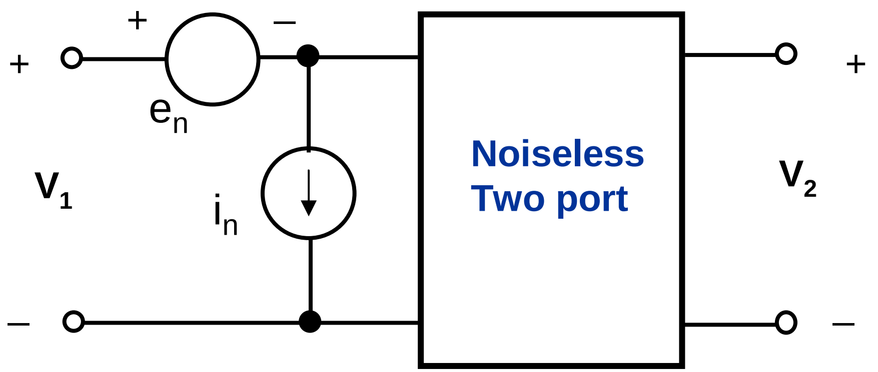
Instead of SA, use Tek TDS 5034 20MHz Scope to capture Popcorn waveform

Popcorn Noise from a SiGe NPN Transistor



Vert: 10mV/div Gain: 100uA/Volt   11nA input referred.

Equivalent Circuit for LF Noise in a Device



Noise in the device is represented at the input by a noise voltage and noise current
These are known as input referred noise voltage and current
If the source has a low impedance, all of e_n will be applied to the device.
The measured output noise will be mainly due to e_n.
We can divide the output noise by voltage gain and get e_n.
Similarly, if driven from a high impedance source, all of i_n will be applied to the device.
The measured output noise will be mainly due to i_n.
We can divide the output noise current by current gain and get i_n.
This way, e_n and i_n are independent of device parameters such as gm or β.
For some Zopt, the output noise will be a minimum.

Mathematical Representation of Noise

For a bipolar, the input referred current noise is represented by the suffix ib. Sib represents the power spectral density (PSD) in units of A^2/Hz. The input Referred voltage noise is generally small in bipolars.

$$S_{ib}(f) = A\tau / (1 + \omega^2\tau^2) + B/f + 2qI_B + 2qI_C/\beta^2 + 4kT/R$$

Popcorn Noise has Lorentzian spectrum
τ time constant of trap

1/f Noise

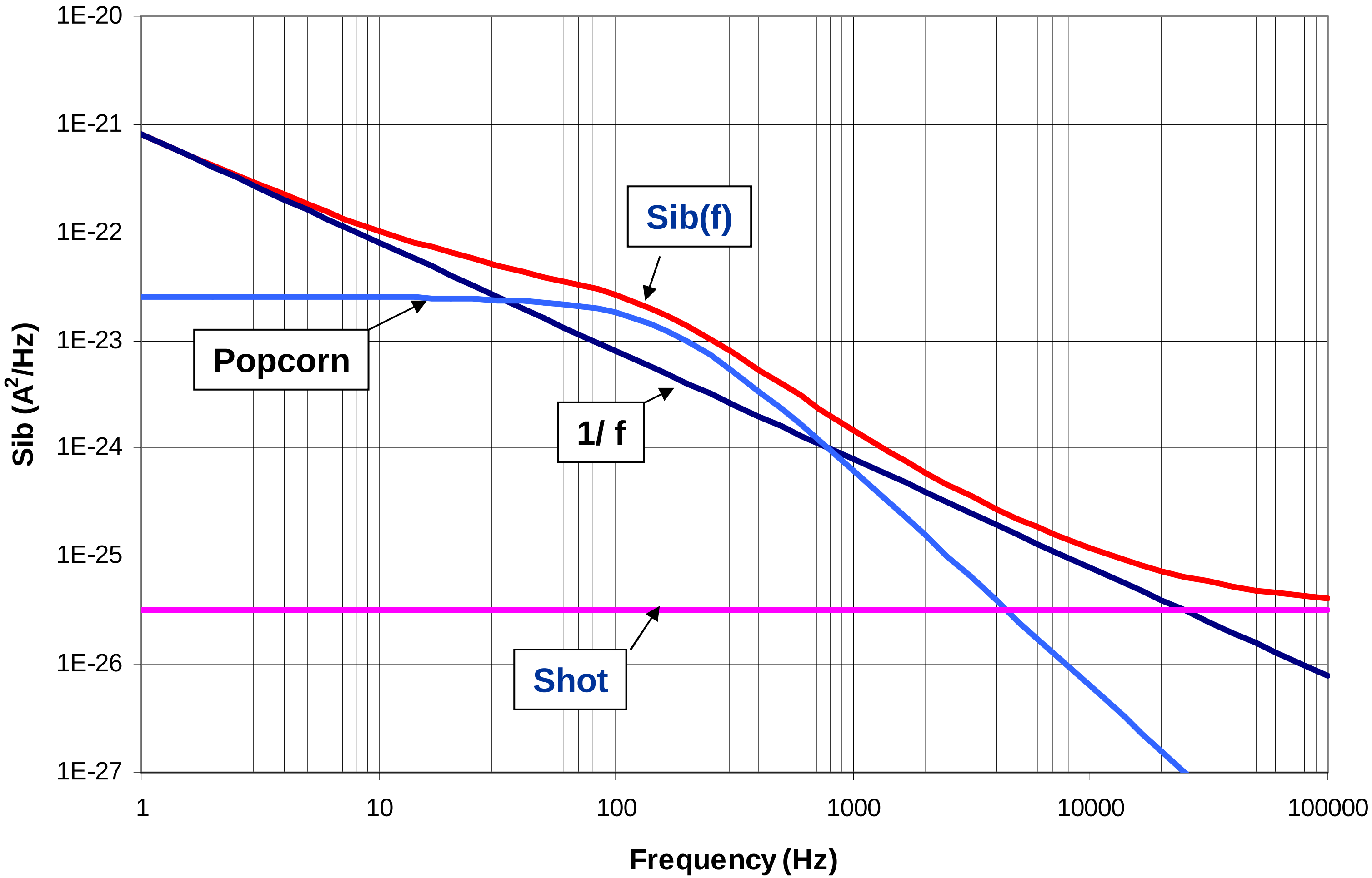
Shot Noise

Thermal Noise

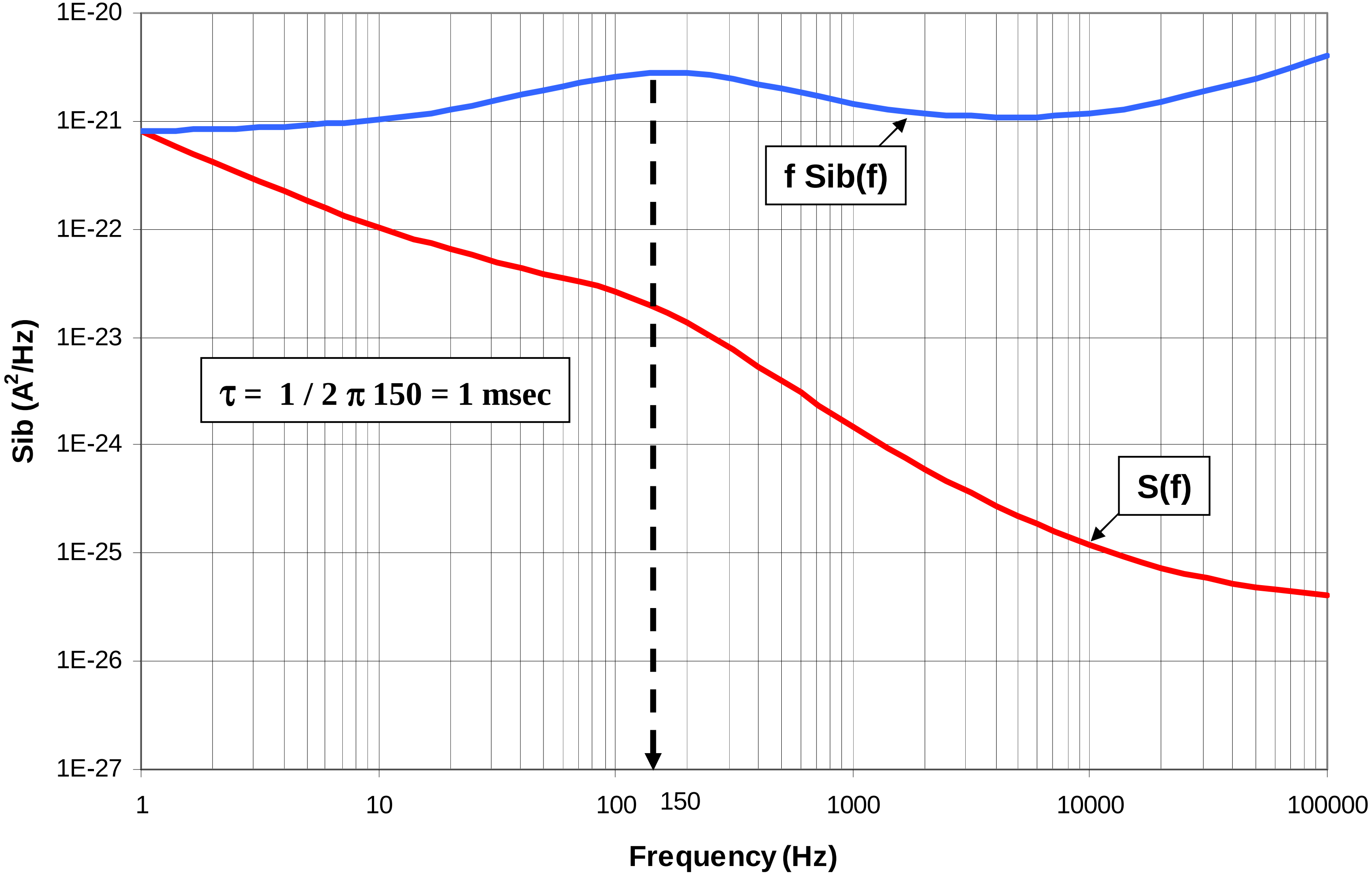
PSD of input referred current noise at the base

Since β is large, the second term is negligible. Measure at a fixed I_B

Factors contributing to overall 1/f noise plot



Identifying the peak due to popcorn noise



Variation of S_{ib} with device parameters

Theory says that Sib α I_B^n ; n=1 means mobility fluctuations
n=2 means carrier number fluctuations

$$S_{ib}(f) = KI_B^2/(Ae.f) + 2qI_B + 2qI_C/\beta^2$$

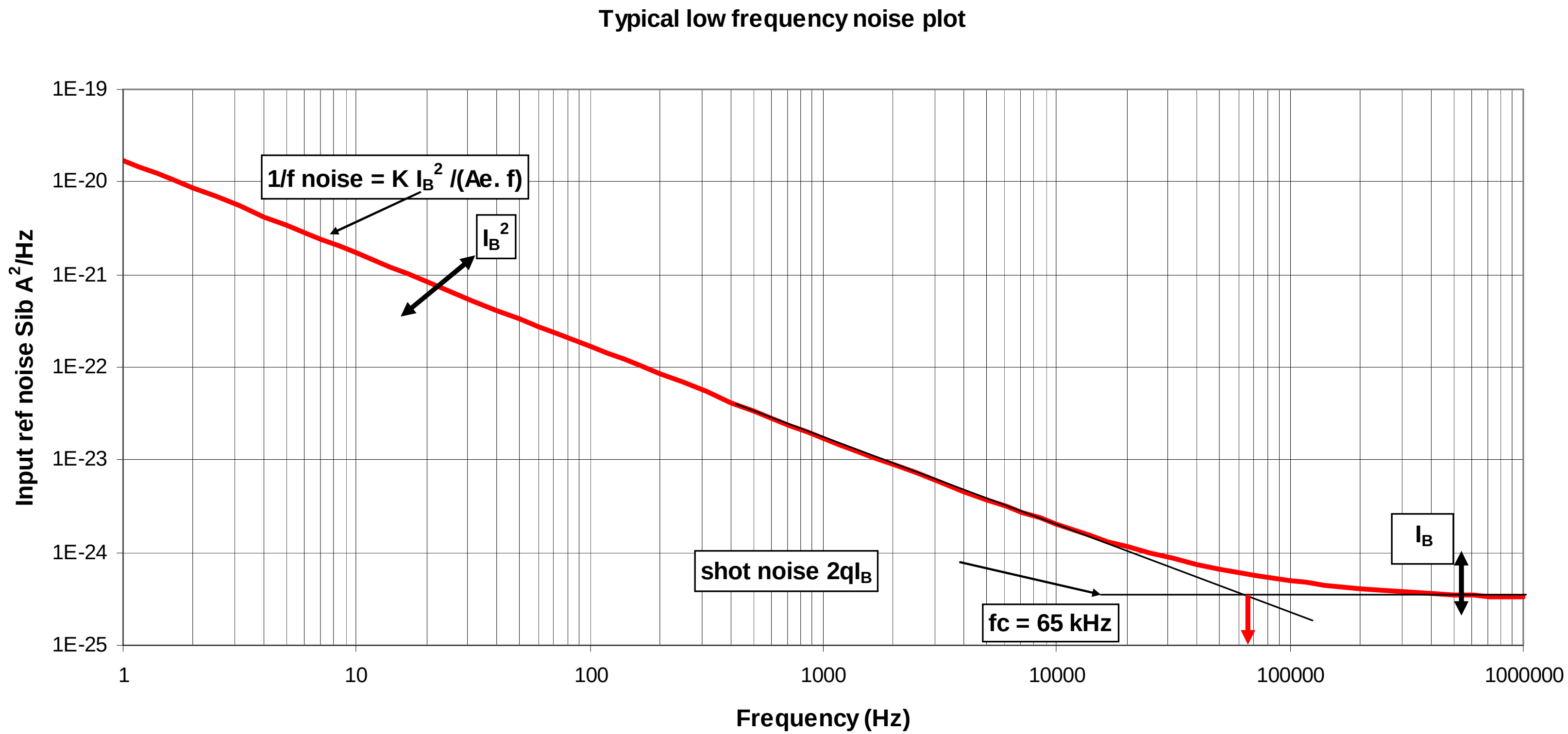
→ negligible

Ae: Emitter area
K : Flicker Noise Coefficient

Interestingly, K ~ 10^{-8} to 10^{-7} for most bipolar processes. K tends to increase with device scaling.
This is very helpful in estimating Sib, even for your competitors!

L.Vandamme, IEEE TED 41(11), 2174-87, 1994.

Flicker Noise Corner Frequency fc



$KI_B^2/(Ae.fc) = 2qI_B$

$fc = KI_B/2qAe = KI_C/2q\beta Ae$

To get a lower fc, use bigger device and operate at a lower current. But f_T will suffer. For a given I_C, higher β will help.

What happens if beta is increased by interfacial oxide ?

- **Generally, poly silicon emitters have an interfacial oxide.**
- **This decreases hole injection into emitter, giving higher beta.**
- **However, if an intentional oxide is grown to boost beta, then Mother Nature takes control !**

What happens is that the Flicker Noise Coefficient K increases exponentially with oxide thickness increasing the corner frequency.
In general,

$$K = Ko \exp (m.t_{ox})$$

$$K.\ Ae = 1.6x10^{-10} \exp (0.536\ t_{ox})$$

tox : oxide thickness in Angstroms
m = 0.3 – 0.6

E.Simeon et al., IEEE TED 43(12), pp 2261-2268, 1996.

Looking at Popcorn Noise – Again!

- Have a method to compare popcorn noise pulses from different devices or even processes
- If the β is high, popcorn pulse height will be high
- For comparison, it is necessary to compute the input referred popcorn pulse height.
- Next, we have to understand how it scales with I_B.

Input referred popcorn pulse height $\Delta I_B = \Delta I_C / \beta$

popcorn pulse height as measured on the scope

The pulse height increases linearly with I_B first and then saturates.

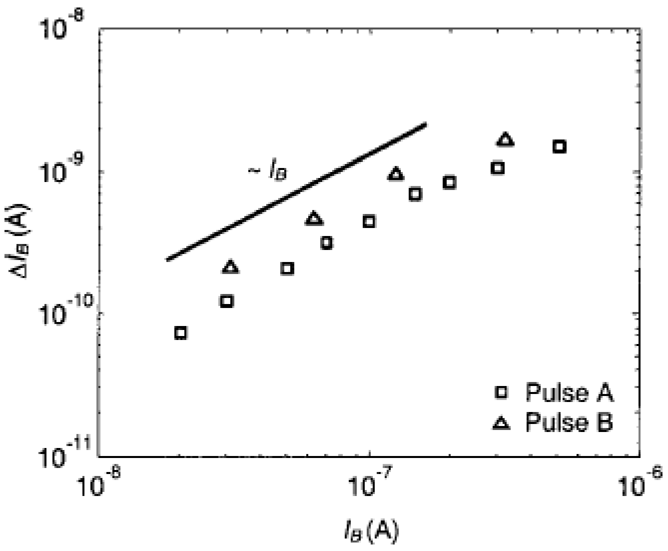


FIG. 4. RTS pulses scaling with the base current. Pulse A was measured on a device with $A_E = 5 \times 1.6\ \mu m^2$, pulse B on a device with $A_E = 5 \times 1.0\ \mu m^2$. $T = 295$ K.

M. Von Haartmann et al., JAP 92(8) pp 4414-4421, Oct 2002

Simplified Theory of Popcorn Noise

- **The popcorn pulse amplitude is explained by a model based on barrier height fluctuations across the EB junction.**
- **The EB junction barrier height fluctuates due to trapped carriers in the space charge region.**
- **Since the current is exponentially related to the barrier height, even small changes in barrier height can cause large changes in current.**
- **The relative popcorn amplitude $\Delta I_B / I_B$ is found to decrease with temperature.**

For values of I_B before the leveling off occurs

$$\Delta I_B = (L_S^2 / Ae)\, I_B \left[\exp(\Delta V_{BE} / kT) - 1 \right]$$

Ls: screening length over which the trapped charge will interact with other carriers
ΔV_{BE}: change in barrier height due to trapped charge

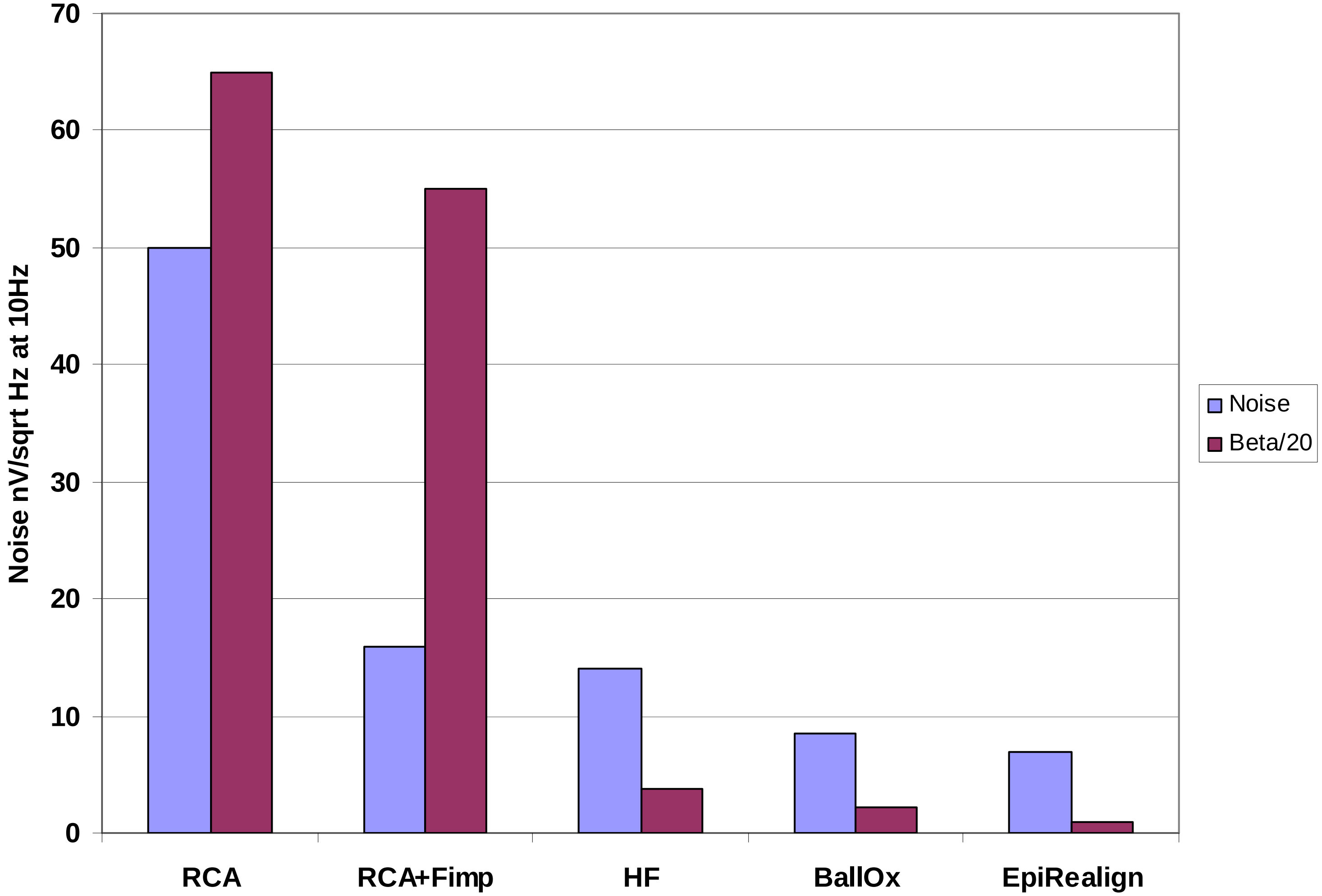
Notice that popcorn pulse height is inversely proportional to Ae.

Increasing the interfacial oxide thickness increases β but also increases the popcorn noise exponentially.

Methods of reducing Flicker Noise

Process Change	Effect
Decrease base implant dose	decrease
Surface clean with Flourinated treatment	decrease
Increase emitter junction depth	decrease
Increase emitter anneal (RTA temp & time)	decrease
Recrystallize the emitter	decrease
Forming gas anneal to passivate dangling bonds	decrease
Increase base width	no change
Increase poly silicon thickness > 5 grain widths	no change
Increase interfacial oxide thickness	increase

Effect of processing on Flicker Noise



S. Shahrivar, Proc IEEE BCTM, pp 236-238, 1990

Methods of reducing Popcorn Noise

This is much more difficult than reducing the 1/f noise. Some of the techniques used for 1/f noise will also be applicable here.

Process Change	Effect
Cleanliness (low particles, cross contamination etc)	decrease
Low EB dislocations (Slow pull, push into furnace)	decrease
Remove metallics by HCl	decrease
Recrystallize the emitter	decrease
Use As instead of Phos emitter	decrease
Eliminate surface junctions/dislocations by passivation	decrease
Increase interfacial oxide thickness	increase

CONCLUSION

- Reviewed various noise sources
- Discussed measurement techniques
- Talked about input referred noise
- Touched on Lorentzian bump in 1/f plots
- Flicker noise corner frequency
- Popcorn and 1/f noise scaling
- Process techniques for reducing noise
- Shown that noise is really a science
- It is not “black magic” as thought before
- Low noise devices make better systems