D·I·T

School of Electronic and Communications Engineering

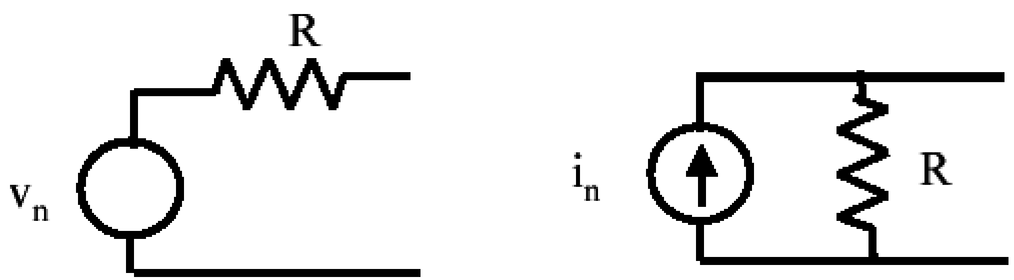
2. Noise Models

Noise Models

- In the above sections, the various physical sources of noise in electronic circuits were described.
- In this section, these sources of noise are brought together to form the small-signal equivalent circuits:
  - resistors (already discussed)
  - diodes,
  - bipolar (BJT) and
  - field-effect (FET) transistors and
  - linear IC (OpAmp)

Resistors

- Noise can be modelled as
  - a Thevenin equivalent voltage source or
  - a Norton equivalent current source.

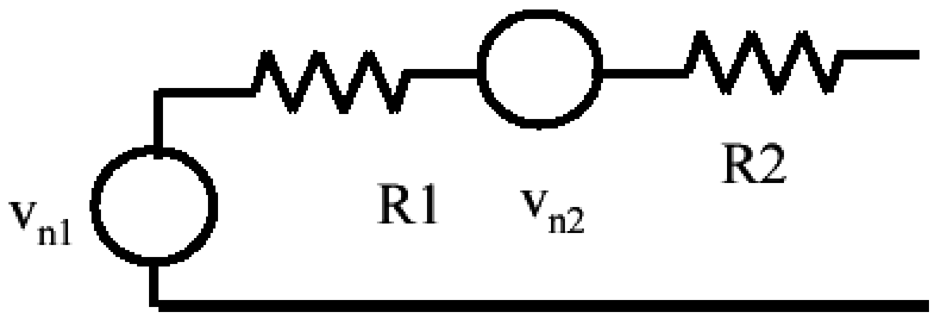


- The noise contributed by the resistor is modeled by the source, thus the resistor is considered noiseless.

Two resistors

- It is important to note that noise sources:
  - Do not have polarity
  - Do not add algebraically, but as RMS sums
- If the sources are not correlated, then:

$$\overline{v}^2_{n,total} = \overline{v}^2_{n1} + \overline{v}^2_{n2} = 4kTBR_1 + 4kTBR_2$$



$$v_n(rms) = \sqrt{\overline{v_n^2}} = \sqrt{\overline{v_{n1}^2} + \overline{v_{n1}^2}} = \sqrt{4kTBR_1 + 4kTBR_1}$$

Correlated resistors

- If the sources are correlated (derived from the same physical noise source), then there is an additional term:

C can vary between –1 and 1.

$$\overline{v_n^2} = \overline{v_{n1}^2} + \overline{v_{n1}^2} + 2Cv_{n1}v_{n2}$$

$$v_n(rms) = \sqrt{\overline{v_n^2}} = \sqrt{\overline{v_{n1}^2} + \overline{v_{n1}^2} + 2Cv_{n1}v_{n2}}$$

Thermal Noise Power

- The available noise power can be calculated from the RMS noise voltage or current:

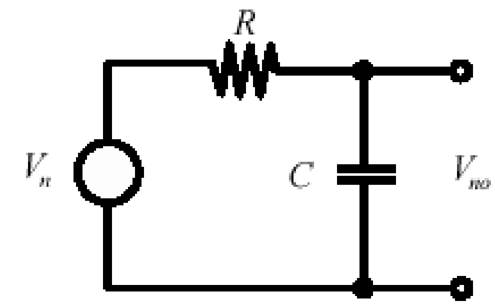
$$P_{no} = \frac{E_{no}^2}{R_L} = \frac{(E_t / 2)^2}{R_S} = kTB$$

- That is, the available noise power from the source is
  - independent of resistance
  - proportional to temperature
  - proportional to bandwidth
  - has no frequency dependence
- ***$P=4 \times 10^{-21}$*** watts in a 1 Hz bandwidth at the standard noise room temperature of 290 K.

Can a resistor produce infinite noise voltage?

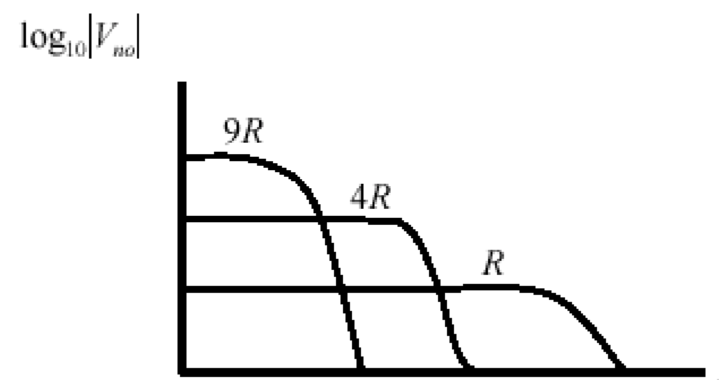
$$\overline{v_n^2} \equiv \overline{v_t^2} = 4kT \cdot R \cdot B$$ therefore $$\overline{v_t^2} \to \infty \text{ when } B \to \infty$$

Equivalent circuit for noisy resistor always have some shunt. Therefore



Low Pass

$$|V_{no}| = |V_{no}| \frac{1}{\sqrt{1+\omega^2 C^2 R^2}}$$



To find the noise power

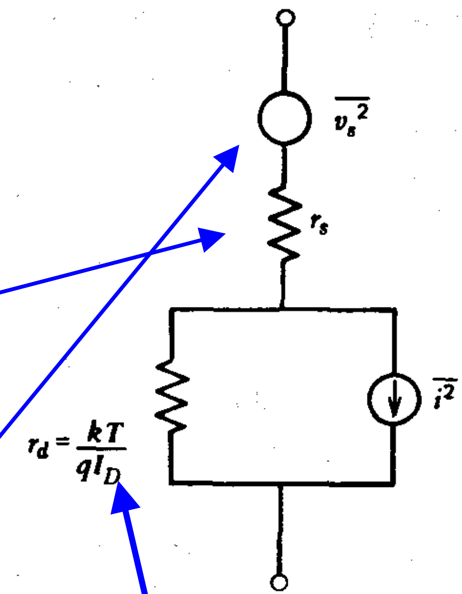
$$\overline{v_{no}^2} = \int_0^\infty |V_{no}|^2 dt = \frac{kT}{C}$$

Therefore total noise power is independent of *R* !!!

Junction Diode

- The equivalent circuit for a junction diode was considered briefly in the consideration of shot noise.
- The basic equivalent circuit of diode (discussed) can be made complete by adding series resistance r_s, as shown.
- Since r_s, is a physical resistor due to the resistivity of the silicon, it exhibits thermal noise.

$$\overline{v_t^2} = 4kT \cdot r_s \cdot B$$



- Experimentally it has been found that any flicker noise present can be represented by a current generator in shunt with r_d, and this is conveniently combined with the shot-noise

$$\overline{i^2} = 2qI_D \cdot B + K\frac{I_d^{\alpha}}{f}B$$

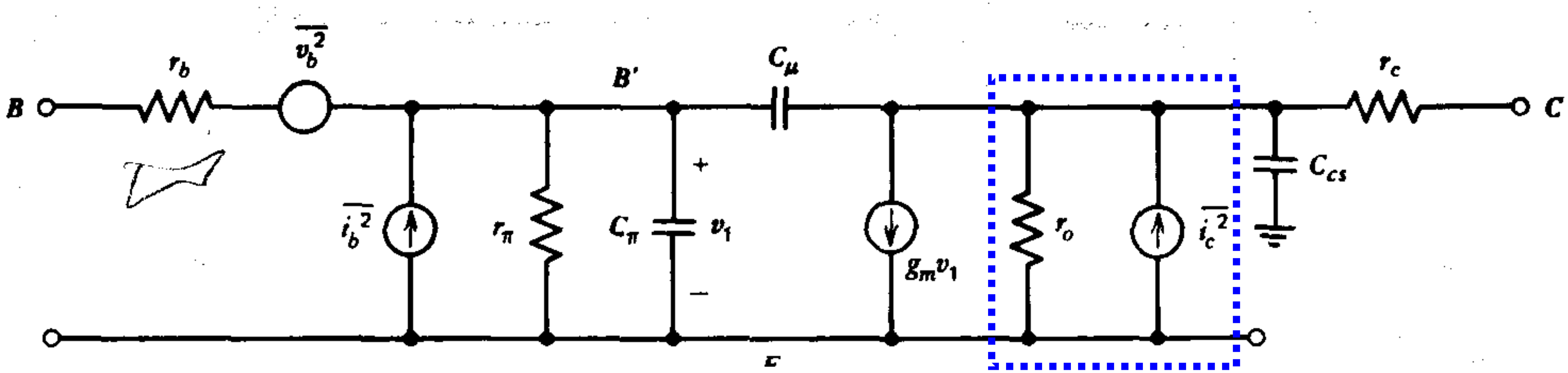
BJT (noise model)

- In a BJT in the forward-active region, minority carriers diffuse and drift across the base region to be collected at the collector-base junction.
- Minority carriers entering the collector-base depletion region are accelerated by the field existing there and swept across this region to the collector.
- The time of arrival at the collector-base junction of the diffusing (or drifting) carriers is a purely random process, and thus the transistor collector current consists of a series of random current pulses.

Contribution I

- Consequently, collector current *Ic* shows *full shot noise*, and this is represented by a shot noise current generator i_c^2 from collector to emitter as shown in the equivalent circuit of BJT

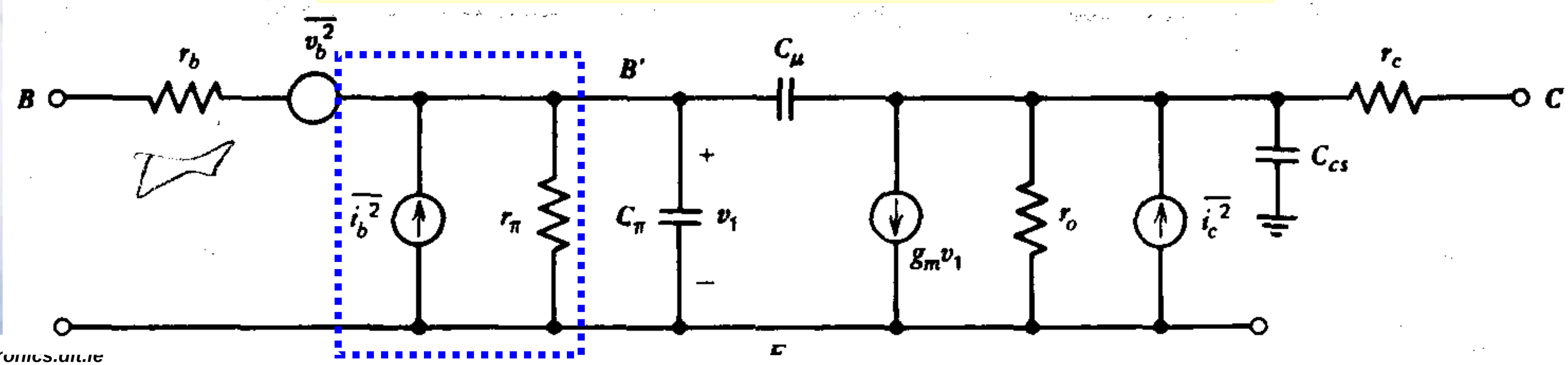
$$\overline{i_c^2} = 2qI_C \cdot B$$



Contribution II

- Base current I_B in a transistor is due to recombination in the base and to carrier injection from the base into the emitter.
- All of these are independent random processes, and thus I_B also shows *full shot noise.*
- Flicker noise and burst noise in a BJT have been found experimentally. This is represented by shot noise current generator

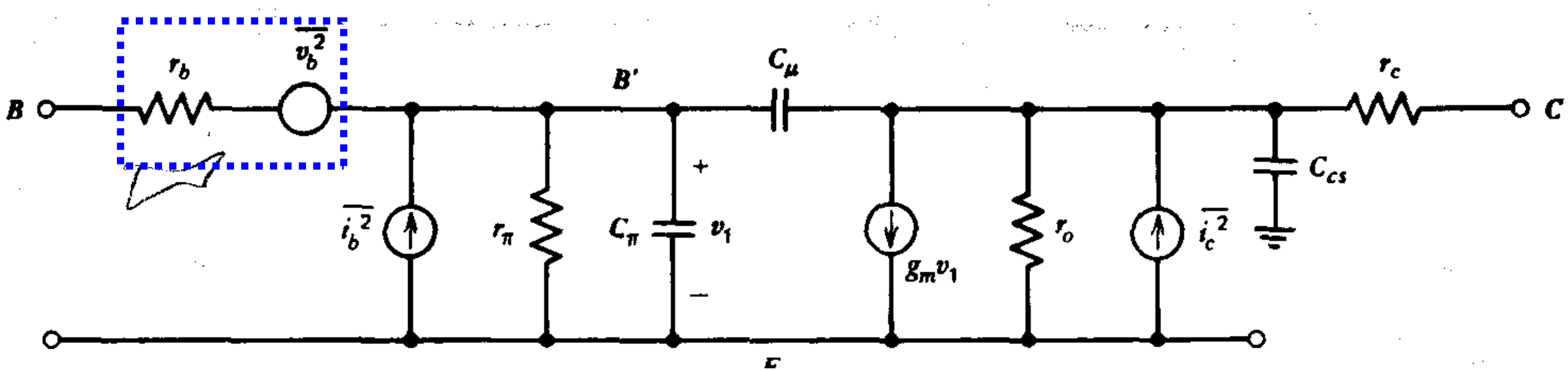
$$\overline{i_b^2} = 2qI_B \cdot B + K_1 \frac{I_b^{\alpha}}{f} B + K_2 \frac{I_b^{c}}{1 + \left(f / f_c\right)^2} B$$



Contribution III

- Transistor base resistor r_b is a physical resistor and thus has thermal noise.
- Collector series resistor r_c also shows thermal noise, but since this is in series with the high-impedance collector node, this noise is negligible and is usually not included in the model.

$$\overline{v_b^2} = 4kTB$$

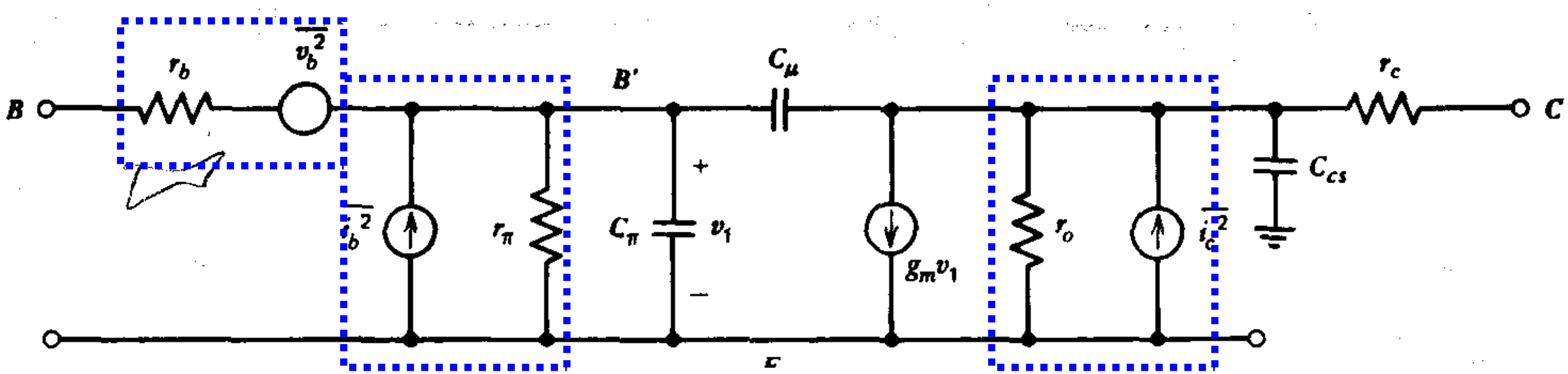


All Contributions

- Shot *noise* in collector current *Ic*, $\overline{i_c^2} = 2qI_C \cdot B$
- Shot, Flicker noise and burst noise in Base current I_B

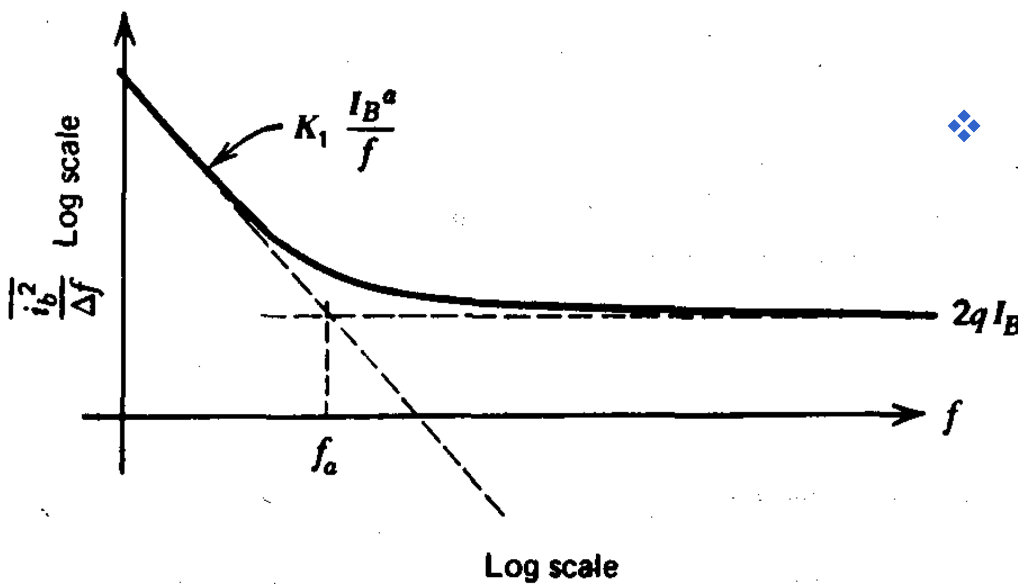
$$\overline{i_b^2} = 2qI_B \cdot B + K_1 \frac{I_b^{\alpha}}{f} B + K_2 \frac{I_b^{c}}{1+\left(f / f_c\right)^2} B$$

- Thermal noise in base resistor r_b. $\overline{v_b^2} = 4kTB$



“corner” frequency

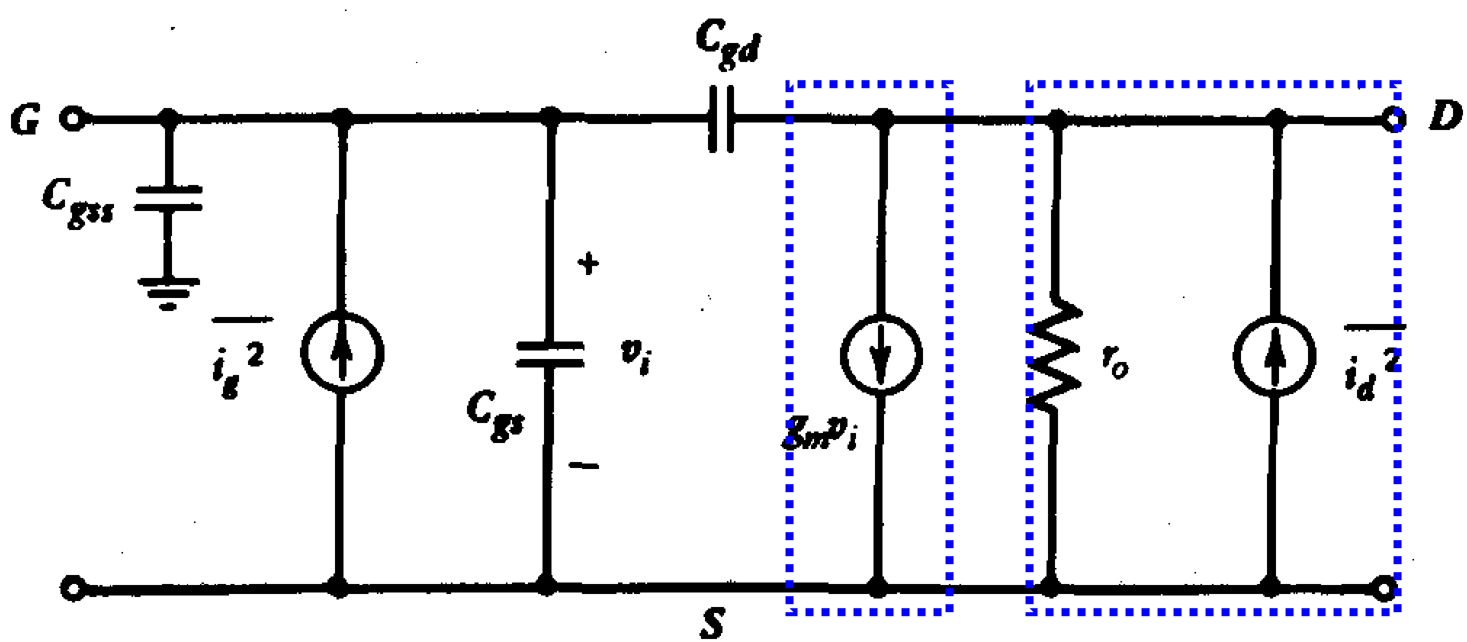
- The base-current noise spectrum can be plotted where burst noise has been neglected for simplicity.
- The shot noise and flicker noise asymptotes meet at a frequency *fa*, which is called the flicker noise "corner" frequency.



- In some transistors using careful processing, *fa* can be as low as 100 Hz.
- In other transistors *fa* can be as high as 10 MHz.

FET noise model

- In FET the resistive channel joining source and drain, so that the drain current is controlled by the gate-source voltage.
- Since the channel material is *resistive*, it exhibits *thermal noise*, and this is the major source of noise in FETs this noise source can be represented by a noise-current generator i_D^2 from drain to source in the FET small-signal equivalent circuit.



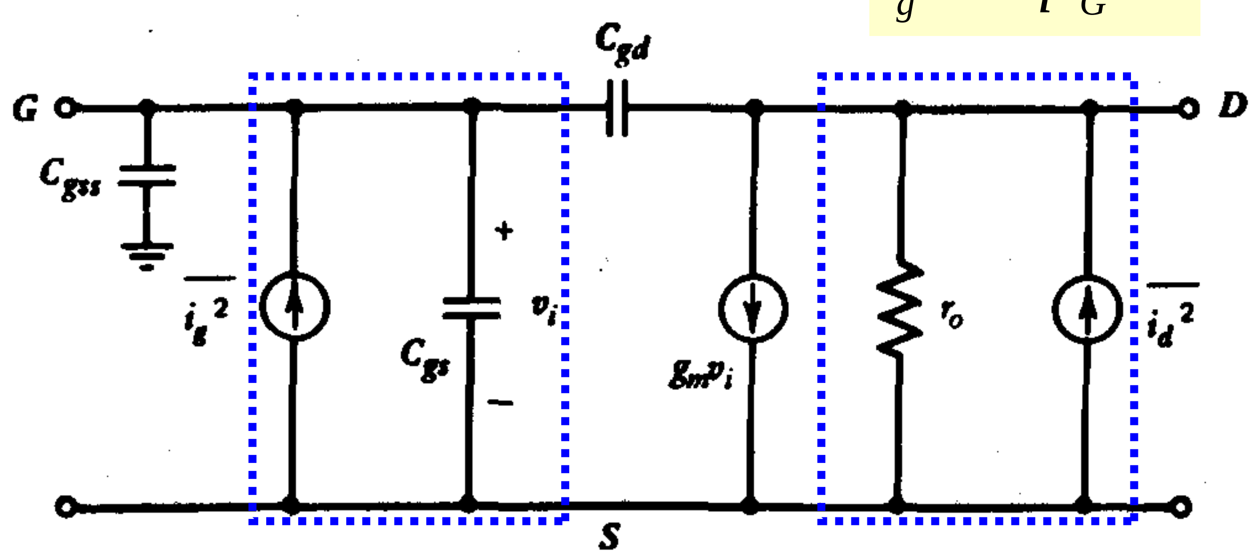
Contributions

- Flicker noise in the FET is also found experimentally to be represented by a drain-source current generator,

$$\overline{i_d^2} = 4kT\left(\frac{2}{3}g_m\right) + K_2 \frac{I_D^a}{f} B$$

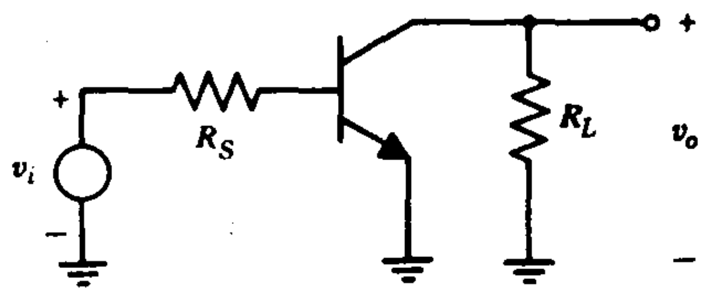
- The other source of noise in FETs is shot noise generated by the gate leakage current and is usually very small. It becomes significant only when the driving-source impedance connected to the FET gate is very large.

$$\overline{i_g^2} = 2qI_G \cdot B$$

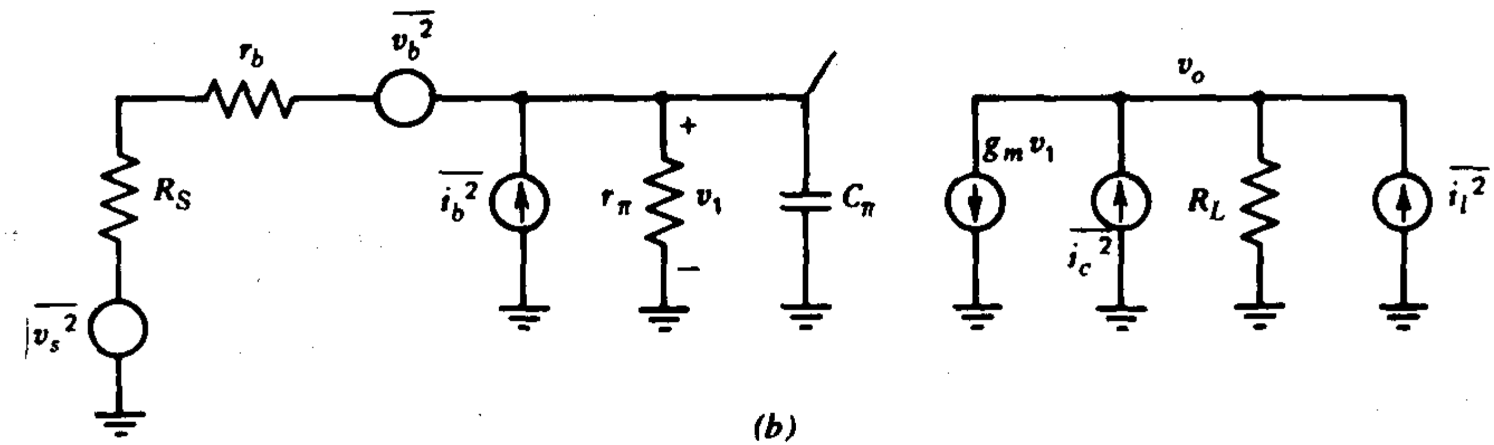


BJT noise performance

- Consider the noise performance of the simple transistor stage with the ac schematic shown below



- Consider the noise performance of the simple transistor stage with the ac schematic shown below



(b)

BJT noise performance (a)

- In this equivalent circuit the external input signal v_i, has been ignored so that output signal v_o is due to noise generators only. C_μ is assumed small and is neglected. Output resistance r_o *is* also neglected. The transistor noise generators are as described previously and in addition

$$\overline{v_s^2} = 4kTR_S B \qquad \overline{i_l^2} = 4kT\frac{1}{R_L}B$$

- The total output noise can be calculated by considering each noise source in turn and performing the calculation as *if* each noise source were a sinusoid with rms value equal to that of the noise source being considered.

BJT noise performance

- The spectral density of the noise generator is equal:

$$\frac{\overline{v_o^2}}{B} = g_m^2 R_L^2 \frac{|Z|^2}{|Z + r_b + R_S|^2}\left[4kT(R_S + r_b) + (R_S + r_b)^2 2qI_B\right] +$$

$$+ R_L^2\left(\frac{4kT}{R_L} + 2qI_C\right)$$

where Z is

$$Z = r_\pi \left\| \frac{1}{j\omega C_\pi}\right.$$

- Substituting for Z gives:

$$\frac{\overline{v_o^2}}{B} = g_m^2 R_L^2 \frac{{r_\pi}^2}{(r_\pi + r_b + R_S)^2} \cdot \frac{1}{1 + (f / f_1)^2}\left[4kT(R_S + r_b) + (R_S + r_b)^2 2qI_B\right] +$$

$$+ R_L^2\left(\frac{4kT}{R_L} + 2qI_C\right)$$

where

$$f_1 = \frac{1}{2\pi\left[r_\pi \| (r_b + R_S)\right]C_\pi}$$

BJT noise spectral density

- The output noise-voltage spectral density has a frequency-dependent part and a constant part.
- The frequency dependence arises because the gain of the stage begins to fall above frequency f_1, and noise due to generators v_s, v_b, and i_b,which appears amplified, also begins to fall.
- The constant term is due to noise generators i_l and i_c
- Assuming I_C=100 μA, R_S=500 Ω, R_L=5 kΩ, β=100, C_π=10 pF, r_b=200Ω