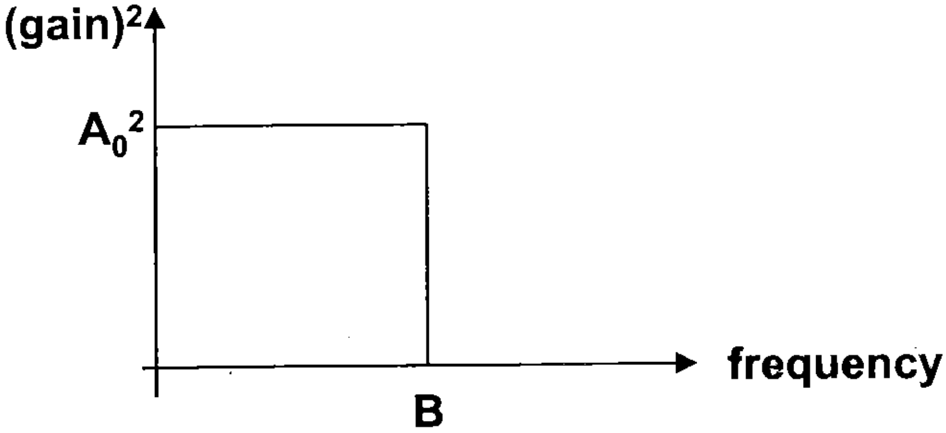
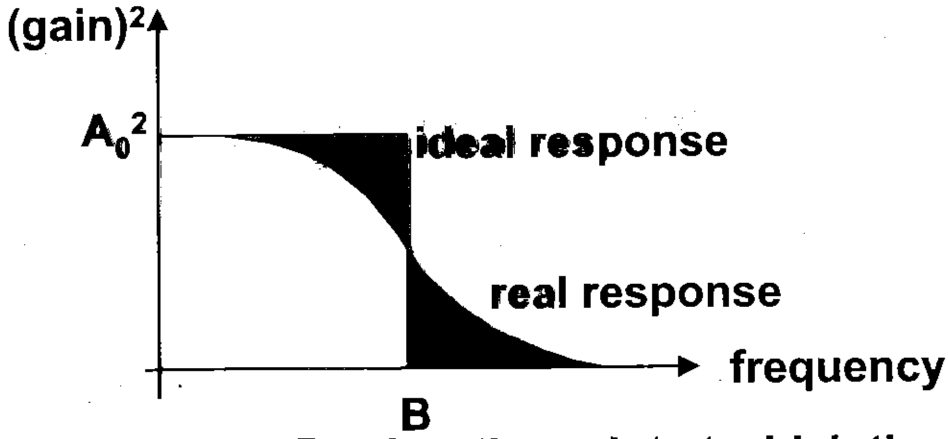
Noise Equivalent Bandwidth

- This is defined as the voltage-gain-squared bandwidth of the circuit
- The ideal case is that the $(\text{gain})^2$ is constant at a value of A_0^2 up to the bandwidth (A_0 = voltage gain)



- But, the behaviour of a real circuit is not abrupt



- The NEB is defined as the point at which the two shaded areas equal

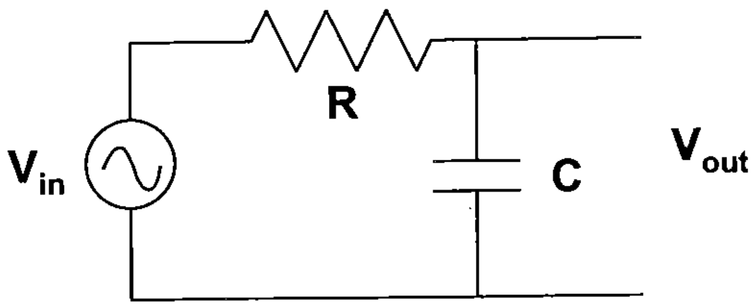
- Mathematically, this is given by

$$B = \frac{1}{|A_0|^2}\int_0^\infty \left|A(f)^2\right| df$$

- So in the ideal case

$$\text{bandwidth} = \frac{1}{A_0^2}\int_0^\infty |A|^2\, df = \frac{A_0^2 B}{A_0^2} = B$$

- If we take the example of an RC low pass filter



- Calculating the transfer function

$$A(\omega) = \frac{v_{out}}{v_{in}} = \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + R}$$

$$= \frac{1}{1 + 2\pi f RC} \quad \text{since } \omega = 2\pi f$$

$$= \frac{f_0}{jf + f_0} \quad \text{where } f_0 = \frac{1}{2\pi RC}$$

- At $f = 0$, $A(f) = A_0 = 1$ for this circuit
- Now we can calculate the noise equivalent bandwidth, using $A_0 = 1$

$$B = \int_0^{\infty} \left(\frac{f_0}{\sqrt{f^2 + f_0^2}} \right)^2 df$$

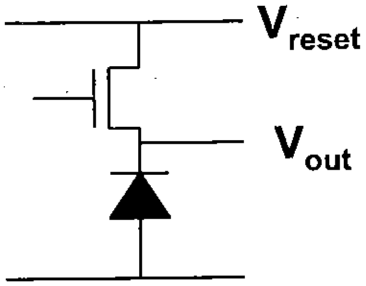
$$= f_0^2 \int_0^{\infty} \left(f_0^2 + f^2 \right)^{-1} df$$

$$= \frac{\pi}{2} f_0$$

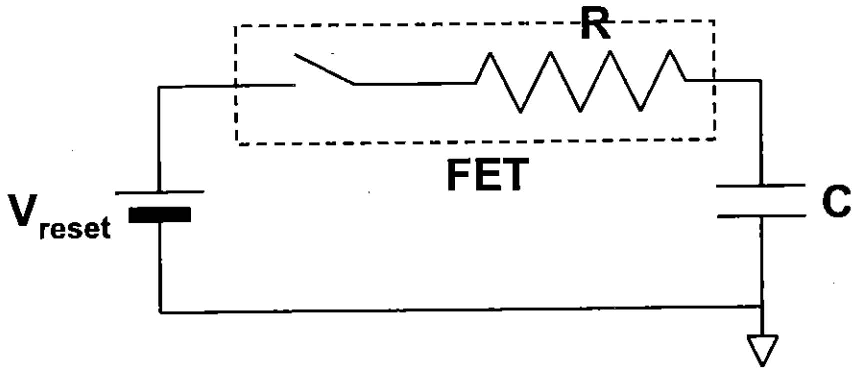
- The reason for choosing this example is that it is directly applicable to the resetting of photodiodes and the output nodes of CCD and photogate pixels

Reset Noise

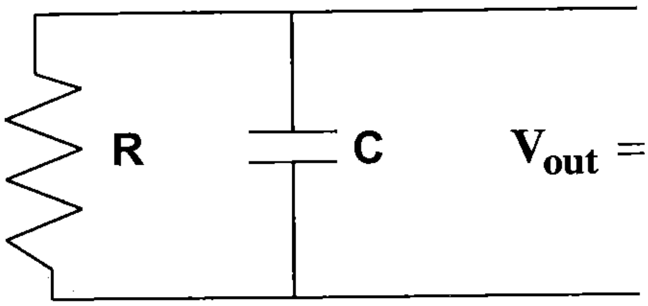
- If we consider a diffusion (either a floating diffusion or a photodiode) being reset through a MOSFET



- Effectively, this is a capacitance being charged through the resistance of the MOSFET channel



- So the ac-equivalent circuit is



$$V_{out} = \sqrt{4kTBR}$$

- From before, the bandwidth is

$$B = \frac{\pi}{2} f_0 = \frac{1}{4RC}$$

- So we find the rms noise voltage

$$\langle V_{out} \rangle = \sqrt{\frac{kT}{C}}$$

- Usually, the noise voltages is expressed in terms of electrons, in order to compare directly with the electrons in the well

- In which case the reset noise on the capacitor is calculated from $Q = nq = Cv_{out}$, and the rms noise electrons is given by

$$\langle n_e \rangle = \frac{C}{q}\sqrt{\frac{kT}{C}} = \frac{\sqrt{kTC}}{q}$$

- This noise is generally called "kTC noise" or, in this case, reset noise

- Calculating this out at room temperature gives

$$\langle n_{kTC,RT} \rangle = 400\sqrt{C(pF)}$$

- For a floating diffusion C ~ 20fF, so n_{kTC} = 55 e^-

- For a $(10\mu m)^2$ photodiode, C ~ 60pF, so n_{kTC} = 100 e^-

  » currently, reset noise limits the read noise in PDs