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## Flicker Noise (1/f Noise) in MOSFETs and its Dependence on Gate-to-Source Voltage ($V_{GS}$)

Flicker noise, also known as 1/f noise, is a significant source of low-frequency noise in MOSFETs. Its dependence on the gate-to-source voltage ($V_{GS}$) arises from its physical origin and impacts device performance, particularly in analog circuit design.

### Physical Origin

Flicker noise originates from the trapping and detrapping of charge carriers at defect sites located near the interface between the silicon (Si) channel and the silicon dioxide (SiO$2$) gate insulator. These defect sites can be interface traps or oxide charges. The gate-to-source voltage ($VGS$) plays a crucial role by:

- **Modulating Carrier Density:** $V_{GS}$ controls the number of charge carriers present in the conducting channel of the MOSFET.
- **Shifting the Fermi Level:** The position of the Fermi level near the interface is altered by $V_{GS}$, which in turn changes the probability of these traps being occupied by charge carriers.
- **Influencing Trap Emission/Capture Rates:** $V_{GS}$ can affect the rates at which carriers are trapped and detrapped by these defect sites.

### Key Equations

Two primary equations describe flicker noise in MOSFETs:

**1. Drain Current Noise Power Spectral Density (PSD):** This equation, based on the McWhorter model, quantifies the noise in the drain current:

$$S_{I_d}(f) = \frac{K_F \cdot I_D^a}{f^\gamma \cdot C_{ox} \cdot W \cdot L} \tag{1}$$

Where:

- $S_{I_d}(f)$: Drain current noise PSD [A$^2$/Hz]
- $K_F$: Flicker noise coefficient (a process-dependent parameter)
- $I_D$: Drain current
- $a$: Bias exponent (typically ranges from 1 to 2)
- $f$: Frequency
- $\gamma \approx 1$: Frequency exponent
- $C_{ox}$: Gate oxide capacitance per unit area
- $W$: Transistor width
- $L$: Transistor length

**2. Gate-Referred Voltage Noise PSD:** This is often more useful for circuit design as it represents the noise voltage at the input (gate):

$$S_{V_g}(f) = \frac{S_{I_d}(f)}{g_m^2} = \frac{K_F \cdot I_D^a}{f \cdot C_{ox} \cdot W \cdot L \cdot g_m^2} \tag{2}$$

Where:

- $S_{V_g}(f)$: Input-referred voltage noise [V$^2$/Hz]
- $g_m$: Transconductance of the MOSFET ($g_m = \partial I_D / \partial V_{GS}$)

## Dependence on $V_{GS}$

The gate-to-source voltage ($V_{GS}$) significantly affects flicker noise through its influence on the drain current ($I_D$) and transconductance ($g_m$), and this dependence varies with the MOSFET operating region:

### Weak Inversion (Subthreshold Region: $V_{GS} \ll V_{TH}$):

- $I_D \propto e^{V_{GS}/(nV_T)}$, where $n$ is the subthreshold slope factor and $V_T$ is the thermal voltage.
- $g_m \propto I_D$
- Substituting into $S_{V_g}(f)$: $S_{V_g} \propto \frac{I_D^{a-2}}{f}$
- For $a \approx 1$, $S_{V_g} \propto \frac{1}{I_D}$, thus **flicker noise decreases as $V_{GS}$ increases**.

### Strong Inversion ($V_{GS} > V_{TH}$):

- $I_D \propto (V_{GS} - V_{TH})^2$ (for long-channel devices)
- $g_m \propto \sqrt{I_D}$
- Substituting into $S_{V_g}(f)$: $S_{V_g} \propto \frac{I_D^{a-1}}{f}$
- For $a \approx 2$, $S_{V_g}$ is approximately **independent of $V_{GS}$**.

### Moderate Inversion:

- The relationship between $I_D$, $g_m$, and $V_{GS}$ is more complex.
- A **minimum in $S_{V_g}$** often occurs due to an optimal ratio between $g_m$ and $I_D$.

## Why $V_{GS}$ Matters for Flicker Noise

1. **Carrier Density:** Increasing $V_{GS}$ leads to a higher concentration of charge carriers at the Si-SiO$2$ interface. This increased carrier density can effectively screen the traps.
2. **Trap Time Constants:** $VGS$ shifts the Fermi level, altering trap energy levels and affecting trapping/detrapping time constants.
3. **Mobility Fluctuations:** Flicker noise is also linked to fluctuations in the effective mobility ($\mu_{eff}$), which depends on $V_{GS}$.

## Some Points to Remember

- **PMOS vs. NMOS:** PMOS devices often show lower flicker noise due to buried channel characteristics.
- **Analog Design:** In LNAs and oscillators, operating in moderate inversion reduces flicker noise.
- **Technology Scaling:** Thinner oxides increase trap density, enhancing flicker noise.
- **SPICE Modeling:** Parameters like $K_F$ and $AF$ (bias exponent) model flicker noise in SPICE simulations.

## Summary of $V_{GS}$ Dependence

Table 1: Dependence of $S_{V_g}(f)$ on $V_{GS}$ in Different Operating Regions

| **Region** | **$S_{V_g}(f)$ Trend vs. $V_{GS}$** |
|---|---|
| Weak Inversion | Decreases with $V_{GS}$ |
| Strong Inversion | Constant (if $a = 2$) |
| Moderate Inversion | Minimum noise |

In conclusion, the gate-to-source voltage ($V_{GS}$) plays a critical role in determining the flicker noise characteristics of MOSFETs. Understanding this dependence across different operating regions is essential for designing low-noise electronic circuits and optimizing device performance.