Analysis of 1/f Noise in CMOS APS

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Motivation

- **Image sensor circuitry sensitive to 1/f noise**
- **1/f noise more pronounced as technology scales – Noise power inversely proportional to channel area**
- **Circuit noise analysis based on stationary 1/f noise model**
  - **Model may not be applicable to APS circuits**
  - **Frequency domain analysis may be inaccurate**

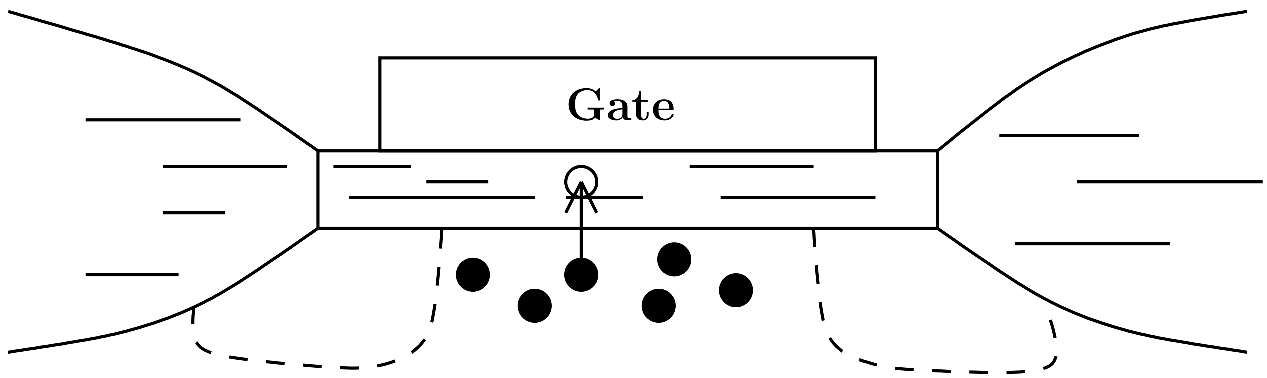
Propose a nonstationary extension of the 1/f noise model
Use it to analyze 1/f noise in APS pixel circuitry

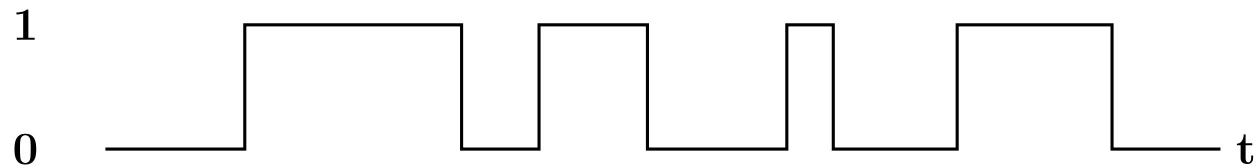
Outline

- Standard stationary 1/f noise model
- Nonstationary extension
- 1/f noise due to follower and access transistors
- 1/f noise due to reset transistor
- Conclusion

Single Trap: RTS Noise

Single trap inside gate oxide: trapped electron number can be modeled as a random telegraph signal (RTS)





Noise waveform

RTS Noise: Lorentzian Spectrum

- The trap captures or releases an electron according to a Poisson process with rate $\boldsymbol{\lambda}$
- Autocovariance of trapped electron number at steady state is $C(\tau) = \frac{1}{4}e^{-2\lambda|\tau|}$
- Power spectral density is $S_{\lambda}(f) = \frac{1}{4}\frac{\lambda}{\lambda^2+(\pi f)^2}$, which is Lorentzian

Stationary 1/f Noise

- The log uniform distribution of λ results in 1/f noise psd

$$S(f) = \int_{\lambda_L}^{\lambda_H} S_\lambda(f) \frac{N_{trap}}{\lambda \log \frac{\lambda_H}{\lambda_L}} d\lambda \approx \frac{kTAN_t}{2\gamma f}$$

  – SPICE 1/f noise parameter: $k_F = \frac{q^2 kTN_t}{C_{ox}\gamma}$
  – For 0.35μ CMOS process: $t_{ox} = 7\text{nm}$, $N_t = 10^{17}\text{eV}^{-1}\text{cm}^{-3}$, and thus $k_F = 5 \times 10^{-24}\text{V}^2\text{F}$

- Problem: To use this model in noise analysis, need to define a low cut off frequency $f_L = 1/t_{on}$

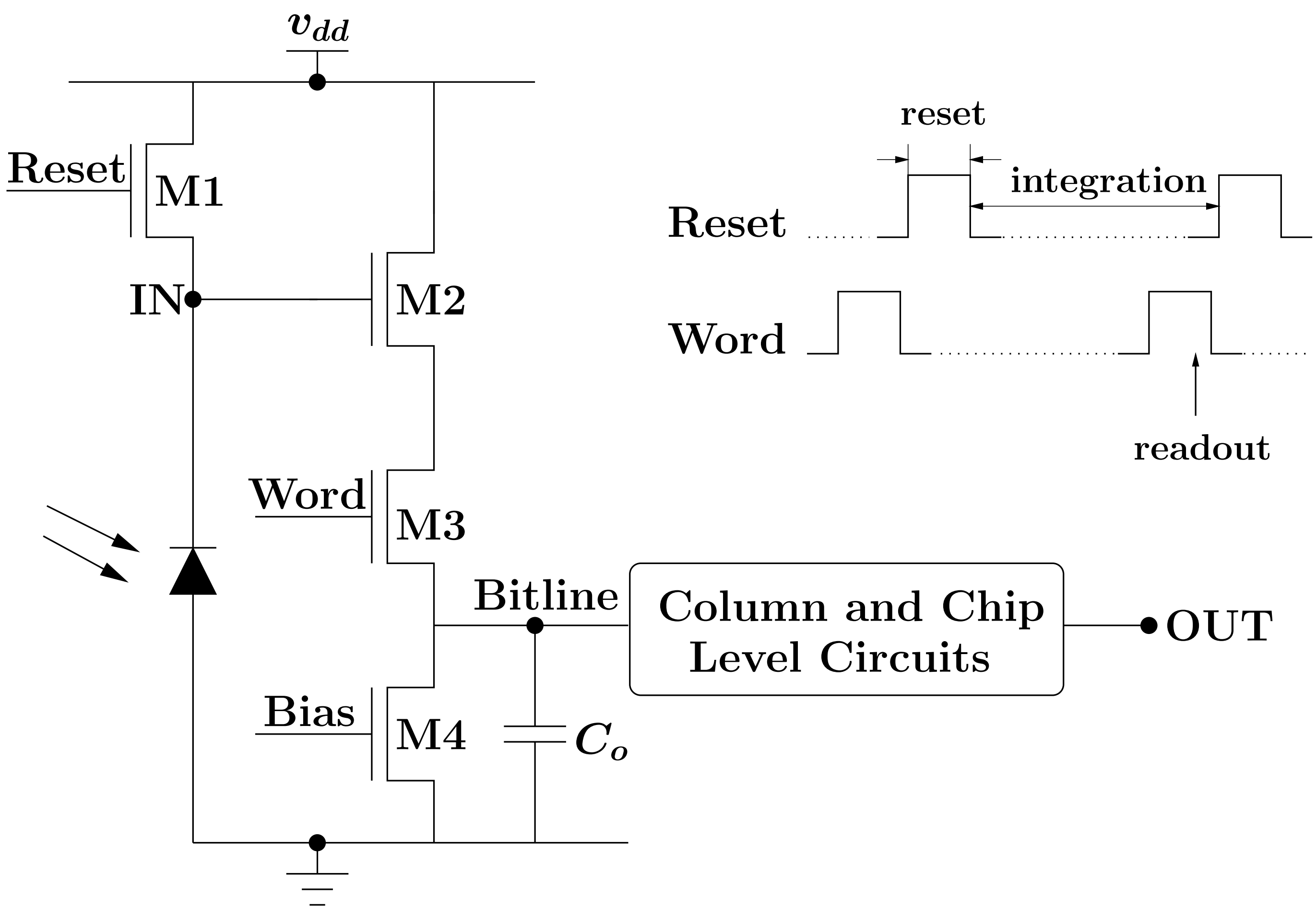
Nonstationary Extension

- Assuming active traps are empty at the time the transistor is turned on
- Time varying autocovariance of trapped electron number for one trap is

$$C_\lambda(t,\tau) = \frac{1}{4} e^{-2\lambda|\tau|}(1 - e^{-4\lambda t}), t \geq 0$$

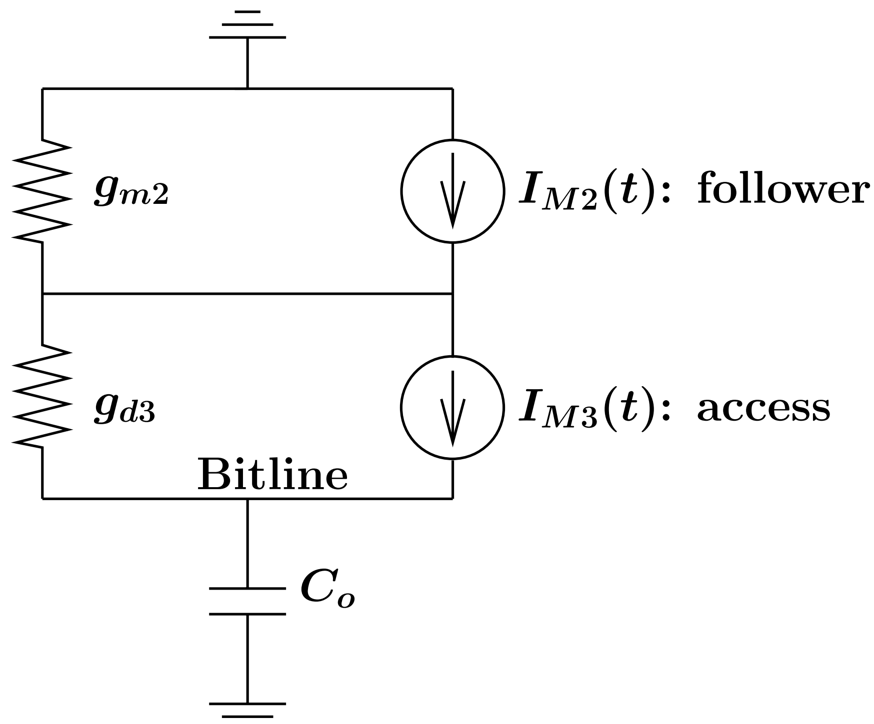
- As $t \to \infty$, $C_\lambda(t,\tau)$ converges to stationary autocovariance
- Summation of $C_\lambda(t,0)$ leads to time varying noise power, avoiding the use of low cut off frequency

APS Circuit and Operation



$L = 0.7\mu$m, $W = 1.4\mu$m, $C_o = 3$pF, $C_{pd} = 22$fF

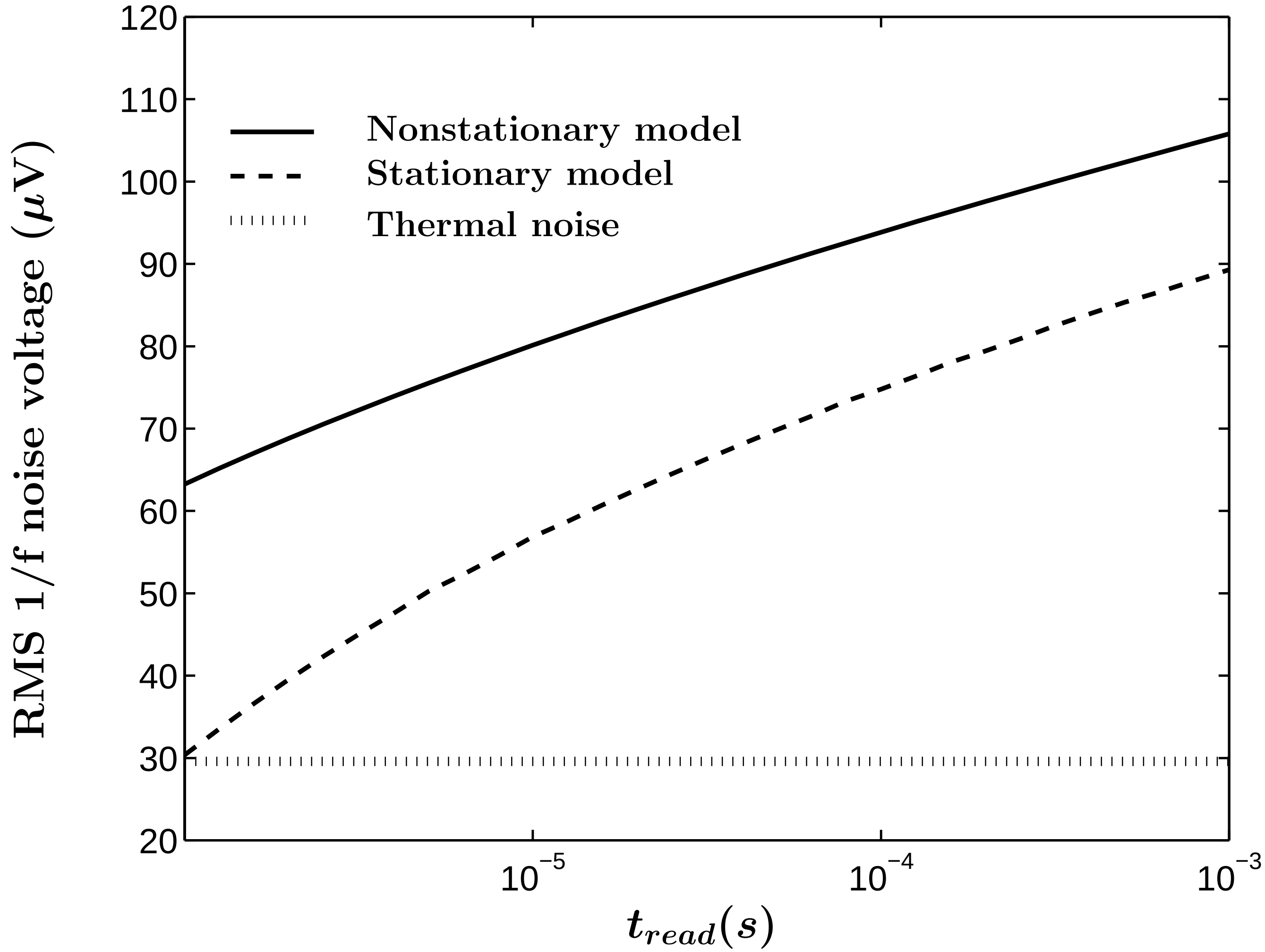
1/f noise During Readout



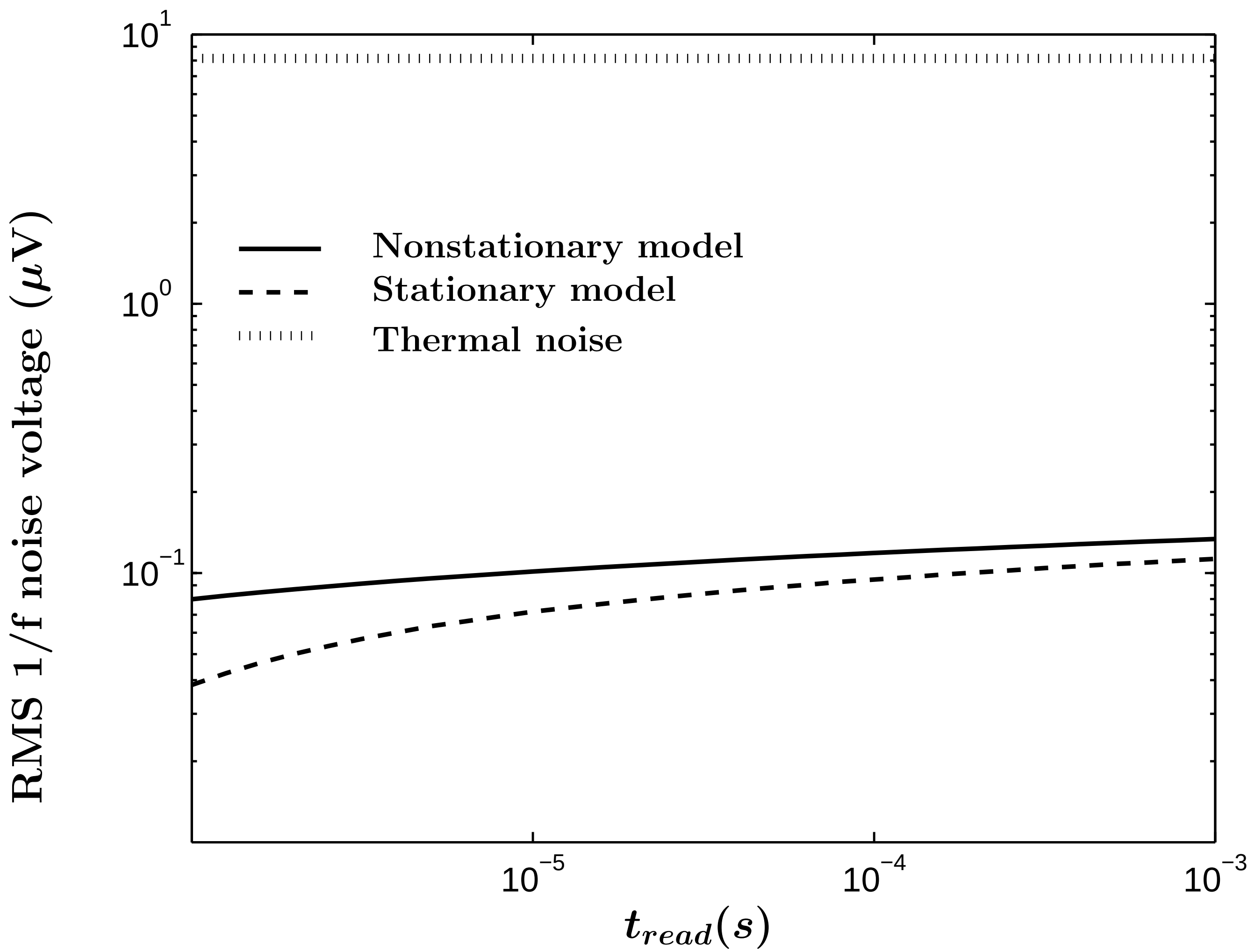
Mean square noise voltage due to each transistor has the form:

$$\overline{V^2(t)} = \left(\frac{q g_M}{A C_{ox}}\right)^2 \frac{e^{-\frac{2g_M}{C_M}t}}{C_M^2} \int_0^t \int_0^t \int_{\lambda_L}^{\lambda_H} g(\lambda)\mathcal{C}_\lambda(s_1, |s_2 - s_1|) e^{\frac{g_M}{C_M}(s_1+s_2)} d\lambda\, ds_1\, ds_2$$

RMS 1/f Noise Voltage Due to Follower Transistor



RMS 1/f Noise Voltage Due to Access Transistor



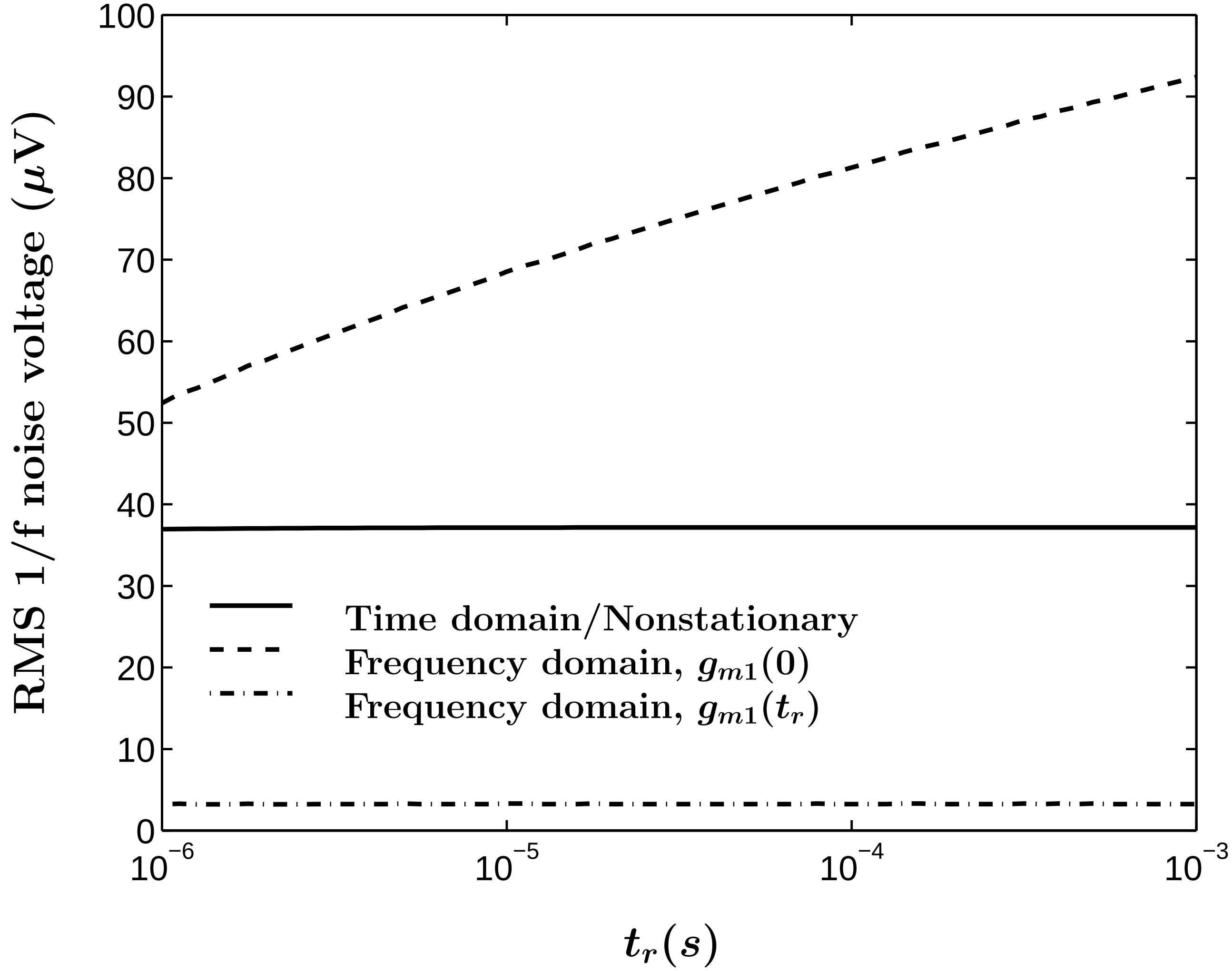
1/f Noise During Reset

- Conventional frequency domain analysis

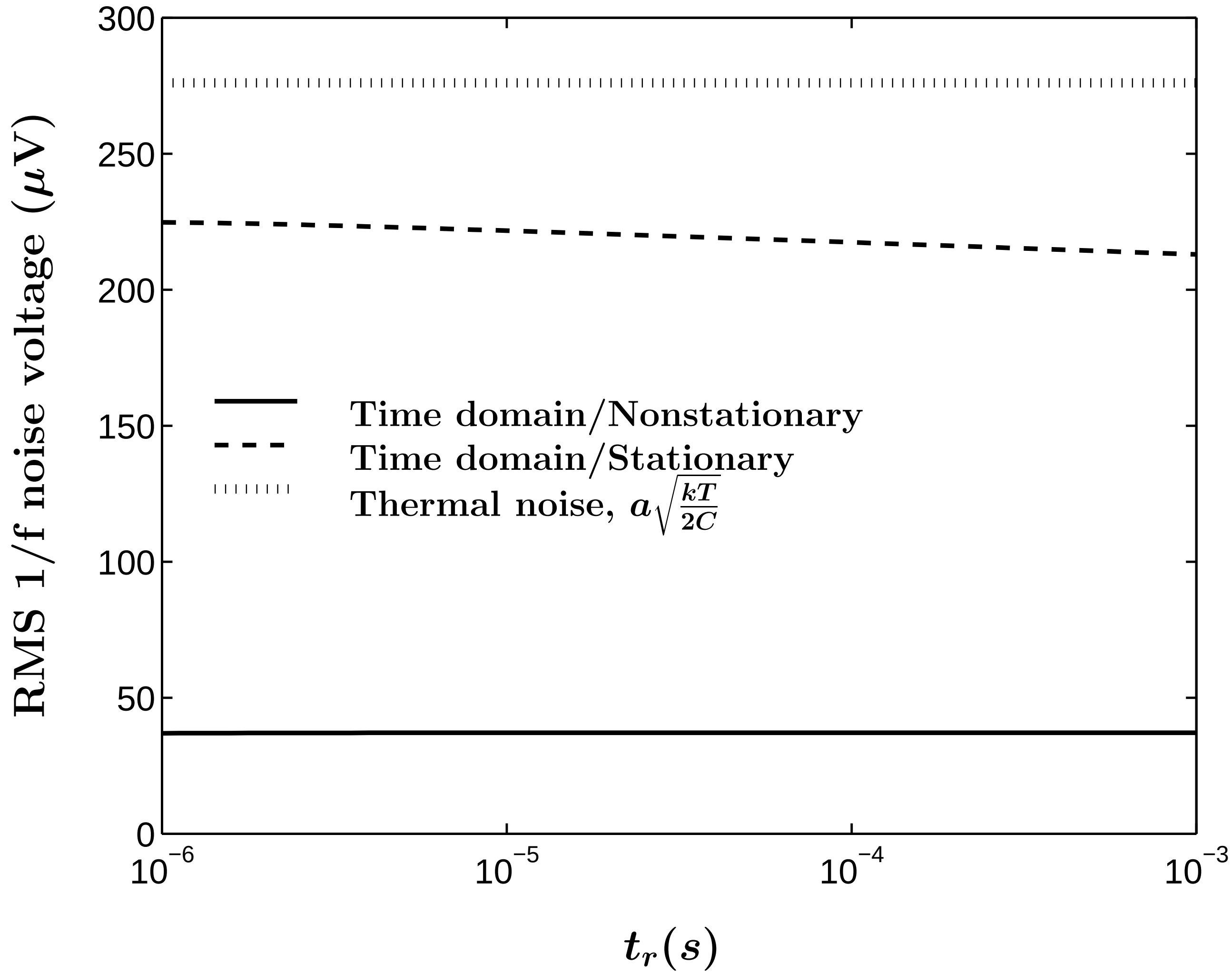
$$\overline{V_{M1}^2(t_r)} = 2a^2 \int_{\frac{1}{t_r}}^{\infty} \frac{S_{I_d}(f)}{g_{m1}^2 + 4\pi^2 f^2 C_{pd}^2} df$$

- Circuit parameters are time varying during reset: g_{m1} is picked arbitrarily
- Consider both the time variability of the reset circuit, and the nonstationarity of the noise source
  - Time domain analysis/Nonstationary 1/f noise model
- Compare with:
  - Frequency domain analysis/Stationary 1/f noise model
  - Time domain analysis/Stationary 1/f noise model

Time Domain/Nonstationary vs. Frequency Domain



Time/Nonstationary vs. Time/Stationary



Conclusion

- **Nonstationary extension of the physical 1/f noise model**
- **Analysis of APS pixel circuitry 1/f noise**
  - **Involves transistors working in subthreshold, linear, and saturation regions**
  - **Frequency domain analysis based on stationary 1/f noise model can generate very inaccurate estimates**