Low-Frequency Shot-Noise Thermometry

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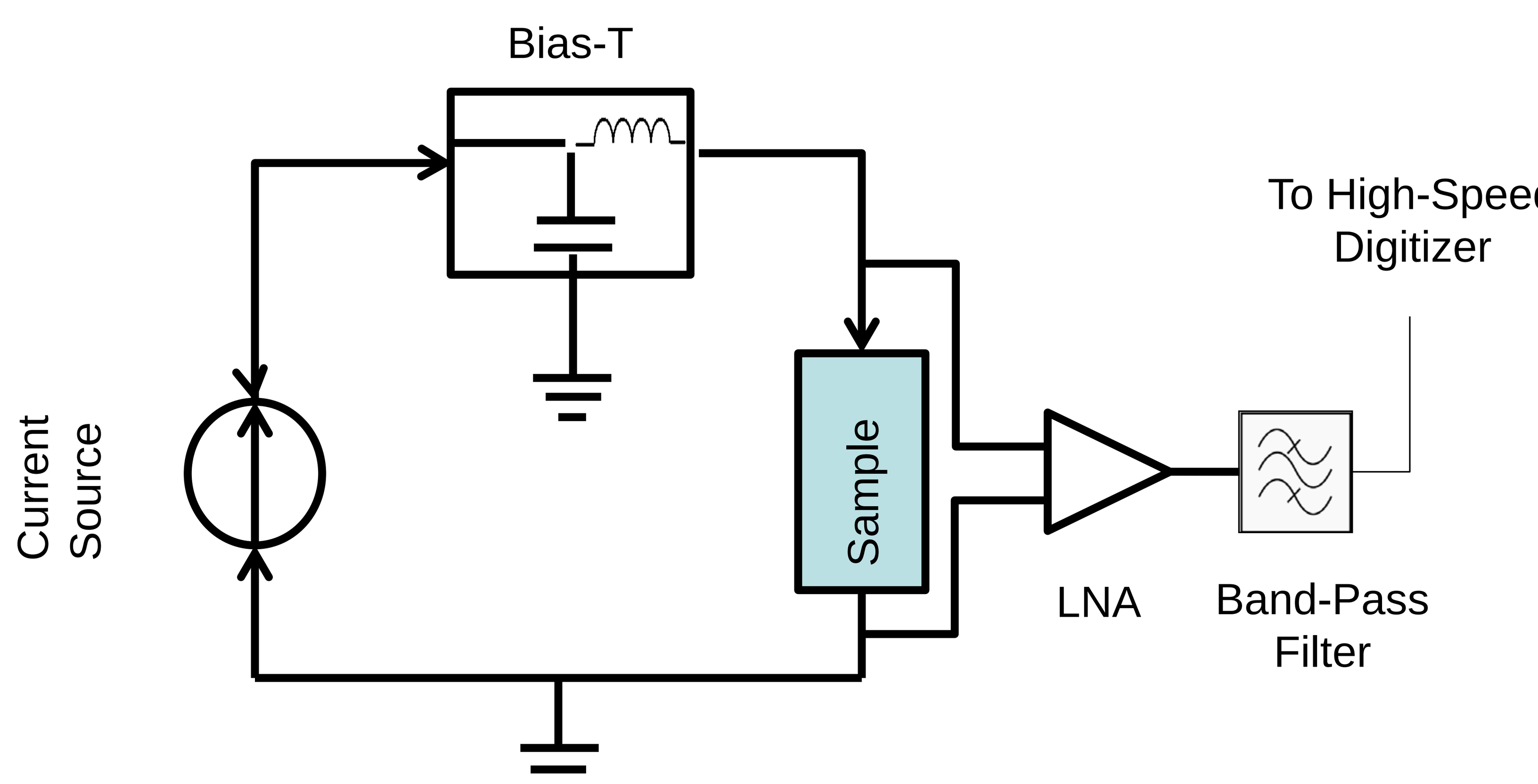
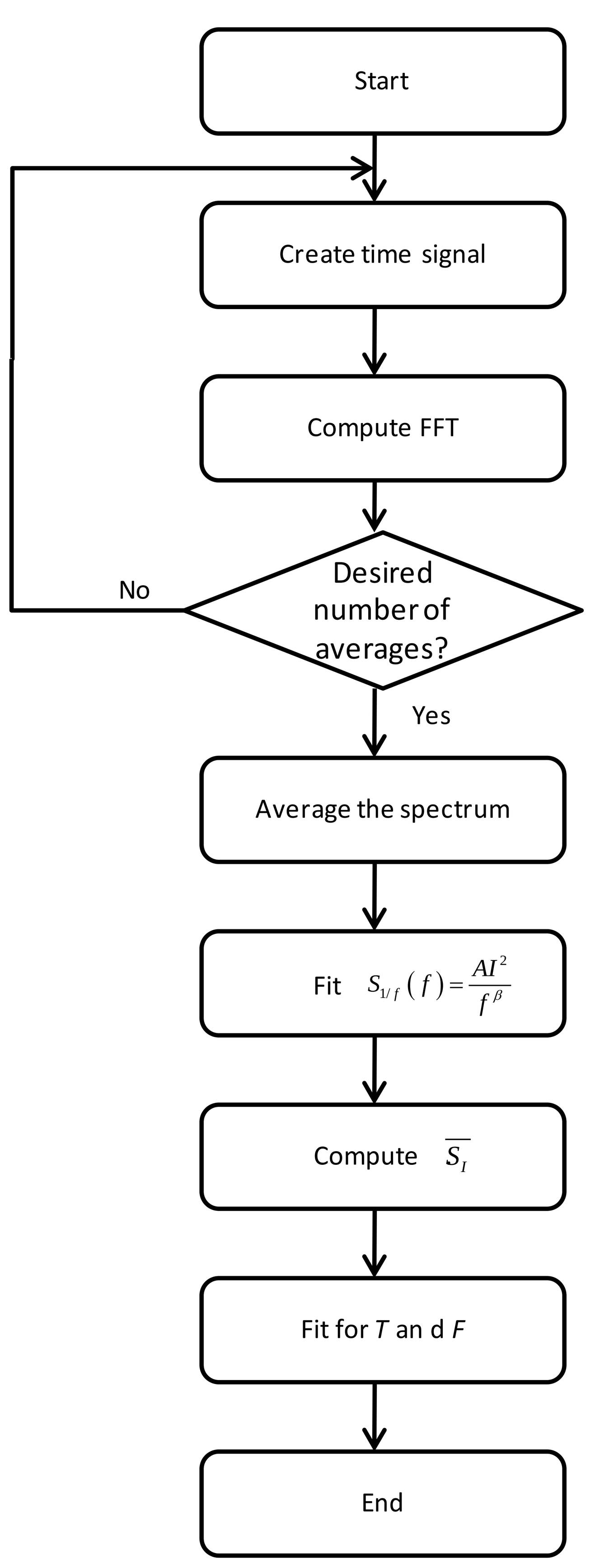
Motivation

- Accurate measurement of temperature by common methods, such as traditional thermometers and thermocouples, become challenging due to complications associated with the small size of nanoscale devices.
- Shot-Noise thermometry is a primary temperature measurement technique, and thus does not require calibration.
- Devices utilizing electrical noise are capable of providing a relatively low-cost, non-intrusive method of obtaining highly accurate temperature measurements.
- The low frequency regime of the noise signal has been avoided in the past due to the presence of 1/f noise; however, for devices such as carbon nanotubes, this additional noise source can encompass a significant portion of the frequency spectrum.

Experimental Setup



Numerical Simulations



- A signal was first generated at three voltage levels that contained all three noise sources discussed above (Johnson, Shot, 1/f) having a certain value for temperature, Fano factor, and 1/f noise parameters *A* and *β*.
- Noise was generated by a normal distribution for Johnson and Shot noise. For 1/f noise, the phase was varied uniformly in frequency space, after which the inverse Fourier transform was taken.
- This signal was then transferred to the frequency domain via fast Fourier transform (FFT) and averaged using Bartlett's method.
- Blind to the parameters utilized to generate the signal, the low-frequency range was fitted to Eq. (4).
- Based on the fit, the 1/f noise was accounted for and the remaining portion was fitted to Eq. (3) to determine the temperature and Fano factor.
- The actual values for Fano-factor and temperature used for signal generation were compared to the calculated values determined by fitting with Eq. (3).
- Accuracy of this method for determining the Fano factor and temperature was evaluated while modifying several different parameters.

Acknowledgements

•Dr. Vidhyadhiraja Sudhindra and Sudeshna Sen of the Jawaharlal Nehru Centre for Advanced Scientific Research for collaborative work on theoretical aspects of noise thermometry.

Based on Results in:
R.A. Sayer, J.D. Engerer, S. Sen, N.S. Vidhyadhiraja and T.S. Fisher, "Low-Frequency Electrical Noise Thermometry For Micro- and Nano-Scale Devices," Proc. IMECE, Denver, Nov 2011..

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Governing Theory

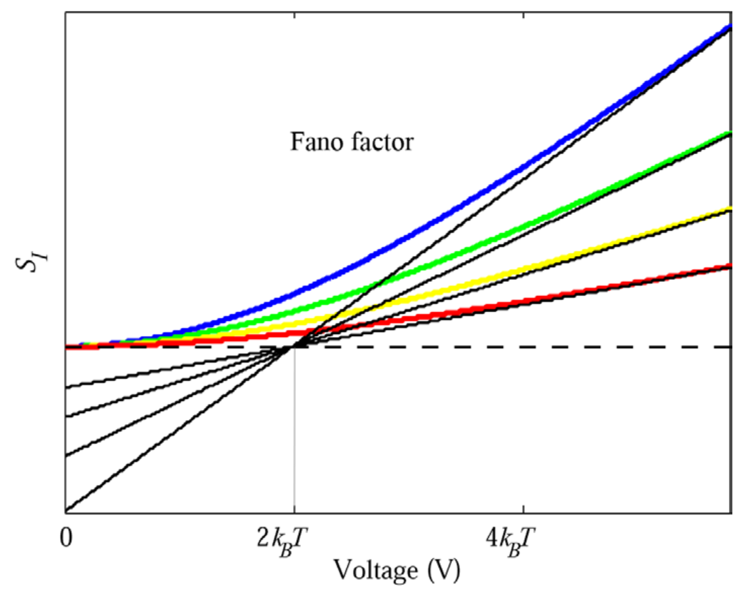
- Johnson Noise is present in any conductor and is the result of random fluctuations of the electron gas, also referred to as Brownian motion. These fluctuations are due to thermal vibrations within the material and obey the following relation for current spectral density:

$$S_{I,J}=\frac{4k_BT}{R} \qquad (1)$$

- Shot-Noise is the result of charge carriers crossing a barrier under an applied bias. Due to their discrete nature of the electrons crossing the junction, an electrical noise is introduced into the system of the following spectral density:

$$S_{I,s}=2eI \qquad (2)$$

- Since it has no temperature dependence, shot-noise initially appears to be of little use in thermometry; however, when measured in conjunction with Johnson noise, the current spectral density obeys the following non-linear relation, where *F* is the Fano factor:



$$S_{I,s+J}=2eIF\coth\left(\frac{eV}{2k_BT}\right)+(1-F)\frac{4k_BT}{R} \qquad (3)$$

- Each of these relations are constant in the frequency domain, so a simple integration of the frequency spectrum of the resulting noise from these sources can lead to accurate temperature measurements. However, in many nanoscale systems, there is an additional noise component referred to as 1/f noise, or flicker noise.

$$S_{I,1/f}=\frac{AI^2}{f^\beta} \qquad (4)$$

Results

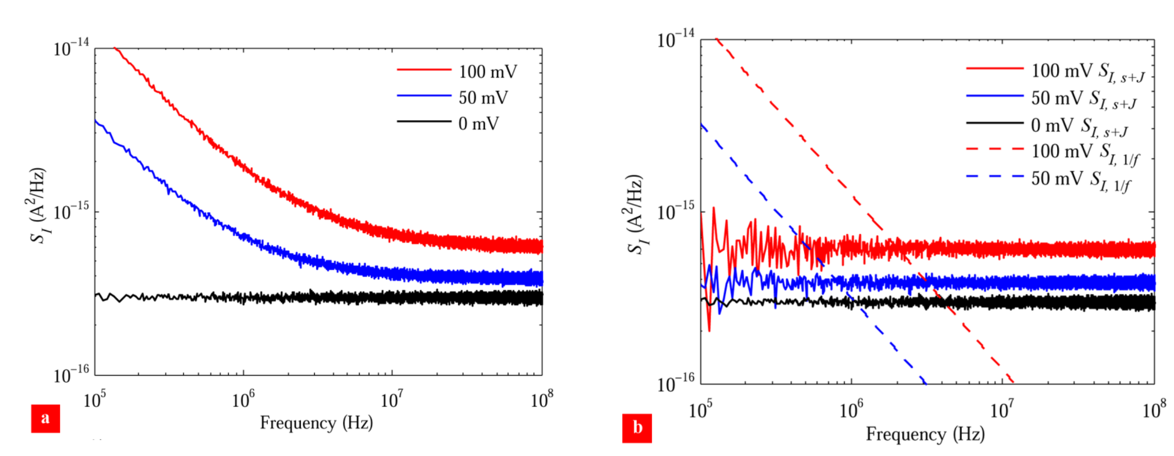


Fig. 1: Noise spectrum at 300 K (a) with 1/*f* noise and (b) after the noise signal has been broken up into its 1/*f* and combined shot and Johnson components. The 1/*f* noise component is obtained from a fit to the low frequency data. 1000 data averages were used. (A = 5 x 10^{-10}, R = 50 Ω, F = 1, β = 1)

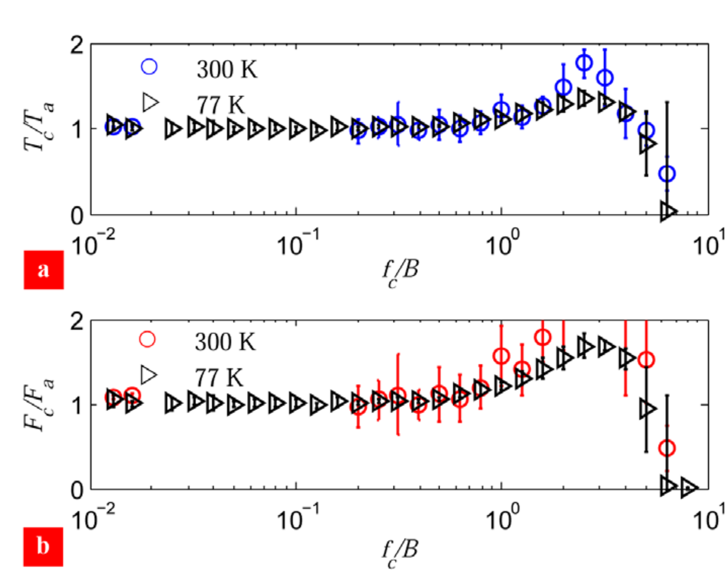


Fig. 2: Effect of 1/*f* noise magnitude on the accuracy of the fit (a) temperature and (b) Fano factor at 77 and 300 K. Error bars represent the 95% confidence interval on the fit. (M = 400, R = 50 Ω, β = 1, F_a = 1)

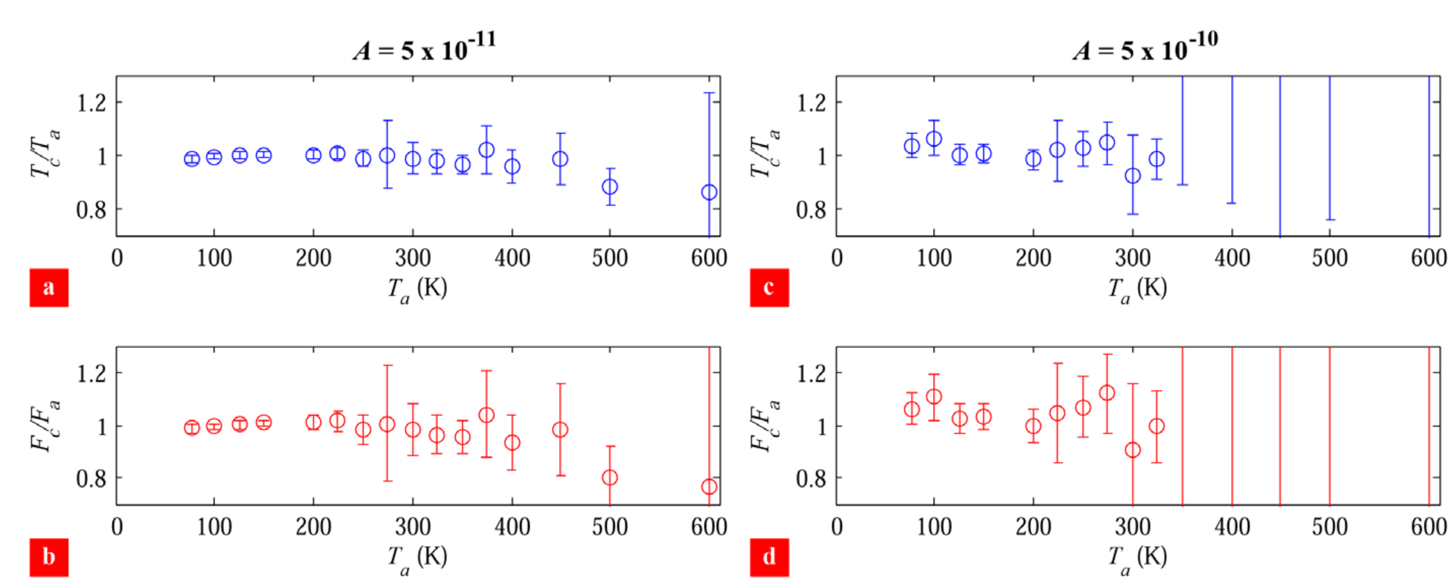


Fig. 3: Fitting accuracy of (a) temperature and (b) Fano factor for simulated device temperature ranging from 77 to 600 K with A = 5 x 10^{-11}. (c) Temperature and (d) Fano factor accuracy for A = 5 x 10^{-10}. (M = 400, R = 50 Ω, β = 1, F_a = 0.7)

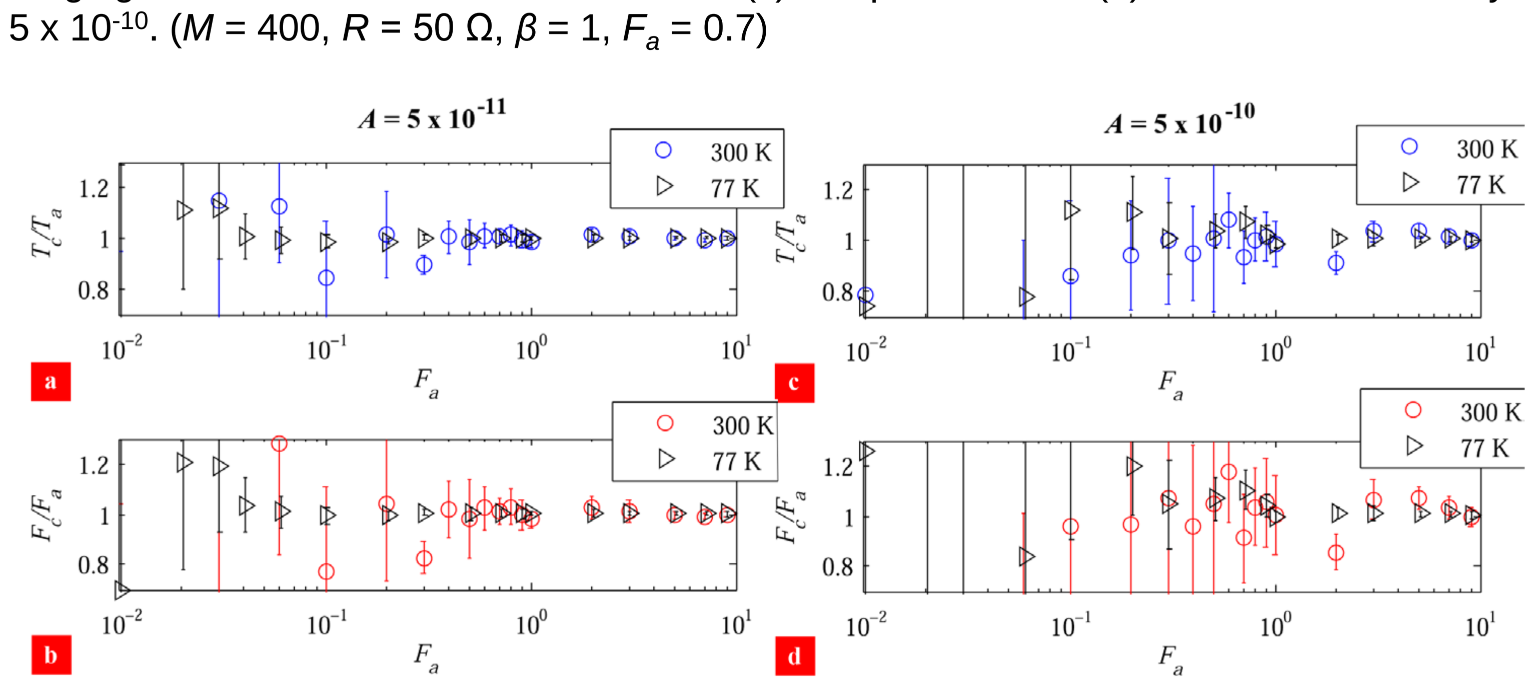


Fig. 4: Fitting accuracy of (a) temperature and (b) Fano factor for simulated device Fano factors spanning three orders of magnitude with A = 5 x 10^{-11}. (c) Temperature and (d) Fano factor accuracy for A = 5 x 10^{-10}. (M = 400, R = 50 Ω, β = 1)