Fluctuation-dissipation and Johnson-Nyquist noise in thermoelectric materials

N.A.M. Tran[1], A.S. Dutt[2], N. B. Pulumati[2], H. Reith[2], A. Hu[1], A. Dumont[3], K. Nielsch[2], A.-M.S. Tremblay[3], G. Schierning[4], B. Reulet[3], T. Szkopek[1]

[1]*Department of Electrical and Computer Engineering, McGill University, Montréal, Québec, H3A 0E9, Canada*

[2]*Institute for Metallic Materials, IFW Dresden, Dresden, 01069, Germany*

[3]*Département de physique, Institut Quantique, Université de Sherbrooke, Sherbrooke, Québec, J1K 2R1, Canada*

[4]*Institut für Energie- und Material-Prozesse, Universität Duisburg-Essen, Duisburg, 47057, Germany*

thomas.szkopek@mcgill.ca

The Johnson-Nyquist noise formula $4k_BTR$ for the spectral density of voltage fluctuations accounts for fluctuations associated solely with Ohmic dissipation [1,2]. Surprisingly, the spectral density of voltage fluctuation in a thermoelectric material, where the transport of charge and heat are correlated, has not been previously studied. In this work [3], we generalize the Johnson-Nyquist formula for thermoelectrics, finding an enhanced voltage fluctuation spectral density $4k_BTR(1 + zT)$ at frequencies f below a thermal cut-off frequency f_T, where zT is the dimensionless thermoelectric *material* figure of merit [4]. For a typical thermoelectric device composed of *n*-type and *p*-type legs, the voltage spectral density is $4k_BTR(1 + ZT)$ below thermal cut-off, where ZT is the dimensionless thermoelectric *device* figure of merit [4]. The origin of the excess voltage fluctuations is the thermoelectric conversion of temperature fluctuations to potential fluctuations.

We confirmed our findings experimentally using state-of-the-art integrated thermoelectric micro-devices [5] with *n*-type BiTeSe and *p*-type Te thermoelectric legs and wideband ($f_T \sim 1$ kHz) response. Measuring the ZT enhanced voltage noise, we experimentally resolve temperature fluctuations with a root mean square amplitude of 0.8 µK $Hz^{-1/2}$ at a mean temperature of 295 K. We thus demonstrate that thermoelectric materials and devices can be used for thermometry with sufficient resolution to measure the fundamental temperature fluctuations associated with the fluctuation-dissipation theorem.

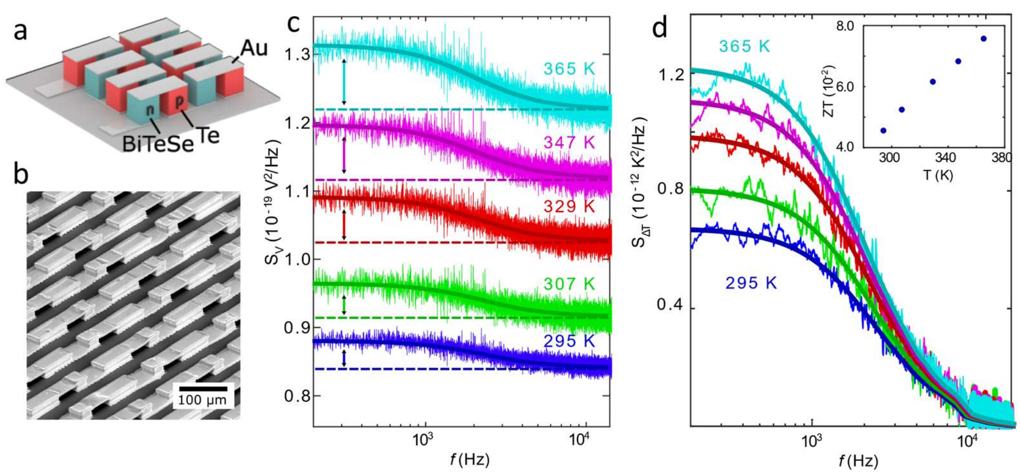

Fig.1. a) Schematic and b) electron microscope image of integrated thermoelectric micro-devices with n-type and p-type legs connected with Au bridges. c) Measured voltage fluctuation spectral density S_V versus frequency f at varying temperature T, showing enhancement at $f < f_T \sim 1$ kHz. Ohmic contribution (dashed line) and theory fit (solid line) are shown. d) Inferred temperature fluctuation spectral density S_T versus f at varying T, with theoretical fit (solid line). Inset shows the device figure of merit ZT versus T.

References

[1] J. B. Johnson, Physical Review **32**, 97 (1928).

[2] H. Nyquist, Physical Review **32**, 110 (1928).

[3] N.A.M. Tran *et al.*, EuroPhysics Letters **141**, 26002 (2023).

[4] D.M. Rowe, CRC Handbook of Thermoelectrics (CRC Press, Boca Raton) 1995.

[5] G. Li *et al.* Nature Electronics **1**, 555 (2018).