Johnson-Nyquist Noise

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Introduction

Near-field heat transfer by evanescent waves is claimed [1,2] to produce heat fluxes 1000 times greater than given by Planck's theory of blackbody radiation. Based on tunneling of evanescent waves through nanoscale gaps, near-field heat transfer is thought enhanced by exciting dipoles in gap surfaces that are dissipated by Joule heating. Confirmation of the physics of near-field heat transfer is therefore of great importance in energy harvesting, e.g., the development [1] of high-energy density thermo-photovoltaic devices.

Background

In support of near-field heat transfer at the nanoscale, experimental data [1,2] for glass plates is limited by flatness to micron size gaps. At the nanoscale, near-field heat transfer [1] between microspheres and flat surfaces is promising as flatness problems are avoided. Nevertheless, support for near-field enhancement of heat transfer relies almost entirely on classical solutions by the Maxwell equations, the validity of which has been questioned [3] because by QM the EM confinement of surface atoms precludes the temperature fluctuations necessary to satisfy the FDT. QM stands for quantum mechanics, EM for electromagnetic, and FDT for fluctuation-dissipation theorem.

Purpose

Invalidity of solutions of Maxwell's equations in near-field heat transfer because of QM restrictions on the FDT suggests the hope for enhancement in energy harvesting cannot be fulfilled. In this regard, a review of the QM restriction on the FDT is presented by considering the voltage signal of the J-N noise from a hypothetical resistor in the surface of a nanoscale gap under EM confinement at ambient temperature. J-N stands for Johnson-Nyquist.

Analysis

In near-field heat transfer solutions of Maxwell equations, the FDT was formulated [4] based on observations of temperature induced voltage fluctuations of J-N noise in resistors. The J-N noise was derived [5] for signals at low-frequencies by SM, but the derivation included the QM restriction on high-frequencies noise from atoms in gap surfaces under the EM confinement of nanoscale gaps. SM stands for statistical mechanics.

The QM relation for the voltage signals of J-N noise in terms of the EM confinement frequency f is described in the thumbnail. In a gap of dimension d, the EM confinement wavelength $\lambda = 2d$ is related to its frequency $f = c/\lambda$, where c is the speed of light. R stands for resistance of the resistor, h for Planck's constant, k for Boltzmann's constant, and T absolute temperature. The SM relation at high-frequency is the same as that for QM at low frequencies. Figures 1 – 3 show J-N noise signals for the R = 1000 ohm resistor in terms of (1) Mean-Square Voltage $\langle V(f)^2 \rangle$ / Hertz, and (2) Mean Voltage $V(f)$ over the bandwidth B of measurement.

Mean Square Voltage The QM Mean-Square Voltage V^2 / Hertz signal was normalized by the SM response. For low-frequencies $f < 3x10^{11}$ Hz (d >500 microns), both SM and QM give the same noise signal of $1.65x10^{-17}$ V^2/Hz. SM at high EM confinement frequencies remains the same while the QM signal is reduced. E.g., at f = 3x10^13 Hz (d = 5 microns) the QM signal is 0.0398 x lower, i.e. $6.5x10^{-19}$ V^2/Hz. At $f = 3x10^{14}$ Hz (d = 0.5 microns) and $3x10^{15}$ Hz (d = 0.05 microns), the QM noise signal is virtually imperceptible at about 20 and 200 orders of magnitude lower than given by SM. It is noted that near-field heat transfer requires gaps d < 0.05 microns to achieve [1] the enhancement necessary for a breakthrough in photovoltaics.

Mean Voltage The Noise Voltage V requires a measurement bandwidth $B = (f_{max} – f_{min})$. Taking $f_{max} = f$ and $f_{min} = 0$, B = f. At low-frequencies $f < 3x10^{11}$ Hz (d > 500 microns), both SM and QM give the same noise signal of 2.2 mV. Again, at higher EM confinement frequencies, the SM noise remains the same while the QM signal is reduced. E.g., at $f = 3x10^{13}$ Hz (d= 5 microns) the QM noise is 0.0398 x lower than by SM, i.e. 0.08 mV. At $f = 3x10^{14}$ Hz (d = 0.5 micron) and $3x10^{15}$ Hz (d = 0.05 micron), the QM noise is imperceptible at about 10 and 100 orders of magnitude lower than given by SM. Again, near-field heat transfer requires gaps d < 0.05 microns to achieve a breakthrough in photovoltaics.

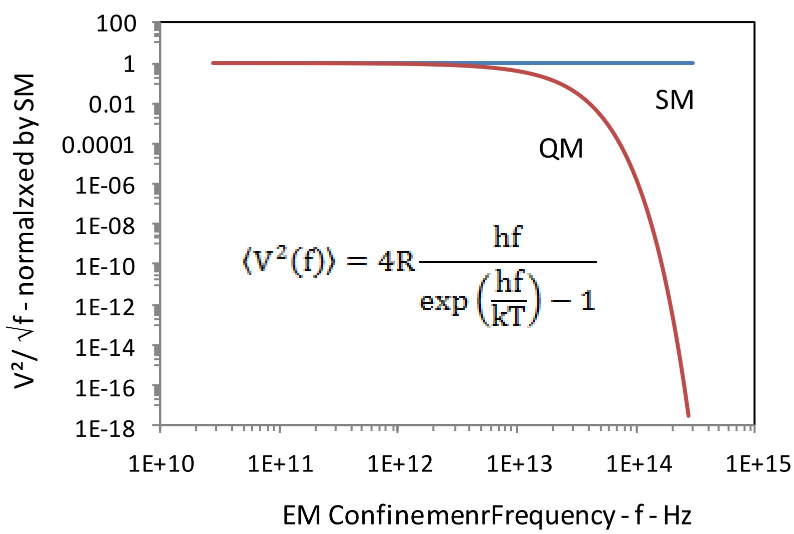

Figure 1 J-N Noise and EM Confinement Frequency

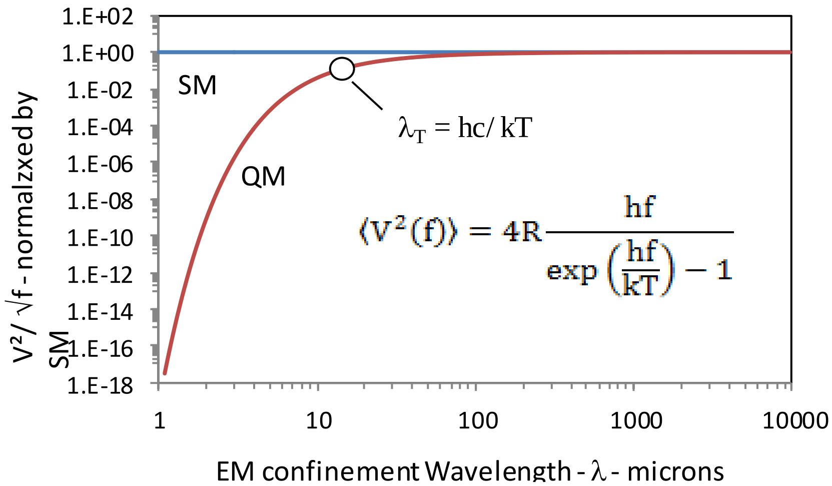

Figure 2 J-N Noise and EM Confinement Wavelength

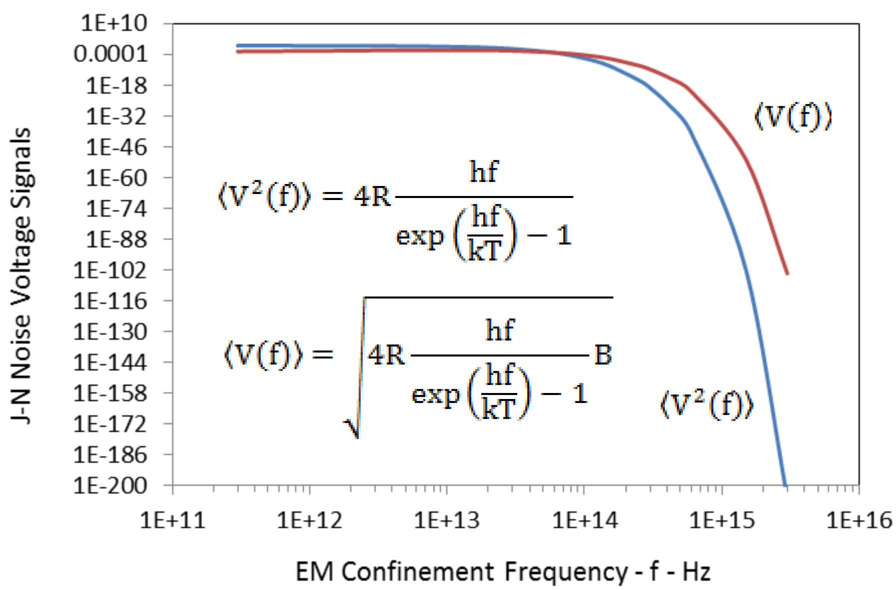

Figure 3 J-N Noisea and EM Confinement Frequency

Conclusions

1. The J-N noise as a measure of the validity of the FDT under EM confinement based on a resistor in the surface of nanoscale gaps having a resistance of 1000 ohms shows the atoms under EM emit almost imperceptible voltage signals at ambient temperature. Hence, the FDT in nanoscale gaps is most likely not satisfied, and therefore near-field heat transfer by the mechanism of tunneling of evanescent waves in nanoscale gaps cannot be supported by solutions of Maxwell's equations.

2. QED induced radiation based on QM is independent of the FDT. EM confinement of thermal emission is precluded in nanoscale gaps, and therefore the surface atoms cannot conserve heat flow by an increase in temperature. Instead, conservation proceeds by the QED induced creation of photons that carry the thermal radiation between gap surfaces.

3. Planck theory is consistent with near-field heat transfer by QED induced radiation.

4. SM that allows the atom to have heat capacity under high EM confinement in nanoscale gaps is refuted by QM.

References

[1] A. Narayanaswamy et al., **"**Breakdown of the Planck blackbody radiation law at nanoscale gaps," Appl Phys A, 96: 357–362 (2009).

[2] R. S. Ottens, et al., "Near-Field Radiative Heat Transfer between Macroscopic Planar Surfaces," PRL, 107, 014301 (2011)

[3] T. Prevenslik, "Radiation at the Nanoscale by Quantum Mechanics," Int. Workshop on Nano-Micro Thermal Radiation, May 23-25, Miyagi, 2012.

[4] S.M. Rytov, et al,, Principles of Statistical Radiophysics, Springer-Verlag, Berlin, Vol. 3, 1987.

[4] H. Nyquist, "Thermal Agitation of Electrical Charge in Conductors," Phys. Rev., 110-113 (1928).