Thermophones and Quantum Mechanics

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Abstract Thermophones for over a century have been thought to function as thermo-acoustic devices converting an alternating current to rapid temperature changes in thin platinum films. Subsequent pressure changes in the surrounding air allow the sound to propagate. Recently, thermophones from nanoscale sheets of carbon nanotubes (CNTs) are claimed to have far lower specific heat than platinum, and therefore more efficient in producing sound because the temperature changes are produced with less power. However, the CNT power would have to be increased to produce the same temperature change as for platinum. Since the sound from the CNT film at low power is louder than for platinum, temperature changes in the thin film cannot be the source of sound. Understanding how thermophones produce sound independent of temperature requires quantum mechanics (QM) as embodied in the theory of QED induced EM radiation. QED stands for quantum electrodynamics and EM for electromagnetic. Atoms in thin films are under EM confinement at levels beyond the visible (VIS) and ultraviolet (UV) that by QM are restricted to vanishing specific heat, and therefore Joule heat cannot be conserved by an increase in temperature – this is a QM size effect regardless of whether the film is platinum or CNTs. Prompt UV-VIS emission is produced by the QED up-conversion of low frequency Joule heat to the EM confinement frequency of the film without any increase in film temperature. Instead, the UV-VIS is absorbed in the air to cause the necessary temperature and attendant pressure changes to produce sound. Recommendations are made that classical heat transfer at the nanoscale be modified for vanishing specific heat as required by QM.

1. Introduction

In 1914, Lord Rayleigh communicated the description of the thermophone by de Lange [1] to the Royal Society. But as early as 1880, Preece [2] produced sound by passing current through micron sized platinum wires affixed to a diaphragm. de Lange reported that Gwozda around 1900 produced sound without a diaphragm by heating a straight wire alone.

Arnold and Crandall [3] produced sound with a platinum thermophone in 1917. Platinum is about six times more resistive than copper, leading to a higher power for a given current. The alternating current I and circular frequency $\omega = 2\pi f$ and f is the frequency, the temperature T is:

$$I^2 R \sin^2(\omega t) = 2a\beta T + aC_S \frac{dT}{dt} \tag{1}$$

where, R is the resistance, a is the area of one side of the film, β is heat loss to the air by conduction, and C_S is the heat capacity per unit area of the film. Setting aside the divergence of dT/dt as the specific heat C_S vanishes, the thickness d is implicit: $C_S = d\rho c_p$ where ρ and c_p are the density and specific heat. The Historical Theory [3] gives the pressure P_{rms} in terms of $Q_{Joule} = I^2 R$ by,

$$P_{rms} = \frac{\sqrt{\alpha_0}\rho_0}{2\sqrt{\pi}T_0} \cdot \frac{Q_{Joule}}{r} \frac{\sqrt{f}}{C_s} \tag{2}$$

where, α_0, ρ_0, and T_0 are the diffusivity, density, and temperature of the surrounding air and r is the distance from the thermophone to the microphone.

In 2008, Xiao et al. [4] showed sound was produced by passing an alternating current through thin CNT films. However, the theory of the Historical Spectrum [3] could not explain the experimental CNT response, and therefore Eqns. 1 and 2 were modified, hereafter referred to as the Current Theory, to include the heat loss to the air by conduction Q_0:

$$I^2 R \sin^2(\omega t) = 2a\beta_0 T + 2aQ_0 + aC_S \frac{dT}{dt} \tag{3}$$

where,
$$Q_0 = -\kappa_0 \left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} \tag{4}$$

and κ_0 is the thermal conductivity of air. The Current Theory [4] gives:,

$$P_{rms} = \frac{\sqrt{\alpha_0}\rho_0}{2\sqrt{\pi}T_0} \frac{Q_{Joule}}{r} \frac{\sqrt{f}}{C_S} X$$
$$\frac{f}{f_2} \Bigg/ \sqrt{\left(1 + \sqrt{\frac{f}{f_1}}\right)^2 + \left(\frac{f}{f_2} + \sqrt{\frac{f}{f_1}}\right)^2} \tag{5}$$

where, $f_1 = a_0 \beta_0^2 / \pi \kappa^2$ and $f_2 = \beta_0 / \pi C_S$.

The thermophone spectrum by Historical [3] and Current [4] Theories is summarized in Fig. 1.

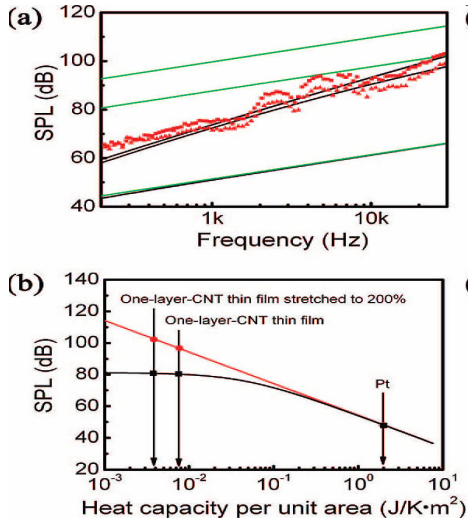

Figure 1 Thermophone Theories

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The data in Fig. 1 are presented for one-layer CNT films of 0.250 microns from which 200% stretching produced 0.25 microns film, and 0.70 microns platinum film. Fig. 1(a) shows experimental (red) in relation to theoretical estimates based on Eqns. 1-2 (3 green parallel lines) and Eqns. 3-5 (2 black lines). The 2 upper green lines correspond to the CNT films and the lower line to platinum. The data is closely fit by Eqns. 3-5. Fig. 1(b) shows Eqns. 3-5 to fit the data for heat capacities $C_S > 0.008$ J/K-m^2.

2. Purpose

Historical and Current Theories of thermophones find basis in temperature changes in the thin film assuming finite specific heat in classical heat transfer. The purpose of this paper is show how QM allows sound to be produced without changing the thin film temperature.

3. Background

Classical Fourier heat conduction theory is generally thought [5-7] not applicable to submicron thin films in electronic circuits that are far smaller than the mean free paths of the phonons that carry heat to the surroundings. Instead, the Boltzmann transport equation (BTE) allows the phonons to be treated as ballistic particles. However, this picture of thin film heat transfer by plasmon carriers does not admit to rapid transient response like the non-thermal EM emission from quantum dots under laser irradiations [8] where the photons are not in equilibrium with the far slower phonon response.

In electronic circuits, Fourier theory is claimed [9] unable to explain the large reduction in conductivity from bulk values to justify the BTE. However, QED induced radiation [10] explains this disparity by EM radiations not included in the heat balance, and therefore the conductivity only *appears* reduced from the bulk. In fact, the conductivity is not reduced with Fourier theory being valid in thin films.

Similarity arguments make the heat transfer in thermophones no different than that in thin films of electronic circuits. By QED induced radiations, atoms in thin films are generally under EM confinement at UV-VIS levels that by QM are restricted to vanishing small levels of thermal kT energy. In effect, the specific heat of the film vanishes so Joule heat cannot be conserved by an increase in temperature. But heat is low frequency EM energy, and therefore the Joule heat is induced by QED to be up-converted to the EM confinement frequency of the film. The heat gain is then conserved by the emission of UV-VIS radiation.

In thermophones, the UV-VIS is absorbed directly in surrounding air molecules, thereby inducing temperature and pressure changes that produce the sound without the film itself changing temperature.

4. QED Theory and Analysis

A thermophone thin film of thickness d over area of width W and length L conserving by QED the absorption of Joule heat Q_{Joule} is illustrated in Fig. 2.

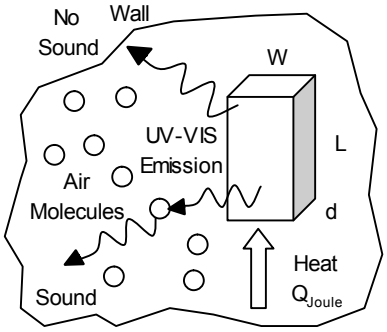

Figure 2. Thermophone producing sound from Joule heat by the QED absorption of the emission of UV-VIS radiation by surrounding air molecules.

4.1. QM Restrictions

QM restricts the allowable kT energy levels of atoms in thin films. At 300 K, the Einstein-Hopf relation [11] giving the Planck energy for the harmonic oscillator in terms of kT as a function of wavelength λ is shown in Fig. 3.

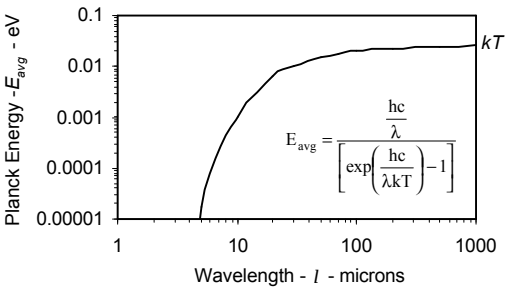

Figure 3. Harmonic Oscillator at 300 K.
In the inset, h is Planck's constant, c is the speed of light, k is Boltzmann's constant, T is absolute temperature, and λ is wavelength.

For atoms absent EM confinement, Fig. 3 shows the kT energy saturates for λ > 100 microns while for λ ~ 5 microns the kT energy is 3 orders of magnitude lower. Under submicron EM confinement, the kT energy is more than 20 orders of magnitude lower, i.e., the kT energy vanishes.

4.2. EM Confinement Frequencies

Unlike EM confinement in NPs having the same frequency in all directions, thin films have EM confinement frequencies [10] that differ in all directions. For the film as a rectangular cavity resonator, the EM confinement wavelength λ is,

$$\frac{1}{\lambda^2} = \frac{1}{(2Wn_r)^2} + \frac{1}{(2Ln_r)^2} + \frac{1}{(2dn_r)^2} \qquad (6)$$

where, n_r is the refractive index of the film. For d << W and L, $\lambda \rightarrow 2dn_r$. Hence, the film thickness d defines the EM confinement frequency f, wavelengths λ, and Planck energy E,

$$f = \frac{c}{\lambda},\ \lambda = 2n_r d,\ \text{and } E = hf \qquad (7)$$

4.3. Vanishing Specific Heat

Classical heat transfer conserves absorbed EM energy by an increase in temperature, but is not applicable [10] to atoms in films because of QM restrictions on thermal kT energy. The EM energy of the confined photons in terms of the energy U of the harmonic oscillator for N atoms given is,

$$U = 3N\frac{hc}{\lambda}\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]^{-1} \qquad (8)$$

For the specific heat C given by ∂U/∂T, the dimensionless specific heat C* is,

$$C^* = \frac{C}{3Nk} = \frac{\left(\frac{hc}{\lambda kT}\right)^2 \exp\left[\frac{hc}{\lambda kT}\right]}{\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]^2} \qquad (9)$$

At 300 K, C* vanishes [8] for $\lambda = 2n_r\delta d < 4$ micron, or for refractive indices $n_r > 2$ at film thicknesses d < 1 micron.

4.4 QM Energy Equation

Classical heat transfer is modified by QM for vanishing specific heat in the theory [8] of QED induced EM radiation,

$$Q_{Joule} - E\frac{dN}{dt} = mc_P\frac{dT}{dt} \sim 0 \qquad (10)$$

where, Q_{Joule} is the Joule heating, and dN/dt is the rate of QED photons produced having Planck energy E. Internal film heating given by the product of mass m, specific heat c_P, and temperature rate dT/dt is negligible. Lacking film temperature increases, convective, conductive, and radiative losses from the film to the surrounding air are neglected. The rate dN/dt of QED photons produced,

$$\frac{dN}{dt} = \frac{Q_{Jouoe}}{E} = \frac{2dn_r}{hc}Q_{Joule} \qquad (11)$$

The QED photon energy E and rate dN/dt for Q_{Joule} = 1 and 4.5 W is illustrated in Fig. 4.

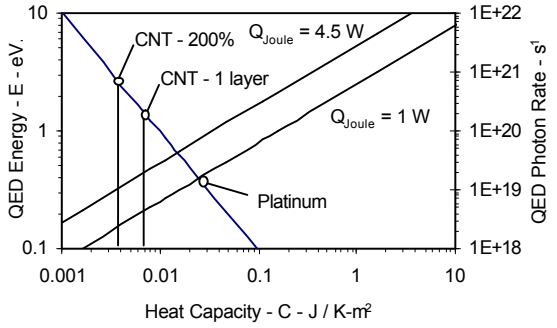

Figure 4. QED Photon Energy and Rate

4.5 SPL Frequency Response

The thermophone sound pressure level (SPL) frequency response upon absorption of the EM emission in the surrounding air is,

$$YQ_{Joule}\left(\frac{f}{f_0}\right)^2 = ar\rho_0 c_0\frac{dT}{dt} \qquad (12)$$

where, Y is a fractional yield.

Taking dt ~ 1/f,

$$\Delta T \sim \frac{YQ_{Joule}}{ar\rho_0 c_0}\frac{f}{f_0^2} \qquad (13)$$

From the gas law,

$$P_{rms} = \rho_0 \frac{R^*}{M}\Delta T \qquad (14)$$

where, R^* is the Universal gas constant, R^* = 8314 J/Kmol-K. M is the molecular weight of air, M = 29. Typically, f_0 is 20 Hz. Combining,

$$P_{rms} = \frac{R^*}{aMc_0}\frac{Q_{Joule}}{r}\frac{f}{f_0^2}Y \qquad (15)$$

The effect of film thickness d on the QED Spectra is included in the yield Y.

4.6 Absorption in Air

In order for thermophones to produce sound, the EM emission is required to be absorbed in the air surroundings. Macroscopic bodies emit far IR that is promptly absorbed within a few tens of microns at the surfaces. However, the EM emission from thin films occurs at Planck energies in the UV-VIS and beyond that penetrate the air with little absorption. Most of the UV-VIS is therefore absorbed by the solid walls that do not produce sound as noted in Fig. 2. The air absorption is given by,

$$I = I_0 \exp{-(\sigma nr)}$$

where, I_0 and I are the EM radiation before and after absorption, σ is the absorption cross-section of the air molecules, and n is their number density. The EM radiation Q absorbed is a fraction of the Joule heat Q_{Joule} supplied,

$$\frac{Q}{Q_{Joule}} = \frac{I_0 - I}{I_0} \sim \sigma nr \qquad (16)$$

Moreover, the thermophone frequency response in Fig. 1(a) shows a difference in slope that suggests Eqn. 15 be modified by yield Y,

$$Y = n\sigma r(A - Bf)$$

$$P_{rms} = n\sigma r\frac{R^*}{aMc_0}\frac{Q_{Joule}}{r}\frac{f}{f_0^2}(A - Bf) \qquad (17)$$

In the UV-VIS, nitrogen is transparent and only oxygen absorption is relatively significant. Absorption of oxygen in the UV produces ozone which is highly absorptive, but the effects of which are neglected here. From the MPI Atlas [12], $\sigma = 1x10^{-24} cm^2$ for oxygen under UV at 0.25 microns. For $n = 4.8x10^{18}$ /cm^3 and r = 5 cm, $n\sigma r = 24x10^{-6}$. The QED induced frequency response for $n\sigma r \sim 10x10^{-6}$ in relation to Current Spectra is illustrated in Fig. 5.

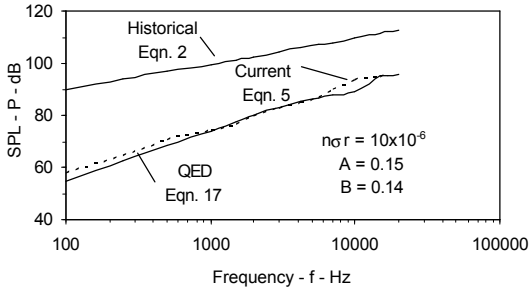

Figure 5. QED Response Spectra in relation to Historical and Current Spectra

4.7 Classical and QM Heat Transfer

The QED theory does not depend on the specific heat C_S so a comparison with Current Spectra is not possible. But the effect of zero specific heat on Current Spectra may be noted by the location of the plateau observed in Fig. 1(b). Classical heat transfer applies to the right of the plateau; whereas, QM controls the plateau itself. Assuming sound is produced by classical heat transfer if the EM emission wavelength exceeds that of NIR radiation at 1 micron,

$$\lambda > 1 \text{ micron} \qquad (18)$$

or by the film thickness d ,

$$d > \frac{1}{2n_r} \text{ micron} \qquad (19)$$

For one-layer CNT sheets having [13] refractive index $n_r \sim 1$, classical heat transfer occurs at film thickness d > 0.5 microns where $C_S > 0.008$ J/K-m^2. For platinum, $n_r \sim 2.33$, classical heat transfer is applicable for d > 0.214 micron where $C_S > 0.61$ J/K-m^2. The classical and QM heat transfer regions are illustrated in Fig. 6.

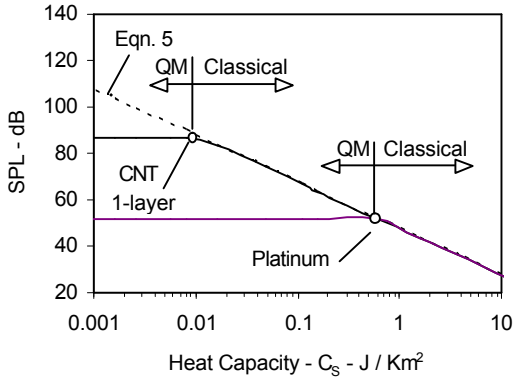

Figure 6. Classical and QM Heat Transfer

5. Discussion and Conclusions

Historical and Current Spectra for thermophones based on classical theory are not valid because the specific heat of the thin film vanishes. Similarity is found with thin films in electronic circuits.

Vanishing specific heat means under Joule heating the film temperature rate diverges. Current Spectra are based on thin CNT films having thicknesses > 0.125 microns. Thermophones having CNT films < 0.125 microns are not yet reported, but in the future as film thicknesses become smaller, say to 0.01 microns as used in electronic circuits, divergence by vanishing specific heat should be expected.

Historical and Current Theories require film temperature changes to be transferred to pressure changes in the air surroundings. The Current Theory that treats the air as a solid in the conductive heat loss from the film is not applicable because air contains convection currents that dominate heat transfer. The heat loss to the air therefore cannot be greater than given by natural convection of about 2 W/m^2K. But the heat loss to the air for one-layer CNT sheets is reported [14] to be 28.9 W/m^2K which is one order of magnitude higher than allowed by natural convection. This means another source of heat loss to the air is present that is not included in the Current Theory.

Temperature changes do not occur in thin films because of vanishing specific heat. QM allows UV-VIS emission to conserve the Joule heat without a temperature change. Unlike the far IR, UV-VIS absorption readily penetrates the distance between the thermophone and the speaker with little absorption. Most of the Joule heat of the thermophone is therefore lost in absorption by the solid walls of the enclosure, or the microphone diaphragm itself. Only a small fraction ~ 10^{-6} of the Joule heat actually produces the sound.

QED Theory that finds basis in the absorption of UV-VIS radiation by air is a more physically correct way of converting a small fraction of Joule heating into sound. That a small fraction of Joule heat actually produces the sound can be understood by considering all of 1 W Joule heat absorbed in the volume of air between the CNT film area a ~ 3 cm x 3 cm and the distance r ~ 5 cm to the microphone. The temperature increase is then about 20 C giving a SPL of 170 dB that is far higher than 90 dB measured.

Absorption efficiency of the UV-VIS in air is very low. Thermophones using absorptive gases may be used, but require the region between the thermophone and the microphone to be sealed. Filling the sealed region with pure nitrogen should reduce the SPL while the SPL should increase in pure oxygen. But nitrogen-oxygen compounds may prove optimum for producing sound, e.g., nitrous oxide has UV absorption [15] cross-sections 2-3 orders of magnitude greater than oxygen.

In heat transfer of thin films or for that matter any structures at the nanoscale, QM based QED induced radiation with zero specific heat rather than classical heat transfer based on bulk values of specific heat are recommended

10. References

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