# THERMOPHONES BY QUANTUM MECHANICS

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## ABSTRACT

Thermophones are thought to produce sound from vibrations by converting current at audio frequencies to rapid temperature changes. However, thermophones recently fabricated from nanoscale sheets of carbon nanotubes (CNTs) produce higher sound pressure levels (SPL) without vibration. Classical heat transfer cannot explain CNT thermophones, and instead quantum mechanics (QM) as embodied in the theory of QED induced EM radiation is proposed. QED stands for quantum electrodynamics and EM for electromagnetic. Atoms in CNT films having thickness < 0.2 microns are under EM confinement at levels beyond the ultraviolet (UV) that by QM have vanishing specific heat, and therefore Joule heat cannot be conserved by an increase in temperature. Conservation proceeds by the QED induced up-conversion of low frequency Joule heat to the UV confinement frequency of the film. Sound is produced from the pressure changes that accompany the absorption of UV emission by the surrounding air.

**KEY WORDS**: thermophones, quantum mechanics

## NOMENCLATURE

| | |
|---|---|
| A,B | constants |
| C | film heat capacity per area, Joule/K-m$^2$ |
| $E_P$ | Planck energy of QED photon, Joule |
| I | current, amps |
| $N_P$ | number of QED photons |
| P | pressure, Pascal |
| Q | heat conduction from film to air, W |
| R | resistance, ohms |
| T | temperature, Kelvin |
| A | area of one side of film, m$^2$ |
| C | speed of light, m/s |
| $c_p$ | specific heat, J/kgm/Kelvin |
| h | Planck's constant |
| k | Boltzmann's constant |
| n | number density of gas, cm$^{-3}$ |
| $n_r$ | refractive index |
| r | distance from film to speaker, m |
| t | time, s |
| d | film thickness, m |
| $\alpha$ | thermal diffusivity, |
| $\rho$ | mass density , kg/m$^3$ |
| $\beta$ | conductive heat loss, W |
| $\sigma$ | gas absorption cross-section, cm$^2$ |
| $\lambda$ | wavelength, m |
| Subscripts | |
| o | air |
| f | film |

## 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 Historical Theory [3] gives the temperature T in terms of the current I,

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

where, R is the resistance, a is the area of one side of the film, $\beta$ is heat loss to the air by conduction, and $\omega$ is the circular frequency of current I. C is the heat capacity per unit area of the film, $C = d\rho_f c_{pf}$ , where d is the thickness, and $\rho_f$ and $c_{pf}$ are the density and specific heat of the film. The Historical Theory [3] gives the pressure P,

$$P = \frac{\sqrt{\alpha_o}\rho_o}{2\sqrt{\pi}T_o}\cdot\frac{I^2R}{r}\frac{\sqrt{f}}{C} \qquad (2)$$

where, $\alpha_0$, $\rho_0$, and $T_0$ are the diffusivity, density, and temperature of the surrounding air.

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, hereinafter referred to as the Current Theory, to include the heat loss to the air by conduction $Q_0$:

$$I^2R\sin^2(\omega t) = 2a\beta_o T + 2aQ_o + aC\frac{dT}{dt} \qquad (3)$$

where,
$$Q_o = -\kappa_o\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} \qquad (4)$$

and $\kappa_o$ is the thermal conductivity of air, and x is the direction normal to the film. The Current Theory [4] gives,

$$P = \frac{\sqrt{\alpha_o}\rho_o}{2\sqrt{\pi}T_o}\frac{I^2R}{r}\frac{\sqrt{f}}{C}\frac{f}{f_2}\Bigg/\sqrt{\left(1+\sqrt{\frac{f}{f_1}}\right)^2+\left(\frac{f}{f_2}+\sqrt{\frac{f}{f_1}}\right)^2} \qquad (5)$$

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

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

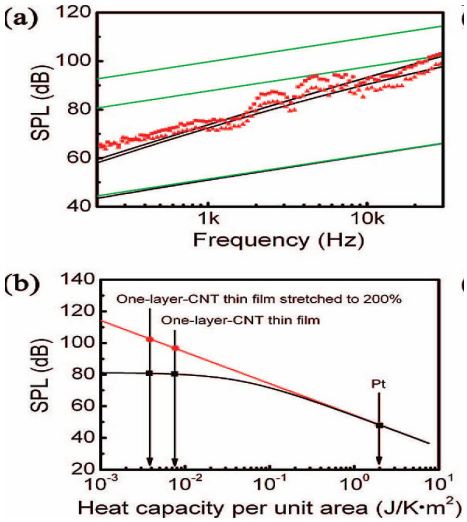


**Figure** 1 Thermophone Theories

The data in Fig. 1 are presented for one-layer CNT films of 0.45 microns from which 200% stretching produced 0.15 micron film. The thickness of the platinum film was 0.70 microns. 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 > 0.008 J/K-m$^2$.

## PURPOSE

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

## 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 from the bulk 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 radiation, atoms in thin films are generally under EM confinement at UV levels that by QM are restricted to vanishing 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 radiation. In thermophones, the UV is absorbed directly in surrounding air molecules, thereby inducing temperature and pressure changes that produce the sound without the film itself changing temperature.

## QED THEORY AND ANALYSIS

A thermophone thin film of thickness d over area of width W and length L conserving by QED induced UV emission the absorption of Joule heat I$^2$R is illustrated in Fig. 2.

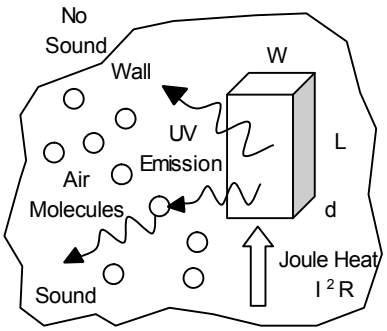


**Figure 2.** Thermophone producing sound from Joule heat by the absorption of the QED induced emission of UV radiation by air. No sound is shown produced upon UV absorption in the wall.

### 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 $E_{avg}$ for the harmonic oscillator in terms of kT as a function of wavelength λ is shown in Fig. 3.

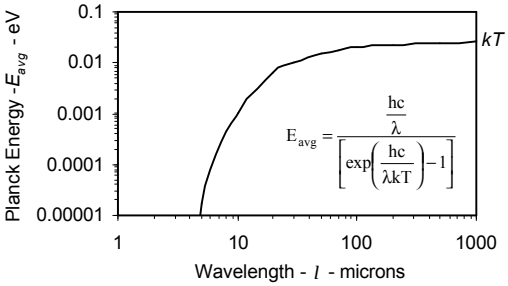


**Figure 3.** Harmonic Oscillator at 300 K.

For atoms absent EM confinement, Fig. 3 shows the kT energy saturates for $\lambda > 50$ microns while for $\lambda \sim 5$ 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.

**EM confinement frequencies**

Unlike EM confinement in NPs having the same frequency in all directions, thin films are only under EM confinement [10] across the thickness. For the film as a rectangular cavity resonator, the EM confinement wavelength $\lambda$ is,

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

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

$$\upsilon = \frac{c}{\lambda},\ \lambda = 2n_r d,\ \text{and}\ E_P = h\upsilon \tag{7}$$

**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 for N atoms is,

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

For the film specific heat $c_{pf}$ given by $\partial U/\partial T$, the dimensionless specific heat C* is,

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

Vanishing specific heat in thermophones evolved from a long history in thin films for electronic circuits. Early work by Kelemen [12] recognized that thin films lacking heat capacity are unstable by themselves under Joule heating. Indeed, the film had to be deposited on a substrate having thickness of a few tens of microns where the specific heat was finite to avoid instability. Recently, instability was found in measurements of thin film conductivity by Davitadze et al. [13]. The instability is inherent in any thin film because the specific heat vanishes.

**QM energy equation**

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

$$I^2R - E_P\frac{dN_P}{dt} = mc_{pf}\frac{dT}{dt} \sim 0 \tag{10}$$

where, $dN_P/dt$ is the rate of QED photons produced having Planck energy $E_P$. Internal film heating given by the product of mass m, specific heat $c_{pf}$, and temperature rate dT/dt approaches zero because $c_{pf}$ vanishes. Lacking temperature increases in the film, the convective, conductive, and radiative losses from the film to the air also vanish. The rate $dN_P/dt$ of QED photons produced,

$$\frac{dN_P}{dt} = \frac{I^2R}{E_P} = \frac{2dn_r}{hc}I^2R \tag{11}$$

Fir CNTs, the refractive index $n_r$ approaches unity [14]. The QED photon energy $E_P$ and rate $dN_P/dt$ at 1 and 4.5 W is illustrated in Fig. 4.

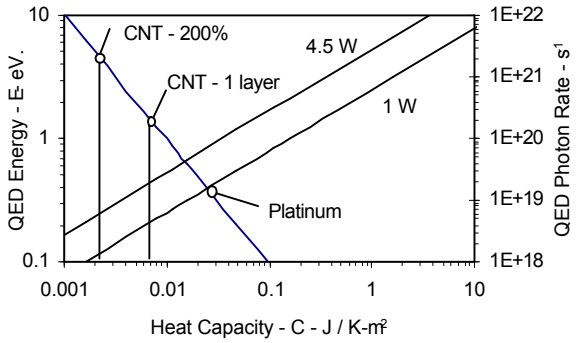


**Figure 4.** QED Photon Energy and Rate

**SPL frequency response**

The SPL frequency response upon absorption of the EM emission in the surrounding air is,

$$I^2R\left(\frac{f}{f_o}\right)^2 Y = ar\rho_o c_o\frac{dT}{dt} \tag{11}$$

where, Y is a fractional yield. Taking $dt \sim 1/f$ and $dT \sim \Delta T$,

$$\Delta T \sim \frac{I^2R}{ar\rho_o c_o}\frac{f}{f_o^2}Y \tag{12}$$

From the gas law,

$$P = \rho_o\frac{R^*}{M}\Delta T \tag{13}$$

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

$$P = \frac{R^*}{aMc_{po}}\frac{I^2R}{r}\frac{f}{f_o^2}Y \tag{14}$$

**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 from their surfaces. However, the EM emission from thin films occurs at Planck energies in the UV that penetrate the air with little absorption, and therefore most of the UV is absorbed by the solid walls that do not produce sound as noted in Fig. 2. The air absorption is,

$$I = I_0\exp(-\sigma nr) \tag{15}$$

where, $I_0$ and I are the EM radiation before and after absorption, $\sigma$ is the absorption cross-section of the air molecules, and n is their number density. The $I^2R$ power absorbed in the surrounding air is,

$$\left(\frac{I_0 - I}{I_0}\right) I^2R \sim \sigma n r I^2 R \qquad (16)$$

Moreover, the thermophone frequency response in Fig. 1(a) shows a difference in slope that suggests Eqn. 14 be modified by yield Y,

$$Y = A - Bf \qquad (17)$$

Rearranging,

$$P = n\sigma r \frac{R^*}{aMc_o} \frac{I^2R}{r} \frac{f}{f_0^2} (A - Bf) \qquad (18)$$

In the UV, nitrogen is transparent and only oxygen absorption is relatively significant. Oxygen in the UV produces ozone which is highly absorptive, but is neglected here. From the MPI Atlas [15], $\sigma = 1x10^{-24} cm^2$ 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.

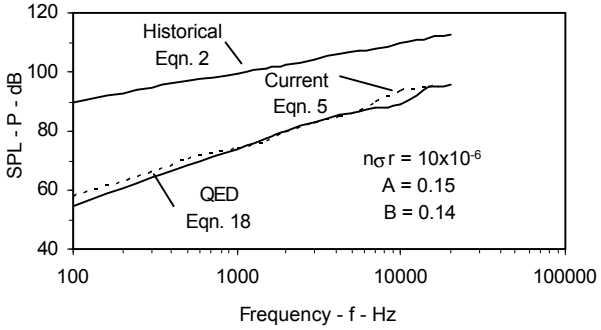


**Figure 5.** QED Response Spectra in relation to Historical and Current Spectra

**Classical and QM heat transfer**

The QED theory does not depend on the specific heat $c_{pf}$ 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 $\lambda$ exceeds that of NIR radiation at 1 micron, or by the film thickness d ,

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

Classical heat transfer in one-layer CNT sheets having [14] refractive index $n_r \sim 1$ occurs at film thickness d > 0.5 microns where C > 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 > 0.61 J/K-$m^2$. The classical and QM heat transfer regions are illustrated in Fig. 6.

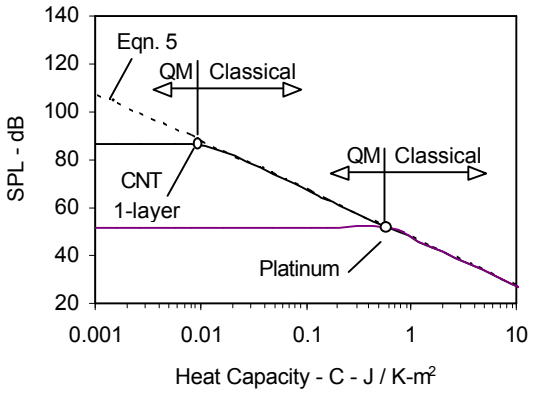


**Figure 6.** Classical and QM Heat Transfer

## DISCUSSION

**Vanishing specific heat**

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 [12,13]. Vanishing specific heat means under Joule heating the film temperature rate diverges. Current Spectra based on thin CNT films have thicknesses > 0.15 microns. Thermophones having CNT films < 0.15 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.

Temperature changes do not occur in thin films because of vanishing specific heat. QM allows UV emission to conserve the Joule heat without a temperature change. Unlike the far IR, UV 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 $\sim 10^{-6}$ of the Joule heat actually produces the sound.

**Sound without vibration**

Historical and Current Theories require film temperature changes to be converted to vibration that cause pressure changes in the air. 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/$m^2$K. But the heat loss to the air for one-layer CNT sheets is reported [16] to be 28.9 W/$m^2$K 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.

QED Theory that finds basis in the absorption of UV radiation by air converts only a small fraction of Joule heating into sound without vibration. Indeed, only a small fraction of Joule heat actually produces the sound which can be understood by considering 1 W of Joule heat absorbed in the volume of air between the CNT film having area a ~ 3 cm x 3 cm and the distance r ~ 5 cm to the microphone. The temperature increase is then about 20 C/s giving a SPL of 170 dB/s that is far higher than the average 90 dB measured.

**Improved CNT design**

Absorption efficiency of the UV in air is very low. Thermophones using UV 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 [17] cross-sections 2-3 orders of magnitude greater than oxygen.

## CONCLUSIONS

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

The BTE as an analytical method for conductivity of thin films is not applicable because spontaneous UV emission is excluded from the film response.

Temperature changes do not occur in thin films because of vanishing specific heat with conservation of Joule heat proceeding by UV emission. But the UV readily penetrates the distance between the thermophone and the microphone with little absorption. Only a small fraction ~ $10^{-6}$ of the Joule heat actually produces the sound.

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 thermophone requires a source of heat loss to the air that is not included in the Current Theory.

QED Theory that finds basis in the absorption of UV radiation by air only converts a small fraction of Joule heating into sound producing a SPL of steady 90 dB.

Thermophones may be improved by using UV absorptive gases, but require a sealed region between the thermophone and the microphone. Filling the sealed region with nitrogen-oxygen gas mixtures may prove optimum for producing sound.

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