Thin Film Heat Transfer

T. Prevenslik

***Abstract*—Heat transfer in thin films treats phonons as particles in the Boltzmann Transport Equation (BTE). However, phonons only allow slow thermal response. Rapid film heat transfer is possible provided films are allowed to promptly emit non-thermal electromagnetic (EM) radiation. Quantum mechanics (QM) used in the response of nanoparticles (NPs) is extended to thin films through the theory of QED induced EM radiation. Here QED stands for quantum electrodynamics. Atoms in thin films are generally under EM confinement at vacuum ultraviolet (VUV) levels that by QM are restricted to vanishing small levels of thermal kT energy, and therefore heat gain cannot be conserved by an increase in temperature. Heat is low frequency EM energy, and therefore the gain is conserved by VUV emission following QED induced up-conversion to the VUV confinement frequency of the film. The effective conductivity appears reduced only because EM emission is excluded from the heat balance. If included, the film maintains bulk conductivity. Similarity with EM emissions from NPs in nanofluids and nanocatalysts in chemical reactions is discussed.**

***Index Terms*—thermal conductivity, thin films, size effects**

I. Introduction

CLASSICAL heat transfer by Fourier heat conduction theory is generally thought [1-3] not applicable to thin films having thickness far smaller than the mean free paths of the electrons and phonons that carry heat to the surroundings. Reduced thermal conductivity is explained by ballistic or non-local heat transfer where the phonons are treated as particles in the BTE.

However, this picture of thin film heat transfer by plasmon carriers does not admit [4,5] to rapid transient response, similar to the non-thermal EM emission from NPs under laser irradiations [6] where the photons are not in equilibrium with the far slower phonon and electron relaxation rates.

In this paper, QED induced EM radiation is proposed to allow rapid heat transfer in thin films by the emission of non-thermal EM radiation. Similarity is found with the QM previously applied [6-8] to NPs where photons are treated as harmonic oscillators through the theory of QED induced EM radiation. Unlike the slow plasmon response in the BTE, QED induced EM radiation allows the film to promptly respond by EM emission to any heat gain, say by lasers, Joule heating, and molecular collisions.

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Moreover, continuum Fourier theory is generally thought [9-11] to fail as the dimensions of the films become comparable to the mean free path of heat carriers – electrons in metals and phonons in semiconductors. However, the effective conductivity only appears reduced. This is so, because heat gain has been conserved by conductive heat flow alone that excludes EM emission losses, and therefore the effective conductivity appears reduced from that of the bulk. In fact, bulk conductivity is not reduced with Fourier theory being valid in thin films.

QED induced EM radiation finds basis in the fact that atoms in thin films are generally under EM confinement at VUV levels that by QM are restricted to vanishing small levels of thermal kT energy. In effect, the heat content and specific heat of the film vanish so heat gain cannot be conserved by an increase in temperature. But heat is low frequency EM energy, and therefore the heat gain 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 VUV radiation. But the VUV is beyond the UV-cutoff of standard photomultipliers, and therefore has not been detected to be included in the heat balance of thin films to date.

II. Purpose

To provide a QM explanation for thin film heat transfer based on QED induced EM radiation.

III. Theory

A thin film of thickness δ over area of width W and length L conserving the absorption of EM radiation Q from lasers, electrical joule heating, and molecular collisions by the emission of VUV radiation is illustrated in Fig. 1.

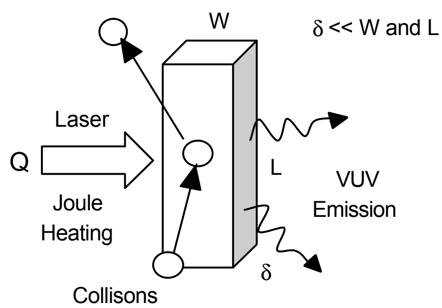

Fig. 1. Thin film conserving absorbed EM energy Q by the emission of VUV radiation.

A. QM Restrictions

QM restricts the allowable kT energy levels of atoms in thin films. At 300 K, the Einstein-Hopf relation [12] giving the Planck energy for the harmonic oscillator in terms of kT as a function of wavelength λ is shown in Fig. 2.

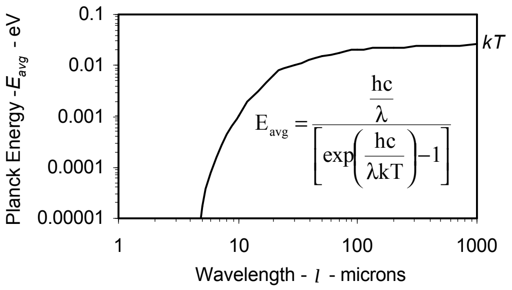

Fig. 2. Harmonic Oscillator at 300 K.
In the inset, h is Planck's constant, c is the speed of light, k is Boltzmann's constant, T is absolute temperature, and λ is wavelength.

For films absent EM confinement, Fig. 2 shows the kT energy saturates for λ > 100 microns in the far infrared (FIR). Fig. 2 also shows kT ~ 1×10^{-5} eV at EM confinement of λ ~ 5 microns. Hence, for atoms under VUV confinement at λ < 0.020 microns, kT << 1×10^{-5} eV, i.e., the kT energy vanishes.

B. EM Confinement Frequencies

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

$$\frac{1}{\lambda_r^2} = \frac{1}{(2W)^2} + \frac{1}{(2L)^2} + \frac{1}{(2\delta)^2} \qquad (1)$$

For δ << W and L, $\lambda_r \rightarrow 2\delta$. Hence, film thickness δ defines the EM confinement frequency f, wavelength λ, and Planck energy E,

$$f = \frac{c}{\lambda},\ \lambda = 2n_r\delta,\ \text{and } E = \frac{hc}{2n_r\delta} \qquad (2)$$

where, n_r is the refractive index of the film.

C. Vanishing Specific Heat

Classical heat transfer conserves absorbed EM energy by an increase in temperature, but is not applicable to atoms in films because of QM restrictions on thermal kT energy. Equivalently, the specific heat of films may be said to vanish.

The Debye specific heat assumes the atoms in the film lattice vibrate at plasmon frequencies. The Einstein specific heat differs in that the film vibrates at EM confinement frequencies during the absorption of EM radiation at optical as well as plasmon frequencies. Similar to NPs in space [8], the generality of Einstein's specific heat is favored over Debye to represent the EM confined photons, the energy U of the film with N atoms given by,

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

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

$$C^* = \frac{C}{3Nk} = \frac{\left(\frac{hc}{\lambda kT}\right)^2 \exp\left[\frac{hc}{\lambda kT}\right]}{\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]^2} \qquad (4)$$

At 300 K, C* vanishes [6] for $\lambda = 2n_r\delta < 5$ microns, or for refractive indices $n_r > 2$ at film thicknesses δ < 1 microns.

D. QM Energy Equation

Classical 1-D heat transfer theory in the film thickness direction is modified by QM for vanishing specific heat and QED induced EM radiation,

$$Q - E\frac{dN}{dt} - K_{bulk}A\frac{\Delta T}{\delta} = Mc_P\frac{dT}{dt} \sim 0 \qquad (5)$$

where, Q is the EM energy absorbed from lasers, Joule heating, and collisions; dN/dt is the rate of QED photons produced having Planck energy E; K_{bulk} is the bulk conductivity; and A = W*L is film area.

Internal film heating given by the product of mass M, specific heat c_P, and temperature rate dT/dt is negligible. Temperature variations in the film are neglected. The Stefan-Boltzmann law for thermal radiation is insignificant at film temperature and replaced by QED induced EM emission for non-thermal EM emission. The effective thermal conductivity K_{eff} is upper bound by K_{bulk},

$$K_{eff} = \frac{Q - E(dN/dt)}{A\,\Delta T/\delta} < K_{bulk} \qquad (6)$$

However, the thin film literature ignores the EM emission giving $K_{eff} << K_{bulk}$. For example, very recent lattice Boltzmann method (LBM) simulations [13] of bulk silicon show thickness-dependent thermal conductivity. Indeed, (Fig. 6 of [13]) shows K_{eff} far less than the bulk value K_{bulk} = 153 W/mK. Moreover, the thickness is found to depend on whether the LBM analysis is assumed gray or with dispersion, the lack of convergence suggesting the LBM itself may be unphysical.

IV. ANALYSIS

A. Ambient Temperature

Ballistic heat transport in thin films is widely expected [1-3,9-11,13] to cause large reductions in thermal conductivity. Typically, the effective conductivity data for thin copper layers at ambient temperature (Fig. 3 of [9]) is reproduced here in Fig. 3. Also shown in Fig. 3 is how the EM emission may be inferred from effective conductivity, the respective Planck energy E and rate dN/dt given in Fig. 4.

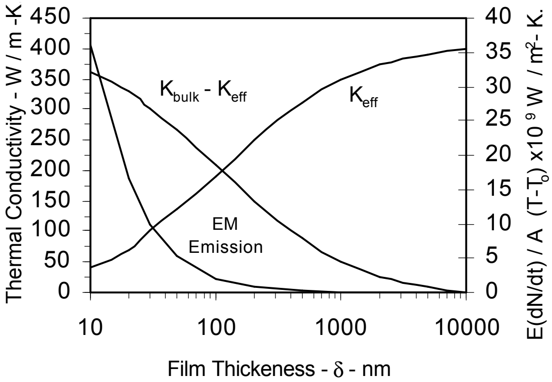

Fig. 3. Effective conductivity K_{eff} with difference (K_{bulk} - K_{eff}), and EM emission $E(dN/dt) / A\ \Delta T = (K_{bulk} - K_{eff}) / \delta$

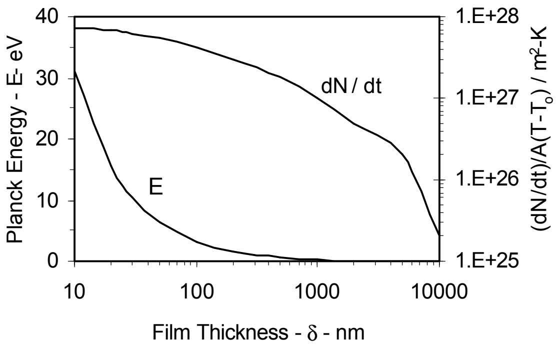

Fig. 4. Inferred EM emission, Planck Energy E and QED photon rate dN/dt

B. Cryogenic Temperature

Inferred EM emission depends on bulk thermal conductivity. Similar to the procedure described for ambient temperature, the effective conductivity K_{eff} of aluminum and CoFe thin films (Fig. 6 of [10]) at cryogenic temperatures from 10 to 300 K may be converted to EM emissions that maintain bulk Kbulk conductivity across the thickness of the film.

V. DISCUSSION

QED induced EM radiation is applicable to diverse areas of physics. Common areas are the electrification of natural processes [14]. Fluid applications are briefly discussed as follows.

A. Nanofluids

Nanofluids comprising NPs in coolants are found to increase thermal conductivity, but the results to date are questionable because the increases far exceed that given by mixing rules.

QED induced heat transfer [7] allows the NPs to act as heat sinks to extract heat Q by molecular collisions from the coolant that after QED induced frequency up-conversion to penetrating VUV is absorbed in coolant walls. Heat transfer efficiency is increased because local thermal equilibrium (LTE) does not exist at the NP surface. LTE is illustrated in Fig. 5.

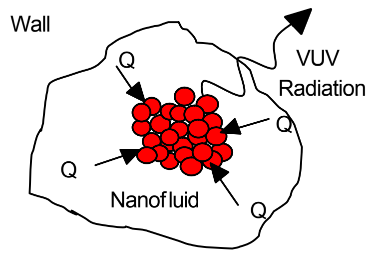

Fig. 5. NP in nanofluid improving heat transfer efficiency by LTE.

B. Nanocatalysts

It is generally thought chemical bonds of reactants are weakened by adsorption to nanocatalysts, the source of necessary EM energy allowing the reactions to proceed to completion is not well understood. Nanocatalysts are treated [15] as NPs in a solution of reactant molecules A and B as shown in Fig. 6.

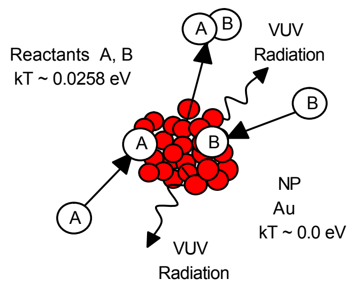

Fig. 6. NPs as catalysts in the chemical reaction $A + B \rightarrow AB$

Because of EM confinement, the NP atoms have vanishing kT energy, while the free A and B molecules have full kT energy. Collisions therefore transfer full kT energy to the NP which accumulates and is up-converted to VUV levels by QED, the VUV enhancing the rate of chemical reaction.

VI. CONCLUSIONS

- QED induced EM radiation allows the apparent reduction in thermal conductivity of thin films to be explained by VUV emission.
- Fourier conduction theory based on bulk thermal conductivity is valid in thin films.
- In thin films, non-thermal EM radiation by QED induced EM radiation is far more significant than thermal radiation given by the Stefan-Boltzmann law.
- There is no need to modify Fourier theory with ballistic heat transfer by the BTE in thin films.
- The generality of QED induced EM radiation allows the extension from NPs to thin films having thicknesses and NP diameters less than 100 nm.
- In nanofluids, QED induced EM radiation naturally provides the necessary non-local equilibrium of NPs with the surroundings to improve heat transfer efficiency of coolants.
- NPs as nanocatalysts allow the kT energy of reactants to be converted by QED to VUV radiation that enhances the chemical reaction.

VII. RECOMMENDATION

Recommendations are made because the conclusions suggest that the BTE in excluding EM emission is not a valid method in the heat transfer of thin films. Conversely, QED induced EM radiation explicitly includes the emission of EM radiations from thin films under Joule heating. The matter can be resolved by measurements of EM radiation. Typical cut-off in photomultipliers is the UV around 200 nm. Thin films of 50 nm having refractive indices > 2 may be subjected to rapid Joule heating. Given the importance of thin film heat transfer in the electronics industry, prompt action is recommended to include EM emission in thin film heat transfer.

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