NEAR-FIELD HEAT TRANSFER BY THE PLANCK LAW

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1. INTRODUCTION

Historically, Near-Field Radiative Heat Transfer (NFRHT) evolved from the inability of the Stefan-Boltzmann law to explain heat flow across evacuated nanoscale gaps between macroscopic bodies. Following the precedent set by Fourier, the NFRHT mechanisms were generally thought [1-4] based on the difference between gap surface temperatures. At the macroscale, Fourier did not face the problem of measuring gap surface temperatures at the nanoscale and in NFRHT was avoided by assuming bulk temperatures at respective gap surfaces. Because of this, the validity of NFRHT theories over the past decades has always been open to question.

Today, all known NFRHT mechanisms transfer heat Q by differences between gap surface temperature. However, the Planck law [5] of quantum mechanics (QM) denies atoms in the surfaces of nanoscale gaps the heat capacity to change in temperature that may be understood by considering the Planck law at 300 K plotted in relation to classical physics in Fig. 1.

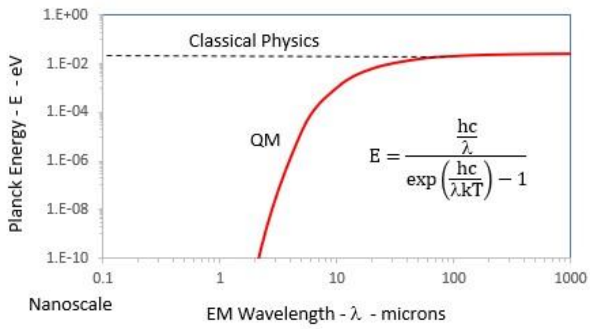

Figure. 1. Planck law of QM at 300 K. In the inset, E is Planck energy, h Planck's constant, c light speed, k Boltzmann's constant, T temperature, and λ the EM wavelength.

The Planck law at 300 K shows classical physics allows the atom to have finite thermal kT heat capacity over all EM wavelengths λ - even at the nanoscale. QM differs as the kT heat capacity decreases for $\lambda < 200$ μm, and vanishes at the nanoscale for $\lambda < 0.1$ μm = 100 nm. What this means is NFRHT faces a dilemma in that all known theories based on phonons, plasmons, polaritons, evanescent waves or variants thereof which require the atoms in the surface of nanoscale gaps to have temperature are clearly invalid. In effect, the Planck law requires any NFRHT theory to be independent of temperature.

2. PURPOSE

The purpose of this paper is to propose EM waves based on temperature independent simple QED heat transfer [6] as the NFRHT mechanism. Non-thermal EM waves standing or travelling across the gap do not require surface temperatures, but presumably were excluded because temperature differences alone defined heat flow. The simple QED theory is illustrated by explaining the production of white light from a Joule heated graphene layer above a nanoscale gap reported in the literature.

3. THEORY

Simple QED is the consequence of the Planck law denying atoms in nanogaps the heat capacity to increase in temperature upon the absorption of heat. QED stands for quantum electrodynamics, a complex theory based on *virtual* photons advanced by Feynman [7] and others. Simple QED is far

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simpler, only requiring the heat capacity of the atoms in nanoscale gaps to vanish allowing conservation to proceed by the creation of *real* photons forming EM waves travelling across the gap. In an evacuated gap, the heat capacity of the surface atoms alone vanishes. Similar to atomic quantum states described by electrons in discrete orbitals, simple QED quantum states are dependent on the dimension d of the gap over which the half-wavelength $\lambda/2$ of the EM waves travel. The Planck energy E of the EM wave is given by the time τ for light to travel across the gap and back, $\tau = 2d/c$. Hence, the Planck energy E of the travelling EM wave is, $E = h/\tau = hc/\lambda$ having wavelength $\lambda = 2d$. But to create the travelling EM wave, the heat Q is required to be placed under EM confinement to the gap dimension d by Poynting vectors of thermal momentum shown in Fig. 2.

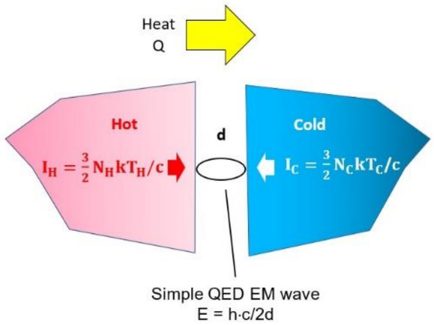

Figure 2. EM confinement of Heat in nanoscale gaps

Since the thermal kT energy of atoms in hot and cold surfaces vanishes by the Planck law, Brownian motion ceases and gap surface temperatures may be considered at absolute zero. To compensate for the surface atoms at absolute zero, the number of atoms N_H in hot and N_C in cold bodies having finite kT energy $U_H = 3/2\ N_H kT_H$ and $U_C = 3/2\ N_C \cdot kT_C$ form Poynting vectors of momenta $I_H = U_H/c$ and $I_C = U_C/c$ directed by respective thermal gradients toward the gap surfaces, the EM waves having wavelength $\lambda = 2d$. Heat Q is carried by EM waves across the gap provided momenta $I_H > I_C$.

4. APPLICATION

Bright white light emission from a Joule heated graphene layer suspended over a nanoscale trench thought [8] caused by hot electrons (~2,800 K) enhancing thermal radiation efficiency was found mediated by the nanoscale depth d (300-1100 nm) of the trench as shown in Fig. 3.

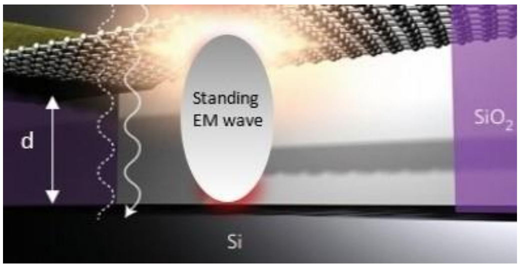

Figure 3. Bright White Light from Graphene

The Joule heated single atom graphene layer (0.337 nm) is thought [8] raised to localized lattice temperatures of 1800 K, but this is questionable as white light requires temperatures as high as 5000 K. Similar to NFRHT by simple QED, the white light emission was mediated by the depth d of the nanoscale trench suggesting standing EM waves in the IR (600 - 2200 nm) form as noted in Fig. 3, and in fact, VIS overtones of the fundamental IR waves standing between the graphene layer and the trench were shown [8] related to the change in Planck energy ΔE between two consecutive interferences.

Nevertheless, the classical Fourier diffusive equation was shown [9] to confirm Joule heating produces high graphene temperatures ~ 2000 K in the graphene layer,

$$\frac{d^2T}{dx^2} + \frac{P}{\kappa WtL} - \frac{2g}{\kappa t}(T - T_o) = 0$$

Simple QED differs significantly from classical Fourier thermal diffusion as the graphene atoms have vanishing heat capacity across the thickness d of the graphene layer that not only precludes temperatures of 2000 K, but requires the graphene to remain at ambient temperature. Instead, NFRHT by simple QED conserves the soft X-ray heat in the trench by creating standing EM waves in the IR that produce the VIS overtones observed as bright white light.

5. CONCLUSIONS

The Planck law precludes heat Q from creating temperature fluctuations in nanoscale gaps which allows NFRHT by simple QED to carry heat across the gap by EM waves.

Heat at the macroscale increases temperature, but at the nanoscale produces EM waves.

All known NFRHT theories based on temperature fluctuations in gaps or which implicitly require temperature differences between gap surfaces are invalid by the Planck law.

Temperature dependent phonons, plasmons, polaritons, and evanescent waves valid on the surface of macroscopic bodies do not exist in nanoscale gaps.

Only temperature independent NFRHT theories are valid at the nanoscale, one of which is simple QED proposed herein based on the Planck law itself.

Joule heat induced 2000 K temperatures do not exist in suspended single atom graphene layers. Instead, Joule heat is conserved by creating soft X-rays across the layer thickness, the heat of which is then conserved in the nanoscale trench by creating standing IR waves.

White light from graphene is a mix of the higher VIS overtones of the fundamental IR standing waves and occurs at ambient temperature - not 2000 K.

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