Near-field enhanced TPV cells

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Abstract: Near-field thermophotovoltaics (nTPV) are thought to enhance thermoelectric efficiency by separating the emitter and PV cell by nanoscale gaps. Experimental verification of nTPV is difficult, and instead, support of concept relies on Near-field Radiation Heat Transfer (NFRHT) analysis based on Rytov's theory of fluctuation temperature. But in nanoscale gaps, the Planck law of quantum mechanics (QM) denies atoms in gap surfaces the heat capacity necessary for temperature fluctuations. What this means is nTPV lacks even a theoretical basis. In effect, the Planck law requires a nTPV theory that does not depend on temperature. One such theory is simple QED based on the Planck law that describes nTPV by temperature independent EM travelling waves that carry the heat across the gap. Application of simple QED to a nTPV device with a 60 nm gap between emitter and InAs PV cell with a bandgap wavelength λ = 3.5 μm suggests no enhancement of nTVP efficiency at nanoscale gaps with only a slight enhancement at 1.75 μm or half the 3.5 μm InAs bandwidth wavelength. Instead of a 60 nm gap, the nTPV efficiency can be significantly enhanced by setting the gap at 1.75 μm to be resonant with the 3.5 μm InAs bandgap. Regardless, the emitter temperature should be increased for higher nTPV efficiency.

Keywords: NFRHT, nTPV, Planck law, simple QED, EM waves, PV cells

I. INTRODUCTION

The nTPV concept of a nanoscale gap in a thermophotovoltaic between the emitter and PV cell began [1] a few decades ago as a consequence of NFRHT research [2-4] directed to explaining why the Stefan-Boltzmann law failed to explain the heat transfer between hot and cold bodies separated by a nanoscale gap d as illustrated in Fig. 1.

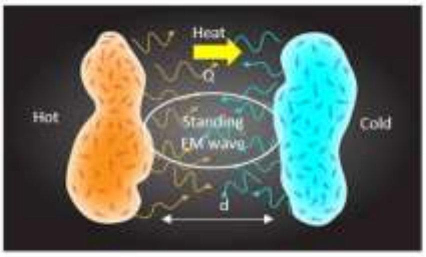

Figure 1. Near-field Radiative Heat Transfer

In NFRHT, the mechanisms by which heat Q flows from hot to cold bodies was extensively sought, all of which assumed surface temperatures of hot and cold bodies, the difficulty of measuring surface temperature in nanoscale gaps avoided by assuming bulk values.

Non-thermal EM waves standing across the gap do not require surface temperatures, but presumably were excluded because since Fourier, temperature differences alone were thought sufficient for describing heat Q flow. Nonetheless, Fig. 1 depicts a temperature independent EM wave transferring heat Q across the gap d.

Today, all known NFRHT mechanisms transfer heat Q by differences in gap surface temperatures. What this means is temperature dependent phonons and evanescent waves known to exist in surfaces of bodies separated by larger gaps are assumed to exist at the nanoscale.

Contrarily, the Planck law [5] of QM denies atoms in the surfaces of nanoscale gaps the heat capacity to change in temperature which may be understood by considering the average Planck energy E of the atom mediated by the Bose distribution,

$$E = \frac{\frac{hc}{\lambda}}{\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} \qquad (1)$$

and at 300 K is plotted in relation to classical physics in Fig. 2.

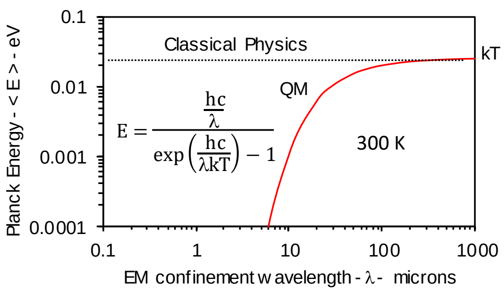

Figure. 2: Planck law of QM at 300 K
In the inset, E is Planck energy, h Planck's constant, c light speed, k Boltzmann's constant, T temperature, and λ the EM wavelength.

The Planck law at 300 K shows classical physics allows the atom to have constant thermal kT heat capacity over all EM wavelengths λ. QM differs as the kT heat capacity decreases for $\lambda < 200\ \mu m$, and vanishes at the nanoscale for $\lambda < 0.1\ \mu m$ = 100 nm. Lacking heat capacity, atoms in nanoscale gap surfaces cannot fluctuate in temperature contrary to Rytov's theory [6] of temperature fluctuations.

Currently, nTPV devices face a dilemma in that all NFRHT theories based on phonons and evanescent waves, or variants thereof which require the atoms in the surface of nanoscale gaps to have temperature are invalid. In effect, the Planck law requires any nTPV theory to be independent of temperature.

II. PURPOSE

The purpose of this paper is to propose temperature independent simple QED heat transfer [7] by EM waves as an alternative to NFRHT theory at the nanoscale and extensions thereof to nTPV devices.

III. THEORY

Simple QED is the consequence of the Planck law denying atoms in nanostructures 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 [8] and others. Simple QED is far simpler only requiring the heat capacity of the atoms in nanostructures to vanish allowing conservation to proceed by the creation of *real* photons comprising EM waves that stand across the nanostructures.

Similar to atomic quantum states described by electrons in discrete orbitals, simple QED quantum states are dependent on the dimension of the nanostructure over which the EM waves stand. The Planck energy E of a simple QED photon standing across a distance d is given by the time τ for light to travel across and back, $\tau = 2d/(c/n)$, where n is the index of refraction of the nanostructure material. Hence, the Planck energy E of the simple QED photons is, $E \sim h/\tau$ having wavelength $\lambda = 2nd$,

$$E = \frac{hc}{2nd} \qquad (2)$$

To illustrate simple QED, consider heat flux Q having wavelength λ_o heating a nanoparticle (NP) of diameter d. For $\lambda_o >> d$, the NP is immersed in the heat flux Q as illustrated in Fig. 3.

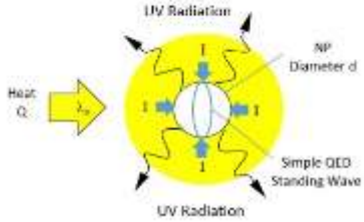

Figure 3. Heating of a NP

Importantly, heat flux Q absorbed by the NP must be placed under brief EM confinement to create the simple QED photons, the process of which depends on the Planck law denying NP atoms the heat capacity to allow the temperature changes required for Fourier heat conduction. Hence, the heat flux Q cannot penetrate the NP surface, and therefore conservation of Q at the NP surface can only proceed by creating non-thermal EM waves to carry the heat Q across and back the NP diameter d in time $\tau = 2nd/c$ as defined in Eqn. 2 for the energy E of the simple QED photon.

The EM confinement at the NP surface is caused by the brief inward spherical Poynting vector S = Q carrying momentum I (shown as blue arrows in Fig. 3). Here, U is the energy from the heat flux Q acting over an increment of time Δt, $U = QA \cdot \Delta t$, where A is the NP surface area, units of S and Q ~ Wm^{-2} and U ~ J giving momentum $I = U/c \sim Nt \cdot s$. Over time Δt, N = U/E simple QED photons having momentum $I_P = h/2nd$ are created, where $NI_P < I$. Once $NI_P > I$, the simple QED photons are emitted to surroundings.

In the interest of whether simple QED photons absent a discrete heat Q may be created from the thermal surroundings alone, consider a NP in the ambient environment at temperature T. The Planck law gives the heat flux Q_T as radiant thermal power energy density,

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

The Q_T momenta $I_T = U_T/c$ driven by the NP at absolute zero, provide the confinement of the simple QED photons, the number N_T of which at temperature T is $N_T = Q_T V/E$, where V is NP volume, and E = hc/2d. At 300 K, $Q_T = 2.71 \times 10^5$ $J/s \cdot m^3$. For Covid-19 vaccines [7] having d ~ 80 nm lipid NPs, $V = 2.68 \times 10^{-22}\ m^3$. Taking n = 1.6, 2nd ~ 254 nm in the UVC with $E = 7.80 \times 10^{-19}$ J or 4.88 eV. Hence, the NPs emit $N_T \sim 100$ UVC photons/s of EM radiation to stimulate the immune system (Fig. 3). Depending on NP size, simple QED radiation from the IR to EUV may be emitted from heat Q_T in ambient surroundings, albeit at low intensity.

The EM confinement of simple QED photons in the NP by the inward spherical momenta is not applicable to NFRHT in gaps between hot and cold bodies as illustrated in Fig. 4.

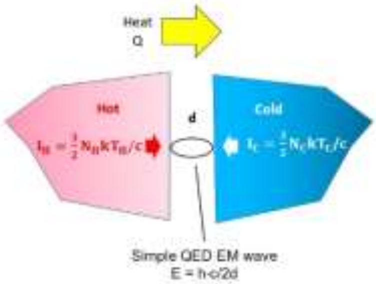

Figure 4. NFRHT.

In NFRHT, heat Q is transferred from hot to cold bodies across a nanoscale gap with vanishing thermal kT energy of atoms in hot and cold gap surfaces as required by the Planck law. To compensate for the surface atoms effectively at absolute zero, the number of adjacent atoms in hot N_H and cold N_C bodies having finite thermal kT energy $U_H = \frac{3}{2} N_H kT_H$ and $U_C = \frac{3}{2} N_C kT_C$ form the Poynting vectors of momentum $I_H = U_H/c$ and $I_C = U_C/c$ directed toward the respective gap surfaces, the momenta providing the EM confinement to form the simple QED photons.

Heat Q flows if the momentum $I_H > I_C$. In the gap, the Planck law precludes conservation of Q by a change in temperature, and instead proceeds by the creating a number N of EM waves, the heat Q/N ~ W/wave delivered to the gap d in time $\Delta t = 2d/c$ is,

$$Q/N = \frac{E}{\Delta t} = \frac{h}{4}\left(\frac{c}{d}\right)^2 \qquad (4)$$

The NFRHT time $\Delta t = d/2c$ is the same as the NP time $\tau = d/2nc$ having refractive index n = 1.

IV. APPLICATION

Commercially available TPV devices [9] are thermophotovoltaic in which thermal photons at high temperatures in the NIR excite the PV cell to produce electricity, but nTPV suggests adding a nanoscale vacuum gap between emitter and PV cell somehow increases the heat Q flow that significantly enhances electrical power density.

Of relevance to nPVT devices, all known NFRHT theories are based on Rytov's fluctuation temperatures [6] that assume photon tunneling by/or evanescent waves. But like NFRHT, experimental verification of a nTPV theory should be expected difficult as temperature differences of only a few degrees across nanoscale gaps can cause high thermal gradients and incorrect estimates of heat flow Q enhancement.

Nevertheless, a 40-fold enhancement of the nTPV output power [10] at a gap distances d = 60 nm was taken [9] as experimental proof of principal of the nTPV concept. The application of simple QED by EM waves in nTPV devices based on [10] is illustrated in Fig. 5.

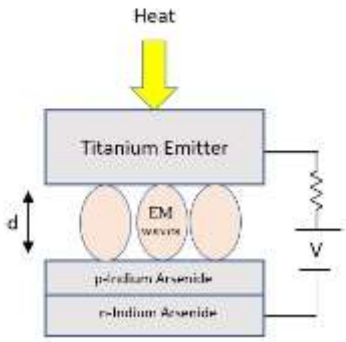

Figure 5. nTVP by EM waves

The simple QED version representative of nTVP devices comprises a titanium emitter separated by a nanoscale gap d from an In/As PV cell. EM waves travel from emitter to cell are depicted carrying heat Q across the gap.

NFRHT theory based on temperature fluctuations is shown [10] in agreement with experiment over al gap sizes and emitter temperatures from 525-665 K. But by simple QED, both NFRHT theory and experiment are invalid at gaps d < 1750 nm as noted in Fig. 6.

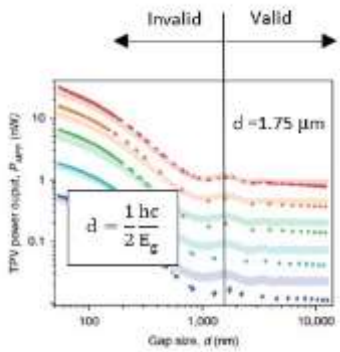

Figure 6 Simple QED and nPVT theory/Experiment

Simple QED based on heat flow Q by EM waves differs significantly from nPVT theory by dependence on the bandgap Eg of the InAs PV cell, E_g = 0.354 eV at λ = 3.5 µm. Indeed, Fig.6 shows small peaking of Q at all temperatures for d = $\lambda/2$ = 1.75 µm. But for d < 1.75 µm, both theory and experiment show Q increases and at 665 K is 40 nW. This is considered invalid because a decrease is expected to mirror the Q response for d > 1.75 µm, i.e., the response of an oscillator is lower both before and after bandgap resonance.

NFRHT based on Rytov's temperature fluctuation theory does not answer the question of why the heat transfer Q increases and not decreases as $d \rightarrow 0$, but in [11] surface contact is shown to transport heat Q at d = 0 across single-digit nanoscale gaps which is difficult to understand as there can be no temperature difference across the contact.

In this regard, simple QED differs. Eqn. 4 shows Q/N becomes large as $d \rightarrow 0$. But the EM wave can only carry heat Q_H/N across the gap if $Q_H/N > Q/N$, but otherwise if $Q_H/N < Q/N$, the wave cannot form and Q = 0. The relation of Q_H/N and Q/N depends on gap d as shown in Fig. 7.

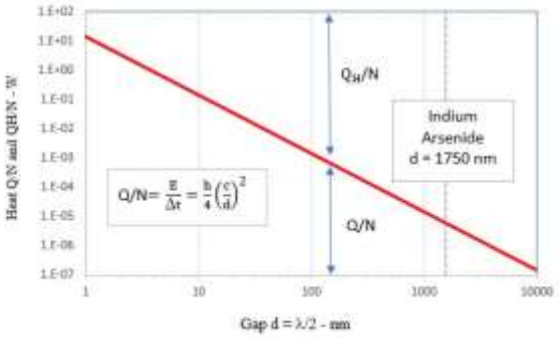

Figure 7. Q/N and QH Relation

Fig. 7 shows the InAs bandgap of d = 1750 nm having Q/N = 7 μW while Fig. 6 for temperatures < 665 K at 1.75 μm gives $Q_H/N < 2$ nW. Since $Q/N > Q_H/N$, simple QED requires heat flow Q = 0 across all gaps d < 1750 nm. Higher Q_H is required to enhance heat Q flow, say by increasing the emitter temperature.

The validity of simple QED depends on vanishing kT heat capacity in nanoscale gaps usually at wavelengths < 100 nm, but the nTPV bandgap requires the kT heat capacity to vanish at $\lambda = 2d = 3$ μm. At 300 K, Fig. 2 shows the Planck energy at $\lambda \sim 6$ μm is, E = 100 μeV, and at 3 μm, E < 100 μeV. Since the kT energy of the atom at which heat produces an increase in temperature is 0.0254 eV, the kT energy at $\lambda = 3$ μm at 3 μm is > 250 times more likely to produce NIR radiation in the 1.75 μm gap than increase in temperature upon absorbing heat. At 300 K, simple QED is indeed valid in d = 1.75 μm gaps.

V. CONCLUSIONS

Near-field PVT devices comprising nanoscale vacuum gaps between the emitter and PV cell producing enhanced heat Q flow based on NFRHT theory of temperature fluctuations is invalid by the Planck law which denies gap surface atoms the heat capacity necessary for temperature fluctuations.

Experiments to verify NFRHT in nPVT devices based on temperature fluctuations are perhaps near impossible as the Planck law denies temperatures to fluctuate in nanoscale gaps. Measurements reported in the literature of temperature differences across nanoscale gaps are fraught with error as the difference in gap surface temperatures sought simply do not exist.

Only temperature independent NFRHT theories for nTPV devices are valid in nanoscale gaps, one of which is simple QED based on the Planck law itself.

Simple QED applied to experimental data of an InAs nPVT device shows a slight peaking in heat Q flow at temperatures < 665 K at the 3.5 μm bandgap wavelength λ of the PV cell, but for λ < 3.5 μm, the heat Q flow increases 40-fold, the latter considered invalid.

NFRHT based on Rytov's fluctuation theory does not predict zero heat Q flow, and therefore contact of gap surfaces is used. But then, the Q flow is thought to increase by conduction even though the temperatures are the same.

Unlike NFRHT, simple QED allows zero heat Q/N flow without contact at the same gap surface temperatures. Based on EM waves, the heat Q_H/N supplied to a gap d is required to satisfy $Q_H/N > Q/N = h(c/d)^2/4$ as otherwise the wave cannot form and Q = 0.

By simple QED, zero nTPV heat flow Q in vacuum gaps between emitter and PV cell may be assumed up to peaking at the bandgap wavelength λ of the PV cell. Hence, simple QED suggests setting the gap $d = \lambda/2$.

Since nTPV bandgaps are in the NIR, 60 nm gaps producing $\lambda = 2d = 120$ nm EM radiation in the EUV is not expected to enhance efficiency above that of NIR nTPV devices.

Simple QED usually applied to nanoscale gaps d < 100 nm is extended to nTPV devices having gaps d < 3 μm as NIR radiation is > 250 times more likely to conserve heat Q flow than an increase in temperature.

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