MEMS/NEMS HEAT TRANSFER BY QUANTUM MECHANICS

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ABSTRACT

Sizes of MEMS electronic devices range from 20 to 1000 microns. MEMS stand for micro-electro-mechanical-systems. Heat transfer in MEMS proceeds on the classical assumption the atom has heat capacity to conserve absorbed EM energy by an increase in temperature. EM stands for electromagnetic. In contrast, NEMS describes devices having sizes < 100 nm. NEMS stands for nano-electro-mechanical-systems. In NEMS devices, heat transfer by the Fourier equation of classical physics that assumes the atom has heat capacity is no longer valid, and instead QM is required. QM stands for quantum mechanics. QM requires the heat capacity of the atom to vanish and therefore any form of EM energy, say Joule heat absorbed in the NEMS device cannot be conserved by the usual increase in temperature. Instead, conservation proceeds by the creation of QED induced radiation that produces excitons and although avoiding hot spot temperatures, the NEMS circuit element is charged and generates 1/*f* noise. QED stands for quantum electrodynamics. By contrast, MEMS devices do indeed increase in temperature under Joule heat but do not create charge. In this arrangement, electronic circuit element design is optimum in the MEMS/NEMS transition region from 20 microns to 100 nm offering the advantage of both avoiding hot spots and 1/*f* noise.

INTRODUCTION

Heat transfer in NEMS circuit elements by the transient Fourier heat conduction equation is thought [1] invalid because the characteristic dimension of the element is comparable to the mean free path of phonon energy carriers. Instead, ballistic transfer heat flow by the BTE is used based on the scattering of phonons by the lattice. Indeed, the BTE and phonon variants thereof are found [2-4] throughout the literature. BTE stands for the Boltzmann transport equation.

Today, the BTE is used to derive the thickness dependent thermal conductivity of thin films. For over 30 years, the reduced conductivity [5] of thin films has been known, but has remained unexplained by the Fourier heat conduction equation. In this regard, the BTE has recently been proposed [1, 6] to explain the reduced conductivity. However, the BTE solutions including the earlier Fourier solutions are questionable because the thin film heat balances excluded QED radiation losses..

By QM, thin films < 100 nm lack the heat capacity to conserve Joule heat lack by an increase in temperature, and instead [7] emit QED radiation at frequencies beyond the UV to the surroundings. But the QED radiation loss is not included [1, 6] in the heat balance, and therefore the thermal conductivity is then concluded to be reduced from bulk. Moreover, QED radiation conserves the Joule heat before thermalization at which time phonons may respond. Hence, heat conduction does not occur, and therefore the notions of thermal conductivity, let alone reduced conductivity have no meaning. In effect, thin film conductivity for all thicknesses simply remains at bulk. The exclusion of QED radiation from the heat balance is understandable as frequencies beyond the UV would normally not be expected upon simply passing current through a thin film,

Conversely, in MEMS circuit elements with sizes > 20 microns, QM allows the atom to have has heat capacity to conserve Joule heat by an increase in temperature, and therefore hot spots may indeed occur. QED radiation and charge are not created in MEMS. The converse is true for NEMS as QED induced 1/*f* noise is created, but not hot spots.

In this arrangement, QM offers circuit elements in the transition region between MEMS and NEMS from 20 microns to 100 nm the significfant advantage of avoiding both hot spots and QED induced 1/*f* noise.

PURPOSE

To propose the design of electronic circuit elements proceed in the MEMS/NEMS transition region from 20 microns to 100 nm. Consistent with QM, hot spots do not occur with heat transfer proceeding by QED induced heat transfer instead of the Fourier equation. However, 1/*f* noise is not created because the QED induced radiation produced in the larger circuit element sizes occurs at frequencies in the IR and beyond where the Planck energy is insufficient to create charge by ionizing the atoms in circuit elements.

THEORY

QM Restrictions

Heat transfer in MEMS is based on classical physics allowing the atom to have thermal kT energy or equivalently the capacity to conserve absorbed Joule heat by an increase in temperature. Absent heat capacity, temperature does not change, and therefore classical heat transfer by the Fourier equation and the BTE that depend on temperature have no meaning. QED heat transfer differs because of QM restrictions. A comparison of the thermal kT energy of the atom by classical physics and QM by the Einstein-Hopf relation [8] is shown in Fig. 1.

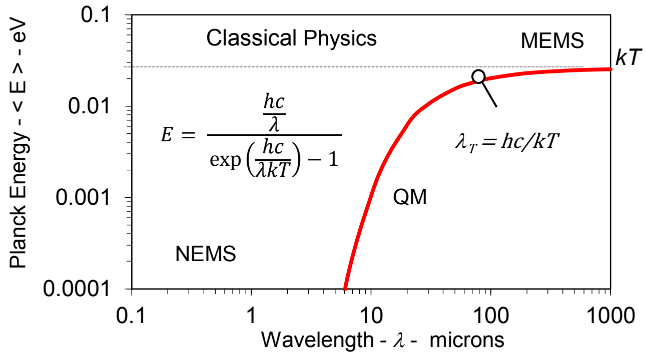

Fig. 1 Heat Capacity of the Atom at 300 K
E is Planck energy, h Planck's constant, c speed of light, k Boltzmann's constant, T temperature, and λ wavelength

QM allows the atom to have kT energy for $\lambda > \lambda_T$ and otherwise is $< kT$. At 300 K, λ_T = 48 microns. For electronic circuit elements of size d, the wavelength $\lambda \sim 2d$. Fig. 1 shows classical heat transfer in MEMS is valid for d > 24 microns. Conversely, NEMS elements confined to λ < 100 nm or d < 50 nm have virtually no heat capacity to conserve Joule heat by an increase in temperature. Optimum design of electronic circuit elements occurs in the region between MEMS and NEMS,

TIR Confinement

Unlike MEMS, QM precludes conservation of Joule heat in NEMS circuit elements by an increase in temperature. Instead, Joule heat is conserved by the creation of non-thermal EM radiation from the QED induced frequency up-conversion of Joule heat to the TIR frequency of the circuit element. TIR stands for total internal reflection.

TIR has a long history. In 1870, Tyndall showed light is trapped by TIR in the surface of a macroscopic body if its RI is greater than that of the surroundings. RI stands for refractive index. Tyndall used water to show TIR confinement of light allowed the transmission through curved transparent tubes. However, TIR need not be limited to the confinement of light. Any form of EM energy may be confined, although in MEMS the confined EM energy is Joule heat.

NEMS differs from MEMS in that circuit elements have high surface to volume ratios. Provided the element has a higher RI than the substrate, the Joule heat is almost entirely absorbed in its surface. Under TIR confinement, QED induces the absorbed Joule heat to undergo spontaneous conversion to surface EM radiation called QED induced radiation. The QED radiation creates excitons (holon and electron pairs) the holons of which charge the circuit element or upon recombination produce EM radiation that is emitted to the surroundings. However, TIR confinement is not permanent, sustaining itself only during the absorption of Joule heat, i.e., absent Joule heat, there is no TIR confinement and excitons from QED radiation are not produced.

QED relies on complex mathematics as described by Feynman [9] although the underlying physics is simple, i.e., photons of wavelength λ are created by supplying EM energy to a QM box with sides separated by λ/2. In this way, QED frequency up-converts Joule heat to the TIR resonance described by the characteristic dimension d of the NEMS circuit element. The Planck energy E of the QED radiation,

$$E = h\upsilon, \quad \upsilon = \frac{c}{\lambda}, \quad \lambda = 2nd \tag{1}$$

where, n is the RI of the circuit element. For film and spherical or cylindrical geometries, d is the thickness or diameter.

QED Induced Radiation

QM allows the atom in MEMS circuit elements to have heat capacity, and therefore QED radiation is not produced. Conversely, QED radiation is produced in NEMS as QM requires the heat capacity of the atom to vanish. In the MEMS/NEMS transition region the heat capacity of the atom is diminished. But because the size d > 100 nm, the QED radiation is created in the IR and beyond that lacks the Planck energy to produce excitons capable of ionizing atoms in the circuit element, and therefore charge is not created. QED radiation may be understood by considering a MEMS or NEMS circuit element in contact with a substrate depicted in Fig. 2.

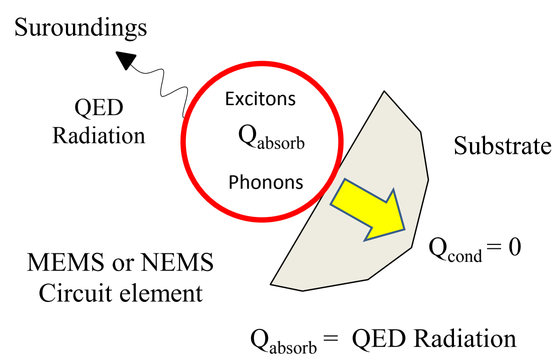

Fig. 2 QED Induced Radiation

In MEMS, absorbed Q_{absorb} energy is conserved by an increase in temperature. But NEMS elements lacking heat capacity are required to conserve Q_{absorb} by other paths. One path is conductive flow Q_{cond} into the substrate by phonons, and another by the creation of QED radiation inside the element. However, phonons only respond after thermalization and even then only at acoustic velocities. In contrast, QED radiation conserves Q_{absorb} at the speed of light well before phonons respond, thereby effectively negating thermal conduction by phonons, i.e., $Q_{cond} \sim 0$. Because of QM, the BTE and Fourier equation are valid only for MEMS and not for NEMS or the NEMS/MEMS region governed by QED induced heat transfer.

Excitons and QED Radiation

QED radiation and excitons (holon and electron pairs) are not produced in MEMS. In NEMS, QED radiation created upon the TIR confinement of Joule heat promptly produces excitons. Holons are free positive charges carriers created as QED induced radiation ejects electrons from the atoms of the circuit element. Electrons loss from the atom are no longer available to maintain charge balance, and therefore holons are free to move under the electric field by hopping from atom to atom through the lattice thereby reducing the resistance of the circuit element. But if the holons recombine with free electrons, EM radiation is created and emitted to the surroundings

QED radiation may be considered as the product of the rate dN_P/dt of the number N_P of QED photons created and their Planck energy E under TIR confinement. Conservation of Joule heat having power P gives the rate of QED photons,

$$\frac{dN_P}{dt} = \frac{P}{E} \tag{2}$$

where, P is power, $P = IV = I^2R$, and V, I, and R are the voltage, current, and resistance.

By the photoelectric effect, the rate dN_{ex}/dt of excitons created depends on the yield Y of excitons / QED photon,

$$\frac{dN_{ex}}{dt} = \eta Y \frac{P}{E} \tag{3}$$

where, Y is taken as unity. Only fraction η of excitons produce charge carriers that change the resistance of the circuit element, the remainder (1-η) upon recombination produce EM radiation that is lost to the surroundings.

Exciton Dynamics

In NEMS, exciton dynamics is characterized by the number of holons and electrons in the circuit element given by Q_H and Q_E, respectively. The rate $\eta P/E$ of excitons created is balanced by the electron Q_E and holon Q_H charges moving toward opposite polarity voltage terminals by their respective μ_E and μ_H mobility in the electric field F. The charge balance,

$$\frac{dQ_E}{dt} = \frac{\eta YP}{E} - Q_E \frac{\mu_E F}{d} \tag{4}$$

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - Q_H \frac{\mu_H F}{d} \tag{5}$$

Both exciton electron and holon equations are symmetric allowing the hole response to represent the electron for the same mobility. For NEMS circuit element characterized by thin films of thickness d, the field $F = V/d$,

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - \frac{\mu_H V}{d^2} Q_H \tag{6}$$

The voltage V across the circuit element takes various forms. For *memristors*, $V = Vo \sin \omega t$,

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - \frac{\mu_H V_o \sin \omega t}{d^2} Q_H \tag{6}$$

where, ω is the circular frequency, $\omega = 2\pi f$, and f is frequency. The holon Q_H solution given by the integrating factor method requires numerical solution.

$$Q_H \exp\left(-\frac{\mu_H V_o}{\omega d^2}\cos \omega t\right) = \frac{\eta YP}{E}\int \exp\left(-\frac{\mu_H V_o}{\omega d^2}\cos \omega t\right) dt \tag{7}$$

In *Spin-valves* and *PCRAM devices*, the voltage V is constant $V = V_o$ step across the thin films giving the closed form solution,

$$Q_H = \frac{d^2}{\mu_H V_o}\left\{\frac{\eta YP}{E}\left[1 - \exp\left(-\frac{\mu_H V_o}{d^2}t\right)\right] + \frac{\mu_H V_o}{d^2} Q_{H0} \exp\left(-\frac{\mu_H V_o}{d^2}t\right)\right\} \tag{8}$$

Holon Q_H response of *nanowires* under constant voltage V_o across their length follow (8) except the film thickness d is replaced by the wire length L.

Electrical Response

In NEMS circuit elements, the excitons on average are centered in the thin film d and need to move $d/2$ to reach opposite polarity voltage terminals. The resistance R is,

$$R = \rho\frac{d}{2A} = \frac{d}{2A}\frac{1}{\mathrm{e}(\mu_E Q_{EO} + \mu_H Q_{HO})/Ad} \approx \frac{d^2}{4\mathrm{e}\mu_H Q_H} \tag{9}$$

where, e is the unit electronic charge. For simplicity, the resistivity ρ assumes $\mu_E = \mu_H$ with the same number Q_E of electrons as Q_H holes. Note the resistivity ρ requires units of per unit volume, where volume is Ad and A is the memristor area.

The initial resistance R_o gives the initial number Q_{HO} of holons.

$$Q_{HO} = \frac{d^2}{4\mathrm{e}\mu_H R_O} \tag{10}$$

For nanowires, film thickness d in (9) and (10) is replaced by length L. The current I is,

$$I = \frac{V}{R} \tag{11}$$

where, $V = V_o$ or $V_o \sin \omega t$.

APPLICATIONS

Applications of QED induced heat transfer to NEMS elements are given [10-15] for memristors, PC-RAM devices, and 1/ *f* noise in nanowires are available [16] on-line, the examples of which are presented in Figs. 3 -5, respectively.

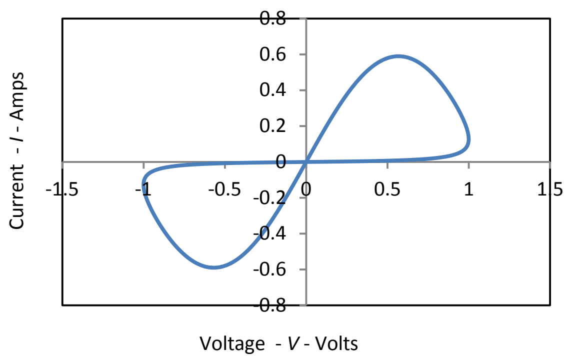

Fig. 3 Memristor *I-V* Curve
d = 50 nm, μ_H = 2x10^{-6} cm^2/V-s

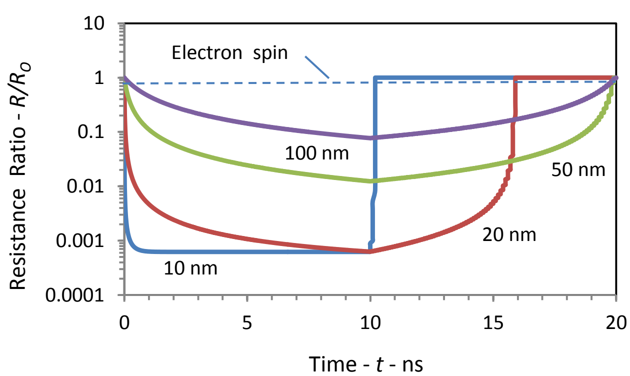

Fig. 4 QED Induced GMR Resistance Ratio *R/Ro* v. Time – ns
+1 V write and -1 V erase

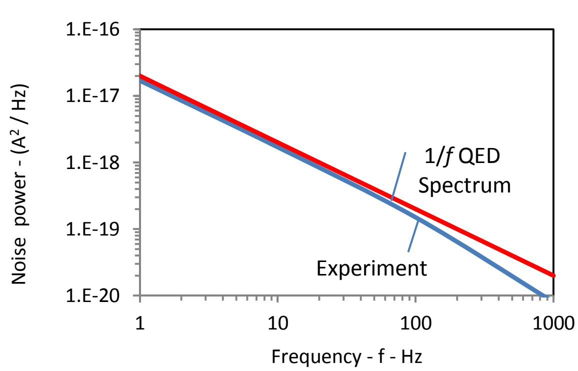

Fig. 5 1/*f* QED Spectrum and Experiment

DISCUSSION

The MEMS/NEMS regions showing the Planck energy of the atom at 300 K with TIR wavelength λ in relation to QM and classical physics is given in Fig. 6.

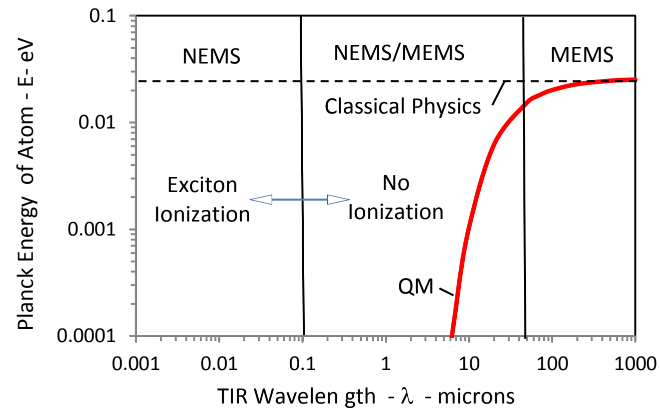

Fig. 6 MEMS/NEMS Regions v. Wavelength

The NEMS region having λ < 0.1 microns is characterized by ionization from QED induced excitons. For MEMS and the transition NEMS/MEMS region marked by λ > 0.1 microns, circuit elements do not charge. Regions of 1/*f* noise and hot spots in terms of characteristic dimension *d* are shown in Fig. 7.

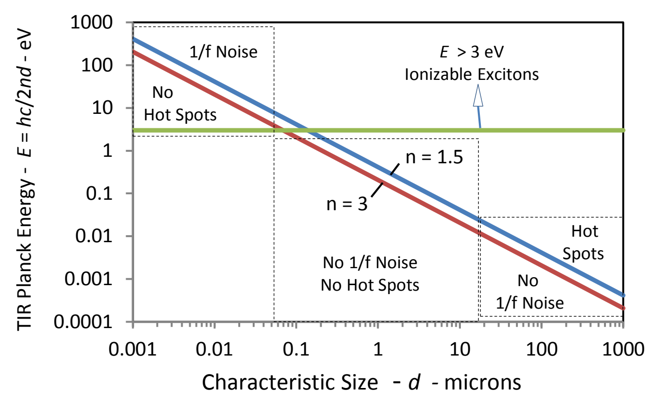

Fig. 7 1/*f* Noise and Hot Spots v. Characteristic Size

Fig. 7 shows the 1/*f* noise and hot spot regions of NEMS/MEMS circuit elements in terms of size dimension *d* taken as half of the TIR wavelength λ in Fig. 6. The Planck energy $E = hc / 2nd$ of QED radiation is shown for RI of n = 1.5 and 3. Ionization of circuit element is assumed for E > 3 eV.

The NEMS region occurs for d < 0.05 microns where there are no hot spots, but 1/*f* noise is produced. The MEMS region for d > 20 microns and E < 0.02 eV shows no 1/*f* noise, but hot spots may occur. In the MEMS/NEMS transition region for 0.050 < d < 20 microns, 1/*f* noise and hot spots do not occur, and therefore offer the optimum size range for all of electronics.

SUMMARY AND CONCLUSIONS

In NEMS, heat transfer analysis by the BTE is thought to supersede the classical Fourier equation because the characteristic dimension of the circuit element is comparable to the mean free path of phonon energy carriers. However, QM suggests heat transfer by both Fourier equation and BTE are invalid for NEMS circuit elements.

Over the past 30 years, thickness dependent thermal conductivity of thin films derived by both the Fourier equation and the BTE has been based on heat balances that exclude QED radiation losses to the surroundings. Because of this exclusion, the thermal conductivity of thin films is found reduced from bulk, but if included, QED induced radiation allows the thermal conductivity to remain at bulk for all thicknesses.

QED induced heat transfer finding basis in QM differs from both the classical Fourier equation and BTE in that the heat capacity of the atom vanishes in NEMS circuit elements. Joule heat is not conserved by an increase in temperature, but rather by the creation of non-thermal EM radiation that produces excitons to charge the circuit element or upon recombination is emitted as EM radiation to the surroundings.

By QED induced radiation, NEMS circuit elements, e.g., memristors, spin-valves, PCRAM films, and nanowires under Joule heating do not produce hot spots, but rather $1/f$ noise. For QED to be valid, the RI of the element is required to be greater than the substrate or surroundings. If so, memristors need not rely on oxygen vacancies, spin-valves do not depend on reduction in the GMR by alignment of electron spins, PCRAM films change resistance by charge and not by melting, and the $1/f$ noise based on free large numbers of electrons in the long–standing Hooge relation based on free electrons QED induced charged holons. In NEMS elements having sizes < 0.05 microns, QED radiation always creates excitons, the holes of which act as charge carriers as first envisioned in PCRAM films by Ovshinsky.

Heat transfer in MEMS circuit elements differs from NEMS as the heat capacity of the atom is always available to conserve Joule heat by an increase in temperature, and therefore analysis by the Fourier equation and the BTE gives valid temperatures provided the size of the element is > 20 microns.

In the NEMS/MEMS transition region having circuit elements between 0.05 and 20 microns, QM suggests $1/f$ noise and hot spots do not occur, and therefore the NEMS/MEMS transition is the optimum size range for all electronics circuit elements.

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