ASME 2013 International Conference on Packaging and Integration of Electronic and Photonic Microsystems
InterPACK2013
July 16-18, 2013, Burlingame, California, USA

InterPACK2013-73173

HEAT TRANSFER IN NANOELECTRONICS BY QUANTUM MECHANICS

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ABSTRACT

Today, the transient Fourier heat conduction equation is not considered valid for the derivation of temperatures from the dissipation of Joule heat in nanoelectronics because the dimension of the circuit element is comparable to the mean free path of phonon energy carriers. Instead, the Boltzmann transport equation (BTE) for ballistic transport based on the scattering of phonons within the element is thought to govern heat transfer. However, phonons respond at acoustic frequencies in times on the order of 10 – 100 ps, and therefore the BTE would not have meaning if the Joule heat is conserved by a faster mechanism.

Unlike phonons with response times limited by acoustic frequencies, heat transfer in nanoelectronics based on QED induced heat transfer conserves Joule heat in times < 1 fs by the creation of EM radiation at optical frequencies. QED stands for quantum electrodynamics. In effect, QED heat transfer negates thermal conduction in nanoelectronics because Joule heat is conserved well before phonons respond.

QED induced heat transfer finds basis in Planck's QM given by the Einstein-Hopf relation in terms of temperature and EM confinement of the atom as a harmonic oscillator. QM stands for quantum mechanics and EM for electromagnetic. Like the Fourier equation, the BTE is based on classical physics allowing the atom in nanoelectronic circuit elements to have finite heat capacity, thereby conserving Joule heat by an increase in temperature. QM differs by requiring the heat capacity of the atom to vanish. Conservation of Joule heat therefore proceeds by QED inducing the creation of excitons (hole and electron pairs) *inside* the circuit element by the frequency up-conversion of Joule heat to the element's TIR confinement frequency. TIR stands for total internal reflection. Under the electric field across the element, the excitons separate to produce a positive space charge of holes that reduce the electrical resistance or upon recombination are lost by the emission of EM radiation to the surroundings.

TIR confinement of EM radiation is the natural consequence of the high surface to volume ratio of the nanoelectronic circuit elements that concentrates Joule heat almost entirely in their surface, the surfaces coinciding with the TIR mode shape of the QED radiation. TIR confinement is not permanent, present only during the absorption of Joule heat.

Charge creation aside, QM requires nanoelectronics circuit elements to remain at ambient temperature while dissipating Joule heat by QED radiation to the surroundings. Hot spots do not occur provided the RI of the circuit element is greater than the substrate or surroundings. RI stands for refractive index.

In this paper, QED radiation is illustrated with memristors, PC-RAM devices, and $1/f$ noise in nanowires, the latter of interest as the advantage of QM in avoiding hot spots in nanoelectronics may be offset by the noise from the holes created in the circuit elements by QED induced radiation.

OVERVIEW

Heat transfer in nanoelectronics is governed by QM, the consequence of which is that the heat capacity of the circuit element vanishes. Joule heat is no longer conserved by an increase in temperature. Instead, conservation proceeds by the QED induced conversion of Joule heat to non-thermal EM radiation to create excitons that upon separation produce space charge of positive charge holes. Thermal management of nanoelectronics is proposed to proceed based on the time dependent Fourier equation using commercial 3D finite element FE programs such as ANSYS and COMSOL. Although FE programs based on classical physics are perfectly valid for circuit boards, cooling systems, and surroundings, QM requires the sub-micron circuit elements to be simulated in the FE model as point or line sources of QED radiation. Hot spots do not occur in nanoelectronics because the QED radiation emitted by the elements is absorbed over large areas of the system. Instead, management of electronic noise may very well control the design of future nanoelectronics.

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BACKGROUND

Nanoelectronics heat transfer is thought [1] unconventional because the transient Fourier heat conduction equation or continuum assumption fails as the characteristic dimension of the circuit element is comparable to the mean free path of phonon energy carriers. Instead, the BTE based on ballistic transfer is employed to derive conductive heat flow based on the scattering of phonons by the lattice. Because of this, the BTE and phonon variants thereof abound [2-4] the literature.

Today, the BTE is primarily directed to the steady state derivation of thickness dependent thermal conductivity of thin films, although the reduced conductivity of thin films has been known [5] for over 30 years. Over this time, the Fourier heat conduction equation has failed to explain thickness dependent thermal conductivity. In contrast, the BTE is claimed [1, 6] to explain reduced thin film conductivity.

However, the BTE [1, 6] and Fourier solutions are questionable because of the heat balances assumed for the films. The problem is thin films emit QED radiation beyond the UV to the surroundings [7] that is not included as a loss in the heat balance, and therefore the thermal conductivity is concluded to be reduced from bulk. Alternatively, if the QED radiation loss is included in the balance, the conductivity remains at bulk. The exclusion of QED radiation from the heat balance is understandable as frequencies beyond the UV would normally not be observed during thin film experiments.

Further, the BTE finds basis in classical physics, and therefore the thermal conductivity of the thin film or collectively the nanoelectronic circuit element is explained by phonons at steady state. However, phonons respond [8] at frequencies < 10 GHz in times > 100 ps, and therefore conduction of Joule heat at acoustic frequencies is just too slow to compete with QED radiation at optical frequencies beyond the UV. In nanoelectronics, QED induced heat transfer therefore conserves Joule heat in circuit elements well before phonons respond.

Moreover, the BTE is generally only applied to steady conductive heat flow. Thermal transients are usually not studied, especially in complex 3D nanoelectronic geometries. Typically, the BTE is limited [9] to steady 1D phonon simulations while transient response is limited to simple estimates [8] of temperatures based on classical physics, e.g., transient temperature changes ΔT for response times τ, electrical power P, heat capacity C, and volume V, are: $\Delta T = P\tau/CV$, i.e., ΔT is bounded as heat capacity C is assumed finite.

In contrast, QM requires the heat capacity C in nanoelectronics circuit elements to vanish. By QM, divergent transient ΔT temperatures are avoided by the creation of QED radiation that charges the element or is emitted to the surroundings.

THEORY

QM Restrictions

Classical physics allows the atom to have thermal kT energy or equivalently the heat capacity necessary to conserve absorbed Joule heat by an increase in temperature. A comparison of the thermal kT energy of the atom by classical physics and QM by the Einstein-Hopf relation [10] is shown in Fig. 1.

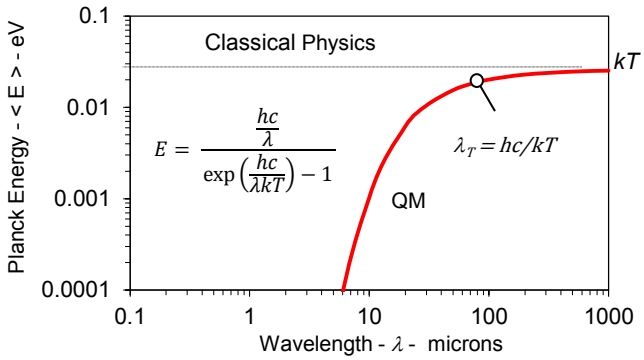

Fig. 1 Heat Capacity of the Atom at 300K
E is Planck energy, h Planck's constant, c speed of light
k Boltzmann's constant, T temperature, and λ wavelength

Both the Fourier equation and the BTE follow classical physics and allow the atom to have the same kT energy in nanoelectronic circuit elements as in conventional electronics. QM differs in that kT energy is only available for $\lambda > \lambda_T$ and otherwise is < kT. At ambient temperature, $\lambda_T \sim 40$ microns. By QM, atoms in nanoelectronics circuit elements under TIR confnement wavelengths $\lambda < 1$ micron therefore have virtually no heat capacity to conserve Joule heat by an increase in temperature.

TIR Confinement

Absent heat capacity, QM precludes conservation of Joule heat in nanoelectronics 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 to the TIR resonance of the circuit element.

In 1870, Tyndall showed light is trapped by TIR in the surface of a body if the RI of the body is greater than that of the surroundings. However, TIR need not be limited to the confinement of light. Any form of EM energy may be confined by TIR, although in nanoelectronics the confined EM energy is Joule heat.

In nanoelectronics, 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. But the surface fully participates with the shape of the

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TIR wave function, and therefore QED induces the absorbed Joule heat to undergo spontaneous conversion to surface EM radiation. TIR confinement induces the creation of excitons from QED radiation without any external EM confinement. Indeed, 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 [11] 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 $\lambda/2$. In this way, QED frequency up-converts Joule heat to the TIR resonance described by the characteristic dimension d of the 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.

APPLICATIONS

Applications of QED induced heat transfer to nanoelectronics [12-15] find commonality in the conversion of Joule heat in circuit elements to non-thermal QED radiation. Subsequently, the QED radiation creates excitons or is emitted to the surroundings as EM radiation. Summaries for the memristor, PC-RAM devices, and 1/ *f* noise in nanowires are as follows.

Memristors

In 1971, Chua [16] hypothesized a passive two-terminal circuit element existed having a resistance that depended on the time–integral of the current. Based on symmetry arguments alone, the notion was held that electronic circuitry based on the three circuit elements - the resistor, capacitor, and inductor was incomplete. For completeness, a fourth element called a memristor was proposed. But lacking an actual prototype, the memristor lay dormant for almost 40 years.

Hewlett-Packard (HP) in 2008 announced [17] the development of a switching memristor circuit element comprising a thin film of titanium dioxide sandwiched between platinum electrodes. HP memristors claim positive charged holes from oxygen vacancies are the source of switching. But the HP theory is phenomenological lacking physical basis to allow extensions to memristors without vacancies.

Indeed, experiments over the past 50 years show memristor behavior without oxygen vacancies. Even electrodes are not necessary, as memristor behavior is observed in a single material, e.g., gold and silicon nanowires. Absent vacancies, memristor behavior in nanowires is explained by the presence of space charge, but the source has never been identified. In contrast, QED theory predicts space charge creation from excitons anytime Joule heat is dissipated in nanoelectronics.

QED Radiation and Excitons QM restrictions on heat capacity require the dissipative Joule power P be conserved by creating number N_P of QED photons in the memristor having Planck energy E. The QED radiation is created at the rate dN_P/dt,

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

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,

$$\frac{dN_{ex}}{dt} = Y\frac{dN_P}{dt} \tag{3}$$

Only a fraction η of excitons created change the memristor resistance, the remainder (1-η) upon recombination produce EM radiation that is lost to the surroundings.

Source of Holes The number of holes and electrons in the memristor is given by Q_H and Q_E, respectively. The rate dN_{ex}/dt of excitons created is balanced by the electron Q_E and hole Q_H charges moving toward voltage terminals by their respective μ_E and μ_H mobility in the electric field F. The charge balance is,

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

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

where, d is the memristor thickness. Both exciton electron and hole equations are symmetric allowing the hole response to represent the electron for the same mobility. Taking $F = V/d$ and $V = Vo \sin \omega t$ gives the number Q_H of hole charges,

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

where, ω *is* circular frequency, $\omega = 2\pi f$, and f is frequency. Conservation of the charge for the number Q_E of electrons is in the excitons is similar.

The hole Q_H solution by the integrating factor method,

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

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Electrical Response On average, the exciton holes and electrons are centered in the film d and need to move $d/2$ to reach opposite polarity voltage terminals. The resistance R is,

$$R = \rho\frac{d}{2A} = \frac{d}{2A}\frac{1}{\mathrm{e}(\mu_E Q_{EO} + \mu_H Q_{HO})/Ad} \approx \frac{d^2}{4\mathrm{e}\mu_H Q_H} \qquad (8)$$

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 memristor area. The initial resistance R_o gives the initial number Q_{HO} of hole charges,

$$Q_{HO} = \frac{d^2}{4\mathrm{e}\mu_H R_O} \qquad (9)$$

The current I is,

$$I = \frac{V}{R} = \frac{V_O \sin \omega t}{R} \qquad (10)$$

Simulations Memristor resistance R depends on the instantaneous number of holes Q_H during each cycle of applied harmonic voltage. The QED induced I-V hysteresis loop of memristors characterized by the "bow-tie" shape reported by Chua [16] and HP [17] is shown in Fig. 2.

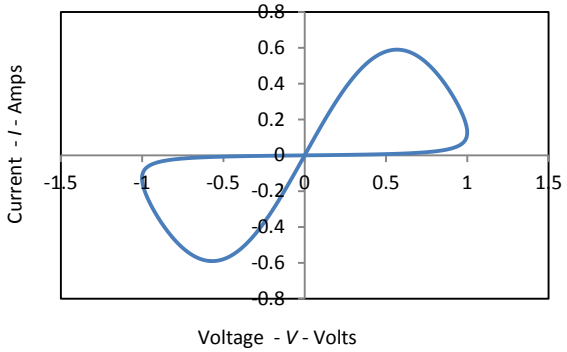

Fig. 2 Memristor I-V Curve
d = 50 nm, μ_H = 2x10^{-6} cm^2/V-s

PC-RAM Devices

In the 1960's, Ovshinsky initiated scientific research in the field of amorphous and disordered GST materials of fundamental importance in the storage of data in PC-RAM devices that continues to this day. GST stands for GdSbTe chalcogenide type glasses and PC-RAM stands for phase-change - random access memory.

The Ovshinsky [18] effect is the significant reduction in resistance of submicron thick GST films under low voltages. In contrast, Chua's [16] memristor gives a continuous decrease and recovery of resistance over the same harmonic cycle, but is superseded by QED induced charge consistent with Ovshinsky's charge carriers [18].

However, PC-RAM theory is not without controversy. Ovshinsky [18] thought the resistance of GST films changed by the redistribution of charge carriers; whereas, others at that time including PC-RAM researchers today [19, 20] argue the resistance changes because the GST crystalline state is transformed to the amorphous state by melting, the Joule heat supplied by lasers and heaters. In this controversy, QM asserts the heat capacity of submicron GST films vanishes, and therefore melting cannot occur, as the Joule heat supplied is not conserved by an increase in temperature. By precluding melting, QM re-opens the controversy between the melting and charge carrier PC-RAM mechanisms.

Instead of increasing GST film temperature, conservation proceeds by the QED induced creation of excitons from EM radiation under TIR confinement. The TIR confinement of QED radiation is enhanced by the fact the Joule heat absorbed in the GST film is concentrated in the TIR mode because of its high surface to volume ratios. The QED radiation having Planck energy beyond the UV produces excitons by the photoelectric effect, the electrons and holes of which change the GST film resistance without melting. QM precludes temperature increases during switching provided submicron GST films are sandwiched in materials of a lower RI. However, thick supramicron GST films follow classical physics and do indeed melt upon heating. In this regard, Chua's [16] conjecture that memristors are the missing fourth element in electronic circuits is superseded by Ovshinsky's [18] charge carriers, the charge carriers being the consequence of QM.

Mobility In PC-RAM devices and memristors, mobility of hole charge carriers is of great importance in defining the current that transfers the charge from excitons to the voltage terminals, but data is limited. In this paper, current is proportional to both mobility and conductivity, Chen et al. [21] expressed mobility μ at ambient temperature by,

$$\mu = \mu_o \exp\left(\alpha F^{1/2}\right) \qquad (11)$$

where, μ_o is the mobility at zero field. Organic light emitting tris-(8-hydroxyquinolate) aluminum (Alq3) film correlates by α = 9.22x10^{-3} (cm/V)$^{1/2}$. The typical GST mobility is independent of GST film thickness, i.e., μ= 2x10^{-5} cm^2/V-s.

Source of Holes Similar to memristors, excitons in GST films change resistance in proportion to the fraction ηP of QED radiation absorbed and the yield Y. The rate dN_{ex}/dt of excitons created is balanced by the electron Q_E and hole Q_H charges lost by neutralization at opposite polarity terminals by their respective μ_E and μ_H mobility in the field F. For constant voltage $V = V_o$, the hole Q_H balance is,

$$\frac{dQ_H}{dt} = \frac{\eta Y P}{E} - \frac{\mu_H V_o}{d^2} Q_H \qquad (12)$$

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The hole Q_H solution,

$$Q_H = \frac{d^2}{\mu_H V_o}\left\{\frac{\eta Y P}{E}\left[1 - \exp\left(-\frac{\mu_H V_o}{d^2}t\right)\right] + \frac{\mu_H V_o}{d^2} Q_{H0} \exp\left(-\frac{\mu_H V_o}{d^2}t\right)\right\} \qquad (13)$$

Simulations The Alq3 mobility [21] was used in the simulations. The electric field F assumed constant voltage V_o = 1 V that for GST film thickness from 10 to 10000 nm, correspond to $F = Vo / d$ of 10^6 to 10^3 V/cm. Equation (11) gives Alq3 hole mobility from 3.04×10^{-3} to 4.03×10^{-7} cm^2/V-s. The resistance R transients are shown in Fig. 3.

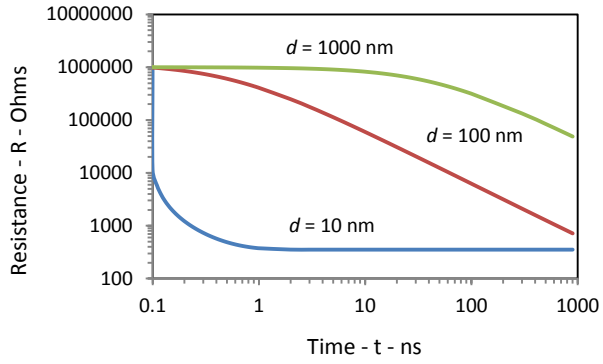

Fig. 3 Transient R – Alq3 Mobility

All GST films were assumed to have an initial resistance $R_o = 1 \times 10^6$ ohms. The 10 nm film resistance R is reduced to 350 ohms in less than 1 ns – a 99.965 % reduction approaching superconductivity. The 100 and 1000 nm films respond far slower. All GST films change resistance by QED induced space charge as Ovshinsky envisioned over 50 years ago.

1/*f* Noise in Nanowires

1/*f* noise is commonly observed in EM measurements of electronic circuits comprising capacitors, resistors, and inductors. Research in 1/*f* noise began in 1925 with Johnson [22] and Nyquist [23] who found vacuum tubes emitted white noise. White noise has a constant power spectrum generated by the thermal agitation of charges inside the resistor itself without any applied voltage. In contrast, 1/*f* noise sometimes called pink noise differs in that under applied voltage the frequency f of the power spectrum is not constant, but rather increases as f is lowered, i.e., having a slope of -1 on a log-log plot of noise vs. frequency.

Over the past 80 years, explanations of 1/*f* noise have proved elusive. Schottky [24] proposed a 1/ f model of exponentially decaying current pulse I caused by the release of electrons from the cathode of a vacuum tube, i.e., $I = Io \cdot e^{-bt}$, For a train of such pulses at an average rate, the power spectrum is of the Lorentzian form which is constant near $f = 0$ and for large f is proportional to $1/f^2$ with a narrow transition region where the power spectrum resembles that of 1/f noise.

Today, 1/f noise is generally explained by free electrons in the Hooge [25] relation,

$$\frac{S_R}{R^2} = \left(\frac{S_I}{I^2}\right)_V = \frac{\alpha}{fN} \qquad (14)$$

where, S_R and S_I are the spectral power density of resistance R and current I, and f is the frequency at which the noise is measured, N is the total number of free electrons, and α is an empirical dimensionless constant.

Hooge claimed the 1/f noise is caused by lattice scattering of electrons. However, this is unlikely as phonon frequencies are far higher than LFN frequencies. LFN stands for low frequency noise. It is difficult to reconcile LFN with the residence time of the electron in the size of the sample. If 1/f noise is a summation of Lorentzians having long characteristic times t >> 1 s, the electrons must stay in the sample much longer than a few seconds. But in a sample with a length of 1 cm, an electron only stays about 0.1 s as its diffusion coefficient D is of order 0.001m^2/s. In nanoelectronics, the residence time of the electron in the circuit element is far smaller. The Hooge relation based on electrons therefore cannot be correct.

Source of Holes Unlike Hooge's relation for LFN based on electrons, QED radiation [15] created by conserving Joule heat produces charge by the photoelectric effect.

$$\frac{dN_P}{dt} = \frac{P}{E} \text{ and } \frac{dN_{ex}}{dt} = Y\frac{dN_P}{dt} \qquad (15)$$

where, dN_p/dt is the rate of QED radiation created. By the photoelectric effect, dN_{ex}/dt is the rate of excitons produced and Y is the exciton yield / QED photon. Like the memristor and PC-RAM devices, only a fraction η of the excitons created produce 1/f noise, the remaining (1-η) excitons upon recombination emit EM radiation to the surroundings. Unlike the probabilistic creation of excitons from an external source of EM radiation having $Y << 1$, QED radiation created *inside* the circuit element surface have $Y = 1$. For voltage V_o across the nanowire, the field $F = V_o / L$,

$$\frac{dQ_H}{dt} = \frac{\eta P}{E} - \frac{\mu_H V_o}{L^2} Q_H \qquad (16)$$

The hole Q_H solution is,

$$Q_H = \frac{L^2}{\mu_H V_o}\left\{\frac{\eta P}{E}\left[1 - \exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right] + \frac{\mu_H V_o}{L^2} Q_{H0} \exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right\} \qquad (17)$$

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In contrast to LFN based on electrons given by the Hooge relation, QED induced excitons are produced by a step change in charged hole Q_H carriers as current enters the NW. Since the step in charge Q_H with time t is a step in current $I = dQ_H/dt$ and since the voltage V_o across the NW is constant, the LFN in NWs is caused by a step change in power $P = V_oI$.

Fourier Transform of Step Change In NWs, the LFN is given by the Fourier transform (FT) of a step change in power, the general form [26] of which is,

$$u(t)t^{\alpha} \leftrightarrow \text{Mag} = \Gamma(\alpha+1)\omega^{-(\alpha+1)}$$

$$\text{Phase} = -\pi(\alpha+1)/2 \qquad (18)$$

where, α is a constant. In the time domain, the unit step function u(t) is defined as u(t) = 0 for $t < 0$, and u(t) = 1 for $t \geq 0$. For $\alpha = 0$, the Gamma function $\Gamma(\alpha+1) = 1$ and the FT(f) for the step in power has the magnitude of $1/f$ in the frequency f domain at phase angle $\theta = -\pi/2$, i.e.,

$$FT(f) = \int_{-\infty}^{\infty} 1e^{-j2\pi ft}\, dt = -\frac{j}{2\pi f} = \frac{1}{2\pi f} \text{ at } \theta = -\frac{\pi}{2} \qquad (19)$$

LFN therefore consists of a $1/f$ noise spectrum given by the FT(f) of the step change in hole charges Q_H created by QED as current enters the NW.

Simulations QED induced $1/f$ noise simulations of SnO_2 NWs were made for the current PSD at a drain bias $V_D = 0.1$ V and gate voltages $V_G = 2.5$ V over the frequency band from 1 to 1000 Hz. PSD stands for power spectral density. See (Fig. 3(a) of [27]). The NW diameter d and length L are 50 nm and 1.5 microns, respectively.

Signaling Power QED theory requires the Joule heat dissipated in the PSD of the NW at a given V_G. However, the PSD in [27] is expressed in signaling [28] terminology,

$$I^2(f, f_o) = \frac{KF \cdot I_D}{C_{cap}L^2} f_o \int_{f_o}^{f} \frac{df}{f} \quad \text{A}^2/\text{Hz} \qquad (20)$$

where, $I^2(f)$ is the current PSD in A^2/Hz. From [27], at $V_G = 2.5$ V and $f_o = 1$ Hz, the PSD = $1.4\text{x}10^{-17}$ A^2/Hz. The constant $KF = 8.14\text{x}10^{-32}$ was fit to the PSD using capacitance $C_{cap} = 1.593\text{x}10^{-16}$ F given in [27]. Integration to $f = 1000$ Hz,

$$I^2(1000,1) = 1.4\text{x}10^{-17}\ln\left(\frac{1000}{1}\right) = 9.66\text{x}10^{-17}\ \text{A}^2 \quad (21)$$

The NW physical current I_{phys} is,

$$I_{phys} = \sqrt{I^2(1000,1)} = 9.83\text{x}10^{-9}\text{A} \qquad (22)$$

The Joule heat is the power $P = V_DI_D$, where V_D and I_D are drain voltage and current. From (Fig. 2(a) of [27]), the $I_D = 0.2\text{x}10^{-6}$ A at $V_D = 0.1$ V. Hence, the power $P = 2\text{x}10^{-8}$ W.

Only a fraction η of the power P produces the excitons in $1/f$ noise, i.e., $\eta P = I_{phys}V_D = 9.83\text{x}10^{-10}$ W << $P = 2\text{x}10^{-8}$ W, where $\eta \sim 0.05$. The remaining $(1-\eta)$ excitons upon recombination emit EM radiation to the surroundings. The TIR confinement barrier of the SnO_2 NWs having $d = 50$ nm diameter and $n = 1.73$ from (1) has Planck energy $E = 7.1$ eV, the barrier confining (and exciting) all lower SnO_2 quantum states, e.g., the 2 eV VIS luminescence of SnO_2 [29] nano rods. Hence, the excitons $\eta P/E$ in (17) are created at $E \sim 2$ eV.

Step Change in Hole Charges The hole SnO_2 mobility μ_H = 172 and 40 cm^2/V-s were simulated. Assuming $Q_{H0} = 0$, the transient hole Q_H charges from (17) simplified to:

$$Q_H = \frac{\eta PL^2}{\mu_H EV_o}\left[1 - \exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right] \qquad (23)$$

where, $\eta P = I_{phys}V_D$ and $V_o = V_D$. Fig. 4 shows the Q_H response for mobilities of 172 and 40 cm^2/V-s is constant in ~ 5 ns at 4 and 17 holes, respectively. Hence, the $1/f$ spectrum for LFN in the frequency domain is justified by the FT of the step in power of holes Q_H in the time domain.

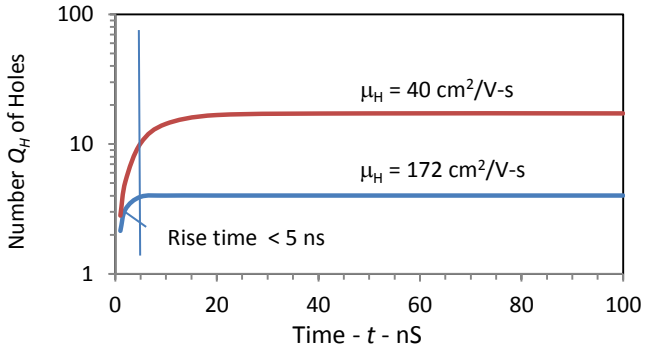

Fig. 4 QED Induced step change in Hole charges

In NWs, the number N of holes is estimated [27] with the modified Hooge relation,

$$I^2(f) = \frac{\alpha_H I_D^2}{Nf} \qquad (24)$$

where, $\alpha_H = 0.045$. For $V_G = 2.5$ V, the PSD gives $I^2(f) = 1.4\text{x}10^{-17}$ A^2/Hz at $f = 1$ Hz. Hence, $N \sim 128$ holes which is greater than the QED induced holes. However, it is noted Hooge [25] based his experimental $1/f$ correlation on electrons – not holes.

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QED Spectral Density QED induced PSD argues the step in charge Q_H created as the current enters the NW under constant voltage V_o produces a step change in power the FT of which establishes LFN has form of a 1/*f* spectrum, but the amplitude requires the physical current I_{phys} to be estimated. From (16),

$$I_{phys} = \mathrm{e}\left(\frac{P}{E} - \frac{\mu_H V_o}{L^2} Q_H\right) \tag{25}$$

and

$$I^2(f, f_o) = \frac{I_{phys}^2}{ln\left(\frac{f}{f_o}\right)} \tag{26}$$

Unlike (23) with ηP (η = 0.05), the fraction (η = 1) is used in (25) because the physical current I_{phys} to create all excitons depends on total power *P*, i.e., ηP produces 1/*f* noise while $(1\text{-}\eta)P$ is lost by VIS luminescence to the surroundings. Taking Q_H = 4 holes, I_{phys} = 9.95x10^{-9} A. From (26), $I^2(f_o)$ = 1.43x^{-17} A^2/Hz. The experiment [27] is lower at $I^2(f_o)$ = 1.4x^{-17} A^2/Hz, but for clarity is depicted even lower in Fig. 5.

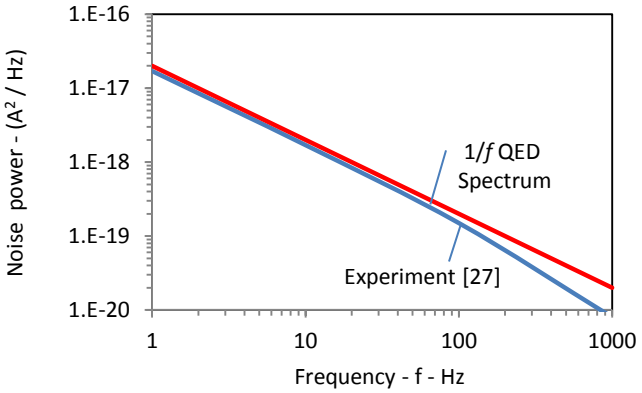

Fig. 5 1/*f* QED Spectrum and Experimental [27] Data

The QED induced 1/*f* PSD is observed coincident with experiment for *f* < 10 Hz, but deviates for *f* > 100 Hz because the data does not follow 1/*f*, but rather $1/f^{\beta}$, where $1 < \beta < 1.5$. Otherwise, the QED induced 1/*f* spectrum simulates experiment without any fitting parameters

EXTENSIONS

Nanowires provide nanoelectronics with interconnects between circuit elements. The abrupt decrease in resistance shown for QED induced photoelectric effect in GST films by Ovshinsky suggests superconductivity already exists or at least may be approached for nanowires at ambient temperature. Indeed, UV induced photo-conductivity [30] has already been observed for $GdBa_2Cu_3O_{6.5}$. Hence, the Ovshinsky Effect may supersede magnetic effects in spintronics, a review of which is planned in a subsequent paper.

SUMMARY

In nanoelectronics, the classical Fourier equation is not thought applicable to heat transfer for circuit elements because the characteristic dimension of the element is comparable to the mean free path of phonon energy carriers. Instead, the BTE is considered acceptable. However, QM suggests both Fourier equation and BTE derivations are invalid in nanoelectronics.

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.

The BTE based on classical statistical mechanics currently used in heat transfer of nanoelectronics is a method of deriving the thermal conductivity of a circuit element under conditions of steady heat flow. The BTE is also claimed to derive transient thermal response, but like the Fourier equation the BTE assumes the atom has heat capacity at the nanoscale. BTE derivations of both steady and transient temperatures in nanoelectronics circuit elements are therefore invalid by QM.

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 nanoelectronics 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 element or upon recombination is emitted as VIS radiation to the surroundings.

By QED induced radiation, the circuit elements, e.g., memristors, PC-RAM devices, and nanowires do not increase in temperature under Joule heating. For QED to be valid, the RI of the element is required to be greater than the surroundings. If so, memristors need not rely on oxygen vacancies, GST films change resistance by charge and not by melting, and the 1/ *f* noise based on large numbers of electrons in the long–standing Hooge relation based on electrons is superseded by a small number of QED induced charged holes. In nanoelectronics, QED radiation always creates excitons, the holes of which act as charge carriers as first envisioned in GST films by Ovshinsky.

The QED simulation of 1/*f* noise in SnO_2 NWs differs from memristors and PC-RAM devices in that the low power level of the PSD suggests the LFN is produced by only a few holes. Indeed, the experimental data was found simulated by < 20 carrier holes and for a mobility 172 cm^2/V-s only a few QED induced hole charges are required. In contrast, the modified Hooge relation predicts the creation of about 100 holes. More

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study is required to confirm or refute whether a few hole charges do indeed produce 1/*f* noise in NWs.

NWs aside, the long-standing puzzle of generic 1/*f* noise may be explained by the FT of abrupt step changes in the time domain, e.g., the sound in striking a piano key and the electronic recording of changes in the stock market index.

The significant reduction in resistance of memristors and GST films as supported by QED induced radiation suggests nanowires as interconnects between circuit elements in nanoelectronics may indeed approach superconductivity at ambient temperature.

Applications of QED induced heat transfer in the thermal management of nanoelectronics are trivial compared to those required for the BTE. Given the BTE is invalid by QM, there is no need to perform tedious phonon scattering derivations of thermal conductivity in circuit elements. The magnitude and frequency of QED radiation may be simply estimated from Joule heat by hand calculations and input as point or line sources into standard FE computer programs such as ANSYS and COMSOL. Unlike conventional electronics, thermal management of hot spot temperatures is not expected to be a problem in nanoelectronics as the QED radiation emitted from a circuit element is absorbed over large areas of the surroundings. Instead, management of electronic noise may pose the greater challenge to nanoelectronics.

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