Nanoelectronics by Quantum Mechanics

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Abstract
In nanoelectronics, QM requires the heat capacity of the atom in circuit elements to vanish thereby precluding the conservation of Joule heat by an increase in temperature. Instead, conservation proceeds by the QED induced conversion of Joule heat to excitons (hole and electron pairs) that charge the circuit element. QM stands for quantum mechanics, QED for quantum electrodynamics, and EM for electromagnetic. Paradoxically, classical physics by allowing the atom to have heat capacity to conserve Joule heat by an increase in temperature does not create the charge necessary to change the resistance of the circuit element.

Introduction

Today, nanoelectronics heat transfer follows conventional electronics. However, for some time, the Fourier heat conduction equation has failed to explain the thickness dependent thermal conductivity of thin film interconnects between circuit elements. Instead, the BTE is shown [1] to explain the reduced thermal conductivity of thin films by the scattering of phonons. BTE stands for the Boltzmann transport equation.

Conversely, the BTE solutions supporting the reduced conductivity of thin films are questionable because the heat balances of the films exclude the QED radiation [2, 3] lost to the surroundings. Because of this, the film conductivity is thought reduced from bulk, but if QED radiation is included in the heat balances, the Joule heat in the film is spontaneously lost by QED radiation at UV levels to the surroundings, i.e., the film conductivity simply remains at bulk as thermal conduction is not required to conserve Joule heat. The omission of QED radiation in the heat balances is understandable as the UV would not normally be detected. Even so, the BTE finds basis in classical physics with phonons serving as the heat carriers that respond at frequencies < 10 GHz in times > 100 ps. Hence, QED radiation at the speed of light effectively negates thermal conduction by phonons as Joule heat is conserved well before phonons respond.

Based in classical physics, the BTE conserves Joule heat by an increase in temperature, but does not produce charge. Paradoxically, charge is required to explain the lowering of resistance in circuit elements. Instead, QED induced excitons finding basis in QM are proposed as the source of charge, the excitons separating under the electric field across the circuit element to produce positive charged holes. Although QM avoids hot spots by precluding temperature increases in nanoelectronics, QED induced charge poses the problem of excessive electronic 1/*f* noise.

QED Induced Radiation

QM Restrictions

Classical physics always allows the atom to have thermal kT energy or the heat capacity to conserve Joule heat by an increase in temperature, but not QM. A comparison of heat capacity of the atom by classical physics and QM is shown in Fig. 1.

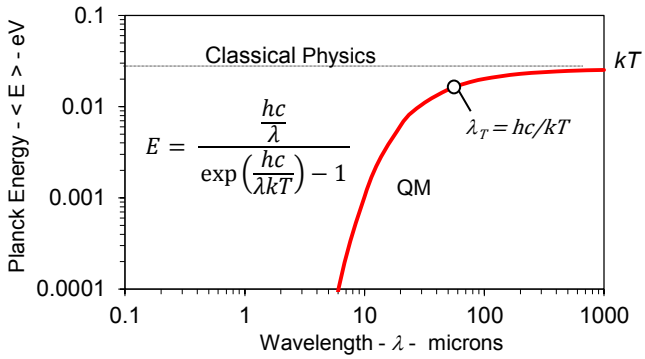

Fig. 1: Heat Capacity of the Atom at 300K
E is Planck energy, h Planck's constant, c speed of light, k Boltzmann's constant, T temperature, and λ wavelength

Both the Fourier law 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 $< kT$. By QM, atoms in nanoelectronics circuit elements under EM confnement wavelengths $\lambda < 1$ micron therefore have virtually no heat capacity to conserve Joule heat by an increase in temperature.

TIR Confinement

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. TIR stands for total internal reflection and RI for refractive index. However, any form of EM energy may be confined by TIR, although in nanoelectronics the confined EM energy is Joule heat. EM stands for electromagnetic. Absent heat capacity, QM precludes conservation of Joule heat in nanoelectronics by an increase in temperature. Instead, conservation proceeds by the creation of excitons from non-thermal EM radiation produced as QED induces the frequency up-conversion of Joule heat to the TIR confinement frequency of the circuit element.

In nanoelectronics, circuit elements have high surface to volume ratios. Provided the circuit 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 TIR wave function, and therefore QED induced radiation spontaneously creates excitons in the surface. TIR confinement is not permanent, sustaining itself only during the absorption of Joule heat, i.e., absent Joule heat, there is no QED induced radiation and excitons are not created. Simply put, QED creates EM radiation of wavelength λ upon supplying Joule heat to a QM box with sides separated by $\lambda/2$. In this way, QED up-converts low frequency Joule heat to the high frequency of the TIR confinement described by the characteristic dimension d of the circuit element.

The Planck energy E of the QED radiation,

$$E = h\upsilon, \;\; \upsilon = \frac{c/n}{\lambda}, \;\; \lambda = 2d \tag{1}$$

where, n is the RI of the circuit element. For films and spherical (or cylindrical) geometries, the characteristic dimension d is the respective thickness or diameter.

APPLICATIONS

The application of QED induced radiation to spin-torque, memristors, and nanowire circuit elements is described by Equations (2) through (6) except as modified in the differential equation for the number Q_H of holes. QM restrictions on heat capacity require the conservation of power P by creating excitons at the rate P/E, the fraction η of which charges the circuit element while the remaining (1-η) excitons upon recombination are lost to the surroundings as QED radiation, i.e., the excitons N_{ex} are created in the circuit element at the rate,

$$\frac{dN_{ex}}{dt} = \eta\frac{P}{E} \tag{2}$$

The rate $\eta P/E$ of excitons is balanced by the paired electron Q_E and hole Q_H charges moving within the circuit element of dimension d toward opposite polarity terminals. In terms of μ_E and μ_H mobilities and the electric field F between voltage terminals,

$$\frac{dQ_E}{dt} = \eta\frac{P}{E} - Q_E\frac{\mu_E F}{d} \;\text{ and }\; \frac{dQ_H}{dt} = \eta\frac{P}{E} - Q_H\frac{\mu_H F}{d} \tag{3}$$

For $F = V/d$, and considering only the hole Q_H equation.

$$\frac{dQ_H}{dt} = \eta\frac{P}{E} - \frac{\mu_H V}{d^2}Q_H \quad \leftarrow \quad V = V_o \;\text{ or }\; V = V_o\sin(\omega t) \tag{4}$$

The circuit element resistance R and current I are,

$$R = \rho\frac{d}{2A} = \frac{d}{2A}\frac{1}{\mathrm{e}(\mu_E Q_{EO} + \mu_H Q_{HO})/Ad} \approx \frac{d^2}{4\mathrm{e}\mu_H Q_H} \quad \text{and} \quad Q_{HO} = \frac{d^2}{4e\mu_H R_O} \tag{5}$$

$$I = \frac{V}{R} = \frac{V_o}{R} \quad \text{or} \quad I = \frac{V_o}{R}\sin(\omega t) \tag{6}$$

Spin-Valves

Spin-valves comprise alternating nanoscale layers of FMs separated by a NM spacer. FM stands for ferromagnetic and NM for non-magnetic. Over a decade ago, theoretical predictions of spin-valves by Slonczewski [4] assumed spin-polarized current produced by passing un-polarized current through the first FM layer remains polarized through the NM spacer. Upon interaction with the second FM layer, the spin angular momentum is transferred from the first to the second FM as a physical spin-torque, the process tending to produce parallel spins that lower the giant

magneto resistance or GMR. However, significant reduction in the GMR by the alignment of spins is not without controversy. The spin-torque propagates by phonons through the FM lattice thereby limiting spin-transfer to frequencies < 10 GHz having response times > 100 ps. However, electron spins respond much faster. Indeed, laser studies in by Boeglin et al. [5] show nanoscale FMs demagnetize on a sub-picosecond time scale (< 350 fs) far faster than phonons respond.

QED induced photoconductivity differs. Provided the RI of the FM is greater than that of the adjacent NM spacers, non-thermal EM radiation beyond the UV is created by the frequency up-conversion of Joule heat to the TIR confinement frequency of the FM. Therefore, excitons are readily created, the positive holes of which act as charge carriers that significantly reduce the GMR of the FM by the dramatic increase in photoconductivity. Reversal of polarity, recovers the GMR. From (4), the number Q_H of holes in the FM is,

$$Q_H = \frac{d^2}{\mu_H V_o}\left\{\eta\frac{P}{E}\left[1-\exp\left(-\frac{\mu_H V_o}{d^2}t\right)\right]+\frac{\mu_H V_o}{d^2}Q_{H0}\exp\left(-\frac{\mu_H V_o}{d^2}t\right)\right\} \tag{7}$$

The QED induced photoconductivity in FMs is simulated [6] for Alq3 film thicknesses of 10, 20, 50, and 100 nm. All films are assumed to have an initial GMR of R_o = 1x10^6 ohms. Voltage V_o = 1 V was applied for 10 ns followed by reversing the voltage polarity V_o = -1 V for 10 ns. The resistance ratio R/R_o transients are shown in Fig. 2. Resistance reduction by electron-spin is almost insignificant compared to QED induced photoconductivity.

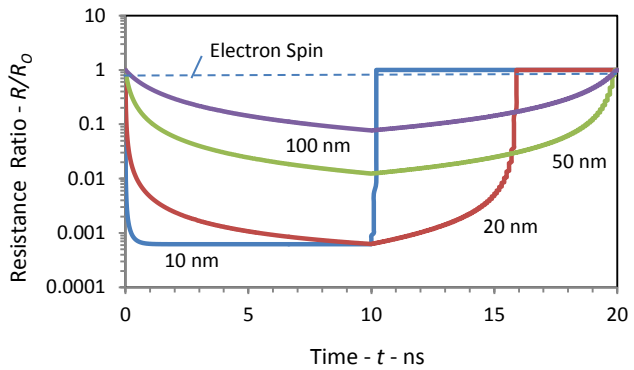

Fig. 2: QED Induced Resistance Ratio *R/Ro* v. Time - ns

Memristors

In 1971, Chua [7] 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 until 2008 when Hewlett-Packard or HP announced the development of a switching memristor circuit element comprising a thin film of TiO_2 sandwiched between Pt electrodes. HP claimed oxygen vacancies are the source of positive charged holes, but many experiments show memristor behavior is independent of oxygen vacancies, e.g., gold and silicon nanowires.

QED induced memristor Q_H solutions [8] follow Equations (2) through (6), but the harmonic voltage $V = V_o \sin(\omega t)$ requires the numerical solution of the integral differential equation,

$$Q_H \exp\left(-\frac{\mu_H V_o}{\omega d^2}\cos\omega t\right) = \eta\frac{P}{E}\int_0^t \exp\left(-\frac{\mu_H V_o}{\omega d^2}\cos\omega t\right)dt \tag{8}$$

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 [7] without any fitting parameters is shown in Fig. 3.

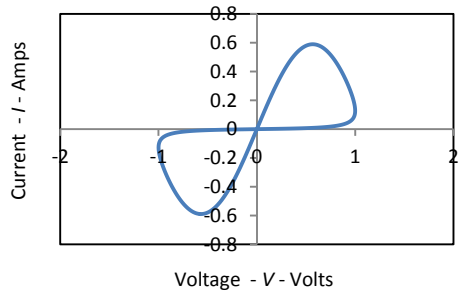

Fig. 3: Memristor I-V Curve $d = 50$ nm, $\mu_H = 2\text{x}10^{-6}$ cm^2/V-s

1/*f* Noise in Nanowires

Research in 1/*f* noise began [9] in 1925 with Johnson and Nyquist. Sometimes called pink noise, 1/*f* noise has a slope of -1 on a log-log plot of noise vs. frequency. QED induced simulations [8] of $d = 50$ nm diameter and $L = 1.5$ micron long SnO_2 nanowires follow Equations (2) through (6) except in (3) the length L replaces the FM and memristor thickness d. The hole Q_H solution is,

$$Q_H = \frac{L^2}{\mu_H V_o}\left\{\eta\frac{P}{E}\left[1-\exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right]+\frac{\mu_H V_o}{L^2}Q_{H0}\exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right\} \tag{9}$$

QED induced 1/*f* noise [8] is shown to produce a step in charge Q_H created as the current enters the nanowire that under constant voltage V_o produces a step change in power in the time domain, the Fourier transform of which is indeed 1/*f* in the frequency domain. Hence, QED induced 1/*f* noise in nanowires closely follows experiment as shown in Fig. 4.

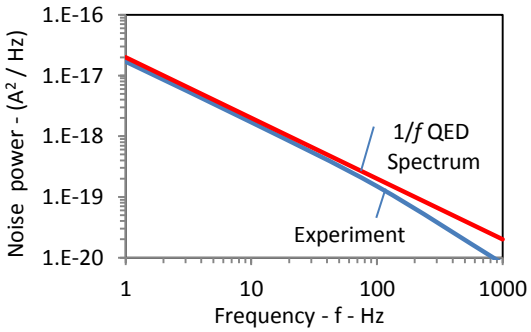

Fig. 4: 1/*f* QED Spectrum and Experimental Data

Conclusions

Classical physics that allows the atom in circuit elements to have heat capacity and conserve Joule heat by an increase in temperature is valid in conventional electronics, but is invalid in nanoelectronics by QM.

In nanoelectronics, classical physics allows circuit elements to increase in temperature by Joule heating whereas the circuit elements charge by QM.

QM conserves Joule heat in nanoelectronics by creating excitons (electron and hole pairs) the fraction η of which charges the circuit element with positive holes while the remaining (1-η) excitons upon recombination emit QED radiation to the surroundings.

In nanoelectronics, the QED induced space charge of holes significantly alters the electrical performance of the circuit element, if not the defining characteristic of the circuit element itself, e.g., the reduction in resistance of FMs in spin-valves, the switching characteristic of memristors, and the 1/*f* noise in nanowires are all caused by the space charge of QED induced holes.

QED induced photoconductivity in FMs dramatically lowers the GMR of spin-valves compared electron spin suggesting superconductivity at ambient temperature may be approached in nanoscale FMs. Lowering of the GMR by alignment of electron spins is relatively insignificant.

Switching by memristors is caused by the abrupt lowering of resistance from the QED induced creation of excitons that separate under the electric field to produce a space charge of holes that change the resistance of the circuit element during the harmonic voltage cycle. Memristor switching has nothing to do with oxygen vacancies or the missing fourth circuit element.

The Fourier transform of the step change in QED induced charge in the time domain as current enters the nanowire is the source of 1/*f* noise in the frequency domain. Indeed, the generic 1/*f* noise observed in other systems is most likely caused by abrupt changes in the time domain, e.g., in music as piano keys are struck or in electronic recordings of changes in stock prices.

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