QED Induced Excitons in Nanoelectronics

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Abstract

In nanoelectronics, light absorption is known to create excitons (holon and electron pairs) that separate under an electric field into free carriers that change the resistance of circuit elements. However, light absorption itself is not required as the Joule heat within the submicron circuit element may be induced by QED to create excitons. QED stands for quantum electrodynamics. QED induced excitons find basis in the QM requirement that the heat capacity of the atom vanishes under TIR confinement. QM stands for quantum mechanics and TIR for total internal reflection. Lacking heat capacity, Joule heat cannot be conserved by an increase in temperature, and instead under TIR confinement the Joule heat is conserved by the QED induced creation of non-thermal EM radiation in the circumferential direction of the circuit element surface. EM stands for electromagnetic. In the manner of a quasi-bound state trapped in a potential well and leaking to the outside world by tunneling, the TIR confinement is temporary sustaining itself only during the absorption of Joule heat, thereby producing a momentary source of intense photoexcitation for the creation of QED induced excitons. Illustrations of QED induced excitons in resistive switching of memristors and spin-valves including extensions to the superconductivity of nanowires at ambient temperature are presented.

Introduction

Over 20 years ago, exciton dynamics in confined systems comprising quantum wells, wires, and dots were extensively [1] investigated. Today, excitons have been extended to nanoscale systems including light absorption in molecules, conjugated polymers, molecular aggregates, and carbon nanotubes. The new aspect [2, 3] of excitons is that the physical size and shape of the material at the nanoscale strongly influences the nature and dynamics of the electronic excitation. What this means is the exciton size is dictated not by the electron–holon Coulomb interaction as in the bulk, but rather finds similarity to the EM confinement of the electron defined by the physical dimensions of the material.

However, light-matter interaction need not proceed by electron confinement. Some time ago, the EM emission from an atom in QED cavity was shown [4] enhanced or suppressed depending on the photon confinement. However, cavity QED theory is restricted to atoms in evacuated space while nanoelectronics circuit elements are solid nanoscopic structures. Indeed, the physical mechanism of QED induced photon confinement in solids is not found in the literature, e.g., cavity QED theory [5] for delocalized excitons based on the Hamiltonian for the EM radiation field excludes the physical mechanism by which the EM radiation field itself is confined in solids.

Purpose

To propose QED induced EM radiation produces excitons from Joule heat that upon delocalization produce the charge carriers that lower the resistance of nanoelectronics circuit elements. QED induced radiation finds basis in the QM requirement that the heat capacity of the atom vanishes under TIR confinement at the nanoscale. Lacking heat capacity, Joule heat cannot be conserved by an increase in temperature, and instead conservation proceeds by the QED induced creation of non-thermal EM radiation in the circumferential direction of the circuit element surface. The TIR confinement is not permanent but temporary, sustaining itself only during the absorption of Joule heat. Absent Joule heat, there is no TIR confinement and excitons are not created. By this mechanism, QED induced EM radiation provides a momentary but intense source of photoexcitation increasing photoconductivity thereby dramatically lowering resistance to allow the circuit element to function as a switch. Reversal of the voltage bias creates excitons that recover the initial resistance.

Theory

QM Restrictions

Conservation of Joule heat by QM differs from classical physics based on Einstein's and Debye's theories [6] that allow the atom to have thermal *kT* energy or equivalently the heat capacity to conserve absorbed EM energy by an increase in temperature. A comparison of the heat capacity of the atom by classical physics and QM given by the Einstein-Hopf relation [7] is shown in Fig. 1.

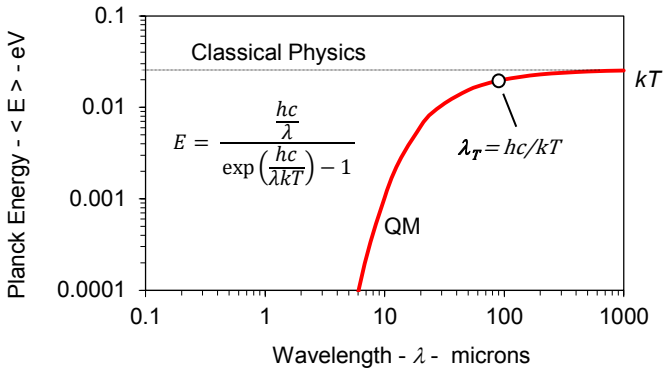

Fig. 1 Heat Capacity of the Atom at 300K
E is Planck energy, *h* Planck's constant, *c* speed of light,
k Boltzmann's constant, *T* absolute temperature, and λ wavelength

Classical physics allows the atom to have the same *kT* energy in nanoelectronics 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. Fig. 1 shows the thermal energy or heat capacity of the atom is < *kT* for $\lambda < 40$ microns. By QM, atoms under EM confnement wavelengths $\lambda < 1$ micron have virtually no heat capacity to conserve energy from any EM source by an increase in temperature.

TIR Confinement

Lack of heat capacity by QM precludes heat absorbed from EM sources to be conserved in nanoelectronics by an increase in temperature. Instead, the EM energy is proposed conserved by the creation of non-thermal EM radiation by 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 provided the refractive index of the body is greater than that of the surroundings. Today, light trapping by TIR is described [8] by MDRs where EM waves propagate around the inside surface of the nanostructure while returning in phase to their starting points. MDR stands for morphology-dependent resonance.

In nanoelectronics, TIR has a special significance and need not be limited to light absorption. Unlike macroscopic bodies, nanoelectronics circuit elements have high surface to volume ratios, and therefore EM energy from any source (lasers, Joule heat, etc.) is absorbed almost entirely in their surfaces. Since the surface coincides with the TIR wave function given by the MDR, QED induces the absorbed EM energy to undergo spontaneous conversion to surface QED photons However, TIR confinement is not permanent sustaining itself only during EM energy absorption, i.e., absent absorption of EM energy, there is no TIR confinement and QED radiation is not created.

QED relies on complex mathematics as described by Feynman [9] although the underlying physics is simple, i.e., photons having Planck energy *E* are created by supplying EM energy to a submicron QM box with sides separated by $\lambda/2$. The MDR for thin films of thickness *d* and width *w* having refractive index *n* is,

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

In thin films, TIR has the starting point in the surface of the film edge and propagates at wavelength $\lambda = 2d$ in the surface along the width *w* of the film. Note: $w > 2d$. However, MDRs in nanowires (NWs) differ from thin films in that $w = d$. The EM waves in TIR propagate around the inside surface of the NW diameter by the circumference πd prior to returning to their starting points,

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

Response Time and Charging

QED induced EM radiation is the prompt conversion of Joule heat at the speed of light far faster than phonons at acoustic velocities can respond, thereby essentially precluding thermal conduction by phonons at the nanoscale. Under TIR confinement at MDRs, the QED induced radiation having Planck energies beyond the UV by the photoelectric effect creates excitons that lower the resistance of the circuit element. Reversal of polarity allows the recovery of the initial resistance to be controlled.

Unlike classical physics that conserves absorbed EM energy by an increase in temperature, conservation by QED charges the nanoelectronics. The QED radiation may excite electrons that then interact with phonons, but the absorbed EM energy is almost totally conserved by the prompt creation of charge, although in materials having low photoelectric yield the QED radiation may be lost to the surroundings.

Applications

In nanoelectronics, QED induced radiation [10] conserves Joule heat by creating charge instead of increasing temperature. Applications include spin-valves, memristors, PC-RAM, and 1/*f* noise.

Spin-Valves

Spin-valve ferromagnetism is based on theoretical predictions by Slonczewski [11] and Berger [12] over a decade ago. Spin-valves comprise alternating nanoscale layers of FMs separated by a NM spacer. FM stands for ferromagnetic and NM for non-magnetic. Spin-valves produce spin-polarized current by passing un-polarized current through a first FM layer, the polarization unchanged as the current flows through the NM spacer. Upon interaction with the second FM layer, a giant magneto-resistance known as GMR is thought to transfer the spin angular momentum from the first to the second FMs as a physical spin-torque, the process tending to produce parallel spins that significantly lower the GMR.

However, significant reduction in the GMR by the alignment of spins is not without controversy. The relatively rigid lattice shields the spins so that any transfer of spin-torque to the second FM is unlikely. Further, spin-torque propagates by phonons through the FM lattices, and therefore limiting spin-transfer to frequencies < 10 GHz having response times > 100 ps. However, electron spins respond much faster.

Indeed, laser studies in femtomagnetism by Boeglin et al. [13] show nanoscale FMs demagnetize on a sub-picosecond time scale (< 350 fs) far faster than phonons can respond. Spin transfer through the lattice therefore cannot be the mechanism for demagnetization. In this regard, Bigot et al. [14] showed about 10 ps for the lattice to thermalize prompting Bovensiepen [15] to suggest spin-valves de-magnetize by light and not spin-transport through the lattice and further noted the dynamics are only observed while the laser field interacts with the FM – an observation bearing remarkable similarity the TIR confinement described by a quasi-bound MDR state, trapped in a potential well but leaking to the outside world by tunneling.

Like any other nanoelectronic circuit element, spin-valves by QM lack the heat capacity to conserve Joule heat by an increase in temperature. Notions of demagnetizing FMs by exceeding the Curie temperature with laser heating as suggested by Bigot et al. [14] and others based on temperature changes, however small may be safely dismissed.

QED induced radiation differs. Provided the RI of the FM is greater than that of the adjacent NM spacers, non-thermal EM radiation at EUV levels is created by the frequency up-conversion of Joule heat to the TIR confinement frequency of the FM. Therefore, excitons are readily created by the photoelectric effect, the positive holons 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.

Consistent with observations [13-15] spin-valve switching is proposed caused by QED induced holons at EUV levels created from Joule heat having nothing to do with the transport and alignment of spins. Indeed, Jiang et al. [16] showed Fe/Alq3/Co spin valve switching occurs by holons alone. Alq3 stands for tris-(8-hydroxyquinolate) aluminum and is representative of organic spin valves. Indeed, Prezioso et al. [17] proposed magnetoresistive and non-volatile electrical switching mechanisms coexist in Alq3 allowing spin-valves to be multifunctional.

1) Photons and Excitons QM restrictions on heat capacity require the dissipative power *P* is conserved by creating number N_P of QED photons in the surface of the FM layer having Planck energy *E*. Only a fraction η of QED radiation creates excitons, the remainder (1-η) is lost to the surroundings. The QED photons are created at the rate dN_P/dt,

$$\frac{dN_P}{dt} = \frac{\eta P}{E} \tag{3}$$

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,

$$\frac{dN_{ex}}{dt} = \eta Y \frac{dN_P}{dt} \tag{4}$$

2) Source of Excitons The rate of creating excitons dN_{ex}/dt 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*.

$$\frac{dQ_E}{dt} = \frac{\eta YP}{E} - Q_E \frac{\mu_E F}{d} \tag{5}$$

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

For simplicity, only the holon Q_H charged equation is considered. Taking $F = V_o/d$,

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - \frac{\mu_H V_o}{d^2} Q_H \tag{7}$$

The holon Q_H solution is,

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

3) Electrical Response On average, the holons and electrons are centered in the film *d* and need to move *d* /2 to reach the voltage terminals, the spin-valve 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 electron charge. The resistivity ρ assumes $\mu_E = \mu_H$ with the same number Q_E of electrons as Q_H holons. Note the resistivity ρ requires units of per unit volume, where volume is *Ad* and *A* is memristor area. The initial resistance R_o corresponds to the number Q_{HO} of initial holon charges,

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

The current *I*,

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

4) 1) Mobility Frenkel [18] argued the current *I* through the GST film cannot be based on mobility μ alone, but also depends on conductivity σ. Hence, the current *I*,

$$I = I_o \exp\left(\frac{\beta F^{\frac{1}{2}}}{kT}\right) \tag{12}$$

where, β is a constant for a given material. Since current is proportional to both mobility and conductivity, Chen et al. [19] expressed mobility μ at ambient temperature by,

$$\mu = \mu_o \exp\left(\alpha F^{1/2}\right) \tag{13}$$

where, μ_o is the mobility at zero field. For Alq3, α = 9.22x10^{-3} (cm/V)$^{1/2}$ and μ_o = 3.04x10^{-7} cm^2/V-s.

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The QED induced switching is simulated for Alq3 film thicknesses of 10, 20, 50, and 100 nm. All films were assumed to have an initial GMR of R_o = 1x10^6 ohms. A 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 and holon transients are shown in Figs. 2 and 3.

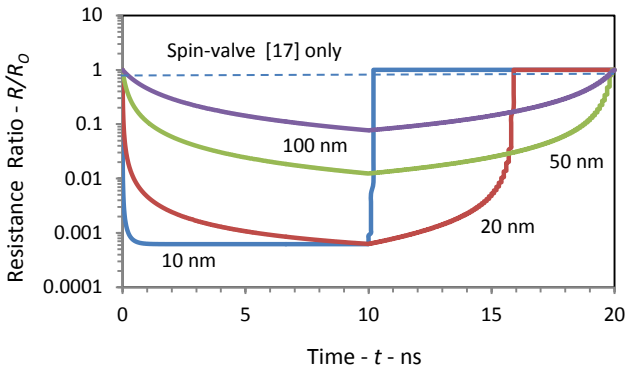

Fig. 2 QED Induced Resistance Ratio *R/Ro* v. Time - ns

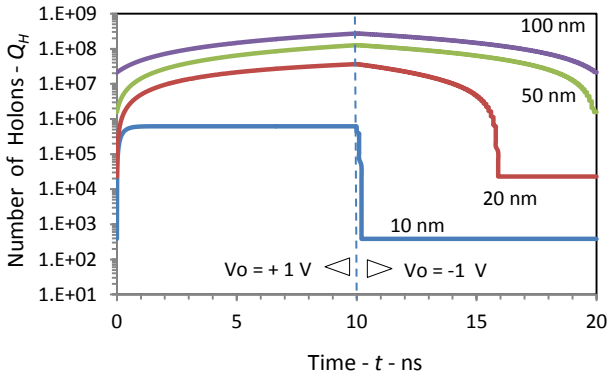

Fig. 3 QED Induced Number of Holons v. Time – ns

The QED induced reduction in GMR *R* is observed to change significantly depending on the film thickness *d*. The 10 nm film resistance ratio R/R_o is reduced to ~ 0.000624 or (R ~ 624 ohms) in < 1 ns. In contrast, magnetic induced GMR reductions are relatively insignificant, i.e., 125 nm Alq3 film [17] at 100 K shows a GMR reduction of about 22% corresponding to R/R_o = 0.78 noted in Fig. 2. As the film thickness increases, R/R_o increases. Reversal of voltage V_o shows an abrupt change for the 10 nm film, the abruptness decreasing as *d* increases. In the simulations, the resistance *R* becomes negative for the 10 and 20 nm films and was corrected to the initial resistance R_o.

The 10 nm film resistance change predicted by the QED induced photoelectric effect in GST films suggests superconductivity already exists or at least may be approached at ambient temperature. Photo-conductivity observed [20] for 250 nm $GdBa_2Cu_3O_{6.5}$ films under Hence laser irradiation (632.8 nm) lacks the Planck energy to produce the holons necessary to approach superconductivity. However, superconductivity at ambient temperature may be possible, say in 10 nm nanowires by the dramatically enhanced photo-conductivity from holons created at Planck energies far beyond the UV by the QED induced photoelectric effect.

Memristors

In 1971, Chua [21] claimed 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.

In 2008, Hewlett-Packard (HP) announced [22] the development of a switching memristor based on a thin film of titanium dioxide (TiO_2) sandwiched between platinum (Pt) electrodes. HP memristor theory assumes positive charged holons from oxygen vacancies are the source of switching. But the theory is

phenomenological lacking physical basis to allow extensions to other memristors without vacancies. In fact, many experiments reported over the past 50 years show memristor behavior. Moreover, sandwiched material between electrodes is not necessary. Indeed, memristor behavior is observed in a single material without electrodes, e.g., gold [23] and silicon [24] nanowires. Lacking vacancies, explanations of memristor behavior assume the presence of space charge, but the source is not identified.

In contrast, QED theory claims space charge is created anytime EM energy is absorbed in nanostructures. Early memristor simulations [25, 26] showed charge is created by QM from the conservation of Joule heat by QED, a brief summary is as follows.

1) Source of Holons The excitons (holon and electron pairs) created by the photoelectric effect produce the total number of holons Q_H and electrons Q_E in the memristor. Under the high electric field F across the memristor thickness d, the holons and electrons promptly move to and are neutralized at the opposite polarity voltage terminals.

Similar to spin-valves, the number of excitons $\eta YP/E$ created is balanced by the electron Q_E and holon Q_H charges move under their respective μ_E and μ_H mobility in the electric field F and are neutralized at opposite polarity voltage terminals. Excluding the electrons in current I flowing through the memristor from the exciton charge balance ,

$$\frac{dQ_E}{dt} = \frac{\eta YP}{E} - Q_E \frac{\mu_E F}{d} \tag{16}$$

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - Q_H \frac{\mu_H F}{d} \tag{17}$$

Both exciton electron and holon equations are identical allowing the holon 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 holon charges,

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - \frac{\mu_H V_o \sin \omega t}{d^2} Q_H \tag{18}$$

where, the circular frequency $\omega = 2\pi f$ and f is frequency.

The holon Q_H solution by integrating factor is,

$$Q_H \exp\left(-\frac{\mu_H V_o}{\omega d^2} \cos \omega t\right) = \frac{\eta YP}{E} \int exp\left(-\frac{\mu_H V_o}{\omega d^2} cos\ \omega t\right) dt \tag{19}$$

2) Electrical Response Similar to the spin-valves, the resistance R is expressed in terms of holon number Q_H and mobility μ_H is given in (8). Similarly, the initial resistance R_o corresponds to the number Q_{HO} of holon charges given in (9). The memristor current I is,

$$I = \frac{V}{R} = \frac{V_O\ sin\ \omega t}{R} \tag{20}$$

3) Simulations Memristor resistance R depends on the instantaneous number of holons Q_H during each cycle of applied harmonic voltage. Plots of the hysteresis loop in the *I-V* follow memristor behavior are shown in Fig. 4

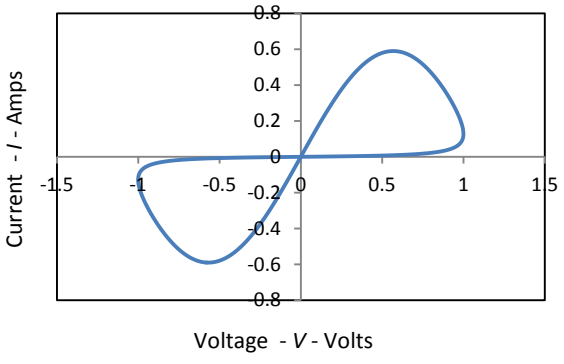

Fig. 4 Memristor *I-V* Curve
d = 50 nm, $\mu_H = 2x10^{-6}$ cm^2/V-s

PC-RAM

In the 1960's, Ovshinsky [27] initiated scientific research in the field of amorphous and disordered materials that continues to this day. The Ovshinsky Effect where the resistance of thin GST films is significantly reduced upon the application of low voltage is of fundamental importance in phase-change - random access memory (PC-RAM) devices. GST stands for GdSbTe chalcogenide type glasses.

However, the Ovshinsky Effect is not without controversy. Ovshinsky thought the resistance of GST films changed by the redistribution of charge carriers; whereas, others at that time including many PC-RAM researchers today [28, 29] argue that the GST resistance changes because the GST crystalline state is transformed to the amorphous state by melting, the 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 heat supplied cannot be conserved by an increase in submicron GST film temperature. By precluding melting, QM re-opens the controversy between the melting and charge carrier PC-RAM mechanisms. Conversely, supramicron GST films follow classical physics and do indeed melt upon heating.

Instead of increasing GST film temperature, conservation proceeds by the QED induced creation of EM radiation within the GST film under TIR confinement. The TIR confinement of QED photons is enhanced by the fact the absorbed heat energy in the GST film is concentrated in the TIR mode because of their high surface to volume ratios. The QED radiation having Planck energy beyond the UV produces excitons by the photoelectric effect, the electrons and holons of which change the GST film resistance. QM precludes temperature increases during switching provided submicron GST films are sandwiched in materials of a lower refractive index. Conversely, thick chalcogenide films follow classical physics and do indeed melt upon heating.

1) Simulations The Alq3 mobility [19] for PC-RAM is the same as that assumed above for the spin-valves simulation. The resistance *R* transient to 1000 ns is shown in Fig. 5. All GST film thicknesses were assumed to have an initial resistance $R_o = 1x10^6$ ohms. The 10 nm GST film resistance *R* is reduced to 350 ohms in less than 1 ns while the 100 nm film requires about 1000 ns. Polarity reversal in PC-RAM follows that given above for QED induced radiation in spin-valves.

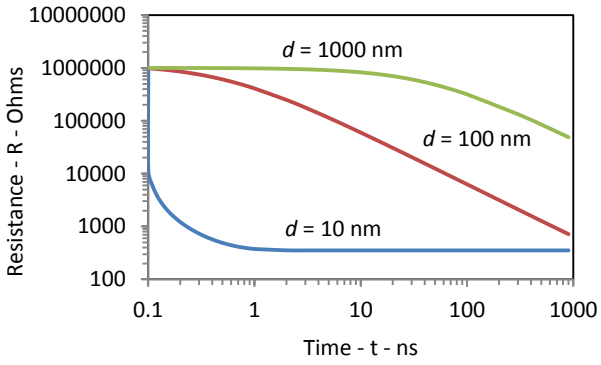

Fig. 5 Transient *R* – Alq3 Mobility

1/f Noise

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 [30] and Nyquist [31] who found vacuum tubes emitted white noise. White noise has a constant power spectrum generated by the thermal agitation of charges inside a resistor by 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 [32] proposed a mathematical model of exponentially decaying current pulse *I* caused by the release of electrons from the cathode of a vacuum tube, i.e., $I = Io \cdot e^{-bt}$, where *Io* is the initial step, *b* is the relaxation rate and *t* is time. 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. Erland et al. [33] state 1/*f* noise is an intermediate between constant white noise with no correlation in time and random $1/f^2$ Brownian motion with no correlation between increments. Since Brownian motion is the integral of white noise, the conclusion is that 1/ *f* noise cannot be obtained by integration. Except for fractional Brownian motion (half-integral of a white noise signal), no physical explanation of 1/ *f* noise has been proposed.

Today, 1/*f* noise is generally explained by free electrons in the Hooge [34] relation,

$$\frac{S_R}{R^2} = \left(\frac{S_I}{I^2}\right)_V = \frac{\alpha}{fN} \tag{21}$$

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.

Later, Hooge [35] described the difficulty of reconciling LFN with the residence time of the electron in the size of the sample. LFN stands for low frequency noise. If 1/*f* noise is a summation of Lorentzians having long characteristic time's $t >> 1$ s, the electrons must stay in the sample much longer than a few seconds. In fact, Weissman [36] argued 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. Weissman asked Hooge: "How can electrons stay in the sample and produce LFN at frequencies below 1 Hz?" Hooge's answer [35] was the 1/*f* noise is caused by lattice scattering of electrons. However, this is unlikely because phonon frequencies are far higher than LFN.

Today, 1/*f* noise continues to be described by the Hooge relation for scattering of electrons. An exception was Handel [37] who proposed a quantum 1/*f* theory that claimed LFN is caused by low-frequency IR photons that are absorbed or emitted in each scattering event. However, the half-wavelength of LFN is far longer than the dimensions of the samples, and therefore the cage effect, better known today as QED cannot be invoked as the EM confinement mechanism by which the EM energy in scattering of electrons produces 1/*f* noise in the IR. Without EM confinement, the IR photons are not created.

2) Source of Holons Similar to other nanoelectronics circuit elements, QED photons created in nanowires by conserving Joule heat produce excitons by the photoelectric effect. Hence, the rate dN_{ex}/dt of excitons created depends on the yield Y of excitons / QED photon. Unlike the probabilistic creation of excitons from an external EM source of radiation having $Y << 1$, QED photons created from Joule heat *inside* the circuit element surface have $Y = 1$ as required by the conservation of EM energy. For a constant voltage V_o across the nanowire, the field $F = V_o/L$,

$$\frac{dQ_H}{dt} = \frac{\eta Y P}{E} - \frac{\mu_H V_o}{L^2} Q_H \tag{22}$$

The holon Q_H solution is,

$$Q_H = \frac{L^2}{\mu_H V_o}\left\{\frac{\eta Y P}{E}\left[1 - \exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right] + \frac{\mu_H V_o}{L^2} Q_{H0} \exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right\} \tag{23}$$

3) Simulations QED theory is compared with Ju et al. [38] experimental data of 1/*f* noise for SnO_2 nanowires. The holon mobility μ_H = 0.0172 m^2/V-s is assumed for SnO_2 10-50 nm wire diameters d with length $L > 10$ microns. The initial resistance R_o = 25x10^6 ohms. The power $P = I^2R$ ranged from 1 to 3 μW. Unlike the large number of electrons in Hooge's 1/*f* correlation, QED only requires a relatively small number of holons. The initial Q_{HO} and final Q_H number of holons in the nanowire is given in Fig. 6.

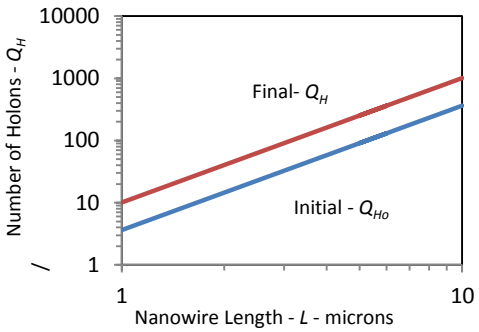

Fig. 6 Initial and final Number of Holons in SnO_2 nanowires

The Fourier transform (FT) of a unit step change of power in the time domain gives the $1/f$ spectrum in the frequency domain,

$$G(2\pi f) = \int_{-\tau/2}^{\tau/2} 1e^{-j\omega t}\, dt = \frac{sin(\pi f \tau)}{\pi f} \tag{24}$$

as shown to have the same slope as $1/f$ in Fig. 7.

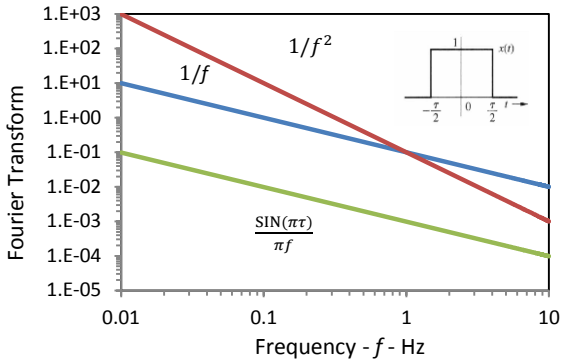

Fig. 7 FT of step change in power gives the $1/f$ spectra for LFN.
The FT is based on the unit step shown in the inset. The $1/f^2$ spectrum is shown only for comparison

Extensions

QED induced heat transfer that conserves Joule heat by creating charge instead of increasing the temperature of nanoelectronics is of importance in nanocomputing and was discussed [39] at ITHERM 2010. Provided interconnects are also submicron, melting by QM does not occur but the charge created unless removed increases the $1/f$ noise. Perhaps, the QED induced charge can be used to power the computer.

Ercan and Anderson [40] discuss quantum cellular automata in relation to the long-standing Landauer [41] limit for the minimum possible amount of thermal energy required to erase one bit of information from memory. The Landauer limit is defined as $kT * \ln 2$, but QM requires kT to vanish in nanoelectroncs. What this means is the Landauer limit also vanishes, and therefore no heat is dissipated in erasing memory. However, the charge may create excessive electronic $1/f$ noise.

Conclusions

Classical physics assumes the atom always has heat capacity. QM differs by restricting the atom's heat capacity to vanishing small levels in nanostructures. Conserving absorbed EM energy by the QED induced creation of photons in the nanostructure surface avoids unphysical findings and heat transfer anomalies.

Nanoelectronics comprised of nanoscale resistors, capacitors, and inductors follow QM and not classical physics. Absorbed EM energy is conserved by creating charge instead of by an increase in temperature as in classical physics.

Spin-valves need not rely on changes in magetoresistance; memristors on oxygen vacancies; and PC-RAM devices on resistance changes by melting. QM by negating the heat capacity of the atom conserves Joule heat by creating non-thermal EM radiation that produces a space charge of positive charged holons from excitons by the photoelectric effect.

Magnetic switching by the alignment of electron spins is inconsequential to the dramatic changes in resistance in FMs from the QED induced charge carriers created from Joule heat.

The Ovshinsky Effect occurs by the production of charge carriers from Joule heat by the QED induced photoelectric effect. Submicron GST films in PCRAM devices do not change resistance by melting but rather by the creation of charge carriers as Ovshinsky first envisioned.

The ubiquitous $1/f$ noise in nanowires is caused by a step change in current from a step change in charge created from Joule heat by QED. For a constant voltage across the wire, the step change in current produces a step change in power, the FT of which gives the $1/f$ spectrum.

By QM, submicron nanoelectronic circuit elements and NW interconnects do not increase in temperature because Joule heat is conserved by the creation of charge. QM negates the long-standing Landauer limit as the kT energy of the atom vanishes at the nanoscale. However, the QED induced charge may significantly increase the $1/f$ noise.

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