Quantum Mechanics and Spin-Valves

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***Abstract*: Spin-valves comprising alternating nanoscale layers of FMs separated by NM spacers are thought to produce parallel electron-spins that lower the giant magneto-resistance of the disordered state known as the GMR, the change in resistance allowing data storage in magnetic recording. FM stands for ferromagnetic and NM for non-magnetic. Spin-valve theory is based on theoretical predictions made over a decade ago, but the mechanism by which spins align is not well understood, if indeed spins are the mechanism for lowering the GMR. The question is whether switching in spin-valves is caused by another mechanism. In this regard, QED induced conductivity is proposed as the resistive switching mechanism. QED stands for quantum electrodynamics. Finding basis in QM that precludes the atoms in submicron FM layers from having the heat capacity to conserve Joule heat by an increase in temperature, conservation proceeds by QED induced frequency up-conversion of Joule heat to non-thermal EM radiation at the TIR resonance of the FM. QM stands for quantum mechanics, EM for electromagnetic, and TIR for total internal reflection. The EM radiation has sufficient Planck energy to create excitons (holon and electron pairs) that as charge carriers significantly lower the GMR by the dramatic increase the conductivity of the FM layers. Extensions of QED induced conductivity in spin-valves to memristors, PCRAM films, and 1/*f* noise in nanowires are briefly summarized.**

Index Terms – Spin-valves, quantum mechanics, quantum electrodynamics, conductivity, Joule heat.

I. INTRODUCTION

Spin-valve ferromagnetism is based on theoretical predictions by Slonczewski [1] and Berger [2] over a decade ago. Spin-valves comprise alternating nanoscale layers of FMs separated by NM spacers. Spin polarized current is produced by passing un-polarized current through the first FM layer, the polarization unchanged as the current flows through the NM spacer. Upon interaction with the second FM layer, the 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, the significant reduction in the GMR by the alignment of spins remains controversial even to this day. The relatively rigid lattice shields the spins so that any physical transfer of spin-torque to the second FM is unlikely. Further, spin-torque propagates by phonons through the FM lattice limiting spin-transfer to frequencies < 10 GHz having response times > 100 ps. However, electron spins are observed to respond much faster.

Indeed, laser studies in femtomagnetism by Boeglin et al. [3] show nanoscale FMs demagnetize on a sub-picosecond time scale (< 350 fs) far faster than phonons can respond. Bigot et al. [4] showed about 10 ps for the lattice to thermalize prompting Bovensiepen [5] to suggest spin-valves de-magnetize by light and not spin-transport through the lattice while noting the dynamics are only observed while the laser field interacts with the FM – an observation bearing remarkable similarity [6] with the TIR confinement described by a quasi-bound MDR state, trapped in a potential well but leaking to the outside world by tunneling. MDR stands for morphology-dependent resonance.

Spin transfer through the lattice therefore cannot be the mechanism for demagnetization. In this regard, Jiang et al. [7] showed spin-transport to be inconsequential in Fe/Alq3/Co spin valves compared to the switching by holes only common to non-volatile electrical switching. Alq3 stands for tris-(8-hydroxyquinolate) aluminum representative of organic spin-valves. The fact that non-volatile electrical switching was recently proposed [8] to coexist with spin-transport only supports switching by holes [7] alone.

Like any other nanoelectronic circuit element, spin-valves by QM lack the heat capacity [9] 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. [4] and others based on temperature changes may be safely dismissed.

QED induced radiation [10] requires the RI of the FM to be greater than that of the adjacent NM spacers. RI stands for refractive index. Non-thermal EM radiation at UV levels is created by the frequency up-conversion of Joule heat to the TIR confinement frequency of the FM. Therefore, excitons (holon and electron pairs) are readily created from the UV, the holons (or holes) of which act as charge carriers that dramatically increase the FM conductivity significantly reduce the GMR, the resistance change used in writing data in magnetic recording heads. In erasing data, the GMR is recovered by simply reversing the bias polarity.

II. PURPOSE

To propose spin-valve switching may have nothing to do with electron spin and instead caused by QED induced conductivity from the conservation of Joule heat with EM radiation that creates excitons which act as charge carriers that lower the GMR. Extensions are made to nanoelectronics circuit elements – memristors and PCRAM films including the 1/*f* noise in nanowire interconnects.

III. THEORY

A. QM Restrictions

Heat transfer in FMs based on the classical theories of Einstein and Debye [11] allow the atom to have thermal kT energy or the heat capacity to conserve absorbed EM energy by an increase in temperature, but not by QM. The heat capacity of the atom by classical physics and QM by the Einstein-Hopf relation [12] is shown in Fig. 1.

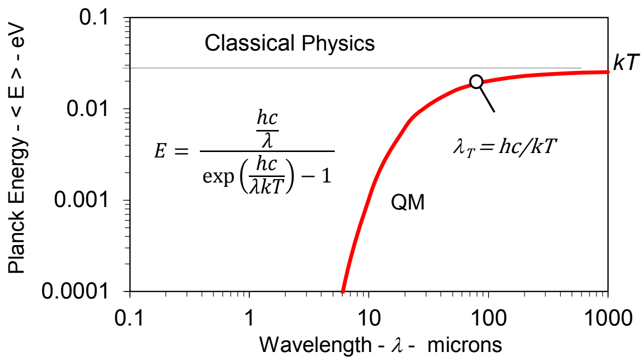

Fig. 1 Heat Capacity of the Atom at 300 K
E is Planck energy, h Planck's constant, c speed of light,
k Boltzmann's constant, T absolute temperature, and λ wavelength

Classical physics allows the atom to have the same kT energy in FMs or any nanoelectronics circuit element as in conventional electronics. QM differs in that kT energy is only available for $\lambda > \lambda_T$ and otherwise is $< kT$. At ambient temperature, Fig. 1 shows the thermal energy or heat capacity of the atom is $< kT$ for $\lambda < 48$ microns. By QM, atoms in FMs under EM confnement wavelengths $\lambda < 1$ micron have virtually no heat capacity to conserve energy from any EM source by an increase in temperature.

B. TIR Confinement

In 1870, Tyndall showed light is trapped by TIR in the surface of a body if the refractive index of the body is greater than that of the surroundings. Today, light trapping by TIR is described [6] by MDRs where EM waves propagate around the inside surface of the body while returning in phase to their starting points.

In FMs, TIR has a special significance and need not be limited to light absorption. Unlike macroscopic bodies, nanoscale FMs 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 FM surface coincides with the TIR wave function given by the MDR, QED induces the absorbed EM energy to undergo spontaneous conversion to QED radiation. Similar to the quasi-bound MDR state observed by Bovensiepen [6] where spin demagnetization is only observed during laser interaction with the FM, TIR confinement is not permanent, sustaining itself only during the absorption of EM energy, i.e., absent absorption of EM energy, there is no QED radiation and excitons are not created to lower the GMR.

QED relies on complex mathematics as described by Feynman [13] although the underlying physics is simple, i.e., EM radiation of wavelength λ is created by supplying EM energy to a submicron QM box with sides separated by $\lambda/2$. In FMs, QED up-converts low-frequency Joule heat to the high frequencies of TIR confinement. Consistent with MDR surface waves, the Planck energy E of QED radiation,

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

where, n is the RI and d the thickness of the FM.

The prompt conversion of Joule heat to QED radiation at the speed of light is far faster than phonons at acoustic velocities respond, thereby essentially negating any thermal conduction by phonons in the FM. Under TIR confinement at MDRs, the QED radiation having Planck energies beyond the UV create excitons and lower the resistance of the GMR. Reversal of polarity recovers the GMR.

IV. SPIN-VALVES

A. QED Radiation and Excitons

QM restrictions on heat capacity require the power P to be conserved by QED inducing the creation of a number N_{ex} of excitons in the surface of the FM. The rate dN_{ex}/dt of excitons created depends on the Planck energy E of QED radiation inside the FM,

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

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

Under the electric field across the FM, the holons separate from their paired electrons. However, only a fraction η of the excitons produce holons in the FMs that lower the GMR, the remaining fraction $(1-\eta)$ upon recombination emit EM radiation that is lost to the surroundings. For the FMs,

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

B. Holon Dynamics

In the FM, the rate of creating excitons $\eta P/E$ is balanced by the number of electron Q_E and holon Q_H charges moving in the electric field F toward opposite polarity voltage terminals by their respective μ_E and μ_H mobilities,

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

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

For simplicity, consider only the holon Q_H equation, For $F = V_o/d$,

$$\frac{dQ_H}{dt} = \frac{\eta P}{E} - Q_H\,\frac{\mu_H V_0}{d^2} \tag{6}$$

The solution for the number Q_H of holons is,

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

C. Electrical Response

On average, the excitons (holons and electrons) are centered in the FM thickness d and need to move d /2 to reach the voltage terminals, the spin-valve resistance R is,

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

where, e is the electron charge. For simplicity, the resistance R 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 the FM area. The resistance R_o corresponds to the initial number Q_{HO} of holon charges,

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

The current I,

$$I = \frac{V}{R} = \frac{V_O}{R} \quad (10)$$

D. Mobility

Since current is proportional to both mobility and conductivity, Chen et al. [14] expressed mobility μ at ambient temperature by,

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

where, μ_o is the mobility at zero field. For Alq3, α = $9.22\text{x}10^{-3}\ (\text{cm/V})^{1/2}$ and $\mu_o = 3.04\text{x}10^{-7}\ \text{cm}^2/\text{V-s}$.

E. Simulations

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 = $1\text{x}10^6$ 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 response are shown in Figs. 2 and 3.

The QED induced reduction in GMR is observed to change significantly depending on the FM thickness d. Fig. 2 shows the GMR for the 10 nm film is reduced 99.9 % to ratio $R/R_o \sim 0.000624$ or ($R \sim 624$ ohms) in < 1 ns. For magnetic induced electron-spin, the GMR reduction is relatively insignificant, i.e., 125 nm Alq3 film [8] at 100 K shows a GMR reduction of about 22% corresponding to R/R_o = 0.78 or ($R \sim 0.78\text{x}10^6$ ohms). As the Alq3 film thickness increases, the QED induced GMR reduction decreases. Fig. 3 shows the holon response for + 1 V writing and – 1 V of erasing data. Reversal of voltage V_o shows an abrupt recovery of the GMR for the 10 nm film.

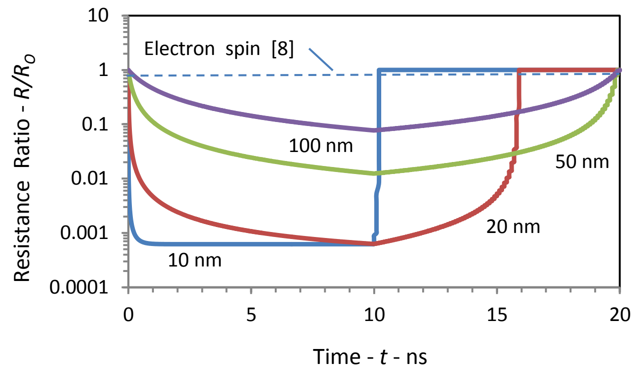

Fig. 2 QED Induced GMR Resistance Ratio *R/Ro* v. Time – ns
+1 V write and -1 V erase

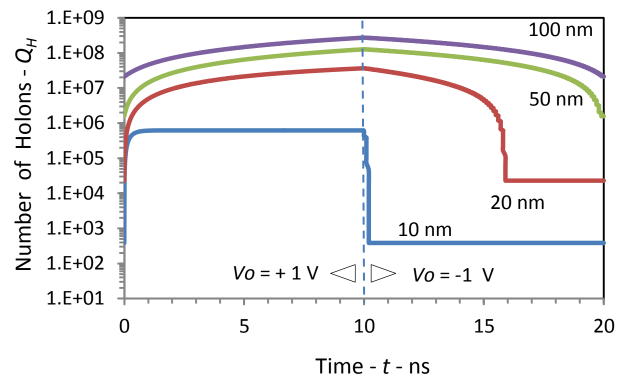

Fig. 3 QED Induced Number of Holons v. Time – ns
+1 V write and -1 V erase cycles

The significant GMR reduction for the 10 nm Alq3 film predicted by QED induced conductivity suggests superconductivity is possible in FMs at ambient temperature.

V. EXTENSIONS

Spin-valves are only one of many nanoelectronics circuit elements [15, 16] explained by QED induced conductivity. Brief summaries for memristors, PCRAM films, and nanowires are as follows

A. Memristors

In 1971, Chua [17] 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, Chua claimed that electronic circuitry based on the three circuit elements - the resistor, capacitor, and inductor was incomplete, and therefore a fourth element called a memristor was proposed for completeness. 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.

In contrast, QED induced memristor Q_H solutions follow (1) through (11), except for (7) as the voltage V is harmonic $V_o \sin(\omega t)$ requiring the numerical solution of the integral differential equation,

$$Q_H \exp\left(-\frac{\mu_H V_o}{\omega d^2}\cos\omega t\right) = \eta\frac{P}{E}\int_0^t \exp\left(-\frac{\mu_H V_o}{\omega d^2}\cos\omega t\right)dt \qquad (12)$$

The QED memristor hysteresis curve is consistent with that described by Chua as the "bow-tie" shape with the cross-over at the origin shown in Fig. 4.

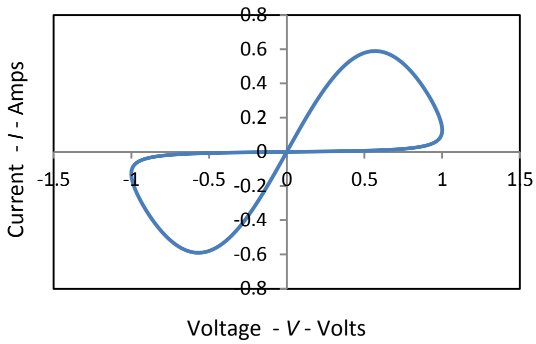

Fig. 4 Memristorm
50 nm TiO_2 Film – QED Induced Hysteresis Curve

The I-V curve for the TiO_2 memristor thought produced by oxygen vacancies is instead produced by holons from QED induced radiation.

B. PCRAM Films

Today, PCRAM films are thought to lower GST resistance by phase change melting from the crystalline to the amorphous state. GST stands for chalcogenide GeSbTe glasses. In contrast, Ovshinsky [18] differed by claiming charge carriers instead of melting changed the GST resistance. QED induced charge is consistent with Ovshinsky's charge carriers, the holons following (1) through (11) with (7) for FMs remaining the same for GST films. In the writing of data, the change in resistance for various GST film thicknesses is shown in Fig. 5.

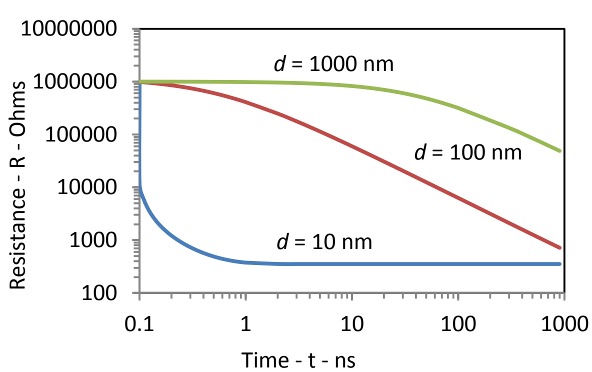

Fig. 5 PCRAM Films
PCRAM Write Response with GST thickness

PCRAM films of GST films have the same general QED response as Alq3 FMs, although the respective mobilities differ. PCRAM recording of data by resistance changes in GST films is caused by QED induced holons, not melting.

C. 1/f Noise in Nanowires

All nanoelectronics includes nanowire interconnects between circuit elements that produce $1/f$ noise. Research in $1/f$ noise has a long history beginning [19] 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. Simulations of $1/f$ noise in SnO_2 nanowires follow Equations (1) through (11), except in (7) the length L replaces the thickness d of the FM layer, memristor, and GST film. For $Q_{H0} = 0$, the solution for the number Q_H of holon is,

$$Q_H = \eta\frac{PL^2}{\mu_H E V_o}\left[1 - exp\left(-\frac{\mu_H V_o}{L^2}t\right)\right] \qquad (13)$$

Fig. 6 shows the number Q_H of holons for SnO_2 mobilities of 172 and 40 cm^2/V-s is a step change to respective 4 and 17 holons with a rise time of ~ 5 ns.

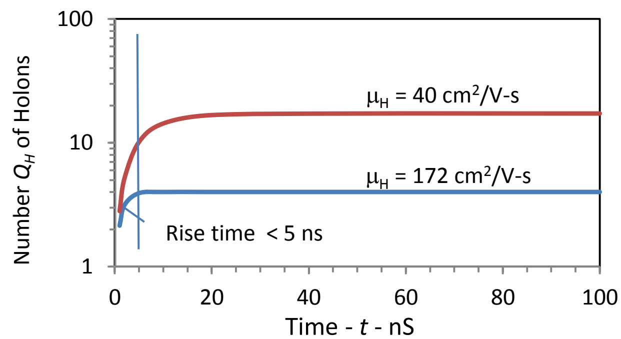

Fig. 6 QED Induced step change in Holon charges

Hence, the current entering the SnO_2 wire causes a step change in QED induced charge or an additional current that under the constant voltage across the wire produces a step change in power, the Fourier transform of which does indeed give the $1/f$ noise spectrum agreeing with experiment [20] as shown in Fig. 7.

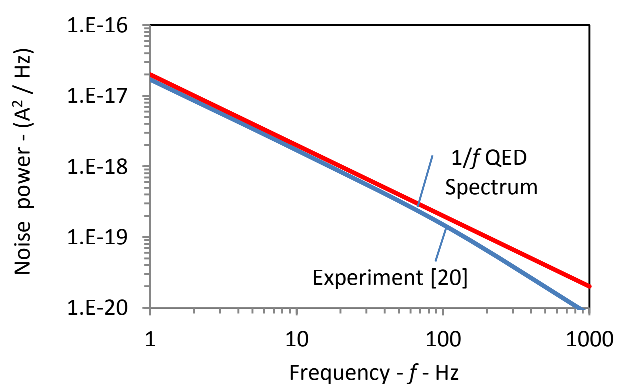

Fig. 7 $1/f$ Noise in 20 nm SnO_2 Nanowires

VI. 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.

Nanoelectronics comprised of nanoscale resistors, capacitors, and inductors follow QM and not classical physics. Joule heat is conserved by creating excitons instead of by an increase in temperature as in classical physics.

Spin-valves need not rely on changes in GMR magetoresistance; or memristors on oxygen vacancies; or PCRAM films on resistance changes by melting. Instead, QM by negating the heat capacity of the atom conserves Joule heat by creating QED radiation that produces a space charge of excitons, the positive charged holons of which act as charge carriers that define their electrical characteristic.

Electron spins may have nothing to do with reductions in the GMR because the dramatic QED induced conductivity by charge carriers is occurring at the same time. Indeed, superconductivity at room temperature may even be possible by QED induced conductivity.

The $1/f$ noise in nanowires is caused by a step change in holon charge carriers created from excitons in conserving Joule heat as current enters the TIR confinement of the nanowire. Since the step in holons is a step in current, and since the voltage across the nanowire is constant, the power undergoes a step in the time domain, the Fourier transform of which is $1/f$ noise in the frequency domain.

The QED simulation of $1/f$ noise in SnO_2 nanowires differs from memristors and PC-RAM films in that the low power levels suggest noise is produced by a small number of holons, i.e., the experimental $1/f$ noise for a mobility of 172 cm^2/V-s was found simulated by only a few holons.

Similarity suggests the ubiquitous $1/f$ noise observed in diverse physical systems having nothing to do with nanowires is most likely caused by the Fourier transform of abrupt changes in the time domain, e.g., in music, upon striking piano keys or in the electronic recording of changes in stock market indices.

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