Spin-Valves by Quantum Mechanics

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***Abstract*: Spin-valve ferromagnetism is based on theoretical predictions over a decade ago. Spin-valves comprise alternating nanoscale layers of FMs separated by NM spacers. FM stands for ferromagnetic and NM for non-magnetic. Spin-polarized current is thought to produce parallel spins and lower the giant magneto-resistance of the disordered spin state known as GMR, the change in resistance allowing data storage in magnetic recording heads. However, the mechanism by which spins order is not well understood, if indeed spins are the mechanism for spin-valve switching. The question is whether switching in spin-valves is caused by another mechanism. In this regard, QED induced photoconductivity is proposed as the switching mechanism in spin-valves finding basis in QM by precluding the atoms in submicron FMs from having the heat capacity to conserve Joule heat by an increase in temperature. QED stands for quantum electrodynamics and QM for quantum mechanics. Instead, conservation proceeds by the QED induced frequency up-conversion of Joule heat to non-thermal EM radiation at the TIR resonance of the FM. EM stands for electromagnetic and TIR for total internal reflection. The EM radiation has sufficient Planck energy to create excitons that dramatically increase the photoconductivity of the FM thereby significantly lowering the GMR. QED induced photoconductivity has been used to explain memristors, PCRAM films, and 1/*f* noise in nanowires.**

Index Terms – Spin-valves, quantum mechanics, quantum electrodynamics, photoconductivity, 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 a NM spacer. FM stands for ferromagnetic and NM for non-magnetic. 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, significant reduction in the GMR by the alignment of spins remains controversial to this day. 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 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 tunnelling. 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 n Fe/Alq3/Co spin valves compared to the switching by holes 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 magnetoresistance only supports the hole [7] mechanism.

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. 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 (holon and electron pairs) are readily created from the EUV by the photoelectric effect, the holons (or positive holes) of which act as charge carriers that dramatically increase the FM photoconductivity thereby significantly reducing the GMR, the latter used in writing in magnetic recording heads. In erasing, the GMR is recovered by simply reversing the bias polarity.

I. PURPOSE

To propose spin-valve switching has nothing to do with electron spin and instead caused by QED induced photoconductivity from the conservation of Joule heat with EM radiation that produces holons by the photoelectric effect that dramatically 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 nanoelectronics is based on Einstein's and Debye's theories [11] that allow the atom to have thermal kT energy or the heat capacity to conserve absorbed EM energy by changes in temperature. The heat capacity of the atom by classical physics and QM by the Einstein-Hopf relation [12] is shown in Fig. 1.

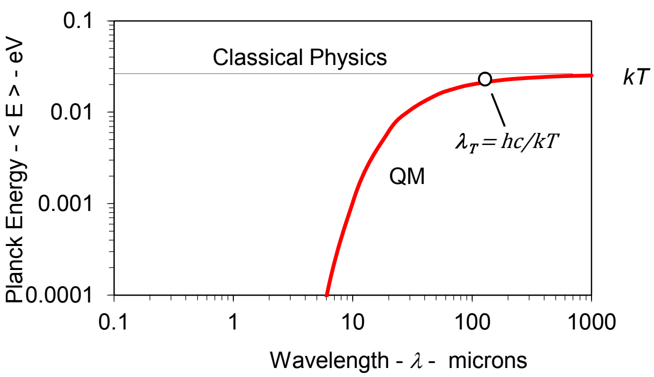

Fig. 1 Heat Capacity of the Atom at 300K
E is Planck energy, h Planck's constant, c speed of light
k Boltzmann's constant, T absolute temperature, and λ wavelength

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.

B. TIR Confinement

Lack of heat capacity by QM precludes Joule heat to be conserved in nanoelectronics by an increase in temperature. Instead, the Joule heat is proposed conserved by the creation of non-thermal EM radiation by 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 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 nanostructure while returning in phase to their starting points.

In nanostructures, TIR has a special significance and need not be limited to light absorption. Unlike macroscopic bodies, nanostructures have high surface to volume ratios, and therefore EM energy from any source (lasers, Joule heat, etc.) is absorbed almost entirely in their surface. Since the nanoelectronics 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. TIR confinement like the quasi-bound MDR state observed by Bovensiepen [5] where spin demagnetization is only observed during laser interaction with the FM. TIR confinement is not permanent sustaining itself only during absorption of EM energy, 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 [13] although the underlying physics is simple, i.e., photons of wavelength λ are created by supplying EM energy to a submicron QM box with sides separated by $\lambda/2$. In this way, QED frequency up-converts absorbed EM energy to the MDR described by the characteristic dimension D_C of the nanoelectronics. Consistent with MDR surface waves, the QED photon energy E and frequency υ are:

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

where, n is the refractive index of the nanostructure.

In nanoelectronics, the prompt conversion of Joule heat to QED photons at the speed of light is far faster than the phonons at acoustic velocities can respond, thereby essentially negating thermal conduction by phonons at the nanoscale. Under TIR confinement at MDRs, the QED photons having Planck energies far beyond the UV create excitons (holon and electron pairs) by the photoelectric effect and lower the resistance of the circuit element. Reversal of polarity recovers the initial resistance or some fraction thereof allowing the resistance of a circuit element to be controlled by the number of holon charge carriers.

IV. SPIN-VALVES

A. Photons and Excitons

QM restrictions on heat capacity require the dissipative power P to be 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 $(1-\eta)$ is lost to the surroundings. The QED photons are created at the rate dN_P/dt,

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

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

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

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

B. 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,

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

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

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

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

The holon Q_H solution is,

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

C. 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,

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

where, e is the electron charge. For simplicity, 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 holon charges,

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

The current I,

$$I = \frac{V}{R} = \frac{V_O}{R} \tag{10}$$

D. Mobility

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

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

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.

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 = 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 response are shown in Figs. 2 and 3.

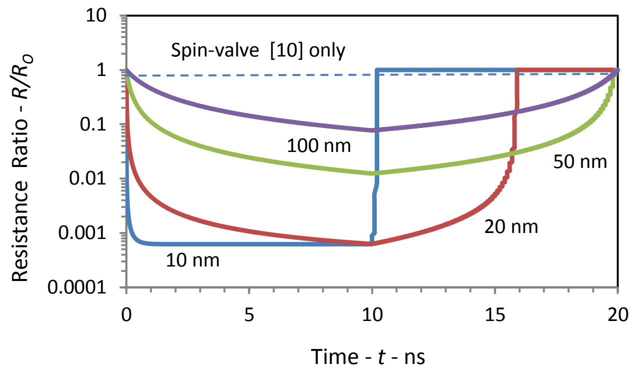

Fig. 2 QED Induced GMR Resistance Ratio R/Ro v. Time – ns +1 V write and -1 V erase

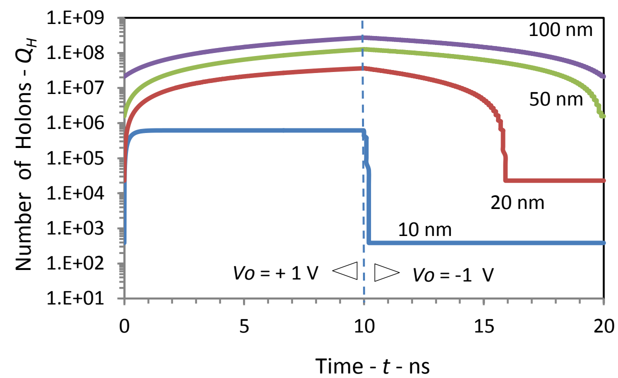

Fig. 3 QED Induced Number of Holons v. Time – ns +1 V write and -1 V erase

The QED induced reduction in GMR 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 [8] at 100 K shows a GMR reduction of about 22% corresponding to R/R_o = 0.78 as 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 significant 10 nm Alq3 film resistance change predicted by the QED induced photoconductivity suggests superconductivity already exists in spin-valves or at least may be approached at ambient temperature.

V. EXTENSIONS

Spin-valves are only one of many nanoelectronics circuit elements [10] including memristors and PCRAM films explained by QED induced radiation. The I-V curve for the titanium dioxide memristor thought produced by oxygen vacancies is instead produced by holons from QED induced radiation by the photoelectric effect. The memristor hysteresis curve with the characteristic cross-over at the origin made based on physical properties alone without fitting parameters is shown in Fig. 4.

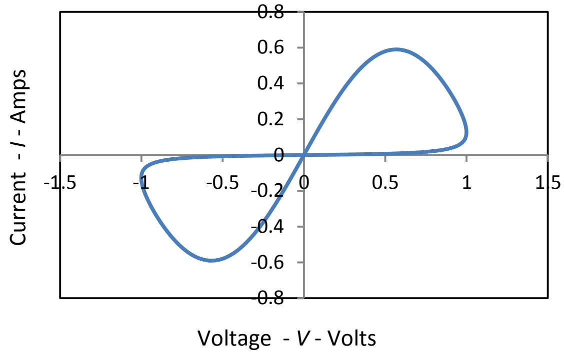

Fig. 4 Memristor
50 nm Titanium Dioxide Film - Hysteresis Curve

The Ovshinsky Effect in PCRAM writing by change in GST film resistance thought produced by phase change melting is instead created by holons from QED induced radiation. The change in resistance for various GST film thicknesses is shown n Fig. 5.

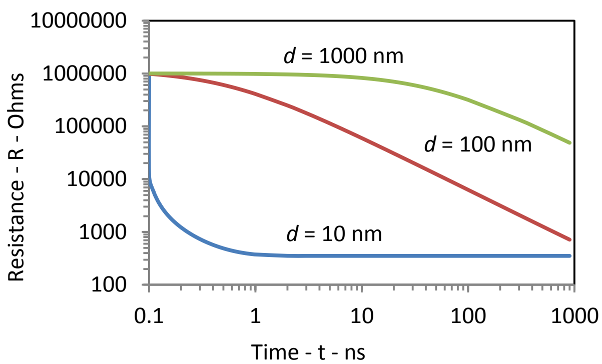

Fig. 5 Ovshinsky Effect
PCRAM Write Response with GST film thickness

All nanoelectronics includes nanowire interconnects that produce $1/f$ noise. The current entering the wire produces a step change in QED induced charge or current that under the voltage across the wire produces a step change in power, the Fourier transform of which giving the $1/f$ noise spectrum shown in Fig. 6. The $1/f^2$ spectrum is shown for reference.

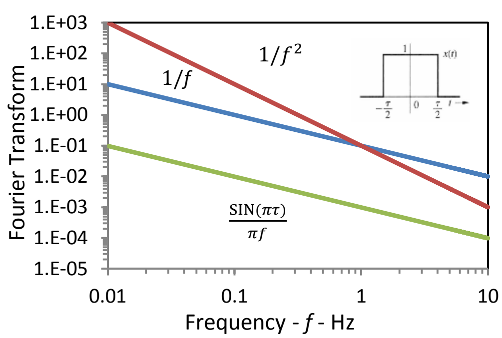

Fig. 6 $1/f$ Noise in 20 nm Tin Oxide Nanowires

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. 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; 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 positive charged holons to explain spin-valves, memristors, and PCRAM films.

Magnetic switching in FMs by spin-valves is inconsequential to the dramatic changes in resistance from the QED induced photoconductivity by holons created from conserving Joule heat with EM radiation. Indeed, superconductivity at room temperature may be possible in spin-valves.

The ubiquitous $1/f$ noise in nanowires is caused by a step change in charge created from Joule heat by QED as current enters the wire.

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