Optoelectronic Readout of STT-RAM Memory Cells Using Plasmon Drag Effect

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Abstract: An optoelectronic readout method for reading the state of STT-RAM cells based on plasmon drag effect is proposed. Our simulations show that the proposed scheme can achieve up to 29.6 Gbit/sec readout speed.

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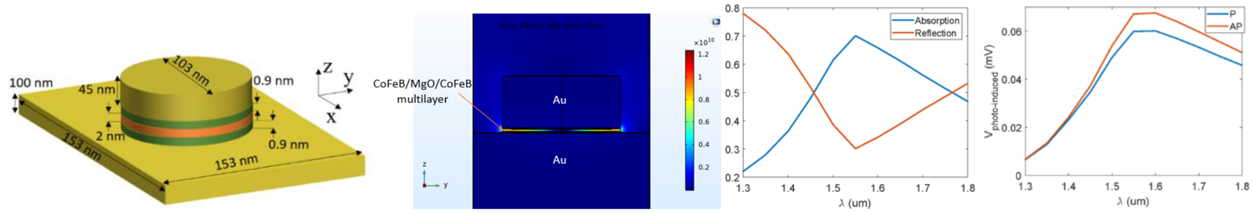
1. Introduction

Utilizing optical methods for readout of random access memory (RAM) cells [1,2] is advantageous as it provides a platform for increased data transfer rate between processors and memory cells, and it simplifies the readout circuitry. Among various types of RAM, spin transfer torque random access memory (STT-RAM) has received great attention because of its scalability, low power consumption, high speed, and high endurance [3, 4]. STT-RAM structure typically includes metal layers [3], which can support plasmonic modes, providing high localization of optical field around the metal surface when illuminated by a laser beam. Therefore, STT-RAM multilayer structure can be designed to support plasmonic modes with high sensitivity to changes in its specific layers [5, 6].

Here, we propose an optoelectronic readout method for STT-RAM array, where excitation of a localized surface plasmon resonance (LSPR) mode memory cells helps increase the readout voltage thus increasing the speed of readout We show that the proposed optoelectronic readout provides a high readout speed of 29.6 Gbit/sec assuming a pulsed laser excitation with 1.7 kW peak power and electronic lock-in detection with noise equivalent power (NEP) of $4\text{nV}/\sqrt{Hz}$. Enhancement of more than 28 times in the photo-induced voltage and thus more than 800 times increase in the readout speed is estimated through our model, compared with the case of out of resonance optical excitation.

2. Plasmonic Resonance and Plasmon Drag Effect in STT-RAM Array

STT-RAM structure is composed of a magnetic tunnel junction (MTJ) which is basically a ferromagnet (CoFeB) / dielectric(MgO) / ferromagnet (CoFeB) multilayer stack, all placed between two metal layers (Au) for electrical contact (Fig. 1(a)). An optical beam from a pulsed laser illuminates an array of STT-RAM cells (parallel readout), eliminating the need for electrical injection of current into memory cells. The optical illumination induces a voltage across each cell, through optical rectification enhanced by the plasmonic excitation (plasmon drag effect or PLDE). The resulting voltage provides a measure for the state of each memory cell (parallel (P) vs anti-parallel (AP)) and is assumed to be detected using electronic circuitry. The design wavelength is 1.55 um, and we use the same material optical properties for our model as we used in our previous work [5]. The geometry and the dimensions of a unit cell of the designed STT-RAM array is shown in Fig. 1(a). The thickness of the Au plane is fixed at 100 nm, which is much thicker than the skin depth of gold at the design wavelength (~23 nm), to avoid the substrate/Au boundary affecting our design. For CoFeB and MgO layers, the thickness is set to 0.9 nm and 2 nm, respectively, which are close to typical thicknesses for STT-RAM [7]. The main design parameters are the nanodics diameter (d), thickness of Au nanodisc (t_{Au}), and unit cell period (p). For efficient excitation of the LSPR mode, it is important to set t_{Au} larger than skin depth of gold. Further increase of t_{Au} helps increase the optical absorption at resonance. We set it to 45 nm. We select a diameter of d=103 nm to set the resonance to the design wavelength. Furthermore, we minimize p to increase the optical absorption at resonance while considering a fabrication limit of 50 nm for spacing between adjacent memory cells. The absorption and reflection spectra for the designed STT-RAM array is shown in Fig. 1(c), showing plasmonic resonance around 1.55 um.



(a) (b) (c) (d)

Fig. 1. (a) Unit cell geometry of the designed STT-RAM (b) Cross-sectional view of unit cell field distribution at resonance (c) Spectrum of the designed STT-RAM array, showing a resonance at λ = 1.55 um (d) Photo-induced voltage calculated assuming optical illumination of 1.7 kW power focusing onto a 20 μm×20 μm area.

In general, the voltage induced in a nanostructure by optical illumination can be formulated based on Euler's equation of motion for point charges, as derived in [8]:

$$V_{\omega-\omega,z}^{(2)} \approx \frac{1}{n^{(0)}q}\int \frac{dz}{A_z(z)}\left[\int dA_z.\left(\frac{\alpha_R}{4}\nabla|\tilde{E}(z)|^2\right)+\frac{|\alpha|}{4}\langle\left|\tilde{E}(z^-)_\perp\right|^2\rangle_{A_z}\hat{n}(z).\hat{z}\right] \qquad (1)$$

where $V_{\omega-\omega,z}^{(2)}$ is the time average of the photo-induced voltage (DC voltage) caused by optical rectification along z direction, $n^{(0)}$ is the zeroth-order charge density in the metal layers, q is the electron charge (=1.6×10-19 C), α is the polarizability of the metal layers and α_R is the real part of it, $A_z(z)$ is the cross section of the metal layers in xy plane at each z location, $\tilde{E}(z)$ is the optical electric field vector, $\tilde{E}_\perp(z^-)$ is the component of electric field normal to the metal surface at a depth equal to the Thomas-Fermi screening length of the metal (l_{TF}), and $\hat{n}(z)$ is an outward unit vector normal to the metal surface at each z location.

Using equation (1), we calculate the photo-induced voltage along z direction for the designed STT-RAM array, for each state of the memory cells with resistance-area (RA=2.9 Ωμm² and tunnel magnetoresistance (TMR) ratio of %165) from [9]. Since the electrical resistivity of Au and CoFeB layers are negligible, we assign the RA and TMR values to the MgO layer only. Hence, taking its thickness into account, the change in the state of STT-RAM cell can be modeled as a change in the conductivity of the MgO from $\sigma_P \approx 690\ S.m^{-1}$for P state, to $\sigma_{AP} \approx 260\ S.m^{-1}$ for AP state.

Assuming a pulsed laser excitation with 1.7 kW peak power and 100 MHz repetition rate, which is focused onto the array with a spot size of 20 μm×20 μm, the calculated photo-induced voltages for one cell in the STT-RAM array are presented in Fig. 1(d). The maximum voltage change between the two states of STT-RAM is 7.47 uV, which occurs near the resonance wavelength. Assuming a noise equivalent power of NEP=4nV/$\sqrt{Hz}$ for electronic lock-in detection of such voltage difference, approximately up to 1.74 MHz for a signal to noise ratio of 3 dB can be achieved for one cell. This means that the laser repetition rate should be 1.74 MHz at its highest for detecting the state of STT-RAM. The focal spot size mentioned above can approximately illuminate 17000 cells simultaneously. Therefore, the proposed scheme has the potential to provide a readout speed as high as 29.6 Gbit/sec (≈17000×1.74 MHz). It should be noted that the PLDE response is extremely fast (in the order of femtosecond scale) [10], meaning the photo-induced voltage can easily respond to the 1.74 MHz laser pulse repetition rate.

In conclusion we present a parallel optoelectronic readout for STT-RAM, which facilitates high speed readout of memory cells based on plasmon drag effect, without any need for additional III-V materials for optoelectronic conversion or mixing. The proposed readout method can also help eliminate the unwanted read disturbance effect, which can be caused by conventional electronic readout as mentioned in [11].

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