Optical Investigation of Radiation Induced Conductivity Changes in STT-RAM Cells

Qiancheng Zhao[1], Mohsen Rajaei[1], Ilya Krivorotov[2], Mikael Nilsson[3], Nader Bagherzadeh[1] and Ozdal Boyraz[1]

[1]*Department of Electrical Engineering and Computer Science, University of California, Irvine, California, USA, 92697.*
[2]*Department of Physics and Astronomy, University of California, Irvine, California, USA, 92697.*
[3]*Department of Chemical Engineering and Materials Science, University of California, Irvine, California, USA, 92697*
oboyraz@uci.edu

Abstract: Plasmonic defect spectroscopy of STT-RAMs under high energy radiation is proposed here. We show that engineered constellation designs of the STT-RAMs can be used to understand radiation defects by measuring optical reflectivity, diffraction, or absorption.

OCIS codes: (240.6680) Surface plasmons; (050.6624) Subwavelength structures; (160.3820) Magneto-optic systems.

1. Introduction

Plasmonic spectroscopy has long been used in biological and chemical sensing due to its high sensitivity to ambient refractive indices and strong field enhancement. Modern electronic devices employ a combination of multiple metallic layers and oxide layers, rendering them suitable for plasmonic studies. Thus, plasmonic spectroscopy can extend its application scope to electronic device characterization and failure mechanism detections. Here, we put forward a method to optically detect the radiation damage on spin transfer torque random access memory (STT-RAM) cells which have multiple metal and dielectric layers. Until now, very little progress has been made by pioneers in thoroughly understanding the ionizing radiation effects on the STT-RAM, because the complexity of the device structure prohibits accurate near field probing. Early studies using electrical method failed to detect noticeable changes in tunneling magnetoresistive (TMR) magnetometers in terms of TMR ratio, coercivity, magnetostatic coupling, and low-frequency noise after irradiation with γ rays [1]. Therefore, an alternative far field detection approach using highly sensitive plasmonic spectroscopy is worth investigating.

In this paper, we present a solution that uses surface plasmon polaritons (SPPs) based spectroscopy [2]. The coupling of SPPs from free space results in a drop of the reflected power [3], which can be used to monitor the SPP mode properties that are influenced by the dielectric material. The radiation damage is assumed to occur mainly in the dielectric medium in our investigation, which creates recombination centers that alter the dielectric conductivity. The simulation results show that the reflectivity from a subwavelength STT-RAM grating at the SPP excitation angle can be enhanced by more than 8 times, given that the dielectric barrier conductivity changes from 0 to 4.1×10^{7} S/m. The investigation proves that this sensitive approach is promising for the detection of dielectric damages in STT-RAM cells. The same approach can be tailored to utilize reflection, diffraction, and absorption.

2. STT-RAM and radiation effects

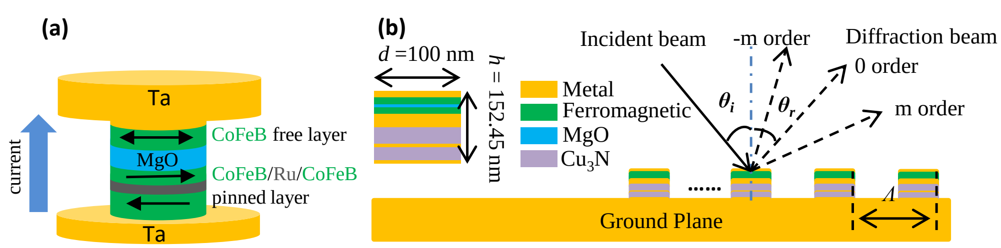

Fig. 1. (a) Individual cell structure. (b) . Simplified concept figure of the grating structure. The metal layer is actually multiple layers composed of Ta, Cu, Ru and PtMn and etc. The ferromagnetic layer refers to the CoFeB and $Co_{70}Fe_{30}$ layer.

STT-RAM is a promising technologies that offers fast write time, unlimited write endurance, non-volatile storage of information, and good scalability [4]. A typical STT-RAM memory element consists of a thin dielectric layer (MgO) sandwiched between ferromagnetic layers (typically CoFeB alloys), which form a magnetic tunnel junction of nanoscale dimensions schematically shown in Fig. 1(a). The core element of an STT-RAM cell has no semiconductor components, and the metal alloys are expected to be robust against ionizing radiation. It has been pointed out that devices employing dielectric barriers are subject to ionizing radiation [5]. The radiation can induce substantial charge buildup in oxides, and lead to an increase of leakage current in MOS devices [6], which eventually changes the thin oxide conductivity.

3. Plasmonic subwavelength grating

The STT-RAM unit cells are arranged in one-dimensional arrays sitting on a metallic plane to embrace the functionality of a reflective grating as shown in Fig. 1(b). This arrangement enables the detection of the RAM optical behavior in a far field fashion. Each unit cell is composed of a core CoFeB/MgO/CoFeB layer with multiple under layers and capping layers. The structure of a cell from bottom to top is: Ta (3 nm)/ CuN (40 nm)/ Ta (3 nm)/ CuN (40 nm)/ Ta (3 nm)/ Ru (10 nm)/ Ta (5 nm)/ PtMn (15 nm)/ $Co_{70}Fe_{30}$ (2.5 nm)/ Ru (0.85 nm)/ $Co_{40}Fe_{40}B_{20}$ (2.4 nm)/ MgO (0.9 nm)/ $Co_{60}Fe_{20}B_{20}$ (1.8 nm)/ Cu (2 nm)/ Ta (5 nm)/ Cu (10 nm)/ Ru (5 nm)/ Ta (3 nm). The unit cell is a cylinder with a total height of 152.45 nm and a diameter of 100 nm. We carefully choose the spatial period of the grating Λ to make it in subwavelength configuration, because subwavelength grating can only support one diffraction and thus has better power efficiency in a broadband range [7]. The wavelength used in this study is 750 nm and is TM polarized (magnetic field perpendicular to the incident plane). The coupling between waves in free space and the SPPs in a grating is regulated as $\pm\beta = k_0\sin(\theta_i) + 2m\pi/\Lambda$, where $k_0 = 2\pi/\lambda$ is the wavenumber in free space, θ_i is the incident angle, m is an integer that represents the diffraction order, and β is the SPP propagation constant. It is worth noting that metal properties may be magnetic field dependent if it is ferromagnetic material. For simplicity, we assume the permeability of all the materials are 1 in our study. The material permittivity data come from Rakic's measurements [8] or a linear combination of the ingredients in alloys. The total reflected power is plotted as a function of the grating period and the incident angle in Fig. 2(a). The blue region represents a sharp drop of reflection at certain incident angles for a given grating period, which is caused by power transfer. Eventually, the SPPs power turns into ohmic loss due to the imaginary permittivity in metal, rendering the device an absorber.

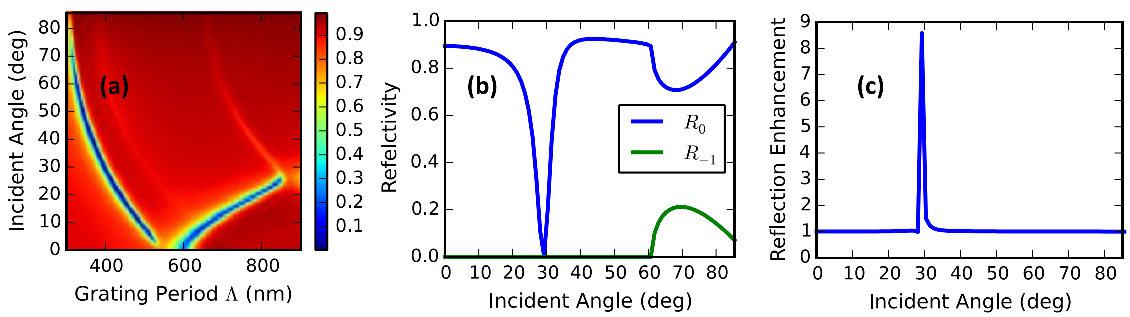

Fig. 2. (a) Grating reflectivity as a function of grating period Λ and incident angle θ_i when illuminated by a TM plane wave at 750 nm. (b) 0 and -1 order diffraction with grating period Λ = 400 nm. (c) 0 order reflectivity enhancement in a 400 nm grating illuminated by 750 nm wavelength when the MgO conductivity jumps from 0 to 4.1×10^7 S/m. At resonant peak 29.95°, the reflection coefficient is enhanced 8.6 times.

Close scrutiny on the grating with Λ = 400 nm in Fig. 2(b) reveals that only m = 0 and m = -1 order diffractions can be observed due to the subwavelength nature of the grating. A sharp reflection dip occurs when the incident angle is 29.25°. The -1 order diffraction emerges when the incident angle is greater than 60°. Based on our assumption that the conductivity of the dielectric layer increases as a result of radiation damage, we assign the MgO conductivity to be 4.1×10^7 S/m in the extreme case. By taking the ratio of the 0 order diffraction power (R_0) in extreme ($\sigma = 4.1\times10^7$ S/m) and ordinary ($\sigma = 0$) cases, the effects of the conductivity change in the STT-RAM subwavelength grating can be identified at the resonance angle of 29.25°, where the reflectivity is enhanced 8.6 times, or more than 9 dB, as shown in Fig. 2(c). Consider the MgO layer is ultra-thin (0.9 nm), the result is significant thanks to SPP's ultra-sensitivity to the dielectric medium.

The investigation indicates that plasmonic spectroscopy can be used in material diagnostics effectively. The optimization on the cell constellations, e.g. blazed gratings, is currently underway to yield higher enhancement. Further studies on radiation induced absorption and nonlinear effects will be performed.

4. References

1. A. Persson, et.al, "Radiation tolerance of a spin-dependent tunnelling magnetometer for space applications," Meas. Sci. Technol. **22**, 045204 (2011).
2. A. Abbas, et.al, "New trends in instrumental design for surface plasmon resonance-based biosensors," Biosens. Bioelectron. **26**, 1815–1824 (2011).
3. P. Berini, "Long-range surface plasmon polaritons," Adv. Opt. Photonics **1**, 484 (2009).
4. D. Apalkov, etl.al, "Spin-transfer Torque Magnetic Random Access Memory (STT-MRAM)," J Emerg Technol Comput Syst **9**, 13:1–13:35 (2013).
5. A. Holmes-Siedle and L. Adams, *Handbook of Radiation Effects*, 2 edition (Oxford University Press, 2002).
6. J. R. Schwank, etl.al, "Radiation Effects in MOS Oxides," IEEE Trans. Nucl. Sci. **55**, 1833–1853 (2008).
7. Y. Huang, el.al, "Phase-gradient gap-plasmon metasurface based blazed grating for real time dispersive imaging," Appl. Phys. Lett. **104**, 161106 (2014).
8. A. D. Rakic, el.al, "Optical Properties of Metallic Films for Vertical-Cavity Optoelectronic Devices," Appl. Opt. **37**, 5271 (1998).