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Plasmonic detection of possible defects in multilayer nanohole array consisting of essential materials in simplified STT-RAM cell

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ABSTRACT

Plasmonic nanostructures are highly used for sensing purposes since they support plasmonic modes which make them highly sensitive to the refractive index change of their surrounding medium. Therefore, they can also be used to detect changes in optical properties of ultrathin layer films in a multilayer plasmonic structure. Here, we investigate the changes in optical properties of ultrathin films of macro structures consisting of STT-RAM layers. Among the highest sensitive plasmonic structures, nanohole array has attracted many research interest because of its ease of fabrication, small footprint, and simplified optical alignment. Hence it is more suitable for defect detection in STT-RAM geometries. Moreover, the periodic nanohole pattern in the nanohole array structure makes it possible to couple the light to the surface plasmon polariton (SPP) mode supported by the structure. To assess the radiation damages and defects in STT-RAM cells we have designed a multilayer nanohole array based on the layers used in STT-RAM structure, consisting 4nm-Ta/1.5nm-CoFeB/2nm-MgO/1.5nm-CoFeB/4nm-Ta layers, all on a 300nm silver layer on top of a PEC boundary. The nanoholes go through all the layers and become closed by the PEC boundary on one side. The dimensions of the designed nanoholes are 313nm depth, 350nm diameter, and 700nm period. Here, we consider the normal incidence of light and investigate zeroth-order reflection coefficient to observe the resonance. Our simulation results show that a 10% change in refractive index of the 2nm-thick MgO layer leads to about 122GHz shift in SPP resonance in reflection pattern.

Keywords: Surface plasmons, STT-RAM, optical detection, nanohole array, multilayer thin film, periodic structure

1. INTRODUCTION

Plasmonic structures are highly used for sensing purposes in biomedical and chemical applications since they support plasmonic modes which makes them highly sensitive to refractive index change of the surrounding medium [1]–[7]. The high sensitivity of such structures comes from the high localization of the plasmonic mode supported in them. Because of their high sensitivity, they can be used to detect changes in extremely thin layers either included in the plasmonic structure itself or on top of it. This idea has also been proposed for investigation of possible radiation damages in spin transfer torque random access memory (STT-RAM) cells by doing far field optical characterization [8]. The main idea is to design a plasmonic structure which supports a highly localized mode called surface plasmon polariton (SPP). To make it possible for the SPP mode to be excited by an incident plane wave, either periodic patterning of the structure or using a prism to couple the light can be done [9]. Here, we prefer to use a periodic patter rather than to use a bulky prism for coupling. To achieve this, using nanohole array structure which is one of the highest sensitive plasmonic structures is a proper option. The reason is that nanohole arrays are easy to fabricate, have small footprint, and have simplified optical alignment.

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The nanohole array design we provide in this paper is to detect possible radiation damage in dielectric layer of a multilayer structure composed of materials used in STT-RAM cells. A typical STT-RAM cell in its simplest form consists of a thin dielectric layer (MgO) sandwiched between ferromagnetic layers (typically CoFeB alloys), which form a magnetic tunnel junction of nanoscale dimensions (Fig. 1). There are also two metallic layers (Ta) at the top and bottom of STT-RAM cells to make the electrical contact [10]. Therefore, we have considered a Ta/CoFeB/MgO/CoFeB/Ta multilayer, same as a typical STT-RAM, for our design of multilayer nanohole array. The main radiation damages in STT-RAM cells is expected to be in the dielectric layer (MgO layer) which is typically a few nanometers thick. In the following, we first discuss whether it is possible to use Ta as the only metallic layer in the structure to design a strong enough SPP mode which shows up in the reflection spectrum. Then, we provide our final design as well as the shift in SPP resonance for a %10 change in refractive index of the MgO layer. Results show that variations in optical properties of ultrathin films in a nanoscale multilayer structure can be detected through this plasmonic approach.

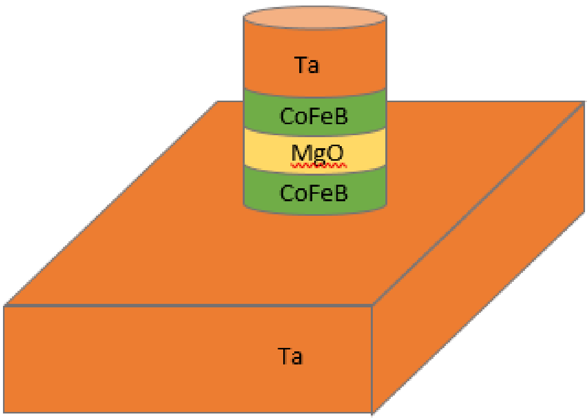


Fig. 1. Typical STT-RAM cell. The magnetic tunnel junction forms between CoFeB layers.

2. INVESTIGATING TANTALUM AS PLASMONIC METAL

Before starting the design of nanohole array, we first checked that whether Ta can support a detectable and sharp enough surface plasmon resonance at its interface with air. To do this, we considered a TM-polarized SPP mode localized at the interface. Using Maxwell's equations and then applying boundary conditions for tangential components of electric and magnetic fields, the following formula for propagation constant (β) of the SPP mode can be obtained [9].

$$\beta = k_0 \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{1}$$

In this formula, ε_m and ε_d are permittivity of the metal and dielectric, respectively.

Using the permittivity data for Ta from [11] and considering air as the dielectric material, we calculated real and imaginary parts of β for the considered SPP mode (Fig. 2). The idea is to choose the frequency at which real part of β has a local maximum above the light line. At this point, the considered SPP mode has the highest localization possible along the interface. As can be seen in Fig. 2, this frequency is around 440THz (λ=682nm) for Ta /air interface. However, the local maximum in this plot is too weak, which means there is almost no surface plasmon resonance happening in this case. This has been approved by our simulations for the nanohole array structure as well. The inability of Ta for creating a sharp plasmonic resonance at its interface with air comes from its high losses at optical frequencies. This is illustrated by Fig. 3 which shows that in the frequencies close to 440THz the absolute value of imaginary part of Ta's permittivity is much larger than absolute value of its real part.

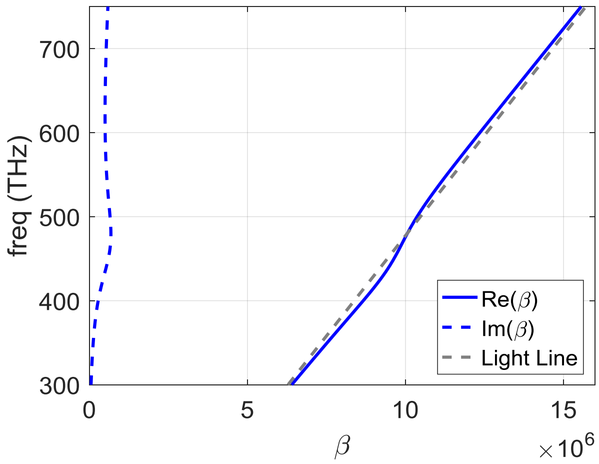


Fig. 2. Propagation constant of SPP mode at Ta/air interface. The interface does not support a strong surface plasmon resonance.

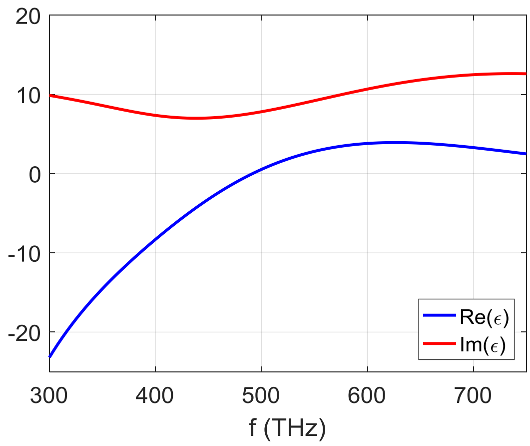


Fig. 3. Real and imaginary parts of permittivity of Ta. Its high losses make it impossible to get a strong enough surface plasmon resonance at Ta/air interface.

3. ADDING AN EXTRA METALLIC LAYER

Up to this point, we have concluded that Ta is not able to support an SPP mode because of its high losses. Therefore, we need to add an extra metallic layer to our multilayer structure. To do so, we chose silver, which is one of the highly used metals in plasmonic designs. However, we want to keep the main layers of STT-RAM cell in our design, thus we are limited in our design mainly due to high losses of Ta. At large frequencies, Ta has higher losses, so the reflection coefficient of the multilayer structure would be too small to be able to reveal the resonance in its spectrum. In other words, high losses of Ta make the surface plasmon resonance of silver less strong or even make it disappear. Hence, larger frequencies are preferred for our design. On the other hand, at very small frequencies, the plasmonic mode would be less localized which means less sensitivity to refractive index changes. This is because of getting far from the surface plasmon frequency of silver/air interface, at which the real part of propagation constant of the SPP mode has its maximum value. Therefore, to choose the design frequency, a trade-off should be made to get low losses in Ta as well as getting highly localized plasmonic mode. Having this in mind, we decided to design the multilayer nanohole array to show its SPP resonance at around 384.6 THz (λ=780nm). It should be mentioned that CoFeB and MgO layers also have some effects, but because of their low thicknesses compared to the thickness of Ta layers in the multilayer structure as well as the fact that they have less losses, they do not significantly affect the resonance frequency.

4. NANOHOLE ARRAY DESIGN AND RESULTS

To design the nanohole array, simulations were done using Lumerical FDTD. To simplify the simulations, we designed a dead-ended nanohole array by putting a PEC boundary condition on one side. The multilayer structure we considered for our design consists of 4nm-Ta/1.5nm-CoFeB/2nm-MgO/1.5nm-CoFeB/4nm-Ta layers, all on a 300nm silver layer on top of a PEC boundary (Fig. 4). Thickness of Ta, CoFeB, and MgO layers are chosen according to the typical thicknesses of layers in STT-RAM cell. The nanoholes go through all the layers and become closed by the PEC boundary. Here, we consider normal incidence of light from the air side and investigate zeroth-order reflection coefficient to design the nanohole array. In our simulations, the material data for Silver, Ta, and CoFeB are taken from the measured data provided in [12], [11], and [13], respectively. For MgO, refractive index is set to the fixed value of 1.73, since it has negligible variation over the frequency range of simulation [14].

Design parameters for nanohole array structure are period (p), nanohole diameter (d), and thickness (Fig. 4). Among these parameters, period has the largest effect on resonance wavelength [15]. Therefore, we started our design by changing the period as the main design parameter. Based on grating formula for the (1, 0) SPP mode, the following formula can give us a rough idea of how changing the period affects resonance wavelength.

$$p = \frac{\lambda}{real\left(\frac{\beta_{spp}}{k_0}\right)} \tag{2}$$

In this formula, β_{spp} is propagation constant of the (1, 0) SPP mode in the nanohole array, k_0 is the propagation constant in free space, and λ is the resonance wavelength. If we consider β_{spp} as being of nearly zero dispersion, this equation implies that resonance wavelength is proportional to the period of nanoholes. Therefore, we can easily increase or decrease resonance wavelength by changing the period.

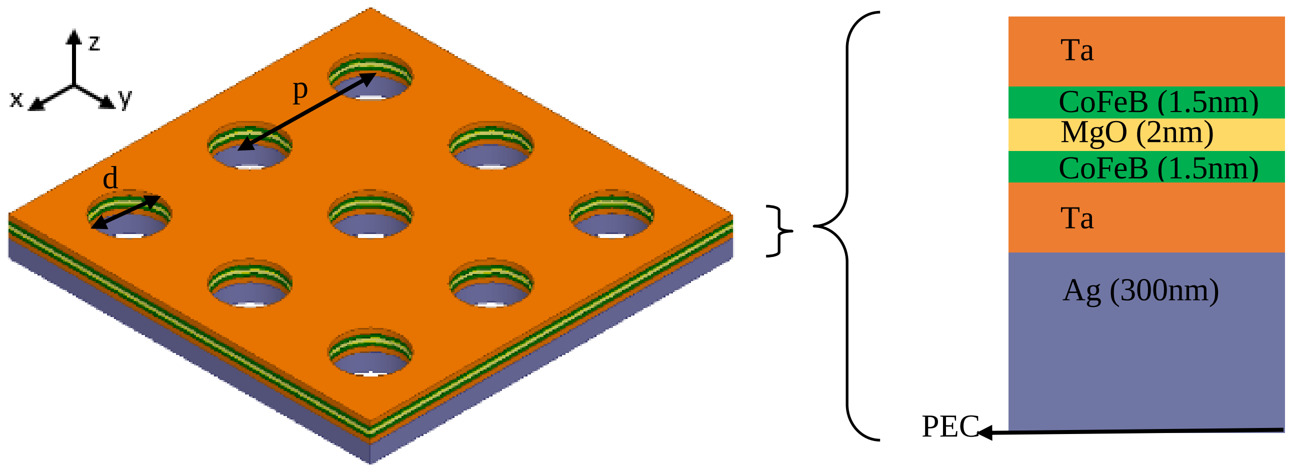


Fig. 4. Multilayer nanohole array structure. Layers of STT-RAM structure are included in the multilayer.

Using a parameter sweep in Lumerical and reading the reflection spectrum, we set the period of the nanohole array to p=700nm to get a resonance wavelength close to 780nm. Then we swept nanohole diameter to fine tune the resonance and get the deepest resonance possible in the reflection spectrum. However, the resonance wavelength changes a little bit as we change nanohole diameter, which is too negligible in this case, so it is not of our concern. The best resonance we obtained for this design was for d=350nm. Thickness of silver was kept constant in the simulations, since it has not much effect in the result as long as it is large enough compared to the skin depth. Thickness of other layers are also fixed because we wanted them to be the same as typical thicknesses used in STT-RAM cells. For the selected nanohole parameters (p=700nm, d=350nm), which shows a resonance at about λ=785nm, the field enhancement at the resonance wavelength and near the reflection surface of the structure is as large as 18 times the incident plane wave. This is illustrated in Fig. 5, which shows the cross section of a unit cell of the nanohole array. As we mentioned before, the field enhancement results in a high sensitivity of the structure to refractive index changes, which is our main goal here.

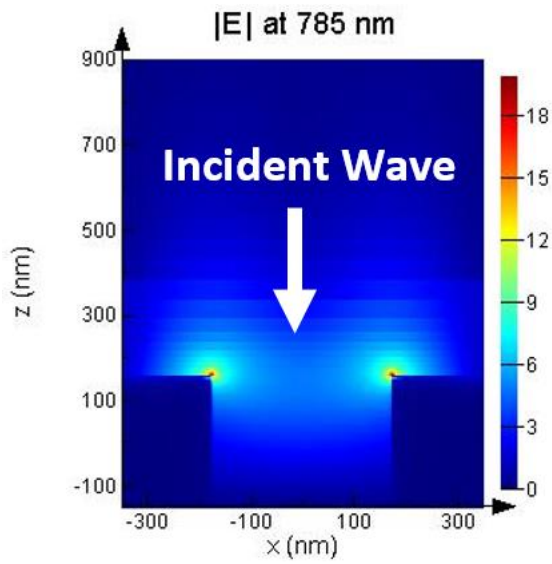
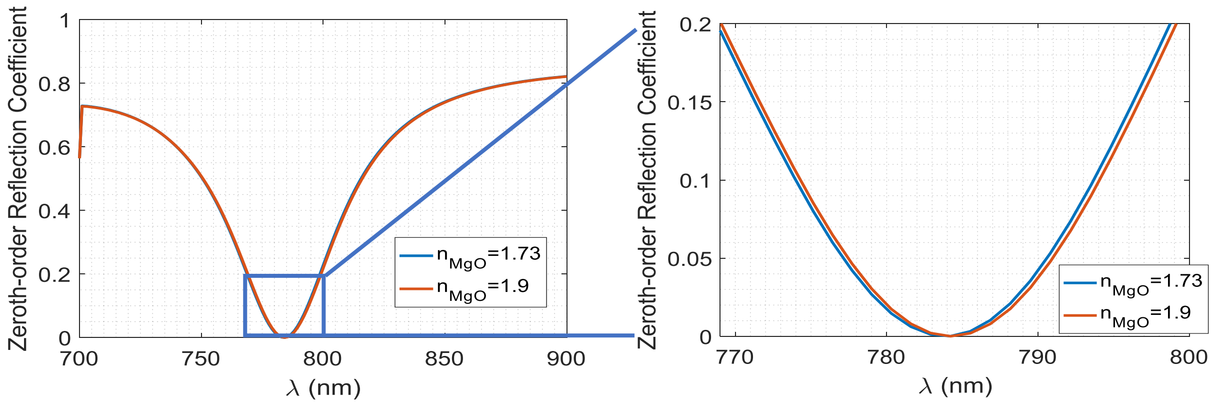


Fig. 5. Field enhancement of the designed multilayer nanohole array (p=700nm, d=350nm) at its resonance wavelength. The field enhancement originating from the excited SPP mode makes the structure sensitive to the refractive index changes.

To show the ability of the designed nanohole array to sense the change of refractive index in the ultrathin MgO layer, we have investigated its resonance which is supposed to show up zeroth-order reflection spectrum as a result of SPP mode excitation. The idea is to change MgO refractive index to 1.9, which is about %10 different from its initial value, and observe the resulting resonance shift. The reflection spectra for both cases are plotted in Fig. 6. At resonance wavelength, the SPP mode is excited by normal incident light, so part of its power propagates along the reflection surface in the form of SPP mode. This prohibits reflection of part of incident power in the direction of zeroth order reflection, causing a resonance dip in zeroth-order reflection spectrum. Since SPP mode is a localized mode, its excitation results in a field enhancement close to the surface, making the nanohole array sensitive to changes in the layers near the surface. In our design, a resonance shift of 122GHz (0.25nm) occurred in reflection spectrum of the designed nanohole array when we changed refractive index of MgO about %10 in the simulation. It is noteworthy to mention that the relatively wide bandwidth of the designed nanohole array (FWHM of about 60nm) is due to its multilayer structure and losses in different layers while a FWHM bandwidth of about 5nm can be obtained for a silver nanohole array with the same thickness.



(a) (b)

Fig. 6. (a) Zeroth-order reflection spectrum of the designed multilayer nanohole array (p=700nm, d=350nm) (b) zoomed view.

5. CONCLUSION

A demonstration of detection of changes in extremely thin layers of a multilayer plasmonic structure based on numerical simulation is presented. The provided design is a multilayer nanohole array structure which contains the main layers of a simplified STT-RAM cell. We investigated the resonance shift in zeroth-order reflection spectrum of the designed nanohole array caused by changing refractive index of the ultrathin dielectric layer (MgO), at which the main radiation damage is expected to happen. We showed that a %10 change in refractive index of the ultrathin MgO layer leads to a 122GHz (0.25nm) shift in SPP resonance.

6. ACKNOWLEDGMENT

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REFERENCES

[1] Homola, J., Yee, S. S., & Gauglitz, G., "Surface plasmon resonance sensors," Sensors and Actuators B: Chemical 54(1), 3-15 (1999).
[2] Lesuffleur, A., Im, H., Lindquist, N. C., & Oh, S. H., "Periodic nanohole arrays with shape-enhanced plasmon resonance as real-time biosensors," Applied Physics Letters 90(24), 243110 (2007).
[3] De Leebeeck, A., Kumar, L. S., De Lange, V., Sinton, D., Gordon, R., & Brolo, A. G., "On-chip surface-based detection with nanohole arrays," Analytical Chemistry 79(11), 4094-4100 (2007).
[4] Lesuffleur, A., Im, H., Lindquist, N. C., Lim, K. S., & Oh, S. H., "Laser-illuminated nanohole arrays for multiplex plasmonic microarray sensing," Optics express 16(1), 219-224 (2008).
[5] Ji, J., O'Connell, J. G., Carter, D. J., & Larson, D. N., "High-throughput nanohole array based system to monitor multiple binding events in real time," Analytical chemistry 80(7), 2491-2498 (2008).
[6] Eftekhari, F., Escobedo, C., Ferreira, J., Duan, X., Girotto, E. M., Brolo, A. G., ... & Sinton, D., "Nanoholes as nanochannels: flow-through plasmonic sensing," Analytical chemistry 81(11), 4308-4311 (2009).
[7] Escobedo, C., Vincent, S., Choudhury, A. I. K., Campbell, J., Brolo, A. G., Sinton, D., & Gordon, R., "Integrated nanohole array surface plasmon resonance sensing device using a dual-wavelength source," Journal of Micromechanics and Microengineering 21(11), 115001 (2011).
[8] Zhao, Q., Rajaei, M., Krivorotov, I., Nilsson, M., Bagherzadeh, N., & Boyraz, O., "Optical investigation of radiation induced conductivity changes in STT-RAM cells," Conference on Lasers and Electro-Optics (CLEO), (pp. 1-2). IEEE (2016).
[9] Maier, S. A., [Plasmonics: fundamentals and applications], Springer Science & Business Media (2007).
[10] Wang, K. L., Alzate, J. G., & Amiri, P. K., "Low-power non-volatile spintronic memory: STT-RAM and beyond," Journal of Physics D: Applied Physics, 46(7), 074003 (2013).
[11] Weber, M. J., [Handbook of optical materials], CRC press 19, (2002).
[12] Palik, E. D., "Handbook of optical constants of solids," Academic press, (1998).
[13] Liang, X., Xu, X., Zheng, R., Lum, Z. A., & Qiu, J., "Optical constant of CoFeB thin film measured with the interference enhancement method," Applied Optics 54(7), 1557-1563 (2015).
[14] Stephens, R. E., & Malitson, I. H., "Index of refraction of magnesium oxide," Journal of Research of the National Bureau of Standards 49(4), 249-252 (1952).
[15] Wu, L., Bai, P., & Li, E. P., "Designing surface plasmon resonance of subwavelength hole arrays by studying absorption," JOSA B 29(4), 521-528 (2012).

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