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Alternative material study for heat assisted magnetic recording transducer application

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In heat assisted magnetic recording (HAMR), optical near field transducer (NFT) is a key component. Au is currently used as NFT material because of its strong surface plasmon effect. Due to the soft property of Au material, reliability of Au NFT becomes a key issue for realizing HAMR production. In this paper, the possibility of alternative materials, including transition metal nitrides (TMNs) and transparent conducting oxides (TCOs) to replace Au is studied. The results show that all of the listed TMN and TCO materials can meet the mechanical requirements at room temperature in terms of hardness and thermal expansion. An optical model, which includes optical waveguide, NFT and FePt media, is used to simulate NFT performances. The results indicate that the resonant wavelengths for NFT with TCO materials are longer than 1500 nm, which is not suitable for HAMR application. TMN materials are suitable for NFT application at wavelength band of around 800 nm. But the NFT efficiency is very low. ZrN is the best material among TMN materials and the efficiency of ZrN NFT is only 13% of the Au NFT's efficiency. Reducing refractive index (n) and increasing extinction coefficient (k) will both lead to efficiency increase. Increasing k contributes more in the efficiency increase, while reducing n has a relatively low NFT absorption. For materials with the same figure of merit, the NFT with larger k material has higher efficiency. Doping materials to increase the material conduction electron density and growing film with larger size grain may be the way to increase k and reduce n . © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4908029>]

INTRODUCTION

In heat assisted magnetic recording (HAMR), an optical near field transducer (NFT) is used to concentrate the laser energy to a magnetic recording medium and heat the medium locally. NFT utilizes the surface plasmon effect to generate a nano-sized optical spot. In order to deliver enough power to the medium, the efficiency of NFT is important. Au is used as NFT material, which has a strong surface plasmon effect. However, it is too soft and has a large thermal expansion. Due to laser absorption, NFT temperature will raise and protrusion in air-bearing surface will happen.^{1–3} The NFT protrusion and high temperature effects on other surround materials make NFT easily damaged. Therefore, the reliability of NFT becomes the most challenging issue in HAMR application. Doping material into Au will increase its hardness.⁴ However, the hardness is not enough for small quantity doping. Large quantity doping will cause its surface plasmon effect to drop tremendously. In order to solve this fatal problem, an alternative material is desired to replace Au as NFT material. The alternative material should possess properties: high surface plasmon effect, comparable hardness, and comparable or smaller coefficient of thermal expansion (CTE) with Al_2O_3 (because the NFT is normally surrounded by Al_2O_3 in the real application).

Transition metal nitrides (TMN) and transparent conducting oxides (TCOs), such as ZrN, TiN, HfN, ZAO, GAO,

and ITO have attracted attention in plasmonic applications because of their good metallic properties.^{5–7} Their surface plasmon effects for nano-particle have been studied, and the results showed that their surface plasmon generations were even better than that of Au nano-particle.⁵ In this paper, we will discuss if some of them are suitable for HAMR NFT application.

PROPERTIES OF TMN AND TCO MATERIALS

The hardnesses and CTEs of the TMN and TCO materials at room temperature are listed in Fig. 1.^{8–17} For comparison, the parameters of Au and Al_2O_3 are also listed. All of the listed TMN and TCO materials have smaller CTE than Au. The hardnesses of these materials are much larger than Au and comparable or larger than Al_2O_3 . Therefore, in terms

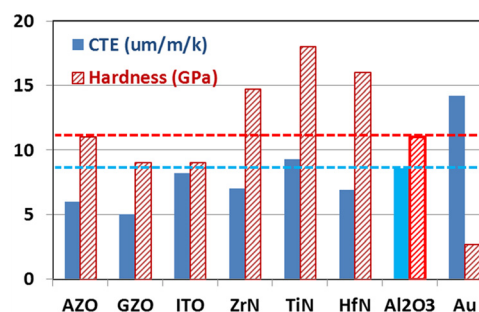


FIG. 1. Values of CTE and hardness of related materials at room temperature.

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of mechanical properties, all of the listed TMN and TCO materials meet the requirements for NFT application.

Fig. 2 shows the optical constants of TMN and TCO materials at room temperature.⁵⁻⁷ A parameter so-called figure of merit (FOM), which is defined as $FOM = -\varepsilon_1/\varepsilon_2 = -(n^2 - k^2)/(2nk)$, is used to measure the quality of material for plasmonics application. The material with larger FOM has the stronger surface plasmon effect. FOMs of TMN and TCO are also plotted in Fig. 2. The FOM peak values of ZrN and HfN are in the band from 600 nm to 1000 nm, which matches with currently used laser wavelength (around 800 nm) in HAMR system. TiN's FOM increases gradually as the wavelength increases from 700 nm. Large FOM values of TCO appear in the wavelength longer than 1400 nm. The material with large FOM has strong surface plasmon effect. However, it is the case in which the surface plasmon device is alone and there is no interaction between surface plasmon element and other device. In HAMR application, the surface plasmon wave radiated by NFT has to be absorbed by the recording layer of medium. Boundary conditions will also affect the efficiency.¹⁸ Therefore, NFT with new material has to be studied in the HAMR application environment, which includes optical waveguide and HAMR media.

OPTICAL PERFORMANCES OF NFT WITH ALTERNATIVE MATERIALS

The model used to study the performances includes optical waveguide, NFT, and FePt medium. It is similar with that in Ref. 19 except that the NFT material is replaced with alternative materials. NFT is lollipop shape surrounded by Al_2O_3 . The thickness of NFT disk is 20 nm. The tip size of NFT in air-bearing surface is $20 \times 20 \text{ nm}^2$. The medium consists of FePt (10 nm)/MgO (4 nm)/Cu (50 nm)/glass substrate. The optical constant of FePt is from Ref. 20. The optical performances are simulated by finite-difference time-domain method (Lumerical FDTD) and the thermal responses of NFT are obtained by simulation with commercial software COMSOL. In this paper, all the results will be presented in relative efficiency (absorbed by the recording

layer of HAMR media) and relative absorption (absorbed by NFT itself) respect to the maximal efficiency and corresponding absorption of Au NFT in the same model.

The simulation results for TCO materials showed that their resonant wavelengths are in the wavelength beyond 1550 nm. Therefore, they are not suitable for HAMR NFT application and we will not discuss them here. Among TMN materials, the results indicated that NFT with ZrN material has the best optical performances. Because of space limitation, the results with ZrN will be presented only in this paper. Fig. 3 shows the dependences of the relative efficiencies and absorptions of ZrN NFT on laser wavelengths at different NFT disk radii. Compared with Au NFT response, ZrN NFT shows a broader resonant peak (TiN and HfN have the same characteristic). This means that there is a larger tolerance for the NFT disk size. The maximal efficiency of ZrN NFT (at wavelength of 880 nm and disk radius of 80 nm) is about 13% of Au NFT efficiency, while the corresponding absorption is about 71% of Au NFT absorption. If assuming the ratio of absorption to efficiency of Au NFT is 1, the ratio of ZrN NFT is 5.1. This means that for a medium to be heated up to a same temperature, ZrN NFT will absorbed more than 4.1 times laser power than Au NFT. This high NFT absorption will definitely lead to a high temperature rise. The thermal simulation results showed that in the case of Au NFT temperature rise of 308 °C, the ZrN temperature rise is 1790 °C. Another reason for higher temperature rise of ZrN NFT is that the thermal conductivity of ZrN is much smaller than that of Au. Such a high temperature is not acceptable for real HAMR head. For HfN and TiN NFTs, the temperature rises and protrusions are even higher and larger than that of ZrN NFT. Therefore, it is not necessary to discuss the results with HfN and TiN.

The optical performances of pure ZrN are poor for NFT application. Doping material can change ZrN optical constant. Therefore, it is necessary to understand how much the performance can be improved by changing n and k . In the studies, an n -factor and a k -factor are defined as the factors to multiply n value and k value of the original ZrN material. Figs. 4(a) and 4(b) show the dependences of NFT relative efficiencies and relative absorptions on disk radii for different k -factors at wavelength of 840 nm. As the k -factor increases, the efficiency increases effectively; the maximal resonant disk size shifts to large size; and the absorption responding to the peak efficiency increases. The dependences of the maximal relative efficiency and corresponding relative absorption on k -factors are plotted in Fig. 4(c). The rate of efficiency increase is larger than the rate of absorption

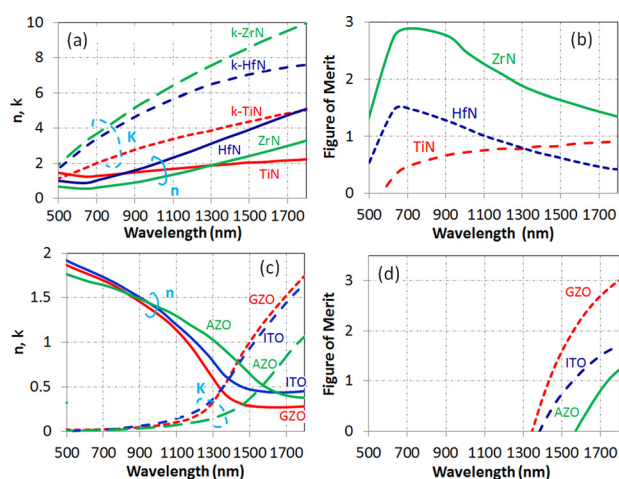


FIG. 2. n and k values and FOMs of TMN materials ((a) and (b)) and TCO materials ((c) and (d)).

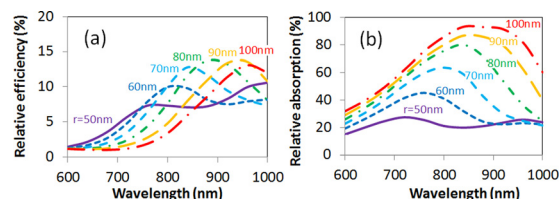


FIG. 3. Dependences of relative efficiencies (a) and relative absorptions (b) (to Au NFT's efficiency and absorption) of ZrN NFT on wavelengths at different NFT disk radii.

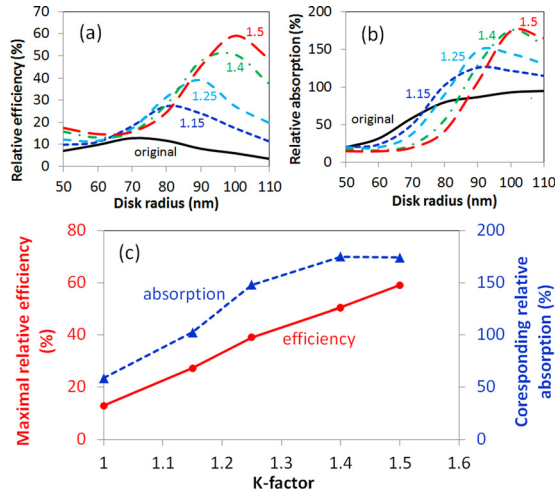


FIG. 4. Dependences of relative efficiencies (a) and relative absorptions (b) (to Au NFT's efficiency and absorption) on NFT disk sizes, as well the maximal relative efficiencies and corresponding relative absorptions (c) for different K-factors at wavelength of 840 nm.

increase. When the efficiency reaches 59% of Au NFT efficiency at k-factor of 1.5, the absorption is about 175% of the absorption of Au NFT. The efficiency increases about 3.5 times, while the absorption increase is about 2 times.

Figs. 5(a) and 5(b) show the n-factor effects on both the relative efficiency and relative absorption. Reducing n-factor causes the efficiency and absorption to increase. However, unlike the case of k-factor change, the maximal resonant disk size keeps the same when the n-factor changes. The dependences of the maximal relative efficiency and corresponding relative absorption on n-factors are plotted in Fig. 5(c). The relative absorption increases almost linearly. The relative efficiency increase is faster than the absorption increase. When the relative efficiency reaches 56% at n-factor of 0.25, the corresponding relative absorption is about 82%, which is only about half of the absorption at k-factor of 1.5. Therefore, for the same achieved efficiency, the material with small n is preferred because of lower NFT absorption.

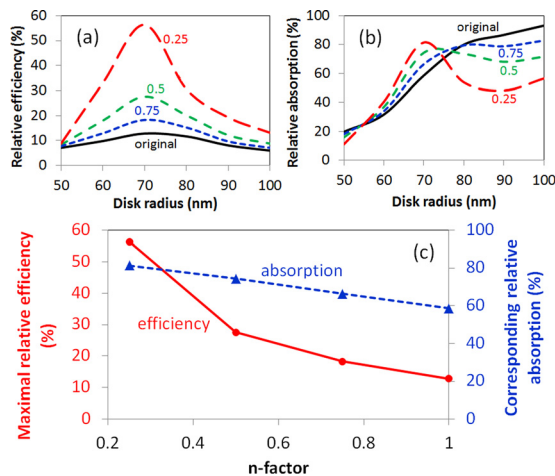


FIG. 5. Dependences of relative efficiencies (a) and relative absorptions (b) (to Au NFT's efficiency and absorption) on NFT disk sizes, as well the maximal relative efficiencies and corresponding relative absorptions (c) for different n-factors at wavelength of 840 nm.

FOM is a parameter to indicate the capability of surface plasmon generation. In NFT application, it is not clear if the material with the same FOM will have the same performances. Figs. 6(a) and 6(b) show the dependences of relative efficiencies and absorptions on NFT disk size at wavelength of 840 nm in the three cases of k-factor of 1.4, n-factor of 0.71429, and n-factor of 0.857145 + k-factor of 1.2. The materials with these three case properties have the same FOM value. The maximal relative efficiencies and its corresponding relative absorptions for the three cases are shown in Fig. 6(c). For HAMR NFT application, materials with same FOM show different performances. The material with a larger k is more beneficial for increasing NFT efficiency. However, it will have relatively larger absorption. In these three studied cases, for n-factor of 0.714, the relative efficiency increases about 47% (from 13% to 19%), while the corresponding relative absorption increases 15% (from 59% to 68%). However, for k-factor of 1.4, the relative efficiency increases from 13% to 51%, while the relative absorption increases from 59% to 175%. The efficiency increases about 3 times, while the absorption increases about 2 times.

Above results have shown that a material with large k will lead to a high NFT efficiency. However, it also leads to a high NFT absorption. Reducing n can not only increase the efficiency but also keep a relatively low NFT absorption as well. For materials with same FOM, the one with larger k will have higher NFT efficiency. Now, let us discuss how to increase k and reduce n effectively. For TMN materials, their dielectric constant can be described by combining Drude model and Lorentz model²¹

$$\varepsilon(\omega) = \varepsilon_{\infty} - \frac{\omega_d^2}{\omega^2 + i\Gamma_d\omega} + \sum_{j=1}^3 \frac{A_j\omega_{Lj}^2}{\omega_{Lj}^2 - \omega^2 - i\Gamma_{Lj}\omega}, \quad (1)$$

where ε_{∞} is a background constant, ω_d is the unscreened plasma frequency, Γ_d is the Drude-term damping factor, ω_{Lj} is the resonance frequency of the j th Lorentz oscillator, and A_j and Γ_{Lj} are its corresponding oscillator strength and broadening term, respectively. The second part is the Drude

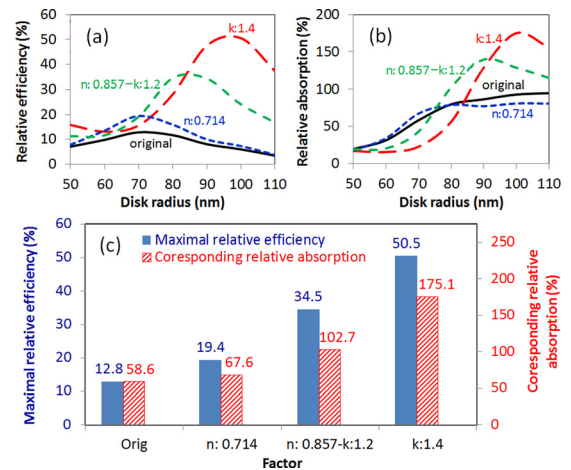
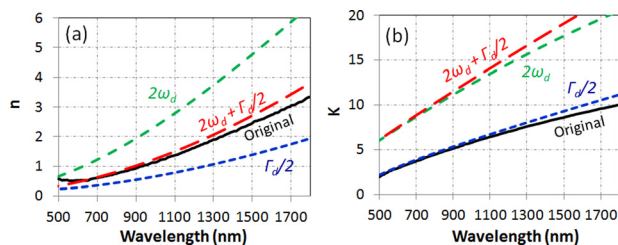


FIG. 6. Dependences of relative efficiencies (a) and absorptions (b) (to Au NFT's efficiency and absorption) on NFT disk sizes, as well the maximal efficiencies and corresponding absorptions (c) for different K-factors and n-factors but same FOM at wavelength of 840 nm.

FIG. 7. Effects of ω_d and Γ_d on n (a) and k (b).

term, characterizing the free electron absorption (intraband electronic transition), while the third part is Lorentz oscillators, describing band-to-band transition (interband electronic transition). ω_d and Γ_d are related with the concentration N and the mean free path (MFP) of conduction electrons as following formulas:²¹

$$\hbar\omega_d = \sqrt{\frac{Ne^2}{\epsilon_0 m^*}}, \quad (2)$$

$$MFP = \hbar \left(\frac{3\pi^2 \epsilon_0}{(m^* e)^2} \right)^{1/3} \frac{\omega_d^{2/3}}{\Gamma_d}, \quad (3)$$

where ϵ_0 is the permittivity of free space, m^* is the electron effective mass, and e is the electron charge.

Fig. 7 plots the optical constants of ZrN fitted with formula (1). In order to understand the effects of ω_d and Γ_d on n and k , the curves of n and k with doubled ω_d and halved Γ_d are also plotted in the figure. A large ω_d leads to a large k and large n . A small Γ_d leads to a small n and slightly large k . Based on formulas (2) and (3), increasing conduction electron density will increase k . The material with larger MFP will have smaller damping factor. To increase the conduction electron density, some materials with more free electrons can be doped into the material. To reduce the damping factor, increasing the grain size of the material to reduce the boundary scattering will be a way.

CONCLUSIONS

TMN and TCO materials possess good mechanical properties and good surface plasmon performances in nanoparticles. However, pure materials are not suitable for HAMR NFT applications. The resonant wavelengths of TCO are longer than 1500 nm, which is not suitable for HAMR application unless that the material with doping can shift its

resonant wavelength to 1500 nm or 1300 nm bands. NFTs with pure TMN materials have very low efficiency and relatively high absorption. In order to heat up media to the same temperature, it will absorb a few times higher laser power compared to Au NFT. This will lead to a very high temperature rise of NFT. Although the mechanical properties of TMN materials are superior to that of Au at room temperature, the poor optical performance and higher NFT temperature may cause the TMN materials to have worse mechanical properties when used in HAMR application. Modifying TMN's optical properties and keeping mechanical properties will be a direction for NFT material study. The material with large k and small n will benefit NFT's efficiency. Reducing n can increase the efficiency, keep the same resonant wavelength, and absorb relatively less laser power. Increasing k leads to more efficiency increase and the resonant NFT size to shift to larger value. For materials with the same FOM, the NFT with larger k material will have higher efficiency. Doping materials to increase TMN's conduction electron density and growing film with large size grain may be a way to obtain the material with large k and small n , which is beneficial to HAMR NFT application.

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