AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **117**, 17E303 (2015); doi: 10.1063/1.4906962
View online: http://dx.doi.org/10.1063/1.4906962
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/117/17?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **117**, 17E303 (2015)

Switching window analysis of a magnetic media grain in microwave assisted magnetic recording

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(Presented 6 November 2014; received 22 September 2014; accepted 13 October 2014; published online 2 February 2015)

In order to achieve the effective magnetic switching of a magnetic media grain in the media for microwave assisted magnetic recording, the effects of property distribution of the grain and applying time of the microwave on the switchable frequency window are studied by micromagnetic simulation. The simulation results show the grain dimension and damping constant distribution causes a slight change in switchable frequency window, while the anisotropy energy density and saturation magnetization variation (±10%) may cause the mismatch of the switchable microwave frequency. The switchable frequency window increases with the applying time of the microwave if the microwave duration is shorter than 0.2 ns. Further increase of applying time of the microwave does not further improve the switchable frequency window significantly in the simulation condition when it starts from time zero. These results indicate that it is critical to control the distribution of the anisotropy energy density and saturation magnetization variation to reduce the mismatch of frequency and achieve effective magnetic switching, and the microwave does not need to be on all the time, which can reduce the energy consumption of the microwave generator in the magnetic head. [http://dx.doi.org/10.1063/1.4906962]

The perpendicular magnetic recording is approaching its maximum recording density limit after achieving a factor of 4–5 over the best longitudinal areal density in hard disk drive. In order to further overcome the superparamagnetic problem, the high magneto crystalline anisotropy recording materials, such as FePt and CoPt, have to be used as the recording media. This leads to increasing medium coercivity and requirement of larger write field. Unfortunately, the required writing field is beyond the maximum field which can be generated by the current writing head.

Microwave assisted magnetic recording (MAMR) provides a solution to overcome the problem. In the past decade, the microwave assisted magnetic switching has been studied from theoretic simulation to experiment study.[1–9] With the assistance of a small optimized radio frequency magnetic field near the natural precession frequency, the resonant magnetic precession drives the magnetization over the energy barrier generated by the high anisotropy, so the quasi-static writing field can be greatly reduced and become much smaller than the so-called Stoner-Wohlfarth limit.

The perpendicular spin torque oscillator was proposed as the local microwave generator,[10] which requires minimal technological change and is compatible with conventional perpendicular recording head structure and fabrication processes.

In this study, two fundamental issues for the application of microwave assisted magnetic switching in hard disk drive are investigated in detail. The first is how the property distribution of magnetic media grain affects the microwave assisted magnetic switching, and the second is how to minimize microwave applying time to achieve effective switching.

The analysis is based on LLG equation with macrospin model in the spherical coordinates

$$\frac{d\theta}{dt} = \frac{\gamma_0}{1+\alpha^2}[h_\varphi + \alpha h_\theta], \quad (1)$$

$$\frac{d\varphi}{dt} = \frac{\gamma_0}{1+\alpha^2}\frac{1}{\sin\theta}[\alpha h_\varphi - h_\theta]. \quad (2)$$

Here, h_θ and h_φ are the normalized effective field along $\vec{e}_\theta$ and $\vec{e}_\varphi$, α is damping constant, and γ_0 is the gyromagnetic ratio

$$h_\theta = -\frac{K_u}{\mu_0 M_s^2}\sin 2\theta - \frac{1}{2}\sin 2\theta\left[(N_x - N_z) + (N_y - N_x)\sin^2\varphi\right] + \left(H_{ax}\cos\theta\cos\varphi + H_{ay}\cos\theta\sin\varphi - H_{az}\sin\theta\right)/M_s, \quad (3)$$

$$h_\varphi = -\frac{1}{2}(N_y - N_x)\sin\theta\sin 2\varphi + (-H_{ax}\sin\varphi + H_{ay}\cos\varphi)/M_s. \quad (4)$$

Here, K_u is anisotropy energy density, M_s is the saturation magnetization, N_x, N_y, and N_z are demagnetizing factors of the grain, H_{ax}, H_{ay}, and H_{az} are the applied magnetic field including quasi static field and microwave field. μ_0 is the permeability of free space.

The magnetic media grain dimension is defined as 6 nm × 6 nm × 8 nm, its saturation magnetization Ms is 570 emu/cc, its anisotropy energy density Ku is 750 × 1000 J/m^3, and the damping constant is 0.02. The total interaction time of simulation is 0.5 ns, the quasi static writing field (H_R) applied on the grain is 30° with z direction in x-z plane, and the microwave field is a circular wave. The initializing conditions of the grain magnetization are $\theta_0 = 0.0001°$, $\varphi_0 = 0°$. The frequency varies from 0 to 60 GHz with step size 0.01 GHz in the simulation.

When no microwave field is applied, the grain can be switched when the H_R is more than 11750 Oe. When the RF

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circular magnetic field with the amplitude in both x and y directions is 500 Oe, the minimal switchable H_R decreases to 8313 Oe (less 29.2%), and the corresponding microwave field frequency is near 42.7 GHz; if the amplitude of the circular field in both x and y directions increases to 750 Oe, the minimal switchable H_R further decreases to 5912 Oe (less 49.7%), and the corresponding microwave field frequency is near 48.1 GHz.

In the following study for the analysis of switching window a magnetic media grain in the microwave field, the amplitudes in both x and y directions are 750 Oe, the quasi DC writing field is 9400 Oe, which is 80% of the switching field without microwave field. In the simulation, the frequency is from 0 to 60 GHz with step size 0.01 GHz, the maximum switchable frequency, minimum switchable frequency and the total switchable frequency points is analysed. The switching probability here is defined as the total switchable frequency point divided by the total frequency point in the range of 1 GHz. Under the above original conditions, the minimum switchable frequency is 33.41 GHz, the maximum switchable frequency is 43.88 GHz, and the total switchable frequency points is 1018, the switching possibility between 36 GHz and 42 GHz is 100% and the switching probability distribution is shown in Fig. 1.

In the following paragraph, the effects of the property distribution of magnetic media grain and the applying time of microwave field on the microwave assisted magnetic switching of a magnetic media grain are analysed.

The demagnetizing field is dependent on the dimension of the grain and is a part of the effective magnetic field applied on the magnetic grain, which affects magnetic oscillation of the magnetic grain. When the x and y dimensions of the grain has ±10% offset, which means the size of grain in x-y dimension varies from 5.4 nm to 6.6 nm, the simulated results in Fig. 2 show the maximum switchable frequency almost keeps constant at 43.9 GHz, the minimum switchable frequency slightly decreases from 33.83 GHz to 32.65 GHz, and total switchable frequency points slightly increase from 983 to 1102. The curve of the switching possibility extends to the low frequency with the increase of the x-y dimension. The common switchable frequency for all size mainly follows the frequency range of the grain with minimal xy dimension between 33.8 GHz and 43.9 GHz. When the z dimension of the grain has ±10% offset, which means its height varies from 7.2 nm to 8.8 nm, the simulated results in Fig. 3 show the maximum switchable frequency almost stays constant at 43.9 GHz, the minimum switchable frequency slightly increases from 32.57 GHz to 34.22 GHz, and total switchable frequency points slightly decreases from 1110 to 930. The curve of the switching possibility shifts to the high frequency with the increase of the z dimension. The common switchable frequency for all size mainly follows the frequency range of the grain with maximal z dimension between 34.2 GHz and 43.9 GHz.

The saturation magnetization affects the demagnetizing field, anisotropy field (for a fixed anisotropy energy density), and magnetic force between the magnetic grain and the total field applied on the magnetic grain; it has stronger effects than the dimension on the oscillation of the magnetic grain. When the saturation magnetization of the grain has ±10% offset, which means the saturation magnetization varies from 513 emu/cc to 627 emu/cc, the simulated results in Fig. 4 show the maximum switchable frequency and the minimum switchable frequency decreases from 51 GHz to 43–44 GHz and

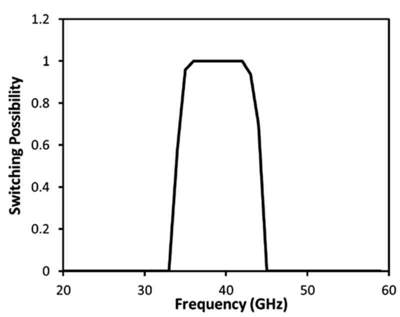

FIG. 1. The switching probability distribution.

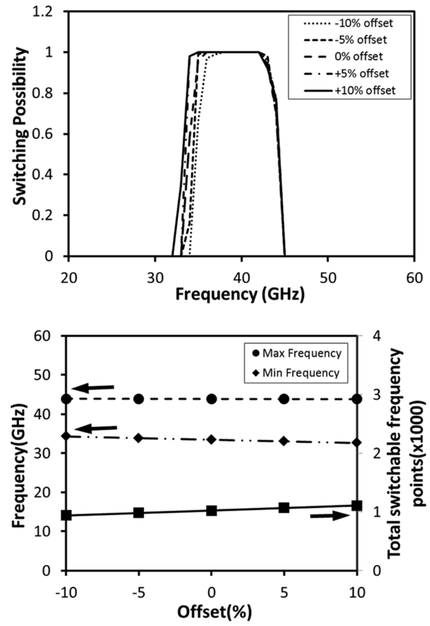

FIG. 2. Effects of x and y dimension offset.

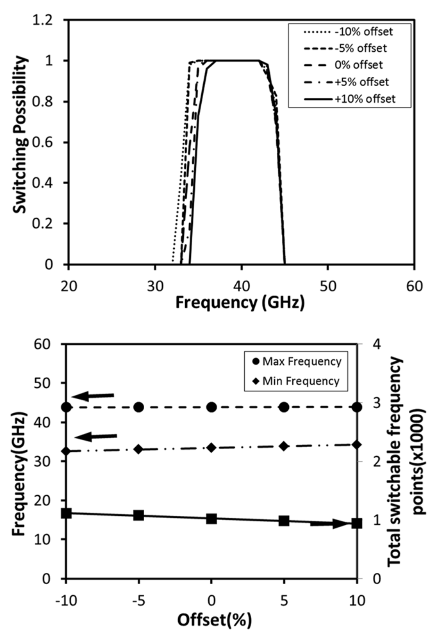

FIG. 3. Effects of z dimension offset.

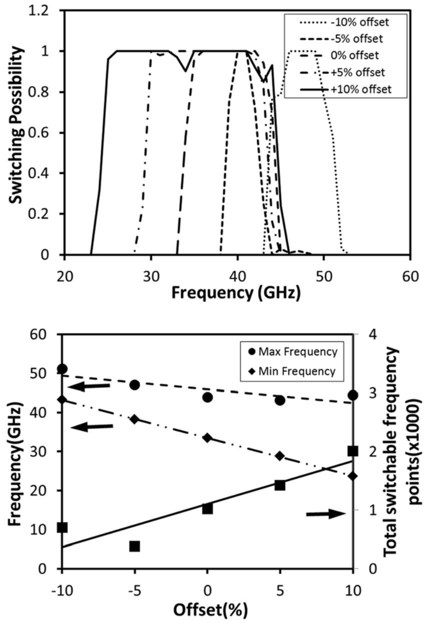

FIG. 4. Effects of saturation magnetization offset.

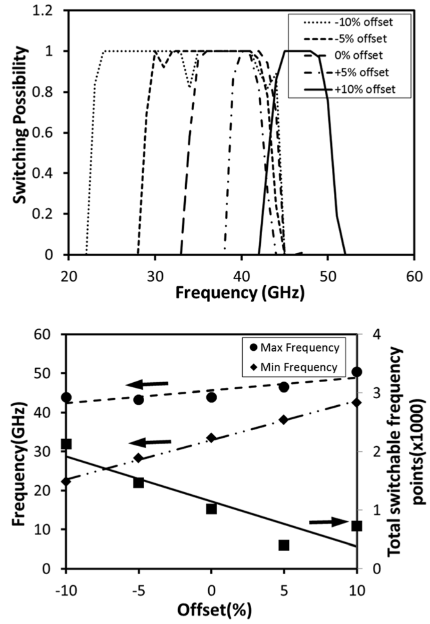

FIG. 5. Effects of the anisotropy energy density offset.

from 43 GHz to 24 GHz, respectively, and total switchable frequency points increase from 700 to 2000. The curve of the switching possibility shifts in both low frequency and high frequency. The common switchable frequency for all saturation magnetization distribution is limited near the 43–45 GHz. In the common switchable frequency area, all switching possibility is less than 1. This indicates that it is very difficult to find a frequency to achieve the 100% switching with the grains under such saturation magnetization distribution.

The dips in the probability curves show a lower switching possibility in the corresponding frequency range. Because the magnetic switching in MAMR is a dynamic precessional switching, and the precession drives the magnetization over (switching) the energy barrier generated by the anisotropy, the properties of the grain, DC magnetic field and microwave (amplitude and frequency) need to match well to achieve effective switching. Any mismatch among them will result in non-switching of grains and therefore lower switching possibility as indicated by the dips in the curves.

The anisotropy field is dependent on the anisotropy energy density of the grain, and the oscillation of the magnetic grain is also highly affected by the anisotropy energy density. When the anisotropy energy density of the grain has $\pm 10\%$ offset, which means the anisotropy energy density varies from 675×1000 J/m to 825×1000 J/m, the simulated results in Fig. 5 show the maximum switchable frequency and the minimum switchable frequency increase from $\sim$43 GHz to 50 GHz and from 22 GHz to 42 GHz, respectively, and total switchable frequency points decrease from 2100 to $\sim$700. The curve of the switching possibility shifts in both low frequency and high frequency. The common switchable frequency for all saturation magnetization distribution is limited near the 43 GHz. In the common switchable frequency area, all switching possibility is also less than 1. This also indicates that it is very difficult to find a frequency to achieve the 100% switching with the grains under such anisotropy energy density distribution.

The damping consumes the energy of the magnetic spin during the oscillation, high damping constant causes the quick dissipation of the oscillating energy. When the damping constant has $\pm 10\%$ offset, which means when the damping constant varies from 0.018 to 0.022, the simulated results in Fig. 6 show the maximum switchable frequency slightly decreases from 44.18 GHz to 43.51 GHz, and the minimum switchable frequency slightly increases from 33.14 GHz to 33.68 GHz, and the total switchable frequency points slightly decrease from 1069 to 948. The curve of the switching possibility shrinks in both low frequency and high frequency. The common switchable frequency to cover the offset of damping constant mainly follows the frequency range of the grain with highest damping constant between 33.7 GHz and 43.5 GHz.

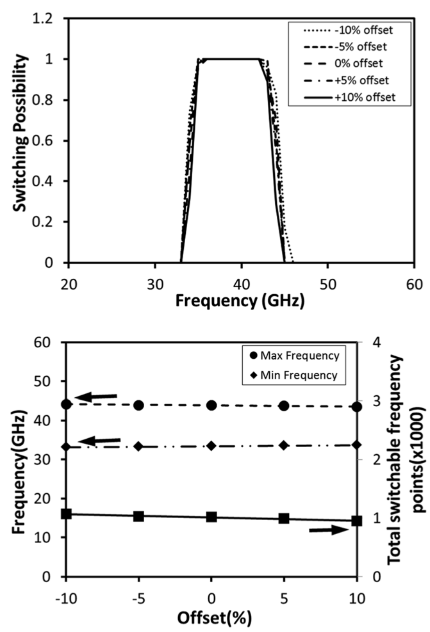

FIG. 6. Effects of damping constant offset.

In order to minimise microwave applying time to achieve effective switching, two types of microwave field placement in operation window are studied: (1) Reducing microwave applying time by shifting the start time; (2) reducing microwave applying time by shifting the ending time. In the simulation, the total simulation time is 0.5 ns.

In this case, the microwave field does not start from time 0 and is delayed by 0–0.5 ns, the total switching points decrease with the shift of start time, when the start time shifts from 0 to 0.1 ns, the maximum switchable frequency increases and the minimum switchable frequency experiences no obvious change, the switchable frequency range become larger, but switching possibility becomes smaller in the range, the total switchable frequency points decrease, as shown in Fig. 7. When the shifting time further increases to 0.2 ns and 0.3 ns, the maximum switchable frequency decreases, minimum switchable frequency increases, so the switchable frequency range becomes smaller. The switching possibility also becomes poor, and the total switchable frequency points further decrease. When the shifting time is 0.4 ns or more, no switching happens.

In this case, the microwave field starts from time 0, but stops earlier than the quasi static writing field, the total switch points increase from 826 to 1018, the maximal switchable frequency increases from 42.5 GHz to 43.9 GHz, and the minimal switchable frequency decreases from 33.8 GHz to 33.4 GHz with applying time of the microwave field from 0.1 ns to 0.5 ns. The main change happens before 0.2 ns, when the ending time is more than 0.2 ns, the change of the total switchable frequency points, maximal switchable frequency and the minimal switchable frequency are not obvious. It can also be observed in the curves of switching possibility for the different applied time, the curves for 0.3 ns, 0.4 ns, and 0.5 ns almost overlap completely, as shown in Fig. 8. So 0.2 ns applied time of microwave field is enough to achieve effective microwave assisted magnetic switching in the conditions for the simulation.

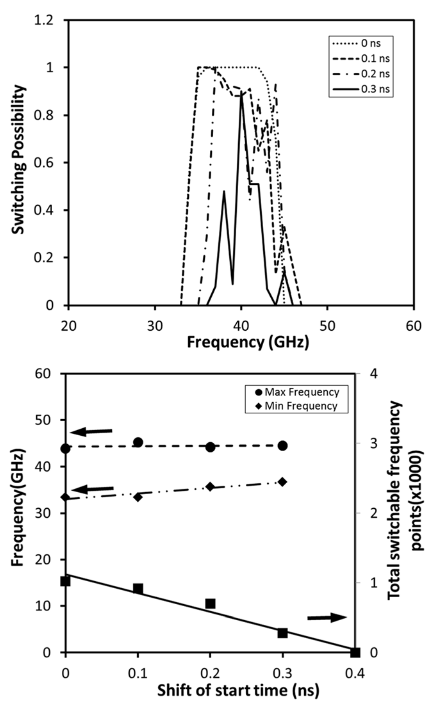

FIG. 7. Effects of shifting of the start time.

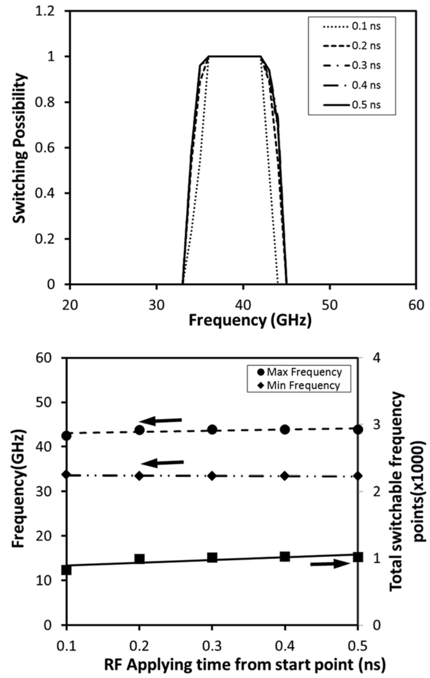

FIG. 8. Effects of shifting of the ending time.

In the analysis above, only one uniform grain is considered in the simulation, but in the real magnetic recording media, there are many grains in one bit and the material in one grain is also not uniform. The interactions between the grains, the non-uniformity, and soft underlayer also affect the magnetic switching in MAMR, the thermal fluctuations are also significant noise sources that cannot be ignored in real applications, and the relative further study will be reported in the future.

In summary, the grain dimension and damping constant distribution cause a slight change in switchable frequency window, while the anisotropy energy density and saturation magnetization variation may mismatch the switchable frequency window, which gives rise to non-switched grains (sources of noise). So it is critical to control the distribution of anisotropy energy density and saturation magnetization variation to reduce the mismatch of frequency to achieve effective magnetic switching. The switchable frequency window increases with the microwave applying time if the microwave duration is shorter than 0.2 ns. Further increase of microwave applying time does not further improve the switchable frequency window significantly, indicating a 0.2 ns microwave applying time is sufficient for the effective magnetic switching of the grain when it starts from time zero in the simulation condition. The results show the microwave does not need to be on all the time, which can reduce the energy consumption of the microwave generator in the magnetic head.

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