THEORY OF MICROWAVE ASSISTED MAGNETIZATION REVERSAL

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I. Background

Microwave assisted magnetization reversal (MAMR) is a method to switch the magnetization direction in nanostructured ferromagnet by applying a direct magnetic field smaller than the anisotropy field of the ferromagnet. The microwave having the frequency close to ferromagnetic resonance (FMR) frequency efficiently excites a large amplitude oscillation of the magnetization around the easy axis, and assists the magnetization switching by a small direct field [1]. A quantitative analysis on a relation between the switching field and microwave frequency has been made by using the Landau-Lifshitz-Gilbert (LLG) equation in a rotating frame [2]. In the rotating frame, the microwave field is converted to a direct field pointing in the switched direction, where the magnitude of this additional field is proportional to the microwave frequency. This additional field in the rotating frame has been considered as an origin of the reduction of the switching field [3]. It should be, however, pointed out that this theoretical view is insufficient to understand the physical mechanisms of MAMR because of the following reason. The numerical simulation of MAMR has clarified that the switching field decreases with increasing the microwave frequency, which is consistent with the physical picture in the previous work. However, when the microwave frequency becomes larger than a certain threshold value, the switching field significantly increases, and the assist effect by the microwave field disappears. The discontinuous change of this switching field with respect to the microwave frequency cannot be explained by the physical mechanism discussed in the previous works, where, since the additional field is proportional to the microwave frequency, the switching field is expected to be decreased monotonically with increasing the microwave frequency. A micromagnetic simulation clarifies that an excitation of spin wave is a possible reason on the discontinuous change of the switching field [4]. It should be, however, mentioned that the jump of the switching field appears even when a macrospin model is used [4].

II. Results in this work

In this work, we present a theory of MAMR based on the macrospin model [5]. We notice that the microwave field in the rotating frame provides not only the direct field but also a torque pointing in the direction of the damping torque. The magnitude of this damping-like torque is also proportional to the microwave frequency. With increasing the microwave frequency, this damping-like torque prevents the switching, resulting in the discontinuous increase of the switching field. Applying the averaging method of the LLG equation on a slowly varying variable, we derived equations determining the switching fields in both low and high frequency regions separated by the threshold frequency [5]. A good agreement between our theory and macrospin simulation guarantees the validity of our study. The result provides a comprehensive picture of MAMR in the macrospin limit.

We also derived the simplified analytical expression of the threshold (critical) frequency in Ref. [6]. In this work, the spin torque switching assisted by microwave was investigated. As pointed out in Ref. [5], the damping-like torque appeared in the rotating frame of MAMR is mathematically similar to the spin torque. This analogy enables us to apply the theory of spin transfer torque switching to the analysis of MAMR. In Ref. [6], we derived the analytical theory of the spin torque switching with microwaves. We notice that the mathematical method developed in Ref. [6] can also be applied to reduce the equations determining the switching field in MAMR. Then, the analytical expression of the critical frequency in MAMR could be

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obtained as [6]

$$f=\frac{\gamma}{2\pi}H_{\mathrm{K}}\frac{\left(H_{\mathrm{ac}}/H_{\mathrm{K}}\right)^{2/3}}{\sqrt{1-\left(H_{\mathrm{ac}}/H_{\mathrm{K}}\right)^{2/3}}}\left[2-\frac{5}{3}\left(H_{\mathrm{ac}}/H_{\mathrm{K}}\right)^{2/3}\right], \tag{1}$$

where γ is the gyromagnetic ratio, whereas H_{K} and H_{ac} are the anisotropy field and the magnitude of the microwave field, respectively (see Eq. (D14) in Ref. [6]). We note that the main work in Ref. [6] is the spin torque switching with microwave, and the derived formula of the critical frequency in MAMR in Ref. [6] is mathematically identical to the equations in Ref. [5], and should be regarded as a simplified equation; that is, Eq. (1) is mathematically identical to Eq. (10) in Ref. [5]. We emphasize that the theory determining the critical frequency of MAMR was originally derived in Ref. [5].

We note that a theoretical analysis similar to our work [5] was independently done by Suto *et al*. simultaneously [7].

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