Two Tone Analysis of Magnesium Oxide Based Magnetic Tunnel Junctions

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Abstract

The magnetic tunnel junction based on magnesium oxide is a device consisting of two ferromagnetic layers separated by the insulating layer of magnesium oxide which has proved to be the foundation of contemporary magnetic read sensors in hard disk drives (HDD). This paper sheds light on the usage of Two-Tone Testing method for the complete treatment of the non-linear impact of sensors related to dynamic ones which is not possible with conventional linear as well as one-tone measurement techniques. Two-tone technique is considered novel, but is challenging in the area of magnetic materials and magnetism because of the device's nature. However, the experimental results demonstrate the usage of "Two-Tone Testing" to characterize the non-linear properties of a magnetic sensor. Addressing non-linear properties of a magnetic sensor helps proper design of magnetic sensors before the production, thereby signifying the importance of this approach.

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1   Introduction

THE growing demand for data storage capacity has resulted in extensive research in this field in the past decade. With the start of commercialization of applications, the idea of Magnetic Tunnel Junction (MTJ) emerged. The high-capacity HDDs require extensive research in this field, which started from the introduction of giant magneto-resistive effects to magnesium oxide MTJs etc. Fast processing of data points and identification of outliers must be clear and precise [1] and MTJ serves this modern requirement very well. MTJ is a device which uses the phenomenon of tunnel magneto-resistance to hold the information for hard disk drives (HDD) and serving the purpose of memory. They are more efficient than the conventional CMOS memories, as they do not require continuous refreshing, thus, reducing the power consumption. A basic structure of MTJ is depicted in Figure 1 which shows its composition consisting of two Ferro-magnetic

layers and a slight Magnesium-Oxide (MgO) barrier which separates them [2].

AlOx and TiOx were also used initially for fabrication of MTJs. One of these layers is an unfastened layer known as Free-Ferromagnetic Layer (FFL), while the other one is known as Reference-Ferromagnetic Layer (RFL). The FFL has the freedom to displace from its position in response to magnetic media field; whereas, the later layer is non-movable. This MTJ device is deployed in Magnetic Read Sensor (MRS) for reference shown in Figure 2(a). The resistivity offered by MTJ is directly proportional to the magnetization directions, i.e., with parallel spins the resistivity is highest and vice versa. Furthermore, the relative orientation of the FFL and RFL is the determinant factor in conductance of the device. The two ferro-magnetic layers are insulated with MgO barrier and due to very small isolation of around $1 \, \eta m$, tunneling is possible which is the cause of current conductivity.

The RFL is often supposed to be affixed to the substrate, as it is mainly immobilized by a finite energy. The thermal variations and room temperature of FFL and RFL could be enumerated through its
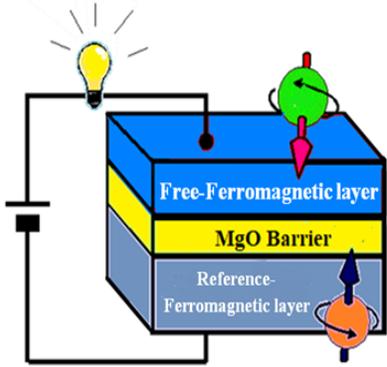
Fig. 1: Basic MTJ structure

Ferromagnetic resonance frequencies (FMR). FFL and RFL possess the normal FMR frequencies at around 7 and 12 GHz respectively [2] (shown in Figure 2(b)). Whilst the oscillations related to FMR are natural to the magnetic read sensors. No technique is evident to measure the contact between the magnetization dynamics and the non-linear aspects of MTJ. This limitation in non-linear characterization is explored here. Oscillations and non-linear behaviors produced at microwave frequency from the magnetization dynamics of MTJ are powerful enough to influence the sensor's overall performance within its operating bandwidth. These non-linear effects of sensors can be characterized by using the static I-V curve measurements. These, un-fortunately, do not represent the magnetization dynamics of MTJ adequately. The two-tone measurement results suggest that such interaction gives rise to dynamic nonlinear effects, which produce the non-linear FFL and RFL coupled modes occurring below the fundamental MTJ frequencies. In magnetic recording, thermal magnetization fluctuations are the major source of magnetic sensors' noise. Thus, these lower-frequency coupled modes may limit the magnetic sensors' signal-to-noise ratio (SNR) [4].

2   Discussion & Testing Mechanism

It has been demonstrated both theoretically and experimentally that I-V MTJ curves display non-linear and asymmetric traits[4]. The MgO-based MTJ possesses two potential contributions of non-linearities, i.e., the spin-dependent static and dynamic effects. Moreover, the defective states also enhance the static effects within the tunnel barrier, whilst the dynamic ones are from dissimilar density of states at the Fermi level for two spin directions.

2.1   One-Tone Measurement

The tunnel magneto-resistance of MTJ is bias dependent, and it reduces with increase in applied DC bias varying from 0 V to 0.4 V [5] which can be observed in Figure 3. The non-linear effects of the MTJ are translated into Magnetic Read Sensors (MRS). The schematics of the MRS is shown in Figure 4. When a basic signal comes in contact with the sensor, it generates higher-order harmonics [6]. The non-linear properties of MTJ can be analyzed by measuring harmonics at a variety of direct current (DC) bias voltage [7].

Using the concept of voltage dependence of MTJ, we studied the relation of input power and 2nd and 3rd harmonic at different applied biases. This is achieved by applying the fundamental frequency f1 at 1 GHz with the help of a signal generator. The chosen fundamental frequency is usually the upper limit of 2.5-inch HDD operating bandwidth. The sensor biasing voltage usually ranges from 100 mV to 150 mV. An alternative current (AC) input power up to -5 dBm can be endured by the sensor. The power excitation can be directly applied using a needle of the Radio Frequency (RF) probe. At signal generator, the input power is depicted in Figure 5. Since there are losses of transmission, the power level is nearly 20dB lesser at the RF probe stage; whereas, at the directional coupler of the coupled port, the power remains at -16 dBm.

In Figure 5, we measured second and third harmonics for different DC biases. The measurement of MgO based MTJ shows the power inclination which fluctuates with application of bias voltage. In case of static non-linearity, the subsequent harmonic power slope will be bias autonomous and assumes an increment by 2 dB/dB power input and 3dB/dB power input for third harmonics. Therefore, it is suggested that dynamic non-linear effects cause the voltage bias dependent slopes of the higher-order harmonics. Furthermore, one-tone is limited in its ability to detect Inter-modulation (IM) effects. Hence, the need for two-tone measurements arises.

2.2   Two-Tone Measurement

The characterization of dynamic non-linear effects, also known as memory effects, can be achieved by using the two-tone testing [9][10]. The availability of these effects in a device can cause the immediate output to rely on immediate input besides the past estimations of both input and output signals. Figure 5 depicts the products of 2nd and 3rd harmonic order Inter-Modulation (IM) and Cross-Modulation (CM) which are produced by applying the two-tone test-
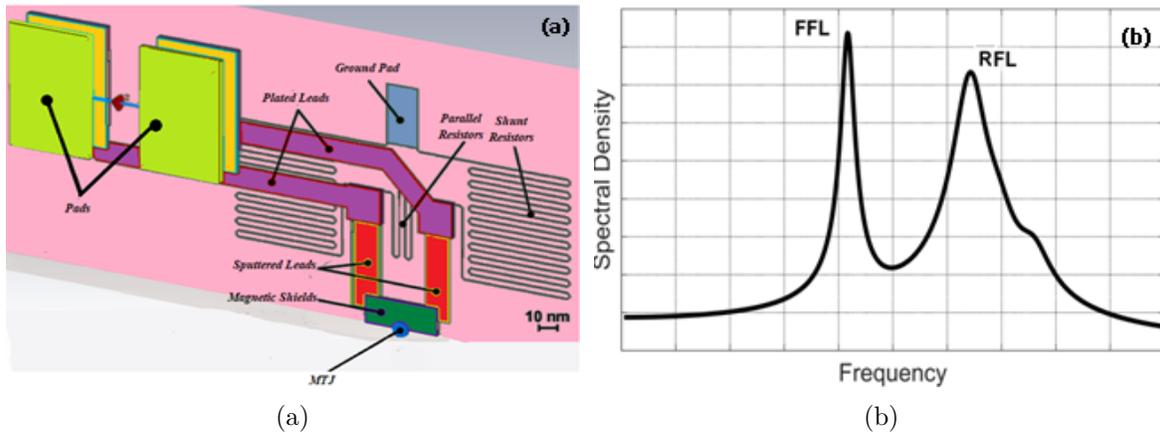
Fig. 2: (a) Magnetic read sensor, (b) the magnetized fluctuations shown in power spectrum
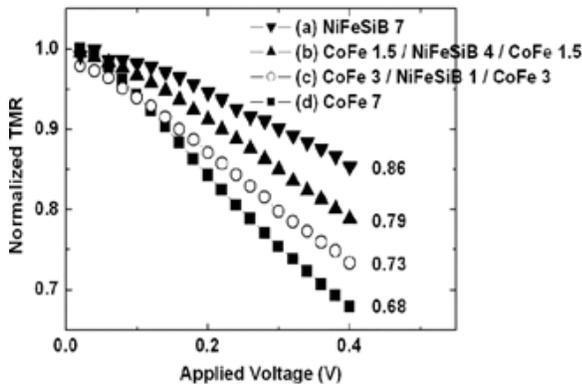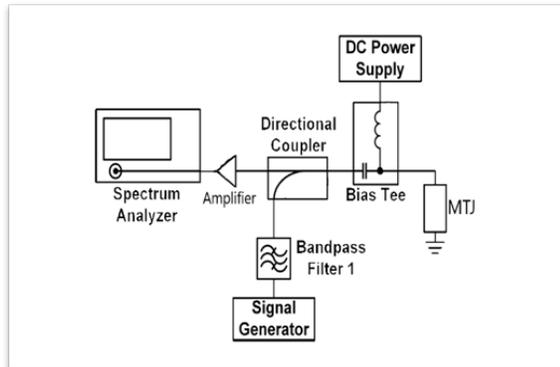

Fig. 3: Effect of voltage variation on TMR [4]

Fig. 4: One-tone measurement system for non-linearity measurement of MRS

ing on a non-linear device. Most interesting results relate to third order's lower and upper IM outcomes $(2\omega1–\omega2)$ and $(2\omega2–\omega1)$, as they generate signal segments in proximity of the excitation frequencies. If static non-linearity occurs, the amplitudes of these results are symmetrical and independent of harmonic spacing (Δf).

3   The Device Model

Figure 6 demonstrates the sensor circuit comprising of the MTJ sensor, parallel resistor R2, shunt resistors R1 and R2, and shield capacitance C. The magnetic sensors currently hold resistance between 200 and 2000 ohm. This variance is resistance of MTJ can be mitigated using the parallel resistor. These resistors deem to offer electrostatic discharge protection; whereas, shield size is used to control the amount of capacitance which can affect the nearby bits of the memory.

The Hammerstein-Wiener model takes into account the non-linear properties of MTJ and dynamic effects [11][12]. This model represents a series arrangement of dynamic non-linear effects as input/output static and dynamic blocks (see Figure 7(b)). Dynamic effects unable to be depicted by the consistent state transfer mechanism proposed by device physics incorporates the filtering impacts (low-pass filter arising from sensor identical circuit) and the magnetization dynamics (FFL/RFL's magnetization procession).

4   Results

Firstly, we recognized the FFL focal frequency at 6.2 GHz utilizing the traditional thermal noise FMR or T-FMR testing method [13]. Secondly, the results show the upper and lower 3rd order inter-modulation (undetected by one-tone measurement) with the help of spectrum analyzer. To calculate the results, harmonic spacing was varied from 104 Hz to 109 Hz and these results are shown in Figure 8. After the application of two-tones, the higher order IM and CM are generated which are significant because they are in the vicinity of the excitation signal.

The two-tone testing was executed at the bias voltage of +150 mV DC inclination and both signal generators supplied the AC power of 0 dBm. The inverse time
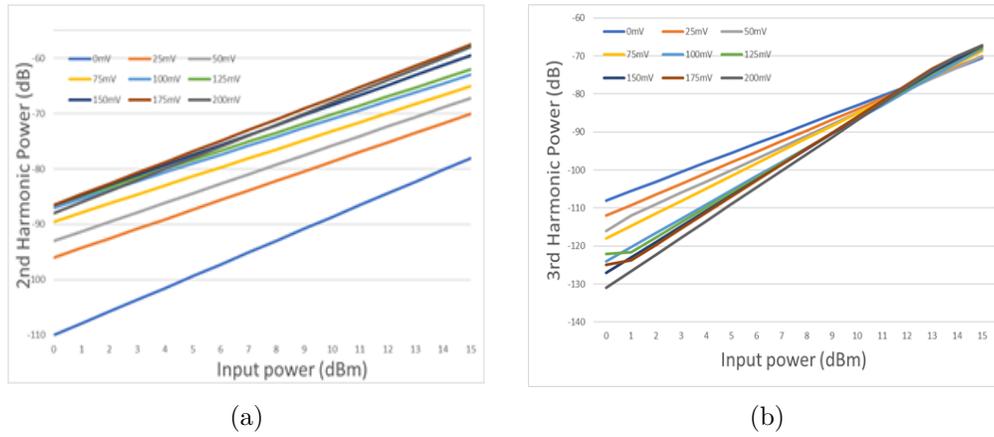
(a)   (b)

Fig. 5: MRS DC-dependence slope; (a) 2nd Harmonics, (b) 3rd Har-monics

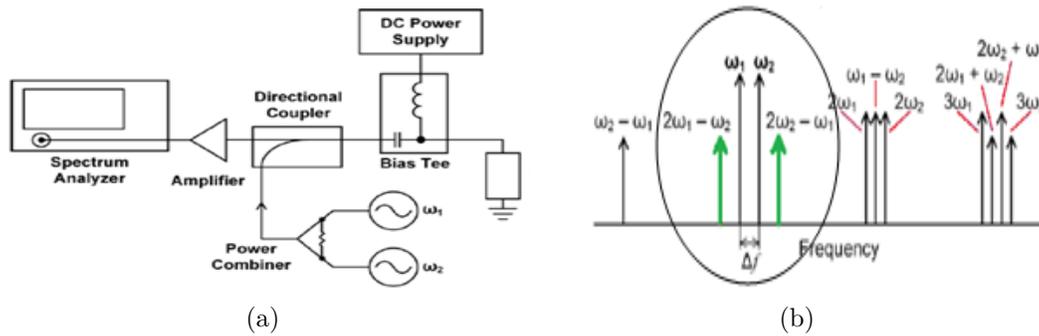(a)   (b)

Fig. 6: (a)Two-Tone measurement system for Non-linearity measurement of MRS (b) Generated IM and CM products by implementing two-tone system
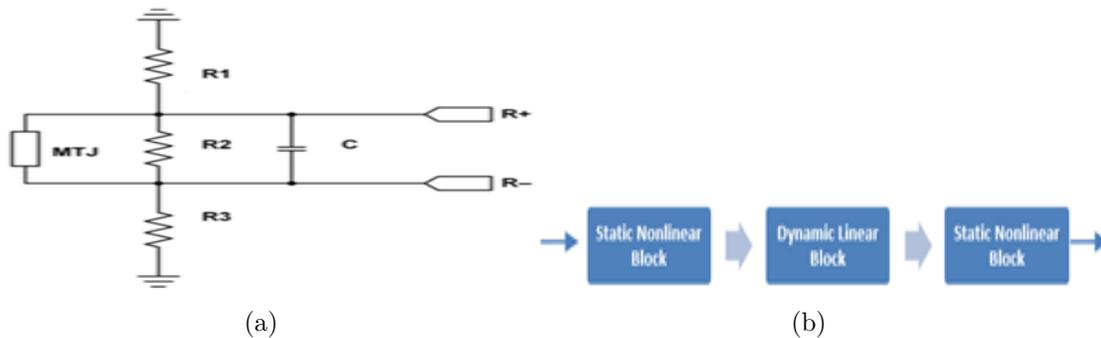

(a)   (b)

Fig. 7: (a) Equivalent circuit of MRS, (b) non-linear model of MRS

constants of dynamic effects in the device are proposed by the leading derivatives of its products at 90 kHz and 4.7 MHz.

At fixed harmonics spacing Δf, the stated values can be utilized for a complete frequency variation. Figure 8 shows a frequency variation executed at harmonics spacing of 90kHz associating the analysis of dynamic non-linear impact on MgO based MTJ concerning lower frequency FMR modes attached to FFL/RFL's frequencie.

5   Conclusion

Initially, the observations on MgO-based MTJs bias-dependent power slopes were made in Figure 5. It appears that in the complete analysis of MTJ devices, non-linear properties and dynamic effects should be considered. Whilst the presence of dynamic effects is only proposed by the independent biasing slopes of the higher-order harmonics; whereas, two-tone testing provides the results which links the analysis to lower frequency modes (FFL and RFL). It can be concluded that using the two-tone measurement technique, we
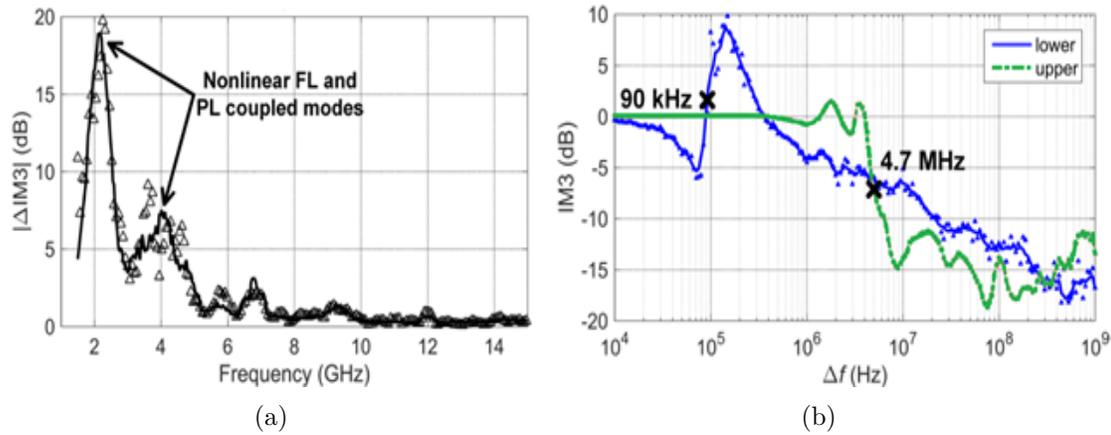
Fig. 8: (a) Two-tone measurements outcome, (b) difference of lower and upper IM3 against the complete frequency sweep at fixed Δf

can distinguish the unaccounted non-linear effects on the MTJ device which was very hard to observe with the conventional characterization techniques (one-tone measurement system)

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