Extraction of the tunnel magnetocapacitance with two-terminal measurements

Yin-Ming Chang,[1] Kai-Shin Li,[1] Hongbo Huang,[2] Mean-Jue Tung,[3] Shi-Yuan Tong,[3] and Minn-Tsong Lin[4,a)]
[1]*Department of Physics, National Taiwan University, 106 Taipei, Taiwan*
[2]*Department of Physics, National Taiwan University, 106 Taipei, Taiwan and Department of Physics, Nanjing University, Nanjing, China*
[3]*Material and Chemical Research Laboratories, Industrial Technology Research Institute, 310 Hsinchu, Taiwan*
[4]*Department of Physics, National Taiwan University, 106 Taipei, Taiwan and Institute of Atomic and Molecular Sciences, Academia Sinica, 106 Taipei, Taiwan*

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The tunnel magnetocapacitance (TMC) of the magnetic tunnel junction has been investigated with a series of complex impedance spectra measured at varying magnetic field. To avoid the circuit complication in the four-terminal measurement with high frequency operation, two-terminal approach was developed by elimination of spin independent contribution apart from the junction area. A subsequent fitting process based on the difference spectra analysis gave the TMC ratio of −0.43% with the opposite dependence on the field as compared to the tunnel magnetoresistance (TMR) of 30.67%. This technique would be applied in the further development and integration of spintronics devices. © *2010 American Institute of Physics*. [doi:10.1063/1.3407509]

I. INTRODUCTION

Magnetic tunneling junction (MTJ), which presents resistance contrast with respect to the magnetization configurations, is known to be the essential building block of spintronics devices with the applications for magnetic sensors and nonvolatile memory. Moreover, it is interesting that not only the junction resistance but also the junction capacitance may change under the variation in magnetic field.[1,2] Since the performance of a MTJ at high sensing frequency is much related to its dielectric properties,[3] this deviation of the junction capacitance from the geometry capacitance has become a matter of importance. However, there exists no conclusive explanation till now to the physical origin of the so called TMC effect. For instance, the magnetic field dependence of the junction capacitance has a reverse trend as compared with the junction resistance,[1,2] and this is in contrast with Kim's calculation where the magnetocapacitance (MC) depends linearly on the magnetic field.[4] Moreover, the derivation of junction capacitance with the real part and the imaginary part of the complex impedance cannot provide the explicit dependence on the junction resistance.[1] And the voltage effect concerning the spin dependent surface screening has not included the magnetization configuration of ferromagnetic layers in a MTJ.[5,6]

While the understanding on the physical origin of the TMC effect remains controversial, the success of the theoretical interpretation must be preconditioned by a proper determination of the TMC ratio in the experiment. In the previous studies of the TMC effect,[1,2] the junction capacitance has been evaluated in the framework of equivalent circuit analysis with four-terminal complex impedance measurements. Aside from their conclusion of the TMC effect, meanwhile, the deduced TMR (so that the tunnel resistance) are found to change with respect to the test frequency. It is then interesting to consider if the tunnel resistance can have significant changes with the alternative current (ac) source of the test frequency below megahertz, which may be regarded as static while considering the instant traversal time of the tunneling process.[7] So the variation in TMR with respect to the test frequency might be an indication of the need in improving the experiment setup and/or analysis technique. In this letter, to avoid circuit complication in four-terminal measurement, the complex impedance spectra have been measured with a two-terminal approach. With help of an auxiliary fitting process, a TMC with the value of −0.43% in a MTJ junction of 30.67% TMR ratio has been extracted by subtraction of spin-independent parts in the spectrum.

II. EXPERIMENT

Magnetic tunnel junctions of layered structure CoFe(30)/Al_2O_3(3)/CoFe(15)/NiFe(10) (in nanometer), whose tunnel resistivity is about 100 MΩ μm^2, were prepared in a magnetron sputtering system of 5×10^{-8} mbar base pressure. All layers were patterned with *in situ* replacement of shadow masks in order to keep the interface intact,[8] and the junction area is defined by the intersection of the two ferromagnetic layers which are 2500 μm in length and 150 μm in width, respectively. The acquisition of complex impedances spectra up to 1 MHz were carried out by Agilent 4294A precision impedance analyzer. And the subsequent fitting process for the equivalent circuit analysis is based on the Levenberg–Marquardt algorithm.[9]

Because of the presence of tunneling current in the parallel-plated structure, the operation of a MTJ can be realized to be a leaking capacitance. And the equivalent circuit is

[a)]Author to whom correspondence should be addressed. Electronic mail: mtlin@phys.ntu.edu.tw.

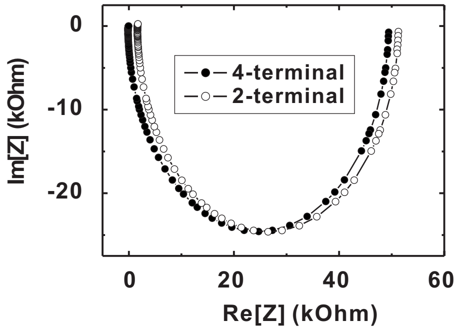

FIG. 1. The impedance spectra of an MTJ shown in Cole–Cole plots. The measurement results of four-terminal (solid circle) and two-terminal (open circle) connection have been shown, respectively. The frequency ranges from 40 Hz to 1 MHz, whereas the real part for the four-terminal measurement becomes negative around 35 kHz.

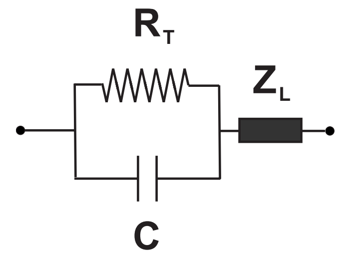

FIG. 2. The schematic illustration for the equivalent circuit of a MTJ with reference to two-terminal measurements. The MTJ has been represented by the parallel connection of tunnel resistance R_T and junction capacitance C whereas Z_L denotes the spin independent contribution apart from the junction area.

usually modeled by the parallel connection of the tunnel resistance and the junction capacitance. The measurements of complex impedance, therefore, aid to reveal the corresponding components. In the technical point of view, however, the phase angle in the four-terminal impedance measurements may be substantially affected by those apart from the junction area, such as the extension of ferromagnetic layers in a cross-striped tunnel junction. This is attributed to the fact that the current and potential probes are situated on the opposite ends of the electrodes, and the resistance of electrodes together with the test lead capacitance comprise a low pass filter which results in the phase detection error at rising frequency,[10] leading to the uncertainty of four-terminal measurements.

III. RESULT AND ANALYSIS

To explicitly illustrate this point, the four-terminal impedance spectrum together with the two-terminal one have been taken for a MTJ. As shown in Fig. 1, their complex impedance spectra from 40 Hz to 1 MHz are presented for the parallel magnetization state of the MTJ. As also mentioned in Refs. 1 and 2, the semicircle curves reveal the typical feature of a capacitive device. It should also be noted that the four-terminal spectrum is not a result of shifting the two-terminal one in the real part, which means the simply inclusion of electrode resistance does not suffice to explain their difference. On the other hand, the negative real part is only observed in the four-terminal measurement as the frequency is higher than 35 kHz. If one decomposes the complex impedance of a parallel resistance-capacitance system, the real part R and the imaginary part X are, respectively, expressed as,

$$R = \frac{R_T}{1 + 4\pi^2 f^2 R_T^2 C^2}, \tag{1}$$

$$X = \frac{-2\pi f C R_T^2}{1 + 4\pi^2 f^2 R_T^2 C^2}, \tag{2}$$

where R_T, C, and f stand for the tunnel resistance, junction capacitance, and test frequency, respectively. Since, the sign of the real part follows that of the junction resistance, the results in Fig. 1 lead to a negative junction resistance, which is not physically meaningful. In order to prevent from such kind of problem resulted from circuit complication in the high frequency operation with the four-terminal measurement, two-terminal connection has been applied to the measurements of complex impedance in the study on TMC effect. A fitting process with subtraction of two spectra is proceeded to eliminate the spin-independent contribution of the electrodes and to uncover the spin-related part of the junction capacitance. Furthermore, the analysis technique will be justified by the comparison between the output of the fitting process and the result of direct current (dc) measurements concerning the junction resistance.

As shown in Fig. 2, the parallel resistance-capacitance description of the system is modified in accordance with the change to two-terminal setup. A serial connection of Z_L has been included to account for the spin independent impedance contribution apart from the junction area. Because the details of Z_L are not relevant to our interests in the TMC effect, the exclusion of Z_L is to be accomplished by the subtraction of two impedance spectra which have been recorded at different magnetic field. The difference of their imaginary parts can thus be expressed as,

$$\Delta X = -2\pi f \left(\frac{C_H R_H^2}{1 + 4\pi^2 f^2 R_H^2 C_H^2} - \frac{C_r R_r^2}{1 + 4\pi^2 f^2 R_r^2 C_r^2} \right) \tag{3}$$

where the subscripts "H" refers to the magnetic field at which the corresponding impedance spectra is measured. Besides, "r" is used to specify the reference impedance spectrum which will later be associated with the one measured at 500 Oe. As a result, C_H, R_H, C_r, and R_r are four parameters left to be determined in the fitting process. In order to work out the over-parametered issue, in which the output of the fitting process can be influenced by the selection of the initial values on fitting parameters, the number of fitting parameters is going to be reduced. So, prior to completing the MC (magnetoresistance) loop by the determination of C_H (R_H) under the varying magnetic field, the degree of freedom on R_r is removed by giving it the dc-measured junction resistance at 500 Oe. A subsequent determination of C_r can be made by the curve fitting with reference to Eq. (3) where C_H, R_H, and C_r are the remaining parameters.

As shown in Fig. 3(a), the imaginary parts of the impedance spectra are corresponding to the measurements at 500 and 79 Oe (for the increasing field branch), respectively. The spin dependent characters can be easily distinguished, and

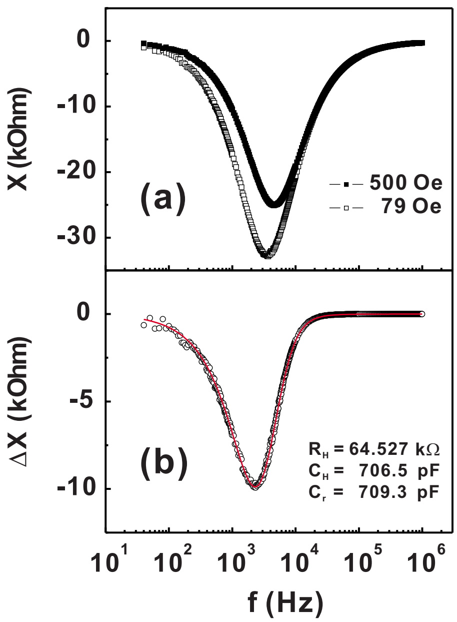

FIG. 3. (Color online) (a) The imaginary part of the impedance spectra which are measured at 500 Oe (solid squares) and 79 Oe (open squares), respectively. (b) The data points (open circles) and the fitting curve (solid line) corresponding to Eq. (3). The output of the fitting parameters are noted as well.

the difference on the frequency where the dips present is mainly attributed to the difference of junction resistance in the neighborhood of parallel and antiparallel magnetization states. On the other hand, the difference spectra of those have also been demonstrated in Fig. 3(b). Based on the aforementioned steps, the outputting values of the fitting parameters together with the resulting curve are presented in Fig. 3(b) as well. The derivation of the curve can be achieved by simply expressing the ΔX in Eq. (3) as a function of frequency since the values of C_H, R_H, C_r, and R_r have been given by the fitting output. It can be seen that the fitting curve has well reproduced the data points.

Therefore, the rest of the labor is nothing but figuring out C_H and R_H under the variation in magnetic field by repeating the kind of two-parametered fittings since the values of C_r and R_r have previously been located. An overview on a series of output for the MC and magnetoresistance loops has been shown in Figs. 4(a) and 4(b), respectively. For the ease of comparison, the trace of the dc magnetoresistance loop is also presented and notified by the dashed line in Fig. 4(b). It can be seen that the fitting results and the dc measurements are in good agreement which indicates the fitting process is well qualified. On the other hand, the capacitance part has the larger values at the higher field, reaching the local minimum as the field sweeps to −41 Oe and rising to the high level again at −500 Oe. The overall loop is approximately symmetric for the decreasing and increasing field branches, resulting in a TMC ratio of −0.43%. Indeed, the TMC effect has a reversed behavior as compared to the TMR effect.

IV. DISCUSSION

Moreover, as mentioned above, the reference impedance spectrum is preset to that with magnetic field of 500 Oe. One

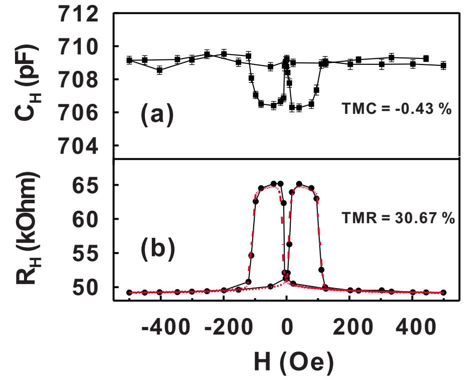

FIG. 4. (Color online) The overview of fitting results concerning (a) the TMC loop (solid square) and (b) the tunnel magnetoresistance loop (solid circle) under varying magnetic field. The tunnel magnetoresistance effect characterized with dc source is denoted by the dashed line for comparison.

may like to refer other field magnitudes to the reference spectrum or alternatively apply the real part for the fitting process, nevertheless, the results remain consistent. Besides, the value of the capacitance in another testing circuit, where a capacitor is connected parallel with selectable resistors, has been resolved with accuracy better than 0.1% (not shown). As compared with the works which have applied four-terminal measurements,[1,2] the issue of phase detection error has been taken care, the changes in TMR ratio with frequency is removed with self-consistency, and the agreement between ac and dc measured TMR has further supported the analysis technique in our studies.

The intrinsic value of $R_T C$, which is independent of the cell size, is known to be an important parameter to estimate the read access time in the memory application of MTJ.[3] This in turn makes the proper evaluation the junction capacitance important in the practical circuit design, otherwise the device operation near gigahertz could be unexpected. In the fundamental point of view, it should be emphasized that in Refs. 2 and 5 the charge accumulation at the interface is thought independent of the conduction process. As a contrast, we like to point out the important roll of the spin polarized tunneling current which passes the magnetization information in ferromagnetic layers through the Al_2O_3 layer. As a result, the spin dependent band filling could be the potential explanation to the correlation between junction capacitance and magnetization states in a MTJ. In other words, the junction resistance and the junction capacitance have coupled to each other through the spin polarized tunneling current, and the spin dependent charge accumulation at the ferromagnet-insulator interface further modifies the value of geometry capacitance.

V. SUMMARY

In summary, we have demonstrated a practical approach for the characterization of TMC effect. By the analysis on the difference of impedance spectra, TMC ratio of −0.43% in an Al_2O_3-based MTJ with 30.67% TMR ratio has been extracted. And the reliability of fitting process has been verified by showing the agreement between the fitting results and the dc measurements for the TMR effect. This analysis technique is essential in one's attempt to study the TMC effect and further incorporate it in the spintronics devices.

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