Oscillating Voltage Dependence of High-Frequency Impedance in Magnetic Tunneling Junctions

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Oscillating voltage ($\mathrm{V_{Os}}$), which depends on the frequency dependence of the magnetoimpedance (MI) effect, was applied to study a magnetic tunneling junction (MTJ) of Ru(5 nm)/Cu(10 nm)/Ru(5 nm)/IrMn(10 nm)/CoFeB(4 nm)/$\mathrm{Al_2\ O_3}$/CoFeB(4 nm)/Ru(5 nm) at frequencies up to 40 MHz. The MI ratio decreased as the $\mathrm{V_{Os}}$ was increased. The MI ratio turned from positive to negative at a certain frequency. An equivalent circuit model was employed to analyze the results. The fact that MTJ can be regarded as the composition of a resistance component and two sets of parallel resistance (R) and capacitance (C) components in series has been utilized to describe the individual impedance contribution from the lead of cross pattern, barrier, and interface. The resistance ($\mathrm{R_{barrier}}$) and capacitance ($\mathrm{C_{barrier}}$) of the barrier effect are functions of $\mathrm{V_{Os}}$. The $\mathrm{R_{barrier}}$ decreases as the $\mathrm{V_{Os}}$ increases, However, $\mathrm{C_{barrier}}$ behaves the opposite way. The tendency is for interfacial resistance $\mathrm{R_{interface}}$ and interfacial capacitance $\mathrm{C_{interface}}$ to have opposite results with increasing $\mathrm{V_{Os}}$. This work provides a detailed investigation of high-frequency transport behavior subjected to $\mathrm{V_{Os}}$, especially useful for MTJ characterization.

***Index Terms*—Magnetic tunneling junctions (MTJs), oscillating voltage.**

I. INTRODUCTION

THE magnetic tunnel junction (MTJ) is an excellent system for investing the spin-polarized electron coherent tunneling effect, and both theoretical and experimental studies on the MTJ are interesting topics of current research [1], [2]. However, studies of magnetoimpedance at high frequencies with varied $\mathrm{V_{Os}}$ on MTJs have not yet drawn much attention. The effects are due to the barrier, interface, magnetic coupling, etc; however, it has been found that MI is quite a suitable method for the nondestructive analysis of an MTJ [3]–[5]. Intriguingly, inverse behavior in both dc [1], [6] and ac [3] has been observed on an MTJ structure, showing not only the inverse behavior in MR, but also in MI, exhibiting inverse behavior, and the impedance [3] has been reported in an MTJ structure, but the most research on the hysteresis properties of MTJ focuses on dc measurement and a low-frequency ac measurement, which shows low resistance in the parallel state and high resistance in the antiparallel state. In this study, the frequency was increased to 40 MHz, and the magnetoimpedance $\mathrm{MI = M|Z|e^{i\theta} = MR + iMX}$ in which $\mathrm{X = X_L - X_C}$ [7], [8] of an MTJ device was studied.

As usual, the MI ratio is defined as $100\ \% \times (|\mathrm{MI}|_{\mathrm{AP}} - |\mathrm{MI}|_{\mathrm{P}})/|\mathrm{MI}|_{\mathrm{P}}$, where the subscript P (AP) stands for the parallel (antiparallel) magnetization orientation state of the MTJ. In fact, the whole system contains nonignorable parasitic inductance and capacitance from wires, and these terms have the effect on the shift of resonant frequency. However, these sensing wires do not have any contribution to the magnetoimpedance effect, and cannot prevent us from analyzing the general magnetoimpedance effect phenomena.

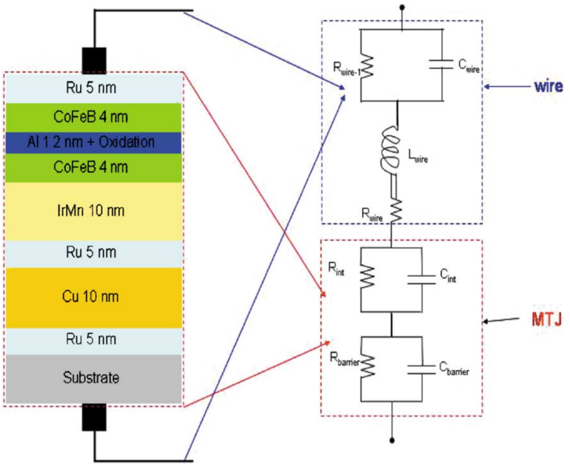

Fig. 1. Structure of the magnetic tunneling junctions is Ru (5 nm)/Cu (10 nm)/Ru(5 nm)/IrMn(10 nm)/CoFeB(4 nm)/Al(1.2 nm)-oxide/CoFeB (4 nm)/ Ru (5 nm) and equivalent circuit with contributions from magneto tunneling junctions.

II. EXPERIMENT

The MTJ structures of Ru(5)/Cu(10)/Ru(5)/IrMn(10)/CoFeB(4)/Al (1.2)-oxide/CoFeB(4)/Ru(5) with DC–MR of 14.3% were deposited on Si/SiO wafers using the magnetron sputtering system, where all thicknesses are given in nanometers, with the junction area 6 × 6 μm as shown in Fig. 1. The ac behavior was determined by using the HP4194 impedance analyzer with the 16047D fixture. A two-point contact was used in a frequency range from 100 Hz to 40 MHz with a varied $\mathrm{V_{Os}}$ of ±0.1 V to ±0.6 V, together with an electromagnet which supplied a dc field up to ±500 Oe.

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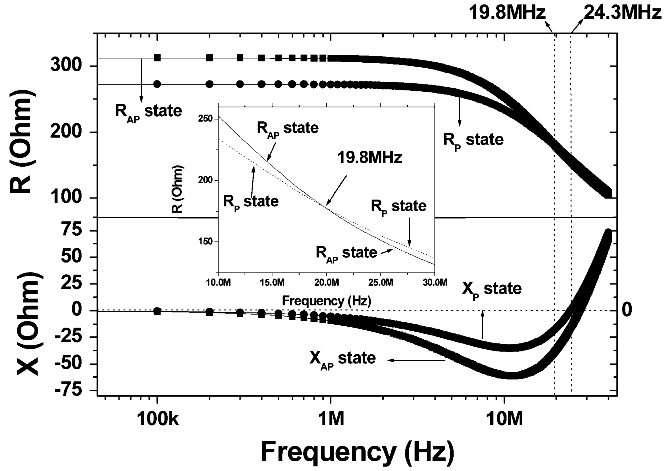

Fig. 2. Frequency dependences of the real part of the impedance (R) and the imaginary part of the impedance (X) for the magneto tunneling junctions in the parallel or antiparallel states. The inset panel shows the crossover frequency of the real part of the impedance, which indicates that the magnetic behavior of MTJ is changed by the driving frequency.

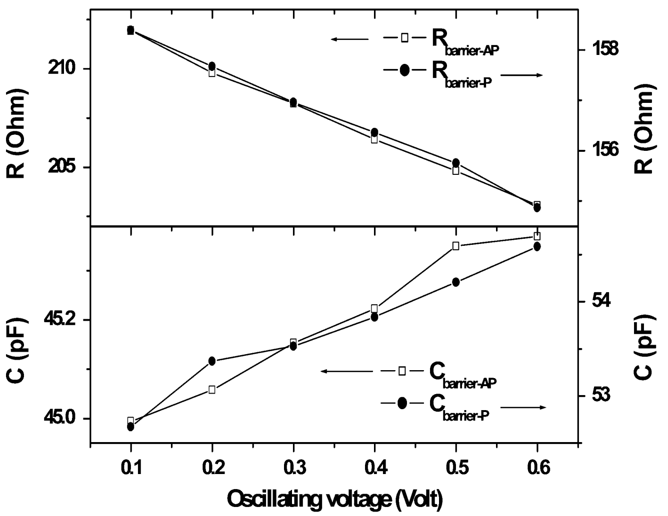

Fig. 3. Resistance and capacitance reduced by the barrier effect at parallel and antiparallel states are functions of the oscillating voltage.

III. Results and Discussions

Fig. 2 shows the frequency dependence of the real part of impedance $(\mathrm{R_{AP}}, \mathrm{R_P})$ and the imaginary part of impedance $(\mathrm{X_{AP}}, \mathrm{X_P})$ for the MTJ in the parallel and antiparallel states. The $\mathrm{R_{AP}}$ and R_P curves decrease with increasing frequency, which indicates that the MTJ includes a significant capacitance effect. The metal/oxide/metal-like structure of MTJ could be analyzed by the Maxwell–Wagner (M–W) model [7] which states the equivalent circuit (EC) of the metal/insulator/metal-type device. The EC consists of two parts—the MTJ and the sensing circuit as sketched in Fig. 1. In the MTJ part, the circuit contains not only the resistance $(\mathrm{R_{barrier}})$ and capacitance $(\mathrm{C_{barrier}})$ from the barrier but also $\mathrm{R_{int}}$ and $\mathrm{C_{int}}$ from the interface, respectively. In the other part, the circuit consists of a resistor, a capacitor, and an ignorable inductor. However, this part does not respond to the variation of the magnetic field. According to the EC theory, $\mathrm{Z} = R_{\mathrm{eff}} + iX_{\mathrm{eff}}$ can be expressed as follows:

$$\begin{aligned} R_{\mathrm{eff}} = {} & \mathrm{R_{barrier}} / \left\{ \left[1 + (2\pi f \mathrm{C_{barrier}} \mathrm{R_{barrier}})^2\right] \right\} \\ & + \mathrm{R_{int}} / \left\{ \left[1 + (2\pi f \mathrm{C_{int}} \mathrm{R_{int}})^2\right] \right\} \\ & + \mathrm{R_{wire}} + \mathrm{R_{wire-1}} / \left\{ \left[1 + (2\pi f \mathrm{C_{wire}} \mathrm{R_{wire-1}})^2\right] \right\} \end{aligned} \tag{1}$$

$$\begin{aligned} X_{\mathrm{eff}} = {} & 2\pi f \left\{ L_{\mathrm{wire}} - \mathrm{C_{barrier}}\ \mathrm{R^2_{barrier}} / \right. \\ & [1 + (2\pi f \mathrm{C_{barrier}} \mathrm{R_{barrier}})^2] \\ & - \mathrm{C_{int}} \mathrm{R^2_{int}} / [1 + (2\pi f \mathrm{C_{int}} \mathrm{R_{int}})^2] \\ & \left. - \mathrm{C_{wire}} \mathrm{R^2_{wire-1}} / [1 + (2\pi f \mathrm{C_{wire}} \mathrm{R_{wire-1}})^2] \right\}. \end{aligned} \tag{2}$$

The solid line sketched by the equations as a function of frequency is displayed in Fig. 2, which shows good agreement with the experimental results (dot). The simulated values of $\mathrm{R_{barrier}}, \mathrm{R_{int}}, \mathrm{C_{barrier}}$, and $\mathrm{C_{int}}$ in the parallel state are found to be 158.39 Ω, 80.86 Ω, 52.76 pF, and 39.28 pF, respectively, and those of $\mathrm{R_{barrier}}, \mathrm{R_{int}}, \mathrm{C_{barrier}}$, and $\mathrm{C_{int}}$ in the antiparallel state are 211.94 Ω, 67.29 Ω, 44.99 pF, and 46.89 pF, respectively. On closer inspection of the real part of the impedance value at the crossover frequency of 19.8 MHz, as shown in the inset panel, it emerges that the real part of the impedance in the parallel state is equal to that in the antiparallel state, and after the crossover frequency 19.8 MHz, the real part of the impedance in the parallel state is larger than that in the antiparallel state. This is due to the different resistance and capacitance of the MTJ in the parallel and antiparallel states. Therefore, with ac current in MTJ, the magnetic behavior can be switched by the driving frequency.

The imaginary part of the impedance of the MTJ in the parallel state $\mathrm{X_P}$ is vanished at a resonance frequency of 24.3 MHz. This means that there is no reactance effect at the resonance frequency in the parallel state, but the reactance effect in the antiparallel state still exists. According to the reactance ratio calculation, it must have a high ratio at 24.3 MHz [3].

Fig. 3 shows the resistance and capacitance reduced by the barrier effect at parallel and antiparallel states are functions of the $\mathrm{V_{Os}}$. Obviously, the trends of the $\mathrm{R_{barrier}}$ or $\mathrm{C_{barrier}}$ at parallel and antiparallel states are the same. However, the $\mathrm{R_{barrier}}$ decreases as the $\mathrm{V_{Os}}$ increases and $\mathrm{C_{barrier}}$ increases as the $\mathrm{V_{Os}}$ increases. With the $\mathrm{V_{Os}}$ increasing, it causes the electrons to obtain higher energy over the barrier potential. Therefore, the $\mathrm{R_{barrier}}$ decreases as the $\mathrm{V_{Os}}$ increases. The capacitance $\mathrm{C_{barrier}}$ is inverse proportional to the effective thickness of the barrier which is thin as $\mathrm{R_{barrier}}$ is small. Therefore, the $\mathrm{R_{barrier}}$ and $\mathrm{C_{barrier}}$ have opposite results with increasing $\mathrm{V_{Os}}$.

Fig. 4 shows the resistance and capacitance reduced by the interface effect at parallel and antiparallel states to be functions of the $\mathrm{V_{Os}}$. The trends of the $\mathrm{R_{int}}$ or $\mathrm{C_{int}}$ at parallel and antiparallel states are similar as Fig. 3. But the $\mathrm{R_{int}}$ increases as the $\mathrm{V_{Os}}$ increases and $\mathrm{C_{int}}$ decreases as the $\mathrm{V_{Os}}$ increases that the result is opposite that of the barrier effect. The disorder and defects on the interface between metal and insulator are known with the ability to trap electrons. As $\mathrm{V_{Os}}$ increases, the electrons become hard-trapped such that the capacitance effect of the interface part will decrease with the $\mathrm{V_{Os}}$ increasing. According

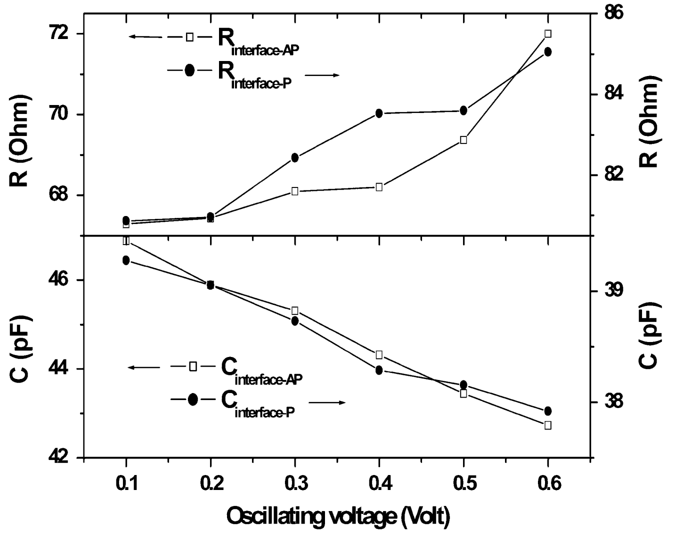

Fig. 4. Resistance and capacitance reduced by the interface effect at parallel and antiparallel states are functions of the oscillating voltage.

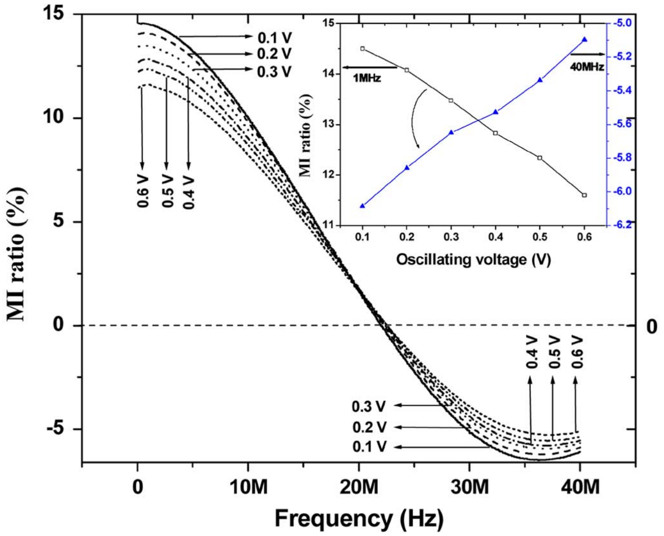

Fig. 5. MI ratio of the MTJ with different oscillating voltage ranging from 100 Hz to 40 MHz. The inset panel shows the MI ratio at 1 MHz and 40 MHz.

to the capacitance is inverse proportion to the resistance, the decrease of the capacitance of the interface leads to the increase of resistance of interface.

Fig. 5 shows the frequency dependence of the MI ratio of the MTJ with different $\mathrm{V_{Os}}$: 0.1 V, 0.2 V, 0.3 V, 0.4 V, 0.5 V, and 0.6 V. At lower frequencies (below 22 MHz), the MI ratio decreased gradually with increasing $\mathrm{V_{Os}}$ as shown in the inset panel in Fig. 5. This result accords with the general cognition that the TMR ratio, which is usually measured with the dc circuit, will decrease with dc bias increasing. As a disorder or defects in the tunnel barrier are known to increase, the $\mathrm{V_{Os}}$ dependence through increased contribution from the spin-independent parts of the two-step tunneling or other spin flip processes [9]. This effect can explain that the increase of VOs reduced the MI ratio. When the frequency is more than 22 MHz (f_z), the MI ratio becomes negative from positive, which implied that the MI loop is reversed [3]. At a higher frequency (over the f_z), the MI ratio increased gradually with increasing $\mathrm{V_{Os}}$ as shown in the inset panel in Fig. 5. This is due to the fact that the MI ratio is negative [3]. If using the absolute value of the MI ratio at high frequency, the result is the same as that in previous discussions.

IV. CONCLUSION

In summary, the $\mathrm{V_{Os}}$, which is dependent of the magnetoimpedance effect of the MTJ, has been studied. The MTJ can be regarded as a combination of resistances $(\mathrm{R_{barrier}}, \mathrm{R_{int}}, \mathrm{R_{wire}}, \mathrm{R_{wire-1}})$, inductances $(\mathrm{L_{wire}})$ and capacitances $(\mathrm{C_{barrier}}, \mathrm{C_{int}}, \mathrm{C_{wire}})$, and equivalent circuit theory can be used to analyze the barrier and interface behaviors of this system. We find that the $\mathrm{V_{Os}}$ (ac bias) behavior of the MTJ is similar to that of dc bias. The MI ratio decreases as $\mathrm{V_{Os}}$ increases. However, it is very interesting to find that the MI ratio becomes negative at a higher frequency. Consequently, our study is useful for MTJ characterization research and for MRAM fabrication.

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