AIP | Journal of Applied Physics

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Citation: Journal of Applied Physics **99**, 08H710 (2006); doi: 10.1063/1.2177125
View online: http://dx.doi.org/10.1063/1.2177125
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/99/8?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **99**, 08H710 (2006)

Impedance behavior of spin-valve transistor

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(Presented on 1 November 2005; published online 28 April 2006; publisher error corrected 3 May 2006)

The magnetoimpedance (MZ) effect of the pseudo-spin-valve transistor (PSVT) was investigated at room temperature in the frequency ranged from 100 Hz to 15 MHz. The PSVT can be regarded as a complex combination of resistors, inductors, and capacitors, while the impedance (Z) consists of a real part, the resistance (R), and an imaginary part, the reactance (X). Besides, all these components exhibit magnetic hysteresis. It is due to the frequency dependent behavior that R does not reach a minimum at the resonant frequency (f_r). The frequency dependences of MZ and MX ratios cross zero at $f_x=6.5$ MHz and at $f_r=3.65$ MHz, respectively. The shape of magnetoreactance (MX) loop is reverse to the magnetoresistance (MR) loop; furthermore, MX ratio changes sign from negative at $f<f_r$ to positive at $f>f_r$. The MZ loop also reverses shape and sign after crossing f_x. For instance, the MZ loop with a ratio of 0.077% at 6 MHz switches to −0.086% and −0.125% at 7 and 8 MHz, respectively. © *2006 American Institute of Physics*.

[DOI: 10.1063/1.2177125]

INTRODUCTION

Since the discovery of giant magnetoresistance (GMR) effect in magnetic multilayer,[1] spintronics is regarded as one of the highly important technologies in this century due to its potential applications in memory, pickup head, and storage industries. Recently, a fundamental device of spintronics named spin transistor has been studied extensively.[2–6] However, the studies of impedance ($Z=|Z|e^{i\varnothing}=R+iX$) as a function of magnetic field on spin transistor are still blank. In ac system, X includes two parts, the capacitance (X_C) and the inductance (X_L). However, in a metallic system, X_C can be ignorable. In this article we extend our previous work[6,7] to study the magnetoimpedance (MZ) behavior of pseudo-spin-valve transistor (PSVT) with frequency (f) ranged from 100 Hz to 15 MHz and do observe magnetic hysteresis on these components, i.e., $|Z|$, $\varnothing$, R, and X. Our finding is opposite to the works[8,9] that magnetic films do not exhibit magnetoimpedance hysteresis.

The MZ ratio is defined as $100\% \times (|Z|_{\mathrm{AP}}-|Z|_{\mathrm{P}})/|Z|_{\mathrm{P}}$, where the subscripts "P" and "AP" stand for the magnetization of the PSV at parallel and antiparallel states, respectively. The ratios of the component of magnetoimpedance are also defined in the same manner, that is, MR ratio$=100\% \times (R_{\mathrm{AP}}-R_{\mathrm{P}})/R_{\mathrm{P}}$, magnetoreactance (MX) ratio$=100\% \times (X_{\mathrm{AP}}-X_{\mathrm{P}})/X_{\mathrm{P}}$, and MP ratio$=100\% \times (\varnothing_{\mathrm{AP}}-\varnothing_{\mathrm{P}})/\varnothing_{\mathrm{P}}$, respectively.

EXPERIMENTS

The PSVT consisted of a PSV emitter, an aluminum base, and a *p*-*n* junction collector on a Si (100) wafer. The structure of the PSV was Si/$\mathrm{Ni_{80}Fe_{20}}$ (3 nm)/Co (1 nm)/Cu (5 nm)/Co (3 nm) which has a MR of 1.8% at dc measurement. Even though the PSV does not show very high MR, it does not prevent us from analyzing the general MZ properties of this kind of spin devices. The *p*-*n* junction was prepared by a standard chemical vapor deposition (CVD) process on a Si(100) wafer, and the size of the PSVT was 0.3×3 cm^2 defined by contact mask. More details about the fabrication can be found in Ref. 6. The MZ behavior is determined by using an HP 4194A impedance analyzer with a 16047D fixture, and together with an electromagnet which can supply a field up to ±100 Oe. Figure 1(a) illustrates the cross sectional structure of the PSVT, and the common collector circuit measurement, and Fig. 1(b) is the sketch of the equivalent circuit of the PSVT and measurement lead. Before taking data, the impedance analyzer was calibrated by standard method[10] to eliminate system error, and Cu wire, and Cu, Co, and $\mathrm{Ni_{80}Fe_{20}}$ films with a thickness of 12 nm were also used to characterize parasitic effects in the measurement circuit.

RESULTS AND DISCUSSIONS

Figure 2 shows frequency dependences of $|Z|$ and $\varnothing$ for the PSVT at zero applied fields, which implies an equivalent circuit as sketched in Fig. 1(b). The circuit mainly contains

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0021-8979/2006/99(8)/08H710/3/$23.00

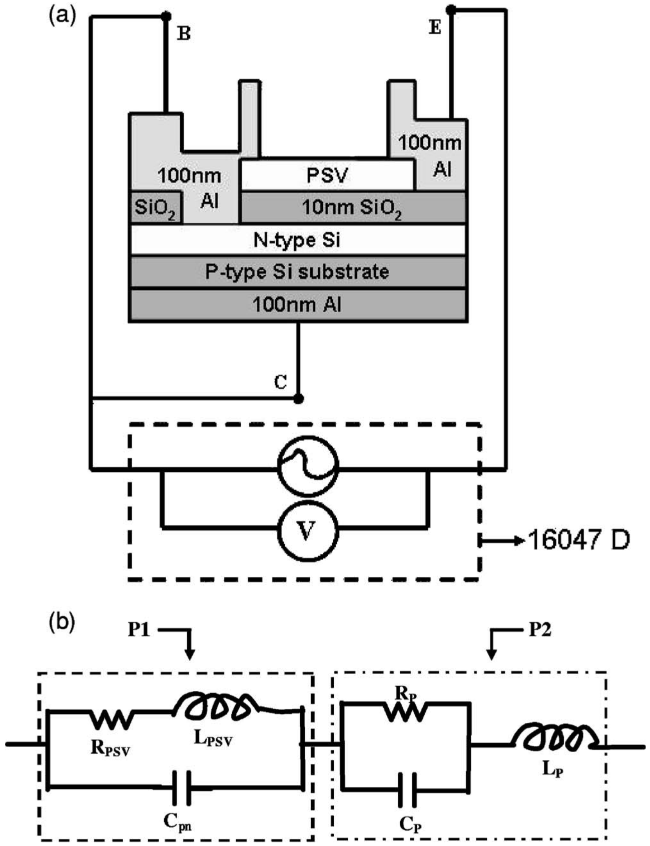

FIG. 1. (a) The cross section and the measurement circuit diagram of the PSVT. HP4194 impedance analyzer with 16047D fixture is used to determine the impedance behavior. (b) The equivalent circuit consists of two parts, P1 (PSVT) and P2 (leads). R, L, and C represent for resistance, inductance, and capacitance, respectively, and their subscripts of PSV, pn, and p stand for pseudo-spin-valve, p-n junction, and parasitic, respectively.

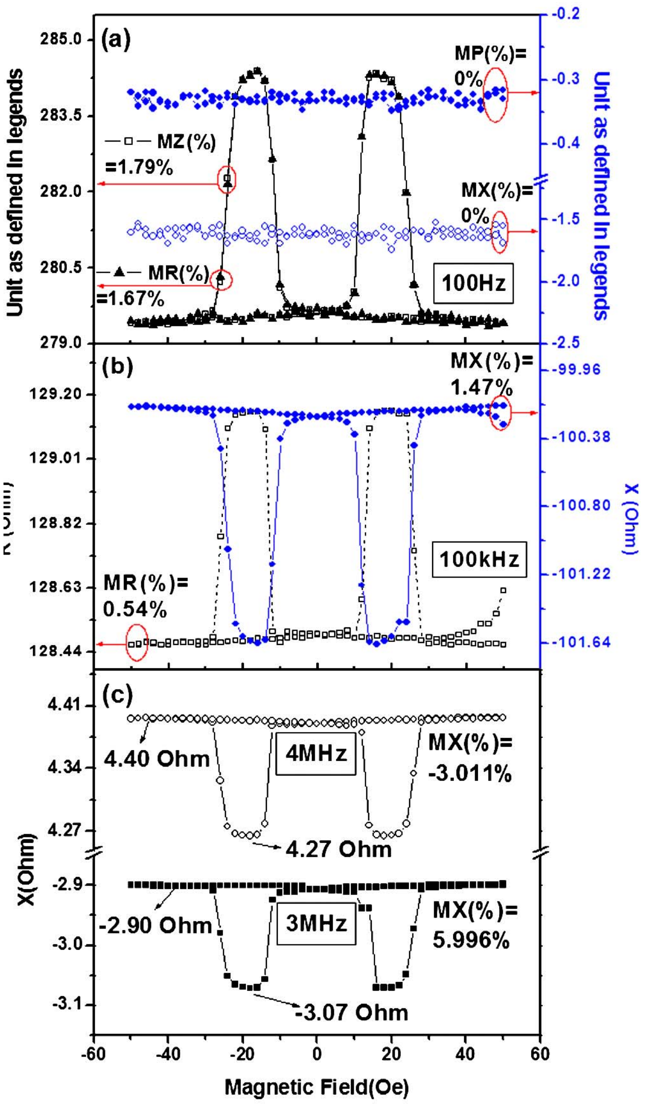

FIG. 3. (Color online) (a) Magnetoimpedance at 100 Hz. At this low frequency, the magnetotransport property can be regarded as dc. (b) At high frequency (100 kHz), MX appears with the shape of loop reverse to MR loop. (c) The value of MX is negative at $f < f_r$, and switches to be positive at $f > f_r$.

two parts, 1 and 2. Part 1 is an equivalent circuit of a PSV and a p-n junction, which are basically the resistance (R_{PSV}) and the inductance (L_{PSV}) of the PSV, and the capacitance of the p-n junction (C_{pn}). Their values are 215 Ω, 10 nH, and 4 nF, respectively, as found by fitting the data of $|Z|(f)$. Parasitic effects of resistance ($R_p = 10\ \Omega$), capacitance ($C_p = 0.01$ nF), and inductance ($L_p = 200$ nH) originated from the leads also have influence on the measurement and cannot be excluded, whose equivalent circuit is labeled by part 2. Consequently, the total impedance of this system [Fig. 1(b)] can be written as

$$Z = R_{\mathrm{eff}} + iX_{\mathrm{eff}} = \left(\frac{1}{R_{\mathrm{PSV}} + i2\pi f L_{\mathrm{PSV}}} + i2\pi f C_{\mathrm{pn}} \right)^{-1} + \left(\frac{1}{R_p} + i2\pi f C_p \right)^{-1} + i2\pi f L_p. \qquad (1)$$

$$R_{\mathrm{eff}} = \frac{R_p}{1 + 4f^2\pi C_p^2 R_p^2} + \frac{R_{\mathrm{PSV}}}{(1 - 4f^2\pi^2 C_{\mathrm{pn}} L_{\mathrm{PSV}})^2 + 4f^2\pi^2 C_{\mathrm{pn}}^2 R_{\mathrm{PSV}}^2}. \qquad (2)$$

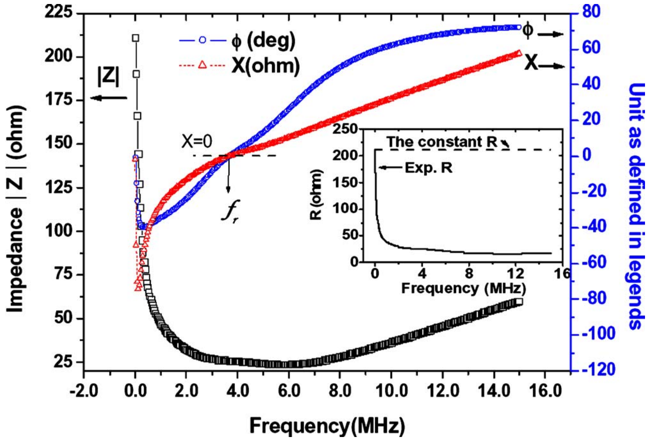

FIG. 2. (Color online) The frequency dependences of $|Z|$, $\varnothing$, and X for the PSVT at zero field. The resonance frequency (f_r) is found at 3.65 MHz, where X and $\varnothing$ vanish. $|Z|(f)$ does not reach minimum at f_r due to the frequency dependent behavior of R_{eff}, as shown in the inserted panel.

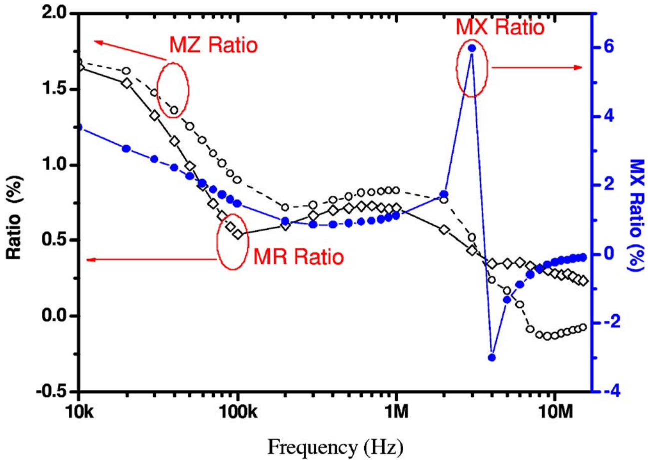

FIG. 4. (Color online) The frequency dependences of MZ, MR, and MX ratios.

$$X_{\mathrm{eff}} = 2f\pi\left(L_p - \frac{C_p}{4f^2\pi^2C_p^2 + \dfrac{1}{R_p^2}} + \frac{L_{\mathrm{PSV}} - 4f^2\pi^2C_{\mathrm{eff}}L_{\mathrm{PSV}}^2 - C_{\mathrm{eff}}R_{\mathrm{PSV}}^2}{(1-4f^2\pi^2C_{\mathrm{eff}}L_{\mathrm{PSV}})^2 + 4f^2\pi^2C_{\mathrm{eff}}^2R_{\mathrm{PSV}}^2} \right). \quad (3)$$

X_{eff} and ϕ_{eff} cross zero at 3.65 MHz which is defined as resonance frequency (f_r), as shown in Fig. 2. Despite having values in nanoscale, C_{pn}, C_p, and L_{PSV} do have large effect of frequency dependence on R_{eff}, as indicated in Eq. (2) and insert panel in Fig. 2. As a result, R_{eff} drops rapidly as f is increased, and hence a nonminimum of $|Z|$ at f_r, as shown in Fig. 2.

Figure 3 shows the hysteresis properties specified at some frequencies. At low frequency, the behavior could be regarded as dc, and hence the field independences in both MX and MP, as shown in Fig. 3(a). Nonzero MX is observed at high frequency as seen in Fig. 3(b) at f=100 kHz. Interestingly, the shape of the MX loop is reverse to the MR loop. Since MR is originated from the positive GMR effect (small resistance at high field) and MX comes from the change of inductance at different fields. At high field all magnetic moments align to the field direction and hence a higher inductance. By contrast at low field, the magnetization of the PSV is antiparallel, which gives lower inductance. That is, the effective inductance of the PSV is field dependent. Intriguingly, MX also changes sign from negative at 3 MHz$<f_r$ to positive at 4 MHz$>f_r$, as shown in Fig. 3(c). This can be understood from Fig. 2 that X crosses zero from negative to positive at f_r.

The frequency dependences of MR, MX, and MZ ratios are shown in Fig. 4. MX ratio exhibits large variation (9%) around f_r=3.65 MHz. MR ratio never touches zero; however, MZ ratio crosses zero from positive to negative at f_x =6.5 MHz. MZ=MR+iMX, and MX loop is always reverse to the MR loop as mentioned before, and furthermore MR is dominated at low frequency while MX is significant at high frequency. Thus, MZ ratio vanishes at a certain frequency (f_x) and reverses the shape while crossing f_x if the value of MX is positive, as seen in Fig. 5. The MZ loop with a ratio of 0.077% at 6 MHz switches to −0.086% and −0.125% at 7 and 8 MHz, respectively.

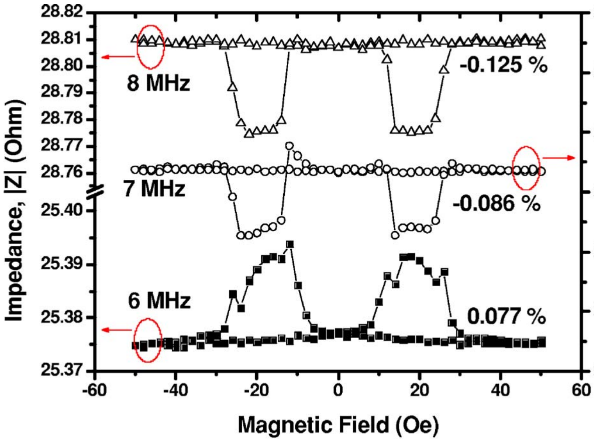

FIG. 5. (Color online) The MZ loop is reverse around f_x=6.58 MHz.

SUMMARY

In summary, the magnetoimpedance effect of PSVT has been investigated at room temperature. It is found that the PSVT can be regarded as a combination of resistances (R_{PSV}, R_p), inductances (L_{PSV}, L_p), and capacitances (C_{pn}, C_p), and equivalent circuit theory can be used to analyze the ac behavior of this system. The vanishing point of X and ϕ was found at f_r=3.65 MHz. MX changes sign from negative at $f<f_r$ to positive at $f>f_r$. It is because of the frequency dependence behavior, R_{eff} does not reach minimum at f_r. The frequency dependence of MR and MX causes the disappearance of MZ ratio at f_x=6.5 MHz and the reverse of MZ loop around f_x.

ACKNOWLEDGMENT

The authors are grateful for the financial support by MOEA, ROC under the Grant No. of A341XSFI10.

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