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Impedance behavior of spin-valve transistor

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The magnetoeimpedance (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_r=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_r. 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.

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 How-ever, the studies of impedance and magnetoresistance hysteresis.

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/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 method10 to eliminate system error, and Cu wire, and Cu, Co, and 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 ∅ 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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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 \( 215 \) \( \Omega \), 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) can be written as

\[
Z = R_{eff} + iX_{eff} = \frac{1}{R_{PSV} + i2\pi fL_{PSV}} + \frac{1}{R_p + i2\pi fC_p} - 1 + i2\pi fL_p. \tag{1}
\]

\[
R_{eff} = \frac{R_p}{1 + 4f^2\frac{\pi^2}{C_p^2}R_p^2} + \frac{R_{PSV}}{1 + 4f^2\frac{\pi^2}{C_{ps}^2}R_{PSV}^2 + 4f^2\frac{\pi^2}{C_{par}^2}R_{PSV}^2}. \tag{2}
\]
frequency dependence behavior, $R_{\text{eff}}$ and $\phi_{\text{eff}}$ cross zero at 3.65 MHz which is defined as resonance frequency ($f_r$), as shown in Fig. 2. Despite having values in nanoscale, $C_{\text{eff}}$, $C_p$, and $L_{\text{PSV}}$ do have large effect of frequency dependence on $R_{\text{eff}}$, as indicated in Eq. (2) and insert panel in Fig. 2. As a result, $R_{\text{eff}}$ 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<$f_1$ 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 $f_r=6.5$ 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 ($f_r$) and reverses the shape while crossing $f_r$ 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.

**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 ($R_{\text{PSV}}, R_p$), inductances ($L_{\text{PSV}}, L_p$), and capacitances ($C_{\text{eff}}, C_p$), and equivalent circuit theory can be used to analyze the ac behavior of this system. The vanishing point of $X$ and $\phi$ 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, $R_{\text{eff}}$ does not reach minimum at $f_r$. The frequency dependence of MR and MX causes the disappearance of MZ ratio at $f_r=6.5$ MHz and the reverse of MX loop around $f_r$.

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