Microwave-induced DC Signal in a Permalloy Thin Strip at Low Applied Magnetic Field

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Abstract

We investigated the ferromagnetic resonance signals in a polycrystalline permalloy thin strip under in-plane low static magnetic field. A series of DC voltages, which contain ferromagnetic resonance or spin wave resonance signals, were measured by inducing microwave frequencies greater than 10 gigahertz. The resonant signals measured in low magnetic field show different properties from those detected in high field condition. Based on the theory of DC effects in ferromagnetic resonance and the experimental data of anisotropic magnetoresistance, a quantitative model was proposed. We found that the shape anisotropy significantly affects magnetization, and distorts the resonant signals in low field condition.

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Anisotropic Magnetoresistance (AMR) effect plays a crucial role in the detection of the electrical properties of ferromagnetic materials. The direct current (DC) effect, which originates from the coupling of microwave-induced radio frequency (rf) current and the time-dependent AMR, have been widely researched and discussed for a long time with growing interest. The AMR is given as \( R = R_0 + R_A \sin^2 \theta \), where \( R_0 \) is the resistance with the magnetization being perpendicular to the rf current, \( R_A \) is the additional resistance and \( \theta \) is the intersection angle between the magnetization \( \mathbf{M} \) and the rf current \( \mathbf{j} \). Permalloy (Py) is an ideal ferromagnetic material with significant AMR and has been widely investigated for its microwave-induced DC signal. In the previous theory for Py, \( \mathbf{M} \) precesses in phase with the rf current under a constant magnetic field when the microwave is applied to the sample, and the material resistance changes with time due to the variation of \( \theta \). During a signal period, the rf current and the alternate resistance generate a nonzero voltage, which can be recorded by lock-in technology in a time-averaging DC form. The DC voltage spectrum measured by sweeping the magnetic field shows pronounced resonance of around 1 \( \mu \)V, including ferromagnetic resonance (FMR), spin wave resonance (SWR) or perpendicular standing spin wave (PSSW) resonance, as which the SWR performs in boundary conditions due to an extremely thin thickness.

Most analysis of those DC voltage signals requires large equipment to provide a static magnetic field \( \mathbf{H} \) greater than 1000 Oe, because the magnetization and spin precession in a high field condition can be easily analyzed. Nevertheless, without relevant research, the complicated low-field feature of signal makes the utilization of microwave-induced DC effect in weak field condition a difficult task. This largely unexplored region limits the miniaturization and energy cost of relational production. Since it is widely pointed out that the anisotropy, which is determined by the shape of a ferromagnetic material sample, produces the assignable influence on the magnetization behavior, we provide a physical model in this letter to explain the low field spectrum in terms of shape anisotropy. Two phenomena, the signal distortion and incompletion, are discussed as a general case.
The experimental configuration is shown in Fig.1(a). For the detection of AMR and DC voltage, a thin Py (Ni$_{80}$Fe$_{20}$) strip with polycrystalline structure has been prepared by University of Manitoba. Our sample’s thickness is thinner than the skin depth in this experiment. The sample’s geometry parameters are: thickness=49nm, width=200μm, length=2400μm, with bond pads on each side. A rectangular waveguide is used to transform the microwave energy into the sample’s plane normally. Our Py sample is fixed between two poles of an electromagnet. The electromagnet provides static magnetic field $H$ (maximal $\approx 1.5T$) parallel to the sample’s plane. All data are measured at room temperature. To better understand the signal of our experiment, a coordinate system is defined, as shown in Fig.1(b). In order to quantify the shape anisotropy of our sample, AMR is measured first.

From the result of AMR measurement, the angle dependence matches $R=R_0+R_A-R_A\sin^2\theta$, while the magnetic field dependence is complicated. With the weakening of $H$, the resistance of our sample is gradually increased to $R_0+R_A$. That is to say, $M$ reverts to the z-axis. Since the direction of $H$ is fixed, other magnetic field affects $M$. Regarding the shape anisotropy of ferromagnetic material with thin strip structure, an anisotropic magnetic field $H_A$ is defined with its direction of the long axis of our sample (z-axis). The physical meaning of $H_A$ is explained as follows. The magnetization intends to align along the z-axis in this thin strip structure because of lower magnetic energy, as if a static magnetic field parallel to the z-axis, pushing the magnetization to its direction. The magnetization precesses around $H+H_A$, which can be treated as the same value and direction as $H$ in the high field condition. In the low field condition ($H$ is less than 200Oe), $H_A$ cannot be neglected. Hence, the magnetization is affected by both shape anisotropy and the external field. Considering of $H_A$, the magnetization is situated between $H$ and $H_A$, and we find:

$$ R(t) = R_0 + R_A - R_A L $$

(1)
with \( L = \sin^2 \theta \left( \frac{H}{H + H_A} \right)^2 \). Here \( L \) describes the angle dependence of AMR in low field condition. With increasing external field \( H \), \( L \) approaches to 1 and \( M \) turns to the direction of \( H \), with an intersection angle \( \theta \) between \( z \)-axis. As demonstrated in Fig.2(a), the resistance \( R_0 \) of our sample for perpendicular magnetization is 89.2\( \Omega \), while \( R_A \) is 1.48\( \Omega \). The fitted anisotropic field \( H_A \) in our sample is 4.8 Oe.

After the measurement of shape anisotropy we further pursue a quantitative description of microwave-induced DC voltage. The resonant DC voltage signal (PSSW and FMR) of microwave response in a different frequency is illustrated in Fig.2(c). Although the FMR is not excited in the PSSW resonant frequency (in our sample, the frequency is about 2 GHz higher than FMR’s), an additional magnetization circumrotating around the equilibrium axis is induced. Such additional magnetization precession also results in DC effect by coupling the rf current. The PSSW acquires higher energy than FMR so that it can be easily distinguished, as shown in Fig.2(c). The magnetic field dependence of FMR signal lines exhibits symmetry and asymmetry shapes\(^4\). In PSSW line shape, the symmetry part is much smaller than that of FMR's in this sample. In low field conditions, the PSSW modes' curves in the embedded figure in Fig.2(c) are distorted with regard to the PSSW signal in high field condition. Furthermore, as the frequency reduces to 10.2GHz, fewer peaks are detected and the signal becomes incomplete.

It is thus reasonable to speculate that the observed signal distortion and incompleteness are caused by \( H_A \). Next, the DC signals are investigated in low field conditions (less than 500Oe). As for a Py thin strip, the DC voltage \( U_{MW} \) with respect to the time-dependent AMR and the microwave at the frequency of \( \omega/2\pi \) can be described as

\[
\langle U_{MW} \rangle = \langle j \cos(\omega t + \Phi) R_A \sin(2\theta(t)) \rangle \quad (\langle \rangle \text{ denotes the time-averaging})
\]

here \( \Phi \) represents the phase difference between the rf current \( j(t) \) and time-dependent AMR \( R(t) \) By combining with Eq. (1) and separating the contributions from microwave frequency
\( \omega/2\pi \) and \( \mathbf{H} \), \( \langle U_{\text{MW}} \rangle \) takes the form:

\[
\langle U_{\text{MW}} \rangle = j R_{\alpha} \beta \cos(\Phi) \sqrt{L - L^2}.
\] (2)

Here \( \beta \) is a frequency-depend coefficient, which represents the intensity of precession. When the microwave is at the resonant frequency, \( \beta \) is maximized. \( \sqrt{L - L^2} \) describes the range of resistance vibration in a certain \( \mathbf{H} \). Noted that a resonant condition is not a prerequisite to the DC signal \( \delta \), DC voltage can also be measured in non-resonant condition. The matching of the theory based on Eq.2 is verified in Fig.3.

The direction of \( \mathbf{H} \) is first set as 45° to show the detailed signal with microwave frequency in the range between 10.3GHz and 10.7GHz, and the signal is presented in Fig.3(a). At different frequencies, the signal curves are significantly different. The complete PSSW signal curve shown in Fig.2(c) is recorded with the form of a quasi-centrosymmetry. Furthermore, the signal curve is distorted when the applied field is reduced. Such phenomenon can named as “signal distortion”. As the assisted microwave frequency in the recorded signal curve down to 10.5GHz, the PSSW resonance signal becomes distorted. In the low field, \( \mathbf{M} \) is strongly influenced by \( \mathbf{H}_A \).

When the Py sample is assisted with the microwave energy of 10.3GHz, the required magnetic field for PSSW resonance at this frequency is weaker than 4.8Oe. Such resonant requirement cannot be fulfilled because \( \mathbf{H}_A \) always exists and \( \mathbf{H} + \mathbf{H}_A \) is still larger than 4.8Oe, resulting in the incomplete PSSW signal curves. This condition is named as “signal incompletion”. Also, as the frequency continues to decrease to 10.3GHz, the signal strength is further reduced.

According to Eq.2, the signal curves nearby zero field are different when the distortion occurs, as shown in Fig.3(b) while the frequency is set as 10.8GHz. Such difference depends on the intersection angle \( \theta \). When \( \theta \) is smaller than 45° and the applied field is minimized, the intensity of DC signal decreases monotonically. Referring again to the Fig.2(b), we may conclude that the signal intensity also
depends on $\sqrt{L - L^2}$, which characterizes the intensity of oscillation of R(t) and is also reduced monotonically. When $\theta$ is larger than $45^\circ$, $\sqrt{L - L^2}$ does not monotonically decrease or increase with $H$. The signal intensity first increases and then vanishes with decreasing applied field. We simulate these signal distortion trends in Fig.3(b). While the applied field is parallel to the length of the sample, no DC signal is recorded because of the minimum $\sqrt{L - L^2}$.

The DC signal corresponding to 10.2GHz microwave is a nonresonant spectrum because the resonant magnetic field is smaller than $H_A$. The spectrum nearby zero-field performs as an asymmetric type with two non-resonant peaks on each side, as shown in Fig.3(c). From the discussion above, no signal is recorded in the parallel configuration because $\sqrt{L - L^2} = 0$. In the non-parallel configuration, the types of signal curves are similar with different mechanisms. When $\theta < 45^\circ$, the DC signal increases (or decreases if the applied field is reversed) is mainly contributed by $\beta$ in Eq.2. When $H$ approaches to the resonant field, the intensity of magnetization precession is strengthened and thus DC voltage signal is enhanced. However, when $H$ is perpendicular to z-axis, $\sqrt{L - L^2}$ becomes the major factor affecting $\langle U_{MW} \rangle$; in other words, with minimized $H$, the oscillation of R intensified with $M$ deviating from the x-axis, and conducing to the strengthened signal.

In conclusion, we discussed the unusual microwave-induced DC voltage signals of an in-plane magnetized permalloy thin strip in low field condition with different configurations and microwave frequencies. The shape anisotropy of this sample is characterized by an additional, static magnetic field with certain magnitude and direction through the measurement of AMR. The detection of a microwave-induced DC voltage shows that this additional magnetic field is strongly involved in the ferromagnetic resonance when the applied field is weak. First, with the decreasing of $H$, the magnitude of $H + H_A$ is not approximately equal to $H$ and the direction of
magnetic is deviated while $H$ is weak. As a result, the DC signal curve is distorted. Second, the additional field contributes a minimum magnitude to $H+H_A$. If the magnetic field required for resonance is weaker than the minimum $H+H_A$, the resonant peak disappears, resulting in the incomplete DC signal curve. In view of the results of the measurement and simulation of AMR and DC voltage signal for the Py thin strip, this low-field model is reasonable to explain the unusual signals in in-plane magnetization. Further research on how to control the shape anisotropy would be meaningful for the detection and utilization of the electrical properties of ferromagnetic materials.

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Figure Captions:

FIG.1. (a) The schematic experimental setup and the structure of our sample. The microwave power is injected to the Py strip directly through a rectangular waveguide, and the signal is measured by the Lock-in amplifier. (b) The defined coordinate system in this paper and the illustration of two resonance mode: z-axis is parallel with the length of the Py sample, x-axis is parallel with the width and y-axis is perpendicular with the plane of this thin strip. \( \mathbf{H} \) under different directions \( \theta \) is due to the applied field or external field, \( \mathbf{H}_A \) is due to the shape of the anisotropic field.

FIG.2. (a) The red data show that the measured AMR depends on the applied magnetic field at different intersection angles \( \theta \) and the blue data is the simulation used by equation (1). (b) The red data indicate that the measured AMR depends on the directions of \( \mathbf{H}_{\text{EX}} \) at different external field and the blue data is the simulation used by equation (1). (c) The measured microwave DC signal at different frequencies and fixed intersection angle \( \theta \) between sample and \( \mathbf{H} \) at 45°. From bottom to top, the signal curves correspond to microwave frequencies of 10.2GHz, 10.8GHz, 11.7GHz, 12GHz, 15GHz, 16.5GHz, 17.1Hz, 17.7GHz, respectively. The detail information of signal curves in low field condition (-200 Oe to 200 Oe) with 10.2GHz and 10.8GHz is also presented.

FIG.3. (a) Fitting (red lines) of the PSSW spectra (gray dots) for different frequencies \( f=\omega/2\pi \) at \( \theta=45^\circ \). (b) Fitting of the PSSW spectra for different angles \( \theta \) at \( f=10.8\text{GHz} \). (c) Fitting of the PSSW spectra for different angles \( \theta \) at \( f=10.2\text{GHz} \).
