Microwave Current-Perpendicular-to-Plane Giant Magnetoresistance of Fe/Cr Superlattices

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The microwave measurement of GMR effect in the CPP geometry is realized and investigated. It is shown that the magnetic field dependence of microwave absorption undoubtedly correlate with the CIP DC magnetoresistance of superlattices.

Key words: magnetic metallic superlattice, giant magnetoresistance, microwave measurement, microwave absorption, thin film

1. Introduction

By now the microwave electromagnetic properties of metallic multilayers were studied in works of unity ^{1), 2)}. The microwave absorption in Fe/Cr/Fe epitaxial sandwiches has been studied in Ref. 1. It is found that the magnetic field dependence of microwave absorption is governed by the giant magnetoresistance (GMR) effect. The transmission of microwaves through Fe/Cr superlattices is investigated in Ref. 2. The unambiguous correlation between the GMR and the effect of magnetic field on microwave transmission is established. These experiments were carried out in the so-called CIP geometry, when the current flowed in the layer planes. At the same time the “current-perpendicular-to-plane” (CPP) geometry attracts a very substantial interest due to more effective incorporation of the surface spin scattering in the process of electronic transport ³⁾. Current flows through a superlattice thickness in this geometry and crosses the layer boundaries many times.

The data of CPP experiments provides the understanding of bulk and interface spin-dependent scattering contributions to the magnetoresistance. Because of the larger magnetoresistance ratio, the serious efforts were mounted to use CPP configuration in practical applications. Particularly, the incorporation of a magnetic superlattice into the base region of a hot electron transducer is inclined to think as a very promising idea. The primary problem is how to measure the CPP magnetoresistance of a multilayer. Very refined methods are used for this purpose. The superconducting contacts and SQUID based techniques are among of these methods, as well as nanowire deposition of multilayer and oblique evaporation on the grooved substrates. All these methods are too complicated.

The new simple method of CPP-magnetoresistance measurement is proposed in this paper, where the absorption of high frequency electromagnetic wave by multilayer under the special conditions is investigated.

The sample is placed inside the microwave resonator in the maximum of electric field. Point out that the opportunity is realized to observe the high frequency analog of giant magnetoresistance effect when microwave electric field (and current) is aligned crosswise the layers. Notice that the electrodynamics of ultrathin objects in the microwave electric field has special features. If the size of the sample is shorter than the wavelength in the free space, we deal with quasistatic regime. The microwave electric field is directed normally to the superlattice plane.

In this situation the electromagnetic fields and currents can not exhibit the usual skin-effect. It will be proved that the electric field inside the superlattice has the component penetrating through the whole metal thick. The magnetic field dependent losses of microwave resonator are caused by this component of electric field.

The magnetic metallic Fe/Cr superlattices were chosen as the subjects of investigation. These superlattices have the non-collinear layers. The plot of magnetic field dependence of electrical resistance has the almost linear part in small fields, and the saturation in high ones. The field dependence of the microwave absorption would be expected to be similar.

2. Experimental

2.1. Samples and GMR

The superlattices used in this study were grown by MBE methods on single crystal MgO (100) substrates with a thickness 0.5 mm. A 70 Å Cr buffer was deposited at a substrate temperature of 600°C to establish the epitaxial orientation with the substrate. The substrate was then cooled to 180°C, and the superlattice was grown by sequential deposition of the Fe and Cr layers.

The follows samples are used in the work: [Fe(15 Å)/Cr(9 Å)]₃₀/Cr(70 Å)/MgO (sample 1); [Fe(21 Å)/Cr(17 Å)]₁₂/Cr(70 Å)/MgO (sample 2) and Fe film with thickness of 710 Å (sample 3). The structures were characterized by X-ray diffraction using Co K_α radiation.

Magnetoresistance (MR) was studied by standard four probe technique in applied fields up to 32 kOe. The MR ratio $r = \Delta R/R$ was calculated as $\Delta R/R = [R(H) - R(0)]/R(0)$ where $R(0)$ and $R(H)$ are the resistivity in zero field and external field H , respectively. Magnetoresistance was measured in film plane (DCIP) at room temperature. The field dependence of magnetoresistance is shown in Fig. 1

The magnetic measurements of these sample⁴⁾ prove the non-collinear arrangement of the magnetic moments in the neighboring Fe layers.

Fig. 1 Magnetoresistance vs. magnetic field

2.2. Microwave measurements

Microwave measurements were carried out at the frequency range of 0.5–2.1 GHz. The sample was placed in the maximum of high-frequency electric field $E_{\sim}$ in the coaxial cavity, see Fig. 2. The vector $E_{\sim}$ is directed along the normal to the superlattice plane. The high-frequency electric field inside the metal is directed by the same manner, if the whole metal thickness is much lower than the skin-depth, as shown below. Hence, the high-frequency currents flow through the superlattice. The CPP geometry is realized in this case. The resonant frequency of the cavity is governed by the distance “d”. The Q-factor of cavities used is not so high, from 1000 to 2000 typically. Notice that the high-frequency magnetic field amplitude is near the zero at the sample surface. Only tangential component of the high-frequency magnetic field is present.

3. Results on microwave GMR

The direct correlation between transmission of microwaves through superlattice and giant magnetoresistance was established in Ref.2. In this paper we deal with microwave absorption. The magnetic field dependence of microwave absorption in the superlattices (the samples No. 1 and 2) is plotted in Fig.3.

The sample No. 3 is not the superlattice but thin Fe film. The film does not exhibit the substantial magnetoresistance. The magnetic field dependence of the microwave absorption may be regarded as negligible from Fig.3.

The steady external magnetic field up to 15 kOe is applied in the plane of superlattice. All the measurements are carried out at room temperature. The accuracy of microwave measurements is estimated as $\pm 5\%$, and $\pm 2\%$ for magnetoresistance.

Fig. 2 Scheme of the microwave measurements.

The sample No. 3 is not the superlattice but thin Fe film. The film does not exhibit the substantial magnetoresistance.

Fig. 3 Microwave transmission.

The magnetic field dependence of the microwave absorption may be regarded as negligible from Fig.3. The dependencies deduced for the superlattices exhibit the same type changes as the field dependence of the magnetoresistance. The sample No. 1 has the saturation field more high than it is reached in our experiment. Therefore, the absorption dependence is almost linear, like the magnetoresistance. The comparison between the magnitude of the microwave absorption (MWCPP) and the magnetoresistance is shown in the Fig.4.

As it has been shown below, the microwave changes are proportional to Q^2 . Despite the relatively low Q-factor of our resonators, the microwave changes exceed the magnetoresistance.

4. Discussion

For a resonant cavity inserted as a transmission element in a waveguide circuit the transmission coefficient can be derived as follows⁵⁾

$$D = \frac{4Q_e^2}{Q_1 Q_2} \frac{1}{1 + Q_e^2 \left(\frac{2d\omega}{\omega_0} \right)^2} \quad (1)$$

Fig. 4 Comparison between microwave transmission and DC magnetoresistance.

Here Q_e is the loaded Q-factor of resonator, Q_1 and Q_2 are the Q-factors of couplings. The quantity ω_0 in equation (1) is the resonant frequency, and $d\omega$ the deviation from resonance. All our measurements are carried out exactly at the resonant frequency when $d\omega = 0$. We take into consideration that the intrinsic Q-factor of cavity is $Q_0 = 2\pi W / \Delta W$, where W is an energy accumulated in the resonator and ΔW the losses per one period:

$$\Delta W = \frac{2\pi}{\omega_0} P_{\text{loss}}, \quad W = \int_V \frac{|H_z|^2}{2} dV,$$

$$P_{\text{loss}} = \frac{1}{2} R_s \int_S H_e^2 ds.$$

Here H_z is an amplitude of high frequency field inside the resonator, H_t is a tangential component P_{loss} a losses power, and R_s is surface resistance. Integration is to be taken over the resonator volume V and over the sample surface S . All things considered, we have for the relative change $D(H)$ of transmission coefficient at the resonant frequency

$$D(H) = \frac{D(H) - D(0)}{D(0)} = -Q_e^2 \left| \frac{\int_S |H_t|^2 ds}{\int_V |H_z|^2 dv} (R_s(H) - R_s(0)) \right| \quad (2)$$

In the right side of the equation (2) only the quantity R_s depends on steady magnetic field.

Now we should discuss more comprehensively what is the sort of conductivity σ contributing the surface resistance R_s . Let us restrict our consideration by the quasistationary conditions $\omega \ll (c / L_{\text{max}})$, L_{max} is the maximal size of sample. Besides, $\sigma / \omega \gg 1$ inside superlattice. Under these conditions, the tangential component of electric field on the metal surface is

proportional to high-frequency magnetic field. Because the latter magnetic field is small at the sample surface, the high-frequency electric field is directed almost normally to the superlattice surface. Therefore the electric field and current inside the sample are directed normally to layers. The combination of Boltzman equation in τ -approximation and Maxwell equations was fulfilled. The equation for the forced plasma-type oscillations of electric vector is derived with allowance made for boundary of the superlattice. The structure of the solution is as follows. The screening component of electric field decays at the distance $z_0 \approx v_F / \omega_0$, where v_F is the Fermi velocity, ω_0 the plasma frequency. Besides the screening component, the another electric field component exists. That component penetrates through the metal superlattice.

The electromagnetic losses are caused by the microwave currents $\mathbf{j}$ flowing in the electric field $\mathbf{E}$. The simple form of conductivity appears in the expression of the microwave absorption: $\sigma_{\text{eff}} = ne^2 / m(1/\tau - i\omega)$, where n is the electrons density, e and m the electron charge and mass. At room temperature $\omega\tau \ll 1$ and the usual DC conductivity contributes in the microwave losses.

5. Summary

In this paper the following main results are presented:

- 1) The measurement is realized of microwave GMR effect in the CPP geometry;
- 2) The magnetic field dependence of microwave absorption evidently correlate with the CIP DC magnetoresistance of Fe/Cr superlattices;
- 3) The effect of microwave magnification of GMR is established;
- 4) The contactless method of the magnetoresistance measurement of metallic superlattices is developed.

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