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Quantitative analysis of the giant magnetoresistance effect at microwave frequencies

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The high frequency analog of giant magnetoresistance (GMR) in the microwave reflection and transmission coefficients of spin valves was measured and quantified. The relative change in transmission is nearly a factor of 2 larger than the electrical transport GMR effect. The change in reflection is of opposite sign and an order of magnitude smaller. A calculation of the reflection and transmission coefficients, considering the interfaces and the decay of the fields within the layers, provides a quantitative relationship to the transport GMR with no free parameters.

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Magnetic-nonmagnetic multilayer films exhibit the phenomenon known as giant magnetoresistance (GMR).[1] Generally the GMR amplitude is measured at a low frequency in the laboratory utilizing standard 4-point probe transport measurements. Since the time scale for electron scattering is around than 10 fs, the phenomenon persists to significantly higher frequencies such as microwave and even far-infrared frequencies; Krebs *et al*. first observed GMR in the microwave regime (μGMR)[2] and, later, Jacquet and Valet observed the magnetorefractive effect in the infrared regime.[3] Recently, high frequency measurement techniques such as these have been proposed as an alternative, non-contact method of measuring GMR.[4]

The μGMR effect has been observed in a variety of geometries: within resonant cavities,[2,5,6] through an antenna circuit,[7] and by direct measurement of transmission[8] or differential absorption.[9] While each of these results shows a correlation between transport GMR and μGMR, the models provided simply predict a correlation but do not quantify the magnitude of the effect.[8,9] We also note that experiments have been limited to separate measurements of either transmission or absorption and have neglected the reflection coefficient. Quantitative efforts have been made in the infrared regime, but an inter-band conduction calculation beyond the simple Drude model appears necessary to quantitatively explain the effect.[3,10]

In this report, we demonstrate the first quantitative prediction of the magnitude of the μGMR effect in a microwave waveguide for both transmission and reflection. This model extends the previous work[8,9] by accounting for the interfaces between the GMR film and the empty waveguide in addition to the skin depth of the film. Furthermore, we report the first observation of the μGMR effect in reflection. By measuring the effect both in reflection and transmission as well as the absolute reflection and transmission coefficients we verify that, with no adjustable parameters, our model produces the correct prediction for these measureable quantities.

Our samples were grown using DC magnetron sputtering and are of the form: 10 nm Ta/ 3 nm NiFe/ 6 nm IrMn/ d_{CoFe} nm CoFe/ 2.5 nm Cu/ 1 nm CoFe/ 2 nm NiFe/ 2 nm Ta where d_{CoFe} was varied from 1.5 to 3.5 nm. Fourteen samples were investigated. The four samples discussed in detail below were grown on 0.97 mm thick glass microscope slides cut to the dimensions of X-band waveguide. Ten additional samples were grown on Si_3N_4 coated Si substrates whose dimensions were slightly narrower than the waveguide cross-section.

The samples were mounted against a small plastic block and placed in the waveguide with the sample plane perpendicular to the direction of microwave propagation. Since the mounting block was placed on the transmission side of the film, it had little effect on the reflection coefficient and the effect on the transmission coefficient was small compared to the effects of interest caused by the film. For the glass substrate samples, silver paint was applied around the sample edges after placement in the waveguide to maximize electrical contact with the waveguide walls and minimize leakage of microwave radiation around the film.

All measurements were made at room temperature. The sheet resistance in zero external field was calculated using the van der Pauw technique[11] from data taken using a Jackson-Adler resistance bridge[12] with four contacts placed at the corners of the sample. A separate 4-point transport measurement determined the relative GMR change, with contacts oriented so that the direction of the electric field in the film was identical to that in the waveguide. Microwave measurements were made at 10.5 GHz using a precision attenuator and phase shifter in a microwave bridge setup.[13] The empty waveguide was used as a reference for the transmission measurements and a piece of copper approximately 1 mm thick was the reference for the reflection measurements.

The exact reflection and transmission coefficients can be calculated directly by solving Maxwell's equations with the appropriate boundary conditions.[14] Enforcement of the boundary conditions can be done directly[15] or by following Jackson[14] and constructing a transfer matrix. This calculation is identical to that for a free-space plane wave with the wavenumber replaced by the propagation constant appropriate for a rectangular waveguide.[16] Just as in the free-space case, the dielectric constant of the film depends on the DC conductivity and is complex, leading to a non-zero absorption coefficient.[14] Full expressions for the transmission and reflection coefficients for a free standing film are given in Ref. 15.

As shown in Ref. 17, the transmission coefficient discussed above can be simplified significantly by assuming both a large impedance mismatch at the air-metal interface and a film thickness much less than the skin depth. The first assumption requires $\sigma >> \varepsilon_0\omega$, where σ is the conductivity, ε_0 is the permittivity of free space and ω is the microwave frequency. At 10 GHz this is valid even for poor conductors.[17] The second assumption is also valid since at 10 GHz, the skin depth for bulk copper is 560 nm and nickel, with a large relative permeability, has a skin depth of 140 nm. Using these same assumptions we extend the work in Ref. 17 and also simplify the reflection coefficient. The resultant transmission, t, and reflection, r, coefficients are

$$t = 4\left(2 + \frac{R_0}{R_S}\right)^{-2} \tag{1}$$

and

$$r = \left(1 + \frac{2R_S}{R_0}\right)^{-2}, \tag{2}$$

where R_S is the sheet resistance of the film and $R_0 = \omega\mu_0 / |\gamma_{air}|$, with γ_{air} the propagation constant of an open waveguide,[15] and μ_0 is the permeability of free space. Note the dependence on the relative permeability dropped out during the simplification, and both the conductivity and thickness of the film are now represented in the single quantity R_S. For X-band waveguide at 10.5 GHz, the value of R_0 is 483 Ω and $|\gamma_{air}| = 1.71\ \text{cm}^{-1}$. Ref. 17 confirms these expressions experimentally on various materials with sheet resistances ranging from 10 kΩ to 0.1 Ω justifying their use for our films with $R_s \approx 20\ \Omega$.

Since the GMR effect depends on the relative orientation of the layer magnetizations, we define the transport GMR ratio as $\Delta\rho/\rho = [\rho(H) - \rho_P]/\rho_P$ where $\rho(H)$ is the field dependent resistivity of the film and ρ_P is the resistivity of the film when the magnetic layers are aligned parallel (P). Assuming $\Delta\rho/\rho \ll 1$, noting that $R_S \propto \rho$, and taking R_s to be the sheet resistance of the film in the P state, we find the analogously defined relative change in the transmission and reflection coefficients to be

$$\frac{\Delta t}{t} = \frac{2R_0}{R_0 + 2R_S}\frac{\Delta R_S}{R_S} \tag{3}$$

and

$$\frac{\Delta r}{r} = \frac{-4R_S}{R_0 + 2R_S}\frac{\Delta R_S}{R_S}\,. \tag{4}$$

A more complex set of expressions may be obtained by accounting for the substrate in addition to the film.[18] Since most glasses have a reported dielectric constant of ~6, we will also consider these more complex expressions when comparing to our data. These expressions do not strongly affect the predictions except in the case of the transmission coefficient as will be discussed below.

Figure 1 compares Δρ/ρ, Δt/t and Δr/r for a sample with $R_s = 23\ \Omega$. Figure 1(a) demonstrates that all three quantities have the same field dependence. In Fig. 1(b), the same data is plotted parametrically as $\Delta t/t$ vs. $\Delta\rho/\rho$ and $\Delta r/r$ vs. $\Delta\rho/\rho$. Clearly $\Delta t/t$ and $\Delta r/r$ are proportional to $\Delta\rho/\rho$ ($=\Delta R_s/R_s$), but $\Delta t/t$ shows a larger response while $\Delta r/r$ is smaller and of opposite sign as expected.

Samples grown on Si substrates yield the same linear correlation of $\Delta t/t$ and $\Delta r/r$ with $\Delta\rho/\rho$. However, high substrate doping and sample dimensions slightly smaller than the waveguide complicate any quantitative analysis. Qualitatively we measure an increase in transmission and decrease in reflection for these samples. We attribute this to leakage of microwaves radiation around the film and this explains the observed reduction in the magnitude of the μGMR effect for these samples.

In Fig. 2, we plot the ratios of $\Delta t/t$ and $\Delta r/r$ to $\Delta\rho/\rho$ versus sheet resistance for each of the samples measured and compare these values to the predicted results from Eqs. (3) and (4) and to those given by Ref. 18 for a film grown on a substrate with dielectric constant of 6.0. The dielectric constant determined from measurements of a blank substrate yielded predicted values between these two curves. The measured absolute transmission and reflection coefficients and their predicted values are given in Table I along with the sample thicknesses, sheet resistances and values of d_{CoFe}. Sample thickness derived from sputter rate calibrations are only stated for informational purposes since the van der Pauw technique directly measures the sheet resistance entering into the model equations (3) and (4). All four microwave quantities measured display the calculated dependences on sheet resistance and the magnitudes of all quantities are correctly predicted. Clearly the dielectric constant of the substrate does not change the theoretical predictions significantly except in the case of the absolute transmission coefficient given in Table I. Thus, Eqs. (2), (3) and (4) can all be used to good approximation for the reflection coefficient, $\Delta t/t$, and $\Delta r/r$ respectively. Since the transmission coefficient is small, the full calculation, including the effects due to the substrate, is necessary for describing the transmission coefficient.

Our measured and calculated ratios of $\Delta t/t$ to $\Delta\rho/\rho$ are all considerably larger than unity in contrast to the results in Ref. 8 where the μGMR transmission signal was observed to be similar to the transport GMR signal and independent of sheet resistance. Since their samples contained Cr non-magnetic layers, we expect these films to have higher sheet resistances leading to a lower slope in the graph of $\Delta t/t$ vs. $\Delta\rho/\rho$. While their free-space model, based only on the skin depth, supports a one-to-one correspondence between the transport GMR effect and the μGMR effect in transmission, it predicts a transmission coefficient near unity and no observed effect in the reflection coefficient. Since they do not report the electrical transport properties of their samples we are unable to verify whether our model accurately describes their data.

Omission of the silver paint applied to establish electrical contact between the sample and waveguide wall reduced both $\Delta t/t$ and $\Delta r/r$ by nearly an order of magnitude. Discrepancies with theory in Fig. 2 and Table I can be attributed primarily to imperfect electrical contact which would systematically decrease the absolute reflection coefficient, $\Delta t/t$ and the magnitude of $\Delta r/r$, and increase the absolute transmission coefficient.

The above agreement between our experiment and theory indicates that an intra-band conduction model fully explains the μGMR effect at frequencies around 10 GHz in both transmission and reflection. In the infrared regime, inter-band contributions most likely will be involved,[10] and we predict the transition to a more complicated model should occur around 10 THz where the electron scattering rates are comparable to IR frequencies. In fact our preliminary studies in this regime indicate the crossover for our samples occurs below 15 THz.

In conclusion, we made the first observation of the μGMR effect in reflection and also measured the effect in transmission. We have demonstrated the first quantitative model without adjustable parameters describing this effect and verified its validity for all four measured microwave quantities.

The magnitudes of the μGMR responses depend on the relative size of the sample sheet resistance in comparison to a single parameter which describes the dimensions of the waveguide and the operation frequency. The response in transmission is larger than previously reported[8] and our prediction indicates it may be up to twice as large as the transport response. Theoretically, these measurements indicate that lack of quantitative agreement in the IR regime[3] is caused by an effect not present at microwave frequencies. And practically, the ability to quantify the μGMR effect and its large magnitude in transmission may make it useful for application in microwave switching devices.

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R_S (Ω/□)	d (Å)	d_{CoFe} (Å)	t_{Exp} (%)	t_{Th} (%)	$t_{(1)}$ (%)	r_{Exp} (%)	r_{Th} (%)	$r_{(2)}$ (%)
20.20	300	35	1.02 ± 0.1 %	0.74	0.60	84.4 ± 1.6 %	85.4	85.2
22.97	300	35	1.35 ± 0.1 %	0.93	0.76	80.7 ± 1.6 %	83.6	83.4
24.12	280	15	1.24 ± 0.1 %	1.01	0.82	80.7 ± 1.6 %	82.9	82.7
26.23	290	25	1.86 ± 0.1 %	1.18	0.96	81.6 ± 1.6 %	81.7	81.4

TABLE I. Parameters for glass samples along with transmission and reflection coefficients. Experimental values (Exp) may be compared to predictions in Ref. 18 assuming a substrate with dielectric constant 6.0 of thickness 0.97 mm (Th) or to the simplified predictions in Eqs. (1) and (2).

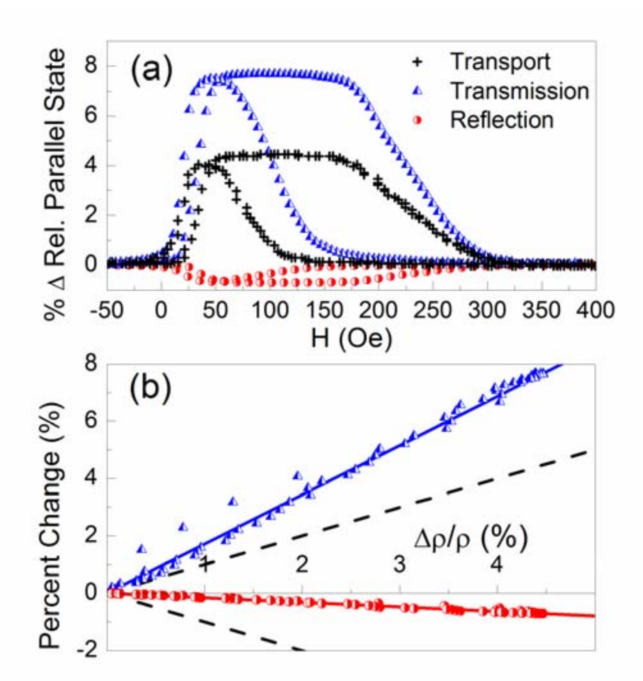

FIG. 1. (color online) (a) Measurements of Δρ/ρ, Δt/t, and Δr/r versus applied field for the sample with R_s = 23 Ω. (b) The same data plotted with Δt/t and Δr/r as a function of Δρ/ρ. Solid lines are fits to the slope of the data while dashed lines indicate a slope of ±1.

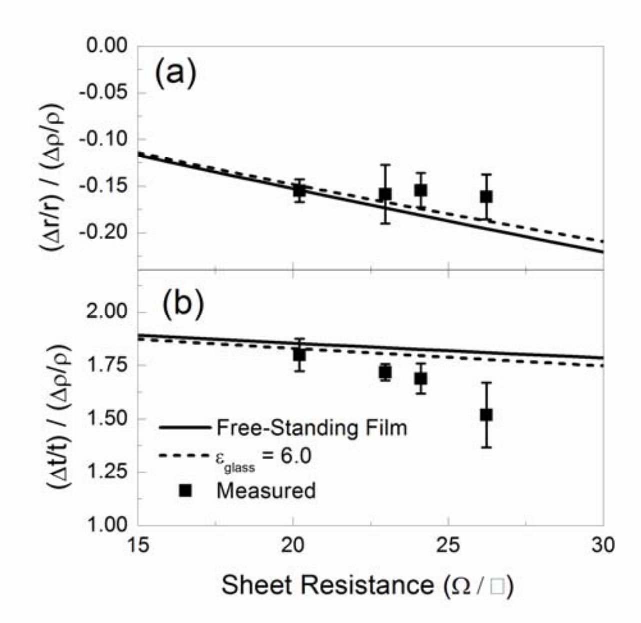

FIG. 2. Measured ratios (a) (Δr/r) / (Δρ/ρ) and (b) (Δt/t) / (Δρ/ρ) plotted versus sheet resistance. Solid lines are the prediction from Eqs. (3) and (4) for a free standing film with no adjustable parameters and dashed lines are the predictions in Ref. 18 including a substrate with a dielectric constant of 6.0.