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Additional Information

Ferromagnetic resonance in FeCoNi electroplated wires

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We have investigated the microwave properties (ferromagnetic resonance and ferromagnetic antiresonance) of FeCoNi magnetic tubes created by electroplating on CuBe wire. Important parameters such as the g factor, magnetization, anisotropy field and damping parameter were obtained from the measurements. One sample, prepared by a method which entails rf-sputtering deposition of an additional FeNi layer, shows a clear ferromagnetic antiresonance.

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I. INTRODUCTION

Amorphous and nanocrystalline magnetic wires,¹⁻⁷ microwires,⁸⁻¹³ and tubes¹⁴⁻²⁰ have been investigated very intensively during the last ten years due to their excellent soft magnetic properties which enable their use in many technological applications. In many cases, it was necessary to spend years of effort to improve the technology of fabrication before real interest in these materials appeared and led to a boom in research. For example, the dependence of the impedance of ferromagnetic wire on an external magnetic field was reported a long time ago.² As the effect was weak, it took more than 30 years before the general theory was written²¹ and more than 50 years went by until the demonstration of the magnetoimpedance sensor.²²

Another example of rediscovery involves electroplated wires. Almost 40 years ago, electroplated wire technology was developed and the wires were extensively studied in order to obtain plated-wire-based memories.¹⁴ The wire consisted of a CuBe nonmagnetic core plated with a few microns of a Fe₂₀Ni₈₀ magnetic layer. The readout was nondestructive and the quality of processing depended critically on the surface roughness of the plated film. Therefore, special efforts were required to control all of the important parameters. Although plated wire memories were not very competitive with thin-film memories due to domain-wall creep problems and relatively large size,¹⁴ the processing work on wire memories resulted in cheap and repeatable production methods.

The magnetoimpedance effect in NiFe plated wire reported by Beach *et al.*¹⁵ was, no doubt, a step in the rediscovery of these materials, not only for technological applica-

tions, but also for study of physics. Although the magnetoelectrical behavior of the FeNi tubes was described by assuming a quasi-single-domain state,¹⁵ many attempts were made to directly study or to take into account the domain structure of FeNi, FeNiCo, or CoP tubes.^{9,16,17} Magnetic bistability,¹⁹ Matteucci and inverse Wiedeman,²³ as well as giant magnetoimpedance effects in electroplated wires, both in linear¹⁶ and nonlinear^{13,20} regimes, were intensively studied during the last few years especially noting that high-order magnetic anisotropy may play a key role in many cases.

Electroplated wires show interesting properties and become competitive from some points of view with wires and microwires. For example, compared to cold drawn wires, bistable CoFeNi plated wires¹⁹ show higher values of the switching field. In low-frequency (<10 MHz) applications using electroplated wires, the magnetoimpedance effect in the nonlinear regime^{15,20} shows outstanding properties such as extremely high sensitivities, especially for even harmonics. As the theories of the effect²⁰ demand intrinsic properties, it is clear that all of the parameters, such as the magnetic layer thickness, roughness, anisotropy, and inhomogeneities, play a critical role. The technology of electroplated wire preparation is cheap and permits high repetition. One should expect to find interesting technological properties as well as physical processes in electroplated wires at both high and low frequencies.

In this work, we investigated high-frequency [ferromagnetic resonance (FMR) and ferromagnetic antiresonance (FMAR)] properties of FeCoNi magnetic tubes electroplated onto CuBe nonmagnetic wire as well as FeCoNi-FeNi bilayer tubes.

II. METHODS

Two types of samples with different compositions of the magnetic layer were studied (see Table II): Type AP: 100 μm

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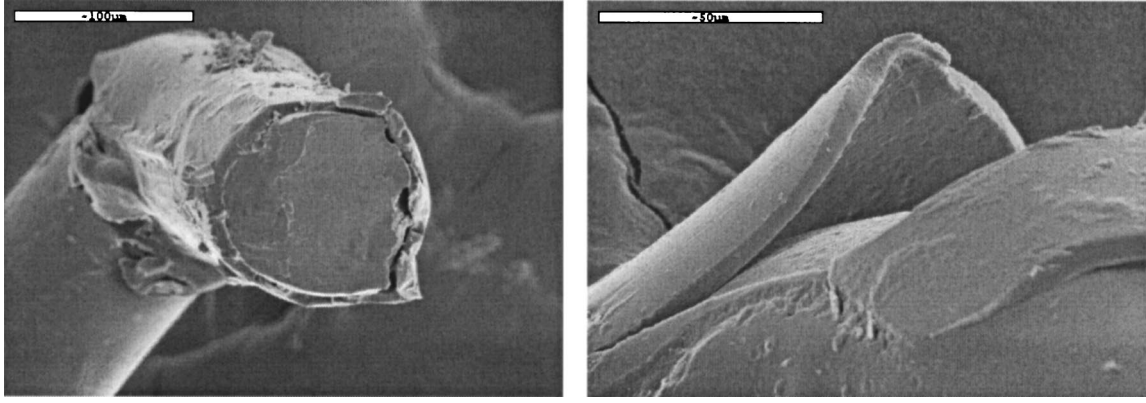


FIG. 1. Scanning electron microscopy image of electroplated wire. The wire has been bent to separate the magnetic shell to the nonmagnetic core.

diameter $\text{Cu}_{98}\text{Be}_2$ nonmagnetic wire covered by a $1 \mu\text{m}$ thick $\text{Fe}_{20}\text{Co}_6\text{Ni}_{74}$ electrodeposited magnetic layer and type TU: $60 \mu\text{m}$ diameter $\text{Cu}_{98}\text{Be}_2$ nonmagnetic wire covered by a $1 \mu\text{m}$ thick $\text{Fe}_{20}\text{Co}_{16}\text{Ni}_{64}$ electrodeposited magnetic layer. To reduce internal stresses and roughness of CuBe substrate, a buffer layer of $3\text{--}4 \mu\text{m}$ thick pure Cu was plated prior to the deposition of the magnetic layer. The quality of the interface can be estimated from the image of the mechanically separated magnetic layer (Fig. 1). The current flow through the sample during electrodeposition created a circumferential magnetic field resulting in a circumferential component of magnetic anisotropy.

In order to study the dependence of the high-frequency response on the parameters of the magnetic layer, we have selected different samples and treatments. Sample AP was given a special heat treatment in an Ar protective atmosphere where a dc magnetic field $H = 1.5 \text{ kA/m}$ was applied parallel to the wire axis for 1 h at a temperature of 300°C . The developed sample is labeled DC. This kind of sample, called FeNi, a composite wire, was prepared depositing a $2 \mu\text{m}$ thick $\text{Fe}_{19}\text{Ni}_{81}$ magnetic layer onto an AP wire with rf sputtering. The base pressure and the argon pressure during this deposition were 10^{-6} and 5×10^{-2} Torr, respectively. We have a specially designed wire rotating system inside the vacuum chamber to guarantee uniform thickness of the sputtered layer.

The longitudinal hysteresis loops for magnetic characterization of the samples were measured by a conventional inductive method for a frequency of 50 Hz in a magnetic field applied parallel to the wire axis.¹⁹ Although the easy magnetization direction was nearly circumferential for all of the present samples, the complex shape of the hysteresis loops gave us clues about the presence of the other components of the anisotropy. The coercive field H_c , of the samples varied between 1.3 and 6.9 Oe (Table II). That is, we have prepared wires with a range of values for H_c as well as magnetic anisotropy.

Microwave studies were done by a cavity-perturbation technique with conventional homodyne detection. The measurements were done at frequencies of 9.7, 26.7, and 56 GHz. An electroplated wire was located in the cavity such that the rf electric field was nearly zero. This is very important for highly conducting samples.²⁴ The dc field was ap-

plied along the axis of the wire while the rf-magnetic field was perpendicular to it.

III. RESULTS AND DISCUSSION

The $\text{Cu}_{98}\text{Be}_2$ nonmagnetic core of the electroplated wires has a resistivity of $3.9 \mu\Omega \text{ cm}$. The magnetic shell has a resistivity of $15 \mu\Omega \text{ cm}$ that gives an electromagnetic skin depth $\delta = \delta_0 / \sqrt{\mu}$ from $2 \mu\text{m}$ at 10 GHz to $0.8 \mu\text{m}$ at 56 GHz. Thus, we have essentially a planar geometry with both the dc and rf field lying in the same “plane.” For narrow lines, we expect to see FMR and FMAR in accord with the conventional equations,²⁵

$$\text{FMR: } \left(\frac{\omega}{\gamma} \right)^2 = (H_R + H_{an})(H_R + H_{an} + 4\pi M_{\text{eff}}) \quad (1)$$

$$\text{FMAR: } \frac{\omega}{\gamma} = H_T + H_{an} + 4\pi M_{\text{eff}} \quad (2)$$

$$\text{for } \omega \geq \gamma(H_{an} + 4\pi M_{\text{eff}}) \approx 2\pi(30 \text{ GHz}),$$

where ω is the angular frequency, $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, H_R and H_T are the resonance and antiresonance fields respectively, H_{an} is an anisotropy field and M_{eff} is the effective magnetization.

Figures 2–4 show the observed spectra, and the resonance field and linewidths are listed in Table I. The FMR spectra at 9.65 GHz are quite symmetric, showing a shape close to Lorentzian (Fig. 2).

One should expect to observe an FMAR for $f = \omega/2\pi > 30 \text{ GHz}$ as was previously observed for magnetic wires⁷ and microwires.²⁴ Although all of these samples show indications of FMAR in the 56 GHz spectra, only the FeNi signal is sufficiently strong to locate the dip with any confidence. Unfortunately, at 56 GHz, the overlap of the FMAR and FMR signals makes it impossible to delineate the FMR linewidth.

In order to obtain the parameter values using Eq. (1) (see Table II), we carried out a polynomial fit (Fig. 5). Clearly, H_{an} is vanishingly small in every case. The g values and $4\pi M_{\text{eff}}$ were calculated for all samples, and they are quite reasonable. The linewidth scales with frequency in only the FeNi sample. This is as expected for Landau–Lifshitz–Gilbert relaxation²⁵

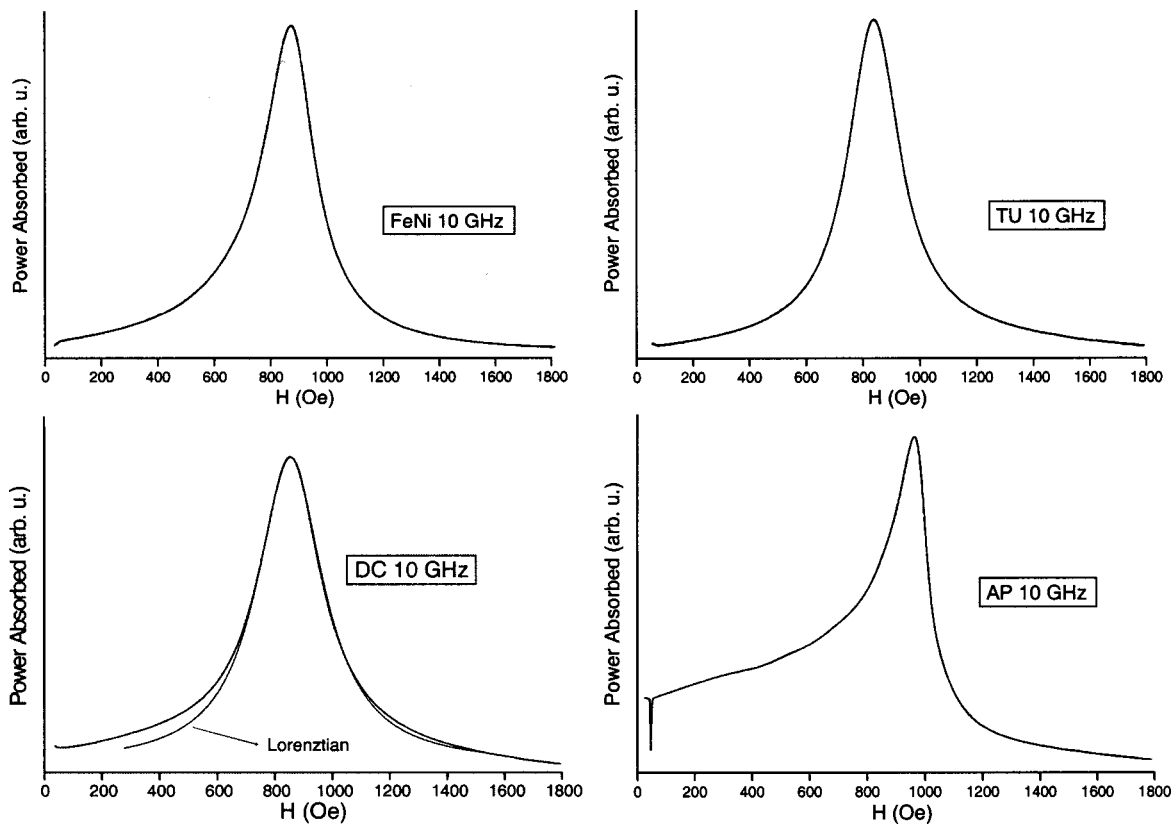


FIG. 2. FMR at 10 GHz.

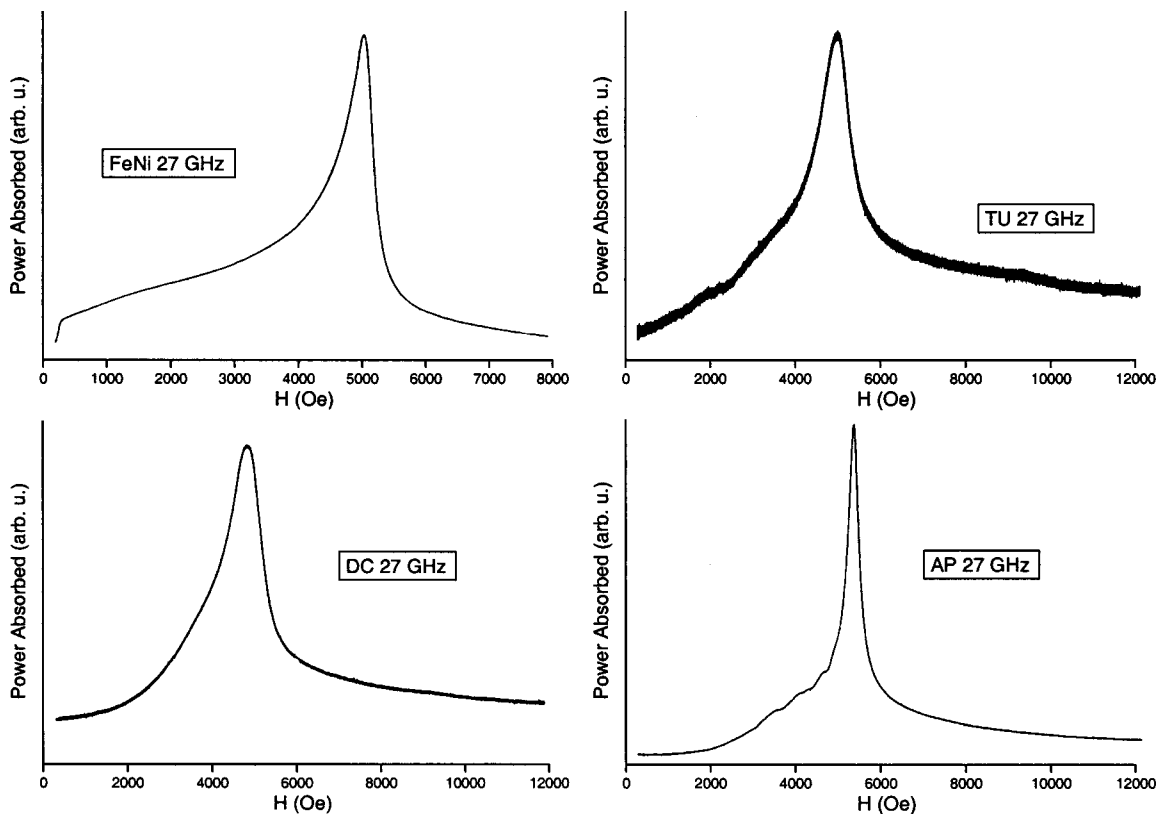


FIG. 3. FMR at 27 GHz.

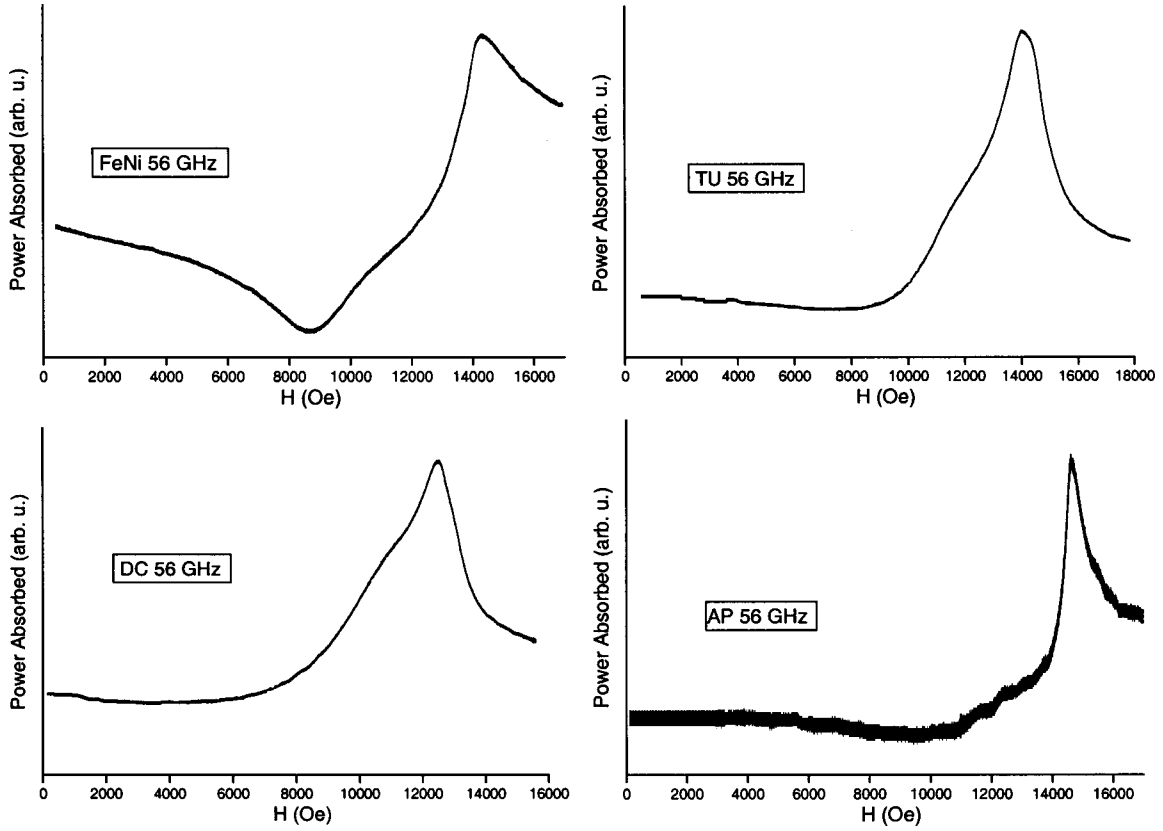


FIG. 4. FMR and FMAR at 56 GHz.

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\alpha}{M} \left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right), \quad (4)$$

where α is damping constant. For the 9.65 GHz measurements where the shape of the resonance line is close to Lorentzian, one may estimate the value of the Gilbert parameter α using

$$\Gamma_{\text{pp}} = \frac{1}{\sqrt{3}} \Delta H_{1/2} = 1.45 \frac{\alpha \omega}{\gamma}, \quad (5)$$

where $\Delta H_{1/2}$ is the resonance linewidth at half amplitude, and Γ_{pp} is the peak-to-peak linewidth for a Lorentzian spectrum. The Gilbert parameter α turns out to be about 0.035 (see Table I), which is rather high for permalloy.²⁵ It is arguable that the distribution of strains widens the spectrum. Different theoretical models were developed recently for the strain parameters for both the general case and FeCoNi electroplated wires.^{20,26}

In principle, one can use the parameter values of Table II to predict the position of the FMAR line at 56 GHz. How-

ever, the linewidth is so large that one cannot neglect the overlap of the FMR and FMAR. Thus, it is not surprising that there is poor agreement between the expected (7.7 kOe) and observed (8.8 kOe) values for H_T .

We have studied FMR and FMAR in the CuBe wires electroplated by FeCoNi magnetic layer. The resonance data are described by a planar geometry with both the dc and rf field lying in the same plane. Parameters, including the g factor, magnetization, anisotropy field and damping parameter were measured, and yield reasonable values although strain distribution may play a role.

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TABLE I. Resonance field in Oe (half-widths $\Delta H_{1/2}$), and Gilbert parameter α .

Sample/Frequency	9.65 GHz	26.7 GHz	56.1 GHz	α
FeNi	880 (295)	5000 (858)	14 300	0.035
DC	860 (288)	4900 (1362)	14 100	0.035
TU	840 (240)	5000 (1238)	14 000	0.030
AP	960 (241)	5300 (440)	14 600	0.030

TABLE II. Parameters values.

Sample	Composition	g_{eff}	$4\pi M_{\text{eff}}$ (kOe)	H_{an} (Oe)	H_c (Oe)
FeNi	Fe ₁₉ Ni ₈₁	2.08	11.6	-4.9	6.3
DC	Fe ₂₀ Co ₆ Ni ₇₄	2.09	11.9	-5.5	1.3
TU	Fe ₂₀ Co ₁₆ Ni ₆₄	2.17	10.2	64.5	3.0
AP	Fe ₂₀ Co ₆ Ni ₇₄	2.12	9.9	8.7	1.6

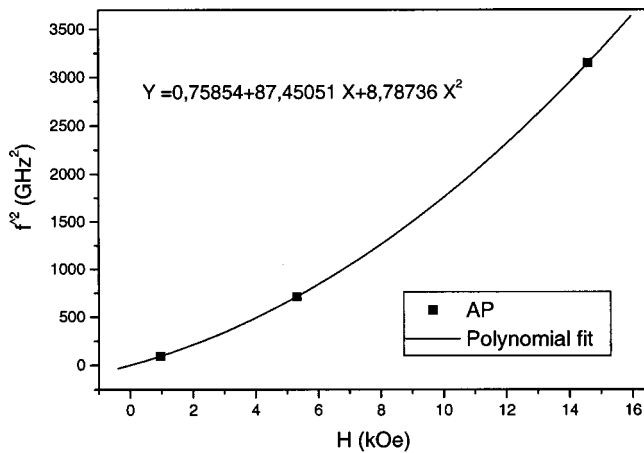


FIG. 5. Example of the polynomial fit (sample AP).

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