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On the Relationship between the Amplification of the NMR Spin Echo Signal and the Mobility of Domain Walls in Cobalt Micro- and Nanowires During Magnetization Reversal

Mamniashvili G., Gegechkori T., Donadze G., & Ivanov G.

1. Ivane Javakhishvili Tbilisi State University, Andronikashvili Institute of Physics, Tbilisi, Georgia

Abstract: A comparative study of the amplification of the NMR two-pulse echo signal in polymer composites based on synthesized and commercial cobalt nano- and microwires during their magnetization reversal was carried out. For this purpose, the two-pulse NMR spin echo method was employed, incorporating an additional magnetic video pulse (MVP) in an external magnetic field. The echo signal enhancement effect in the case of synthesized microwires is much greater than that of commercial nanowires, which may be due to the lower pinning force of domain walls and their greater mobility in them. This information may be useful for improving the technology for manufacturing cobalt nano- and microwires for use in sensors, memory devices, and permanent magnets that do not contain rare-earth elements, as well as in other applications.

INTRODUCTION

Magnetic nanowires are one-dimensional systems in which magnetization is organized into domains separated by domain walls (DWs)—narrow regions where the direction of magnetization changes. The dynamic behavior of DWs under applied magnetic fields plays a key role in applications such as spintronics, magnetic logic, and data storage. The use of NMR to study domain wall dynamics in magnetic nanowires is a rapidly developing research area. Nuclear magnetic resonance (NMR) techniques have proven valuable for investigating DW dynamics in magnetic nanowires, where traditional magnetic characterization methods often lack sufficient spatial or temporal resolution [1].

Traditional methods, such as magneto-optical Kerr effect (MOKE) microscopy or magnetoresistance measurements, provide macroscopic or surface-sensitive information. In contrast, NMR offers microscopic, site-specific insight into the local magnetic environment and spin dynamics within a nanowire.

In ferromagnetic materials, the local hyperfine field (HFF) at nuclear sites depends on the orientation and magnitude of the electron magnetization. Within domain walls, where magnetization rotates gradually, strong spatial variations in hyperfine fields arise. This results in enhanced coupling to the radiofrequency (RF) field: within DWs, the alternating magnetization induced by the RF pulse acts as an amplifier of the local RF field acting on the nuclei, often increasing NMR sensitivity by a factor of about 10^4 for DWs, compared to approximately 10^2 for nuclei within magnetic domains. Consequently, in many experiments, NMR signals predominantly originate from nuclei located within domain walls, making this method a selective tool for studying DW dynamics [2]. Since DWs are easily controlled by magnetic video-pulses (MVPs), their use provides a convenient approach for studying the formation of echo signals under the influence of MVPs [3]. Under the influence of applied MVPs, DWs can rapidly accelerate to velocities of several hundred meters per second. Methods for further increasing these velocities are being actively investigated to improve the performance of magnetic memory and logic technologies.

The dynamics of DWs in a single-crystal ferrite sample were first studied by Galt [4]. It was shown that the DW velocity (V) depends linearly on the amplitude of the MVP H_m:

$$V = S\,(H_m - H_0) \qquad (1)$$

where S is the DW mobility, H_0 is the critical pinning field below which the DW is pinned, and H_m is the MVP amplitude.

Even a small DW displacement can be accompanied by a large rotation of M. In this case, the rotation angle of M within the DW is proportional to the DW displacement. This process is accompanied by a change in the HFF at the nuclei, which is also proportional to the DW displacement, due to HFF anisotropy in magnets.

In this study, we employ a simple and effective electroless low-temperature chemical method for synthesizing cobalt micro- and nanowires through the self-organization of magnetic cobalt nanoparticles under the influence of a magnetic field, using the chemical synthesis technology for magnetic nanoparticles and nanowires described in [5].

Cobalt nanoparticles possess magnetic dipole moments. The presence of an external magnetic field forces them to align parallel to the field. Dipole–dipole interactions between magnetic nanoparticles generate attractive forces between cobalt particles, leading to their self-organization into nanowires and thereby reducing the total energy of the system. The resulting smaller nanoparticles fill the gaps between the ordered particles, contributing to the formation of smooth cobalt nanowires.

The NMR two-pulse echo (TPE) method, combined with an additional MVP, is used to study the characteristics of domain wall (DW) pinning centers in cobalt micro- and nanowires [6]. As shown in [6], the use of nuclear spin echo signals from nuclei located in the DWs of cobalt nanowires, in combination with MVP, is a convenient method for studying DW pinning centers and their mobility. This approach is of interest for controlling the synthesis of cobalt nanowires for potential applications in the development of permanent magnets that do not rely on rare-earth elements, as well as in information-processing devices and sensors. It is well known that the coercive force of a magnetic sample is directly related to the efficiency of DW pinning and, consequently, to the difficulty of detaching the DW from its pinning site.

In this paper, the magnetic and structural properties of the synthesized microwires and commercial nanowires are investigated using NMR and electron microscopy techniques. The NMR two-pulse echo (TPE) method, combined with an additional MVP, is used for the comparative study of the characteristics of DW pinning centers in cobalt micro- and nanowires during the magnetization reversal [6].

EXPERIMENTAL RESULTS AND DISCUSSION

The simple and inexpensive electroless method used in this study for synthesizing cobalt microwires is based on their formation from a chemical solution placed in a magnetic field. This method is described in detail in [5].

Figure 1 shows an electron diffraction pattern of a synthesized microwire sample obtained using a TESCAN VEGAS XMU scanning electron microscope.

<u>Fig. 1</u>: Electron diffraction pattern of a synthesized microwire sample.

An estimate of the average microparticle size based on the obtained histograms yielded values of 16 and 7.5 µm for the length and width of the microwires, respectively. As can be seen from Fig. 1, the synthesized sample is an agglomeration of much smaller submicron particles.

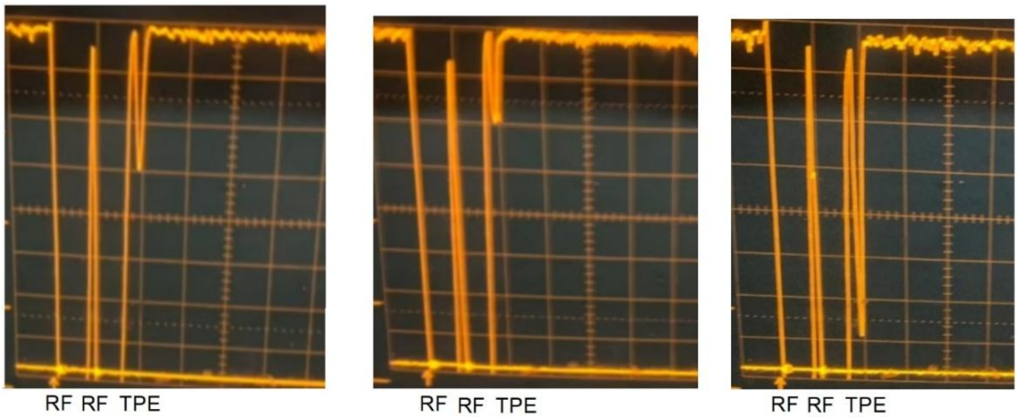
After obtaining the samples, capsules containing epoxy composites synthesized from the obtained wires were manufactured. The capsule containing the resulting sample was placed between magnets for 1 day in a magnetic field of 500 Oe.

Comparative measurements were conducted using commercial microwires from the German company PlasmaChem (Surface & Nano Technology). Their average diameter is 200–300 nm, and length is 200 µm, so they should be considered microwires rather than nanowires. These wires were used to produce cobalt–polymer nanocomposites, the properties of which were compared with those of polymer composites made from our synthesized cobalt microwires.

NMR measurements were performed on a phase-incoherent spin-echo spectrometer [3] in the frequency range of 200–400 MHz at a temperature of 293 K. A commercial Lecher-type generator with a two-wire line, including two inductors with different numbers of turns, was used in the 200–400 MHz range. With pulse lengths of 0.1–50 µs, the maximum amplitude of the RF field obtained on the sample was approximately 3.0 Oe, and the rise time of the fronts was no worse than 0.15 µs. The receiver dead time was about 1 µs.

NMR measurements were conducted using the TPE method with additional MVP H_m [5], applied in the interval between RF pulses, and in an external magnetic field H up to 200 Oe, generated by Helmholtz coils. The characteristic parameters of the RF pulses used were: a duration of 1 µs and a delay of 10 µs between RF pulses. A carrier frequency of approximately 213 MHz at room temperature coincides with the resonance frequency of nuclei at the center of the domain wall in the face-centered cubic phase of cobalt.

Figure 2 shows the dependence of the NMR TPE intensity in the studied cobalt microcomposite sample on the increasing magnetic field H, directed along and opposite to the magnetization M.



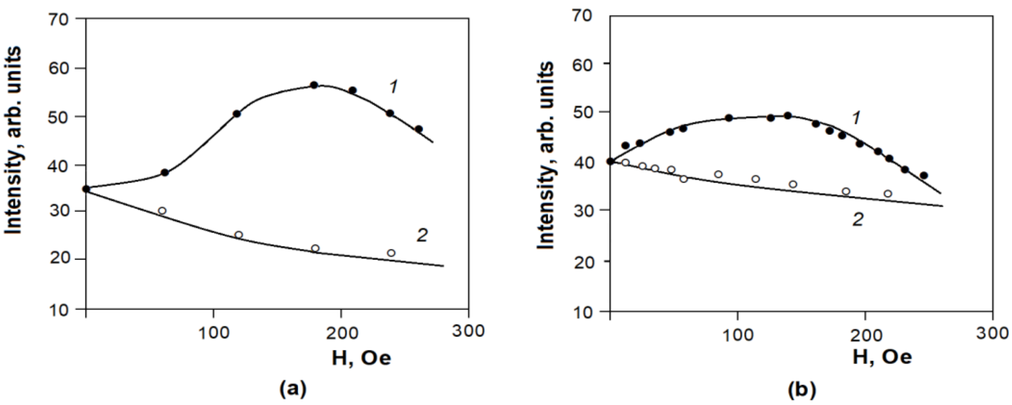
<u>Fig. 2</u>: Dependence of the NMR TPE intensity in the studied cobalt microcomposite sample on the increasing magnetic field H, directed along and opposite to the magnetization M: (a) H = 0, (b) H directed along M, and (c) H directed opposite to M.

As can be seen from Figure 2, a pronounced amplification of the echo signal is observed when **H** is directed opposite to M, whereas attenuation occurs when the field is applied along the magnetization direction. Measurements were carried out in an external magnetic field of H = 130 Oe, corresponding to the maximum increase in the magnetic susceptibility of the sample during magnetization reversal [6].

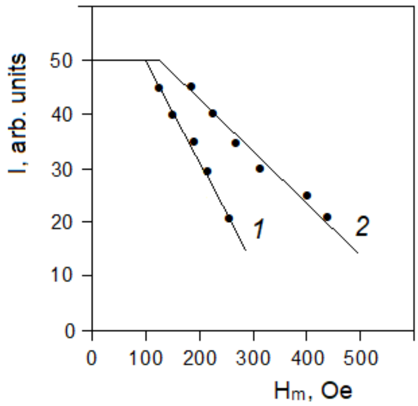
The dependences of NMR echo amplification and suppression on the value of **H** for the synthesized and commercial samples are shown in Figure 3.

Figure 3 shows the dependences of the TPE signal intensity on the amplitude of the MVP acting in the interval between the two RF pulses. It is seen that the TPE amplification effect is much larger in synthesized microwires as compared with one for commercial nanowires.

The dependence of the TPE signal intensity on the amplitude of the MVP acting between two RF pulses is shown for micro- and nanowires in Figure 4.



<u>Fig. 3</u>: Dependence of the TPE intensity I on the external magnetic field H, directed opposite (1) and along (2) the magnetization direction, for (a) a sample based on synthesized microwires and (b) a sample based on commercial nanowires (H = 130 Oe).



<u>Fig. 4</u>: Dependence of the TPE signal intensity on the amplitude of the 1 μs MVP H_m acting between two RF pulses: (1) a synthesized microwire and (2) a commercial nanowire.

As can be seen from Figure 4, the DW pinning force is lower in the sample based on synthesized microwires. The DW mobility, as determined by the parameter S from (1) and, consequently, by the slope of the $I(H_m)$ dependence in Figure 4, is higher.

The increase in the TPE signal intensity is apparently associated with an increase in the magnetic susceptibility, χ_{dis}, due to DW displacement during magnetization reversal. This leads to an increase in the gain of the transverse RF field acting on the nuclei, $\eta_{eff} \approx A \cdot \chi_{dis}$, where A is the hyperfine coupling constant, and to a corresponding increase in the absorbed NMR power, $P \sim \eta_{eff}^2 H_{RF}^2$ [2]. The echo signal enhancement effect in the case of synthesized microwires is much greater than that of commercial nanowires, which may be due to the lower pinning force of domain walls and their greater mobility in them accordingly Figure 4

CONCLUSION

Comparative studies of the amplification of the NMR two-pulse echo in polymer composites based on synthesized and commercial cobalt nano- and microwires during magnetization reversal were carried out. A two-pulse NMR spin-echo method with an additional magnetic video pulse in an external magnetic field was used. The magnetization inversion process was accompanied by an increase in the magnetic susceptibility of the sample and the associated amplification of the NMR two-pulse echo signal. The echo signal amplification effect in the case of synthesized microwires is much greater than that of commercial nanowires, which may be due to the lower pinning force of domain walls and their greater mobility in them.

These results may be useful for the development of cobalt microwires for sensors, memory devices, rare-earth-free permanent magnets, and other applications.

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