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Use of anisotropy of light transmittance in a system to measure the frequency of nanowires' rotation in a viscous liquid

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ABSTRACT

Fe nanowires with diameters of ca. 80 nm and lengths ranging from 1 to 3 μm were immersed in a viscous liquid and exposed to a static magnetic field in order to orient them in a specific direction. The nanowire suspension was illuminated with a laser beam. The light intensity was measured at the input and output. It was observed that the light transmittance of the nanowire system was strongly dependent on the nanowires' orientation in relation to the laser beam. The phenomenon was applied to measure the rotation frequency of the nanowires immersed in a liquid with a viscosity of 2 Pa · s. Rotation of the nanowires was enforced by a rotating magnetic field generated by a rotating magnet. On the basis of the obtained results it was observed that the highest frequency of the nanowires' rotation in the applied liquid, in a rotating magnetic field with induction of 46 mT, exceeded 382 Hz.

1. Introduction

Nanowires and their systems are currently used in numerous applications, such as atomic force microscopy [1,2], sensorics [3,4], electronics [5], microwave systems [6] and especially in biology and medicine [7–10].

Because our research is directed at novel applications of magnetic nanowires, we carried out investigations evaluating the possibility of controlling the rotation of magnetic nanowires immersed in a viscous liquid.

Such control is very useful in "supercatalysis". The idea of supercatalysis has been developed by the authors. It consists in that the activity of a catalyst in the form of Fe nanowires depends on that whether they are in motion or immobilized. In case of nanowires rotating at a frequency of 333 Hz their catalytic activity increases by ca. three times in comparison to motionless nanowires ([11] – patent application; paper in preparation).

Preliminary considerations allowed us to infer that the measurement of rotation frequency of magnetic nanowires based on the electro-magnetic induction phenomenon would be rather difficult because of the relatively weak magnetic signal expected from such tiny magnetic objects as nanowires.

As a basis for the developed method of controlling the rotation motion of nanowires, we considered the dependence of light transmittance of a nanowire system on the orientation of this system in relation to the light beam direction. The dependence was evident when ca. 5 mg of magnetic nanowires, placed in a glass phial filled with car oil, were subjected to a rotating magnetic field. The nanowires, moving in response to the interaction with the field, caused the modulation of the daylight reflected from them. The augmented effect was obtained after use of the light generated by a semiconductor laser (650 nm). As the modulation frequency of the reflected light was consistent with the frequency of the rotating magnetic field, we inferred that the effect could be used to measure the frequency of rotation of magnetic nanowires in viscous liquids.

As a result of the performed studies it has been shown that the light transmittance of an ordered nanowires system depends on the orientation of the nanowires in relation to the direction of the light beam and that this phenomenon can be used for measuring the frequency of rotational motion of nanowires immersed in a viscous liquid.

2. Experiment and results

In the studies, 25 mg of Fe nanowires were used. The nanowires were made by a known method – electrolytic deposition with the use of nanoporous anodic aluminum oxide (AAO) templates [12]. As raw materials in the process of the nanowire manufacture we used hydrated iron sulfate ($FeSO_4 \cdot 7H_2O$) and boric acid (H_3BO_3). Both the reactants were analytically pure (Hempur). The substrates were dissolved in distilled water to

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obtain solutions with concentrations of 120 g/l and 45 g/l, respectively. The solutions were mixed in a ratio of 1:1 and stirred with the use of a magnetic stirrer at 200 rpm for 5 min.

AAO templates in the shape of discs with an area of ca. 2.3 cm^2, a thickness of 60 μm and a pore diameter of 80 nm (Whatman) were used as dies to form the nanowires. On one surface of each AAO template a thin film of vacuum evaporated gold was used, which acted as a cathode. Sections of Fe wire of 99.99% purity, 0.6 mm in diameter and 7 cm long were used as the anodes.

The process of electrolytic deposition was conducted in a two-electrode system. The AAO template with a deposited electrode and the iron wire were connected to corresponding poles of an electric current source (HUA YI Electronic supplier, 0–10 A, 0–100 V), and then immersed in 40 ml of the mixture of previously prepared solutions of hydrated iron sulfate and boric acid. The supplied voltage was adjusted so as to obtain a current of 40 mA. The distance between the anode and cathode in this process was 2 cm and the process duration was 30 min.

After completion of the electrolytic deposition process, the AAO template, with nanopores filled with iron, was dissolved in a basic solution of NaOH (analytical purity, Hempur) with a concentration of 240 g/l in order to free the nanowires. In a single manufacturing process, ca. 5 mg of nanowires were achieved.

On the basis of SEM observations, it was shown that the diameter of the nanowires was ca. 80 nm and their length ranged from 1 to 3 μm (Fig. 1).

The nanowires were placed in a glass phial with an inner diameter of 6 mm and a wall thickness of 1 mm. The phial was filled with engine oil, Mobil 1 15W40, with a viscosity of 0.163 Pa s, which acted as viscous liquid. The viscosity was measured at 20 °C with the use of a Höppler viscometer (Model KF30). At a distance of 14 mm from the phial wall a commercially available Nd–Fe–B permanent magnet in the shape of a cylinder (length 14 mm, diameter 8 mm) was placed. The magnetic parameters of the magnet were as follows: $B_r=1.3$ T, $_JH_c=1800$ kA/m and $(BH)_{max}=320$ kJ/m^3. The magnet acted as a magnetic field source, orienting the nanowires in the desired direction. Induction of this field, inside the phial and at the point on its axis, at the height of the magnet rotation axis, was ca. 6 mT. The measurement of the magnetic field induction was taken with an F.W. Bell 5100 Series gaussmeter.

The suspension of the nanowires in the oil was illuminated with a light beam generated by a semiconductor laser ($\lambda=650$ nm). The light intensity at the system input was 440 lx. The light intensity of the laser beam after transition through the suspension was registered in time with a luxmeter (Mastech Lx 1330 B). Transmittance was calculated with the formula:

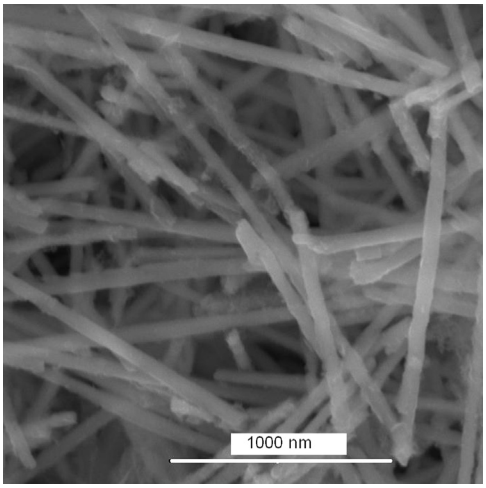

Fig. 1. SEM view of the Fe nanowires made in the electrolytic deposition process using an AAO template as a die.

$$T = \frac{E}{E_o} \times 100\% \tag{1}$$

where: T – the light transmittance of the nanowire system, E – the illumination intensity at the output of the system, E_o – the illumination intensity at the input of the system.

Transmittance was measured for two orientations of the nanowires in relation to the light beam: parallel $\alpha=0°$ and perpendicular $\alpha=90°$ (Fig. 2).

Just before the measurement of light intensity, in order to ensure the same arrangement of nanowire systems for both orientations, $\alpha=0°$ and $\alpha=90°$, the nanowires were dispersed. The process was carried out with a disperser in the form of an additional fast rotating permanent magnet with the same properties as the orienting magnet. The magnet was fixed in a special fixture and rotated at 5000 rpm. As a drive, an electric motor (Fig. 2a) was applied. The disperser was fixed at a distance of 7 mm from the axis of the phial (3 mm from its wall) so that the induction of magnetic field inside the phial was about five times higher than the induction of the field generated by the orienting magnet (26 mT). Such a ratio for both inductions ensured higher values of the dispersing forces in comparison with the orienting forces, and thus satisfactory efficiency of the dispergation process.

The measurements of illumination intensity were carried out in the dark.

Studies on the effect of the orientation direction of a nanowire system on its transmittance T were carried out in the static magnetic field of an orienting permanent magnet, directly after the dispergation process and after removal of the disperser from the system. In such conditions, the suspension of the magnetic particles is unstable. Particular nanowires orient in the direction of the magnetic field very quickly (Fig. 2b), linking in relatively long aggregates [13] (Fig. 2c) and are displaced in the direction of the highest field gradient (Fig. 2d). Because of these motions, the transmittance of the nanowire suspension changes over time. This makes its measurement difficult but the influence of the orientation direction on the transmittance is distinct (Fig. 3).

The most rapid changes take place in the first seconds of interaction of the static magnetic field with the nanowires. For the nanowire system oriented parallel to the light beam ($\alpha=0°$), in the first 10 s the transmittance rises from 3% to 50%. Further increase is significantly lower. In the following 90 s, the transmittance reaches the value of 76%.

For perpendicular orientation of the nanowire system ($\alpha=90°$) in the static magnetic field, the time – transmittance dependence – is similar, in terms of quality, to that for parallel orientation ($\alpha=0°$). However, the transmittance values are significantly lower. In the first 10 s, the transmittance achieves 18% but in the next 90 s, it rises only by about 11%, finally reaching the value of 29%.

Rapid changes in transmittance, occurring during the first 10 s after ceasing the dispergation, are connected mainly to the rotations of the nanowires (their orienting in the static magnetic field). Linear displacements of aggregates, along the direction of the highest gradient of the magnetic field induction, do not play an important role at this stage of the phenomenon, due to their remarkably lower rates. The movements, acting as a gradually uncovered screen, cause a slow increase in transmittance, noticeable later (after 10 s).

The most important observation at this stage of the experiment is the strong dependence of the transmittance of a nanowire system on its orientation in relation to the light beam direction (Fig. 3). During the first 10 s of the measurement, the system of nanowires oriented parallel to the light beam ($\alpha=0°$) shows three