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Eddy-current sensing of superparamagnetic nanoparticles with spiral-like copper circuits

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ABSTRACT

In the late years, magnetic nanoparticles are being increasingly used for biological analysis due to their good performance in both magnetic separation and magnetic detection. Recently, a novel method of superparamagnetic particle detection inspired on eddy current sensing was reported. An increase of the impedance of an RF-current carrying copper conductor is induced by the nanoparticles, whose origin relies on their superparamagnetic behaviour. The detection method joins large sensitivity, low-cost and simplicity which make it highly promising for biodetection as well as for particle characterisation. With the double aim of deepening in the physical origin of this particular kind of electromagnetic induction and of improving the sensing performance, this paper studies the detection of superparamagnetic iron oxide nanoparticles with copper-based printed wiring boards. As a result, the analysis of different geometries has lead to designs which spectacularly enhance the sensitivity respect to previous reports.

1. Introduction

The intersection of nanoparticles technology and molecular biology is nowadays affording major opportunities for devising new applications, processes or phenomena based on the nanoscale-associated properties [1,2]. In particular, the advances in superparamagnetic particles (SPP) detection promise a spectacular expansion of their application as biomolecular labels in biodetection technology [3–7]. Lowering the detection limit is a fundamental challenge that should desirably go with low costs, and fabrication and handling simplicity.

Recently, a conceptually novel method of SPP detection has been reported which benefits from their superparamagnetic state [8]. The thermally mediated agitation of their magnetic moment characteristic of the superparamagnetism makes possible the detection via a particular mechanism of eddy-current induction in an alternating-current-carrying conductor.

This technique shares some features with the eddy current testing (ECT) commonly used in non-destructive assays for inspecting conductive materials [9,10]. ECT is based on the mutual induction between an ac-current-carrying coil and the test material.

In the case of impedance-based detection of SPP, any significant effect from the main current upon the particles is unlikely: on one hand, they are too small for significant eddy currents to be induced in them and, on the other, large magnetic fields should be used to produce their magnetisation orientation. In fact, the magnetic moment of the SPP is rapidly switching due to thermal excitation, their oscillation rate being dependent on the temperature and the characteristics of the particles, but mostly independent of the main current flowing in the conductor. The changing magnetic field so produced induces in the conductor high frequency eddy currents which increase its impedance. Thus, being an electromagnetic induction, it is not the conventional mutual induction. This fact entails some remarkable differences in the detection particularities with respect to ECT, especially those regarding the frequency-related behaviour.

The present study undertakes the frequency analysis of different printed copper sensing circuits with the double purpose of providing a framework that should facilitate improved designs, and the deepening in the related physical comprehension of the superparamagnetic-induced detection.

2. Samples and methods

Commercial iron oxide nanoparticles were provided by NanoGap SL (NGAP NP FeO 2204-W) dispersed in water with concentration 2% (w/w) and nominal average size 10.5 nm. A

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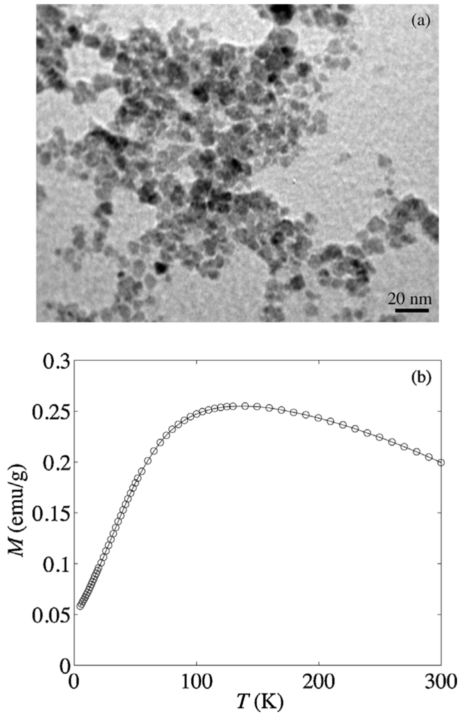

Fig. 1. (a) Transmission electron micrography of the iron oxide nanoparticles and (b) ZFC curve of a test sample strip with 640 μg of nanoparticles.

transmission electron microscopy image of the particles is shown in Fig. 1(a). The testing sample was prepared depositing and drying 40 μL of this solution onto a 10 mm × 2 mm blotting paper, 20 μm thick. The zero field cooling (ZFC) curve of the test sample strip was obtained by a SQUID magnetometer confirming the superparamagnetic state above the blocking temperature T_B = 140 K (see Fig. 1(b)). Fitting on the experimental data with a classical non-interacting superparamagnetism model, assuming a log-normal distribution of sizes, gives an average size of 13 nm with a standard deviation of 5 nm, both consistent with the technical data provided by the supplier.

The sensing printed circuits have been manufactured on a copper-clad laminate FR-4 by photoengraving using 35 μm thick and 0.4 mm wide traces. Several geometries of planar conductor lines have been analysed. Fig. 2 shows the designs used for the printed wiring boards (PWB): (a) PWB1 consists of a single straight line 40 mm long, (b) circuit PWB3M is a meander-line structure with three parallel 12 mm long conducting lines separated 0.4 mm and (c) PWB3S is a three-turn spiral-like circuit in which the traces are separated differently in the sensing area (0.4 mm) and in the rest of it (4 mm). A rectangular glass slot of 10.0 mm × 0.3 mm was installed over the sensing area [8] of every PWB to insert the SPP test strip (the SPP sample and the PWB are shown in the photographs of Fig. 2; on the corresponding templates appearing in the same figure, a rectangle has been drawn to indicate the sensing area).

Impedance measurements were performed with a 4294A Agilent Technologies Impedance Analyzer in the range from 1 MHz to 110 MHz using an exciting voltage of 500 mV. One metre test leads with 4-terminal port configuration were used to connect the sensing PWB to the analyser.

The response or sensitivity of the sensors is evaluated as the difference of impedance with and without SPP per unit mass.

3. Experimental results

The integration of the sensing element in a PWB entailed several advantages with respect to the single wires or ribbons used in the

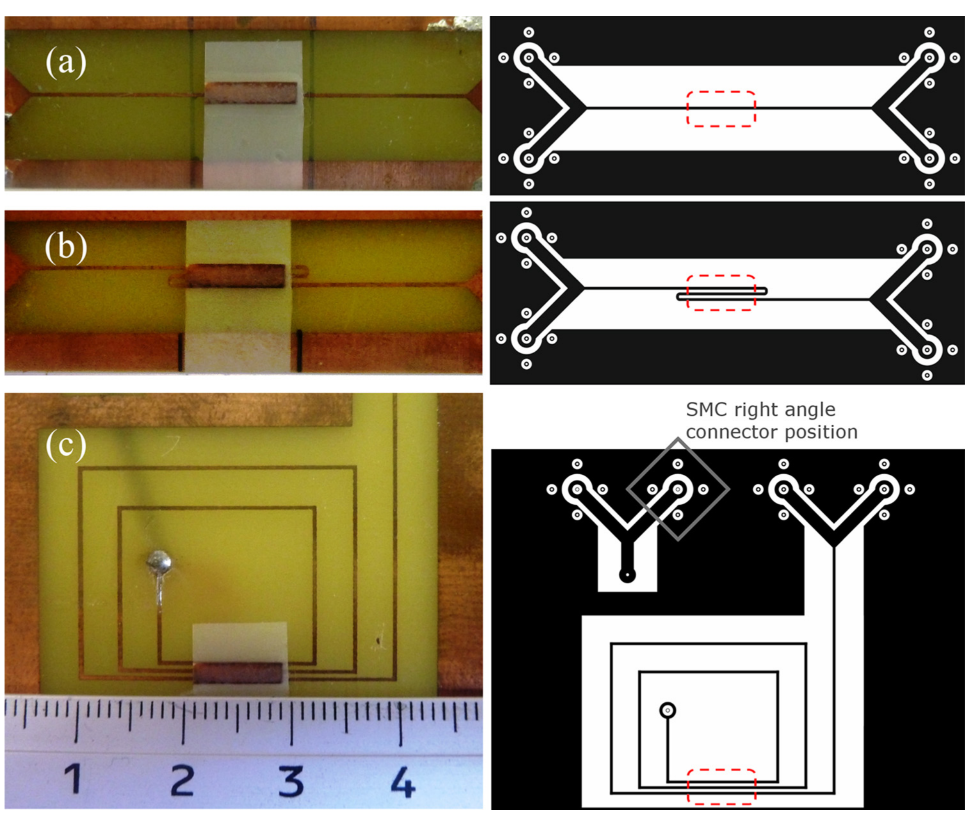

Fig. 2. Photographs of the sensing circuits and the SPP testing sample; on the right, template images of the three circuits indicating the sensing area over which the SPP sample is placed: (a) PWB1, an only straight strip, (b) PWB3M, a meander-line structure and (c) PWB3S, a three spires planar spiral-like circuit.