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Magnetostatic interactions in dense nanowire arrays

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Abstract

We demonstrate the importance of magnetostatic interactions in dense arrays of ferromagnetic nanowires. Beginning from a simple micromagnetic model, we have calculated the interaction field for saturated magnetization in the plane of the array (perpendicular to the axes of the wires) and normal to the plane, using a hybrid (numerical and analytical) strategy. The slope of interaction field versus wire length changes dramatically at the transition between a dipolar regime (at very small lengths) and a monopolar regime (for longer nanowires). We present the interaction fields and the applied fields at saturation for large nanowire arrays. These results are compared with experiment for electrodeposited arrays, and very good agreement is obtained. This shows that the high field behavior of such arrays is dominated by magnetostatic effects and that a nanowire array behaves like a double-sided distribution of magnetic monopoles.

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Keywords: Interaction field; Ferromagnetic nanowire arrays; Magnetized cylinder; Micromagnetics

1. Introduction

Arrays of ferromagnetic nanowires have been widely studied in order to understand their physical properties and to assess their usefulness in technical applications. These arrays may be readily fabricated by electrodeposition of Co, Ni, Fe and their alloys into the pores of various types of templates [1–6]. It has been observed that the applied fields necessary to saturate these arrays, both in the plane of the membrane and normal to the plane, are quite large. An attempt has been made [7,8] to model the observed behavior as arising from interactions between wires acting as point dipoles. While such a model is appropriate for nanodot arrays [9] and for very low aspect ratio cylinders [10], this is clearly not the case for wires which are many orders of magnitude longer than their diameters and than inter-wire spacings. We describe here a simple method for determining

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the magnetostatic field acting on a wire in an array. We first calculate the field produced by a wire saturated either along its axis (out-of-plane for the array) or normal to its axis (in-plane). We then obtain the field acting on a typical wire, by dividing the array into two regions. The region closest to the wire is treated by summing the effects of the other wires in the region by numerical methods. Beyond this region, the array is treated as a continuum, and its effect is calculated analytically. The results are then compared with experiment. The calculated and measured saturation fields are shown to agree well, showing that magnetostatic effects dominate the behavior of the arrays at saturation and above.

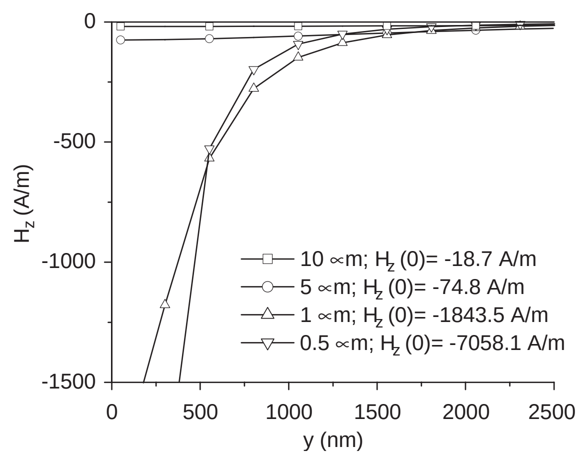

Fig. 1. The magnetic field from a positively axially magnetized nanowire along its median for different values of the wire length. The radius of the wire is 25 nm and the saturation magnetization 1.7×10^6 A/m. The origin of the y coordinate corresponds to the wire surface.

2. Magnetic field produced by a uniformly magnetized nanowire

First, we obtain the magnetic field produced by a uniformly axially magnetized nanowire whose radius is much less than its length. From symmetry, it is sufficient to calculate the field in a plane, yOz, in which the Oz axis corresponds to the wire axis, and $z = 0$ is at the median of the wire. The y-axis is normal to the wire, with $y = 0$ at the surface of the wire. Assuming that all wires are of the same length, we are interested in the fields for $-l/2 < z < l/2$, where l is the wire length, and $y > R$, where R is the wire radius. We find that for $y > 3R$, the fields can be obtained accurately by treating the wire as a linear chain of several thousand point dipoles. In the region $R < y < 3R$, that is for distances which may correspond to nearest neighbors, it is necessary to divide the wire into a grid of cubic and prismatic cells, each of which contains a point dipole. In order to perform numerical calculations, we need to specify $R^2 M_s$, where M_s is the saturation magnetization. In the following figures, we have taken R to be 25 nm, and M_s to be that of Co.

Fig. 1 shows the field, H_z, at $z = 0$ as a function of y, for positive axial magnetization, for four wire lengths, treated as linear distributions of 10 500 magnetic dipoles. In the dipole approximation the dipole corresponds to $M_s V$, where V is the wire volume. In fact, Fig. 1 shows that the field at $z = 0$ is very small, except for the shortest wires. The variation of this field with length is opposite to that predicted by the magnetic dipole approximation [7,8]. In the following figures, we show contour plots of the field for $-l/2 < z < l/2$ and for $80\,\text{nm} < y < 2500\,\text{nm}$. In Fig. 2 we show contours of H_z for axial magnetization; in Fig. 3 we show contours of H_y for transverse magnetization (parallel to y).

We may see from Figs. 2 and 3 that the magnetic dipole approximation, as we should expect, is valid only for ferromagnetic nanodots. For an axially magnetized wire, as the length of the wire increases, the magnetic field becomes smaller in its median region and becomes larger at its ends, where all sources of magnetic field are localized; the distribution of the magnetic field changes very little if one considers the ferromagnetic cylinder as a volume distribution of magnetic moments. That is, the treatment of a nanowire as a linear distribution of point magnetic moments works well in this application. For transversely magnetized wires, the in-plane magnetic field H_y is relatively uniformly distributed along the Oz axis with steep variations at the limits $z = l/2$ and $z = -l/2$ and its average value is almost independent of wire length. The numerical calculations show