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Dielectric relaxation in nanopillar NiFe–silicon structures in high magnetic fields

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Abstract

We explore the dielectric relaxation properties of NiFe nanowires in a nanoporous silicon template. Dielectric data of the NiFe–silicon structure show a strong relaxation resonance near 30 K. This system shows Arrhenius type of behavior in the temperature dependence of dissipation peaks vs. frequency. We report magnetic field dependence of dipolar relaxation rate and the appearance of structure in the dielectric spectrum related to multiple relaxation rates. A magnetic field affects both the exponential prefactor in the Arrhenius formula and the activation energy. From this field dependence we derive a simple exponential field dependence for the prefactor and linear field approximation for the activation energy which describes the data. We find a significant angular dependence of the dielectric relaxation spectrum for regular silicon and nanostructured silicon vs. magnetic field direction, and describe a simple sum rule that describes this dependence. We find that although similar behavior is observed in both template and nanostructured materials, the NiFe–silicon shows a more complex, magnetic field dependent relaxation spectrum.

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Keywords: Si:P; Nanostructured silicon; NiFe nanowires; Dielectric relaxation; High magnetic fields

1. Introduction

Dielectric relaxation is an important method to describe insulating or semiconducting systems since dc transport on very high resistance samples becomes increasingly difficult at low temperatures. Whenever the system in the insulating state exhibits a dipolar structure it is possible to find dielectric relaxation in some range of temperature and frequency due to the resonance condition $\ln(f) \sim 1/T$. In the present work we have been exploring the dielectric relaxation of NiFe nanowires electrodeposited in nanoporous silicon templates [1] as shown in Fig. 1. Although our work follows the general dielectric response seen in for semiconducting materials [2–6], the present investigation extends such studies to very high magnetic fields, where multiple relaxation structure emerges, and magnetic field direction dependent dielectric relaxation appears.

2. Experimental methods and results

Fabrication of magnetic nanowire arrays by electrodeposition is important for diverse applications in fields such as magnetic recording and bio-magnetics [7–9]. The nanoporous silicon was prepared by electrochemical etching of silicon substrate in a sulphate based electroplating bath [1]. The target pore diameter was controlled by resistance of template and the length of nanopores by changing of the etching time. Later NiFe was electrochemically deposited from a sulphate based electroplating bath into nanoporous silicon by using a Ni foil as anode. Fig. 1 shows a scanning electron microscope (SEM) image of the structure

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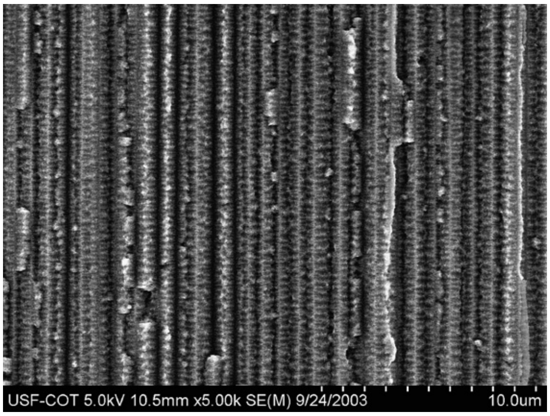

Fig. 1. High resolution SEM image of 290 nm diameter and 145 μm deep nanopores electrochemically etched in *n*-type Si substrate (resistivity: 0.4–0.6 Ohm cm).

and morphology of the nanostructured Si template [1]. Parameters associated with these materials include the electrical transport gap of 0.153 eV, which makes the dc conductivity difficult to measure below about 50 K. The NiFe ratio is 81:19, i.e. permalloy. The coercive field is below 500 Gauss, and the magnetization exhibits a Curie law dependence with decreasing temperature. There is no evidence for magnetic order above 4.2 K.

Dielectric measurements were carried out on [1 0 0] oriented Si:P and nanopillar NiFe–silicon. Sample geometries were rectangular, with dimensions typically 2 mm × 1 mm × 0.5 mm. For both samples results are collected with parallel plate silver paste electrodes normal to [1 0 0] direction, and in the case of the NiFe–Si, also normal to the nanopillars. The real (capacitative—*C*) and loss (dissipative—*D*) signals were measured with an ac capacitance bridge and lock-in amplifier. Measurements were carried out vs. temperature, frequency, and magnetic field at the National High Magnetic Field Laboratory. The results presented in Figs. 2–4 are obtained for ac electrical field perpendicular to the direction of the magnetic field (90° in the present notation).

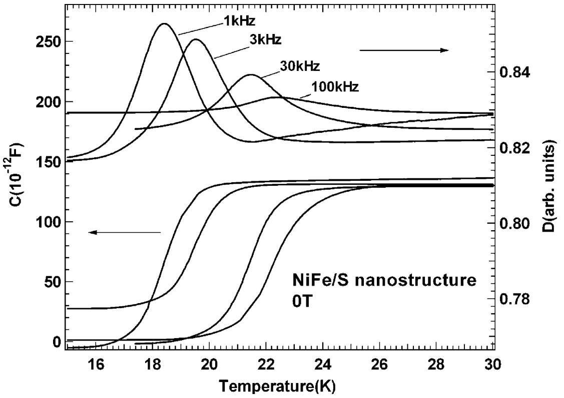

Fig. 2. Temperature dependence of real (left axis) and imaginary (right axis) dielectric constant for 1, 3, 30, and 100 kHz at zero magnetic field.

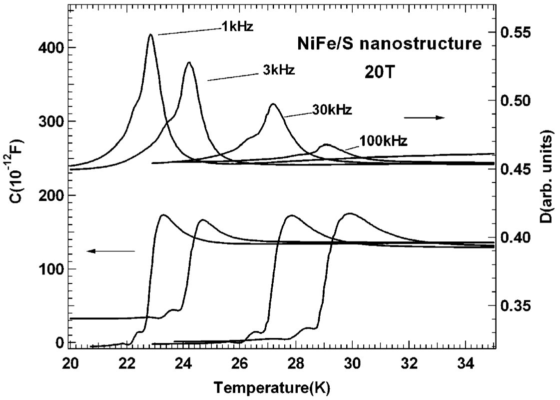

Fig. 3. Temperature dependence of real (left axis) and imaginary (right axis) dielectric constant for 1, 3, 30, and 100 kHz at constant magnetic field (20 T).

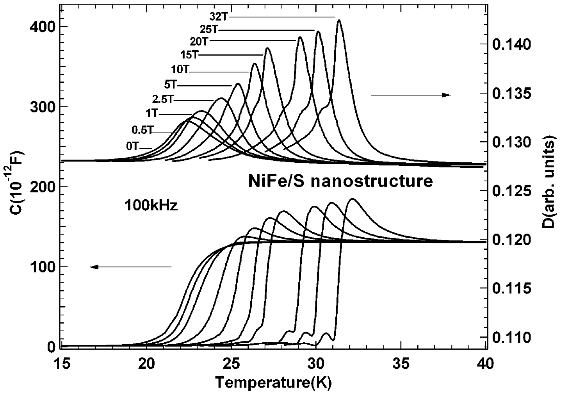

Fig. 4. Temperature dependence of real (left axis) and imaginary (right axis) dielectric constant (100 kHz) for different magnetic fields.

A dielectric system with a characteristic dipolar relaxation time $\tau = \varepsilon/\sigma$ has a characteristic frequency and temperature where the response exhibits a peak in the dissipation *D* (or ε'') and a phase shift in the capacitance *C* (or ε') response [10–12]. The relationship between *f* and *T* at resonance will follow an Arrhenius form for the relaxation rate $1/\tau = f(T) = f_0\exp(-E_a/T)$. Typical results for the frequency dependence are shown in Fig. 2 for the nanostructured NiFe–silicon system where capacitance and dissipation are monitored vs. temperature and frequency for zero magnetic field and in Fig. 3 for 20 T. In Fig. 4 the magnetic field dependence is shown for a frequency of 100 kHz. We find that the general behavior seen in Figs. 2–4 is characteristic of both the silicon template which is a Si:P system with about 10^{14} carriers/cm^3, and for the NiFe system, except for some important differences to be discussed in Section 3 below. In what follows, our analysis is carried out on the most pronounced peak feature in the dissipation.

The general frequency–temperature–magnetic field dependence of the dielectric relaxation may be summarized as shown in Fig. 5a. Here, for a specific field, an Arrhenius relation is followed for ln(*f*) vs. 1/*T*, where the slope