New reed switch design based on magnetic silver

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Abstract

A new composite magnetic material — silver doped with strontium ferrite nanoparticles (SFO NPs) — opens the way to the construction of reed switches which are based on a new design, which utilizes the fact that the SFO@Ag is metallic-conductive and magnetic at the same time. The induction of magnetism in the inert and stable conductive metals, as well as the use of powder instead of failure-prone metallic reeds, makes this new switch design attractive. Both the magnetic and conductive properties of the switch can be controlled by changing the percentage of the entrapped SFO NPs. This affects the magnetic saturation moments of the composites and the resistivity, as also shown by Hall Effect measurements.

Introduction

Magnetic switches, including reed switches, Hall effect sensors and magneto-resistive sensors, are widely used in various fields and applications due to their low open–circuit current consumption, better endurance under harsh environments and good mechanical stability [1, 2]. Standard reed switches [3] have a general design symbolized by ⭕️ — a flexible magnetic reed closes an electric circuit upon applying a magnetic field and opens the circuit when the field is removed (or vice versa) [4]. The reeds which close the electric circuit are made of a magnetized metal, mainly permalloy [5] [Ni 52% Fe 48%] [6, 7], placed in an inert-gas sleeve for protection. It is found in laptop position sensors, in car speedometer pulse counters, in pacemakers [8] and more [2, 9]. Reed switches are the preferable choice in many applications due to their simplicity and compatibility with low-power applications [10], making them highly used to date. They suffer, however, from a number of drawbacks such as wear and breakage, especially in applications where the device undergoes shocks and vibrations; bouncing [11]; and in cases of size limitations [12]. Reed switches also require surface coating such as Au-Rh or Au-Ru [5] for protection of the reeds from carbon contaminations [13], which can also lead to switch failure by surface erosion [7].

Here we describe a new design of reed switch which is based on the use of a new dual function metallic powder, which is both magnetic and conductive. The ability to obtain this dual functionality is based on the recently developed material methodology of molecular doping of metals [14, 15]. This methodology has been used to affect classical properties of metals such as their conductivity [16], work function [17], corrosion resistance [18], redox-potential [19] and catalytic activity [20], or induce properties which metals classically do not have such as luminescence [21] or ionic conductivity [22]. Of relevance to this report is the recent study in which the coinage metals — copper, silver and gold — were induced with magnetism by the extending the doping procedures from molecules to nanoparticles (NP), specifically to the NPs (d = 60 nm) of the ferromagnetic strontium ferrite, SrFe₁₂O₁₉ (SFO) [23]. Interestingly, the entrapment of these magnetic NPs in these metals (denoted SFO@metal) showed enhancement of the magnetic moment compared to bare NPs. The dual functionality of these materials opens possibilities for new design of devices which require both magnetism and metallic conductivity. We demonstrate the feasibility of this potential by a new design of a reed switch, the
operation of which indeed requires both magnetic response and electric conductivity, using SFO@Ag. Because of the entrapment no separation between the two components occurs after cycling of the powder in the switch, as would be the case in simple mixing of the two components. Conductivity and magnetism in the same material are also needed for observing the Hall effect [24], which indeed was detected in this composite material, are part of its full characterization.

### Experimental details

#### Chemicals and materials

Strontium ferrite nanoparticles (SrFe_{12}O_{19} (SFO), average size of 60 nm) were purchased from US Research Nanomaterials Inc. Ethylene glycol (EG, 99%) was purchased from Alfa Aesar. Silver nitrate (99.0%) was purchased from Sigma Aldrich.

#### Synthesis of SFO@Ag

The first step involves the dispersion of the SFO nanoparticles (NPs) in ethylene glycol (EG), which serves as a solvent, dispersant of the NP and a reducing agent for Ag. Silver nitrate (AgNO\(_3\)) was added and dissolved, and the suspension of the NPs in this solution was stirred with an overhead mechanical stirrer. The reduction of Ag\(^{1+}\) by EG requires basic conditions and therefore an NaOH solution (270 \(\mu\)l, 50 wt\%) (NaOH/Ag \(=\) 1 molar ratio) was added after 3 min of stirring. The suspension was kept under heating and stirring for 80 min. The product, SFO@Ag, was then filtered under vacuum using 0.2 \(\mu\)m Nylon filter paper (Merck Milipore), washed twice with distilled water, dried overnight under vacuum and ground. 280 mg of dry dark-grey powder at 5.97 SFO wt\% were received. Other SFO wt\% concentrations (table 1) were prepared similarly.

#### Hall effect measurements

Rectangular pellets were prepared by placing \(\sim 120\) mg of the powder in a \(5 \times 10\) \(\text{mm}^2\) press mold and pressed under vacuum at 4000 psi for 10 min. The width of the pressed pellets was 390–460 \(\mu\)m. Hall measurements were performed using a traditional van der Pauw configuration with four contacts at the corners of the samples. The system used was a low resistivity configuration of Lake Shore model 8404 at DC Magnetic Field of 1 T. Ohmic tests of the sample contacts were performed prior to measurements.

#### Additional instrumentation and measurements

High resolution scanning electron microscopy (HR-SEM) was carried out with an FEI Sirion instrument fitted with an EDS free detector. Nitrogen adsorption/desorption isotherms were obtained with a Micromeritics ASAP 2020 instrument, from which surface areas were determined using the BET equation, and pores size from the BJH equation. Density measurements were performed using a Micromeritics Accupyc 1340 pycnometer. The SFO concentrations in the composite were determined by the powder x-ray diffraction (XRD) Rietveld method [25] using a Philips diffractometer (CuK\(_{\alpha1}\) (1.5406 \(\text{Å}\)) with a step scan mode 0.02 s\(^{-1}\)). Isothermal magnetization was measured with a commercial (Quantum Design) superconducting quantum interference device (SQUID) magnetometer. Reed switch resistance was measured by SAKAL DT-832 multimeter. Chronoamperometry was carried out with a CH instruments potentiostat at 3 V.

### Table 1. Magnetization and resistance of SFO@Ag.

| Composite | SFO [wt%] | Remanence | Max moment (at 30 kOe) | SFO wt% | Resistance [Ω] |
|-----------|-----------|-----------|------------------------|---------|---------------|
| SFO@Ag    | 0.89      | 0.7       | 2.8                    | 1.0     | 55 ± 2        |
|           | 1.82      | 1.0       | 4.0                    | 2.0     | 56 ± 5        |
|           | 6.89      | 1.2       | 4.6                    | 4.0     | 143 ± 15      |
| SFO NPs   |           |           |                        | 67.0    | 16.9          |

**Table 1.** Magnetization and resistance of SFO@Ag.
Results and discussion

The macroscopic behavior of magnetic SFO@Ag as a permanent magnet is shown in figure 1(a) for a pressed disc, magnetized by a permanent dc magnet: It is seen that iron powder sprinkled around it, follow the magnetic field lines.

HR-SEM imaging (figure 1(b)) shows that the SFO@Ag (5.97 wt%) powder is composed of micrometric silver aggregates with both individual and aggregated SFO NPs. Nitrogen adsorption-desorption isotherms (figure 1(c)) analyzed by the BET equation reveal a low surface area of 2.3 m² g⁻¹. The good compliance with that equation (figure 1(c), inset) indicates that the powder, the density of which is 9.2 g ml⁻¹, is homogeneous.

XRD patterns (figure 1(d)) shows that the crystal structure is not affected by the doping, and confirms the presence of the SFO. The silver crystallite size, determined from XRD pattern using the Scherrer equation, is 55 nm (figure 1(d)) compared with 42 nm for pure silver prepared by the same method. The resistance is 143 ± 15 Ω, higher than pure silver (43 ± 9 Ω), but still a very good conductor for the switch purposes. Several other concentrations of SFO were tested as well (table 1) and it was found that the closed circle resistivity improves with lowering of the SFO concentration. However, since the magnetization is lowered as well (table 1 and figure 1(e)), the high SFO concentration was taken; this concentration still retains high metal conductivity.

Hall Effect measurements were conducted in order to examine the conductive response of the composite. We recall that in the Hall Effect measurements the resistivity, \( \rho \), is calculated directly from:

\[
\rho = \frac{R_H}{\mu_H};
\]

where \( \mu_H \) is the Hall charge carriers (electrons) mobility (in cm² V⁻¹ s⁻¹) and \( R_H \), the Hall coefficient (in cm³ C⁻¹), is:

\[
R_H = \frac{1}{n^* e} = \frac{V_H}{I^* B},
\]

where \( n \) is the charge carriers’ density (in cm⁻³), \( e \) is the charge of an electron (in C), \( V_H \) is the measured Hall voltage (in V), \( t \) is the thickness of the sample (in cm), \( I \) is the applied current (in A) and \( B \) is the applied magnetic field (in G). Therefore:
were carried out on these discs: a m o u n to fd o p a n ti sd u et ot h el o w e rn u m b e ro fs i l v e ra t o m sp er cm³ and therefore also in the amount of separated from the metal matrix upon repeatedly switch operation. The design can be tailored and modi-

unlike simple mixture of magnetic and conductive components, the entrapped magnetic NPs cannot be needed; there is no need for mechanical movement of the wire reeds; and the reeds are simple metal wires. Powders are much less exposed to mechanical failures; the powder does not need coating; no inert-gas sleeve is w i t har e sp o n se t i m eo f speci-

applications of this switch; the average is higher—4.68 ± 0.14 mA for 5000 cycles of closing and opening with a response time of ∼0.1 s.

In conclusion, the new reed switch design provides several features not found in the classical reed switch: Powders are much less exposed to mechanical failures; the powder does not need coating; no inert-gas sleeve is needed; there is no need for mechanical movement of the wire reeds; and the reeds are simple metal wires. Unlike simple mixture of magnetic and conductive components, the entrapped magnetic NPs cannot be separated from the metal matrix upon repeatedly switch operation. The design can be tailored and modified for specific requirements’ including miniaturization.

that is, the resistivity decreases (and conductivity increases) when the Hall mobility and the charge carrier’s density increase. For measuring the Hall effect, two different SFO loadings (1.63 and 5.97 wt%) in silver, as well as pure silver powder were pressed to 5*10 mm² pellets (390–460 μm thick). Three types of measurements were carried out on these discs: (a) Charge carrier density (n) (figure 2(a)): The decrease in n with growing amount of dopant is due to the lower number of silver atoms per cm³ and therefore also in the amount of conduction electrons. (b) Charge carriers mobility (μH) (figure 2(b)): Unexpectedly, the low loading enhances the mobility compared to pure silver, whereas the high loading decreases it. The significant increase in the Hall mobility at low SFO loading (1.63 wt%) can be explained by the ability of the dopant (up to certain amount) to fill the pores and holes between the silver aggregates. The SFO particles act as bridges between the silver aggregates, due to the conductivity mechanism of SFO [26, 27], which improves the ability of the electrons to drift along the sample at fixed electric field. At higher dopant loadings (5.97 wt%), the SFO NPs are more aggregated and therefore separate the silver aggregates to the degree of affecting the electrons mobility. (c) Resistivity (ρ): The results (figure 2(c)) show that the resistivity of the powder-pressed pure silver, while higher than bulk silver [28], remains in the same order of magnitude. According to equation (3), the resistivity depends reciprocally on the charge carrier concentration and the mobility. Therefore, the high loading SFO@Ag exhibits somewhat higher resistivity in comparison to un-doped silver, whereas the resistivity of the low loading SFO@Ag decreases due to the mobility increase and despite the slight decrease in charge carrier concentration.

Our concept design of the reed switch shows the feasibility of a repeatedly operating a reed switch with the composite powder. In the new design magnetized reeds are not needed — simple conductive wire reeds, such as the conductive copper wires linked to the switch, are sufficient, as the magnetic-conductive powder closes and opens the circuit by nearing or removing an external magnet to it — see figure 3. It was constructed as follows: two copper wires were glued to the upper side of a hollow glass tube with a space of about 1 cm between them and were connected on the other side through an electrical circuit with a white LED lamp. ~20 mg of the SFO@Ag powder was placed in a glass tube (vacuum, as in some current reed switch designs is not needed) and held on the bottom side gravitationally (open circuit); nearing a magnet, lifts the conductive powder, and the circuit closes. In order to demonstrate the cycling ability of the device, a device was built were the external magnet was rotated, with an electrical motor, at a frequency of ~1.8 Hz, and the copper wires were connected to a potentiostat (CH instruments, at V = 3 V)). Chronoamperometry (figure 4) showed stability of passing at least 1.0 milliamp (a current which suf-fi-

Figure 2. Electrical and Hall effect parameters of the composites. (a) Carrier density, (b) carrier mobility and (c) resistivity of 5.97 wt% SFO@Ag (red), 1.63 wt% SFO@Ag (blue), Ag control (gray) and literature value [26] of Ag (black).

$$\rho = \frac{1}{e \mu_H n}$$

Figure 4.
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