Electrical Properties of Nanostructured Magnetic Colloid and Influence of Magnetic Field *

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We investigate the electrical properties of the nanostructured magnetic colloid without and with magnetic field. The competition between the directional motion of the charged magnetic nanoparticles and other minor nonmagnetic impurities (also small amount of ions) under applied voltage and their random orientation due to thermal activation is implemented to elaborate the electrically conduction mechanism under zero magnetic field. Two equivalent electric circuits are employed for explaining the charging and discharging processes. The tunnelling conduction mechanism upon application of externally magnetic field may exist in the nanostructured magnetic colloid. The alternation of the two conduction mechanisms accounts for the current spikes when the magnetic field is switched on or off. This work presents the peculiar electrical phenomena of the magnetically colloidal system.

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Magnetic colloid is a stable suspension of magnetic nanoparticles dispersed in a suitable organic or inorganic liquid carrier, which is also called magnetic fluid or ferrofluid. The first stable surfacted magnetic colloid was made by Papell in the 1960s using size reduction method and was used to produce magnetic propellant under zero-gravity condition in space.[1] Since then, the methods for fabricating magnetic colloids have been optimized and diversified gradually. These result in improvement of the quality of the magnetic colloids. Until now, many properties of the magnetic colloids have been discovered and studied extensively by researchers, for instance, phase separation and aggregation,[2−5] heat and mass transfer,[6] hydrodynamic,[7,8] magneto-optical,[9] and optical properties.[10,11] Nowadays, as the techniques of magnetic colloids are sophisticated and knowledge of magnetic colloids is comprehensive, many applications based on magnetic colloids have been implemented in the fields of acoustics, mechanics, optics, biomedicine, etc., and some devices are commercially available. In addition, many potential devices based on magnetic colloids have been demonstrated by researchers in laboratories.[12−16]

Electric transport properties and electric resistance are critical parameters of the optoelectronic and electronic devices. Furthermore, materials with tunable electric properties are favourable for their applications. Therefore, many researchers are interested in this scope.[17−20] Then magnetoresistance material attracts great interest in the past years.[21−23] Its resistivity is dependent on the externally applied magnetic field. Furthermore, the magnetoresistance of nanosized materials (such as, nanowires, nanoconstrictions, nanocontacts) is revealed to be very large and much attention is paid to it by researchers.[24−28] All of the above studies are based on solid materials, and few attempts have been made on a colloidal system, which seems to possess relatively complex physical processes. In this Letter, we study the electrical properties of the nanostructured magnetic colloid and the influence of the applied magnetic field.

The nanostructured magnetic colloid employed in this work is a water-based magnetite magnetic fluid with density of 1.20 g/ml purchased from Anhui Jinke Magnetic Liquids Co., Ltd. The waterproof glue is used at one end of a capillary with inner diameter of about 1.5 mm to fix an electrode and seal the outlet. Then, the magnetic fluid is injected into the capillary from the other end. Afterward, another electrode is placed at the other end of the capillary and make sure of good contact between the electrode and the magnetic fluid. Finally, the waterproof glue is used again at this end to fix the electrode and seal the magnetic fluid inside the capillary. The real photograph of the home-made ultimate sample is shown in

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the upper part of Fig. 1. The length of the magnetic fluid inside the capillary between the two electrodes is around 20 mm.

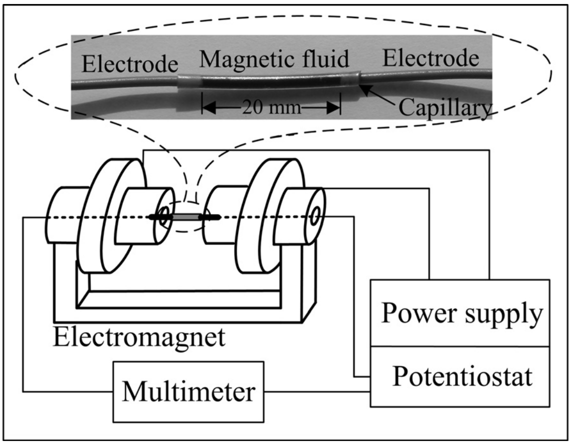

Fig. 1. Experimental setup for studying the electrical properties of the magnetic fluid.

Figure 1 shows the experimental setup for studying the electrical properties of the magnetic fluid. A potentiostat is used as the electric source and the sample and a multimeter are connected to it in series. In our experiment, the voltage of the potentiostat is set at 1.3 V and the multimeter is utilized to monitor the current of the circuit. An electromagnet with a hole in the middle of each pole is introduced to the electric circuit to generate a magnetic field in the sample region for investigating the influence of magnetic field on the electrical properties of the magnetic fluid.

When the voltage is applied to the two electrodes, the multimeter displays that the current of the circuit decreases with time monotonically and then reaches a steady state value after a long time relaxation, which is shown in Fig. 2. The current I in Fig. 2 is normalized to the first recorded value I_0. From Fig. 2, we can see that tens of minutes are needed for the electrical relaxation process. This relaxation property is assigned to the charging effect and Brownian motion of the nanoparticles. Upon applying voltage to the electrodes, the magnetic nanoparticles and other minor nonmagnetic impurities will be charged. Meanwhile, a small amount of ions (like Fe^{2+}, Fe^{3+}) may exist in the magnetic fluid. The positively charged species (magnetic nanoparticles and nonmagnetic impurities) and ions will be attracted to the negative electrode and the negatively ones will be attracted to the positive electrode. This causes the current in the magnetic fluid. In the one-dimensional conduction case, the current density $j(t)$ is given by[29]

$$j(t) = \sum_i n_i(x,t) q_i(x,t) \mu_i(x,t) E(x,t), \qquad (1)$$

where n_i, q_i and μ_i are the density, charge and mobility of the ith charged species and ions, respectively. $E(x,t)$ is the electric field at position x and at time t. Owing to the Brownian motion of the nanoparticles and the viscous drag of the magnetic fluid, the charged species and ions are not attracted to the electrodes immediately, which will result in the space-charge-limited effects and obstruct the motion of the later charged species and ions due to Coulomb repulsion effect. Therefore, the mobility of the charged species and ions μ_i decreases with time, while the density of the charged species and ions n_i may increase with time. According to Eq. (1), the experimental decrease of current in the magnetic fluid with time implies that the former predominates over the latter in this process. With time elapsing, a dynamic balance will be built between the directional motion and the random orientation (also Coulomb repulsion and viscous drag) of the charged species and ions. Then, the current within the magnetic fluid comes to a final steady value. It is worth noting that Novotny and Harbour have also discovered the electrically monotonic relaxation property of a nonaqueous magnetic colloid contained in a thin planar cell by a sudden application of constant electric field except the short charging capacitive spikes.[29]

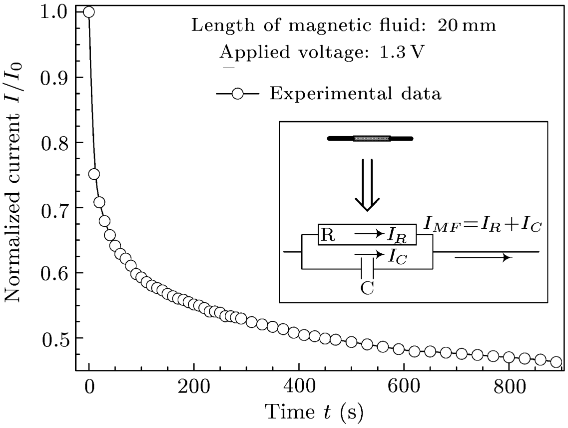

Fig. 2. Normalized current passing through the magnetic fluid as a function of time t.

Another conduction mechanism that may occur in the magnetic fluid is the tunnelling-type conduction between the nanoparticles. When the magnetic nanoparticles approach each other, part of the charges on the charged nanoparticles will tunnel to the other ones according to quantum mechanics. This tunnel resistance decreases with the spin polarization of the magnetic fluid. That is, the tunnelling conduction effect is enhanced when the magnetic moments of the nanoparticles are aligned in parallel.[22] Though magnetite ($\mathrm{Fe_3O_4}$ with spinel structure) is half metal with 100% spin polarization of conduction electrons,[21] the magnetite nanoparticles with single magnetic domains in the magnetic fluid move randomly under zero magnetic field due to thermal agitation, which makes the durative parallelism between the magnetic moments of the nanoparticles impossible. Hence, the tunnelling-type conduction mechanism is insignificant in the magnetic fluid at zero magnetic field. Altogether, the conduction current in the magnetic fluid under zero magnetic field should be attributed to the interaction between the directional motion of the charged species and ions within the electric field and their random Brownian motion. Due to small amount, the ions give little contribution to the current when comparing with the charged species.

In order to testify that the magnetic nanoparticles and other minor nonmagnetic impurities are charged, we have carried out a discharging experiment. After electrifying the magnetic fluid for an hour, the two electrodes are connected with each other by a multimeter to monitor the discharging current as shown in the inset of Fig. 3. The normalized discharging current as a function of time is depicted in Fig. 3, which expresses a typical discharging feature of a capacitor. This is ascribed to the charging effect of the magnetic fluid when it is electrified. However, this discharging process has a much long characteristic time, which is caused by the Brownian motion of the nanoparticles and the viscous drag of the magnetic fluid. When the two electrodes are connected to each other, the opposite charged species within the magnetic fluid can not quickly move to the electrodes for neutralization because of Brownian motion and viscous drag of the magnetic fluid. Thereby, long time is required for the charged species to neutralize, so is the discharging process. This discharging effect confirms that the magnetic nanoparticles (also a few nonmagnetic impurities, but they alone can not lead to this phenomenon) have been charged during the previous step. If charging effect does not exist, the current in the magnetic fluid is only carried by the ions. Then the discharging phenomenon can not occur. Thus the above-mentioned analysis of conduction mechanism within the magnetic fluid is supported.

Considering the particular electrical properties of the magnetic fluid, the magnetic fluid in the circuit can be taken as an equivalent resistance and an equivalent capacitor in parallel connection. Its equivalent circuit is shown in the insets of Figs. 2 and 3. Thus, during the charging process the current flowing through the magnetic fluid, I_{MF}, is the summation of the current flowing through the equivalent resistance $R(I_R)$ and the equivalent capacitor C (I_C), that is, $I_{MF} = I_R + I_C$. At the beginning of electrifying the magnetic fluid, I_R is considered as a constant because the applied voltage is constant. I_C decreases with time when the charging of the equivalent capacitor proceeds. Consequently, the total current I_{MF} decreases with time as shown in Fig. 2. After a long time, charging the equivalent capacitor is completed and then $I_C = 0$. Now the total current $I_{MF} = I_R$ is almost a constant, which is illustrated in Fig. 2. As shown in Fig. 3, during the discharging process the current passing through the multimeter I_A is equal to the discharging current of the equivalent capacitor C (I_C), which is the discharging current I_{MF} of the magnetic fluid, that is, $I_{MF} = I_C = I_A$. Therefore, the total time-dependent current of the circuit is like the discharging effect of a capacitor as exhibited in Fig. 3.

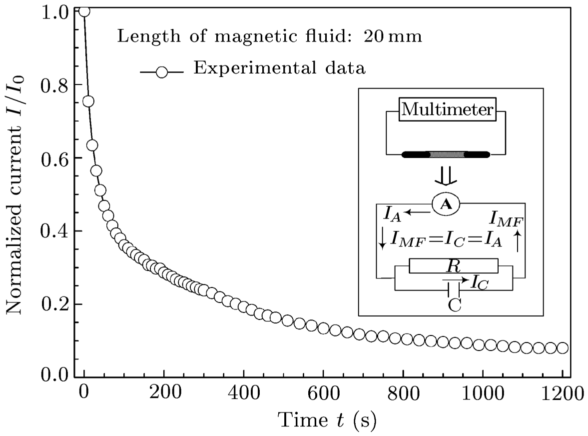

Fig. 3. Normalized discharging current of the magnetic fluid as a function of time t.

When a magnetic field of around 522 Oe is applied along the length of the magnetic fluid as shown in Fig. 1, the current of the circuit goes through a fast increase followed by a monotonic decrease to a final steady value. The similar phenomenon is also observed when the external magnetic field is switched off. The experimental results are depicted in Fig. 4. Before experimentalizing, the magnetic fluid has been electrified for a long time (one and a half hour in our experiment) and the final constant current of the circuit is attained. When the magnetic field is switched on, the magnetic nanoparticles are magnetized and the magnetic moments of most of them are aligned in parallel with the external magnetic field to some degree.[30] Then, the tunnelling conduction mechanism occurs and the directional motion of charged species (magnetic nanoparticles and few nonmagnetic impurities) and ions weakens. This results in a discharging effect of the preceding charged species and a discharging current spike is formed, as shown in Fig. 4. A new dynamic electric balance will be established after a relaxation process. When the magnetic field is switched off, the magnetic nanoparticles disperse into the liquid carrier and the Brownian motion prevails again. At this time, the conduction mechanism of the magnetic fluid is assigned to the directional motion of the charged species and ions. At the beginning of switching off of the magnetic field, the magnetic nanoparticles bear less electric charges due to the previous tunnelling conduction step when the magnetic field is applied. Then, the charged species have relatively large mobility, which leads to the large conduction current. Afterward, the accumulation of number of charged species and charges of each species increase the space-charge-limited effects within the magnetic fluid, which causes the reduction of current as mentioned above. The constant current is obtained when another dynamic electric balance is constructed.

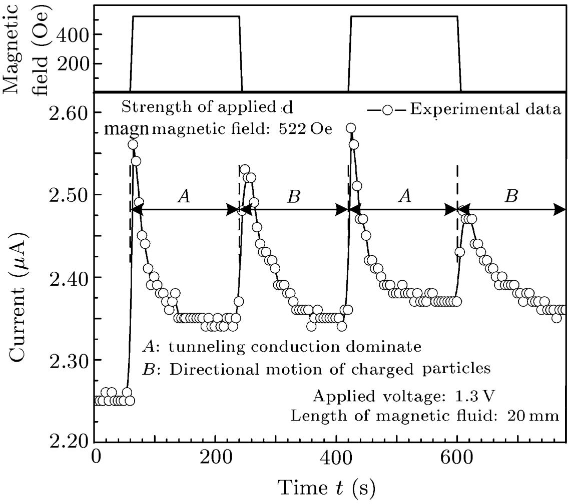

Fig. 4. Influence of switching-on/off magnetic field on the electrical properties of the magnetic fluid. The strength of the applied magnetic field is 522 Oe and the voltage of the potentiostat is set at 1.3 V. A and B denote two regions, where tunnelling conduction dominates and the directional motion of charged species takes place, respectively.

In conclusion, we have investigated the electrical properties of a nanostructured magnetic colloid (water-based magnetite magnetic fluid). The electrically relaxation properties under zero magnetic field are ascribed to the charging effect of the nanoparticles (and minor nonmagnetic impurities) and confirmed by the discharging experiment. An equivalent resistance and an equivalent capacitor in parallel connection are employed to interpret the electrical relaxation of the magnetic fluid. In addition, the influence of magnetic field on the electrical properties of the magnetic fluid has been experimented and the physical mechanisms are clarified.

References

[1] Papell S S 1965 *US Patent* 3215572
[2] Hong C Y et al 1999 *Appl. Phys. Lett.* **75** 2196
[3] Yang S Y et al 2005 *J. Appl. Phys.* **97** 093907
[4] Fang W X et al 2005 *Chin. Phys. Lett.* **22** 2386
[5] Xu C et al 2005 *Chin. Phys. Lett.* **22** 485
[6] Blums E 2002*J. Magn. Magn. Mater.* **252** 189
[7] Luo W, Du T and Huang J 1999 *Phys. Rev. Lett.* **82** 4134
[8] Zhang J H et al 2005 *Chin. Phys. Lett.* **22** 2944
[9] Yang S Y et al 2001 *J. Magn. Magn. Mater.* **226-230** 1992
[10] Pu S et al 2005 *Appl. Phys. Lett.* **86** 171904
[11] Pu S et al 2004 *J. Appl. Phys.* **96** 5930
[12] Chieh J J et al 2007 *Appl. Phys. Lett.* **90** 133505
[13] Pu S et al 2007 *J. Appl. Phys.* **101** 053532
[14] Pu S et al 2006 *J. Appl. Phys.* **99** 093516
[15] Pu S et al 2005 *Appl. Phys. Lett.* **87** 021901
[16] Seo J W et al 2005 *J. Microelectromech. Sys.* **14** 763
[17] Bertoni M I et al 2005 *J. Appl. Phys.* **97** 103713
[18] Dugaev V K, Berakdar J and Barnaś J 2006 *Phys. Rev. Lett.* **96** 047208
[19] Paulson S et al 2000 *Science* **290** 1742
[20] Sagmeister M et al 2006 *Phys. Rev. Lett.* **96** 156601
[21] Furubayashi T 2003 *J. Appl. Phys.* **93** 8026
[22] Chen P et al 2001 *Phys. Rev. Lett.* **87** 107202
[23] Tatara G et al 1999 *Phys. Rev. Lett.* **83** 2030
[24] Ebels U et al 2000 *Phys. Rev. Lett.* **84** 983
[25] Rüster C et al 2003 *Phys. Rev. Lett.* **91** 216602
[26] Zhuravlev M Y et al 2003 *Appl. Phys. Lett.* **83** 3534
[27] Hua S Z and Chopra H D 2003 *Phys. Rev.* B **67** 060401
[28] García N, Muñoz M and Zhao Y W 1999 *Phys. Rev. Lett.* **82** 2923
[29] Novotny V J and Harbour J R 1984 *Appl. Phys. Lett.* **44** 264
[30] Hong C Y et al 1997 *J. Appl. Phys.* **81** 4275