Metallic Iron-Based Nanoparticles for Biomedical Applications

H. Khurshid1, V. Tzitzios2, L Colak1, F. Fang3 and G.C. Hadjipanayis1

1Department of Physics and Astronomy, University of DE19711
2Institute of Materials Science, “Demokritos” Agia Paraskevi 15310 Athens, Greece
3Department of Material Science and Engineering, University of DE 19711

This study is focused on the fabrication and characterization of core-shell structured iron/iron-oxide nanoparticles for potential use in biomedical applications. In particular, we have investigated the effect of Pt seeding and the injection temperature of Fe(CO)5 precursor on the particle’s morphology and magnetic properties. Injection of the iron precursor at low temperature led to a mixture of core-shell structured particles and separate Fe-oxide particles. Whereas, injection at high temperatures led to only core-shell nanoparticles without any separate iron oxides. The importance of the use of Pt(acac)2 to achieve more uniform and oxide free particles is investigated in detail.

Introduction

Iron based nanoparticles have been studied extensively over the past couple of decades [1] because of their wide range of applications including recording media, environmental remediation and biomedicines [2-5]. With increasing interest in their use for the latter applications, there are some critical issues in the nanoparticles that need to be addressed with their in-vivo applications. These include a strong magnetic susceptibility, aqueous dispersion, uniform size and shape, biocompatibility and fictionalizations with the desired surface chemistry.

A variety of synthesis methods have been reported previously including mechanical milling in organic liquids, vapor phase deposition and polyol reduction techniques which resulted in a larger size, polycrystalline and non-aqueous dispersed particles. Synthesis of nanoparticles by the thermal decomposition of metal carbonyls gives relatively uniform, small size single crystal and ferrofluid particles [6]. Farrel et. al. [1] reported the synthesis of iron nanoparticles using the metal carbonyl precursor at low injection temperatures (100°C) with the Pt seeds present in octyl ether. In our earlier work, we reported the synthesis of water dispersible core-shell structured iron/iron-oxide nanoparticles by heterogeneous nucleation method. The objectives of this work are to study the effect of Pt seeding and the injection temperatures of the iron precursor on the particles size, morphology and magnetic properties.

Experiment

We have performed a series of experiments for the synthesis of nanoparticles using organometallic routes. Heterogeneous samples were made using Pt(acac)2 as a seeding material. Homogeneous samples were made without the Pt seeds. Two different injection temperatures were investigated, 100°C and 287°C. A mixture of oleic acid and
oleylamine with 1:1 molar ratios was used as surfactant and 10 ml octyl ether as solvent with 0.01 mM Pt(acac)$_2$ for seeding. The refluxing temperature was kept 287$^\circ$C for all the reactions along with different injection temperatures for the 1.5 mM Fe precursor. For the heterogeneously nucleated iron nanoparticles made at low injection temperatures of the Fe precursor, an additional 10 ml octyl-ether was added during step 2 of the synthesis following an injection of 7.8 mM Fe(CO)$_5$ at 100$^\circ$C. The solution was heated up to 260$^\circ$C, and then cooled down to room temperature; later it was washed with ethanol and then dispersed in hexane.

**Results and Discussions**

A typical XRD (X-ray diffraction) micrograph of the particles made by using Pt seeds and low temperature injection of iron precursor shows a strong iron (110) reflection at 44.7$^\circ$ along with a much smaller peak at 35.5$^\circ$ corresponding to the spinel iron oxide (Fig.1). No reflections from Pt or FePt were observed, possibly because of the very small amount Pt as compared to the Fe in the sample.

**Table 1:** Particle morphology and synthetic conditions of different samples.

| Synthesis                 | Pt seeds | Fe precursor Injection Temperature ($^\circ$C) | Particles Morphology          |
|---------------------------|----------|-----------------------------------------------|-------------------------------|
| Heterogeneous nucleation  | Yes      | 100                                           | Core-shell Fe + Oxides        |
| Heterogeneous nucleation  | Yes      | 287                                           | Core-shell                    |
| Homogeneous nucleation    | No       | 287                                           | Core-shell + Oxides           |
| Homogeneous nucleation    | No       | 100                                           | Irregular oxides              |

Table 1 lists all the samples discussed in this paper and the synthetic conditions used for their preparation. Variations in these conditions led to the formation of separate oxides along with Fe(core)/Fe-O (shell) structured nanoparticles.

Conventional TEM studies (Fig.2A) revealed that the heterogeneously nucleated particles prepared at high injection temperature have a core-shell structure. The presence of two different kinds of rings (Fig. 2B) bright spotty pattern rings and continuous broad rings in the electron diffraction indicate two different phases with different grain sizes. The bright spotty rings can be indexed as BCC iron and the broad ones as FCC iron oxide. The selected area diffraction is consistent with the XRD data as all the rings correspond to the characteristic reflections of $\alpha$-Fe and the spinel iron oxide. The high resolution TEM image (HRTEM) shows clearly that both core and shell are crystalline. The measured lattice spacing of the core was found to be $d=0.202$
nm which corresponds to the (110) lattice planes of alpha iron; the shell lattice spacing is d=0.252nm corresponding to the (311) planes of the spinel iron oxide. The Fe core is a single crystal; however, the oxide shell is composed of small crystallites which are oriented differently as can be clearly seen in Fig.2C. The figure shows clearly that the single crystal Fe core is surrounded by several oxide crystallites and hence causing the broad diffraction ring. Gangopadhyay et al [7] and Wang et al [8] have also seen the same behavior in iron nanoparticles synthesis by gas phase vaporization method; when exposed to air the particles surface got oxidized making a thick oxide shell around the core.

Heterogeneously nucleated particles prepared at low temperature injection (Fig.3B) show two different morphologies in the same sample: larger core-shell (average size 12 nm) and smaller single crystalline particles (~2nm). On the other hand, homogeneously nucleated particles at the same injection temperature are irregularly shaped (Fig. 3A). The Pt seeds are acting like catalytic centers for the deposition of iron crystals around them and therefore they help to control the average particle size [9]. When the iron precursor was injected at 287ºC, the solution temperature was raised up to 15ºC which can be attributed to the exothermic nature of the reaction. Homogeneously nucleated particles prepared at high injection temperature exhibit both core-shell particles coexisting with very few small oxide particles (Fig. 3D); whereas the high temperature injection of Fe(CO)5 along with Pt seeds resulted in core-shell structured particles (10±2.3 nm) without the formation of separate oxide crystallites (Fig.3C). It was reported that Fe(CO)5 decomposes faster at higher temperatures, which suggests that the higher reaction rate suppresses the oxide crystallite formation [6].

In order to determine the oxidation state of the shell, a high resolution XPS spectrum of Fe core level (Fig.6) was taken from the grown iron particles using Mg Kα X-ray source. In the surface analysis only iron oxide can be detected which is attributed to the shell of these nanoparticles. The Fe 2p spectrum shows broad peaks of 2p 3/2 and 2p 1/2 and no shake-up satellite peaks between the main peaks [10], suggesting that the Fe oxide is Fe3O4 rather than Fe2O3. The broad peaks are attributed to the existence of dual iron oxidation states, bivalent and trivalent Fe cations, which have different but very close binding energies.

The room temperature magnetization for the heterogeneously nucleated nanoparticles at low injection temperature is 95 emu/g (the loop was taken with an applied field of 10 kOe). Taking into account the values of magnetization for bulk, the value of M_s for a nanoparticle with a 10 nm Fe core and 2.5 nm oxide shell, coated with a layer (1.7 nm) of oleic acid, is estimated to be 115 emu/g. The lower value of magnetization is probably because of the non-uniformity of core and small oxide particles present in this sample. The zero field cooled and field cooled curves (Fig 5) for these particles at an applied field of 100 Oe indicate a superparamagnetic behavior in these particles with blocking temperature above 200 ºK. It is believed that this magnetic behavior of core-shell nanoparticles is dominated by the iron oxide crystallites at 100 Oe.
The heterogeneously nucleated particles at high injection temperature have a room temperature magnetization of 82 emu/g and exhibit a strong ferromagnetic behavior with a coercivity of 325 Oe. Homogenously nucleated particles at high injection temperature however, showed a decreased coercivity of 182 Oe. The higher value of coercivity in earlier sample is most probably because of the hard phase oxide shell which is a higher anisotropy phase.

Conclusions

The effect of Pt seeding and Fe precursor injection temperatures on the particles morphology and magnetic properties was investigated. Iron precursor injection at low temperature led to core-shell structure particles along with separate oxide crystallites while at high injection temperature the formation of separate oxides can be avoided. The Pt provides the nuclei for the growth of iron crystals around them and hence helps to control the average particle size. We strongly believe that the Fe/Fe-O particles might be better for the biomedical applications since they are biocompatible and have a higher coercivity needed for the hyperthermia applications.

Acknowledgment

The authors would like to thank Dr. A. M. Gabay and Ms. Lubna R. Shah for helpful discussions. This work was supported by National Science Foundation (DMR0302544)

References

1. D. Farrell, S. A. Majetich and J. P. Wilcoxon, J. Phys. Chem. B 107, 11022 (2003)
2. T. K. Jain, M. a. Morales, S. K. Sahoo, D. L. Leslie-Pelecky and V. Labhasetwar, Molecular Pharmaceutics 2, 194 (2005)
3. M. Maeda, C. S. Kuroda, T. Shimura, M. Tada, and M. Abe S. Yamamuro and K. Sumiyama H. Handa J. Appl. Phys. 99, 08H103 (2006)
4. H. Khurshid, S. Balakrishnan, L. Colak, M. J. Bonder and G. C. Hadjipanayis, IEEE Transactions on Magnets (accepted) ID: MAGCON-09-03-0477.R1
5. H. Khurshid, S. H. Kim, M. J. Bonder, L. Colak, Bakhtyar. Ali, S. I. Shah1, K L. Kiick, and G.C. Hadjipanayis, J. Appl. Phys. 105, 07B308 (2009)
6. Pedro Tartaj, Maria del Puerto Morales, Sabino Veintemillas-Verdaguer, Teresita Gonzalez-Carreno and Carlos J. Serna, J.Phys D. Appl.Phys. 36 R182 (2003)

7. Gangopadhyay, S.; Hadjipanayis, G. C.; Sorensen, C. M.; Klabunde K. J.; Papaefthymiou, V.; Kostikas, A. Phys.Rev.B 45,9778 (1992)

8. C. M. Wang, D. R. Baer, L. E. Thomas, J. E. Amonette, Jiji Antony, YouQiang and G. Duscher J. Appl. Phys 98, 094308(2005)

9. K. Simeonidis, S. Moudikoudis, I. Tsioussis, M. Angelakeris, C. Dendrinou Samara, O. Kalogirou, J. Mag. Mag. Mat 320, 1631 (2008)

10. Y. Gao and S. A. Chambers J. Cryst. Growth, 174, 446 (1996)

Captions

Fig.1: XRD micrograph of particles made by using heterogeneously nucleated particles at low injection temperature showing a strong iron (110) with a small reflection (311) of the spinel iron oxide.

Fig.2: Heterogeneous nucleation at high injection (A) Bright field image showing core-shell of particles, (B) electron diffraction of “A” and (C) HRTEM for one of the particles

Fig.3: Bright field TEM images of (A) homogeneously nucleated particles at low temperature, (B) heterogeneously nucleated particles at low temperature, (C) heterogeneously nucleated particles at high temperature and (D) homogeneously nucleated particles at high temperature injection of the iron precursor.

Fig.4: Room temperature magnetization curves of (black) heterogeneously nucleated particles at low temperature, (red) heterogeneously nucleated particles at high temperature and (green) homogeneously nucleated particles at a high temperature injection of iron precursor.

Fig.5: The zero field-cooled and field-cooled curves for the heterogeneously nucleated particles at low injection temperature indicate a superparamagnetic behavior with blocking temperature near 200 K

Fig.6: High resolution XPS scan of F2p scan of a heterogeneously nucleated particle’s sample
Fig. 1

Fig. 2
Fig. 3

Fig. 4
Fig. 5

Fig. 6

Fe 2p XPS core level spectra

Fe 2p$^{1/2}$ Fe 2p$^2$

Mg Kα

hv = 1253.6 eV

θ = 45 degree