Processing of ferromagnetic iron nanowire arrays

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Abstract

We report a fabrication of ferromagnetic iron nanowires by thermally decomposing iron pentacarbonyl molecules under the magnetic field. The nanowire array is fabricated through the pile-up of magnetic iron particles under the magnetic field. We observed that shapes of nanowires depend on iron pentacarbonyl vapor pressures. We observed three pressure ranges responsible for three kinds of nanowire shapes. We explained this pressure dependence and suggested a growth mechanism of the nanowires.

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1. Introduction

The ferromagnetic nanowires (NWs) have been a special interest because of their potential applicability to a high density perpendicular magnetic recording with their excellent magnetic properties [1–4]. That is, the ferromagnetic NWs possess high coercivities and ratio of remanences to saturation magnetizations close to 1, which arise from a nearly zero demagnetization factor parallel to NWs [5]. Due to this, a variety of methods which fabricate arrays of ferromagnetic NWs have been reported by many researchers. These include electrochemical deposition of metals into the well defined arrays of nanopore templates made of either aluminum oxides [6–11] or polymer membranes [12–15]. These methods may be used in fabricating a variety of arrays of ferromagnetic NWs by controlling the nanopore sizes, the lengths, and the separation between the nanopores in the templates.

In this work, we report a fabrication of arrays of ferromagnetic iron nanowires which are fabricated when the iron pentacarbonyl molecules are thermally decomposed in the presence of the magnetic field. When the magnetic particles are produced under the magnetic field, they serve as building blocks of nanowires. However, note that only the magnetic particles had been produced when the iron pentacarbonyl molecules were decomposed without magnetic field [16]. Here, the magnetic

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particles include iron molecules, small iron nanoclusters, and iron nanoclusters, depending on iron pentacarbonyl vapor pressure. The pressure dependence of major species of magnetic particles was the reason that we observed three regimes of iron pentacarbonyl vapor pressures at which three different types of nanowires were obtained. These arrays of nanowires were characterized with scanning electron microscope (SEM).

2. Experimental

Fig. 1 represents a schematic that the nanowires are fabricated through the pile-up of magnetic particles. Briefly, the magnetic particles were initially produced through the thermal decomposition of iron pentacarbonyl molecules with a resistive heater (nichrome wire). The resistive heater was placed in the middle of a pair of permanent disc magnets which were spaced by a glass tube as described in the previous work [17]. The magnetic field strength was 3000–4000 gauss in the middle of a pair of permanent disc magnets. The magnetic particles produced near to the resistive heater environment were pulled linearly by the magnetic field and then piled up parallel to the magnetic field direction (or perpendicular to the substrates attached to the magnet surfaces) to become a array of nanowires. That is, the magnetic particles served as building blocks of nanowires. The resistive heater was turned on only shortly (i.e., 1 min or so) because the decomposition of iron pentacarbonyl molecules into iron atoms and carbon monoxide molecules and the following magnetic iron particle formation occurred immediately. The resistive heater temperature ranged from 300 to 400 °C in order to only break the Fe–CO bonds. Above 500 °C, the CO molecule itself can be dissociated into C and O atoms and, as a result, the undesired products such as metal oxides and carbides can be produced. The major species of magnetic particles produced through thermal decomposition of iron pentacarbonyl molecules include iron molecules, small iron
nanoclusters, and iron nanoclusters, depending on the iron pentacarbonyl vapor pressure. Here, the three terminologies, i.e., iron molecule, small iron nanocluster, and iron nanocluster are not the exactly determined sizes. They just mean that the clusters are of progressively larger sizes when the metal atom density increased. This pressure dependence of the major species of magnetic particles originates from the fact that the density of iron atoms produced through thermal decomposition of iron pentacarbonyl molecules is proportional to the iron pentacarbonyl vapor pressure. That is, iron molecules are the major species when the density of iron atoms is low whereas small iron nanoclusters and then, iron nanoclusters are produced when the density of iron atoms increases.

3. Results and discussion

The arrays of ferromagnetic iron nanowires produced at three pressure ranges of iron pentacarbonyl vapors are presented in Fig. 2(a)–(c). The pressure ranges responsible for Fig. 2(a)–(c) and major iron species are roughly (1) \( p < 1 \) Torr (iron molecules), (2) \( 2 < p < 4 \) Torr (iron molecules and small iron nanoclusters, and (3) \( p > 5 \) Torr (iron nanoclusters), respectively. As mentioned before, the three terminologies, i.e., iron molecule, small iron nanocluster, and iron nanocluster are not the exactly determined sizes. They just mean that the clusters are of progressively larger sizes when the metal atom density increased. Also, note that the growing nanowires will produce inhomogeneous magnetic field and thus, act as magnets in the presence of magnetic field. They will draw iron particles to them and will affect growth of nanowires.

For \( p < 1 \) Torr, the nanowires look like stalagmites. In this case, the major species of magnetic particles, i.e., the components of nanowires are iron molecules. The iron molecules are drawn by magnetic field to become a nanowire. Since the major components are molecules, the nanowires grow such as stalagmites. We speculate that the molecules melt when they pile-up to become a nanowire.

For \( 2 < p < 4 \) Torr, the major species of magnetic particles are iron molecules and small iron nanoclusters and thus, the nanowires are composed of both molecules and small nanoclusters. In a nanowire, the iron molecules will make small nanoclusters to be strongly held together because
we speculate that they melt in a nanowire. The molten iron molecules also make nearby nanowires to be strongly tied together, which is the reason that the nanowires look like cemented bundles of nanowires, as shown in the magnified SEM micrograph in Fig. 2(b). Here, the nanowires exist as bundles, which will be explained later. We speculate that the small nanoclusters are big enough to maintain their inner shell structures even though their outer shells more or less melt when they pile-up to become a nanowire.

Finally, for $p > 5$ Torr, the major species of magnetic particles are iron nanoclusters and thus, the nanowires are composed of nanoclusters. Since there are negligible amount of iron molecules in this pressure range, individual nanowires are produced. However, the nanowires exist as bundles, as can be seen in the magnified SEM micrograph in Fig. 2(c) because both branching and grouping of nanowires occur while the nanowires grow, as explained below.

Fig. 3(a)–(d) show how the nanowires are fabricated. Initially, the magnetic particles, i.e., the component of nanowires are attracted linearly by magnetic field, as shown in Fig. 3(a). Since the magnetic particles already deposited onto the substrates also can act as magnets in the presence of magnetic field, they can draw other magnetic particles near to them, as shown in Fig. 3(b). The already formed nanowires will produce inhomogeneous magnetic field. As a result, a branch of a nanowire is formed, as shown in Fig. 3(c). As can clearly be seen in the inserted SEM micrograph in Fig. 2(c), the nanowires do exist as bundles. One reason for this is the branching of nanowires because once a branch is formed, more branches can be more easily formed than ever due to inhomogeneous magnetic field formed by branched nanowires. The other reason is grouping of nearby nanowires, as shown in Fig. 3(d). We speculate that this grouping happens because when the nanoclusters pile-up onto a long nanowire, they make the nanowire wiggle due to collisional energy effect. This wiggling motion (or other motions such as rocking, waving, etc.) makes nearby nanowires to be grouped one another to form a bundle.

In the case that the magnetic particles are molecules, the branching in a nanowire and the grouping of nearby nanowires will hardly occur because the nanowires just grow as thick stalagmites, as can be seen in Fig. 2(a). Note that the morphology of nanowires in Fig. 2(b) is somewhere between that in Fig. 2(a) and that in Fig. 2(c). The reason for this is that the major species of magnetic particles in nanowires in Fig. 2(b) are molecules and small nanoclusters. In this case, the molecules will make small nanoclusters to be strongly held one another in a nanowire and also make nanowires in bundles to be strongly tied one another by filling some empty spaces. However, when the major species of magnetic particles in nanowires are nanoclusters, the nanowires will grow according to the mechanism shown in Fig. 3(a)–(d) and thus, will look like those shown in Fig. 2(c).

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