Magnetic and magneto optical characteristics of nanowire arrays embedded in anodic aluminium oxide

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Abstract. Our recent work on the fabrication and properties of ordered elemental (Co, Fe) and alloy (Co$_{1-x}$Pt$_x$) nanowire arrays embedded in anodic aluminium oxide (AAO) templates is reviewed. Nanowires with diameters from sub-micron to nano-metre have been fabricated using an electrodeposition technique. The nanowire array structure, crystallographic structure, magnetic properties, and magneto-optical properties have all been investigated. The wire size and photon energy dependent magneto-optical properties of Co and Fe nanowire arrays in the regime of visible spectrum were found to be considerably different from their bulk counterparts. The crystal structure of Co$_{1-x}$Pt$_x$ (0 < $x$ ≤ 0.2) alloy nanowire arrays varies with the chemical composition: the c-axis is predominantly orientated for Co-rich Co$_{1-x}$Pt$_x$ wires and non-textured for pure Pt wires. Composition dependent squareness ($M_r/M_s$) and coercivity (perpendicular and parallel to the wire axis) have been observed. Furthermore, by rapid thermal annealing treatment, we found that nanowires with different composition showed different response to the annealing temperatures. The corresponding changes in crystal structure, the shape of hysteresis loops, saturation magnetization, coercivity, squareness and magneto-optical properties after annealing have been studied.

1. Introduction

Science and technology on the nanometre scale have attracted intense interest over recent years as they exhibit new and exciting properties compared with their bulk counterparts [1-9]. Such materials come in a wide range of forms, such as dots and particles and lines: a recent review of the fabrication and properties of magnetic nanostructures has been presented by Martin et al [10]. One important sub-group in the general classification is that of magnetic nanowire arrays which may have potential in future applications as high-density storage media. The wires may consist of a single magnetic element [11,12] or a magnetic alloy [13,14]. The magnetic properties of nanowires have been extensively investigated with particular emphasis on three areas, namely, the factors that determine the effective easy axis of the wires [15,16], magnetization reversal processes within the array [17] and magnetic interactions between wires [10] respectively. Studies also have been performed on the composition [17], optical [18], magneto-optical [19] and annealing temperature [14] dependent properties.

To fabricate nanowires, several techniques have been intensively used [5-9] to provide nano-structure as a template. One of the most popularly employed templates in the preparation of
various metal, semiconductor and oxide nanowire arrays [5-9,20] is porous anodic aluminium oxide (AAO). The pores in AAO films are reasonably uniform in diameter and length, almost parallel to one another and the pore density and pore diameter can be relatively easily controlled by varying chemical or electrochemical parameters. At the same time, the technique is cost-effective, simple to operate, and it enables further deposition into the nano-channels by a variety of techniques [7, 21-23]. Many types of nanowire arrays have been prepared based on AAO templates and a wide range of properties have been explored such as electrochemical nano-electrode-arrays [24], catalytical [25], tribological [26], photoluminescent [22], magnetic [21-23, 27], electronic [22], and optical [20].

Investigations of the properties of ferromagnetic nano-wire arrays based on AAO templates [10-12] have also been extensive. Much research was devoted to the study of the optical properties and magnetisation behaviours. In contrast the study of magneto-optical (MO) related properties of nanowires based on AAO templates are relatively few [19,28,29] and virtually nothing is known about the effects of heat treatment on the MO behaviour. Accordingly, in this paper we shall present our MO studies on as-deposited Fe, Co, Co1-xPtx and post annealed alloy magnetic nanowire arrays.

Recent studies of CoPt and FePt alloys have largely centred on their potential applications in high-density magnetic and magneto-optical recording [30-32]. Requirements for higher magnetic recording density demand that materials consist of magnetically isolated grains less than 10 nm in diameter. Low noise demands that materials have high magnetocrystalline anisotropy to inhibit thermal fluctuations that tend to destabilize the magnetization of the recorded bits [33]. Intensive efforts have been devoted to attain the combined goals of a high areal density of bits and adequate thermal stability [34-36]. Magnetic nanowires [19,28,29] arrays based on anodic aluminium oxide (AAO) present in principle an attractive potential medium because when deposited the wires comprise a highly ordered pattern of reasonably magnetically isolated units [11,13,28]. For Co1-xPt x nanowires, there are only a few reports currently available [14,37,38], for instance, a squareness of 0.96 for CoPt nanowire embedded in AAO with a wire diameter of 80 nm has been reported by Yasui et al [38]. The Co (1-x) Pt x nanowire arrays we shall report here are 6 times smaller in wire diameter compared with those reported by Yasui et al. [38].

In this paper we shall first present the fabrication technique of the AAO templates and magnetic nanowire arrays and consider the parameters that affect the nanowire dimensions, followed by applying a range of techniques, such as transmission electron microscopy (TEM), scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), X-ray diffraction (XRD), vibration sample magnetometry (VSM), UV-visible spectroscopy and rapid thermal annealing (RTA) to characterise the nano-structure, crystal structure, magnetic properties, annealing effects and UV-visible spectra for Co1-xPt x nanowire arrays, as an example. The magneto-optical characteristics of elemental Co, Fe nanowire as a function of nano-wire diameters, lengths and photon energy will then be presented, followed by the investigation of the annealing effect on the magneto-optical properties of Co1-xPt x alloy nanowire arrays.

2. Experimental

2.1 AAO and nanowire arrays fabrication

There are three known methods to electro-deposit nanowires onto AAO nanopores so far, namely, alternating current (AC) electro-deposition, direct current (DC) electro-deposition and pulse current electro-deposition, while all the AAO templates are prepared by applying a DC voltage between the aluminium electrode and the cathode. By controlling the anodic operating conditions, the pore size dispersion, the diameter, length and mean separation could be adjusted in a controlled manner.

In our experiments, high purity (99.999%) Al foil (1 cm × 2.5 cm × 0.3 mm) was ultrasonically degreased in trichloroethylene for 10 minutes, etched in 1.0 M NaOH at room temperature for 10 minutes to remove the native oxide and subsequently washed thoroughly with distilled water. It was then electropolished in a mixed solution of HClO₄:CH₃CH₂OH = 1:4 (by volume) for about 45 seconds with a constant current density about 0.35 A·cm⁻². The electropolished Al foil was promptly rinsed with distilled water and mounted in an electrochemical cell as the anode sandwiched between two aluminium or lead foils, which serve as cathodes. Depending upon anodization conditions (such as anodization voltage, concentration of electrolytes, bath temperature and anodization time), anodic
aluminium oxide membranes with pore diameters ranging from 3 nm to 400 nm and pore lengths ranging from tens of nanometers up to 100 µm can be produced. Practically, sulphuric acid was used to prepare the AAO templates of small pore diameter ranging from 3 nm to about 50 nm, phosphoric acid was used to fabricate templates with large pore diameter (≥60 nm). Oxalic acid was used to make AAO membranes with medium pore diameter. In order to improve the quality of AAO template, a mixed solution of three electrolytes mentioned above was also used.

Various metallic nanowires were electrodeposited using our in-house electrodeposition system which is capable of outputting a 0–30 V alternating-current (AC) signal with sinusoidal, triangular or rectangular waveforms. The system has a maximum power output of 20 W and an adjustable frequency range of 1.8 Hz–10 kHz. It is a two-electrode system, the resulting AAO template with Al substrate acted as a working electrode and two plates of graphite were used as counter electrodes. In this work, iron, cobalt and Co_{1-x}Pt_{x} alloy nanowires were fabricated. An electrolyte consisting of FeSO_{4}·7H_{2}O (120g/l), boric acid (45g/l) and ascorbic acid (1.5g/l) was used for preparation of iron nanowires, whilst CoSO_{4}·7H_{2}O (120g/l) and boric acid (45g/l) were used for cobalt nanowires. In order to fabricate the Co_{1-x}Pt_{x} alloy nanowires with different atomic ratio, electrolytes of aqueous solutions of CoSO_{4}·7H_{2}O and PtCl_{4} with different weight concentration ratio (CoSO_{4}·7 H_{2}O: PtCl_{4}), namely, 192:1, 130:1, 60:1, 1:1, 1:10, 1:25 buffered by 45g/l boric acid, were used, and the corresponding atomic ratio (Co: Pt) in nanowires as determined by EDS are (96:4), (92:8), (87:13), (80:20), (14:86) and (0:100)), respectively. The Al substrates were then etched away by an amalgamation process using saturated HgCl_{2} aqueous solution and washed thoroughly with distilled water. Several alloy nanowire samples with compositions of Co_{x}Pt_{y} and Co_{x}Pt_{13}, made under exactly the same conditions, were subject to rapid thermal annealing for 30 seconds at temperatures up to 800 °C under the protection of a nitrogen atmosphere (a given sample was annealed at one temperature only).

![Figure 1. TEM ((a), (b)) images of Co nanowires freed from the AAO matrix with diameter of about 25 nm; (c) SEM plan view of nanowire array with diameter of about 50 nm; (d) SEM image of the surface of a partially dissolved AAO embedded nanowire array used for the EDS analysis.](image)

2.2 Characterisation of the nanowire arrays

The structures of the composite films were studied by scanning electron microscopy (SEM). The nanowire arrays were found to be highly ordered. The packing density of the nanopores was estimated to be about 10% to 50% for a range of values of the wire diameter. To determine the actual diameter and the length of the nano-wires, the AAO templates were dissolved and the free-standing wires measured by TEM. The crystal structures of nanowires with different diameter, compositions and annealed at different temperatures were studied by XRD. The chemical composition of alloy
nanowires was investigated by EDS. To this end, the AAO matrix of an as-deposited sample was partially etched in a 0.1 M NaOH solution for 3 minutes in order to expose nanowires at the surface. Figure 1 shows typical TEM and SEM images of nanowire composite and AAO template.

The magneto-optical studies were undertaken with our in-house developed equipment. The MO measurements of nanowire array composite films were carried out using a phase sensitive detection technique [19], a photo-elastic modulator (Hinds Instruments) and a diode laser, which generated light source with a wavelength of 670 (1.85 eV) and power of 3 mW. For the photon energy dependence measurements, a grating monochromator (Oriel model 7725 with a tungsten lamp) and a photomultiplier (Hamamatsu R955) were used. All optical measurements were carried out with light at normal incidence to the nanowire array surface and magnetic fields (up to 10 kOe) were perpendicular to the surface (i.e. along the length of the nanowires). The magneto optical setup was calibrated for the measurement of absolute values of the Stokes parameters [39], from which the Faraday rotation angle (FRA) and the ratio of the axes of the ellipse (tanχ) of the light could be derived.

3. Results and discussion
3.1 Structural and magnetic properties of Co1-xPtx nanowire
All Co1-xPtx nanowire arrays studied have an average diameter of 14 nm and a very high aspect ratio. The composition dependent properties are shown in Figure 2.

![Figure 2](image)

Figure 2. (a) X-ray diffraction spectra of Co1-xPtx nanowire arrays: Pt (a), Co14Pt86 (b), Co86Pt20 (c), Co97Pt13 (d), Co92Pt8 (e), Co96Pt4 (f), and Co (g); (b) composition dependent magnetic properties measured at room temperature: M/Ms with applied field along the nanowire axis (V); coercivity Hc with the external field parallel (♦) and normal (•) to the wire axis. The dotted lines in the diagrams are a guide to eyes only.
Figure 2(a) shows the X-ray diffraction patterns. For Co nanowires (curve g) only hcp (002) diffraction is clearly identifiable, showing a predominated c-axis orientated along the length of the wires. Samples with composition of Co$_{94}$Pt$_4$ (curve f), Co$_{92}$Pt$_8$ (curve e) and Co$_{91}$Pt$_{13}$ (curve d) also comprise an hcp phase: the three identifiable peaks are (100), (002) and (110). The hump in the 2θ ranges of 15 to 30$^\circ$ is characteristic of the porous amorphous alumina (Al$_2$O$_3$) [40]. The lack of the (101) reflection suggests that the wires are textured. Nanowire arrays with 86 atomic % of Pt (curve b) or above (curve a) are of Pt fcc phase. These nanowires are found to be nonferromagnetic at room temperature and the first four most prominent peaks are (111), (200), (220) and (311). These diffraction peaks suggest that the wires are polycrystalline with randomly orientated grains.

Magnetic properties were measured by VSM. Figure 2(b) shows the variations of $M_r/M_s$ (V) with applied field along wire axis and $H_c$, with applied field parallel (♦) and perpendicular (•) to the wire axis respectively as a function of the chemical composition. Within the narrow composition range between 80% and 100% of Co, a maximum value of parallel $H_c$ is observed for the Co$_{80}$Pt$_{20}$ samples. Figure 2(b) also shows that coercivity is affected only minimally by the composition during this region. The wires with atomic ratio 96:4 (Co: Pt) have a value of $M_r/M_s$ ratio of 0.91, which is the largest value found for the as-deposited samples (Figure 2(b)).

The study of the effects of annealing on the magnetic and optical properties has been focused on Co$_{87}$Pt$_{13}$ and Co$_{96}$Pt$_4$ nanowire arrays. The annealing temperature dependent properties are illustrated in Figure 3.

![Figure 3](image_url)

Figure 3. (a) X-ray diffraction patterns of Co$_{87}$Pt$_{13}$ nanowire arrays as a function of $T_A$ (for $T_A$ up to 600 °C); (b) typical $M/M_s$–$H$ loops of Co$_{96}$Pt$_4$ nanowire arrays measured with external field parallel (♦) and normal (•) to the wire axis (unfilled symbols for as-deposited sample, filled symbols for samples rapid thermally annealed at 600 °C for 30 seconds); (c) ultraviolet- visible absorption spectra of samples annealed at 500, 600, 650, 700, and 800 °C.
Figure 3 (a) shows the XRD results for as-deposited Co$_{96}$Pt$_4$ and samples annealed at different temperatures. An obvious difference is observed between the as-deposited sample and the annealed samples: the latter have more prominent diffraction peaks, which we presume has come from stress relief or low temperature grain growth. On the other hand, the spectra show no great changes with annealing temperature, $T_A$, in the range of 300 – 600 °C, although to the naked eye, the sample annealed at 600 °C had changed colour slightly and seemed somewhat less opaque. The latter result is confirmed by optical absorbance spectra obtained over the ultra-violet and visible regions, as shown in Figure 3 (c). From the UV-visible absorption spectra, a blue shift of the absorption band edge with the increasing of the annealing temperature was found for both Co$_{87}$Pt$_{13}$ and Co$_{96}$Pt$_4$ nanowire arrays. Samples became more transparent under higher annealing temperatures and finally degrade to non-magnetic materials at room temperature. The decrease in absorbance (i.e. increased transmission of light) is clearly marked as the annealing temperature is increased.

![Figure 3](image)

Figure 3. Various magnetic properties measured as a function of annealing temperature ($T_A$): (a) saturation magnetization (♦) for Co$_{96}$Pt$_4$ and (●) for Co$_{87}$Pt$_{13}$; (b) coercivity $H_c$, with the external field parallel (◊) and normal (○) to the wire axis (filled symbols for Co$_{96}$Pt$_4$ and unfilled for Co$_{87}$Pt$_{13}$); (c) $M_r/M_s$ with the field applied along the nanowire axis (♦) for Co$_{96}$Pt$_4$ and (●) for Co$_{87}$Pt$_{13}$). All magnetic measurements performed at room temperature and the dotted lines in the diagrams are a guide to eyes only.
Returning to the X-ray spectra, Co$_{96}$Pt$_4$ nanowire material comprises an hcp phase: peaks (100), (002) and (110) are recorded. The lattice parameters of the nanowires were determined to be $a = (2.516 \, \text{Å}, 2.499 \, \text{Å})$ and $c = (4.080 \, \text{Å}, 4.120 \, \text{Å})$ for the as-deposited sample and the sample annealed at 600$^\circ$C respectively. Comparison with the values for pure cobalt, namely $a = 2.503 \, \text{Å}$ and $c = 4.060 \, \text{Å}$, indicates that the lattice parameters are affected only minimally by the annealing procedure. The absence of a (101) peak together with the relative magnitude of the (002) peak indicate that the c-axis of the grains within a wire tends predominantly to lie parallel to the wire axis as discussed earlier.

In Figure 3(b) is shown the comparison of typical hysteresis loops for as deposited Co$_{96}$Pt$_4$ and samples annealed at 600$^\circ$C. Similar behaviour has also been found for Co$_{87}$Pt$_{13}$ nanowire samples except that for the latter ones, the maximum parallel coercivity and squareness are obtained after annealing at 650$^\circ$C. The as-deposited sample has a value of $M_s$ that is fairly close to that of bulk cobalt (1420 emu/cc). It is observed that the parallel coercivity and squareness have increased considerably after annealing at 600$^\circ$C.

The variation of $M_s$, coercivity, and squareness as a function of $T_A$ are illustrated in Figure 4 (a), (b) and (c). $M_s$ is also found to be almost linearly proportional to the Co content.

From Figure 4 (a), it can be seen that saturation magnetization for alloy nanowire arrays with composition of Co$_{96}$Pt$_4$ remains constant at first with $T_A$ but falls by about 10% following an anneal at 500$^\circ$C. Thereafter, the saturation magnetization decreases more rapidly. $M_s$ for as-deposited and samples annealed at 650$^\circ$C are (1360, 220) emu/cc for Co$_{96}$Pt$_4$ and (1190, 940) emu/cc for Co$_{87}$Pt$_{13}$, which decreased by a factor of 79% and 16% respectively. The most likely explanation for the decrease in net magnetic moment is the diffusion of Co atoms from the nanowires into the alumina-lined pores or reaction at the interface to combine and form a non-magnetic (Al,Co)$_2$O$_3$ [41]. Support for this proposition is drawn from colour changes observed when samples are annealed and this is accompanied physically by increased transparency to visible light. The UV-visible spectra in Figure 3(a) appear to support this hypothesis; a blue shift in absorption edge in the UV-visible spectra is observed, i.e., the optical absorption edge shifted to higher photon energies. Furthermore, it should be added that the absorption of Co atoms by the dielectric oxide would probably increase the transparency of the sample as observed, reducing the saturation magnetization of the samples at higher temperature. Samples annealed at 700$^\circ$C were effectively non-magnetic at room temperature.

The VSM data were also used to obtain coercivity values and the results are shown in Figure 4 (b) with the external field applied parallel and perpendicular to the wire axis (filled symbols for Co$_{96}$Pt$_4$ and unfilled for Co$_{87}$Pt$_{13}$).

Taking Co$_{96}$Pt$_4$ as an example, the value of perpendicular coercivity is about 500 Oe and there is very little variation with $T_A$. $H_c$ values parallel to the wire axis are much larger in value (by a factor of at least 3) and furthermore, some variation is discerned with $T_A$. The as-deposited sample has a parallel $H_c$ of 1560 Oe, which then increases to a maximum value of 2,500 Oe after annealing at 600$^\circ$C. Similar behaviour was observed for the coercivity measured at 45$^\circ$ to the wire axis. It is apparent that the annealing process does not radically alter the magnetic behaviour apart from the increase in coercivity alluded to above. The squareness ratio reaches a maximum value of 0.99 for the loop traced along the major axis of wires annealed at 600$^\circ$C, whilst the maximum value for Co$_{87}$Pt$_{13}$ is 0.98, attained after annealing at 650$^\circ$C. It is interesting to note that there is a slight difference in the rate of decrease of $M_s$ values for sample Co$_{96}$Pt$_4$ and sample Co$_{87}$Pt$_{13}$. The latter appears to be slower. For Co$_{96}$Pt$_4$, $H_c$ both parallel $H_c$ and squareness reached the maximum values after annealing at 600$^\circ$C and decrease rapidly afterwards, while the Co$_{87}$Pt$_{13}$ sample undergoes a somewhat higher annealing temperature without serious degradation to the magnetic properties. Deterioration started to happen at 650°C for Co$_{96}$Pt$_4$, but for Co$_{87}$Pt$_{13}$, the change observed is not as significant as that of Co$_{96}$Pt$_4$. However, after annealing at 700$^\circ$C, both are found to be no longer magnetic. The increase in parallel $H_c$ is not easy to explain, factors such as stress relief and remove of local discontinuities in exchange coupling at low annealing temperature might reduce the coercivity. On the other hand, it could promote coherent rotation, which may have a higher coercivity than that for the equivalent incoherent modes. Re-crystallization and change of grain size are factors that should also be included. The other possibility of the degradation is the absorption of Co atoms into the Al$_2$O$_3$ pores, which could cause a reduction of the nanowires’ effective magnetic diameter. The difference of the expansion coefficient of nanowires and alumina under thermal annealing, which in turn changes the aspect ratio of an
individual wire, is also likely to enhance the easy axis coercivity.

3.2 Magneto-optical characteristics of elemental Co and Fe nanowire arrays

In this section we shall briefly examine the magneto optical properties of elemental Co and Fe nanowire arrays embedded in AAO. In terms of array structures, the regular arrays of Co and Fe nanowires are much similar to those of the binary alloy nanowires discussed earlier.

A schematic diagram of the experimental setup for the measurement of MO properties is shown in Figure 5(A). A detailed description of the optical setup can be found elsewhere [19].

![Figure 5(A)](image)

Figure 5(A). Schematics of the optical set-up: light source (Laser), polarizer (P), sample (S), photoelastic modulator (PEM), analyzer (A), photodetector (D) and Hall probe (P1).

![Figure 5(B)](image)

Figure 5(B). (a)-(d) normalized Stokes parameters for a 63 nm diameter Co nano-wire array; (e) the corresponding FRA loop; and (f) the field dependence of $\tan \chi$.

The magneto optical properties of Co nanowire arrays with a wire diameter of 63 nm are shown in Figure 5(B): (a)-(d) the normalized Stokes parameters [19,39], (e) the Faraday rotation angle (FRA) and (e) the ratio of the axes of the ellipse $\tan \chi$ [39]. The Stokes parameters [39] $s'_3 (45^\circ)$ and $s'_3 (0^\circ)$,
measured at 1/f, shown in (c) and (d) of Figure 5(B) respectively, are expected to be identical [19]. In (e) of Figure 5(B), the FRA is shown as a function of external magnetic fields. The maximum Faraday rotation angle for the sample is about 0.25°. In (f) of Figure 5(B) the magnetic field dependence of \( \tan \chi \) is displayed. The FRA as a function of length for both Co and Fe nano-wires having the same average diameter of 22 nm are illustrated in Figure 6(a). The FRA increases approximately linearly with nanowire length, consistent with the classical Faraday effect.

Figure 6(b) displays the FRA per length as a function of nanowire diameters. It can be seen that FRA/length increases with an increase of nanowire diameter. The maximum FRA per length of the largest diameter sample measured, 144 nm for Co and 160 nm for Fe respectively, are 1015 deg cm\(^{-1}\) and 6500 deg cm\(^{-1}\), while those of the smallest diameter (7 nm) are 375 deg cm\(^{-1}\) and 850 deg cm\(^{-1}\). Bulk Fe is known [42] to have a FRA/length of about \(3.8 \times 10^5\) deg cm\(^{-1}\), which is about two to three orders of magnitude larger than that of the nanowire arrays. The value of FRA per nanowire length for Fe samples increases much faster than that of Co samples as the nanowire diameter increases.

![Figure 6](image_url)

Figure 6. (a) FRA as a function of nanowire length measured at saturation magnetisation (diameter: 22 nm); (b) the FRA per length versus nano-wire diameter; (c) the photon energy dependent FRA per length of Fe nanowire with diameter of 55 nm (•) and 7 nm (♦). The dotted lines in the diagrams are a guide to eyes only.
The photon energy dependence of FRA is illustrated in Figure 6(c), showing FRA per nanowire length for two AAO embedded Fe nanowire arrays with diameters of 7 nm and 55 nm. It can be seen that the two curves have similar trends, that is, FRA increases with increasing photon energy initially and decreases at higher photon energies. Due to lack of data points at higher energy, the precise energy at the peak value of FRA has yet to be determined. It can be estimated from the diagram, however, that the peak should lie between 2.7 to 3 eV. This feature appeared to be in agreement with a large change of the Kerr rotation of bulk Fe at similar energies, reported by Buschow and co-workers [43]. The values of FRA per length for the 55 nm wires were slightly larger those of the 7 nm wires. This is consistent with the nano-wire diameter dependence of the FRA per length for Fe.

3.3 The effect of annealing on the MO properties of Co$_{1-x}$Pt$_x$ nanowire arrays

We shall now examine the annealing effect on the MO properties of Co$_{1-x}$Pt$_x$ nanowire arrays. Ellipticity, tan$\chi$, of the emergent beam is derived from the signal obtained at a frequency of 2f and depends upon the first and third Stokes parameters. From the four measured Stokes parameters, we see that the maximum values of $s'_1$ (second Stokes parameter) are very close to unity, which indicates that the emergent light is still highly linearly polarized. Moreover, the annealing procedure has produced an overall increase in response to magnetization (from +ve to –ve saturation field) of about 38%. A similar change is observed in the third parameter, $s'_2$. Once again annealing at 300 °C produces a significant increase in $s'_3$. The variations in $s'_1$ and $s'_2$ are important because they impinge on the value of the FRA, a parameter of primary interest in any device application.

The variation of FRA and the ellipticity over a wide range of annealing temperatures is shown in Figure 7. Clearly, the behaviour of both quantities follows a similar trend, namely an initial increase rising to a maximum at $T_A = 300$ °C followed by a gradual decline. After annealing at 700 °C the samples are no longer ferromagnetic at room temperature. As seen from the diagram, the maximum FRA increases upon annealing from 0.39° to 0.54° or, equivalently, from 8.0×10$^3$ °/cm to 1.1×10$^4$ °/cm. These values are much smaller than those quoted for a film of pure cobalt [14], a result that in part reflects the low magnetic packing factor (estimated as 0.12) of the nanowire array. As shown in the solid circle curve in Figure 7, annealing does result in a large relative increase but the absolute value of tan$\chi$ remains very small – a result consistent with the light retaining its linearly polarized nature.

![Figure 7 Maximum values of Faraday rotation angle (◊), and tan$\chi$ (● ellipticity) for Co$_{96}$Pt$_4$ nanowire arrays as a function of annealing temperature ($T_A$). Magnetic field applied parallel to the wire axis.](image)

Comparing Figure 7 with Figure 4 (a), it is noticeable that the changes in FRA as a function of annealing temperatures are not proportional to the changes in $M_s$ over the entire temperature range. We may conclude that the saturation magnetization is not the only determinant that fixes the observed Faraday rotation angle. It is likely that the discontinuous geometry of the magnetic material also plays a role in influencing the MO properties of the AAO based Co$_{96}$Pt$_4$ nanowire arrays. When coupled with
other possible changes induced by annealing, e.g., stress relief, it becomes evident that the actual values of FRA and $\tan \chi$ are not easy to predict subsequent to an annealing treatment.

4. Summary and future work

To summarise, we have fabricated elemental and alloy nanowires by means of AC electrodeposition. The anodization conditions and related AAO template properties, nanostructure, crystal structure, magnetic properties, optical properties, MO properties and annealing effect have all been studied.

It has been observed that the magnetic behaviour of Co$_{1-x}$Pt$_x$ nanowire arrays is influenced by Pt content. The values of parallel coercivity are found to increase with the Pt content within the composition range $0 < x \leq 0.2$, while perpendicular coercivity shows a different trend. The crystal structure of the alloy nanowire arrays varies with the chemical composition, ranging from the predominant c-axis oriented to non-textured structure with the increasing of Pt content.

By studying the magnetic behaviour of Co-rich cobalt platinum nanowire arrays (Co$_{98}$Pt$_4$ and Co$_{97}$Pt$_{13}$), it is clear that samples with different composition responded differently to the annealing temperature. For alloys with a higher Co:Pt atomic ratio, such as Co$_{98}$Pt$_4$, the optimum properties such as coercivity and squareness, which may be of relevance to applications as a recording medium, are attained at an annealing temperature of 600 °C, while for samples with a slightly lower composition ratio (Co$_{97}$Pt$_{13}$), the appropriate annealing regime is around 650 °C. Fortunately, this is below the temperature at which irreversible, deleterious changes occur in the microstructure of the films.

MO properties have also been successfully performed on Co$_{98}$Pt$_4$ and Co$_{97}$Pt$_{13}$ as a function of the annealing temperature. The results presented above show that samples annealed at 300 °C are sufficiently transparent to transmit light and at the same time possess an enhanced Faraday rotation angle. Although it is not easy to predict the precise reasons that the $M_s$ is not proportional to the FRA, we have demonstrated that the measurement of FRA provides an effective means of monitoring the properties of AAO based nanowire arrays. Furthermore, a suitable annealing regime can improve the MO properties of such arrays.

For the investigation of MO response of Co nano-wire arrays, both as function of nanowire diameters and lengths, we found that for a constant nanowire diameter the FRA of the nanowires was linearly proportional to the nanowire length. The nano-composite films present magneto optical characteristics that are substantially different from those of bulk materials. Photon energy dependent MO studies were carried out on Fe nanowire arrays and the values of FRA were found to increase with photon energies initially and to decrease at higher photon energies with an estimated peak position between 2.7 and 3.0 eV. Our investigation clearly demonstrated that the MO technique was a useful tool for probing magnetism in these transparent or semi-transparent novel nano-composite films.

We wish to point out that further work is currently undertaken in our research group to study the annealing effect on Co$_{1-x}$Pt$_x$ and Fe$_{1-x}$Pt$_x$ alloy nanowire arrays with $x$ ranging from 0 to 1, especially the alloy materials with composition about 50:50 and having a very small diameter (about 7 nm). In principle the annealing could transform the disordered fcc structure of CoPt into an ordered fct phase, which would possess a very high magnetocrystalline anisotropy and very large coercivity. The study of the MO properties of these materials remains to be one of our main objectives.

Furthermore we are currently beeing studying the magnetic nanowire arrays using the X-ray magnetic circular dichroism (XMCD) technique. X-ray magnetic dichroism spectroscopy and microscopy are used to obtain information about the element-specific magnetic properties of the alloy nanowires. Preliminary work on Co and CoPt has already been carried out and will be reported elsewhere. Magnetic nanowires with different diameter, composition and length are to be fabricated and investigate also by using X-ray magnetic transmission microscopy to investigate of the magnetic domain reversal and propagation in individual nanowires.

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