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Electrodeposition of highly ordered macroporous iridium oxide through self-assembled colloidal templates

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Iridium oxide electrodeposited through a self-assembled colloidal template has an inverse opal structure. Monolayers present long range hexagonal arrangements of hemispherical nanocavities while multilayers present 3D honeycomb structures with spherical voids. The films are amorphous, have several electroactive redox states and are electrochromic. The nanostructure modifies their reflectivity thus indicating these films could be used as tunable photonic devices.

Introduction

Iridium oxide (IrOx) films are well known for their applications in electrochromism,^{1, 2} physiology^{3, 4} and pH sensing.⁵⁻⁷ However, the preparation of plain IrOx films is not trivial and that of nanostructured IrOx films even more challenging. Many articles describe the preparation of IrOx nanoparticles,⁸ nanowires,^{9, 10} and nanocrystals^{11, 12} but very few report the preparation of nanostructured IrOx films.^{13, 14} Here we describe, for the first time, the fabrication of highly ordered micrometre thick macroporous films of iridium oxide using electrodeposition through a self-assembled colloidal template. The films are grown by potentiostatic cycling in an iridium complex solution. A few cycles produce highly ordered arrays of hemispherical cups with long range hexagonal symmetry. Growth can be finely controlled via the cycle number and structures ranging from fully open to partially closed cups can be prepared. Further cycling yields porous films up to 3 template layers thick with a 3D honeycomb internal structure. Upon characterisation with X-Ray diffraction, Raman spectroscopy, SEM, voltammetry, and reflectivity measurements, the films are found to be amorphous, to have structural dimensions faithful to that of the template, several electroactive redox states and reflectivity spectra significantly different from that of non-structured films. Such films should find applications in biology (IrOx is conducting, non reactive and biocompatible) but particularly optics because their optical density can be electrochemically controlled and the cavity diameters correspond to UV-visible wavelengths.

Experimental

Gold electrodes and colloidal templates were prepared and characterised as described previously¹⁵. The IrOx deposition solution¹⁶ was prepared as follows: Anhydrous IrCl₄ (0.07 g, Alfa-Aesar) was dissolved in 50 ml of water then stirred for 30 min. Aqueous H₂O₂ (0.5 ml, 30%, Aldrich) was added and the resulting solution was stirred for 10 min. Oxalic acid dehydrate (~250 mg, Aldrich) was added and the solution was stirred for another 10 min. The pH was slowly adjusted to

10.5 by addition of potassium carbonate (Aldrich). The resulting yellowish brown solution was covered and left at room temperature for 3 – 4 days to stabilise after which it appeared deep purple. The deposition of IrOx was carried out by cyclic voltammetry between –0.8 and +0.7 V vs. SCE at 100 mV s⁻¹ with a PGSTAT30 (Autolab, Eco Chemie) with the cell inside a grounded Faraday cage. The template was dissolved with dimethylformamide under sonication and the films were washed in pure water. Scanning electron images were acquired with an XL30 ESEM (Philips) and a JSM 6500F (Jeol). Raman spectra were recorded on a Renishaw Raman 2000 microscope with a 633 nm HeNe laser and a 1 μm diameter spot size. Reflectivity spectra were carried out with a coherent white-light source with the sample mounted on a goniometric stage¹⁷.

Results and discussion

IrOx films are produced by electrochemical oxidation of iridium electrodes,^{18, 19} thermal decomposition of iridium salts,²⁰ reactive sputtering,²¹ chemical vapour deposition,¹⁴ mixing solid IrO₂ with a matrix²² or by electrodeposition from a soluble precursor.^{16, 23} The latter was chosen because of our experience in the templated electrodeposition of nanostructured materials.²⁴⁻²⁸ Templated electrodeposition has proved to be an excellent means to tune the properties of materials by modifying their structure rather than their elemental composition. Using this method, nanostructured gold films are prepared to control surface plasmons and produce tuneable photonic surfaces^{15, 29-33} and to amplify Surface Enhanced Raman signals^{34, 35} or control wetting and design hydrophobic surfaces.³⁶ Similarly nanostructured templated Ni₈₀Fe₂₀ films are prepared with different coercivities by selecting templates with different dimensions.^{37, 38} In all cases, the internal geometry and the dimensions of the cavities determine the properties of the material.

The template is prepared by placing a drop of colloidal suspension of monodisperse spheres onto a gold coated glass slide and controlling solvent evaporation to produce a deposit of spheres. Driven by capillary forces the spheres assemble

Insert Figure 1A here

Insert Figure 1B here

Fig. 1 Voltammograms for the growth of IrOx films on gold electrodes recorded in the deposition solution at 100 mV s^{-1} . A) no template, B) with a 600 nm diameter polystyrene template. Voltammetric cycle numbers are indicated against corresponding line styles. The current density was calculated using the geometric electrode area.

into long range, hexagonal close packed arrays³⁹ which form the mould for the electrodeposition. Adsorbing a cysteamine monolayer onto the gold substrate improves its wettability and controls its surface charge to help anchor the first layer of spheres.⁴⁰ To produce a film the substrate and its template are immersed in an electrolyte containing a precursor (a salt or a complex) and the substrate is connected to a potentiostat which drives the deposition. Growth occurs within the voids between the spheres. The spheres are removed by dissolution and the film obtained is the cast of the template. Thicknesses ranging from fractions of a template layer to several template layers can be obtained by adjusting the deposition time. Up to $\frac{1}{2} d$ where d is the sphere diameter, the film consists of a hexagonal arrangement of sphere segment cups. Beyond $\frac{1}{2} d$, the film turns into a network of interconnecting sphere and sphere segment cavities akin to a reticulated three dimensional honeycomb construction. The film structure is tailored by selecting the diameters of the spheres (typically between 100 nm and $2 \mu\text{m}$) and the deposition time. The procedure has been used to prepare metals and alloys,^{25, 38, 41, 42} semiconductors,⁴³ conducting polymers^{26, 44} and oxides.⁴⁵⁻⁴⁷

Insert Figure 2 here

Fig. 2 Anodic (\blacktriangle , \bullet) and cathodic (Δ , \circ) charge densities recorded during film growth for a structured film (triangles) and a flat film (circles) against the number of voltammetric cycles. Conditions similar to Fig. 1.

The preparation of IrOx films followed the recipe reported by Yamanaka.¹⁶ Fig. 1 shows a typical set of voltammograms recorded during deposition. In absence of template, Fig. 1A, the voltammograms are similar to those produced by potential cycling of an iridium wire in acid.^{1, 41} The larger current density observed when depositing with the template, Fig. 1B, suggests a greater efficiency, possibly because the homogeneous reaction¹⁶ which leads to the oxide deposition is confined within the voids of the template. The voltammograms are much less slanted, thus suggesting a better conductivity in the structured film. The anodic and cathodic peaks have been reported to correspond to the transitions between three different oxidation states, namely Ir(III) for $E < C1$, Ir(IV) for $A1 < E < C2$ and Ir(V) for $E > A2$.²³ During the growth of templated films, the charge passed depends almost linearly on the number of voltammetric cycles, Fig. 2, and the anodic to cathodic charge ratio is equal to one at all cycle numbers. This suggests that the whole of the film is reversibly oxidised and reduced during cycling and demonstrates that cyclic voltammetry provides a fine degree of control over the amount of oxide deposited. Results are markedly different with flat films. Further voltammetric characterisation of the

films in basic conditions ($0.1 \text{ M Na}_2\text{CO}_3$, pH 10.9) (in acid the templated films have broad voltammetric peaks harder to analyse) produced a linear relationship between the peak currents and the scan rate therefore indicating the absence of kinetic effects over the $20 - 200 \text{ mV s}^{-1}$ range studied. Both flat and structured films were seen to change colour during potential cycling (from transparent for $E < 0.3 \text{ V vs. SCE}$ to dark blue for $E > 0.5 \text{ V vs. SCE}$) thus indicating that the electrochromism of the IrOx films did not disappear with the templated structure.

Insert Figure 3 here

Fig. 3 Micrographs of IrOx films produced by cyclic voltammetry (same conditions as in Fig. 1) with a 600 nm diameter polystyrene template. A) ~ 20 cycles, B) ~ 40 cycles, $h \sim \frac{1}{4} d$, C) ~ 60 cycles, $h \sim \frac{1}{2} d$, D) ~ 80 cycles, E) ~ 100 cycles, $h \sim d$, F) ~ 200 cycles, $h > d$

In Fig. 3, SEM micrographs taken at different stages of deposition show the remarkable structure of the film left after removal of the template. Initially, Fig. 3A, the presence of the deposit is only confirmed by the difference in contrast between the gold substrate and IrOx but the hexagonal symmetry is already obvious. After fewer than ten cycles the shape of the deposit appears, Fig. 3B, but the underlying granular structure of the substrate is still clearly visible. When the film thickness, h , reaches a height of $\sim \frac{1}{2} d$, Fig. 3C, the smooth wall of the IrOx cups can be seen. The cup diameters follow closely that of the polystyrene spheres of the template. Except for the cup rims which show variations in texture, Fig. 3D, the film is uniform and free from defects over a very long range. Beyond $\frac{1}{2} d$, the cups gradually close, Fig. 3E but again the films are virtually free of defects. Fig. 3F shows a typical film grown through several template layers; the 3D honeycomb internal structure characteristic of inverted opals is clearly visible. Up to one template layer, the film thickness measured by SEM is found to be linearly related to the number of voltammetric cycles (similar results are found with films deposited without template). Beyond $1 d$, it has not been possible to establish the relationship between cycle number and film thickness as the later becomes difficult to measure. Furthermore an evaluation of the thickness deposited from the charge passed and account of the interstitial volume within the template necessitates measuring the density of the deposit as the porosity of the material is reported to produce significant differences between the density of bulk IrOx, circa 11 g cm^{-3} , and that of electrodeposited films circa 2 g cm^{-3} .²³ Characterisation with X-Ray diffraction only produced a spectrum for the underlying gold substrate. However Raman microscopy clearly showed that the material was amorphous as deposited but became crystalline after annealing at 460°C .

Insert Figure 4A here

Insert Figure 4B here

Fig. 4 Normalised reflectivity spectra recorded on A) a non-structured film and B) a structured film supporting plasmon, $\sim \frac{1}{2} d$, in air but with the films taken out of the solution in the bleached state.

Angle resolved reflectivity spectra of structured and non-structured IrOx films ($\frac{1}{2}d$ thick), Fig. 4, clearly demonstrate that, as with gold films,³³ the presence of the nanostructure imparts new optical properties to the material. In the case of the flat film, Fig. 4A, the reflectivity spectrum (normalized to the reflectivity from an aluminum mirror) changes in intensity with angle of incidence but does not change in wavelength or shape. For the structured film, Fig. 4B, in contrast there is a clear change in the position of minimum reflectivity with angle. Two plasmon bands are observed in the data, Bragg diffracted by the periodicity of the dishes into the plane of the surface. The dispersion of these modes is governed by the high refractive index IrOx layer and the size of the dishes d . Initially coupled at 0° incidence, these modes tune to shorter wavelength with increasing incident angle, indicative of delocalized behavior. Electrochromism was also observed when reflectivity spectra were recorded under potentiostatic control. For example, the intensity reflected at 770 nm varied from 100% at -0.3 V (the bleached state) to 67% at 0 V, 34% at $+0.1$ V, 21% at $+0.2$ V and 16% at $+0.7$ V (the dark state). Detailed results recorded under potentiostatic control for different thicknesses will be reported subsequently.

Conclusions

This article reports the first successful preparation of highly ordered iridium oxide films via electrodeposition through a self-assembled colloidal template of polystyrene spheres. The films are true casts of the template; monolayer films present a long range hexagonal arrangement of hemispherical cavities while multilayer films present a 3D honeycomb structure with spherical voids characteristic of inverse opal structures. This approach avoids the shrinkage normally observed with chemical and thermal transformations. The films are found to be amorphous, to have several electroactive redox states and to be electrochromic. Compared to flat films the reflectivity of structured films is found to depend on the angle of incidence and wavelength of the incident light. These preliminary optical results suggest that nanostructured IrOx films could be used as electrochemically or chemically (IrOx is pH sensitive) tunable photonic devices.

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Notes and references

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References

1. G. Beni, J. L. Shay, S. Gottesfeld and D. E. McIntyre, *Appl. Phys. Lett.*, 1978, **33**, 208-210.
2. J. D. E. McIntyre, W. F. Peck and S. Nakahara, *J Electrochem Soc*, 1980, **127**, 1264-1268.
3. R. D. Meyer, S. F. Cogan, T. H. Nguyen and R. D. Rauh, *Ieee Transactions on Rehabilitation Engineering*, 2001, **9**, 2-11.
4. S. C. Mailley, M. Hyland, P. Mailley, J. M. McLaughlin and E. T. McAdams, *Materials Science & Engineering C-Biomimetic and Supramolecular Systems*, 2002, **21**, 167-175.
5. D. O. Wipf, F. Y. Ge, T. W. Spaine and J. E. Bauer, *Anal Chem*, 2000, **72**, 4921-4927.
6. K. G. Kreider, M. J. Tarlov and J. P. Cline, *Sensors and Actuators, B: Chemical*, 1995, **B28**, 167-172.
7. I. A. Ges, B. L. Ivanov, D. K. Schaffer, E. A. Lima, A. A. Werdich and F. J. Baudenbacher, *Biosens Bioelectron*, 2005, **21**, 248-256.
8. T. Pauporte, F. Andolfatto and R. Durand, *Electrochim Acta*, 1999, **45**, 431-439.
9. R. S. Chen, Y. S. Huang, Y. M. Liang, D. S. Tsai and K. K. Tiong, *Journal of Alloys and Compounds*, 2004, **383**, 273-276.
10. F. Y. Zhang, R. Barrowcliff, G. Stecker, W. Pan, D. L. Wang and S. T. Hsu, *Jpn. J. Appl. Phys. Part 2 - Lett. Express Lett.*, 2005, **44**, L398-L401.
11. R. S. Chen, A. Korotcov, Y. S. Huang and D. S. Tsai, *Nanotechnology*, 2006, **17**, R67-R87.
12. A. Korotcov, Y. S. Huang, D. S. Tsai and K. K. Tiong, *Journal of Physics-Condensed Matter*, 2006, **18**, 1121-1136.
13. A. M. Serventi, M. A. El Khakani, R. G. Saint-Jacques and D. G. Rickerby, *Journal of Materials Research*, 2001, **16**, 2336-2342.
14. Y. L. Chen, C. C. Hsu, Y. H. Song, Y. Chi, A. J. Carty, S. M. Peng and G. H. Lee, *Chemical Vapor Deposition*, 2006, **12**, 442-447.
15. P. N. Bartlett, J. J. Baumberg, S. Coyle and M. E. Abdelsalam, *Faraday Discuss.*, 2004, **125**, 117-132.
16. K. Yamanaka, *Japanese Journal of Applied Physics Part 1-Regular Papers Short Notes & Review Papers*, 1989, **28**, 632-637.
17. M. C. Netti, M. D. B. Charlton, G. J. Parker and J. J. Baumberg, *Appl. Phys. Lett.*, 2000, **76**, 991-993.
18. M. Huppaufl and B. Lengeler, *J Electrochem Soc*, 1993, **140**, 598-602.
19. M. Wang, S. Yao and M. Madou, *Sens. Actuator B-Chem.*, 2002, **81**, 313-315.
20. C. Mousty, G. Foti, C. Comminellis and V. Reid, *Electrochim Acta*, 1999, **45**, 451-456.
21. L. M. Schiavone, W. C. Dautremontsmith, G. Beni and J. L. Shay, *Appl. Phys. Lett.*, 1979, **35**, 823-825.
22. J. Yano, K. Noguchi, S. Yamasaki and S. Yamazaki, *Electrochem Commun*, 2004, **6**, 110-114.
23. M. A. Petit and V. Plichon, *Journal of Electroanalytical Chemistry*, 1998, **444**, 247-252.
24. G. S. Attard, P. N. Bartlett, N. R. B. Coleman, J. M. Elliott, J. R. Owen and J. H. Wang, *Science*, 1997, **278**, 838-840.
25. P. N. Bartlett, P. R. Birkin and M. A. Ghanem, *Chem Commun*, 2000, 1671-1672.

-
26. P. N. Bartlett, P. R. Birkin, M. A. Ghanem and C. S. Toh, *J Mater Chem*, 2001, **11**, 849-853.
27. S. A. G. Evans, J. M. Elliott, L. M. Andrews, P. N. Bartlett, P. J. Doyle and G. Denuault, *Anal Chem*, 2002, **74**, 1322-1326.
- 5 28. T. Imokawa, K.-J. Williams and G. Denuault, *Anal Chem*, 2006, **78**, 265-271.
29. T. A. Kelf, Y. Sugawara, J. J. Baumberg, M. Abdelsalam and P. N. Bartlett, *Physical Review Letters*, 2005, **95**.
30. G. V. Prakash, L. Besombes, T. Kelf, J. J. Baumberg, P. N. Bartlett and M. E. Abdelsalam, *Opt Lett*, 2004, **29**, 1500-1502.
- 10 31. S. Coyle, G. V. Prakash, J. J. Baumberg, M. Abdelsalem and P. N. Bartlett, *Appl. Phys. Lett.*, 2003, **83**, 767-769.
32. S. Coyle, M. C. Netti, J. J. Baumberg, M. A. Ghanem, P. R. Birkin, P. N. Bartlett and D. M. Whittaker, *Physical Review Letters*, 2001, **87**, 17.
- 15 33. M. C. Netti, S. Coyle, J. J. Baumberg, M. A. Ghanem, P. R. Birkin, P. N. Bartlett and D. M. Whittaker, *Adv Mater*, 2001, **13**, 1368-1370.
34. S. Cintra, M. E. Abdelsalam, P. N. Bartlett, J. J. Baumberg, T. A. Kelf, Y. Sugawara and A. E. Russell, *Faraday Discuss.*, 2006, **132**, 191-199.
- 20 35. M. E. Abdelsalam, P. N. Bartlett, J. J. Baumberg, S. Cintra, T. A. Kelf and A. E. Russell, *Electrochem Commun*, 2005, **7**, 740-744.
- 25 36. M. E. Abdelsalam, P. N. Bartlett, T. Kelf and J. Baumberg, *Langmuir*, 2005, **21**, 1753-1757.
37. A. A. Zhukov, M. A. Ghanem, A. Goncharov, P. A. J. de Groot, I. S. El-Hallag, P. N. Bartlett, R. Boardman and H. Fangohr, *Journal of Magnetism and Magnetic Materials*, 2004, **272-76**, 1621-1622.
- 30 38. P. N. Bartlett, M. A. Ghanem, I. S. El Hallag, P. de Groot and A. Zhukov, *J Mater Chem*, 2003, **13**, 2596-2602.
39. N. D. Denkov, O. D. Velev, P. A. Kralchevsky, I. B. Ivanov, H. Yoshimura and K. Nagayama, *Langmuir*, 1992, **8**, 3183-3190.
- 35 40. M. Kawasaki, T. Sato and T. Yoshimoto, *Langmuir*, 2000, **16**, 5409-5417.
41. L. D. Burke and R. A. Scannell, *Platinum Metals Review*, 1984, **28**, 56 - 61.

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