Titanium Oxide Film: A New Biomaterial For Artificial Heart Valve Prepared by Ion Beam Enhanced Deposition

Xianghuai Liu, Feng Zhang, Zhihong Zheng, Nan Huang
Ion Beam Laboratory, Shanghai Institute of Metallurgy,
Chinese Academy of Sciences, Shanghai 200050, P.R.China

ABSTRACT

Titanium oxide films were prepared by ion beam enhanced deposition, where the films were synthesized by depositing titanium atoms and simultaneously bombarding with xenon ion beam at an energy of 40 keV in an O_2 environment. Structure and composition of titanium oxide films were investigated by X-ray Diffraction (XRD), Rutherford Backscattering Spectroscopy (RBS) and X-ray photoelectron spectroscopy (XPS). The results show that the structure of the prepared films exhibit a rutile phase structure with high (200) orientation, and the O/Ti ratio of the titanium oxide films was about 2:1. XPS analysis shows that Ti^{2+}, Ti^{3+} and Ti^{4+} chemical states exist on the titanium oxide films. The blood compatibility of the titanium oxide films was studied by measurements of blood clotting time and platelet adhesion. The results show that the anticoagulation property of titanium oxide films improved significantly and better than that of LTI-carbon, which was widely used to fabricate artificial heart valve.

I. Introduction

The biomaterial, which has to be contact with blood such as artificial heart valve, needs good blood compatibility. Low temperature isotropic pyrolytic carbon (LTI-carbon) and titanium alloys are usually used for fabrication of artificial heart valves because of their combination of blood compatibility and high resistance to degradation, wear and fatigue. But there are also some serious problems. The main problem of mechanical heart valves is their thromboginicity. Life-time anticoagulant therapy is necessary to minimize the risk of thromboembolic complications. So it is very important to find a new biomaterial with high blood compatibility.

Various types of cardiac valve prostheses have been developed and applied clinically for heart valve replacement for the past several decades. Many works have been done to find a new biomaterial with good blood compatibility all over the world. For example, P. Baurschmidt an his coworkers studied the blood compatibility of a-SiC and wanted to use this material as artificial heart valve[1]. A tilting flat disk-type ceramic valve has been developed by Mitamura and his coworkers[3]. The valve is comprised of a single-crystal alumina ceramic disk and TiN valve cage. The blood compatibility of diamond like carbon (DLC) was also studied by I. Dion[4]. In the 1980's, M. Schaldach and his coworkers researched the blood compatibility of Ta^{5+} doped rutile type TiO_2 ceramics[5]. Of all these materials, only TiO_2 ceramics shows good hemocompatibility in comparison to LTI-carbon. In spite of the improved hemocompatibility of this doped, semiconducting rutile ceramic in comparison to LTI-carbon, the technological problems related to the surface roughness of this material made the manufacturing costs prohibitive[6]. No more works were reported about TiO_2 ceramics. It is also found that the good biocompatibility of titanium is associated with the oxide layer on surface[7]. This would be advantageous if titanium oxide were used as artificial heat valve. So, we used ion beam enhanced deposition (IBED) to synthesize rutile-type titanium oxide films and research its blood compatibility.

Ion beam enhanced deposition(IBED) is one of the important technique to produce thin films and coatings. It refers to the situation in which a film is deposited on a substrate while being simultaneously bombarded with an ion beam which has an energy ranging from several tens of electron volts to about one hundred kilo-electron volts. The advantages of this method are that it can be expected to provide strong adherent films because the interface between substrate and the film is mixed by high energy ions, chemical composition can be controlled easily and the process to produce the desirable film structure takes place at a relatively low substrate temperature(T_s).

The purpose of this paper is to study the blood compatibility of titanium oxide film prepared by ion beam enhanced deposition.

II. Experimental

The titanium oxide films were deposited onto optically polished silicon (100) substrate by electron beam evaporation of Ti at a rate of 0.4 nm/sec in an oxygen atmosphere, which was monitored with a quartz crystal. A beam of energetic xenon ions was used to bombard the growing TiO_{2-x} films simultaneously. The angle of incidence of the titanium vapor stream and xenon ion beam to the substrate were 45^0 respectively. The xenon source was operated at a fixed energy of 40 keV. The ion beam current density was maintained between 5~60 $\mu A/cm^2$. The base pressure in the deposition chamber was 7×10^{-5} Pa. During deposition, the deposition chamber was backfilled with high purity O_2 gas to a pressure between 8.0×10^{-4} to 1.5×10^{-3} Pa. The substrate temperature was controlled below 250^{0}C during deposition. The structure and composition of the films were studied by X-ray diffraction analysis (XRD), Rutherford backscattering spectroscopy (RBS), and X-ray photoelectron spectroscopy (XPS).

Platelet adhesion[8] and clotting time measurement[9] was used to judge blood compatibility of titanium oxide films. In the experiment of platelet adhesion, sample were merged into the platelet rich plasma and incubated at 37^{0}C for 0.5 hour. after rinsing, fixing and critical point drying, the specimens were observed by optical microscopy and scanning electron microscopy (SEM). Twenty fields of vision were investigated to obtain the morphology and statistical results of the adhered platelets.

The kinetic method of measurement of the thromboresistant property was used to determine clotting time. Blood was dropped onto a testing sample and incubated for predetermined time. The red blood cells which had not been trapped in a thrombus were haemolysed, and the free haemoglobin was dispersed in the distilled water. The concentration of free haemoglobin in the water was colorimetrically measured as the optical density at 540 nm with a spectrometer. In addition to titanium oxide films, the clotting properties of LTI-carbon and titanium were investigated for comparison.

III. Results and Discussion

The composition of TiO_2 films synthesized on carbon plates was measured using the RBS method. It can be seen that each component in the film is well distributed as shown in Fig. 1. The ratio of oxygen and titanium in the films which is determined by the height of each peak is about 1.85.

Fig. 2 shows the XRD patterns of TiO_{2-x} films synthesized by Xe^+ with different current density. It can be seen that the films exhibit a highly (100) orientation and increase the degree of (100) orientation with ion beam current density decreasing. When the current density decreased to 5 $\mu A/cm^2$, only (200) and its second diffraction (400) peaks were detected. The uniqueness suggests good (200) orientation.

X-ray photoelectron spectroscopy of Ti 2p from natural surface of titanium oxide films as shown in Fig. 3(a) shows that the binding energy of Ti 2p3/2 and Ti 2p1/2 were observed to be at 458.6 eV and 464.4 eV which is assigned to the Ti^{4+} in TiO_2, with a peak separation of 5.8 eV between these two peaks. After 20 minutes of argon ion sputtering, another two Ti 2p3/2 peaks were detected, which located at ~455 eV and ~456.7 eV as shown in Fig. 3(b). These two peaks were due to the Ti^{2+} and Ti^{3+} states in the TiO and Ti_2O_3 respectively. It's found that with increase of oxygen pressure, the concentration of Ti^{4+} increased rapidly. It is well known that Ti^{2+} and Ti^{3+} is very easy to be oxidized. So, no Ti^{2+} and Ti^{3+} states were detected at the surface. At the same time, the fully oxidation on the surface prevent oxygen in air from reaction with titanium near surface which exists in the form of Ti^{2+} and Ti^{3+}. Details on XPS results are described in the another paper[10].

The blood compatibility of titanium oxide films prepared with different O_2 pressure were measured by clotting time and platelet adhesion. Fig. 4 shows the blood profiles on the tested materials. The optical density (at 540nm) of the haemolysed haemoglobin solution changes with time. The higher the optical density, the better the thromboresistance. The experiments shows that the clotting time of IBED-synthesized films is better than that of LTI-carbon and titanium. Fig. 5 shows scanning electron micrographs of adherent platelets spread on the IBED-synthesized films and LTI-carbon. It can be seen that the number of platelets adhering to the IBED-coated titanium oxide layers is much less than that adhering to the LTI-carbon surface. Significant numbers of platelets are observed on the LTI-carbon surface with much aggregation. Many deformed platelets, such as pseudopodium, are also observed on the LTI-carbon surface. On IBED-synthesized films, the aggregation of platelets and formation of pseudopodium are not significant. In a word, the blood compatibility of titanium oxide films prepared by IBED is better than that of LTI-carbon.

It was demonstrated that the formation of thrombus on an artificial biomaterial is correlated with charge (electron) transfer from the inactive state of fibrinogen to the surface of the biomaterial. During the process, fibrinogen decomposes to fibrinmonomer and fibrinopeptides. After this process, the resulting monomers give rise to polymers before finally cross-linking to an irreversible thrombus[2]. So fibrinogen plays a central role in hemostasis[11,12]. Not only does it participate in the coagulation cascade, but it also promotes adhesion of platelets and activated them when adsorbed onto certain solid surfaces[12,13,14]. Fibrinogen has an electronic structure similar to a semiconductor and has a 1.8 eV band gap[15]. Certain electronic structure states on the material surface could possibly inhibit the transfer of the charge carrier. The transfer of electron is determined by the femi level of the film and protein. In order to inhibit the transfer of the charge carrier from fibrinogen to titanium oxide film. The femi level of titanium oxide film must be close to the bottom of conduct band, that is to say, reduce work function of the film.

It is found that the optical band gap of IBED-synthesized titanium oxide is about 3.0 eV, and the concentration of Ti^{2+} and Ti^{3+} is very high. The exist of large amount of Ti^{2+} and Ti^{3+} result in lower work function. This makes titanium oxide films prepared by IBED exhibit better blood compatibility

V. Conclusions

Titanium oxide films were prepared by ion beam enhanced deposition, where the films were synthesized by depositing titanium atoms by electron beam and simultaneously bombardment with xenon ions in an O_2 atmosphere. RBS shows that the atomic ratio of O/Ti is about 1.85:1. XPS analysis shows that Ti^{2+}, Ti^{3+} and Ti^{4+} chemical states exist on the titanium oxide films. XRD analysis shows that the films exhibit a highly (100) orientation and increase the degree of (100) orientation with ion beam current density decreasing. Clotting time measurement shows that the clotting time of titanium oxide films is longer than that of LTI-carbon. There are also less platelets adhered and deformed on the titanium oxide films compared to that of LTI-carbon. We think that the exist of Ti^{2+} and Ti^{3+} is beneficial for blood compatibility.

Acknowledgments

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References

1. Bolz A and Schaldach M., Artificial Organs, 144(4), 160(1990)

2. P. Baurschmidt and M. Schaldach, Med. Biol. Eng. Comput., 18,496(1980)

3. Mitamura Y., Hosooka K. and Matsumoto T., J. Biomater. Appl., 4(11), 33(1989)

4. I. Dion, X. Roques, C. Baquey, E. Baudet, B. B. Cathalinat and N. More, Biomedical Materials and Engineering, 5, 51(1993)

5. R. Ebert and Schaldach M., Proceeding of world congress on medical physics and biomedical engineering, Hambarg, 3.07(1982)

6. A. Bolz and M. Schaldach, Artificial Organs, 14,260(1990)

7. Jianguo Li, Biomaterials, 14, 229(1993)

8. M. Amiji and K. Park, Biomaterials, 13, 682(1992)

9. Y. Imai and Y. Nose, J. Biomed. Mater. Res., 6, 165(1972)

10. Feng Zhang, S. Jin, Yingjun Mao, Yu Chen, Zhihong Zheng, Xianghuai Liu, Thin Solid Films, in press(1997)

11. R. Sipehia and A. S. Chawla, Biomater. Org., 10,229(1982)

12. D. F. Williams, Blood Compatibility, Vol. 1, P. 5, CRC Press, Boca Raton, FL(1987)

13. E. Nyilas and T. H. Chiu, Artif. Organ., 2, 56(1978)

14. S. M. Slack and T. A. Horbett, J. Biomater. Sci. Polym. Edn., 2, 227(1991)

15. D. Eley and D. Spiey, Trans. Faraday Soc., 56, 1432(1960)

Captions

Fig. 1: Typical RBS spectrum of titanium oxide films prepared by IBED

Fig. 2: XRD pattern of titanium oxide films synthesized by Xe^+ with different current density

Fig. 3(a): Ti 2p XPS spectrum on natural surface of titanium oxide films

Fig. 3(b): Ti 2p XPS spectrum of titanium oxide films after 20 minutes of argon ion sputtering

Fig. 4: The blood clotting profiles on various material surfaces

Fig. 5: Scanning electron micrographs of platelets spread on titanium oxide film (A) and LTI-carbon (B)

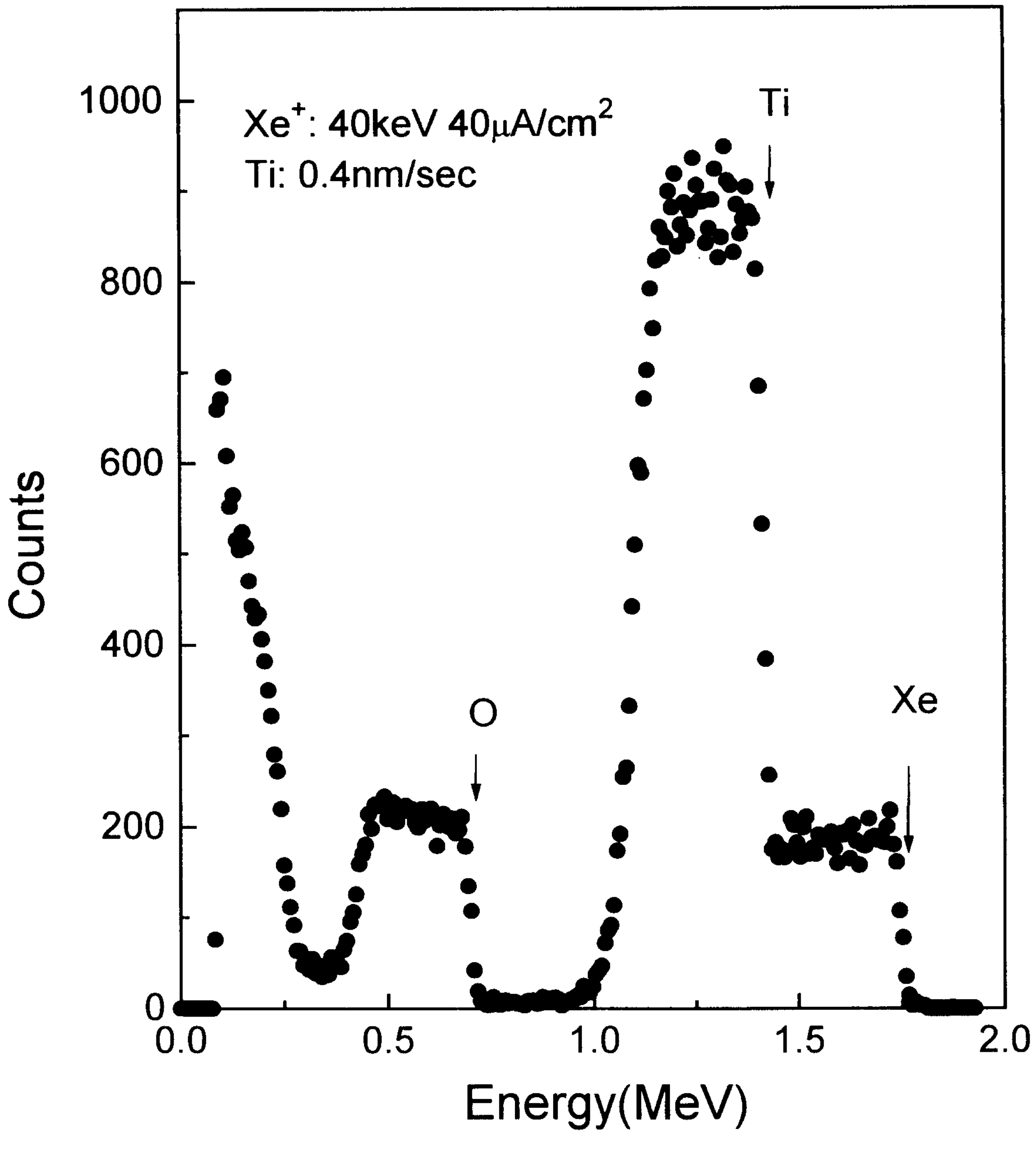Xe$^+$: 40keV 40μA/cm^2
Ti: 0.4nm/sec
Ti
O
Xe
Counts
0
200
400
600
800
1000
0.0
0.5
1.0
1.5
2.0
Energy(MeV)

Fig. 1

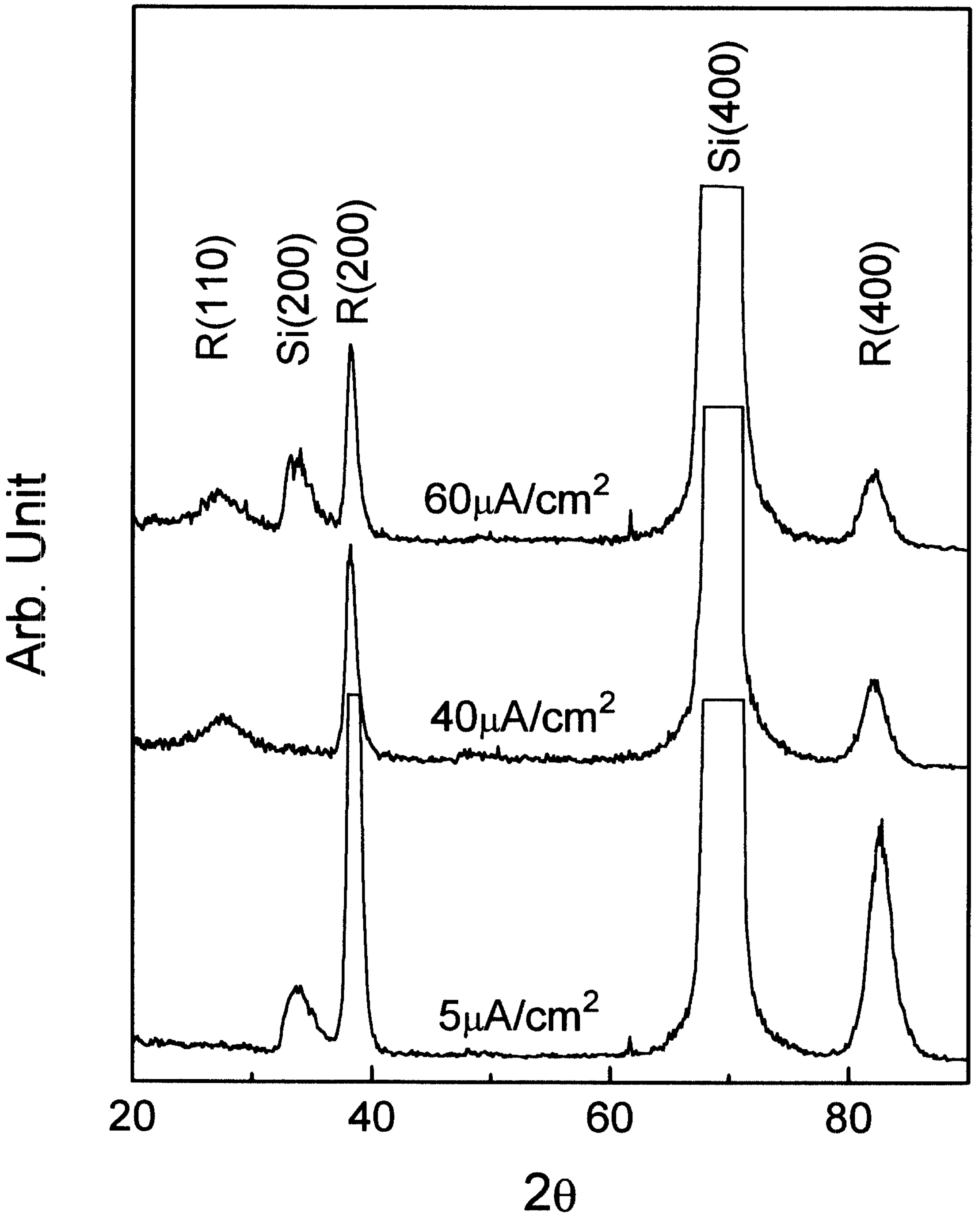
R(110)
Si(200)
R(200)
Si(400)
R(400)
60μA/cm2
40μA/cm2
5μA/cm2
Arb. Unit
20
40
60
80
2θ

Fig. 2

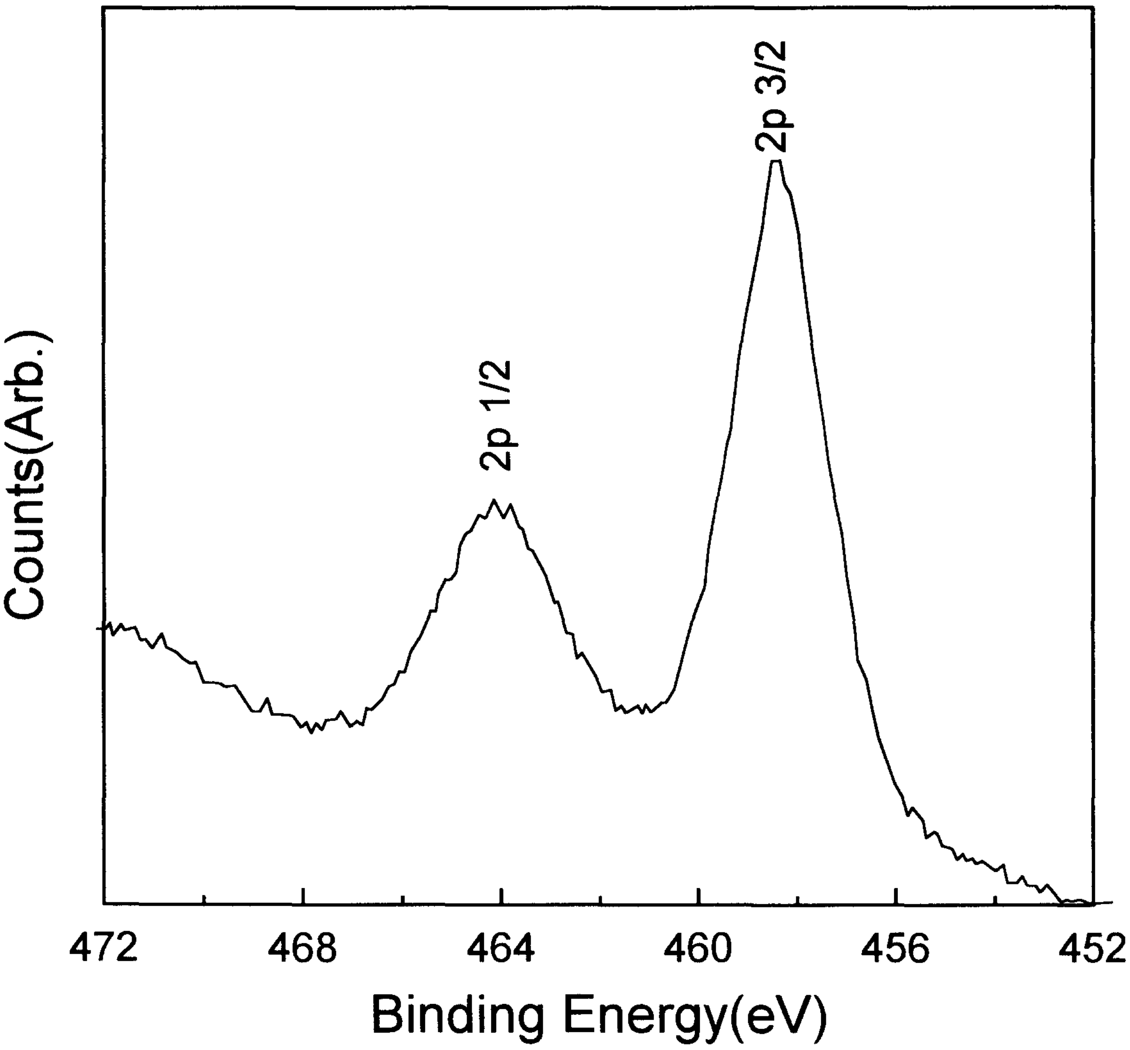
Counts(Arb.)
2p 1/2
2p 3/2
472
468
464
460
456
452
Binding Energy(eV)

Fig. 3(a)

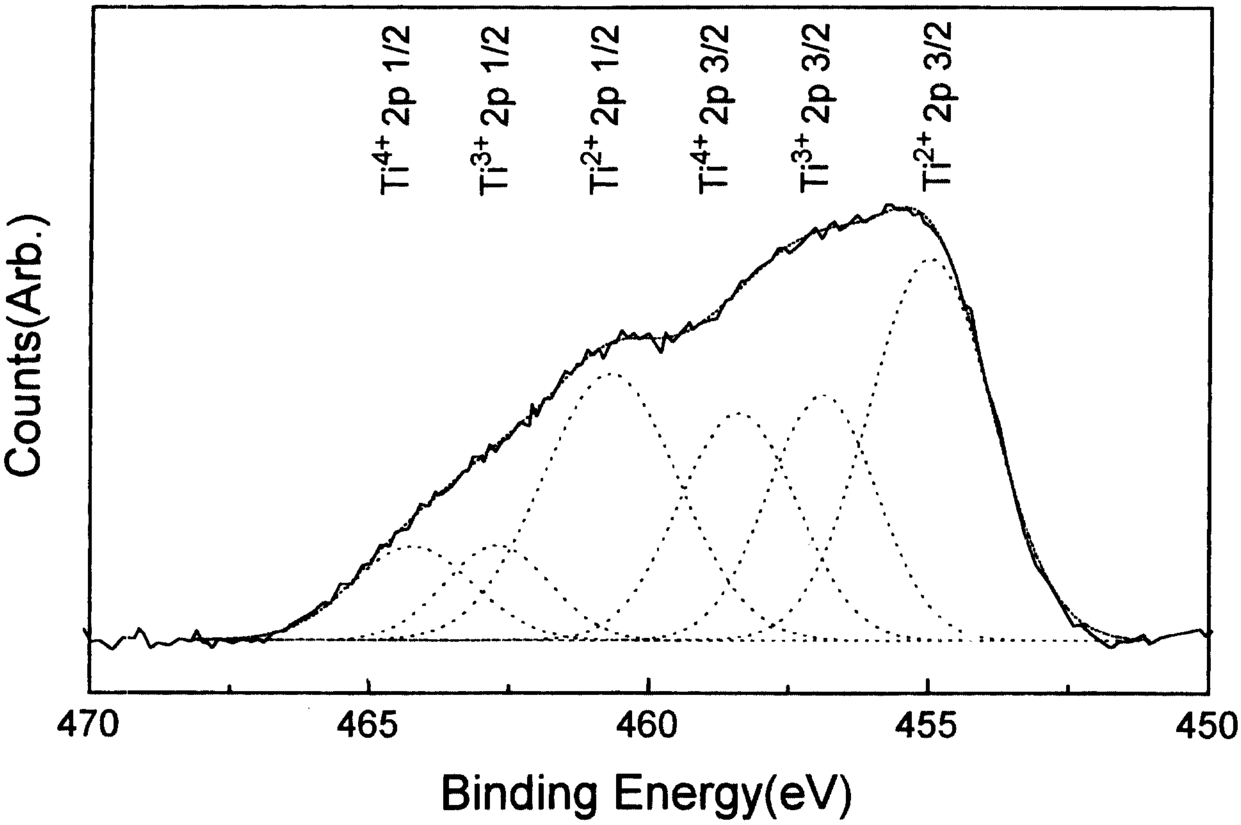
Ti^{4+} 2p 1/2
Ti^{3+} 2p 1/2
Ti^{2+} 2p 1/2
Ti^{4+} 2p 3/2
Ti^{3+} 2p 3/2
Ti^{2+} 2p 3/2
Counts(Arb.)
470
465
460
455
450
Binding Energy(eV)

Fig. 3(b)

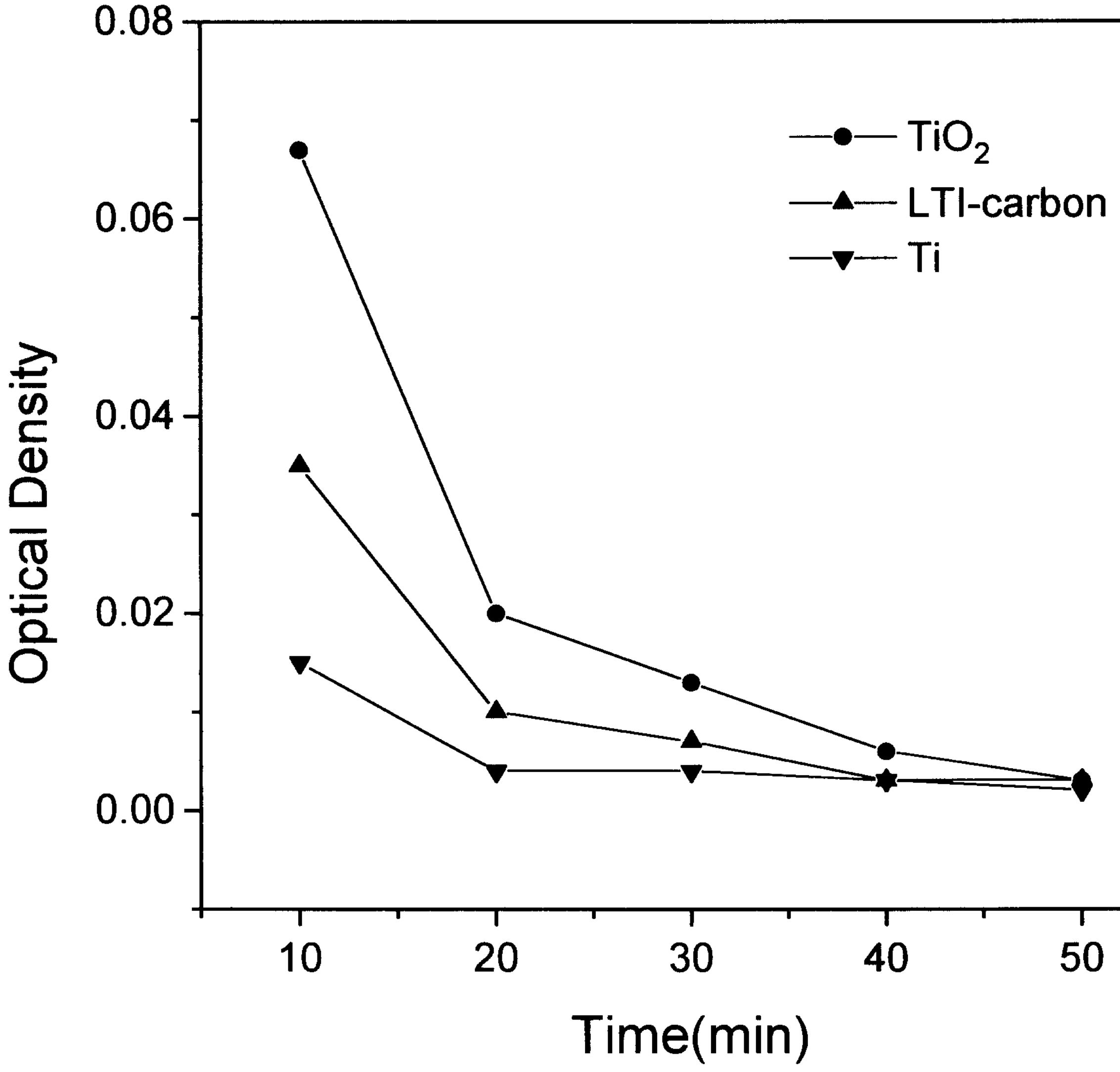
0.08
0.06
0.04
0.02
0.00
Optical Density
10
20
30
40
50
Time(min)
TiO2
LTI-carbon
Ti

Fig. 4

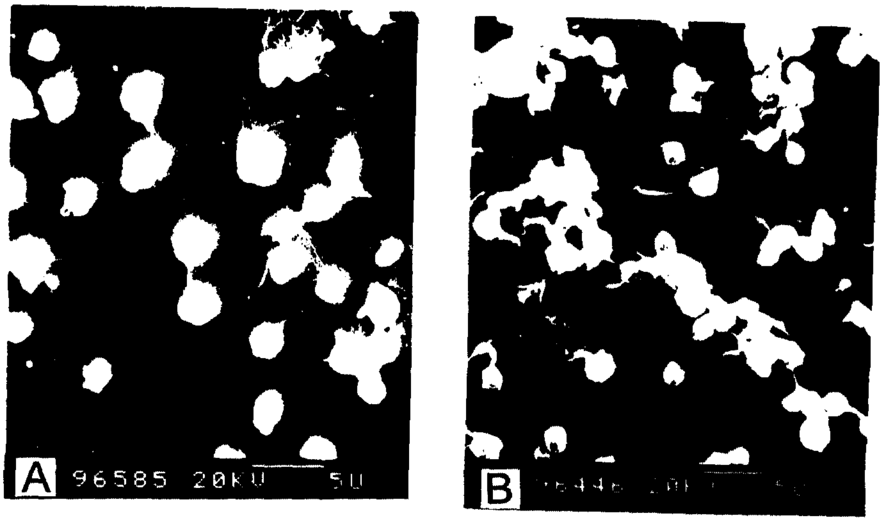

Fig. 5