

The Oxyanions of Calix[4]arene: The NMR Investigation of the Structure of the Oxyanions of Calix[4]arene

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The structure and conformational behavior of the oxyanions of calix[4]arene have been studied by the NMR spectrum. The structure of the oxyanions of calix[4]arene was completely dependent upon the counter cation in present. All of the anions derived from in the presence of NaH and KH appear to exist as a cone conformation, whereas those produced with lithium cation such as *n*-butyllithium and LiOD show a more varied conformational behavior. The mono and tetraanions with lithium cation exist as a cone conformation, the trianions appear to exist as a partial cone conformation, and the dianions appear to disproportionate to the mono and trianions. The conformational stability decreases in the order of Li^+ oxyanion > Na^+ oxyanion > K^+ oxyanion.

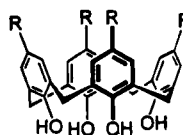
Introduction

Calixarenes are basket-shaped compounds^{1,2} currently receiving attention because of their ability to form a complex with ions or neutral molecules. In particular calix[4]arenes possess conformationally flexible structures for which the four "up-down" conformations³⁻⁵ pictured in Figure 1. This can be designated as a "cone", "partial cone", "1,2-alternate", and "1,3-alternate" conformation. Each of these conformations possesses a distinctive pattern of the ¹H NMR resonances for the protons of the methylene groups between the aryl rings, thus allowing a clear identification of a particular conformation.

Calix[4]arenes which all four aryl rings are free phenolic units exist primarily as a cone conformation as a result of strong intramolecular hydrogen bonding, which also leads to a greater acidity than the monomeric phenolic analog. This phenomena, called "hyperacidity" by Sprengling,⁶ was first experimentally demonstrated for the calixarenes by Böhmer and coworkers⁷ for the mononitrocalix[4]arene and subsequently by Shinkai and coworkers⁸ for the tetranitrocalix[4]arene. Particularly, Shinkai's group determined the exact dissociation constants of the *p*-nitrocalix[4]arene, which shows a quite interesting value such as $\text{p}K_1=2.9$, $\text{p}K_2=10.9$, $\text{p}K_3=12.3$, and $\text{p}K_4$ more than 14.

The formation of ethers and esters of calix[4]arenes is often carried out in the presence of very strong bases such as NaH, and the conformation of the product has been shown to be strongly dependent on the reaction conditions as well as reagents.^{5,9,10} It was of interest, therefore, to study on the ionization behavior of calix[4]arenes under such condition. Previously, Gutsche and Nam^{11,12} reported the brief characteristics of the oxyanion structure. This present work was undertaken to determine the structural change and the flex-

ibility of the oxyanions of calix[4]arene dependent upon bases. The conformational change was observed by the NMR spectrum. The NMR studies were carried out with calix[4]arene **1**, as a typical standard calix[4]arene. To investigate the effect of the *para* substituents on the upper rim of the calixarene for the conformational change, *p*-dimethylaminomethylcalix[4]arene **2**, *p*-methylcalix[4]arene **3** and *p*-allylcalix[4]arene **4** were also examined.



- 1**, R=H, **2**, R=CH₂N(CH₃)₂
3, R=CH₃, **4**, R=CH₂CH=CH₂

Results and Discussion

Treatment of a DMSO-*d*₆ solution of a calix[4]arene with incremental amount of base generates solutions that has been analyzed by means of ¹H NMR. The spectral changes are observed until four equivalents of base have been added. The conformational identity of the various species can be established by inspection of the 3-5 ppm region of the ¹H NMR spectra which arises from the bridging CH₂ protons, a pair of doublets signifying a cone conformation, two sets of pair of doublets signifying a partial cone conformation, and a singlet signifying a 1,3-alternate conformation if four of the OH group at the lower rim of calix[4]arene are free.

The addition of varying amounts of *n*-butyllithium to calix[4]arene **1** in DMSO-*d*₆ solution produced the ¹H NMR spectra as shown in Figure 2. The most revealing portions of the spectra are 2.5-5.0 ppm region associated with methylene resonances and the 5.8-7.2 ppm region associated with the aromatic protons resonances. In the case of one equivalent of *n*-butyllithium the aromatic protons show a doublet and a triplet like those of without base with slightly shifted upfield and the methylene resonance show two broad humps, commensurate with a flexible cone conformation. A similar pattern again commensurate with a cone conformation, is observed with four or more equivalents of *n*-butyllithium, but in this case the aromatic peaks are shifted considerably upfield and the distinctive methylene doublets

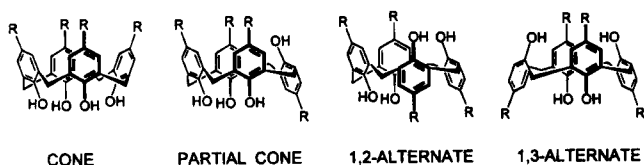


Figure 1. Conformations of calix[4]arene.

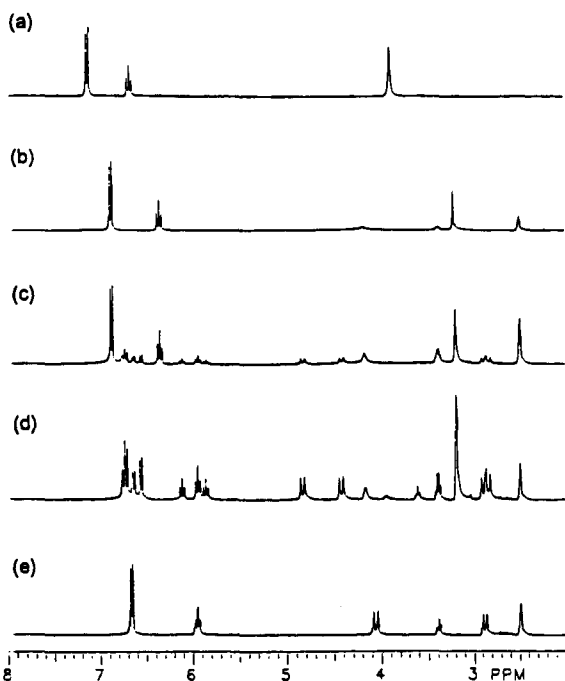


Figure 2. ^1H NMR spectra of **1** in the presence of *n*-BuLi in DMSO- d_6 . (a) without base, (b) 1 equivalent of *n*-BuLi, (c) 2 equivalents of *n*-BuLi, (d) 3 equivalents of *n*-BuLi, (e) 4 equivalents of *n*-BuLi.

are also shifted upfield.

The pattern of the ^1H NMR spectra arising from addition of two and three equivalents of *n*-butyllithium are quite complicated due to the conformational change. The oxyanions generated with three equivalents of *n*-butyllithium show four doublets at 6.6–6.9 ppm and three triplet at δ 5.9–6.2 ppm for the aromatic resonances and two sets of pair of doublets at 2.8–4.8 ppm, completely consistent with a partial cone conformation. The ^1H NMR spectrum generated from two equivalents of *n*-butyllithium, however, is best interpreted as a superposition of the spectra of the mono and trianions, suggesting that a dianion might be unstable and disproportionates¹³ to equal amounts of these anions. Treatment with trifluoroacetic acid of each of the solutions containing **1** and *n*-butyllithium regenerates the parent calix[4]arene unchanged, demonstrating that no decomposition occurs upon the formation of the oxyanions. The conformational flexibility of the oxyanions of **1** was measured by means of variable temperature ^1H NMR spectra. The parent calix[4]arene **1** in the absence of base coalesces below 20 °C. The coalescence temperature of the monoanion increases to 40 °C and the tri- and tetraanions, however, are much more conformationally stable, showing no tendency to approach a coalescence point up to 140 °C respectively as summarized in Table 1.

Treatment of **1** with LiOD, which is much weaker base than *n*-butyllithium, shows an interesting spectral features as shown in Figure 3. In the case of one to three equivalents of LiOD, all three anions show the same spectral characteristics observed in Figure 2 which was produced by the *n*-butyllithium except a multiplet at 3.4 ppm.¹⁴ Monoanion appears in a cone conformation and trianion in a partial cone conformation. Also dianion appears as a mixture of mono

Table 1. Conformation and coalescence temperature of calix[4]arene **1** oxyanions^a in the presence of different bases

Anions	Conformation and Coalescence Temperature			
	<i>n</i> -BuLi ^b	LiOD ^c	NaH ^d	NaOD ^e
Mono	cone, 40 °C	cone, 40 °C	cone, 40 °C	cone
Di	mixture of mono and trianions	mixture of mono and trianions	cone	cone
Tri	partial cone, <140 °C	partial cone, <140 °C	cone	cone
Tetra	cone, <140 °C	not found	cone	not found

^a All analyses are based on ^1H NMR spectra in DMSO- d_6 . ^b 1.6 N *n*-butyllithium in hexane used. ^c 9% LiOD in D₂O used. ^d 60% Oil dispersion used. ^e 40% NaOH in D₂O used.



Figure 3. ^1H NMR spectra of **1** in the presence of LiOD in DMSO- d_6 . (a) without base, (b) 1 equivalent of LiOD, (c) 2 equivalents of LiOD, (d) 3 or more equivalents of LiOD.

and trianions as observed with *n*-butyllithium base. But in the presence of four or more equivalent of LiOD the spectra show the same partial cone conformation seen with three equivalents of LiOD. The cone conformation observed with four equivalents of *n*-butyllithium was not seen in this cases. This suggests that the trianion of **1** is a weaker acid than water in DMSO, so the tetraanions of oxycalix[4]arene can not be generated with LiOD. This observation was confirmed by the addition of one drop of D₂O to the each anion solutions derived from *n*-butyllithium, which changed to

the spectral feature in Figure 2 to Figure 3 as expected from LiOD experiment. As expected, the tetraanion cone conformation derived from *n*-butyllithium changed to the trianion partial cone conformation with addition of D₂O. This observation strongly indicate that the structure of the oxyanions of calix[4]arene was determined by the counter ion.

Treatment of **1** with NaH in DMSO-*d*₆ gave the quite different spectral characteristics obtained with *n*-butyllithium. With NaH only a flexible cone conformation was observed in all four cases and the variable temperature ¹H NMR measurements show that each of them have approximately the same coalescence temperature at about 40 °C, indicative of more flexible species than those generated by *n*-butyllithium. Experimental problems¹⁵ made difficult a complete study of the species generated *via* KH, so only a solution containing the tetraanion of **1** was investigated in detail. Its ¹H NMR spectrum at 20 °C has a sharp singlet at 6.4 ppm for the aromatic protons and a broad singlet at 3.1 ppm for the bridge methylene protons. At higher temperature the resonance at 3.1 ppm becomes sharper, suggesting that at 20 °C the compound is in a cone conformation and already somewhat above its coalescence temperature. The qualitative studies of the solution containing between one to four equivalents of KH indicate that the oxyanions generated from KH are also in a cone conformation as observed in the oxyanions from NaH.

Competitive calix[4]arene oxyanion binding to the lithium

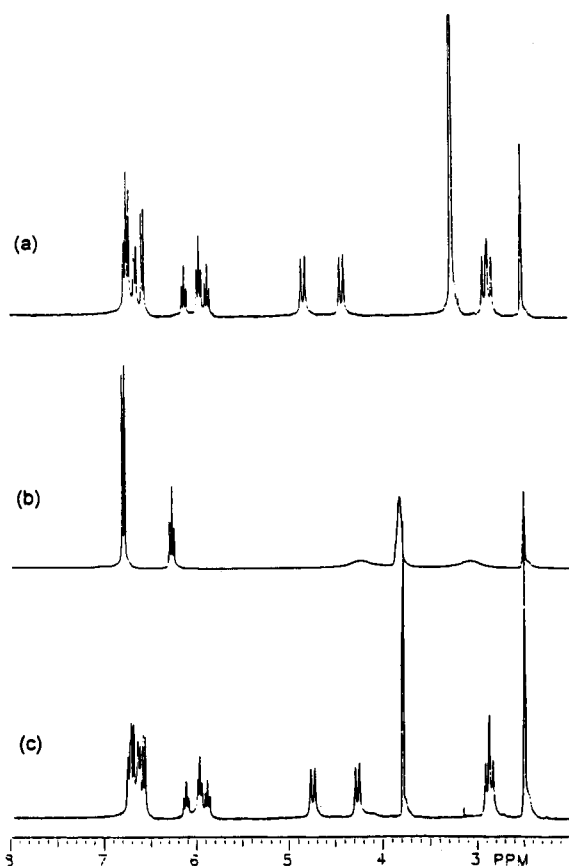


Figure 4. ¹H NMR spectra of **1** in DMSO-*d*₆. (a) 4 equivalents of LiOD, (b) 4 equivalents of NaOD, (c) 4 equivalents of NaOD followed by 4 equivalents of LiClO₄.

and sodium metal ion reveals that calix[4]arene **1** oxyanions show the very strong tendency toward lithium ion over sodium. The anion species generated from more than four equivalents of NaOD show a cone conformation, but as soon as LiClO₄ added to the sodium oxyanion solution, the ¹H NMR changed from (b) to (c) in Figure 4, indicating that the cone conformation became a partial cone in the presence of lithium ion. Quantitative measurement data are not available at this point, but the strong preference toward lithium over sodium for the calix[4]arene oxyanion is evident.

The ¹H NMR studies of **2** in the presence of *n*-butyllithium, LiOD, NaH, NaOD, and KH show the exact same phenomena. For example, in the case of *n*-butyllithium mono and tetraanion appear in a cone conformation and trianion in a partial cone conformation. The dianion species are not observed, rather seen as a mixture of mono and trianion species. In the presence of LiOD, mono, di, and trianions show the same spectral feature as seen with *n*-butyllithium as observed with calix[4]arene **1**. Treatment of **2** with NaH gave the same spectral pattern observed in **1** and also the competitive experiments between lithium and sodium to the oxyanion **2** reveal the strong preference toward lithium over sodium. Beside **1** and **2**, *p*-methylcalix[4]arene **3** as well as *p*-allylcalix[4]arene **4** were tested under the same conditions applied above. The exact same conformational changes were observed, indicating that the conformational characteristics of the calix[4]arene oxyanions was a consequence of the calix[4]arene framework itself rather than the *para* substituents.

Conformation characteristics and coalescence temperature of calix[4]arene **1** and **2** oxyanions generated by *n*-butyllithium, LiOD, NaH, NaOD, and KH in DMSO-*d*₆ solution are summarized in Table 1 and Table 2. Table 3 shows the chemical shifts data for each of the anion species of calix[4]arene **2** in DMSO-*d*₆ solution. Even though there are many different features in ¹H NMR spectra depending on the metal ions of the anion species, overall chemical shifts are reasonably close to each other in the same anion species. All of the proton signals shifted upfield upon making anion species. For example, N-methyl protons shifted from 2.18 ppm to 2.0 ppm and aromatic protons shifted from 6.85 ppm to 6.6 ppm regardless of bases used. The similar upfield shift also was observed on the bridge methylene protons, indicating that the conformational structures of ox-

Table 2. Conformation and coalescence temperature of calix[4]arene **2** oxyanions in the presence of different bases^a

Anions	Conformation and Coalescence Temperature				
	<i>n</i> -BuLi	LiOD	NaH	NaOD	KH ^b
Mono	cone, 90 °C	cone, 90 °C	cone, 90 °C	cone, 90 °C	—
Di	mixtures of mono and trianions	mixtures of mono and trianions	cone, 90 °C	cone, 90 °C	—
Tri	partial cone, <140 °C	partial cone, <140 °C	cone, 90 °C	cone, 90 °C	—
Tetra	cone, <140 °C	not found	cone, 90 °C	not found	cone, >20

^aThe same bases in Table 1 used. ^b35% Oil dispersion used.

Table 3. The chemical shifts (ppm) of ^1H NMR spectra of **2** in the presence of bases in DMSO-d_6 : H1 (N-CH_3), H2 ($\text{ArCH}_2\text{N-}$), H3 (ArH), H4 (ArCH_2Ar)

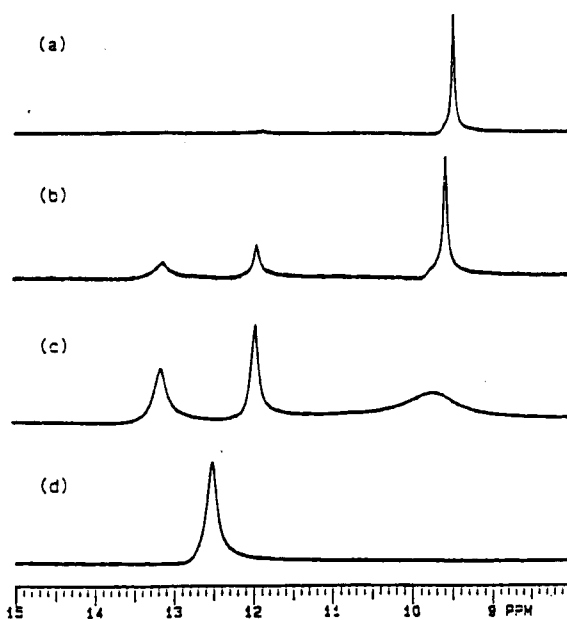
Bases	H1	H2	H3	H4
w/o base	2.18	3.27	6.85	4.27, 3.15
1 eq. NaH	2.03	3.04	6.75	4.20, 3.10
<i>n</i> -BuLi ^a	2.03	3.04	6.74	4.23, 3.18
2 eq. NaH	2.02	2.99	6.67	4.22, 3.10
<i>n</i> -BuLi	— ^b	—	—	—
3 eq. NaH	2.01	2.95	6.55	4.30, 2.88
<i>n</i> -BuLi	2.03, 2.01	3.00	6.4-6.5	2.5-4.8
4 eq. NaH	1.97	2.84	6.64	4.08, 2.55
<i>n</i> -BuLi	2.00	2.93	6.53	4.05, 2.72
KH	1.97	2.96	6.53	3.10

^a *n*-BuLi represent *n*-butyllithium. ^b Dianion with *n*-BuLi was not observed.

yanions mainly depend on the nature of counter ion, but the chemical shift of oxyanions could be controlled by the nature of anion itself regardless of counter ion.

It is instructive to compare the tetraanion species obtained with *n*-butyllithium, NaH, and KH. They all show the cone conformation. But, the tetraanion from *n*-butyllithium possesses a very rigid structure, the NMR spectra showing no coalescence up to 160 °C. The tetraanion species from NaH possesses a relatively flexible structure, with the NMR showing coalescence around 90 °C. The tetraanion species obtained with KH possesses a very flexible structure, the NMR showing that coalescence has already occurred at 20 °C. To understand these difference it is necessary to consider the relationship between the size of the metal ion and the size of the "bottom" of the calix[4]arene. It is not easy to determine the exact size of the bottom of the calix[4]arene, but molecular mechanics calculation and X-ray crystallography¹⁶ of the calix[4]arene show a value close to 2.6 Å between adjacent oxygen atoms. Therefore, the strong preference for lithium over sodium and potassium comes from the fact that the lithium ion is small enough¹⁷ to fit the cavity of the calix[4]arene or that the lithium ion is small enough to form a circular lithium bond. But, sodium and potassium ion would not be expected to do this so readily because of their larger size.

The oxyanion solution generated by the lithium bases also was investigated by the ^7Li NMR. The addition of varying amounts of *n*-butyllithium to calix[4]arene **2** in DMSO-d_6 solution produces whose ^7Li NMR spectra are shown in Figure 5. The mono and tetraanions show a single resonance, commensurate with the symmetry of the cone conformation that is inferred from their ^1H NMR spectra. The solution containing two and three equivalents of *n*-butyllithium, on the other hand, show a multiple resonances, consistent with a less symmetric conformation. The solution produced by the three equivalents of bases which was confirmed by ^1H NMR as a partial cone conformation, has two relatively sharp resonances in the 12-13.5 ppm region and a very broad resonance at about 9 ppm. The solution with two equivalents of *n*-butyllithium also has two resonances in the 12-13.5 ppm region and a sharp resonance at 9.6

**Figure 5.** ^7Li NMR spectra of **1** in the presence of *n*-BuLi in DMSO-d_6 . (a) 1 equivalent of *n*-BuLi, (b) 2 equivalents of *n*-BuLi, (c) 3 equivalents of *n*-BuLi, (d) 4 equivalents of *n*-BuLi.

ppm, very close to the single resonance in the monoanion, providing additional evidence that this solution is a mixture of tri and monoanions.

Conclusion

Based on the ^1H NMR and ^7Li NMR of the oxyanions of calix[4]arenes, the most probable conformations of the each anion produced by *n*-butyllithium are proposed. First, the monoanion show a cone conformation structure. Second, the dianions are simply a mixture of the mono and trianions. But there is as yet no clear explanation for this phenomena. Third, the trianions are most likely to assume as a partial cone conformation. Fourth, the tetraanion are obviously cone conformation. All of the oxyanions from NaH and KH appear as a cone conformation. Even though we proposed the most likely conformation of the oxyanion species based on the NMR studies, the detailed structure of these each oxyanions can not be materialized at this moment.

Experiment

Deuterated NMR solvents, 9% LiOD in D_2O and 40% NaOD in D_2O was purchased from Aldrich and used without further purification. Nuclear magnetic resonance (NMR) spectra were recorded on a Varian 300 MHz spectrometer. The ^1H NMR chemical shifts were recorded as values in ppm relative to tetramethylsilane as an internal standard. The ^1H NMR spectrum was recorded with 0.02 M solution in DMSO-d_6 for the base titration. The ^7Li NMR chemical shift were recorded as values in ppm relative to Li_2SO_4 as an external standard. Calix[4]arene **1**¹⁸, **2**¹⁹, **3**¹⁹, and **4**¹⁸ was prepared by the reported procedures.

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Reference

1. Böhmer, V. *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 713.
2. Shinkai, S. *Tetrahedron* **1993**, *49*, 8933.
3. Gutsche, C. D. *Topics in Current Chemistry* **1984**, *123*, 3.
4. Iwamoto, K.; Shimizu, H.; Araki, K.; Shinkai, S. *J. Am. Chem. Soc.* **1993**, *115*, 3997.
5. Pappalardo, S.; Ferguson, G.; Neri, P.; Rocco, C. *J. Org. Chem.* **1995**, *60*, 4576.
6. Sprenging, G. R. *J. Am. Chem. Soc.* **1954**, *76*, 1190.
7. Böhmer, V.; Schade, E.; Vogt, W. *Makrol. Chem., Rapid Comm.* **1984**, *5*, 221.
8. Shinkai, S.; Araki, K.; Koreish, H.; Tsubaki, T.; Manabe, O. *Chem. Lett.* **1986**, 1351.
9. Iqbal, M.; Mangiafico, T.; Gutsche, C. D. *Tetrahedron* **1987**, *43*, 4917.
10. Gutsche, C. D.; Amrutareddy, P. *J. Org. Chem.* **1991**, *56*, 4783.
11. Gutsche, C. D.; Iqbal, M.; Nam, K. C.; See, K.; Alam, I. *Pure Appl. Chem.* **1988**, *60*, 483.
12. Gutsche, C. D.; Alam, I.; Iqbal, M.; Mangiafico, T.; Nam, K. C.; Rogers, J.; See, K. *J. Inclusion Phenomena and Molecular Recognition in Chemistry* **1989**, *7*, 61.
13. Shinkai reported the following pK_a values⁸ of *p*-nitro-calix[4]arene such as $pK_1=2.9$, $pK_2=10.9$, $pK_3=12.3$, and pK_4 more than 14. Even though we were not dealing *p*-nitrocalix[4]arene here, we might correlate the difference of the pK_a of calixarene **1** with the values obtained for *p*-nitrocalix[4]arene. The difference between pK_1 to pK_2 is 8, but it is only 1.4 between pK_2 to pK_3 . This suggests that the third proton from calix[4]arene might be lost as easy as the second one. That would explain why we could not detect the dianion species, but the mixture of mono and trianions.
14. A multiplet at 3.4 ppm was attributed from *n*-butyllithium, which was confirmed by the separate experiment.
15. Commercially available 35% oil dispersed KH used, but due to the homogeneity problem, it was not possible to weigh the exact amount of KH.
16. Ninagawa, A.; Matsuda, H. *Macromol. Chem. Rapid Comm.* **1982**, *3*, 65.
17. (a) Shannon, R.; Prewitt, C. T. *Acta Crystallogr.* **1969**, *B25*, 925. (b) Shannon, R. D. *ibid.* **1976**, *A32*, 751.
18. Gutsche, C. D.; Lin, L. G. *Tetrahedron* **1985**, 1633.
19. Gutsche, C. D.; Nam, K. C. *J. Am. Chem. Soc.* **1988**, *110*, 6153.

Structural Properties of TiO₂ Films Grown by Pulsed Laser DepositionHa-Sub Yoon, Seong Kyu Kim, and Hoong-Sun Im^{†*}

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Pure titanium dioxide (TiO₂) films were prepared by pulsed laser deposition on a single crystal Si(100) substrate. We have investigated the growth of crystalline titanium dioxide films with respect to substrate temperature and ambient oxygen pressure. The structural properties of the films were analyzed by X-ray diffraction. We found that the anatase as well as the rutile phases could be formed from the original rutile phase of the target TiO₂. At 0.75 torr of ambient oxygen pressure, the structure of TiO₂ film was amorphous at room temperature, anatase between 300 and 600 °C, a mixture of anatase and rutile between 700 and 800 °C, and only rutile at 900 °C and above. However, at a low ambient oxygen pressure, the rutile phase became dominant; the only rutile phase was obtained at the ambient oxygen pressure of 0.01 torr and the substrate temperature of 800 °C. Therefore, the film structures were largely influenced by substrate temperature and ambient oxygen pressure.

Introduction

Titanium dioxide (TiO₂) has various attractive properties such as high refractive index, high permittivity, semiconductor properties and chemical stability. Because of these properties TiO₂ films find wide applications. They have been used as gas sensors, antireflection coating, dielec-

tric materials in optoelectronics, protective layers in integrated circuits, and photocatalysts in solar energy conversion and in environmental cleaning. The bulk TiO₂ has three crystalline polymorphs: the rutile, the anatase and the brookite. The rutile is known to be the most stable phase, while the anatase phase is less stable and forms at lower temperatures. The brookite phase can form only under extreme conditions.

The films have been prepared by various techniques such

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