Effects of Post Annealing on Electrical Performance of Polycrystalline Ga$_2$O$_3$ Photodetector on Sapphire

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Abstract

Effects of post annealing on the physical and electrical properties of solar-blind polycrystalline gallium oxide (Ga$_2$O$_3$) ultraviolet photodetectors on the sapphire substrate are investigated. The grain size of poly-Ga$_2$O$_3$ becomes larger with the post annealing temperature (PAT) increasing from 800 °C to 1000 °C, but it gets smaller with further raising PAT to 1100 °C. A blue shift is observed at the absorption edge of the transmittance spectra of Ga$_2$O$_3$ on sapphire as increasing PAT, due to the incorporation of Al from the sapphire substrate into Ga$_2$O$_3$ to form (Al$_x$Ga$_{1-x}$)$_2$O$_3$. The high-resolution X-ray diffraction and transmittance spectra measurement indicate that the substitutional Al composition and bandgap of (Al$_x$Ga$_{1-x}$)$_2$O$_3$ annealed at 1100 °C can be above 0.30 and 5.10 eV, respectively. The $R_{\max}$ of the sample annealed at 1000 °C increases about 500% compared to the as-deposited device, and the sample annealed at 1000 °C has short rise time and decay time of 0.148 s and 0.067 s, respectively. This work may pave a way for the fabrication of poly-Ga$_2$O$_3$ ultraviolet photodetector and find a method to improve responsivity and speed of response.

Keywords: Gallium oxide (Ga$_2$O$_3$), Post annealing, Solar-blind, Ultraviolet, Photodetector

Background

Deep ultraviolet (DUV) solar-blind photodetectors have a wide range of applications such as monitoring ozone holes and detecting flames with the inherent advantage of strong anti-interference ability [1]. Compared with traditional semiconductor materials like silicon and germanium, wide bandgap semiconductor materials are considered to be ideal materials for solar-blind photodetectors which have better selectivity for ultraviolet light and better adaptability in harsh environments [2]. Lots of researchers have been focused on AlGaN, MgZnO, and Ga$_2$O$_3$ DUV solar-blind photodetectors [2–4]. Ga$_2$O$_3$ attracts great attention due to its superior optical properties, chemical stability, and high strength with a bandgap of 4.8 eV, which is a promising material for solar-blind photodetectors [5–13]. Ga$_2$O$_3$ thin films have been obtained on foreign substrates by molecular beam epitaxy (MBE) [5, 6], radio-frequency magnetron sputtering (RFMS) [7], pulsed laser deposition (PLD) [8, 9], atomic layer deposition (ALD) [10], halide vapor phase epitaxy (HVPE) [11], metal-organic chemical vapor deposition (MOCVD) [12], and sol-gel method [13]. Among these methods, RFMS deposition has been widely used to fabricate various films due to its advantages of easy controllability, high efficiency, harmless, and low cost. Therefore, we used this method to grow Ga$_2$O$_3$ thin films for DUV solar-blind photodetectors.

In this work, poly-Ga$_2$O$_3$ solar-blind photodetectors were fabricated on the sapphire substrate. It is demonstrated that the Al atoms are incorporated from the sapphire substrate into Ga$_2$O$_3$ to form (Al$_x$Ga$_{1-x}$)$_2$O$_3$ after post thermal annealing. The structural properties,
substitutional Al composition $x$, optical properties, and photodetector performance of poly-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ films with different post annealing temperatures (PATs) were investigated.

**Method**

In this experiment, poly-Ga$_2$O$_3$ thin films were grown on single-polished (0006)-oriented sapphire substrates by RFMS at 600 °C with the sputtering power of 120 W. The working pressure was kept constant at 5 mTorr and the flow of argon was 20 sccm throughout the deposition. The thickness of the films deposited on sapphire was measured to be around 164 nm. After the deposition, post thermal annealing was carried out in an air atmosphere for 1 h at 800 °C, 900 °C, 1000 °C, and 1100 °C. After annealing, the samples were cooled to room temperature with a speed of 100 °C/min. The 30 nm Ti and 80 nm Ni were then deposited by magnetron sputtering as an electrode. After the interdigital electrode patterning and etching, the metallic contacts on Ga$_2$O$_3$ were formed by the rapid thermal annealing at 470 °C in a nitrogen atmosphere [14]. The fabricated poly-Ga$_2$O$_3$ solar-blind photodetectors have metal-semiconductor-metal (MSM) interdigital electrodes as shown in Fig. 1. The length, width, and space between the fingers were 500 μm, 6 μm, and 15 μm, respectively, and the total length of the fingers is 1.8 cm.

**Results and Discussion**

The structural properties of the Ga$_2$O$_3$ films were investigated by high-resolution X-ray diffraction (HRXRD). Figure 2 presents the HRXRD curves for the samples that as-deposited and annealed at different temperatures. Peaks corresponding to (201), (400), (111), (402), (600), (510), and (603) planes of β-Ga$_2$O$_3$ crystals [15] reveal that the Ga$_2$O$_3$ film consists of monoclinic β-Ga$_2$O$_3$ polycrystalline with random orientation. The as-deposited sample exhibits a higher peak intensity for the (400) plane compared to the other planes. The PAT leads to the improvement of the intensities of (201), (400), (402), and (603) planes.

Figure 3a and b focus on the HRXRD peaks for (201) and (603) planes, respectively. The full width at half maximum (FWHM) of the peak was used to calculate the grain size by solving the Debye-Scherrer formula [16] to evaluate the dependence of the crystalline quality of Ga$_2$O$_3$ films on PAT. It can be seen from Table 1 that higher annealing temperature yields larger grain size as PAT increases from 800 °C to 1000 °C, but the grain size decreases slightly at the PAT of 1100 °C. The diffusion of Al from the Al$_2$O$_3$ substrates into Ga$_2$O$_3$ films underwent a PAT above 1000 °C has been widely observed [17–19]. As shown in Fig. 3c, the peaks of HRXRD shifting to the higher diffraction angle is due to that Al from the sapphire substrate diffuses into Ga$_2$O$_3$ film to form (Al$_x$Ga$_{1-x}$)$_2$O$_3$ after annealing.

Based on the Bragg’s law, the plane spacing $d$ of (201) and (603) planes of (Al$_x$Ga$_{1-x}$)$_2$O$_3$ are calculated and shown in Fig. 3d, respectively. According to Ref. [20], the lattice parameters can be calculated by $a = (12.21 - 0.42x)$ Å, $b = (3.04 - 0.13x)$ Å, $c = (5.81 - 0.17x)$ Å, $β = (103.87 + 0.31x)^\circ$. The $d$ of (603) is expressed as [21]

$$
\frac{1}{d^2} = \frac{h^2}{a^2 \sin^2 \beta} + \frac{k^2}{b^2} + \frac{l^2}{c^2 \sin^2 \beta} - \frac{2hl \cos \beta}{ac \sin \beta} \quad (1)
$$

where $h = -6$, $k = 0$, and $l = 3$. Based on the values in Fig. 3d, the $x$ of poly-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ can be achieved. The bandgap $E_g$ of (Al$_x$Ga$_{1-x}$)$_2$O$_3$ can be calculated by


\[ E_g(x) = (1-x)E_g[Ga_2O_3] + xE_g[Al_2O_3] - nx(1-x), \]  

(2)

where \( E_g[Ga_2O_3] = 4.65 \text{ eV}, E_g[Al_2O_3] = 7.24 \text{ eV}, n = 1.87 \text{ eV} \) [22]. The calculated \( x \) and \( E_g \) values of the poly-(Al\(_x\)Ga\(_{1-x}\))\(_2\)O\(_3\) are shown in Table 2. An \( x \) value above 0.30 is achieved in the sample after a PAT at 1100 °C.

Atomic force microscope (AFM) images in Fig. 4 show that the surface root-mean-square (RMS) roughness values of the as-deposited film and the samples annealed at 800 °C and 900 °C are 3.62 nm, 10.1 nm, and 14.1 nm, respectively. The recrystallization caused by the high PAT results in a larger grain size, which can be additionally confirmed by a rougher surface.

The values of \( E_g \) of the (Al\(_x\)Ga\(_{1-x}\))\(_2\)O\(_3\) thin films before and after annealing were characterized by measuring the transmittance spectra. As shown in Fig. 5a, the annealed samples have a blue shift at the absorption edge compared to the as-deposited one. A shorter \( \lambda \) is acquired with the increase of PAT, due to the incorporation of Al. The Ga\(_2\)O\(_3\) samples have a very low transmittance even in the visible range, which might be due to the nonradiative complex absorption induced by the defects in the materials. The absorption coefficient \( \alpha \) of the films is calculated by [23, 24].

| Temperature (°C) | FWHM (°) | Grain size (nm) |
|------------------|----------|----------------|
| As-deposited     | 0.49135  | 15.99          |
| 800              | 0.47789  | 16.22          |
| 900              | 0.37031  | 20.93          |
| 1000             | 0.28513  | 27.18          |
| 1100             | 0.29602  | 26.18          |

Table 2 Comparison of the calculated Al content and \( E_g \) of poly-(Al\(_x\)Ga\(_{1-x}\))\(_2\)O\(_3\) after thermal annealing according to HRXRD in Fig. 3 and experimental results of transmittance spectra

| Substitutional Al composition | 800°C | 900°C | 1000°C | 1100°C |
|------------------------------|-------|-------|--------|--------|
| Calculated \( E_g \)         | 4.67 eV | 4.79 eV | 4.90 eV | 5.13 eV |
| Experimental \( E_g \)        | 4.72 eV | 4.78 eV | 4.81 eV | 5.10 eV |

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\[ \alpha = (1/t) \ln \left[ \frac{(1-r)^2}{T} \right], \]  

(3)

where \( T \) is the transmittance, \( r \) is the reflectance, and \( t \) is the film thickness. The relation between absorption coefficient \( \alpha \) and incident photon energy \( h\nu \) follows a power law of the form

\[ (ahv) = B(h\nu - E_g)^{1/2}, \]  

(4)

where \( B \) is the absorption edge width parameter [23]. By using these formulas, the relationship between \( h\nu \) and \((ahv)^2\) can be obtained as shown in Fig. 5b. By extrapolating the linear regions of the plot to the horizontal axis, the \( E_g \) values of the samples are evaluated as 4.65 eV, 4.72 eV, 4.78 eV, 4.81 eV, and 5.10 eV. As shown in Table 2, the experimental \( E_g \) values of the samples are consistent with those calculated based on the HRXRD results.

To investigate the responsivity \( R \) and photocurrent \( I_{\text{photo}} \) of poly-(Al\(_x\)Ga\(_{1-x}\))\(_2\)O\(_3\) photodetectors, optical measurements varied different illumination \( \lambda \) from 220 to 300 nm with a \( P_{\text{light}} \) of 0.5 mW/cm\(^2\). The \( R \) is calculated by

\[ R = \frac{(I_{\text{photo}} - I_{\text{dark}})}{(P_{\text{light}}S)}, \]  

(5)

where \( I_{\text{dark}} \) is the dark current and \( S \) is the effective illuminated area. Figure 6 shows a visible blue shift in maximum \( R \) of the annealed samples compared to the as-deposited film. This proves that a larger \( E_g \) of polycrystalline samples has been obtained after annealing with the diffusion of Al from the sapphire substrate into Ga\(_2\)O\(_3\) to form (Al\(_x\)Ga\(_{1-x}\))\(_2\)O\(_3\). The \( R_{\text{max}} \) of the device annealed at 1100 °C is 35 \( \mu \)A/W, which is smaller than the 0.037 A/W, 0.903 A/W, and 1.13 mA/W those were grown by MBE [5], PLD [25], and sol-gel method [26], respectively, due to the fact that the poly-Ga\(_2\)O\(_3\) has a low transmittance, as shown in Fig. 5a. But compared to the as-deposited device, the \( R_{\text{max}} \) of the device annealed at 1000 °C increases by about 500%. It is noted that \( R \) of devices decreases at wavelength shorter than that at \( R_{\text{max}} \), similar to that in [27]. This could be due to the energy loss occurs during the relaxation process of carriers in case of photon energy above \( E_g \) of materials. \( R_{\text{max}} \) increasing with the PAT rising from 800 °C to 1000 °C is attributed to the increased grain size of the film.

Figure 7 shows the photocurrent \( I_{\text{photo}} \), dark current \( I_{\text{dark}} \), and PDCR versus bias voltage \( V_{\text{bias}} \) for the photodetectors under the illumination intensity of 0.5 mW/cm\(^2\) and \( \lambda \) of 254 nm. As shown in Fig. 7a, \( I_{\text{photo}} \) increases almost linearly with the \( V_{\text{bias}} \). Furthermore, as PAT raises from 800 °C to 1000 °C, photodetectors gain a larger \( I_{\text{photo}} \) but the \( I_{\text{photo}} \) of the device annealed at 1100 °C is lower than that of the as-deposited sample, due to the energy of the photon is less than bangap of.
the sample annealed at 1100 °C, which cannot generate photo-carriers. The annealed samples show a higher $I_{\text{dark}}$ than the as-deposited sample, as depicted in Fig. 7b. It is speculated that the recrystallization enhances the conductivity of poly-Ga$_2$O$_3$, resulting in the enhancement of both $I_{\text{photo}}$ and $I_{\text{dark}}$ of the photodetectors, and the
PDCR of the sample with a PAT of 1000 °C is higher than those of the other samples. It can be noted that the dark current of the sample annealed at 900 °C is larger than others, which may be ascribed to the increased carriers with the PAT increasing, but with the PAT further increasing, the increased grain size with PAT can reduce the photogenerated carriers transportation time, improving the relaxation time properties of the devices.

Table 4 shows the comparison of the $I_{\text{dark}}$, rise time ($\tau_r$), and decay time ($\tau_d$) of solar-blind photodetectors based on $\beta$-, $\alpha$-, and $\epsilon$-Ga$_2$O$_3$ thin films synthesized by RFMS [30] and other techniques [2, 6, 26, 31–34]. As seen, the device has both low dark current and fast response time is difficult, but the photodetector we fabricated presents the low dark current and fast response time.

**Conclusions**

In summary, we deposited poly-Ga$_2$O$_3$ thin film by magnetron sputtering on the c-plane sapphire substrate with post thermal annealing under different temperature; then, the ultraviolet poly-Ga$_2$O$_3$ photodetector was fabricated. Compared to the as-deposited Ga$_2$O$_3$ thin film, the annealed samples possess a larger grain size and a wider bandgap due to the recrystallization and the diffusion of the Al into Ga$_2$O$_3$. The $R_{\text{max}}$ of the device annealed at 1000 °C increases about 500% compared to the as-deposited device, and the sample annealed at 1000 °C shows a low dark current of 0.0033 nA under...
the bias of 5 V. Furthermore, the solar-blind photodetector fabricated on the film annealed at 1000 °C shows fast response time, with a rise and decay time of 0.148 s and 0.067 s, respectively. These results are useful to fabricate the DUV photodetectors with low dark current and fast response time.

Abbreviations
Ga2O3: Gallium oxide; PAT: Post annealing temperature; DUV: Deep ultraviolet; MBE: Molecular beam epitaxy; RFMS: Radio-frequency magnetron sputtering; PLD: Pulsed laser deposition; ALD: Atomic layer deposition; HVPE: Halide vapor phase epitaxy; MOCVD: Metal-organic chemical vapor deposition; MSM: Metal-semiconductor-metal; HRXRD: High-resolution X-ray diffraction; FWHM: Full width at half maximum; AFM: Atomic Force Microscope; RMS: Root-mean-square

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Authors’ Contributions
HDH and YCL carried out the experiments and drafted the manuscript. GQH, YL, JDY, CZF, YFZ, HL, YBW, YCL, and HDH designed the experiments. GQH, HDH and YCL helped to revise the manuscript. GQH supported the study. All the authors read and approved the final manuscript.

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Availability of Data and Materials
The datasets supporting the conclusions of this article are included within the article.

Competing Interests
The authors declare that they have no competing interests.

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References
1. Itzler M, Donati S, Unlu MS, Kato K (2004) Introduction to the issue on Photodetectors and Imaging. IEEE Journal of Selected Topics in Quantum Electronics 10:665–667
2. Li W, Zhao X, Zhi Y, Zhang X, Chen Z, Chu X, Yang H, Wu Z, Tang W (2018) Fabrication of cerium-doped β-Ga2O3 epitaxial thin films and deep ultraviolet photodetectors. Appl Opt 57:538–543
3. Zhang W, Xu J, Ye W, Li Y, Qi Z, Dai J, Wu Z, Chen C, Yin J, Li J, Jiang H, Fang Y (2015) High-performance AlGaN metal-semiconductor-metal solar-blind ultraviolet photodetectors by localized surface plasmon enhancement. Appl Phys Lett 106:021112
4. Yang W, Hullavarad SS, Nagaraj B, Takeuchi I, Sharma RP, Venkatesan T (2003) Compositionally-tuned epitaxial cubic Mg2Zn1−xO on Si (100) for deep ultraviolet photodetectors. Appl Phys Lett 82:3424–3426
5. Oshima T, Okumo T, Fujita S (2007) Ga2O3 thin film growth on c-plane sapphire substrates by molecular beam epitaxy for deep-ultraviolet photodetectors. Japanese Journal of Applied Physics 46:7217
6. Guo D, Wu Z, Li P, An Y, Liu H, Guo X, Yan H, Wang G, Sun C, Li L, Tang WH (2014) Fabrication of β-Ga2O3 thin films and solar-blind photodetectors by laser MBE technology. Opt Mat Express 4:1067–1076
7. Kim JH, Lee JM (2016) Electrical and optical properties of near UV transparent conductive ITO/Ga2O3 multilayer films deposited by RF magnetron sputtering. Appl Phys Lett 109:172107
8. Seiler W, Selmane M, Abdelouahedi K, Perrère J (2015) Epitaxial growth of gallium oxide films on c-cut sapphire substrate. Thin Solid Films 589:556–562
9. Pettman DJ, Gallas B, Hebert C, Perrère J, Binet L, Barboux P, Portier X (2013) Characterization of oxygen deficient gallium oxide films grown by PLD. Applied Surface Science 278:153–157
10. Comstock DJ, Elam JW (2012) Atomic layer deposition of Ga2O3 films using trimethylgallium and ozone. Chemistry of Materials 24:4011–4018
11. Nikolaev VL, Pechinkin AL, Stepanov SI, Nikiforov AN, Chikiryaka AV, Sharafidinov SS, Bougrov VE, Romanov AE (2016) Epitaxial growth of β-Ga2O3 on (001) substrate by halide vapour phase epitaxy. Materials Science in Semiconductor Processing 78:153–157
12. Chen Y, Liang H, Xia X, Shen R, Liu Y, Luo Y, Du G (2015) Effect of growth pressure on the characteristics of β-Ga2O3 films grown on GaAs (100) substrates by MOCD method. Applied Surface Science 325:258–261
13. Li Y, Trinchi A, Wlodarski W, Galaitis K, Kalantar-zadeh K (2003) Investigation of the oxygen gas sensing performance of Ga2O3 thin films with different dopants. Sensors and Actuators B: Chemical 93:431–434
14. Higashishawi M, Sasaki K, Kamimura T, Wong MH, Krishnamurthy D, Kuramata A, Masa T, Yamakoshi S (2013) Depletion-mode Ga2O3 metal-oxide-semiconductor field-effect transistors on β-Ga2O3 (010) substrates and temperature dependence of their device characteristics. Appl Phys Lett 103: 123511
15. Åhman J, Svensson G, Albertsson J (1996) A reinvestigation of B-gallium oxide. Acta Cryst Sect C 52:1336–1338
16. Yu F, Yuan DR, Duan XL, Guo SY, Wang XQ, Cheng XF, Kong LM (2008) A simple process to synthesize sphere-shaped gallium nitride nanoparticles for transparent ceramic. Journal of Alloys and Compounds 465:567–570
17. Fleischer M, Hennieder W, Mesmer H (1990) Stability of semiconductor gallium oxide thin films. Thin Solid Films 190:993–1002
18. Battiston GA, Gerbasi R, Porchia M, Bertocchini F, Caccavale F (1996) Chemical vapour deposition and characterization of gallium oxide thin films. Thin Solid Films 279:115–118
19. Goyal A, Yadav BS, Thakur OP, Kapoor AK, Muralidharan R (2014) Effect of annealing on β-Ga2O3 film grown by pulse laser deposition technique. Journal of Alloys and Compounds 583:214–219
20. Kiennert C, Jenderka M, Lenzen J, Lorenz M (2015) Lattice parameters and Raman-active phonon modes of [β-AlGa1−xO3 films. Journal of Applied Physics 117:125703
21. Li J, Chen X, Ma T, Cui X, Ren F, Gu S, Zhang R, Zheng Y, Ringer SP, Fu L, Tan HH, Jagadish C, Ye J (2018) Identification and modulation of electronic band structures of single-phase β-Al(Ga1−x)2O3 alloys grown by laser molecular beam epitaxy. Appl Phys Lett 113:041901
22. Peeliers H, Varley JB, Speck JS, Van de Walle CG (2018) Structural and electronic properties of Ga2O3-Al2O3 alloys. Appl Phys Lett 112:242101
23. Ullalapalli SK, Verneri RS, Ramana CV (2010) Structural transformation induced changes in the optical properties of nanocrystalline tungsten oxide thin films. Appl Phys Lett 96:171903
24. Subrahmanyan A, Karuppasamy A (2007) Optical and electrochromic properties of oxygen sputtered tungsten oxide (WO3) thin films. Solar energy materials and solar cells 91:266–274
25. Yu F, Du S, Wuu D (2015) Pulsed laser deposition of gallium oxide films for high performance solar-blind photodetectors. Opt Mat Express 5:1240–1249
26. Shen H, Yin Y, Tian K, Baskaran K, Duan L, Zhao X, Tiwari A (2018) Growth and characterization of β-Ga2O3 thin films by sol-gel method for fast-response solar-blind ultraviolet photodetectors. Journal of Alloys and Compounds 766:601–608
27. Hu GC, Shan CX, Zhang N, Jiang MM, WP SH, Shen DZ (2015) High gain Ga2O3 solar-blind photodetectors realized via a carrier multiplication process. Opt express 23:13354–13561
28. Guo DY, Wu ZP, An YH, Guo XC, Chu XL, Sun CL, Li LH, Li PG, Tang WH (2014) Oxygen vacancy tuned Ohmic-Schottky conversion for enhanced performance in β-Ga2O3 solar-blind ultraviolet photodetectors. Appl Phys Lett 105:023507
29. Liu N, Fang G, Zeng W, Zhou H, Cheng F, Zheng Q, Yuan L, Zou X, Zhao X (2010) Direct growth of lateral ZnO nanorod UV photodetectors with Schotky contact by a single-step hydrothermal reaction. ACS Appl Mater Interfaces 2:1973–1979
30. Wang J, Ye L, Wang X, Zhang H, Li L, Kong C, Li W (2019) High transmittance β-Ga2O3 thin films deposited by magnetron sputtering and...
31. Pratyush AS, Krishnamoorthy S, Solanke SV, Xia Z, Muralidharan R, Rajan S, Nath DN (2017) High responsivity in molecular beam epitaxy grown $\beta$-Ga$_2$O$_3$ metal semiconductor metal solar blind deep-UV photodetector. Appl Phys Lett 110:221107

32. Zhang D, Zheng W, Lin RC, Li TT, Zhang ZJ, Huang F (2018) High quality $\beta$-Ga$_2$O$_3$ film grown with N$_2$O for high sensitivity solar-blind-ultraviolet photodetector with fast response speed. Journal of Alloys and Compounds 735:150–154

33. Hou X, Sun H, Long S, Tromp C5, Salagaj T, Qin Y, Zhang Z, Tan P, Yu S, Liu M (2019) Ultrahigh-performance solar-blind photodetector based on o-phase-dominated Ga$_2$O$_3$ film with record low dark current of 81 fA. IEEE Electron Device Letters 40:1483–1486

34. Pavesi M, Fabbri F, Boschi F, Piacentini G, Baraldi A, Bosi M, Gombia E, Parisini A, Fornari R (2018) $\varepsilon$-Ga$_2$O$_3$ epilayers as a material for solar-blind UV photodetectors. Materials Chemistry and Physics 205:502–507

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