Simultaneous quality improvement of the roughness and refractive index of SiC thin films

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Abstract: We deposite silicon carbide thin layers on cleaned Si (100) substrates using the plasma enhanced chemical vapor deposition method, and show that the RFTIR spectrum is periodic in the near and medium infrared ranges. It is shown that both the deposition rate and the uniformity of the thin films are decreased by increasing the substrate temperature, and that the refractive index is increased by increasing the substrate temperature. This shows that there is a trade-off between the quality improvement of the uniformity and refractive index.

Key words: SiC; PECVD; RFTIR; thickness measurement; refractive index
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1. Introduction

Graphene, a single hexagonally ordered layer of carbon atoms, has a unique electronic band structure with comic "Dirac points"[1]. There are two important methods for obtaining graphene samples. In the first "mechanical" method, the carbon monolayers are mechanically split off the bulk graphite crystals and deposited onto a SiO_2/Si substrate[2]. The second method uses the epitaxial growth of graphite on single crystal silicon carbide[3]. Both the Si and C faces of SiC have a honeycomb structure, and therefore the $(3)^{1/2} \times (3)^{1/2}$ R 30° surface unit cell of the graphene layer is constructed above both surfaces, where SiC is vacuum annealed at temperatures above 1400 ℃[3, 4]. The different prospective electronic applications of SiC also put specific demands on the properties of SiC material used for device production processes[5]. SiC is therefore a key material in semiconductor micro- and nano-device fabrication. SiC is considered to be a useful material for structural and electronic applications because it has excellent physical and electrical properties, such as high temperature stability, extreme hardness, excellent resistance to chemical attack, a wide energy band gap, and high electron mobility[4]. SiC is also used as a substrate for epitaxial graphene, which is a new material composed of one or more graphene layers that are grown on a SiC substrate. It can be lithographically patterned to produce electronic devices that are similar to carbon annotate-based devices[5]. Recently, various deposition methods for SiC have been researched and widely developed[6]. Among these methods, deposition using PECVD has been investigated by various research groups due to its advantage of a low deposition temperature[7]. In many other research efforts, SiC thin films deposited using PECVD at low temperatures show amorphous and hydrogenated properties between those of an organic and an inorganic polymer because the source gases decompose into complex mixtures of monomers under plasma, and these mixtures react on the substrate at a relatively low temperature[8]. The importance of SiC material in semiconductor device fabrication, especially graphene-based devices, and recent improvements in deposition methods, especially PECVD methods, motivated us to study the refractive index, morphology and uniformity of grown SiC thin layers on Si substrates for simultaneous quality improvement of the uniformity and refractive index. We hope that such studies pave the way to growing high quality layers of graphene at lower cost and by a more simple method. In this study, SiC thin films are deposited on Si substrates by a plasma-enhanced chemical vapor deposition (PECVD) technique to investigate the effect of the substrate temperature on the refractive index, deposition rate, morphology and uniformity. It is shown that the roughness of the surface decreases, while the refractive index increases by increasing the substrate temperature. We also show, by annealing the SiC thin film at 900 ℃ for 2 h in N_2 atmosphere, that the refractive index increases but the roughness decreases. This means that for nano-applications a trade-off should be done between the refractive index and the surface roughness.

2. Experimental procedure and results

Thin films of hydrogenated amorphous silicon carbide are deposited on Si (100) substrates by PECVD systems operating at an RF frequency of 13.56 MHz. The substrate temperature is chosen as 300, 420, 540, 670, and 770 ℃. SiH_4 gas is used as the silicon source and CH_4 as the carbon source. During the deposition of five runs, the flow rates of CH_4, SiH_4 and N_2 are fixed at 250, 25 and 150 sccm, respectively. The RF power and deposition pressure are fixed at 400 W and 1200 mTorr, respectively. The 3 inch Si substrate is cleaned by {1HF : $10H_2O$} etchant solution, followed by acetone, alcohol and DI water. Finally the samples are dried by highly pure N_2 gas. Using Eq. (1), the thin film uniformity is calculated[9],

$$\text{Uniformity} = (d_{\max} - d_{\min}/2d_{\text{ave}}), \tag{1}$$

where $d_{\max}$, $d_{\min}$ and d_{ave} are the maximum, minimum and average thickness of the silicon dioxide films, respectively, and are measured by ergolux AMC optical microscopy. The RFTIR

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Table 1. The process parameters and experimental results.

Run No.	Substrate temperature (℃)	Deposition rate (A/min)	Non-uniformity (%)	Average thickness (nm)	δ_ν ($\nu_1 - \nu_2$) (cm^{-1})	Annealing temperature (℃)	Reflective index before annealing	Reflective index after annealing
R_1	300	163	0/84	980	2057.2	900	2.48	2.67
R_2	420	125	1/3	750	2313.0	900	2.58	2.88
R_3	520	91	1/6	560	3234.9	900	2.76	3.15
R_4	670	88	2/1	530	2560.2	900	3.68	3.85
R_5	770	28	6/4	170	7906.3	900	3.72	3.96

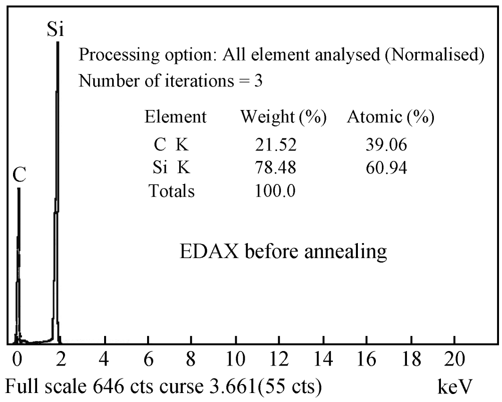

Fig. 1. The composition of the thin film before annealing (for process $CH_4/SiH_4 = 10$ at 420 ℃).

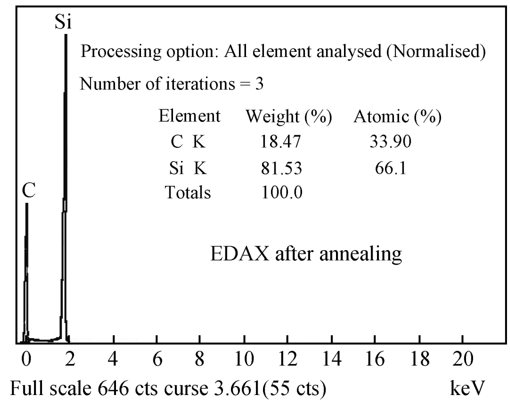

Fig. 2. The composition of the thin film after annealing at 900 ℃ (for process $CH_4/SiH_4 = 10$ at 420 ℃).

spectrum of SiC in the near and medium infrared window is measured by the Fourier transform infrared model WQF-400N. The refractive index is calculated by using Eq. (2)[10],

$$n = 1/2t_{\text{ave}}\delta\nu, \tag{2}$$

where n, t_{ave} and $\delta\nu(= \nu_1 - \nu_2)$ are the refractive index, the average thickness of the thin film and the difference between two subsequent peaks in the RFTIR spectrum, respectively.

The process parameters and experimental results are shown in Table 1. After the deposition of the layers, their composition is checked by the EDAX method before and after annealing. In this method, only the surface layer of the thin films is scanned by electrons, and Figures 2 and 3 show that the thin films include Si and C. The uniformity and roughness of the thin films are checked by the AFM method. Since the roughnesses of the thin films are different from each other, and we want to see the peaks and valleys of the films, we set up different values for the scale bar of the z-direction (Fig. 3). In other words, if we see Fig. 3(a) in the scale of Fig. 3(c), the roughness will be fine. As Figure 3 shows, film roughness decreases when substrate temperature increases. Some thin films are annealed at 900 ℃ for 2 h in N_2 ambient and their refractive index is measured. As Figure 4 shows, the refractive index after annealing is higher than the one before annealing.

3. Discussion and conclusion

We have shown that by increasing substrate temperature, deposition rate and uniformity decrease due to a decrement in the surface absorption of carbon atoms and hydrogenates in thin films[11, 12]. As Figure 5 shows, both deposition rate

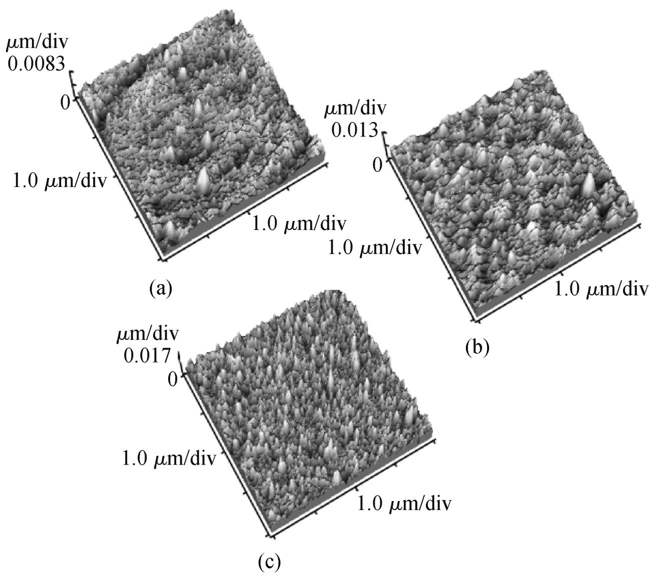

Fig. 3. The roughness of the thin film when the substrate temperature is equal to (a) 300 ℃, (b) 420 ℃ and (c) 540 ℃.

and uniformity decrease with increasing substrate temperature. Therefore, as expected, AFM images show more roughness when the substrate temperature increases (Fig. 3). Using histogram curves (Fig. 3), the root mean square roughness (R_{ms}) and average roughness (R_{ave}) is calculated. R_{ms} equals 1.50, 2.79 and 3.36 nm when the substrate temperature is equal to 300, 420 and 540 ℃, respectively. Also, R_{ave} is equal to 1.12, 2.29 and 3.20 nm when the substrate temperature is equal to 300, 420 and 540 ℃, respectively. Roughness and uniformity therefore decrease when the substrate temperature increases.

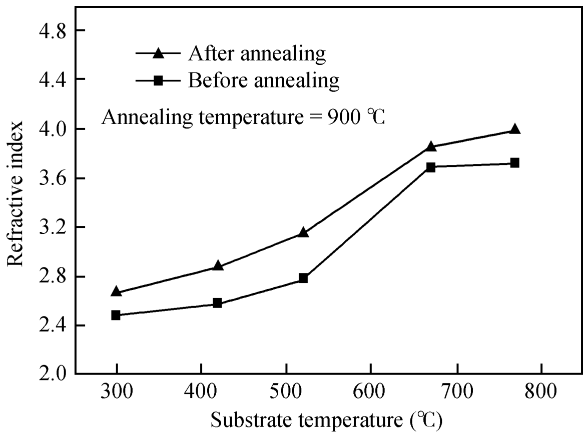

Fig. 4. The refractive index of the thin film before and after annealing.

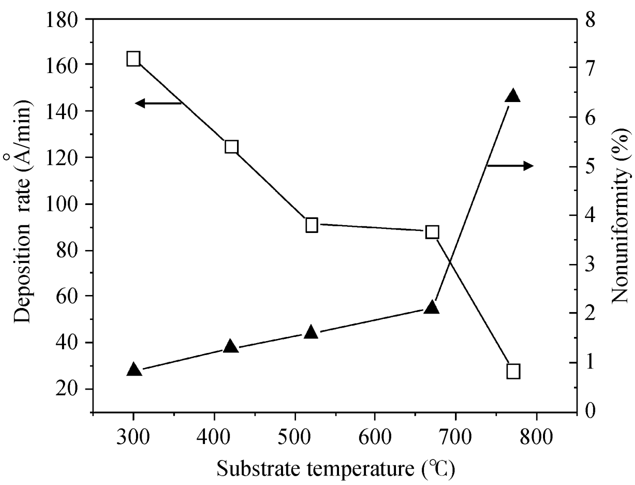

Fig. 5. The deposition rate and non-uniformity of the thin film versus substrate temperature.

These results are in agreement with other work[11, 12]. Gaikwad *et al.*[13] showed that the refractive index of thin films increases when the substrate temperature increases due to variations in its perfect stoicheiometry and density. For calculating the refractive index, we need an FTIR spectrum of the thin films. Figure 6 shows an FTIR spectrum of a thin film when the substrate temperature is equal to 420 ℃. Two subsequent peaks are placed at 6959.3 cm^{-1} and 9272.3 cm^{-1}, and the wave number difference is equal to 2313 cm^{-1}. The average thickness of the film is equal to 0.75 μm when the substrate temperature is equal to 420 ℃ (Table 1). Therefore, using Eq. (2), the refractive index is calculated to be 2.58, which is close to the refractive index of SiC, 2.7. As Table 1 shows, the refractive index increases when the substrate temperature increases. This result is in good agreement with other work[13].

Based on the above results and explanations, the roughness decreases and the refractive index increases when the substrate temperature increases. To justify the effect of annealing on thin films, we anneal them at 900 ℃ in N_2 ambient. As Figure 2 shows, the stoichiometry of the films changes after the annealing process, so the surface absorption of the carbon atoms decreases, while the surface absorption of the silicon atoms increases. Then, as is expected and as is shown in Figure 4, the

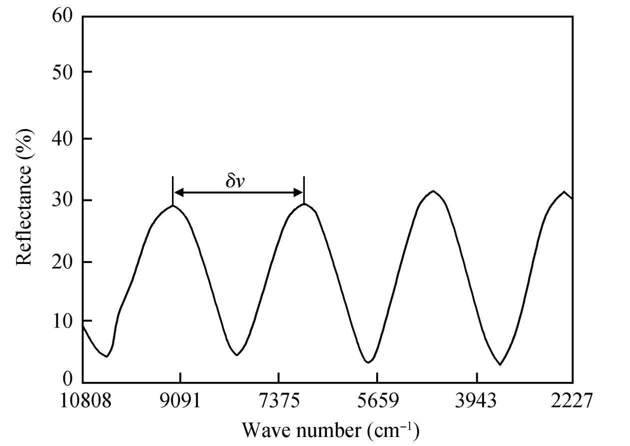

Fig. 6. The FTIR spectrum of a thin film when the substrate temperature is equal to 420 ℃.

refractive index increases after annealing.

4. Summary

Three-inch Si substrates were cleaned by {1HF : 10H_2O} etchant solution, followed by acetone, alcohol and DI water, and then dried with a highly pure N_2 gun. The SiC films were grown on a Si substrate using the PECVD method. It was shown that both the deposition rate and uniformity of the thin films decreases when the substrate temperature increases. By using the RFTIR spectrum technique, the refractive index at different temperatures was measured, and it was shown that the refractive index of thin films decreases when the substrate temperature increases. We also showed that the roughness of the thin films decreases when the substrate temperature increases. The samples were annealed at 900 ℃ for 2 h in N_2 atmosphere, and it was shown that the refractive index increases after annealing. There is therefore a trade-off between the quality improvement of the roughness and the refractive index. We believe that our results are important for improving the quality of the manufacturing process of SiC, especially in the nanodevice field.

References

[1] Neto A H C, Guinca F, Peres N M R, et al. Comparative study of the nature of chemical bonding of corrugated graphene on Ru (001) and Rh (111) by electronic structure calculations. Rev Mod Phys, 2009, 81: 109

[2] Zhang Y, Jiang Z, Small J P, et al. Unconventional electronic and magnetic functions of nanographene-based host–guest systems. Phys Rev Lett, 2006, 96: 136806

[3] Bertran E, Martinez E, Viera G, et al. *In-situ* monitoring of laser annealing by micro-Raman spectroscopy for hydrogenated silicon nano-particles produced in radio frequency glow discharge. Diamond Related Mater, 2001, 10: 1115

[4] Mattausch A, Bockstcdtc M, Pankratov O. *Ab initio* study of graphene on SiC. Phys Rev B, 2004, 69: 45322

[5] Al-Temimy A, Riedl C, Starke U. Low temperature growth of epitaxial graphene on SiC induced by carbon evaporation. Appl Phys Lett, 2009, 95: 231907

[6] Choa S H, Choia Y Y, Kimb Y H, et al. The changing behavior of the dielectric constant of a-SiC: films deposited by remote

PECVD with various deposition conditions using HMDS and PPCS. Journal of Ceramic Processing Research, 2010, 11(5): 581

[7] Simchi H, Sareminia G, Shafiekhani A, et al. Passivation of InSb surface for manufacturing infrared devices. Infrared Phys Technol, 2008, 51: 263

[8] Kim Y T, Yoon S G, Kim H, et al. Crystallization of a-Si:H and a-SiC:H thin films deposited by PECVD. Journal of Ceramic Processing, 2005, 6(4): 294

[9] Ricciardi C, Primiceli A, Germani G, et al. Microstructure analysis of a-SiC:H thin films grown by high-growth-rate PECVD. Journal of Nano-Crystalline Solids, 2006, 325: 1380

[10] Chu J, Liu P, Chang Y. Fourth international conference on thin film physics and applications. Proc SPIE, 2000, 4086: 1

[11] Bergemeister E A, von Muchen W, Pettenpaul E. Carbon-mediated effects in silicon and in silicon-related materials. Mater Chem Phys, 1996, 44(2): 101

[12] Jung C K, Lim D C, Jee H G, et al. Rapid thermal annealing effect on amorphous hydrocarbon film deposited by CH_4/Ar dielectric barrier discharge plasma on Si wafer: surface morphology and chemical evaluation. J Appl Phys, 2009, 105: 094909

[13] Gaikwad S A, Samuel E P, Patil D S, et al. Temperature dependent analysis of refractive index, band gap and recombination coefficient in nitride semiconductor lasers. Ind J Pure & Appl Phys, 2007, 45: 238