Surface Profile for Monolayer Chemical Vapor Deposition Synthesis of 2D-Materials

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ABSTRACT

Frequency analysis of surface morphological growth for CVD monolayer has been done. Si surface by 10 keV Ar^+ ion bombardment at an oblique angle incidence of 45° for various ion fluences of order ~10^{17} Ar^+ cm^{-2} at room temperature is compared with 60°. Surface morphology of low energy Ar^+ ion sputtering has been investigated by atomic force microscopy. A detailed analysis of the spectral densities and dynamic plots of Si ripple is discussed within the framework of statistical models related with Ion Beam Sputtering induced pattern formation process. The dynamic scaling behavior of Si ripples produced by low energy Ar^+ ion erosion has been done at an angle of 35˚, 45˚ & 60˚ respectively. The surface profiles spectrum of various parameters shows the clear pictures of height, kinks, roughness and ripples wavelength that was introduced by the radiation.

KEYWORDS : Chemical Vapor Deposition, Monolayer, Surface Morphology, 2D-Materials.

INTRODUCTION

The root-mean-square roughness and correlation length of the rippled surface are observed to increase with ion fluence. Ripple wavelength is also found to increase slowly with ion fluence upto ~10^{17} $Ar^+.cm^{-2}$ and then shows a rapid coarsening behavior [1]. The production of ripples is found to be governed by surface mass redistribution effects rather than curvature dependency of sputtered erosion. This is an worth addition to the understanding of ion beam nanopatterns for ion energies less than 10 keV but also for ion irradiation of energy range 10 keV and above. Low energy ion sputtering is well known as a single step process for nanopatterning on a large area surface [2]. By varying ion incidence angle, ion and target combination, different types of patterns like rim, dot, hills, ripple waves etc, can be formed on a wide range of materials. The statistical growth dynamics of Si nanostructures by ion beam erosion has been investigated. But a very few study has been initiated for ion beam induced pattern formation on silicon surface [3]. Thus, the detail analysis of the growth of interface dynamics of Si surface due to ion beam erosion will explore better understanding of pattern evolution mechanism which in one hand, will make further advancement of the theoretical models on ion beam induced pattern formation phenomena on compound 2D material surfaces that can be deposited on Si surface by chemical vapor deposition method and in other hand will enrich the control on ion erosion technique of pattern formation process [4]. Silicon has drawn particular attention for its very large, atomically flat and chemically inert surfaces which make them highly beneficial as a substrate for preparing optoelectronic and micro energy applications [5]. Again, this substrates patterned in nm scale are used extensively in material science. Recently, ion-bombarded silicon surface is found suitable to selectively organize light absorbing emitting properties useful for photovoltaic's and energy conversion [6, 7]. Low energy ion sputtering process is well known as a single step process for nanopatterning on a large and bulk surface area. By varying ion incidence angle, ion fluence and target combination, different types of ripple patterns etc, can be formed on a wide range of other 2D materials like MnS, SnS, SnS_2, etc [8]. In this approach, the surface roughness, effective area for absorbance is measured as a function of time and radial distance which are used to obtain exponents describing their dependence on the respective parameters. In recent years, the dynamic scaling behavior of thin film growth by various deposition methods has been widely studied. Also, the growth dynamics of Si nanostructures by ion beam erosion has been investigated. But a very few study has been initiated for ion beam induced pattern formation on silicon surface [9, 10].

EXPERIMENTAL

Cleaved silicon surface of area 1 cm^2 were irradiated by 10 keV Ar^+ ions at an oblique incidence angle 35˚, 45˚ & 60˚ respectively with respect to surface normal. These samples were sputtered with Ar^+ ion beam having low energy to a dose of 1×10^{17} Ar^+cm^{-2}. Electron Cyclotron Resonance (ECR) ion source was used to carry out this research. Uniform irradiation was achieved by scanning the beam over the Si (100) samples. The ion fluences were varied from 1×10^{17} to 3×10^{18} Ar^+/cm^2. The average ion beam current was around 4.5A. The target chamber and plasma chamber were maintained in high vacuums ~10^{-7} mbar which was reduced during irradiation. The morphology of the irradiated silicon samples were investigated using Atomic Force Microscopy (AFM), Multi-Mode AFM instrumentation. The AFM surface morphology of all the samples was taken in contact mode. The surface rms roughness and other statistical information of the surfaces were extracted from the AFM images using WSxM and further statistical analysis were done.

RESULTS

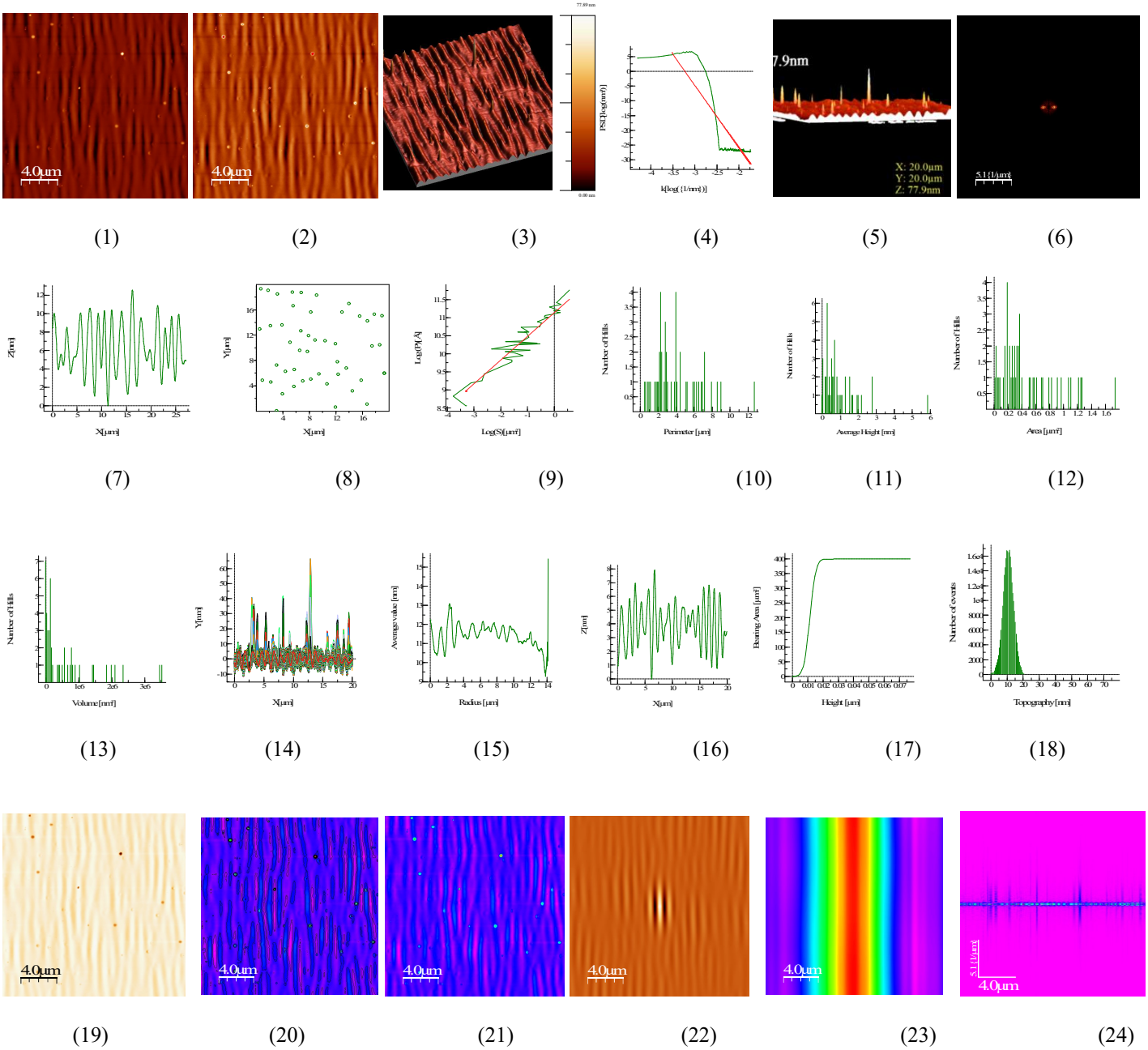

Fig 1 : (1) Actual AFM micrograph of Si ripples at 35˚ Ar^+ ion irradiation, (2) Equalized image morphology, (3) 3D View morphology, (4) Power Spectral Density, (5) Cross 3D view, (6) 2D FFT, (7) Z-Profile for fig (1), (8) Center Hole Plot, (9) Fractal analysis, (10) Hills vs. Perimeter Histogram, (11) Hills vs. Average Height Histogram, (12) Hills vs. Area Histogram, (13) Hills vs. Volume Histogram, (14) Image to Curve Plot of Y-axis, (15) Radial Averages, (16) Arbitrary Z-Profile for fig (1), (17) Bearing Area Plot, (18) RMS Roughness Analysis, (19) Convoluted Image, (20) Ripples contours morphology, (21) Image palette spectrum, (22) Wavelet profile, (23) Wavelet analysis spectrum morphology, (24) 1D-FFT columns.

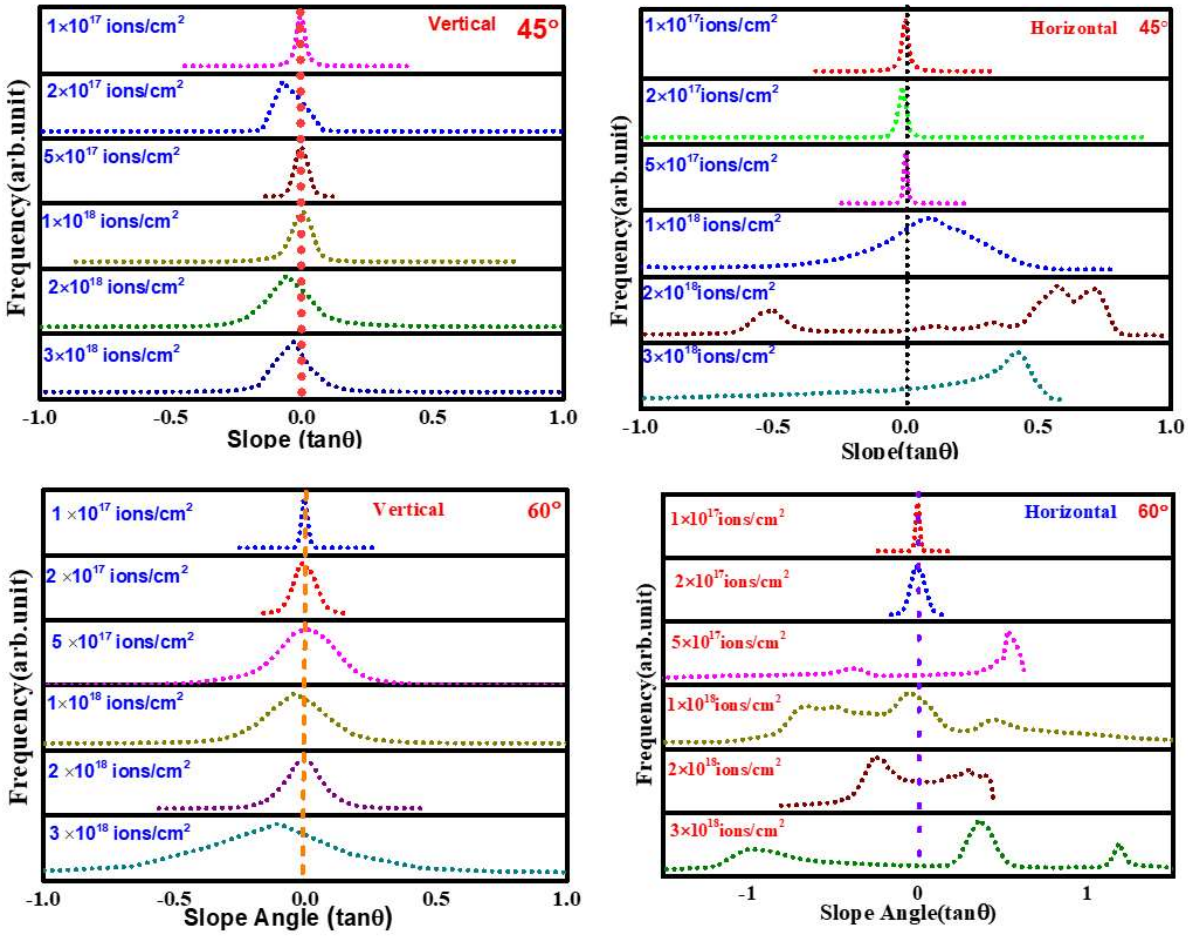

Fig 2 : Frequency Vs Slope Angle variations at different angles of 45˚ and 60˚ respectively.

DISCUSSIONS

We analyse that at an oblique incidence of 35˚ the ripple are closer to each other as well as the average increment in the height is less than at 45˚. This same patterns are visible for the 60˚ structure. A drastic slope variation takes place at 60˚. But in the case of 45˚ the ripple behaviour and slope also changes. Due to the ion fluences the lateral width of the ripple wave is increased [11, 12]. This change is clearly visible by the image to curve plot. Also the peaks or the kinks become some what flat-top in case of 45˚. We also see that the power spectral densities in case of 45˚ of incidence is increased [13, 14]. The center map shows that at 60˚ the holes in the normalized surface area is also increased. This shows the abrupt peaks are produced in these zones. We also see that the bearing area, volume and ripple wavelength increases at 45˚ irradiation. The 3D cross view clarify the sharpness of the peaks that are present at 35˚ and 60˚ [15, 16]. The calculated PSD for 45˚ is approximately 8W/Hz by analysing the curves at some points which is greater than for 35˚, 6.5 W/Hz and 60˚, 4W/Hz [17, 18]. The wavelet spectrum clearly shows the phase change of the induced ripples at these two angles. These ripples could be used as a better option from the previous versions of the pristine Si samples [19, 20].

CONCLUSIONS

Slope change is a crucial parameter in the ripple formation. It is directly linked with the chemical vapor deposition of 2D-materials. AFM characterization was carried out on the samples of Si substrate after irradiating them at an oblique incidence of 35˚, 45˚ and 60˚ by Ar^+ low ion beam with energy in the range of 10 keV ion bombardment for various ion fluences of order ~10^{17} Ar^+ cm^{-2}. We conclude that there are abrupt changes that took place on the surface morphology of the Si substrate. In this way we can enhance the surface characteristics. This can be utilized for better performance in advanced applications which include chemical vapor deposition of some 2D-materials like MnS, SnS for their optical sensing properties in near future. It can be concluded that mass deposition and redistribution plays a significant role in surface pattern formation.

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DATA AVAILABILITY STATEMENT

All the data are provided in this research paper.

CONFLICT OF INTEREST

The authors declare no known competing interests.

REFERENCES

[1]. A. Gupta, T. Sakthivel, and S. Seal, *Recent development in 2D materials beyond graphene.* Progress in Materials Science, vol. 73: p. 44-126, 2015 [doi: 10.1016/j.pmatsci.2015.02.002].

[2]. E. O. Yewande et al., "Morphological regions and oblique-incidence dot formation in a model of surface sputtering," *Phys. Rev. B*, vol. 73, no. 11, p. 115434, 2006 [doi:10.1103/PhysRevB.73.115434].

[3]. H. Hofsäss et al., "Propagation of ripple patterns on Si during ion bombardment," *Phys. Rev. B*, vol. 88, no. 7, p. 075426, 2013 [doi:10.1103/PhysRevB.88.075426].

[4]. B. Ziberi et al., "Ripple pattern formation on silicon surfaces by low-energy ion-beam erosion: Experiment and theory," *Phys. Rev. B*, vol. 72, no. 23, p. 235310, 2005 [doi:10.1103/PhysRevB.72.235310].

[5]. C. S. Madi et al., "Mass redistribution causes the structural richness of ion-irradiated surfaces." *Phys. Rev. Lett.*, vol. 106, no. 6, p. 066101, 2011 [doi:10.1103/PhysRevLett.106.066101].

[6]. A. M. Azad et al., "Solid-state gas sensors: A review," *J. Electrochem. Soc.*, vol. 139, no. 12, p. 3690-3704, 1992 Dec. 1 [doi:10.1149/1.2069145].

[7]. S. Dhall et al., "A review on environmental gas sensors: Materials and technologies," *Sens. Int.*, vol. 2, p. 100116, 2021 Jan. 1 [doi:10.1016/j.sintl.2021.100116].

[8]. S. K. Mohanta et al., "Structural modifications in InP nanostructures prepared by Ar+-ion irradiation," *J. Appl. Phys.*, vol. 102, no. 7, 2007 [doi:10.1063/1.2786574].

[9]. M. Castro and R. Cuerno, "Hydrodynamic approach to surface pattern formation by ion beams." *Appl. Surf. Sci.*, vol. 258, no. 9, p. 4171-4178, 2012 [doi:10.1016/j.apsusc.2011.09.008].

[10]. Sumit Kumar and S. K. Garg, "A Review on Si-Substrate Surface Analysis for 2D-Materials Applications." *International Journal of Scientific Development and Research*, vol. 10, issue 2, p. b358-b370, 2025 [doi.one/10.1729/Journal.43821].

[11]. T. Kumar et al., "An approach to tune the amplitude of surface ripple patterns," *Appl. Phys. Lett.*, vol. 103, no. 13, 2013 [doi:10.1063/1.4822302].

[12]. L. Y. Jian et al., "Surface morphology-dependent sensitivity of thin-film-structured indium oxide-based NO2," *J. Electron. Mater.*, vol. 48, no. 4, pp. 2391-2397, 2019 Apr. 15 [doi:10.1007/s11664-019-06945-w].

[13]. M. Kwoka et al., "AFM study of the surface morphology of L-CVD SnO2 thin films," *Thin Solid Films*, vol. 515, no. 23, pp. 8328-8331, 2007 Sept. 14 [doi:10.1016/j.tsf.2007.03.035].

[14]. E. K. Shokr et al., "Optical and electrical properties of thin films of MnS/metal/MnS for photocatalysis and gas sensing applications," *Optik*, vol. 296, p. 171549, 2024 [doi:10.1016/j.ijleo.2023.171549].

[15]. J. Sun et al., "SnS2 nanoparticle-based gas sensor with highly sensitive NO2 detection at room temperature," *Mater. Lett.*, vol. 308, p. 131214, 2022 [doi:10.1016/j.matlet.2021.131214].

[16]. N. G. Patel et al., "Indium tin oxide (ITO) thin film gas sensor for detection of methanol at room temperature," *Sens. Actuators B*, vol. 96, no. 1-2, pp. 180-189, 2003 Nov. 15 [doi:10.1016/S0925-4005(03)00524-0].

[17]. Sumit Kumar and S. K. Garg, "Holes Parameters by Low Energy Ar+ Ion on Si-Ripples." *International Journal of Scientific Development and Research*, vol. 10, issue 2, p. b141-b155, 2025 [doi.one/10.1729/Journal.43723].

[18]. H. Hofsäss, "Surface instability and pattern formation by ion-induced erosion and mass redistribution." *Appl. Phys. A*, vol. 114, no. 2, p. 401-422, 2014 [doi:10.1007/s00339-013-8170-9].

[19]. C. Dong et al., "A review on WO3 based gas sensors: Morphology control and enhanced sensing properties," *J. Alloys Compd.*, vol. 820, p. 153194, 2020 Apr. 15 [doi:10.1016/j.jallcom.2019.153194].

[20]. W. L. Chan and E. Chason, "Making waves: Kinetic processes controlling surface evolution during low energy ion sputtering." *J. Appl. Phys.*, vol. 101, no. 12, p. 121301, 2007 [doi:10.1063/1.2749198].