Study of low energy Si$_5^-$ and Cs$^-$ implantation induced amorphization effects in Si(1 0 0)

H P Lenka$^{1}$, B Joseph$^{1,4}$, P K Kuiri$^1$, G Sahu$^1$, P Mishra$^2$, D Ghose$^2$ and D P Mahapatra$^{1,3}$

$^1$ Institute of Physics, Sachivalaya Marg, Bhubaneswar - 751005, India
$^2$ Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata - 700064, India

E-mail: dpm@iopb.res.in

Received 9 July 2008, in final form 3 September 2008
Published 13 October 2008
Online at stacks.iop.org/JPhysD/41/215305

Abstract

The damage growth and surface modifications in Si(1 0 0), induced by 25 keV Si$_5^-$ cluster ions, as a function of fluence, $\phi$, has been studied using atomic force microscopy (AFM) and channelling Rutherford backscattering spectrometry (RBS/C). RBS/C results indicate a nonlinear growth in damage from which it has been possible to get a threshold fluence, $\phi_0$, for amorphization as $2.5 \times 10^{13}$ ions cm$^{-2}$. For $\phi$ below $\phi_0$, a growth in damage as well as surface roughness has been observed. At a $\phi$ of $1 \times 10^{14}$ ions cm$^{-2}$, damage saturation coupled with a much reduced surface roughness has been found. In this case a power spectrum analysis of AFM data showed a significant drop in spectral density, as compared with the same obtained for a fluence, $\phi < \phi_0$. This drop, together with damage saturation, can be correlated with a transition to a stress relaxed amorphous phase. Irradiation with similar mass Cs$^-$ ions, at the same energy and fluence, has been found to result in a reduced accumulation of defects in the near surface region leading to reduced surface features.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Cluster ion implantation can be regarded as a forerunner technology as compared with the conventional ion implantation technique used to dope sub-micrometre devices [1, 2]. Using cluster ions very shallow implantation can be achieved at very low energy. However, with cluster implantation, nonlinear effects arising in the energy loss processes, as a result of the correlated motion of the constituent atoms, play an important role in deciding the defect structure near the target surface. In addition to resulting in a nonlinear growth in subsurface damage, cluster ion impact, through sputtering, can also result in kinetic roughening and smoothing of the surface exposed [3]. In view of all this, there has been a lot of activity involving low energy cluster ion irradiation related to nonlinear sputtering [4], nonlinear damage and defect production [5–7], along with the formation of various kinds of surface features [8–12].

In connection with the above, Si presents itself as a very important material where low energy cluster ions can be used for shallow implantation of interest to technology. In some earlier work, contrary to common expectation, amorphization upon ion irradiation has been shown to start from the surface rather than the ion projected range [13]. Results of molecular dynamics (MD) simulations with 5 keV Si show that the ion impacts produce unrelaxed amorphous patches that have a fast quenched, liquid-like structure [14]. With the increase in ion fluence these regions overlap producing a continuous amorphous layer [15]. In fact, with the increase in ion fluence, there is a superlinear growth of amorphous volume fraction with a lot of stress build-up in the matrix. At a high fluence there is an abrupt transition to a state with a flat amorphous-to-crystalline (a/c) interface [16, 17]. In such a case, out-of-plane
plastic flow with a reduction in the in-plane stress has been observed [18]. All this suggests that ion irradiation induced amorphization in Si is more like a phase transition, initiated by a spontaneous collapse of the damaged region. Very recent MD simulations carried out by Marqués et al show it to be initiated by a high concentration of interstitial-vacancy (IV) pairs or bond defects, formed in the system [19]. Similar results have also been shown by Nord et al [20] who have pointed out that the subsequent transition resulting in a uniform amorphous layer is neither a complete homogeneous nor a complete heterogeneous mechanism. This makes Si an ideal system to study using low energy cluster ions where such a transition to a complete amorphous state is expected at a lower fluence, primarily because of overlapping of collision cascades coming from constituent atoms.

In this paper we show some results of a systematic study of the subsurface damage produced and the surface features generated in Si(1 0 0), from $S_i^-$ and a similar mass Cs$^-\$ ion implantation at 25 keV. Channelling Rutherford backscattering spectrometry (RBS/C) and atomic force microscopy (AFM) have been used for sample characterization. Increase in cluster ion fluence has been found to result in nonlinear growth and saturation in damage leading to amorphization. The transition to an amorphized state is found to be associated with a significant drop in the power spectral density (PSD) of AFM data which initially increases with increase in fluence.

2. Experimental details

Cleaned Si(1 0 0) wafers (p-type, 1–2.5 $\Omega \text{cm}$) were irradiated with 25 keV singly charged negative ions, namely, $S_i^-$ and Cs$^-$ from a SNICS-II ion source (NEC, USA) using a low energy ion implanter facility. Mass analysis of the cluster ions was carried out using a 45° sector magnet (ME/q² = 18 MeV amu). The base pressure in the target chamber during irradiation was maintained around 2 × 10⁻⁷ mbar. All the irradiations were carried out at room temperature with a beam flux of (2–3) × 10¹⁰ ions cm⁻² s⁻¹ (ion current of 2–3 nA) at $\sim 7^\circ$ off the sample normal. In each case one part of the sample was kept unimplanted to serve as a reference. Five samples named S1–S5 were systematically irradiated with ions of similar mass (Si⁵ or Cs⁵) with gradually increasing ion fluence from $2 \times 10^{11}$ to $1 \times 10^{14}$ cm⁻². Three of these, namely, S1, S3 and S5, were irradiated using $S_i^-$ clusters to fluences of $2 \times 10^{11}$ cm⁻², $1.2 \times 10^{13}$ cm⁻² and $1 \times 10^{14}$ cm⁻², respectively. The remaining two samples, S2 and S4, were irradiated with 25 keV Cs⁻ ions to fluences of $1 \times 10^{13}$ cm⁻² and $6 \times 10^{13}$ cm⁻², respectively. These data are shown in table 1.

RBS/C measurements were carried out on all the samples with 1.35 MeV He⁺ with a Si surface barrier detector placed at 130° relative to the incident beam direction. The measurements were carried out at a steady beam current of 5 nA, using the 3 MV Pelletron accelerator (9SDH2, NEC, USA) facility at IOP, Bhubaneswar.

Following irradiation, the surface topography was examined by AFM in tapping mode, using a multi-mode scanning probe microscope (Nanoscope IV, Veeco, USA) facility at SINP, Kolkata. Measurements were performed in ambient conditions using a Si cantilever with a nominal tip radius less than 10 nm. Image processing and analysis of the AFM data were carried out using the standard WSxM software package [21, 22].

3. Results and discussions

3.1. Subsurface damage: RBS/C studies

The RBS/C results as measured for all five samples, namely, S1–S5 and a virgin sample (unirradiated area), are presented in figure 1(a). A random spectrum for an unirradiated sample is also included in the figure for comparison. From the figure, one can observe a gradual increase in surface peak intensity with the increase in ion fluence, $\phi$. This increase in the area of the surface peak, over and above that in the virgin sample, indicates growth in damage produced with the increase in the number of displacements. Very low fluence irradiation, as in the case of S1 and S2, is found to induce very little damage, too small to be seen through RBS/C data. However, the increase in irradiation fluence from S1 to S3 (with cluster ions) and that from S2 to S4 (for Cs ions) is seen to result in enhancements of the surface peak, indicating an increase in defect production near the surface. For sample S5, with the highest cluster irradiation fluence, the surface peak is seen to be the most intense. This sample, with a total single atom fluence of $5 \times 10^{14}$ cm⁻², is expected to have an amorphous layer with a thickness of 8–10 nm extending from the surface [23]. As will be shown later this is indeed true, but the RBS/C spectrum does not hit the random value. This is because the system resolution, in the present case, is $\sim 16$ keV. This corresponds to a width of around 30 nm resulting in a spread of the actual signal [24]. At 25 keV per ion, it is the nuclear energy loss that is almost entirely responsible for the damage production. Since a 5-atom Si cluster is expected to break up into 5 constituent atoms, ignoring nonlinear effects, one may compare the damage produced by 25 keV Cs ions with the same produced by 5 keV Si atoms at five times the fluence. A SRIM [25] estimation shows the range of 25 keV Cs ions in Si to be about 20.5 ± 5.9 nm, almost double that for 5 keV Si in Si. Because of this Cs⁻ irradiation produces a damage distribution going deeper into the bulk as compared with $S_i^-$ irradiation. This is clearly seen in the case of S4. It is also true for S2. However, in figure 1(a), it is difficult to see the differences between the RBS/C spectra for S2 and a virgin sample at and near the surface peak region. This is due to very little damage produced in the lattice. Due to the same reason (of much
displaced Si atoms, triangles represent data for Si5 and Cs implantations, respectively. We denote this as the number of displaced Si atoms, in the irradiated lattice. We denote this as the number of displaced Si atoms in the irradiated lattice. We denote this as the number of displaced Si atoms in the irradiated lattice.

Figure 1. (a) RBS/C spectra for Si(1 0 0), implanted with 25 keV Si5 and Cs − for different values of implantation fluence together with the same for a virgin sample. (b) Fluence (φ) dependence of κd(φ), for various implantations. Circles and triangles represent data for Si5 and Cs implantations, respectively. The continuous curve is a fit to the data points with clusters S1, S3 and S5 only.

To get an idea about damage saturation and the amorphization threshold, as has been done earlier [6, 26], we have fitted the three points as obtained for Si5 irradiation (namely, for S1, S3 and S5) to an equation of the form

\[ \kappa_d(\phi) = a(1 - e^{-\phi/\phi_0}), \]  

where \( a \) is a constant and \( \phi_0 \) corresponds to the threshold fluence for damage saturation. The best fit, as indicated by the smooth curve in figure 1(b), yields a value of \( \phi_0 \) equal to \((2.5 \pm 7\%) \times 10^{13} \text{cm}^{-2}\). One can see that, at a fluence of \( 6 \times 10^{13} \text{cm}^{-2} \), the \( \kappa_d \) value corresponding to 25 keV Cs atoms is almost the same as that expected for a similar mass Si5 cluster at the same energy. This means that the heavy single atom induced cascades produce almost the same amount of damage or defects as those generated by a similar mass cluster ion. At this high fluence, because of overlapping of damage produced cluster induced nonlinear effects are difficult to detect. However, in this case there are defects extending into the bulk while those for a cluster ion are better confined in a surface layer.

The above \( \phi_0 \) value of \( 2.5 \times 10^{13} \text{cm}^{-2} \) as obtained for Si5 clusters, where damage saturation starts, corresponds to a total atomic fluence of \( \sim 1.25 \times 10^{14} \text{cm}^{-2} \). This agrees with the finding of Agarwal et al [23] who have shown the amorphization threshold, for 5 keV Si in Si, to be \((1-3)\times10^{14} \text{cm}^{-2}\). In fact, with clusters, as expected, the present value agrees with the lower limit. In view of this, at an Si5 cluster fluence of \( 1 \times 10^{14} \text{cm}^{-2} \) (corresponding to an atomic fluence of \( 5 \times 10^{14} \text{cm}^{-2} \)), we are already well above the threshold for amorphization.

3.2. Surface morphology: AFM studies

As has been mentioned earlier, AFM has been used to study the surface topography in various samples. Some AFM pictures (top view), for \((5 \mu\text{m} \times 5 \mu\text{m})\) scanned areas, taken of the samples are shown in figures 2 and 3. Figures 2(a) and (b) correspond to samples S1 and S2, while figures 3(a) and (b) correspond to samples S3 and S4, respectively.

Usually the features on irradiated surfaces are described through a height–height correlation function which contains three important roughness parameters: (i) the vertical correlation length \( \sigma \), (ii) the lateral correlation length \( \xi \) and (iii) the roughness exponent \( \alpha \). The vertical correlation length, \( \xi \), describes the lateral characteristics of the surface, the roughness exponent \( \alpha \) describing the static scaling properties. The most commonly reported parameter of surface roughness, i.e. \( \sigma \), or the root-mean-square (rms) roughness, characterizes the surface only along the vertical direction. This is defined as standard deviation of the surface height profile, \( h(x, y) \), at each point \((x, y)\) of a reference surface plane from the mean height \((\langle h \rangle)\), as given by

\[ \sigma = \left[ \frac{1}{N} \sum_{i=1}^{N} (h_i - \langle h \rangle)^2 \right]^{1/2}, \]  

where \( N \) is the number of pixels, \( h_i = h(x, y) \) being the height at the \( i \)th pixel.
Figure 2. Surface morphology of samples (a) S1 and (b) S2. Both samples have the same monomer fluence as that of S2, i.e. $1 \times 10^{12}$ atoms cm$^{-2}$.

In the case of sample S1, as shown in figure 2(a), one can clearly see black dots corresponding to nanometre sized pits and bright spots corresponding to hillocks (colour bars indicating the heights). The observed hillocks are seen to have heights ranging between 1 and 6 nm with an average height of 1.64 nm. It has an rms roughness, $\sigma$, of 0.34 nm. Compared with this, there was hardly any surface feature in the case of a pristine Si(1 0 0) sample (AFM data not shown here). The rms roughness, $\sigma$, of the pristine sample, was found to be 0.13 nm, which is about one-third of that for S1, corresponding to a smooth polished surface.

In the case of the lowest fluence Cs implanted sample, S2, the $\sigma$ for surface roughness was found to be 0.21 nm, lying between that for S1 (0.34 nm) and the pristine sample (0.13 nm). What is important to see here is that Cs implantation to a five times higher fluence is not able to generate a surface roughness as observed in the case of S1. Compared with the above, S3 implanted with Si$_5$ clusters to a fluence sixty times that of the sample S1 was found to have an rms roughness, $\sigma$, of 1.21 nm. However, the above sixty-fold increase in the Si$_5$ cluster fluence from S1 to S3 did not result in a proportionate increase in the number of nanohillocks in S3. The surface topography of the sample S4, implanted with Cs to a fluence five times that of S3, is shown in figure 3(b). However, a much smaller number of nanohillocks, compared to the S3 sample, could be seen. It has a $\sigma$ value of 0.42 nm which is significantly smaller than that observed for S3. The enhanced surface roughness as seen with Si$_5$ implantations in S1 as compared with S2 (and S3 as compared to S4), even with lower fluence of irradiations, is primarily due to molecular effects coming from the overlapping of collision cascades of
Compared with this, the Si5 cluster implanted S1 sample, with modulations over a similar length scale as the pristine sample. In view of this, a sensitivity only in the vertical direction. For example, two characterization of the surface because it is limited by its reciprocal space, \( \xi \) length, \( (\) The Cs implanted sample, S2, also has a smooth surface, \( \mu \) m. Furthermore, it has a \( \gamma \) close to 1. The Cs implanted sample, S2, also has a smooth surface, \( \sigma = 0.21 \) nm. The corresponding \( C(q) \) indicates surface modulations over a similar length scale as the pristine sample. Compared with this, the Si5 cluster implanted S1 sample, with one-fifth of the fluence as in S2, shows modulations with a higher value of \( q_c \) of the order of 0.006 nm\(^{-1}\). This indicates a correlation length, \( \xi \), of the order of 170 nm. As shown earlier, it has a \( \sigma \) value of 0.34 nm. The Fourier index \( \gamma \) is seen to be about 2.5. This yields an \( \alpha \) value of 0.25, indicating the surface to be self-affine with anisotropic scaling of surface modulations along lateral and perpendicular directions.

The \( C(q) \) for the higher fluence Cs irradiated sample, S4, shows a \( q_c \) which is almost similar to that for the lower fluence Si5 implanted sample, S1, indicating a similar correlation length, \( \xi \), of 170 nm. However, it shows a \( \gamma \) value of around 2.2 resulting in an \( \alpha \) value \( \sim 0.1 \). With a \( \sigma \) value of 0.42 nm, it has a higher roughness. This means that with a 300 times higher fluence, Cs ions generate similar surface features as obtained for low dose Si5 implanted sample, S1. Compared with this, the Si5 cluster implanted sample S3, with a fluence which is
one-fifth of that in S4, shows a $\gamma$ value close to 4, indicating an $\alpha$ value close to unity. This indicates the surface modulations to be self-similar. But this sample has the highest surface roughness, $\sigma$, of 1.21 nm with an average height of 5 nm.

Now we look at what happens when the cluster fluence is increased to a value well beyond the amorphization threshold as in the case of S5. An AFM image of the top view of S5, taken with a (5 $\mu$m $\times$ 5 $\mu$m) scan size, is shown in figure 4(b). The $C(q)$ spectrum for S5 is also shown along with that for S3 in the same figure. One can clearly see that increasing the cluster ion fluence from $1.2 \times 10^{13}$ to $1 \times 10^{14}$ cm$^{-2}$, in going from S3 to S5, has resulted in no further change in the $\gamma$ value which has been found to saturate at 4. But the surface modulations changed to have a $\sigma$ value of 0.21 nm with a correlation length $\xi \sim 125$ nm. With the $\alpha$ value close to 1, the surface features in S5 are self-similar indicating isotropic scaling. However, as compared with the S3 case, $C(q)$ shows a significant reduction in the magnitude. At $q_c$, the ratio between the two is about 33. This can also be seen using the formula $C(q) = [\alpha^{2}\xi^{2}/\pi\gamma]$ at $q_c = 1/\xi$. Since S3 and S5 have almost the same $\alpha$ as well as $\xi$ values, the ratio of the $C(q)$'s turns out to be nearly the same as the ratio of the $\sigma^2$ for the two cases. This is seen to be $(1.2/0.21)^2$ which is just about right. It is important to mention that the surface modulations in S5 show a mean height of 0.6 nm. The small value of $C(q)$ for S5 is therefore seen to be coming from a correlation between small but nearly equal heights with a small $\sigma$ value. Compared with this $C(q)$ in S3 comes from a correlation between higher heights, with an average value of 5 nm, again with a much higher value of $\sigma$.

Earlier, 5 keV Si impact on Si has been shown to result in the creation of amorphous pockets coming from local melting and rapid quenching [14]. The stress produced can result in the formation of pits and bumps on the surface. This is in addition to the roughening resulting from sputtering. This local melting and the associated movement of atoms, at a lower fluence as in S1, may be responsible for a $\gamma$ value between 2 and 3. It also leads to a higher surface roughness as compared with a pristine sample. At a lower fluence there are sparsely distributed amorphous pockets in the matrix. Increase in the implantation fluence results in a fast growth in the number of amorphous patches resulting in a growth in surface roughness, $\sigma$. This also results in a growth in the mean height, $h$, of surface structures produced, resulting in a growth of height–height correlation. Merging of amorphized regions at a higher fluence results in a building up of stress from a large number of bond defects. Finally there could be stress relaxation as the damaged lattice becomes unstable. This could result in a transition to a state with smaller surface features which is achieved by an effective movement of atoms in a lateral direction. This could be the reason behind getting a $\gamma$ value close to 4 as proposed for surface diffusion. This is probably how a smooth a/c interface can occur in Si under high fluence ion irradiation [16, 17]. This way crystalline to amorphous transition in Si, upon ion irradiation, is more like a phase transition induced by an accumulation of sufficient number of defects which was also suggested by several groups earlier [16, 40, 41]. In the present case, onset of this occurs at a cluster fluence of around $2.5 \times 10^{13}$ cm$^{-2}$. For a much higher cluster fluence (as in S5), a continuous amorphous layer parallel to the surface is produced, leading to much reduced values for $\sigma$ and $C(q)$. It is therefore not surprising that the $\xi$, $\alpha$ and $\gamma$ values as obtained for S5 are very similar to those obtained for a-Si films [29]. This also confirms that the top surface of the S5 sample is actually amorphized, in agreement with channelling data (figure 1(b)) where saturation in damage production has been obtained. It is also important to realize that $k_B$ for S4 is much higher than that in the case of S3 (figure 1(b)). In fact it is closer to that in S5. However, complete amorphization does not occur here because the defects produced by Cs implantation are distributed over a greater depth resulting in comparatively less defect accumulation near the surface.

4. Conclusion

To conclude, we have carried out a systematic study of 25 keV Si$_5^+$ implantation induced damage and surface modifications in Si(1 0 0) where a nonlinear growth in subsurface damage, with fluence, is observed. The damage produced by similar mass Cs$^+$ ions, of the same energy, is seen to be distributed over a greater depth leading to much reduced surface features. With Si$_5$ clusters, the threshold fluence for amorphization of Si surface is found to be $2.5 \times 10^{13}$ clusters cm$^{-2}$, in agreement with earlier published data. Most importantly, at a higher cluster fluence a transition to an amorphous state resulting in a much reduced surface roughness is indicated.

Acknowledgments

The authors would like to thank A K Behera for the efficient running of the low energy implanter facility and all the operators of accelerator laboratory, IOP, during RBS/C runs. They acknowledge the cooperation of Professor S Varma of IOP and Dr S Bhattacharjee of IMMT, Bhubaneswar, for technical help regarding some preliminary AFM measurements and checks. One of the authors (HPL) wishes to thank Professor Kai Nordlund of Computational Material Physics Division, University of Helsinki, for some very useful suggestions and discussions.

References

[1] Popok V N and Campbell E B 2006 Rev. Adv. Mater. Sci. 11 19
[2] Yamada I, Matsuo J, Toyoda N and Kirkpatrick A 2001 Mater. Sci. Eng. R: Rep. 34 231
[3] Teranishi Y, Kondou K, Fujiwara Y, Nonaka H, Tomita M, Yamamoto K, Fujimoto T and Ichimura S 2006 Japan. J. Appl. Phys. 45 5528
[4] Andersen H H, Brunelle A, Della-Negra S, Depauw J, Jacquet D, Le Beyec Y, Chaumont J and Bernas H 1998 Phys. Rev. Lett. 80 5433
[5] Samartsev A V, Duvenbeck A and Wucher A 2005 Phys. Rev. B 72 115417
[6] Shao L, Nastasi M, Wang X, Liu J and Chu W K 2002 Nucl. Instrum. Methods B 242 503
[7] Liu J, Wang X, Shao L, Lu X and Chu W K 2002 Nucl. Instrum. Methods B 190 787
[8] Lenka H P, Joseph B, Kuiri P K, Sahu G and Mahapatra D P 2007 Nucl. Instrum. Methods B 256 665
[7] Titov A I, Azarov A Y, Nikulina L M and Kucheyev S O 2006 Phys. Rev. B 73 064111
[8] Prasalovich S, Popok V N, Persson P and Campbell E E B 2005 Eur. Phys. J. D 36 79
[9] Samela J, Nordlund K, Popok V N and Campbell E E B 2008 Phys. Rev. B 77 075309
[10] Park H S, Jung H J and Choi W K 2005 Thin Solid Films 475 36
[11] Allen L P, Fenner D B, Santeufemio C, Brooks W and Yamada I 2002 J. Appl. Phys. 92 3671
[12] Popok V N, Prasalovich S V and Campbell E E B 2003 Nucl. Instrum. Methods B 207 145
[13] Nakajima K, Toyofuku H and Kimura K 2001 Japan. J. Appl. Phys. 40 2119
[14] Diax dela Rubia T and Gilmer G H 1995 Phys. Rev. Lett. 74 2507
[15] Campisano S, Coffa S, Raineri V, Priolo F and Rimini E 1993 Nucl. Instrum. Methods B 80–81 514
[16] Holland O W, Pennycook S J and Albert G L 1989 Appl. Phys. Lett. 55 2503
[17] Bai G and Nicolet M A 1991 J. Appl. Phys. 70 649
[18] Volkert C A 1991 J. Appl. Phys. 70 3521
[19] Marques L A, Pelaz L, Lopez P, Santos I and Aboy M 2007 Phys. Rev. B 76 153201
Marques L A, Pelaz L, Aboy M, Enriquez L and Barbolla J 2003 Phys. Rev. Lett. 91 135504
Marques L A, Pelaz L, Hernandez J, Barbolla J and Gilmer G H 2001 Phys. Rev. B 64 045214
[20] Nord J, Nordlund K and Keinonen J 2002 Phys. Rev. B 65 165329
[21] WSxM free software. Available at www.nanotech.es
[22] Horcas I, Fernandez R, Gomez-Rodriguez J M, Colchero J, Gomez-Herrero J and Baro A M 2007 Rev. Sci. Instrum. 78 013705
[23] Agarwal A, Haynes T E, Eaglesham D J, Gossmann H J, Jacobson D C, Poate J M and Erokhin Y E 1997 Appl. Phys. Lett. 70 3332
[24] Chu W K, Mayer J W and Nicolet M A 1978 Backscattering Spectrometry (Orlando, FL: Academic) pp 120 and 328
[25] SRIM 2008 - a version of the TRIM program: Ziegler J F, Biersack J P and Littmark U 1995 The Stopping and Range of Ions in Matter (New York: Perganion)
[26] Dobeli M, Ender R M, Fischer U S, Safen H A and Vetterli D 1994 Nucl. Instrum. Methods B 94 388
[27] Eklund E A, Synder E J and Williams R S 1993 Surf. Sci. 285 157
[28] Makeev M A, Cuerno R and Barabasi A-L 2002 Nucl. Instrum. Methods B 197 185
[29] Bray K R and Parsons G N 2001 Phys. Rev. B 65 035311
[30] Fenner D B 2004 J. Appl. Phys. 95 5408
[31] Fang S J, Haplepete S, Chen W, Helms C R and Edwards H 1997 J. Appl. Phys. 82 5891
[32] Fang S J, Chen W, Yamanaka T and Heims C R 1996 Appl. Phys. Lett. 68 2837
[33] Petri R, Brault P, Vatel O, Henry D, Andre E, Dumas P and Salvan F 1994 J. Appl. Phys. 75 7498
[34] Tong W M, Williams R S, Yanase A, Segawa Y and Anderson M S 1994 Phys. Rev. Lett. 72 3374
[35] Rupp C and Duparre A 1996 Thin Solid Films 288 8
[36] Senthilkumar M, Sahoo N K, Thakur S and Tokas R B 2005 Appl. Surf. Sci. 252 1608
[37] Herring C 1950 J. Appl. Phys. 10 3521
[38] Tong W M, Synder E J, Williams R S, Yanase A, Segawa Y and Anderson M S 1992 Surf. Sci. 277 L63
[39] Mayr S G and Averback R S 2001 Phys. Rev. Lett. 87 196106
[40] Swanson M L, Parsons J R and Hoelke C W 1971 Radiat. Eff. 9 249
[41] Motooka T, Harada S and Ishimaru M 1997 Phys. Rev. Lett. 78 2980